Collection of Papers on Hydrogeology

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S S D FOSTER

B Sc C Eng MICE MIGeol AIL FIWES

D Sc THESIS
UNIVERSITY OF LONDON

Faculty:	Science
Department:	Geology
Subject:	Hydrogeology

June 1982

'we see a science (hydrogeology) emerging from
its geological roots and early hydraulic applications,
becoming of greater importance in the affairs of man'

Allan Freeze & John Cherry, 1979
'Groundwater' (Prentice-Hall), preface

ACKNOWLEDGEMENT

With thanks to certain staff of King's College, London for my academic education, to the Institute of Geological Sciences, and its customers in Britain and overseas, for the opportunity to have researched a wide range of hydrogeological topics, to my colleagues over more than 15 years for their collaboration and stimulation and to my wife and daughter for patience and encouragement.

ACADEMIC & PROFESSIONAL QUALIFICATIONS

1965	B Sc Honours (Upper Second Class) Geology (with Physics, Chemistry & Mathematics) University of London (King's College)
1973	Chartered Engineer Member of Institution of Civil Engineers (London) (Specialist Categories: Hydrology & Geotechnics)
1973 1979	Member/Fellow of Institution of Water Engineers & Scientists (London)
1979	Member of Institution of Geologists (London)
1981	Associate of Institute of Linguists (London) (Category: English-Spanish)

PROFESSIONAL AWARDS

1974	Whitaker Medal (presented April 1975) Institution of Water Engineers & Scientists for outstanding paper on application of geological science to water engineering
1977	R A Carr Premium (presented November 1978) Institution of Civil Engineers (London) for praiseworthy paper on groundwater engineering

RECENT PROFESSIONAL ACTIVITIES

1977-1982	Research Leader of Groundwater Flow & Pollution Section Institute of Geological Sciences (Hydrogeology Unit)
1975-1982	Subcommittee/Working Group Member for DoE Standing Technical Advisory Committee on Water Quality
1980-1982	Short-Term Consultant on Groundwater Pollution to WHO — International Reference Centre for Wastes Disposal (Zurich) and WHO — Pan-American Health Organisation (Lima)
1975-1982	Visiting Advisor to a) Costa Rica/Servicio Nacional de Aguas b) Botswana/Ministry of Mineral Resources & Water Affairs on Large-Scale Groundwater Supply Development
1981	Visiting Lecturer at Universidad Autonoma de Madrid International Graduate Post-Experience Course on Study of Groundwater Chemistry & Pollution
1979	Specialist Assessor (Hydrogeology) at DoE Public Inquiry on STWA Shropshire Groundwater Scheme
1976-1977	Manager of Anglo-Botswana GS10 Project: Evaluation of Underground Water Resources
1976	Co-ordinator of ODM Mission to Sri Lanka on Economics of Groundwater Resource Use in Agricultural Development

BACKGROUND TO PUBLISHED WORK

The published work is presented as evidence of authorative standing in the field of hydrogeology, especially in relation to the British Chalk (the principal national aquifer) and to groundwater pollution.

The scientific publications listed below, which collectively constitute this thesis, have been individually classified on three separate criteria:

(a) *Type of Publication*

W submission subject to normal guidelines and refereeing

X invited contribution to conference proceedings or journal

Y publication agreed and promoted by IGS directorate

Z discussion contribution to conference or journal

(b) *Status of Authorship*

a sole author

b co-author with colleagues working under my direct supervision, first authorship when also writing paper concerned

c+ co-author with other colleagues

d+ co-author with groundwater specialists from other organisations

e+ co-author with professionals from other organisations of different disciplines

(+ first authorship indicates leadership in corresponding research and/or in writing paper)

(c) *Topic of Research*

A groundwater and pollutant movement in the unsaturated zone

B groundwater and pollutant movement in the saturated zone, especially of fissured porous aquifers

C groundwater pollution investigation

D groundwater resources evaluation

E geotechnical groundwater problems

(* identifies those publications which relate in some way or other to groundwater in the British Chalk, a long-standing research interest)

In addition to the publications listed, a significant role was played in writing some anonymous publications, whose size prevents presentation here, including:

GLC Thames Flood Prevention Project
1st/2nd Report of Studies (1969/1971)

WHO — International Reference Centre for Wastes Disposal
Manuals on Groundwater Pollution & On-Site Sanitation
(in press)

LIST OF PUBLISHED WORK

(1)	1982	Foster S S D, Cripps A C & Smith-Carington A K Nitrate leaching to groundwater Phil Trans Royal Soc London 296 : 477-489 & 574 RSL Symposium 'The Nitrogen Cycle' (London, 1981) 175-187 & 272	X	b	A*
(2)	1982	Farr J L, Spray P R & Foster S S D Groundwater supply exploration in semi-arid regions for livestock extension - a technical and economic appraisal Water Supply & Management 6 : 343-353	W	b	D
(3)	1982	Foster S S D, Bath A H, Farr J L & Lewis W J The likelihood of active groundwater recharge in the Botswana Kalahari J Hydrol 55 : 113-136	W	b	A
(4)	1982	Foster S S D & Bath A H The distribution of agricultural soil leachates in the unsaturated zone of the British Chalk IAH Symposium 'Impact of Agricultural Activities on Groundwater' (Prague, 1982) (in press)	X	c	A*
(5)	1982	Foster S S D, Mackie C D & Townend P Exploration, evaluation and development of large-scale groundwater supplies in the Botswana Kalahari Proc Inst Civil Engrs I (in press)	W	e	D
(6)	1981	Oakes D B, Young C P & Foster S S D The effect of farming practices on groundwater quality in the United Kingdom RvD Symposium 'Quality of Groundwater' (Noordwijkerhout, 1981) Studies Environ Science W7 : 27-40 Science Total Environ 21 : 17-30	X	d	C*
(7)	1981	Lewis W J, Foster S S D, Read G H & Schertenleib R The need for an integrated approach to water supply and sanitation in developing countries RvD Symposium 'Quality of Groundwater' (Noordwijkerhout, 1981) Studies Environ Science 17 : 199-205 Science Total Environ 21 : 53-59	X	e	C
(8)	1981	Barker J A & Foster S S D A diffusion exchange model for solute movement in fissured porous rock Quart J Eng Geol 14 : 17-24	W	c	A*
(9)	1980	Foster S S D & Smith-Carington A K The interpretation of tritium in the Chalk unsaturated zone J Hydrol 46 : 343-364	W	b	A*

(10)— Lewis W J, Farr J L & Foster S S D
The pollution hazard to village water supplies
1980 in eastern Botswana W b C
Proc Inst Civil Engrs II : 69 : 281-293

(11)— Foster S S D
ICE Conference 'Water Resources - a Changing
Strategy' (London, 1979)
(a) Combined use of surface and groundwater
1980 resources/Regional groundwater development Z a D
in temperate and arid zones : 95-96

(b) Improving the health consequences of Z a C
tropical water resource development : 196-197

(12)— Foster S S D & Young C P
Conséquences de l'utilisation agricole des sols
sur les qualité de l'eau souterraine et notamment
1979 sur la teneur en nitrate
Bull BRGM (2: III) 3 : 245-256
(Hydrogéologie brittanique - progrès récents)
Groundwater contamination due to agricultural X d C*
1980 land-use practices in the United Kingdom
UNESCO-IHP Studies & Reports in Hydrology Series
'Aquifer Contamination & Protection' 30 : 268-282
Effects of agricultural land-use on groundwater
1981 quality with special reference to nitrate
Royal Soc London 'A survey of British
Hydrogeology' : 47-59

(13)— Foster S S D & Cripps A C
ICE Symposium 'Thames Barrier Design'
1978 (London, 1977) : 62-64 Z b E
Thames Barrier - site investigation and
geotechnical considerations

(14)— Foster S S D
1978 ICE Symposium 'Thames Groundwater Scheme'
(Reading, 1978) : 91-94 Z a B*
Characteristics and yield of fissured Chalk

(15)— Foster S S D & Price M
British examples of a hydrogeological approach
1978 to the evaluation of drainage problems in X c E
subsurface engineering
SIAMOS 'Water in Mining & Underground Works'
(Granada, 1978) I : 409-428

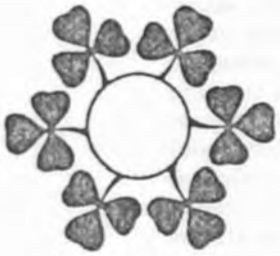
(16)— Foster S S D & Robertson A S
1977 Evaluation of a semi-confined Chalk aquifer W b B*
in East Anglia
Proc Inst Civil Engrs II : 63 : 803-817

(17)— Price M, Robertson A S & Foster S S D
Chalk permability - a study of vertical
1977 variation using water injection tests and W b B*
borehole flow logging
Water Services 81 : 603-610

(18) 1976	Foster S S D, Stirling W G N & Paterson I B Groundwater storage in Fife and Kinross - its potential as a regional resource IGS Report Series 76/9 : 21pp	Y	e	D
(19) 1976	Foster S S D Proc Inst Civil Engrs II : 61 : 849-850 A numerical model for pumping test analysis	Z	a	B
(20) 1976	Foster S S D & Milton V A Hydrological basis for the large-scale development of groundwater storage capacity in the East Yorkshire Chalk IGS Report Series 76/3 : 71pp	Y	b	D*
(21) 1976	Foster S S D, Parry E L & Chilton P J Groundwater resources development and saline water intrusion in the Chalk aquifer of North Humberside IGS Report Series 76/4 : 34pp	Y	b	D*
(22) 1976	Foster S S D The vulnerability of British groundwater resources to pollution by agricultural leachates ADAS-ARC Conference 'Agriculture & Water Quality' (Nottingham, 1974) MAFF Tech Bull 32 : 68-91	X	a	C*
(23) 1976	Price M, Bird M J & Foster S S D Chalk pore-size measurements and their significance Water Services 80 : 596-600	W	c	A*
(24) 1975	Foster S S D IWES Symposium 'Maintenance of Water Quality' (Cambridge, 1975) : 40 Protective measures for groundwater resources	Z	a	C
(25) 1975	Foster S S D The Chalk groundwater tritium anomaly - a possible explanation J Hydrol 25 : 159-163	W	a	A*
(26) 1975	Foster S S D & Crease R I Hydraulic behaviour of the Chalk aquifer in the Yorkshire Wolds Proc Inst Engrs II : 59 : 181-188	W	e	B*
(27) 1975	Foster S S D Quart J Eng Geol 8 : 125 Rapid groundwater flow in fissures in the Chalk: an example from south Hampshire	Z	a	B*
(28) 1975	Foster S S D ICE-IHD-IH Conference 'Engineering Hydrology Today' (London, 1975) 128-129 Groundwater yield estimation from models	Z	a	D

(29)	1974	Foster S S D & Crease R I Nitrate pollution of Chalk groundwater in East Yorkshire - a hydrogeological appraisal J Inst Water Engrs 28 : 178-194 WRA Conference 'Groundwater Pollution in Europe' (Reading, 1972) WIC : 269-274	W	e	C*
(30)	1974	Foster S S D Groundwater storage - riverflow relations in a Chalk catchment J Hydrol 23 : 299-311	W	a	B*
(31)	1974	Foster S S D & Milton V A The permeability and storage of an unconfined Chalk aquifer IAHS Hydrol Sci Bull 19 : 485-500	W	b	B*
(32)	1974	Price M & Foster S S D Water supplies from Ulster valley gravels Proc Inst Civil Engrs II : 57 : 451-456	W	b	D
(33)	1974	Foster S S D & Price M Ground Water 12 : 49 Hydraulics of sheetlike solution cavities	Z	b	B
(34)	1974	Foster S S D & Lovelock P E R WRA Conference ' Groundwater Pollution in Europe' (Reading, 1972) WIC : 67-68 Hydrogeological factors in groundwater pollution	Z	c	C
(35)	1972	Gray D A & Foster S S D Urban influences upon groundwater conditions in the Thames Flood Plain Deposits of Central London RSL Symposium 'Problems associated with subsidence of southeastern England' (London, 1971) Phil Trans Royal Soc London A : 272 : 245-257	X	c	E
(36)	1970	Foster S S D ICE Conference 'Groundwater Engineering' (London, 1970) : 105-106 Control of groundwater by water lowering	Z	a	E

THE
NITROGEN
CYCLE



The Royal Society of London

THE NITROGEN CYCLE

Nitrogen has a fundamental effect on our lives. It is a component of all living cells: of amino acids and nucleic acid bases. Substantial amounts of chemically fixed nitrogen are essential for crop productivity; nitrogen affects our food supplies and our balance of payments. Nitrogenous compounds may also be pollutants. Environmentalists and water-supply engineers are concerned about increasing nitrate concentrations in many waters of the United Kingdom, there is evidence that nitrate-derived products are potential health hazards, and there is controversy as to whether the losses of gaseous products of nitrogen from the Earth's surface affect the ozone layer, which shields the Earth from harmful ultraviolet irradiation. These and other aspects are considered in the papers of this volume, which were presented at a two-day Discussion Meeting of the Royal Society in June 1981. Collectively they provide an up-to-date account of various aspects of the nitrogen cycle of the United Kingdom both in a local and international context. They will be of value to workers in agriculture, forestry, the environment, the water industry, marine biology, ecology, microbiology and biochemistry.

THE NITROGEN CYCLE

A ROYAL SOCIETY DISCUSSION
HELD ON 17 AND 18 JUNE 1981

ORGANIZED BY
W. D. P. STEWART, F.R.S., AND T. ROSSWALL

LONDON
THE ROYAL SOCIETY
1982

CONTENTS

AGRICULTURE AND THE NITROGEN CYCLE

Phil. Trans. R. Soc. Lond. **296**, 477–489 (1982)
Printed in Great Britain

Nitrate leaching to groundwater

BY S. S. D. FOSTER, A. C. CRIPPS AND AMANDA SMITH-CARINGTON

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Groundwater provides over 30% of developed supplies of potable water in Britain. The outcrops of the important aquifers form extensive tracts of agricultural land. Groundwater resources largely originate as rainfall that infiltrates this land. During the 1970s, growing concern about rising, or elevated, groundwater nitrate concentrations, in relation to current drinking water standards, stimulated a major national research effort on the extent of diffuse pollution resulting from agricultural land-use practices.

The results presented derive from intensive and continuing studies of a number of small groundwater catchments in eastern England. It is in this predominantly arable region that the groundwater nitrate problem is most widespread and severe. The distribution of nitrate in the unsaturated and saturated zones of the aquifers concerned is summarized. These data have important implications for the water-supply industry, but their interpretation is discussed primarily in relation to what can be deduced about both the recent and long-term histories of leaching from the more permeable agricultural soils.

INTRODUCTION

Occurrence and significance of groundwater resources

In Britain, groundwater abstraction, predominantly for potable water-supply, averages about 7000 Ml d^{-1}, of which some 50% is from the Cretaceous Chalk, 35% from the Triassic Sandstone and the remainder from smaller aquifers, notably the Jurassic Limestone and the Cretaceous Lower Greensand. The main aquifer outcrops (figure 1) form extensive areas of valuable farmland in eastern, central and southern England. Groundwater resources, which largely originate in these areas as infiltrating excess rainfall are, and always have been, directly vulnerable to diffuse pollution by agricultural practices.

Over much of the aquifer outcrop areas (the unconfined aquifers), the groundwater table, even at its highest seasonal level, is below 10 m depth and quite widely exceeds 20 m depth. Rainfall infiltrating below the depth of influence of plant roots will pass vertically downward through the aerated (or unsaturated) zone before recharging the main groundwater body (or saturated zone). Such recharge then becomes incorporated in the lateral flow of the regional groundwater system and, if not abstracted for water-supply, will eventually discharge to form the baseflow of streams and rivers. In eastern and central England the major aquifers are extensively covered by a variable suite of Pleistocene glacial (drift) deposits (figure 1), which to varying degrees confine groundwater, reduce recharge rates from infiltrating rainfall and thus form the semi-confined aquifers.

Although a fraction of the groundwater and dissolved salts in natural circulation may be discharged in the same year that they originated as infiltration from agricultural soils, it must be stressed that groundwater residence times for British aquifers will more often exceed 10, or even 20, years (Foster & Crease 1974; Foster 1976). At considerable depth below the groundwater table and in the deeper confined aquifers, circulation may be exceedingly slow and, in certain areas, groundwater has been dated back to at least 10 ka B.P. Thus groundwater systems are quite different from surface watercourses in that the effects of pollution incidents become apparent much more slowly in water supplies but persist much longer.

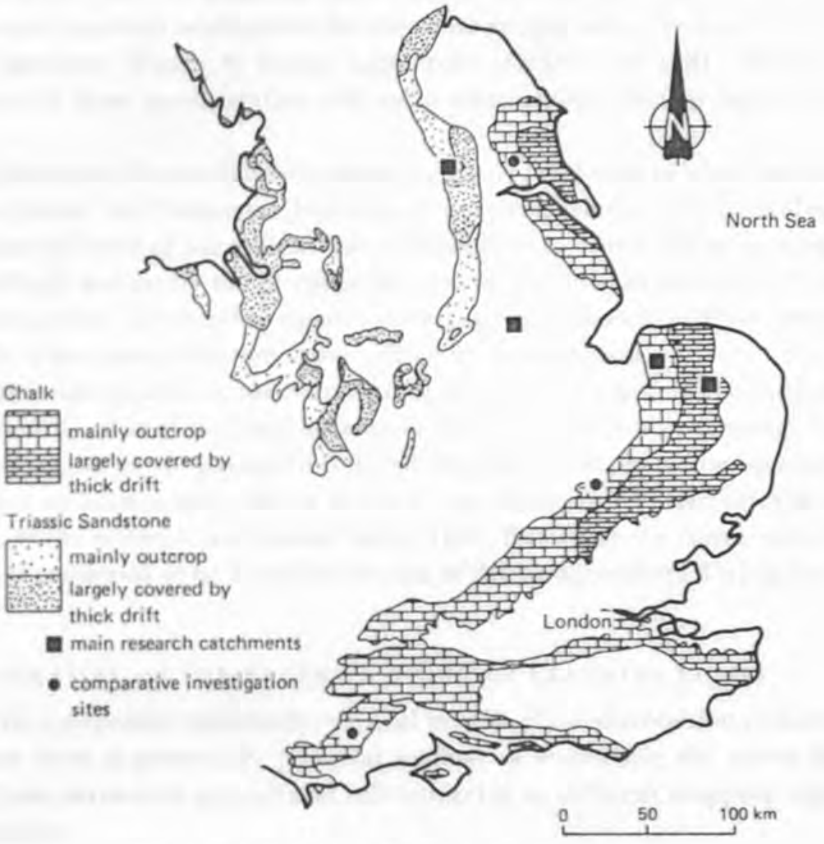


FIGURE 1. Distribution of major British aquifers.

The main British aquifers are all of the porous bedrock type, in which discontinuities (fissures) have a varying, but often overriding, influence on overall groundwater, solute and pollutant movement, but in which the pore water of the rock matrix will often play an important role in retarding the movement of solutes and pollutants.

Approach and scope of the paper

Among the substances added to, and/or generated by, agricultural soils, nitrates are most prominent, since they are very soluble, readily leached, and represent a health hazard at a relatively low concentration in water supplies.

Discussion of nitrate leaching to groundwater will be limited to that from agricultural soils, although it should be noted that nitrate may also be leached from most unsewered sanitation units, certain sewage disposal and waste-water reclamation processes and from farmyard livestock effluents during their handling, storage and disposal. Such leaching, however, is more of local than regional significance, at least in the British context.

The results presented derive exclusively from a continuing I.G.S. research project, which began in 1975. It is being executed primarily through the detailed long-term study of four small groundwater catchments (figure 1) to public water-supply boreholes experiencing a significant, and growing, nitrate problem. The research is part of a coordinated programme in which the Water Research Centre and the Regional Water Authorities are also involved. The results to date have important practical implications for the water-supply industry, which have received interim review elsewhere (Foster & Young 1979, 1981; Oakes *et al.* 1981). However, some significant aspects of their interpretation still await clarification through further long-term fieldwork.

In this paper, however, the results are discussed primarily in relation to what can be deduced about both the recent and long-term histories of nitrate leaching from agricultural soils. Reliable estimates of leaching losses from the permeable soils, which occur on most aquifer outcrops, are difficult and costly to determine by agricultural field experiments. At the same time they are likely, other factors being equal, to be greater than those from lower-permeability less-aerated soils, where denitrification losses will be more significant.

Since the aquifer outcrop areas occur mainly in the drier parts of England and their associated soils are well drained, most of the land area involved is used for arable farming. There is a corresponding bias in this paper. In eastern England the widespread ploughing-up of permanent pasture is believed to have taken place in the nineteenth century and had certainly affected more than 80% of the research catchments before 1935. Elsewhere the conversion of pasture to arable land has continued to be a marked feature of British agriculture during this century.

APPRAISAL OF THE RECENT HISTORY OF LEACHING LOSSES

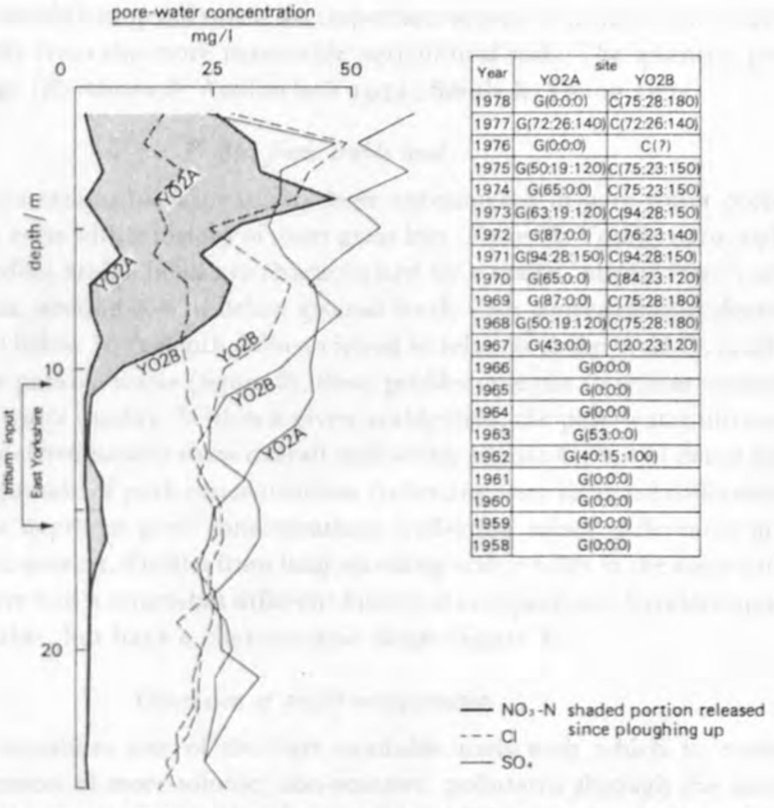
If they could be interpreted confidently, vertical profiles of the distribution of nitrate in the unsaturated zone form a potentially powerful method of evaluating the recent history of leaching losses from permeable agricultural soils subjected to different cropping régimes and fertilizer applications.

It is only feasible to sample the pore water of the unsaturated zone. The methods of sampling and analysis for nitrate (and the other frequent determinands) have been described elsewhere (Foster & Young 1979, 1981). Among unsaturated zone pore-water profiles from British aquifers, those from the Chalk offer the best possibility of detailed interpretation, because of this formation's greater overall areal uniformity in hydraulic properties on the small scale. They have been shown to be related to the history of agricultural practice on the overlying land, and are alone discussed further in this section.

Profiles from pasture land

Profiles from unfertilized and fertilized permanent grassland (e.g. figures 2 and 3) have been shown to be characterized by low and uniform nitrate concentrations, frequently less than 2 mg NO_3-N l^{-1}. They suggest that corresponding leaching losses do not generally exceed 10 kg N ha^{-1} annually, except perhaps where rates of inorganic N fertilizer application are, by current standards, abnormally high (over 250 kg N ha^{-1} annually).

Profiles from beneath a large, now partitioned, field in East Yorkshire (figure 2), show the marked effect of ploughing-in of pasture with subsequent continuous cereal cropping. The enhanced mineralization of organic N in the soil biomass consequent upon the aeration caused



Year	site YO2A	YO2B
1978	G(0:0:0)	C(75:28:180)
1977	G(72:26:140)	C(72:26:140)
1976	G(0:0:0)	C(?)
1975	G(50:19:120)	C(75:23:150)
1974	G(65:0:0)	C(75:23:150)
1973	G(63:19:120)	C(94:28:150)
1972	G(87:0:0)	C(76:23:140)
1971	G(94:28:150)	C(94:28:150)
1970	G(65:0:0)	C(84:23:120)
1969	G(87:0:0)	C(75:28:180)
1968	G(50:19:120)	C(75:28:180)
1967	G(43:0:0)	C(20:23:120)
1966	G(0:0:0)	
1965	G(0:0:0)	
1964	G(0:0:0)	
1963	G(53:0:0)	
1962	G(40:15:100)	
1961	G(0:0:0)	
1960	G(0:0:0)	
1959	G(0:0:0)	
1958	G(0:0:0)	

FIGURE 2. Pore-water profiles for Chalk unsaturated zone in East Yorkshire showing the effects of partial conversion from pasture to arable land in autumn 1966 (G, permanent grassland; C, winter or spring cereals; (N:Cl:SO_4) ratio (kilograms per hectare) applied annually in fertilizers.)

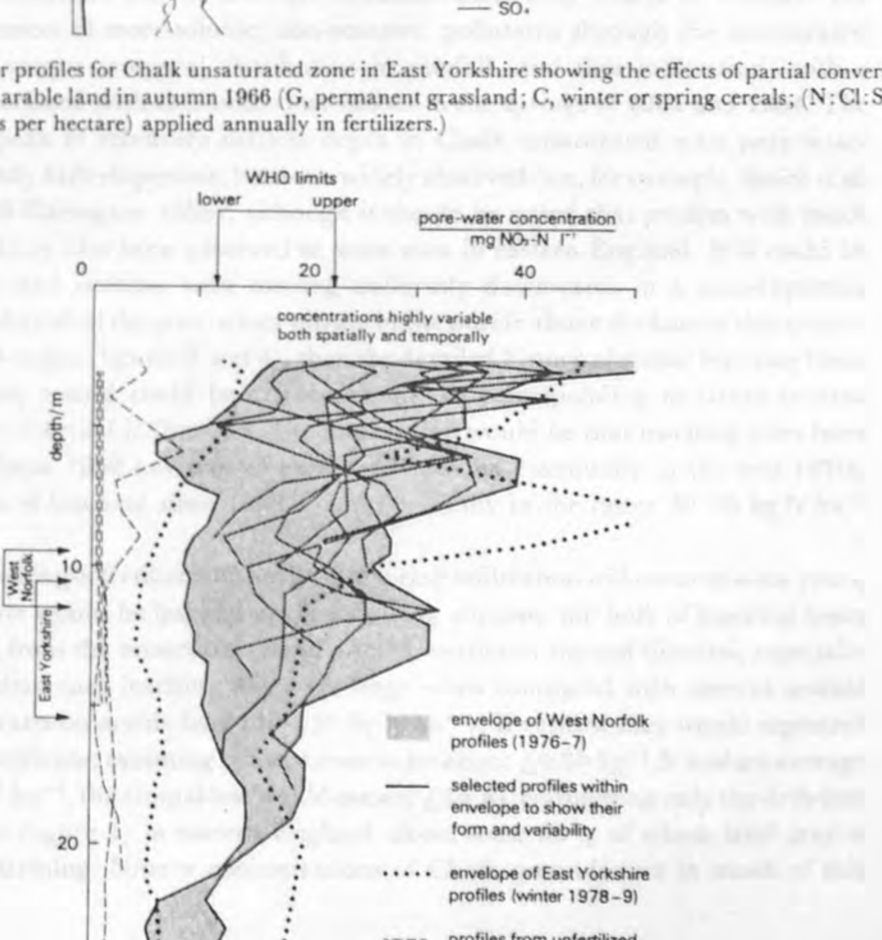


FIGURE 3. Summary of nitrate profiles for Chalk unsaturated zone beneath long-standing arable land.

by ploughing-in of established grassland is an important source of nitrate that might be lost by leaching, especially from the more permeable agricultural soils. The quantity potentially available is very large (Reinhorn & Avnimelech 1974; Smith & Young 1975).

Profiles from arable land

High nitrate concentrations have invariably been encountered in pore-water profiles from beneath arable land, even with a history of short grass leys (Foster & Young 1979, 1981). The profiles for long-standing arable fields are characterized by a major 'nitrate front', which has reached, or formed at, around 3–8 m below ground level, with concentrations decreasing to 10–20 mg NO_3-N l^{-1} below 10 m depth. When viewed in relation to the W.H.O. (and E.E.C.) recommendations for potable water (figure 3), these profiles give rise to serious concern about future Chalk groundwater quality. Within a given arable field, the pore-water nitrate profiles (and those for other determinands) show overall uniformity (figure 4), but in detail significant variations in the magnitude of peak concentrations (reflecting very localized differences in soil leaching) and in the depth to peak concentrations (reflecting minor differences in the net groundwater flux) are present. Profiles from long-standing arable fields in the same catchment, each of which will have had a somewhat different history of cropping and fertilizer application, are much more variable, but have a characteristic shape (figure 3).

Discussion of profile interpretation

Natural tritium constitutes one of the best available tools with which to evaluate the mechanisms of movement of more-soluble, non-reactive, pollutants through the unsaturated zone, because of its unique temporal distribution in rainfall (and thus infiltration) with a pronounced peak associated with thermonuclear fallout in the springs of 1963 and 1964. The preservation of this peak at relatively shallow depth in Chalk unsaturated zone pore-water profiles, with apparently little dispersion, has been widely observed (see, for example, Smith *et al.* 1970; Foster & Smith-Carington 1980), although it should be noted that profiles with much broader peak width have also been observed at some sites in eastern England. If it could be assumed that solutes and isotopes were moving uniformly downwards in a non-dispersive ('piston') flow, such that all of the pore-water nitrate in the profile above the base of this tritium peak was of post-1963 origin (figures 3 and 4), then the detailed history of recent leaching losses for the given cropping record could be deduced from the corresponding moisture content profiles and estimates of actual infiltration. The implication would be that leaching rates have risen steadily from about 1960 onwards to exceed 80 kg N ha^{-1} annually in the mid-1970s. Average annual rates of leaching since 1963 would be mainly in the range 50–70 kg N ha^{-1} (table 1).

Although direct leaching of fertilizer nitrate by late spring infiltration will occur in some years, and any unused nitrate would be leached in the following autumn, the bulk of leaching losses are probably derived from the mineralization of organic matter in the soil biomass, especially in autumn. Nevertheless, such leaching losses are large when compared with current annual fertilizer application rates on arable land (80–130 kg N ha^{-1}). If verified they would represent an enormous loss of nutrients: assuming current costs to be about £0.30 kg^{-1} N and an average annual loss of 80 kg N ha^{-1}, the annual loss would exceed £15 M, considering only the drift-free aquifer outcrop areas (figure 1) in eastern England alone, some 80 % of whose land area is dedicated to arable farming. Nitrate concentrations of Chalk groundwater in much of this

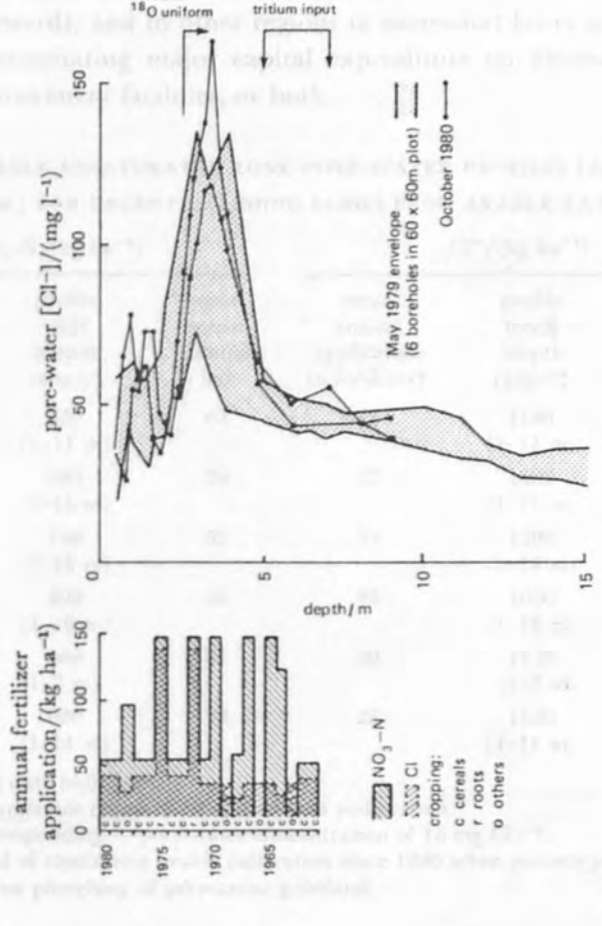


FIGURE 4. Multiple and sequential unsaturated zone pore-water profiles for an individual long-standing arable field on Cambridge Chalk.

region would, by implication, rise steadily to reach intolerable levels (in excess of 22.6 mg NO_3-N l^{-1}) from the 1990s onwards, and in other regions to somewhat lower levels at later dates (Young *et al.* 1976), necessitating major capital expenditure on alternative water-supply development or water treatment facilities, or both.

TABLE 1. ANALYSIS OF CHALK UNSATURATED ZONE PORE-WATER PROFILES (ASSUMING NON-DISPERSIVE FLOW) FOR RECENT LEACHING LOSSES FROM ARABLE LAND

	NO_3^--N/(kg ha^{-1})			Cl^-/(kg ha^{-1})		
site (sampling date)	mean annual application in fertilizer†	profile total (depth range)‡	equiv. mean annual loss	mean annual application in fertilizer†	profile total§ (depth range)‡	equiv. mean annual loss
N01X (Feb. 1976)	132	830 (1–11 m)	64	72	1180 (1–11 m)	91
N60 (Apr. 1977)	143	980 (1–11 m)	70	77	1460 (1–11 m)	104
Y08 (Oct. 1978)	125	780 (1–16 m)	52	78	1290 (1–16 m)	86
Y09–10 (Oct. 1978)	153	600 (1–16 m)	40	88	1000 (1–16 m)	67
C01–06 (May 1979)	78	980 (1–7 m)	61	50	1170 (1–7 m)	73
Y02B‖ (Oct. 1978)	75 100¶	1020 (1–11 m)	93	25	1150 (1–11 m)	104

† During period 1963 to sampling date indicated.

‡ From below main root zone to apparent depth of 1963–4 tritium penetration.

§ After deducting background corresponding to pore-water concentration of 15 mg Cl l^{-1}.

‖ Figures for Y02B relate to period of continuous arable cultivation since 1966 when pasture ploughed in.

¶ Allowing 300 kg N ha^{-1} release on ploughing of permanent grassland.

The possibility of substantial nitrate attenuation through denitrification within the unsaturated zone, beneath arable land at least, seems rather unlikely (Foster & Young 1979, 1981). Biochemical denitrification cannot yet be discounted, however, since significant (insoluble) organic carbon concentrations and, occasionally, nitrate-reducing bacteria populations have now been measured at a considerable depth below the soil interface at a few sites (Whitelaw & Rees 1980; Hall 1981).

In view of the scale of its implications, the profile interpretation above warrants a detailed re-examination. Two difficulties are immediately apparent.

First, in eastern England arable farming practices underwent their most important post-war change, to more continuous cereal cropping sustained by much higher N fertilizer applications, during the period 1955–65, and have been relatively constant since then. The 'implied date' of major increases in the pore-water nitrate profiles is from the late 1960s. Thus a considerable time-lag in the response of soil biomass mineralization to increased inputs of organic N from crop residues would have to be invoked. Bearing in mind the complexity of the soil system this may be feasible. At some sites in southern England with rather different cropping histories, however, nitrate profiles have been simulated by using surprisingly simple 'release rules' (Oakes *et al.* 1981), based on the observation that an equivalent of only 50% of applied fertilizer N is taken up by the crop (Kolenbrander 1977) and the assumption that, for permeable arable soils, an amount equivalent to all the unused fertilizer N will be released and leached from the soil, by one process or another, during the subsequent 3 years.

Secondly, in the analysis of the pore-water profiles for a non-nutrient, non-reactive, ion such as chloride, it is only possible to approach a satisfactory mass balance for the post-1963 period (table 1) by assuming rather extreme values for the chloride content of rainfall and of the various brands of soil fertilizers and additives.

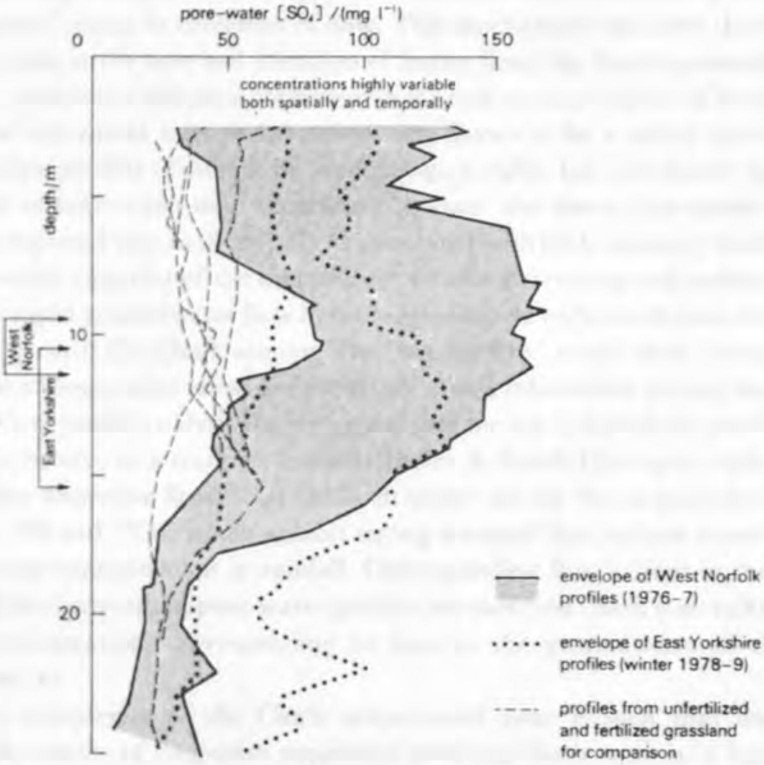


FIGURE 5. Summary of sulphate profiles for Chalk unsaturated zone beneath long-standing arable land.

Similar can be said of sulphate, which is present in the profiles from beneath arable land in enormous quantities (figure 5) with maximum annual leaching rates perhaps reaching 250 kg SO_4 ha^{-1}. Although the rate of migration of sulphate is likely to differ significantly from that of chloride, because of their differing physicochemical properties, the sulphate distribution does not appear to be solubility controlled nor related to the oxidation of naturally occurring sulphides. Thus this sulphate was probably derived largely from the original manufactured forms of N fertilizer, $(NH_4)_2SO_4$, and P fertilizer, $Ca(H_2PO_4)_2$–$CaSO_4$, with the implied somewhat lower leaching rates in recent years (figure 5) reflecting gradual replacement by NH_4NO_3 and $NH_4H_2PO_4$ during the 1960s. (In passing it must be mentioned that there is accumulating evidence of a concomitant increase in the leaching or mobility, or both, of Ca, Na, Mg, K, Ba, Sr, B and perhaps other ions, as a direct result of modern arable farming practices or indirectly through modification of unsaturated zone water–rock equilibria caused by the changing composition of soil leachates; these are likely to confront the water supply industry with additional future problems.)

The Chalk unsaturated zone pore-water to which the solute profiles relate is generally believed to be essentially immobile and, below about 2 m depth, the rock matrix is expected to remain almost fully saturated because of the very small pore sizes (Foster 1975), although this may not be true at all sites (Wellings & Bell 1980). Solute transport downwards from the zone of plant influence is thought to be controlled by a mechanism involving solute exchange, by lateral molecular diffusion, between mobile microfissure water and immobile pore water, the former eluting solutes from high-concentration 'regions' in the matrix and transferring them to lower-concentration 'regions' along its direction of flow. This mechanism has been shown to be very sensitive to variations in the rate and duration of fissure flow, the fissure geometry and the porosity and aqueous molecular diffusion coefficient in the rock matrix (Barker & Foster 1981). Non-dispersive solute movement in such formations was shown to be a rather special case. Detailed analysis of tritium profiles (Foster & Smith-Carington 1980) has also shown that perhaps up to 20% or more of infiltration may completely 'bypass' the above slow mode of downward movement. It is suspected that such 'bypass' is associated with high-intensity winter rainfall exceeding the infiltration capacity of the microfissure system, decreasing soil moisture potentials and allowing very rapid groundwater flow in the larger fissures with insufficient time for significant solute exchange with the Chalk matrix. The 'bypass flow' could often contain relatively low nitrate concentrations, since these are prevalent in soil infiltration during most of the winter period. The tritium profile analysis also suggested that the top 2–3 m of the profile, including the soil itself, must behave in a complex fashion (Foster & Smith-Carington 1980), with rapid mixing and highly dispersive flow. This has been borne out by recent pore-water profiling for stable isotopes (^{2}H and ^{18}O), which exhibit strong seasonal fluctuations about a fairly constant long-term mean concentration in rainfall. Corresponding fluctuations in their concentration in the top 2–3 m of sequential pore-water profiles are observed (Bath *et al.* 1981), with relatively constant concentration, corresponding to that in the groundwater of the saturated zone, below (figure 4).

It is concluded that the complexity of the Chalk unsaturated zone is such that final interpretation must await the results of long-term sequential profiling. Such work is in hand but has so far produced conflicting results. Although clear downward movement of tritium and nitrate have been observed at some sites (Foster & Smith-Carington 1980; Oakes *et al.* 1981), there is as yet no definite evidence for the systematic, non-dispersive, downward movement of the main 'nitrate front' beneath long-standing arable land. Indeed, results from a site of very detailed investigation on the Cambridge Chalk show marked changes in peak concentration more consistent with dispersive flow, possibly coupled with denitrification (figure 4).

If such a flow mechanism predominated the downward movement of nitrate, it is possible that the more recent rates of leaching loss, while increasing from earlier (pre-1965) values of about 40 kg N ha^{-1} annually, are significantly less than those implied by non-dispersive flow. Since long-term mean annual infiltration is mainly in the range 200–300 mm and arable land occupies up to 80% of the aquifer outcrop area, in the absence of denitrification, leaching rates become critical to water-supply interests in eastern England in the range 55–80 kg N ha^{-1} annually.

Current outlook

Among current trends in agricultural practice, the move from spring-sown to winter-sown cereals and perhaps also the introduction of minimal cultivation techniques should reduce nitrate leaching to groundwater from permeable arable land.

The forecast renewed increase in fertilizer application to cereals and the continued major increases on grass, however, may well prove detrimental to water-supply interests.

LONGER-TERM HISTORY OF LEACHING LOSSES

The distribution of nitrate and other solutes in the saturated zone of unconfined aquifers, and particularly at depth in that zone, relates in a general way to the longer-term history of leaching losses from agricultural soils. The data cannot be interpreted directly since they reflect the influence not only of variable leaching rates but also varying land-use, especially increasing arable acreages, unknown but perhaps significant denitrification (since nitrate-reducing bacteria have been recovered at depths of more than 20 m below groundwater table), and complex groundwater flow régimes with unknown dispersion, in which vertical, as well as lateral, flow components are present.

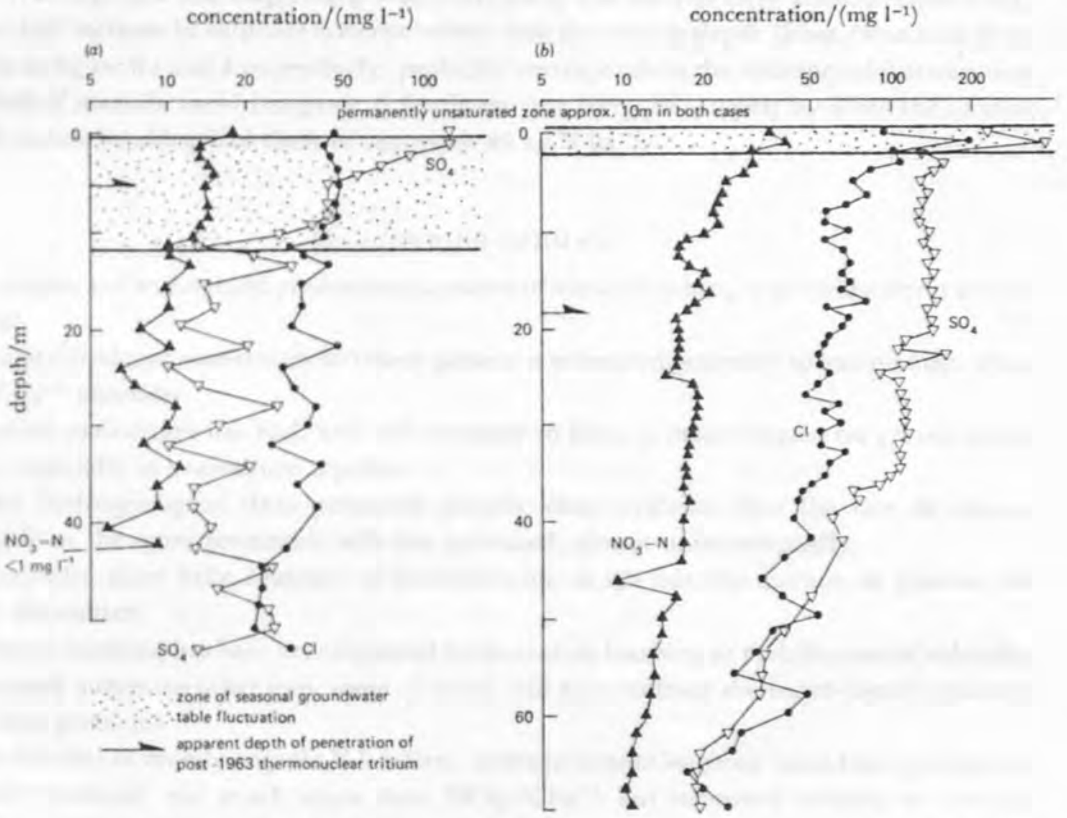


FIGURE 6. Chemical profiles of saturated zone pore-waters from outcrop areas of (*a*) West Norfolk Chalk in 1976 and (*b*) South Yorkshire Triassic Sandstone in 1980.

However, in eastern England where, for example, more than 80% of the research catchments have been under continuous arable cropping since 1935 (the earliest land-use survey at field level) and probably throughout this century, some interesting observations can be drawn from chemical pore-water profiles in the saturated zone (figure 6). (In passing it should be mentioned that pore-water chemistry has been shown generally to agree quite closely with that of groundwater pumped from the corresponding depth interval, although, as would be expected from the above discussion, significant differences have been sometimes observed in the Chalk at depths of known major fissuring.)

At depths where chloride and sulphate concentrations of less than 20 mg l^{-1} occur, probably corresponding to the period before the widespread introduction of inorganic fertilizers (i.e. before 1940), concentrations of 8–10 mg NO_3-N l^{-1} persist and probably reflect annual leaching rates of at least 25 kg N ha^{-1} from arable land, presumably at that time fertilized more by organic manures. Steadily increasing concentrations above that depth probably reflect increasing overall use of naturally occurring and manufactured inorganic fertilizer compounds, such as $NaNO_3$, KCl and $Ca_3(PO_4)_2$, and $(NH_4)_2SO_4$ and $Ca(H_2PO_4)_2$–$CaSO_4$ respectively. The marked increase in sulphate concentrations with decreasing depth (from 10 m and 40 m upwards in figure 6*a* and *b* respectively) probably corresponds to the widespread introduction after 1940 of manufactured inorganic N fertilizers (the $(NH_4)_2SO_4$ types) by when the annual rates of nitrate leaching had risen to approach 40 kg N ha^{-1}.

CONCLUDING SUMMARY

1. A major, and in England predominant, source of nitrate leaching to groundwater is arable farmland.

2. Unfertilized and moderately fertilized pasture is estimated generally to lose no more than 10 kg N ha^{-1} annually.

3. Arable agriculture has had, and will continue to have, a major impact on groundwater quality, especially in unconfined aquifers.

4. The hydrogeological data presented provide clear evidence that the rate of nitrate leaching from the more permeable soils has increased, almost uninterruptedly.

5. They also show little evidence of denitrification *in situ* but this cannot, at present, be entirely discounted.

6. Nitrate leaching has been accompanied by increasing leaching or mobilization of chloride, sulphate and numerous other ions, some of which will also confront the water-supply industry with future problems.

7. In the days of mainly organic N fertilizer, average annual leaching losses from permeable soils were probably not much more than 25 kg N ha^{-1} but increased steadily to around 40 kg N ha^{-1} with the increasing use of inorganic forms.

8. The interpretation of the more recent rates of leaching depends on the precise groundwater flow régime and solute transport mechanisms in the Chalk unsaturated zone, which remain contentious.

9. If an essentially non-dispersive flow is assumed, as suggested by the evidence of tritium profiles, then annual leaching rates since 1963 average 50–70 kg N ha^{-1}.

10. In the 1970s, with modern arable farming practices, annual leaching rates would exceed 80 kg N ha^{-1}, an annual loss of nutrient valued in excess of £15 M from the arable land of the aquifer outcrops in eastern England alone.

11. Such losses would also imply the widespread need for alternative water supplies or water treatment facilities or both, from the 1990s onwards.

12. The régime of solute transport in the Chalk unsaturated zone is highly sensitive to the detailed properties of the fissured porous rock and to the molecular diffusion coefficient of the solute in question.

13. It is possible that the characteristic shape of Chalk unsaturated zone nitrate profiles under long-standing arable land could reflect a more dispersive mode of solute transport.

14. In this case the annual leaching losses, although increasing and well in excess of 40 kg N ha^{-1}, could be significantly less than indicated above.

15. Long-term sequential profiling in individual arable fields is required to resolve the contention; however, the limited results so far available are conflicting.

16. Even at best the nitrate leaching losses are substantial, when viewed in relation to the cost of the equivalent manufactured nutrient, and warrant continued research on methods of restricting them to a practical minimum.

17. Of direct relevance to water-supply and environmental interests would be large-scale medium-term experiments on leaching losses in well monitored groundwater catchments, involving cultivation of new winter cereal strains with the best available husbandry to maximize crop yields but not necessarily to minimize labour costs.

18. In the formulation of detailed guidelines for future agricultural practice it may be pertinent to consider independently the outcrop–recharge areas of the main water-supply aquifers.

This paper is published by permission of the Director of the N.E.R.C. Institute of Geological Sciences. A major part of the research work was funded by the Department of the Environment and carried out with close liaison and active collaboration from the Anglian and Yorkshire Water Authorities. The authors acknowledge the key role played by their colleague, Lionel Bridge, in promoting the associated field investigations. They also thank Dr R. J. Dowdell (A.R.C. Letcombe Laboratory) and Dr. N. Watchorn (I.C.I. Jealotts Hill Research Station) for most helpful discussion on agricultural practices.

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S. S. D. Foster. A major concern in my paper was the interpretation of the 'nitrate front', as opposed to nitrate peak, which appears to be characteristic of the Chalk unsaturated zone pore-water profiles from beneath *long-standing* arable land in eastern England (figures 3 and 4). *If* the downward movement of nitrate is part of an essentially non-dispersive flow and *if* no significant denitrification is occurring *in situ* (assumptions discussed in some detail in my paper but neither of which have, in my view, as yet been adequately verified), then the form of the profiles ought to relate directly to a history of increasing inputs from the overlying agricultural soils, presumably as an *indirect* result of the major increases in nitrate fertilizer application to arable land during 1955–65. However, a considerable time-lag for the corresponding increase in the rate of leaching losses would apparently need to be invoked.

In some other cases, it would appear that peaks in the unsaturated zone pore-water nitrate profiles can be directly related to changes in land use, such as the ploughing-up of grassland for cultivation (figure 2).

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Volume 6 Number 4 1982

Water Supply & Management

Editor: Asit K. Biswas, Ottawa, Canada

Pergamon Press

Oxford · New York · Toronto · Sydney · Paris · Frankfurt

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Water Supply & Management, Vol. 6 pp. 000-000, 1982
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Groundwater Supply Exploration in Semi-Arid Regions for Livestock Extension— a Technical and Economic Appraisal

J. L. FARR*†, P. R. SPRAY‡§ and S. S. D. FOSTER*‡

ABSTRACT

By reference to a sample area in southern Botswana, of little known but generally unfavourable hydrogeological conditions, various technical approaches to the groundwater search over large areas, for livestock watering, are detailed and subjected to economic appraisal. A methodology to rationalize the choice of approach is proposed, based on the required improvement in subsequent borehole success rate to justify the cost of each approach. An attempt is made to define the ceiling on groundwater search expenditure, which is imposed by the economics of cattle ranching.

INTRODUCTION

Overall background

The rearing of livestock is the traditional enterprise in many of the world's semi-arid regions, including the Kalahari, Sahel, Chaco and Australian Outback.

Large tracts of land are normally grazed at low livestock densities and, in the absence of permanent surface water, animals are watered at certain strategic points. Irrigation of fodder crops is not normally practised, because of the unavailability or the cost of water, or of other factors. Livestock rearing is vital to the livelihood of the human population in the areas concerned and to the economy of the corresponding nations. In many cases there is interest in extending and up-grading grazing areas to increase beef cattle herds, and in this connection, provision of adequate water supplies represents a major, if not the largest, capital investment.

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The scale of projected water demand in a given area and the economic value of the water resource should dictate the depth of knowledge of the local groundwater system required for planning purposes. In the case of livestock rearing, water demands are small and dispersed. The effective level of exploitation rarely exceeds the equivalent of 0.2 mm/a and there is very little risk of cattle watering seriously depleting available groundwater, even where no known resource replenishment is currently occurring. Thus only a qualitative knowledge of groundwater occurrence is necessary for the planning and development of livestock water supplies (Foster and Farr, 1976). However, very large semi-arid areas are involved, and the location of any formation capable of reliably yielding groundwater supplies of adequate quantity and acceptable quality will represent a significant problem in numerous hydrogeological conditions.

Botswana perspective

The Botswana national herd now exceeds 3 million mature cattle and collectively represents a major and growing demand on groundwater (current abstraction being estimated at 40–45 Mm^3/a). Plans exist to develop (or to intensify the development of) under-utilised land, so as to allow a continued expansion of the livestock industry and to relieve currently overgrazed areas. Some 1000 new commercial ranches of 64 km^2 are projected (each capable of grazing up to a maximum of 600 cattle), together with new and improved communal grazing areas. Over 1000 water supply boreholes will thus be required at a capital cost approaching US$10 million, excluding pumping plant.

The selection of grazing development areas is based on a number of factors, including current land use, grazing potential, socio-economic considerations, but it is often not possible to give high priority to groundwater availability or to knowledge of hydrogeological conditions. Consequently, the provision of water supplies often has to be undertaken in areas of little known and/or relatively difficult groundwater conditions.

Hydrogeological knowledge of sample area

An area of a little over 3000 km^2 in southern Botswana (Kweneng District), containing 50 newly designated ranches, was chosen for study. Each ranch must have at least one borehole capable of supplying 0.5 l/s of water with less than 5000 ppm total dissolved solids.

The sample area is underlain by Karoo rocks, which are covered by up to 30 m of Kalahari Beds (desert calcretes and aeolian sands). No detailed geological map is available and there are only very limited subsurface geological data from a few earlier boreholes. However, across much of the area the bedrock is believed to be Stormberg Basalt, overlying Cave Sandstone. The latter, particularly at its junction with the basalt, certainly represents the most promising water supply prospect (Fig. 1), since it is known to be a consistent aquifer throughout Botswana, but over the greater part of the sample area its depth of occurrence is unknown.

Water may be encountered within the Stormberg Basalt, in weathered zones between individual lava flows and in fractures, and adequate supplies for livestock rearing may be obtained. Their detection, however, is virtually impossible with any known geophysical or remote sensing technique, unless the associated feature is unusually thick and wide in relation to its depth below surface. There is also a possibility of encountering isolated

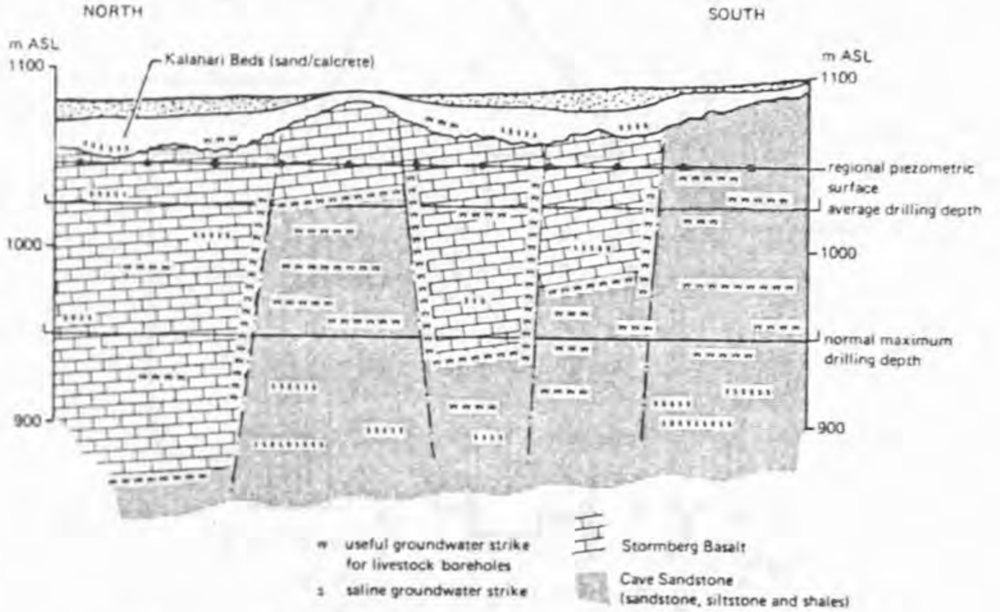

Fig. 1. Hypothetical hydrogeological section across southern Botswana sample area to illustrate probable type of geological structure and groundwater occurrence (vertical exaggeration × 200).

"perched" groundwater tables at, or near, the base of the Kalahari Beds, from which adequate supplies for livestock rearing can sometimes be drawn. Although fairly common, especially where the pre-Kalahari surface is weathered and irregular, they are also extremely difficult to detect by remote methods.

A statistical analysis of the national borehole archive for neighbouring areas (Fig. 2) reveals the following:

(a) The mean depth of boreholes drilled in the basalt alone (about 70 m) was almost the same as that for other formations, although the latter included more boreholes that were taken to depths in excess of 150 m. However, 42% of those boreholes in basalt alone had inadequate yield compared to only 14% of those in other formations. But where groundwater was encountered in the basalt, it was struck at shallower depths (20–40 m) than in other formations (60–80 m).

(b) Groundwater occurrence at the base of the Kalahari Beds was surprisingly frequent, with 43% of all boreholes encountering some water here, but supplies were often small and saline.

To summarise, the hydrogeological knowledge of the sample area is sparse; there being no consistent information on depth of groundwater strike, groundwater levels, spatial variations in groundwater yield and quality. This situation pertains in *many* other areas of potential livestock extension, since the commonest criterion for their selection is the absence of existing land development.

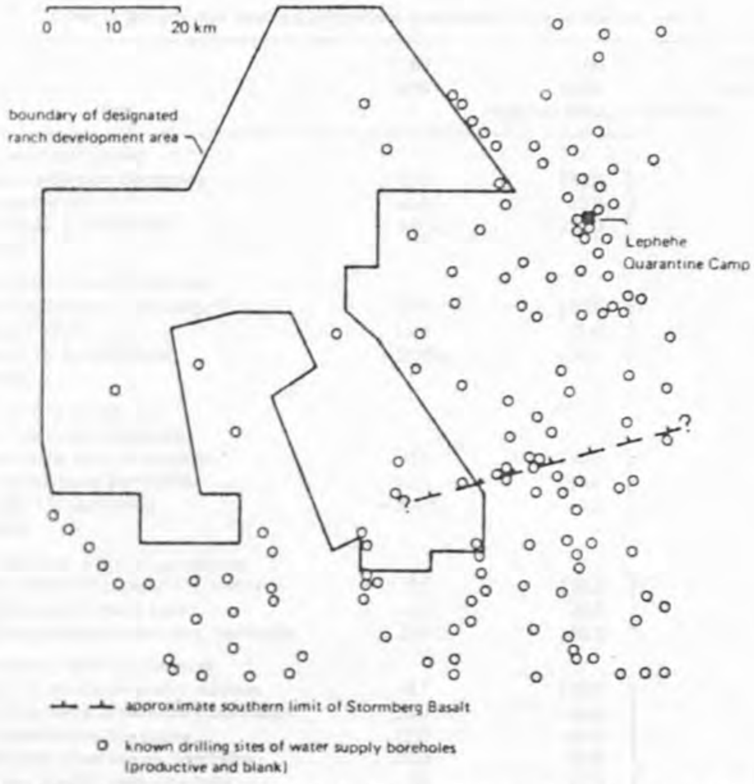

Fig. 2. Previous water supply borehole drilling adjacent to southern Botswana sample area.

GROUNDWATER EXPLORATION: THE POSSIBLE APPROACHES

A number of possible approaches to the groundwater search, of varying sophistication and cost, are discussed below. Each, when used on a group (rather than piecemeal) basis, will improve hydrogeological knowledge and thereby allow some increase in the success rate for water supply boreholes above that of "wildcat" drilling (S_0). The application and cost of the various approaches are appraised in the context of the southern Botswana sample area. A fair measure of hydrogeological judgement is required to decide the level of implementation necessary in each case to give significant advance in groundwater understanding and hope of corresponding improvement in borehole success rate. The levels implied by the costs quoted (Table 1) are considered *minimal* for the sample area concerned. For other areas, these costs will vary with geological complexity.

(1) *Grid-controlled drilling*

In "wildcat" drilling, trial production boreholes are located almost at random; sited simply for convenience or with local non-professional advice (from "diviners" or "stick men"). Drilling is commonly continued until water is struck or rig depth capacity is reached and, since it is not geologically controlled, the results from initial boreholes are

Table 1. Sample cost analysis for various approaches to groundwater search

Item	Unit item	Total item	Overall unit search cost(C)
	(approx. costs in US$1000)		
(1) *Grid controlled drilling*			
15 trial production boreholes	12.0	180.0	1.5
staff supervision	sum	15.0	
(less sale) 15 S_0 successful boreholes	$-8.0/S_0$	-120.0	
(2) *Geologically-controlled drilling*			
10 trial production boreholes	12.0	120.0	1.3
staff supervision	sum	25.0	
(less sale) 10 S_0 successful boreholes	$-8.0/S_0$	-80.0	
(3) *Long traverse geophysics*			
300 km resistivity/magnetic traverse (with some soundings)	0.5	150.0	3.4
5 trial production boreholes	12.0	60.0	
(less sale) $5S_0$ successful boreholes	$-8.0/S_0$	-40.0	
(4) *Short and long traverse geophysics*			
300 km resistivity/magnetic traverse	0.5	150.0	4.4
5 detailed geophysical sites	6.0	30.0	
2 × 150 m cored exploratory boreholes	20.0	40.0	
(5) *Hydrostratigraphic exploration*			
300 km resistivity/magnetic traverse	0.5	150.0	6.9
5 × 150 m cored exploratory boreholes	20.0	100.0	
5 trial production boreholes	12.0	60.0	
3 additional observation boreholes	10.0	30.0	
5 × 3 day aquifer pumping tests	5.0	25.0	
various laboratory testing	sum	10.0	
geophysical borehole logging	sum	10.0	
(less sale) 5 S_0 successful boreholes	$-8.0/S_0$	-40.0	

Notes: (a) Based on sample area in southern Botswana requiring 50 water supply boreholes, in a hydrogeologically little-known area of some 3000 km^2; thus C is derived by dividing the total net cost of the approach concerned by 50.

(b) 1980 Botswana costs using government drilling plant, personnel, professional services, field equipment, and assuming US$1.0 ≡ Pula 0.8. Figures may vary if private consultants and/or commercial drilling contractors are employed.

(c) Assumes that successful boreholes can be sold and, for simplicity, that the *initial* success rate for trial production boreholes is equal to, and the sale value of *successful* boreholes inversely proportional to, the "wildcat" drilling success rate (S_0), the latter also being controlled by the drilling costs of small private contractors (US$8000), rather than of government drilling plant (US$12,000). Thus C is rendered independent of S_0; more realistic assumptions complicate, but do not invalidate, the analysis.

unlikely to have much influence on the siting (or the completion) of subsequent boreholes. The cost of the associated groundwater search is virtually nil.

A modification to this approach would be to drill a proportion of the required production boreholes on a widely-spaced grid over the designated area, completing any successful boreholes for permanent production. If professionally supervised, the results could be used to interpret the hydrogeology, and thus to site (or to design the completion of) further boreholes or to decide whether the prospects justified continuing the drilling programme. Considering the probable conditions in the sample area, a 15-km grid was here considered the minimum initial requirement.

(2) *Geology-controlled drilling*

The "grid-controlled" approach is still somewhat random geologically, since it does not make use of such pre-existing information as may be available. An improvement would be to examine any available data on the designated area (including water borehole archives, mineral prospecting reports, aerial photographs, satellite images and airborne geophysical surveys) to give some idea of its geological structure. This would often point to features of potential hydrogeological significance and a certain number of trial production boreholes (say 10 in the case of the sample area) could be sited on such features to investigate their hydrogeological role. The results of drilling could be used progressively to interpret hydrogeological conditions and hence site further production boreholes.

(3) *Long traverse geophysics*

A common approach to subsurface geological exploration uses surface geophysical surveys; these have been used with some success for groundwater in the Kalahari (Jennings, 1971; Worthington, 1977). Surveys are normally limited by cost considerations to the electrical resistivity method, occasionally supported with gravimetric, magnetic, electromagnetic or shallow seismic refraction techniques (e.g. Zohdy *et al.*, 1974). Logical selection of geophysical technique(s) presupposes some geological knowledge of the designated area. If the geology is totally unknown,then experimentation with a variety of techniques would be necessary before the main geophysical programme could be undertaken. The choice of technique(s) depends largely on the geometry, depth and contrast in geophysical properties of the features of potential hydrogeological interest. Where subvertical faults, or similar features, represent the most important prospect, geoelectric traversing will probably be most applicable, while geoelectric soundings should prove more definitive where subhorizontal lithological contacts are the main features under investigation.

In the southern Botswana sample area, a minimal geophysical programme would consist of 300 km of geoelectric and geomagnetic traverse lines forming an open grid, together with about 15 geoelectric soundings. From these the geophysicist should be able to delineate areas where the Stormberg Basalt is thin or absent, together with any major fault zones. A number of locations with characteristic geophysical signature (say 5) could be investigated by the drilling of trial production boreholes, under hydrogeological supervision, to permit interpretation of the geophysical results.

(4) *Short and long traverse geophysics*

A refinement of the above approach would be to select, in any adjacent developed area of suspected similar geology, a number of productive and blank (unsuccessful) boreholes (say 5) and run detailed short traverse geophysical surveys across the sites in order to establish their geophysical signature or anomaly. Those associated with productive boreholes could then be readily identified when undertaking long-traverse geophysics in the designated area, without the need for trial production boreholes. However, for confident interpretation, it would probably also be necessary to drill cored exploratory boreholes at two or three of these sites.

(5) *Hydrostratigraphic exploration*

This approach is that normally used as the first stage in the quantitative evaluation of groundwater resources and would include cored exploratory boreholes (in the designated area) in addition to surface geophysical surveys, to determine the stratigraphic sequence accurately. Aquifer pumping tests with observation boreholes, and other selected field and laboratory measurements, would be used to interpret this sequence hydrogeologically. As will be seen from the cost estimates for the sample area (Table 1), this is altogether a much more expensive approach.

COST EFFECTIVENESS OF GROUNDWATER EXPLORATION

The groundwater search techniques are only justified if they increase the chances of subsequent boreholes being successful, such that the *overall saving* in drilling costs, in the long run, is *greater* than the cost of the search.

The average cost of drilling a successful borehole can be written d/S, where d is the average production borehole drilling cost and S the success rate following use of a given search technique. Now, if the unit cost of a given technique is C, we would choose technique n rather than m, if its incremental cost was less than the saving in drilling costs:

$$(C_n - C_m) < \left(\frac{d}{S_m} - \frac{d}{S_n}\right). \qquad \text{(a)}$$

Although it is possible to estimate d and C, at present few reliable data on S corresponding to different search techniques exist. For a given technique S will, in any case, vary with geological conditions. However, some useful inferences can still be made.

Maximum justifiable expenditure on groundwater search

Different geological environments will have different success rates for "wildcat" drilling (S_0). The *maximum* justifiable expenditure on groundwater search (C_{max}) will be given when $S_n = 1.0$, or perhaps 0.9, since it might be assumed that even the most sophisticated search technique will not improve the borehole success rate to much more than 90%, thus:

$$C_{max} = \frac{d(1 - S_0)}{S_0}\left(\text{or } \frac{d}{S_0} - \frac{d}{0.9}\right). \qquad \text{(b)}$$

In Botswana the cost of narrow diameter production boreholes (d) is typically about US$12,000, although small contractors using very slow equipment are sometimes used at costs nearer US$8000, and using these figures the maximum justifiable expenditure on the groundwater search, for a given "wildcat" drilling success rate, can be calculated (Fig. 3). Not surprisingly, the more favourable the geological environment is to "wildcat" drilling, the lower is the justified search expenditure.

If "wildcat" drilling can achieve a 75% success rate, and a ranch owner can get a water supply borehole drilled for US$8000, reasonable assumptions for some areas of Bots-

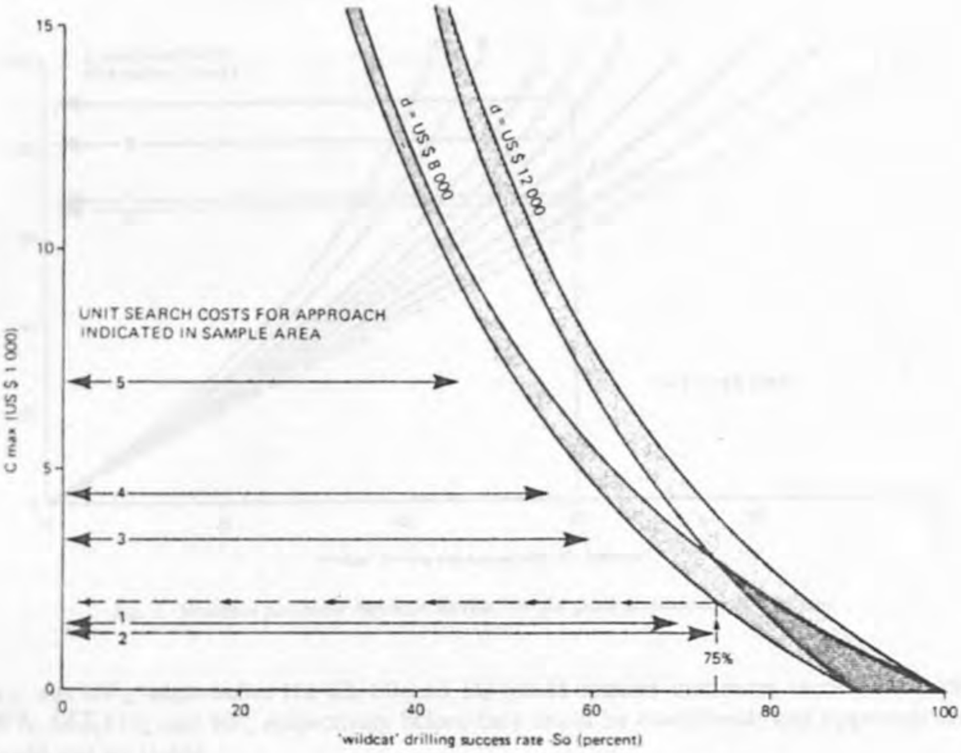

Fig. 3. Maximum justifiable cost of groundwater search.

wana, then it will not be worth spending more than US$2000 on any form of groundwater search (Fig. 3), however good it is. Thus only the "controlled drilling" approaches are worth considering (Table 1), and it has to be considered whether these have any chance of raising the success rate to over 90%. However, where the "wildcat" success rate is only 50%, all techniques except full hydrostratigraphic exploration (5) could at least be considered.

Minimum justifiable improvement in borehole success rate

The success rate that each approach will enjoy in a given geological environment is not known. However, we can calculate the *minimum* success rate (S_{min}) each technique would need to have before it can be considered:

$$S_{min} = \frac{dS_0}{(d - CS_0)}. \tag{c}$$

This shows the proportion of production boreholes that would have to be successful (after being sited with the aid of a particular method of groundwater search) for that approach to be economically viable. This can be represented graphically for a given borehole drilling cost (*d*), say US$8000 (Fig. 4). Thus, for example, if the "wildcat" success

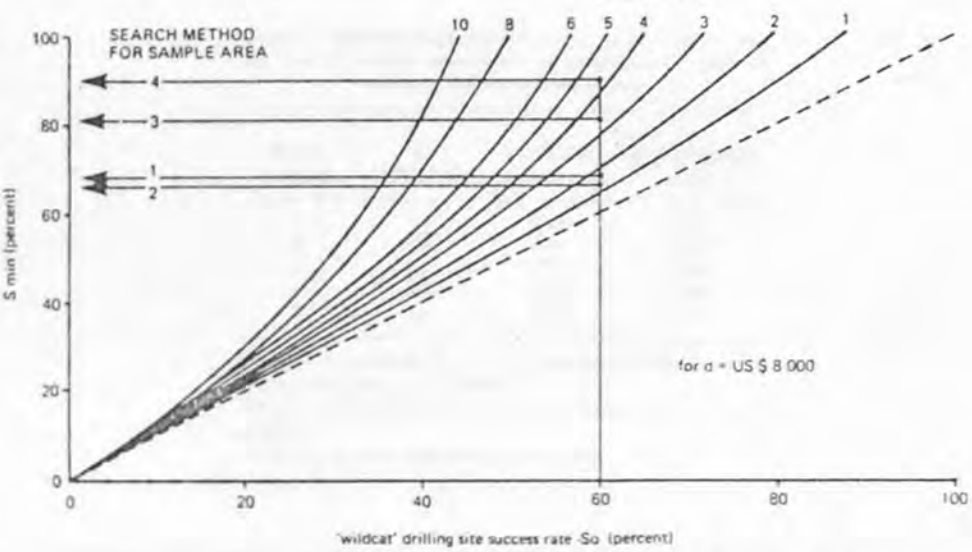

Fig. 4. Minimum justifiable borehole success rate for given groundwater search cost.

rate was 60%, approaches (1), (2), (3) and (4) would require minimum success rates of 68%, 66%, 81% and 90% respectively before they could be considered, and approach (5) would not be viable.

It must be emphasized that these are only the minimum rates needed for an approach to be considered and it does not follow that, if in this example, approach (4) was expected to give a success rate of 90% (9% above minimum) that it should be employed. The "controlled drilling" approaches would only have to achieve very small increases in success rate above the justifiable minimum to be preferred.

Using this analysis, and considering the geology of a particular area and the related feasible ranges of success rate for different groundwater search techniques, the hydrogeologist, groundwater engineer and water resources planner should be better able to advise on which approach to employ.

Technique selection for sample area

As mentioned, the success rate of reported boreholes around the southern Botswana sample area was 58%, when basalt alone was encountered, and 86% elsewhere. Many of these boreholes were sited by "wildcatting", but we must also expect that some blank boreholes have not been reported. If it is assumed that the actual "wildcat" drilling success rates were 45 and 70% respectively, then we can derive, using Equation (c), the minimum justifiable success rates for the various approaches described (Table 2).

In the basalt-free area, the choice of approach lies between "wildcat" drilling and "controlled" drilling: all other approaches probably being too expensive. "Controlled" drilling would be justifiable if it were able to increase the success rate by about 10%. Such an increase certainly appears feasible and would, thus, be recommended.

Table 2. Minimum subsequent borehole success rate to justify use of various approaches to groundwater search in southern Botswana sample area

Search method	C (US$1000)	S_{min} (A) Basalt areas	S_{min} (B) Non-basalt areas
1	1.5	0.49	0.81
2	1.3	0.48	0.79
3	3.4	0.55	>1.00
4	4.4	0.60	>1.00
5	6.9	0.73	>1.00

Notes: (a) Assumes S_0 for (A) and (B) of 0.45 and 0.70 respectively and d = US$8000.
(b) Unit groundwater search costs (C) based on analysis in Table 1.
(c) If $S_{min} > 1.00$, approach is not viable.

In the basalt-capped area, there is a wider choice, but the relatively small increase in success rate required by approaches (1), (2) and (3), are all more likely to be achieved. However, it is questionable whether, in this type of terrain, long traverse geophysics would lead to a significantly higher success rate than the "controlled drilling" approaches and the latter would probably be recommended.

Maximum economic expenditure on water provision

Livestock rearing can only support a certain level of investment if it is to remain profitable. There is thus an upper limit on the expenditure that should be used in providing water, that is on $(d/s) + C$, imposing a further constraint on viable groundwater search techniques.

Unfortunately, information on the economics of livestock rearing in Botswana is sparse, and the calculation is too sensitive to the acceptable rate of return on investment to provide much guidance. Data from one estimate of the net income, over 20 years, from a 64 km^2 ranch (World Bank, 1977) suggests that it would not be possible to achieve a 10% real rate of return. If however, farmers would be prepared to accept a discounted return of only 4% plus inflation (Sandford, 1977), then the same net income would allow an initial investment as high as US$175,000; even with US$80,000 required for purchase of cattle, and US$35,000 for ranch improvements, US$60,000 would be available for water provision. A relatively large sum could then, in theory, be used for the groundwater search, although in practice it is unlikely that cattle ranchers in Botswana would be prepared to so invest at present.

A separate question is whether government, that is the tax payer, should undertake any additional expenditure. It might be argued, for example, that the first ranchers in an area face more difficulty over water provision than later arrivals, because when some boreholes have been drilled and hydrogeological conditions evaluated, it should become easier to site subsequent boreholes successfully. Ideally, this would call for taxes on the later arrivals in an area to recover subsidies for water provision that would have been paid to those people initiating the groundwater search. Alternatively, it could be argued that ranchers are, in some cases, not prepared to spend as much money on water provision as is economically justified, considering the profits they could expect to make. Thus there might be scope for taxing cattle sales to finance government contributions to water provision. In any event, there is no economic justification for the total (government plus private sector) input on water provision to be more than that dictated by the economics of livestock rearing. There may, however, be socio-political arguments for subsidising livestock rearing using income from other sectors of the national economy.

The water search for livestock rearing, if adequately supervised and archived, can provide useful data on groundwater occurrence which may be very valuable for future purposes, as yet unforeseen, such as new urban or mining development, or more intensive agriculture. Government could, therefore, consider subsidising the groundwater search, or expanding the program of exploration beyond that strictly justified for livestock, because of such longer-term national interests.

CONCLUDING REMARKS

A logical method of evaluating the most appropriate approach to groundwater exploration for livestock rearing in terrains of relatively unfavourable, little known, hydrogeology has been presented. More information needs to be collected on the success rate both of "wildcat" drilling and of the various approaches suggested. Such information must be disaggregated into broad groups of differing hydrogeological environment. The final selection of groundwater search method will be constrained by the economics of livestock rearing, after taking account of government policy on the level of any subsidies to, or within, this sector. An important conclusion is that low cost approaches to the groundwater search may often be most justified economically, as well as being more easily implemented in nations lacking financial resources.

A similar philosophy might be taken towards the siting of boreholes for provision of improved water supplies for rural populations, although the search area would obviously be more constrained by various factors including public health considerations, and the economics largely dictated by the availability and cost of development of alternative water resources.

Acknowledgements—This paper is published by permission of the Permanent Secretary of the Ministry of Mineral Resources & Water Affairs, Gaborone, and the Director of the (NERC) Institute of Geological Sciences, London. It was derived from work undertaken by an Anglo-Botswana technical co-operation project, funded by the Overseas Development Administration, London. The authors wish to express their gratitude to Jane Baron, David Jones and Roger Peart for provision of certain relevant data.

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This issue is the complete Volume 55

Vol. 55 – No. 1/4 – February 1982 ISSN: 0022-1694

Journal of Hydrology

Elsevier Scientific Publishing Company
Amsterdam – Oxford – New York

Journal of Hydrology, 55 (1982) 113—136
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

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THE LIKELIHOOD OF ACTIVE GROUNDWATER RECHARGE IN THE BOTSWANA KALAHARI

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(Received December 1, 1979; revised and accepted December 14, 1980)

ABSTRACT

Foster, S.S.D., Bath, A.H., Farr, J.L. and Lewis, W.J., 1982. The likelihood of active groundwater recharge in the Botswana Kalahari. J. Hydrol., 55: 113—136.

The Kalahari is the world's most extensive mantle of sand. A fundamental, but very difficult, problem in the evaluation of groundwater resources in the region is the estimation of the magnitude of any active infiltration, from modern rainfall through the sand-cover to certain deep aquifers.

The results of a reconnaissance study of the unsaturated sand-cover, including its physical properties, chemical and isotopic profiles of its pore-water composition, are presented. The profiles appear to exhibit evaporative features and to suggest that, in an area with a mean annual rainfall of 450 mm, diffuse recharge should not be presumed to be occurring where the sand-cover is more than ~4 m deep.

INTRODUCTION

Research perspective

The Kalahari occupies over $2.5 \cdot 10^6$ km^2 of southern Africa including all but the northern and eastern margins of Botswana, and stretches southwards into the Cape Province of South Africa and eastwards into South West Africa/Namibia. It is essentially a flat sand-covered semi-arid region with a mean annual rainfall of between 250 and 550 mm. Only in the extreme southwest do true desert conditions prevail and elsewhere the region is, for the most part, quite well vegetated.

[*1] This author gave a lecture relating, in part, to this paper at the Geological Society of London, Hydrogeological Group Meeting on "Physical Controls on the Movement of Water and Solutes through the Unsaturated Zone" at Burlington House, London, on January 8, 1980.

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In this region, virtually devoid of surface water, the availability of groundwater resources is critical to all development. To establish the presence (or absence) of active groundwater replenishment is fundamental in the formulation of a logical resource management policy. In recent years, the increased intensity of mineral exploration and the development, or projected development, of new mining enterprises is bringing the subject of groundwater resources to the economic forefront (Foster and Farr, 1976; Foster et al., 1981).

Prior to 1977, research on the possibility of active groundwater recharge in the Kalahari had been restricted to the broadest level of regional reconnaissance. Certain writers (Martin, 1961; Boocock and van Straten, 1962; Bailleul, 1975; Smit, 1977) have contended, albeit without much direct evidence, that no active recharge of any underlying aquifer could take place where the thickness of sand-cover exceeds a few metres, because of seasonal moisture retention in the sands and complete loss by subsequent evapotranspiration.

Other work, involving, isotopic analyses of pumped groundwater samples (Mazor et al., 1974, 1977; Verhagen et al., 1975), has tended to support the concept of continuing active recharge over wide areas, but Hutton and Loehnert (1977) give an alternative interpretation involving chemical evolution of groundwaters that infiltrated during historic pluvial periods. All of these latter works were handicapped by having to use pumped samples from existing water-supply boreholes, frequently penetrating multi-aquifer sequences and of uncertain construction, with probable mixing and possible well-head contamination. Results, therefore, may often be inconsistent or ambiguous, and difficult to interpret.

Natural groundwater replenishment in semi-arid regions can take place by two distinct mechanisms: (a) diffuse infiltration of excess rainfall; and (b) local streambed recharge along ephemeral watercourses. A further limitation of research methods which only utilise water samples from the saturated zone, is that they are not readily capable of resolving these respective components.

Research approach

In the Botswana Kalahari significant surface runoff is both highly localised and rather rare. Although some groundwater recharge of associated origin may occur locally, determination of the magnitude of any diffuse infiltration from modern rainfall is regarded as the more important, but more contentious, question.

The approach introduced for assessment of this potential recharge is based on study of the Kalahari Beds, and in particular on the surficial sand-cover which, hydrogeologically speaking, forms the uppermost part of the unsaturated zone.

The reconnaissance drilling programme was carried out in central Kweneng

District (Figs. 1 and 2), towards the end of the 1977 dry season (Fig. 3). The groundwater resources of this area are being evaluated as a source of water supply for projected diamond mine and township development at Jwaneng (Foster et al., 1981). A highly-mobile multi-purpose drilling rig, with tools for dry augering in unconsolidated sands together with air-hammer percussion and air-flush rotary coring in consolidated strata, was used to obtain accurate and uncontaminated samples of soil and rock to allow study of their geological and physical properties and of the chemical and isotopic

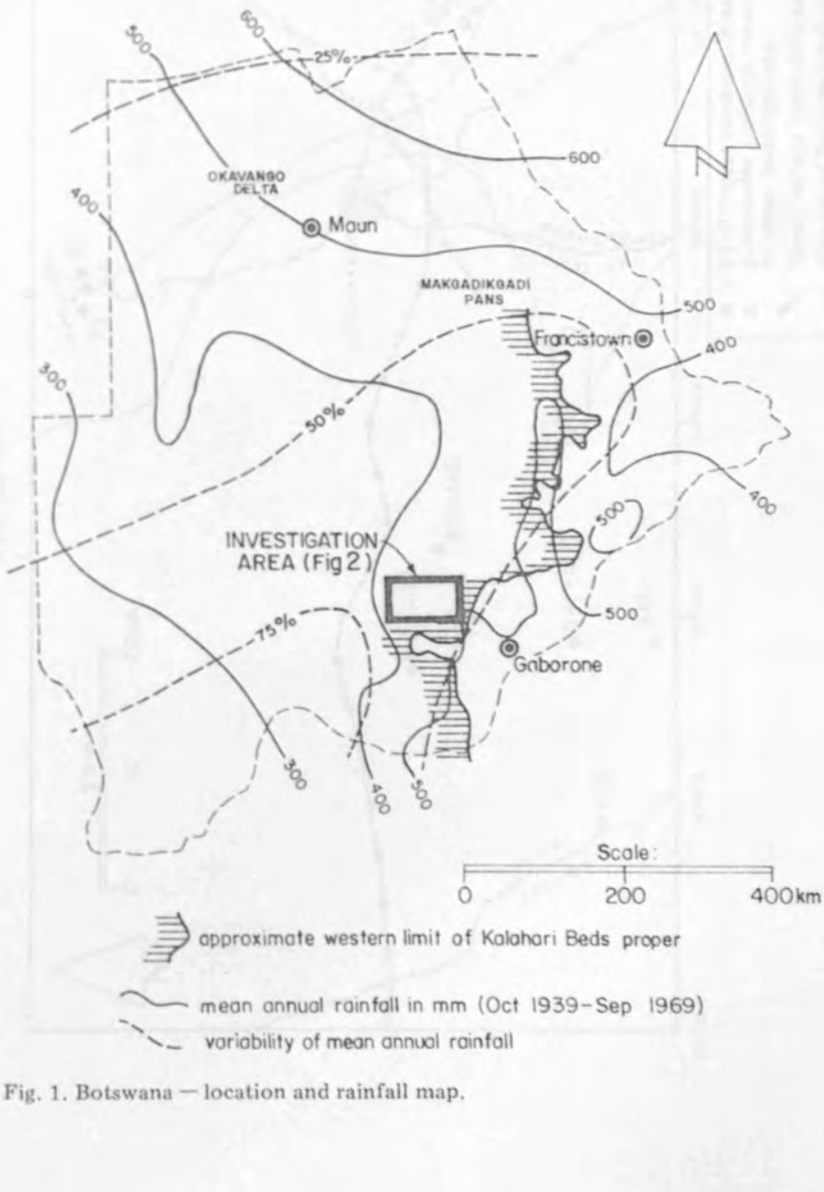


Fig. 1. Botswana — location and rainfall map.

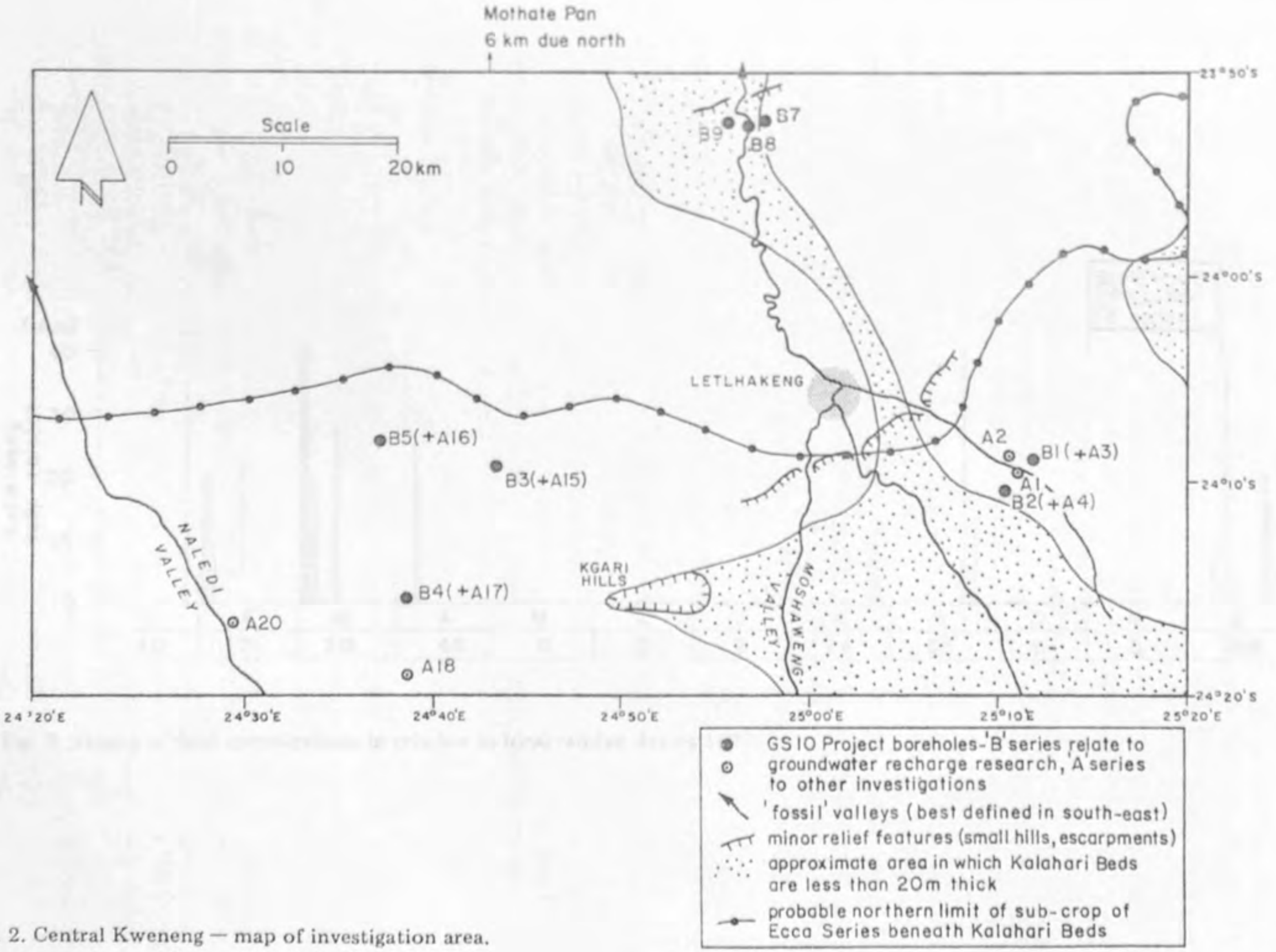


Fig. 2. Central Kweneng — map of investigation area.

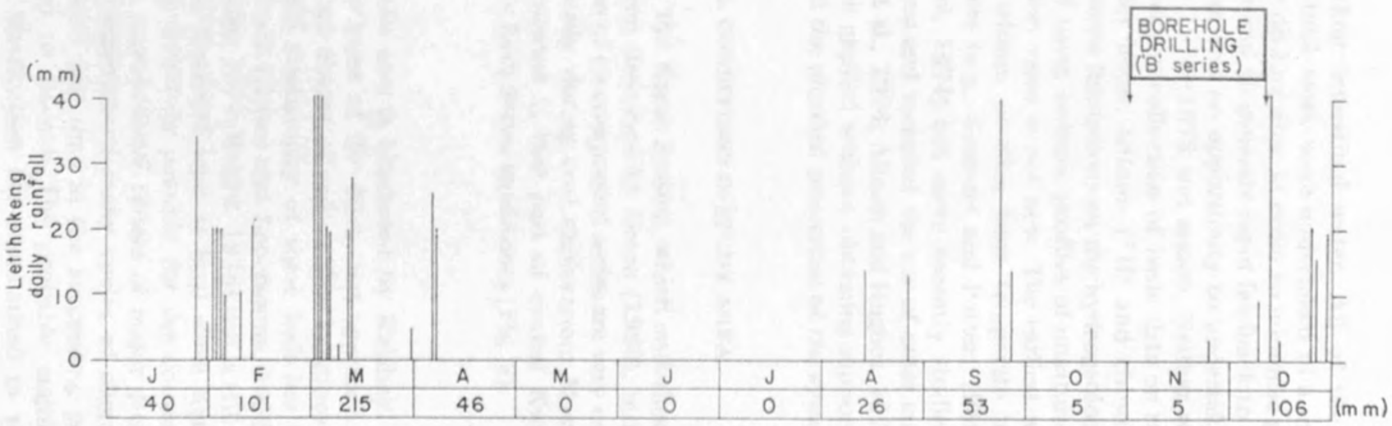


Fig. 3. Timing of field investigations in relation to local rainfall during 1977.

characteristics of their interstitial water. All of the sample handling and much of the analytical work were undertaken in a mobile field laboratory located close to the drilling sites, in order to minimise pore-water contamination or evaporation and to generate rapid feedback to the drilling operation. Unfortunately, there was no opportunity to undertake repeat sampling immediately after the 1977—1978 wet season. Neither was it possible to exercise any control over the collection of basic data on rainfall, potential evaporation, groundwater levels, tritium (^{3}H) and chloride (Cl) fallout. This inevitably imposes some limitations on the hydrogeological interpretation.

The technique of using isotopic profiles of unsaturated-zone moisture for estimating infiltration rates is not new. The earliest work involved analysis of environmental tritium profiles from temperate humid regions of the Northern Hemisphere (e.g., Schmalz and Polzer, 1969; Smith et al., 1970; Andersen and Sevel, 1974) but more recently studies have been made in relatively arid regions and included the use of other environmental constituents (e.g., Dinçer et al., 1974; Allison and Hughes, 1978). However, isotopic techniques are often applied without obtaining supporting data on the pore-water chemistry and the physical properties of the system concerned.

GEOHYDROLOGICAL CONDITIONS IN STUDY AREA

In general terms, the Karoo System, which underlies much of the Botswana Kalahari, has been described by Green (1966), but the distribution and stratigraphy of some of its component series are very complex and have only been elucidated locally during coal exploration. Most of the drilling programme was implemented in that part of central Kweneng believed to be directly underlain by Ecca Series sandstones (Fig. 2).

Superficial geology

Virtually the entire area is blanketed by Kalahari Beds (Fig. 4), which typically have a thickness of 20—40 m, but approach 60 m in pre-Kalahari buried valleys and are absent at only a few locations, where bedrock outcrops. The origin and stratigraphy of these beds has been the subject of a major geological debate (Cahen and Lepersonne, 1952; King, 1962; Grove, 1969; Grey and Cooke, 1977; Wright, 1978) and is still contentious. Most of southern Africa has remained land at least since Karoo (Cariboniferous—Jurassic) time. It is therefore possible for the continental Kalahari Beds, which relate to the aggradational phases of major geomorphological cycles (during which were experienced many cycles of climatic change), to have accumulated at almost any time in the succeeding period of over 60 Ma, from the Cretaceous to Recent. The probable major subdivisions of the sequence and their distribution are summarised in very general terms in Table I.

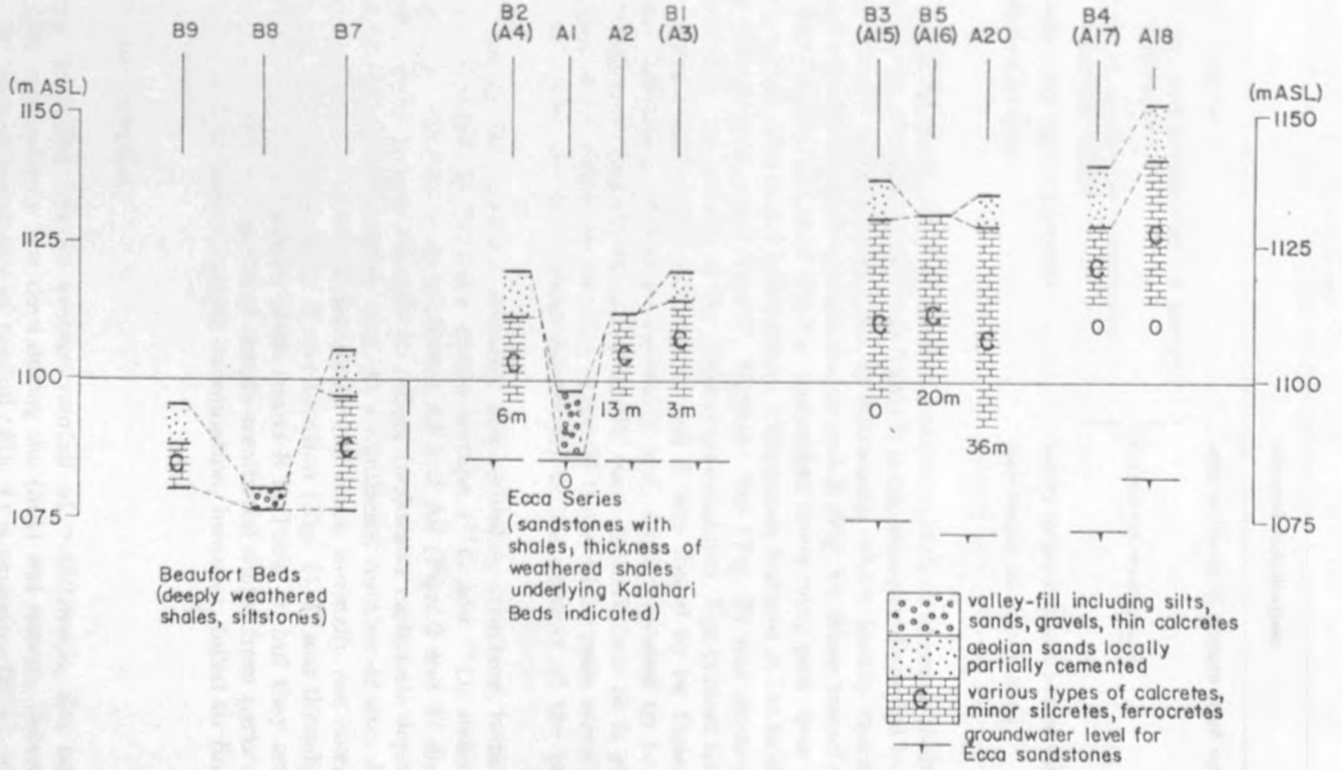


Fig. 4. Simplified geological profiles of investigation boreholes.

TABLE I

Simplified Kalahari Bed stratrigraphy

Unit		General distribution
E	Valley deposits	only in floors of re-excavated valleys
D	Aeolian sands (redistributed in part by fluvial processes)	extremely widespread
C	Calcretes, silcretes (with ferrocretes frequently at top)	
B	Marls, sandy calcretes, gravels	locally in pre-Kalahari buried valleys
A	Silcreted breccias	very locally on Karoo strata

In central Kweneng the flat, sand and calcrete, plateau (formed mainly by representatives of units C and D in Table I) is occasionally dissected by well-defined "fossil" valleys (mekgacha in Setswana), which locally reach bedrock, and contain deposits attributable to unit E (Fig. 4). When traced northwards these valleys debouch onto a somewhat lower-lying plain over which their course wanders rather indefinitely. Ubiquitous features in the landscape are the innumerable small "pans". Mothate Pan (Fig. 2) was studied geologically during the course of the present investigation. The typical Kalahari Beds sequence was *completely absent* and it was found to be floored by lacustrine sediments of low permeability and, what appeared to be, *very* deeply-weathered Stormberg Series basalt; such groundwater as is present was found to be highly saline. The origin of these minor pans remains unknown but they do not appear significant in the context of the present paper.

The calcretes have variable lithology and secondary structure, both vertically and laterally; preliminary stable isotope (^{13}C and ^{18}O) determinations on core material from boreholes A*3* and A*4* (Figs. 2 and 4) show no systematic trend but are thought to reflect freshwater carbonate deposition without significant evaporative loss. At a significant number of sites drilled, the calcrete—silcrete unit is underlain by red clays, normally not more than 10 m thick, but reaching 36 m at one location (Fig. 4). It was thought that these clays might be Kalahari Marls (units B in Table I), but they are considered more likely to represent deeply-weathered shales from parts of the Ecca Series; palynological sample examination, however, failed to find any diagnostic spores.

Climate and vegetation

Central Kweneng has an average rainfall of ~450 mm/a, the bulk of which falls on relatively few days during the (hot) wet season, December—March. The annual variability of rainfall (Fig. 1) is excessive (65%), with an extreme deviation of ±300 mm/a. Mean daily *potential* rates of evapotranspiration are also high (up to 8 mm/day in the wet season), but rainfall intensities in excess of 50 mm/day have been recorded and, on a 10-day basis, rainfall will sometimes considerably exceed potential evapotranspiration on some occasions. Despite the frequently high rainfall intensities, surface runoff has been observed only rarely and locally, although some water may stand in pans and in certain parts of fossil valleys for limited periods.

There is almost no rain during the (cool) dry season (May—August) but nevertheless the vegetation cover is normally adequate to feed at least 10 cattle per km^2 and much of the land area is used, or designated, for livestock grazing. The vegetation system is of a bush-and-tree savanna type and, although modified locally by over-grazing and fire, it conforms with what might be expected for a tropical region with a mean rainfall of 400—500 mm/a (Balek, 1977). The bush—tree canopy does not exceed 20% and although this varies on a broad scale with the thickness of sand-cover, the local distribution of bushes and trees is not believed to reflect detailed variations in the lithology of the sand.

Groundwater occurrence

Some of the Ecca Series sandstones in central Kweneng form an important, but complex, aquifer system with most favourable hydraulic properties (transmissivity consistently exceeding 100 m^2/day and storativity probably greater than 0.01). Groundwater levels are generally somewhat below the base of the Kalahari Beds and hydraulic gradients extremely low. Only limited groundwater level data exist for five observation boreholes; absolute fluctuations in the period 1969—1972 did not exceed 0.6 m (most of which could have been ascribed to barometric effects), but there is a suggestion of very minor recharge at some sites in January 1967 and January 1972.

All existing production water-supply boreholes show the Ecca groundwater to have remarkably low salinity (total dissolved solids and chloride concentration mainly in the ranges 300—700 and 50—100 mg/l, respectively), presumably reflecting "fossil" recharge of a historic, relatively much wetter, climatic episode. In semi-unconfined Ecca aquifers Ca—HCO$_3$ groundwaters predominate, but where confined below significant shales, Na increases and may become the principal cation.

During 1977, 17 production boreholes were sampled for tritium (^{3}H) and radiocarbon (^{14}C) analyses; a few boreholes in the area having been sampled for this purpose on one earlier occasion (Mazor et al., 1974). The ^{3}H concentrations are mostly very low (less than 1 TU) and with a few exceptions cannot be taken as significantly different from zero (that is, no definite post-1956 water present). However, these results in themselves cannot be regarded as conclusive evidence of the absence of active groundwater recharge because of the limitation of pumped sampling in non-homogeneous, complex aquifers.

The corresponding ^{14}C results for the Ca—HCO_3 groundwater exhibit a preferred range of 50—65 pmC, but interpretation is complicated by the dilution effect which dissolution of "fossil" carbonate has on naturally-decaying levels of ^{14}C taken up from soil carbon dioxide during groundwater recharge and requires a detailed knowledge of the groundwater chemistry and historic carbonate speciation. Taking the simplistic, and perhaps unjustified, assumption of an initial activity of 85 pmC, the results represent ages of 2000—4500 yr. B.P. Measurements of ^{13}C provide a method of estimating the extent of the above dilution; in this case ($\delta^{13}C = -12‰$ to $-15‰$) they appear to rule out the possibility of extreme exchange and the samples could be significantly younger. The few groundwater samples with very low Ca/Na ratios have less than 10 pmC, probably indicating ages of more than 10,000 yr. B.P. Grey and Cooke (1977) give the possible chronology for the two most recent pluvial episodes in the Kalahari as 750—2500 and 13,000—18,000 yr. B.P., respectively; the latter being a prolonged very wet episode in which the Great Makgadikgadi Lake reached its maximum extension and during which the "fossil" valleys were re-excavated.

ANALYSIS OF METEOROLOGICAL DATA

The basic hydrometeorological statistics for central Kweneng are sparse and may not be representative, although usable data on daily rainfall and potential evaporation for the period 1961—1977 may be derived, in part by correction and correlation from neighbouring areas. Moreover, for semi-arid environments there is no reliable method available for the calculation of actual evaporation and of excess rainfall (potential groundwater recharge) from the basic data; the point at which actual evapotranspiration rates start to fall below potential and the rate at which the discrepancy increases being highly controversial topics in soil-water physics. Nevertheless, such calculations are of some interest in the context of the present paper.

Rainfall

Daily rainfall figures are available for Letlhakeng, with the limitation that on numerous occasions average values of the rainfall accumulating during a number of days are reported and that the local spatial variation of rainfall is probably high.

These rainfall data (Fig. 5) show that the 1976/1977 wet season, preceding the reconnaissance drilling/sampling programme, brought above average precipitation, as had five-out-of-six of the preceding years. The chemical and isotopic profiles of the sand-cover will thus represent the condition at the end of the *dry season* during a relatively *wet climatic cycle*.

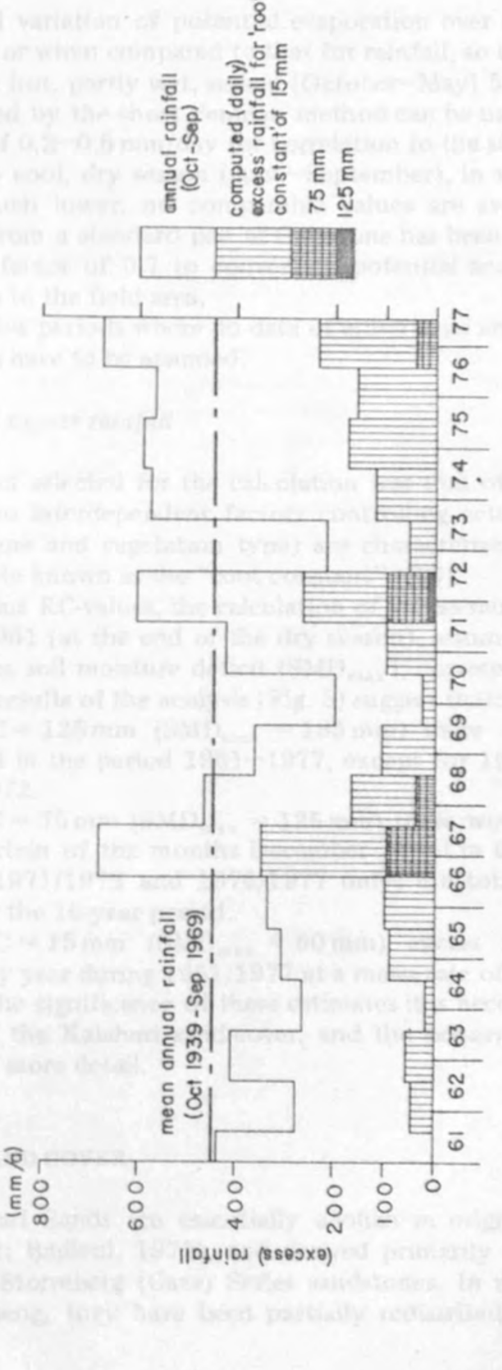


Fig. 5. Summary of analysis of meteorological data for Letlhakeng for period October 1961—September 1977.

Potential evaporation

The spatial variation of potential evaporation over much of Botswana is relatively minor when compared to that for rainfall, so that:

(a) For the hot, partly wet, season (October—May) 5-day values for Gaborone computed by the short Penman method can be used, adding an empirical estimate of 0.2—0.6 mm/day for correlation to the study area.

(b) For the cool, dry season (June—September), in which potential evaporation is much lower, no comparable values are available but the daily evaporation from a standard pan at Gaborone has been used, multiplying by an empirical factor of 0.7 to convert to potential and adding 0.1 mm/day for correction to the field area.

(c) In the few periods where no data of either type are available, long-term average values have to be assumed.

Estimation of excess rainfall

The method selected for the calculation was that of Grindley (1968), in which the two interdependent factors controlling actual evaporation (soil-moisture regime and vegetation type) are characterised by a single mathematical variable known as the "root constant" (RC).

Using various RC-values, the calculation of excess rainfall was commenced in October 1961 (at the end of the dry season), assuming the existence of a near-maximum soil moisture deficit ($\mathrm{SMD}_{\max}$), corresponding to the respective RC. The results of the analysis (Fig. 5) suggest that:

(a) For RC = 125 mm ($\mathrm{SMD}_{\max}$ = 185 mm) there would have been no excess rainfall in the period 1961—1977, except for 10 mm on a single day in *January 1972*.

(b) For RC = 75 mm ($\mathrm{SMD}_{\max}$ = 125 mm) there would have been excess rainfall in certain of the months December—April in the years 1966/1967, 1967/1968, 1971/1972 and 1976/1977 only; the total being 260 mm, or 16 mm/a over the 16-year period.

(c) For RC = 15 mm ($\mathrm{SMD}_{\max}$ = 50 mm) excess rainfall would have occurred every year during 1961/1977 at a mean rate of ~130 mm/a.

To assess the significance of these estimates it is necessary to examine the properties of the Kalahari sand-cover, and the behaviour of its associated vegetation, in more detail.

KALAHARI SAND-COVER

The Kalahari Sands are essentially aeolian in origin (Boocock and van Straten, 1961; Bailleul, 1975), and derived primarily from the weathering of Ecca and Stormberg (Cave) Series sandstones. In most areas, including central Kweneng, they have been partially redistributed by surface sheetwashing and related fluvial processes, bioturbated, and stabilised by vegetation. They comprise a sequence of red-brown (locally grey) quartz sands up to 9 m thick, with uniform (dominantly fine) grain size. The sands rest upon calcrete and are themselves semi-consolidated by calcareous cement towards their base; the extent of cementation was found to vary over short distances laterally.

Hydrophysical properties

Carefully-collected auger samples were subjected to a number of simple tests in the mobile field laboratory: (a) mechanical grain-size analysis; (b) moisture content; and (c) bulk density at field saturation. The former confirmed the highly uniform, fairly-well sorted, aeolian character of the sands (Folk graphic mean grain-size of $\sim 2.4\,\phi$ (0.18 mm), standard deviation of $\sim 0.8\,\phi$; Trask sorting coefficient of ~ 1.4), revealing those horizons where fluvial redistribution had occurred and those with incipient cementation (Figs. 6—8). The bulk density of the sand samples at field saturation was estimated quite consistently at $\sim 1.4\ \text{g/cm}^3$ (implying loose packing); although it is realised that substantial errors (perhaps as high as 15%) in this important parameter may arise as a result of sample disturbance. Values increased with partial cementation to at least $1.7\ \text{g/cm}^3$.

The field moisture contents (Fig. 7) at the end of the 1977 dry season (the time of sampling) were low, remarkably uniform in distribution and showed a broad correlation with grain-size variations. They were mainly in the range 1.5—3.5 wt.% (2.0—5.0 vol.%, assuming the above bulk density), but at the base of the sands, where partial cementation was present, increased to a *maximum* of 8 wt.% (probably ~14 vol.%).

Although a gross simplification of the soil-water physics of the system, the "moisture deficit" of a sand profile can be evaluated from knowledge of the "specific retention", or "unit field capacity", of the sand. This is not an easy parameter to determine because of its sensitivity to sorting and packing. A centrifuge method, similar to that described by Johnson et al. (1963), was used; repacked and pre-saturated samples of sand of 1 cm thickness (with duplicates) were subjected to centrifugation at 20° C for 1 hr. at 2560 r.p.m., a speed sufficient to create a mean sample tension of 0.5 bar (5 m H_2O) and assumed to simulate *full* (long-term) gravity drainage. This mean tension may be rather high and the centrifuge value is believed to be less than the field value by a factor of 1.1—1.3 (Piper, 1933). Some experimentation on varying sample thickness and on reproducibility of results was undertaken; the latter gave a range of 9.2—11.4% on a single sample re-tested on six occasions.

The centrifuge specific retention results (Fig. 8) fall in the range 4—15%, with values over 8—10% being recorded only by samples with some degree of fluvial redistribution or cementation. Thus values of unit field capacity of 6%, 8% and 10% have been tentatively taken for non-cemented, re-distributed and partially cemented sand, respectively, but it is recognised that these

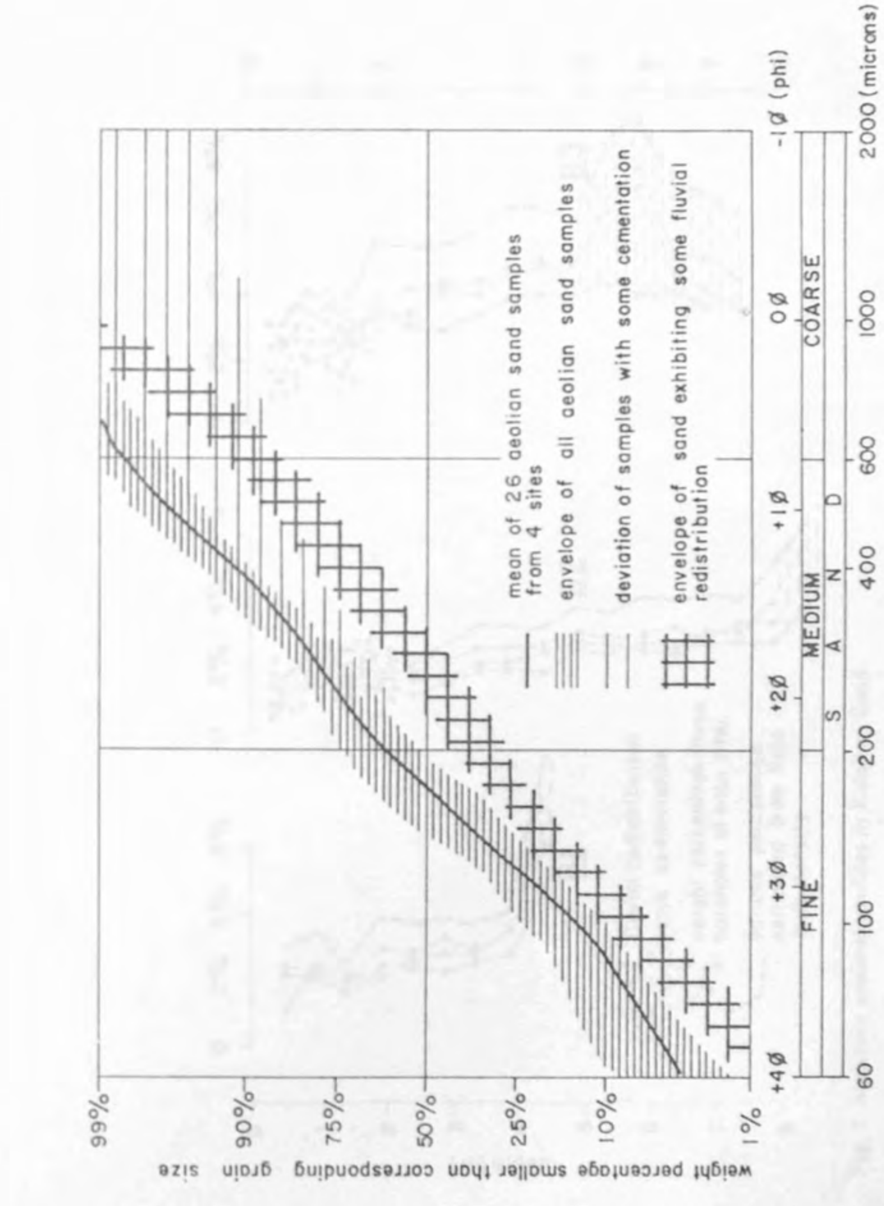


Fig. 6. Summary of grain-size distributions for Kalahari Sand samples.

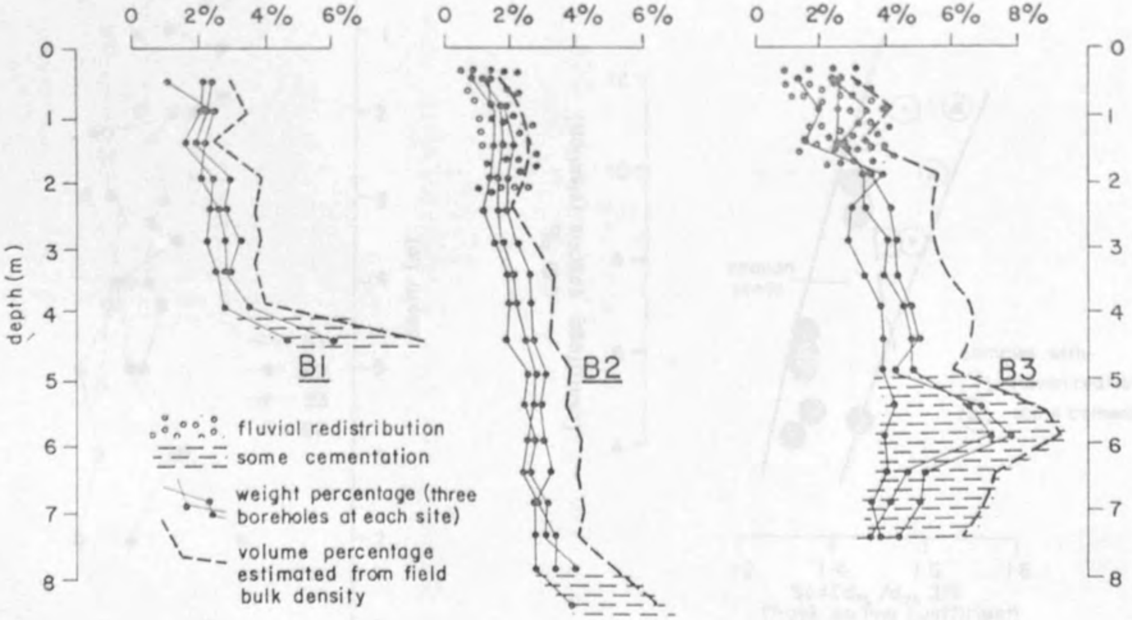


Fig. 7. Moisture content profiles in Kalahari Sand.

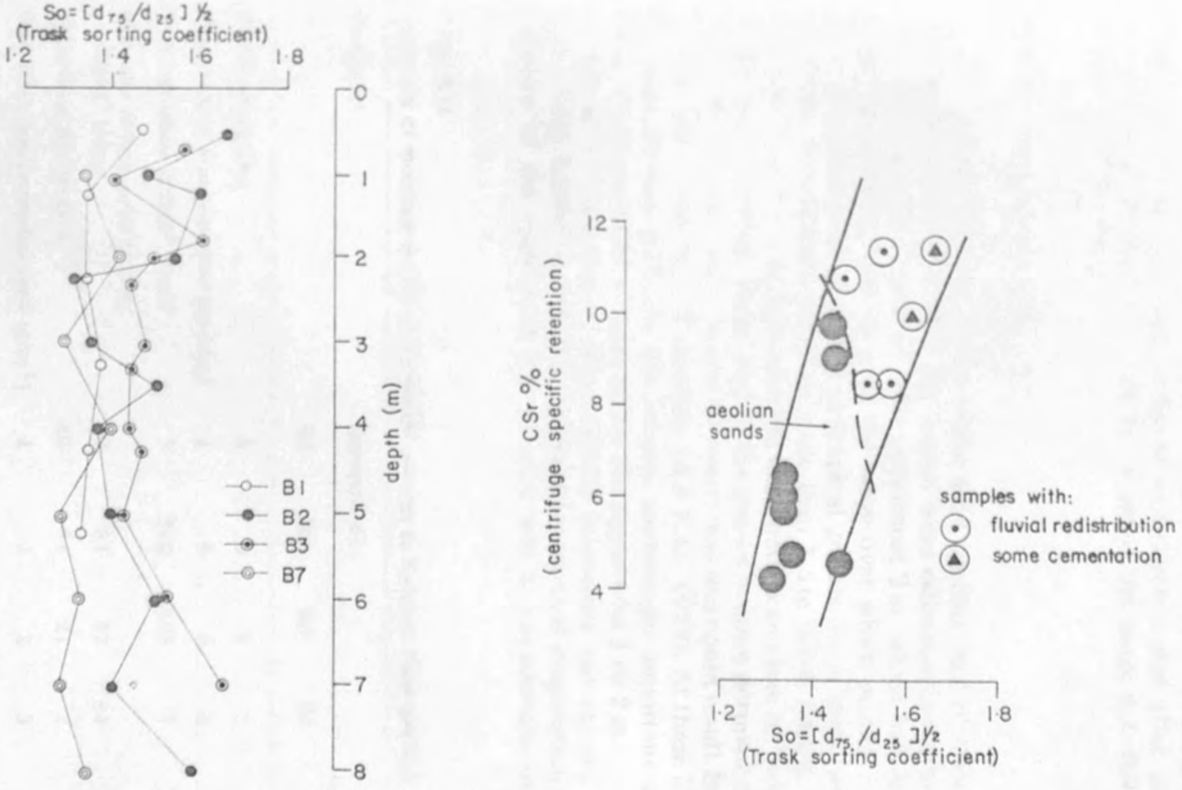


Fig. 8. Specific retention and sorting coefficient of Kalahari Sand.

results may be also subject to significant error because of the use of disturbed samples. The field capacity has been estimated independently by sampling beneath a cleared, irrigated and covered plot after allowing four days for drainage (A.P.R.U., 1979); values in the range 6.2–8.0 vol.% were obtained for 24 samples.

Role in hydrological cycle

The moisture deficits of the entire sand profiles, and of their uppermost 2 m, at the end of the 1977 dry season were estimated using the values for unit field capacity (Table II). The uppermost 2 m, which had deficits in the range 80–100 mm, was taken as the range over which moisture would have been unquestionably available to tropical grasses, since they exhibit significant root development down to more than 1.5 m depth (Balek, 1977). It is probable that the moisture contents must have been close to "wilting point" at the time of survey, since most of the grasses became dormant much earlier in the dry season, but it should be noted that this could result from climatic factors other than lack of moisture (A.P.R.U., 1979). At these low moisture contents thermal gradients will become increasingly important in the movement of soil moisture, at least within the uppermost 1 or 2 m.

During the wet season, when rainfall intensities can exceed 50 mm/day and 10-day rainfall intermittently exceeds potential evaporation, the storage capacity of the uppermost 2 m of sand will be occasionally exceeded and

TABLE II

Summary of moisture deficit and chloride content in Kalahari Sand profiles

Parameter	Borehole site					
	B*1*	B*2*	B*3*	B*4*	B*7*	B*9*
Profile depth (m)	6	9	8	?	9	6
Thickness of non-cemented sand (m)	4	8	5	4	8	3
Total moisture deficit* (mm)	?	270	135	?	335	155
Moisture deficit down to 2 m depth* (mm)	80	84	82	84	92	100
Total Cl in profile (g/m^2)	40	64	21	?	36	30
Unit Cl in non-cemented sand (g/m^3)	4	4	2	3	3	1

No Kalahari Sand was encountered at borehole sites B5 and B*8*, and B*6* was drilled in an area outside that considered in this paper.

* Assuming low values of unit field capacity for non-cemented, redistributed and partially-cemented sand of 6%, 8% and 10%, respectively, and corresponding field bulk densities of 1.4, 1.4 and 1.7 g/cm^3.

moisture will penetrate to greater depths. Gravity-aided redistribution of moisture through the profile will proceed rapidly during the first few days, but as the saturation reduces the potential gradient, hydraulic conductivity and the rate of moisture movement will decrease markedly (Youngs, 1958). The total moisture storage capacity in sand profiles of more than ~4 m depth (Table II) would only be exceeded, however, following the most exceptional sequence of rainfall events, unless the value of unit field capacity has been seriously overestimated.

The RC appropriate for grass-covered sand will depend to significant degree on how readily the tropical grasses can draw on water stored below 2 m depth, but in any case is most unlikely to be less than 50 mm. Because of the low moisture contents, the soil-water film will probably be discontinuous and upward movement from *below the zone of direct root influence* can be expected to be an isothermal vapour-phase transfer and, as such, will occur at low rates. Any deeper rooted vegetation, such as bushes, is likely to draw moisture directly from the full thickness of the sand profiles, to continue some growth throughout the dry season and to be characterised by much higher RC-values. All of the drilling sites were selected to be as remote as possible from larger bushes and trees, but it must be remembered that the lateral influence of their roots has been shown to exceed 10 m (A.P.R.U., 1979).

The balance of the meteorological and hydrophysical data, thus, would allow occasional infiltration to significant depths during the wet season, at overall mean rates of perhaps 25–35 mm/a, but this moisture may be largely or totally lost during subsequent dry seasons, either directly or indirectly, by evapotranspiration.

CHEMICAL AND ISOTOPIC PROFILES OF KALAHARI BEDS

Experimental methods

It had been hoped to extract uncontaminated fluid samples in the field laboratory representative, chemically and isotopically, of in situ pore moisture by a centrifuge extraction technique (Edmunds and Bath, 1976). However, the sand-moisture contents proved insufficient for any significant fluid recovery. Direct bulk elutriation also did not prove feasible because of the unacceptable dilution in relation to Cl determination and of the production of a colloidal suspension in the elutriate from the ferric staining on the sand which interferred with other analyses.

A technique of elutriation utilising the centrifuge was thus developed: 15–20 ml of deionised water were pipetted onto the top of each sand sample (of ~150 gm) packed into the four centrifuge liners and the set of liners was spun at 1000 r.p.m. for 5 min. and at ~3000 r.p.m. for a further 30 min. Elutriate recovery was 30–70% and spiking sand samples with NaCl solution suggested errors in the estimation of pore-moisture solute concentration of up to a maximum of ±20%. The method has certain unavoidable disadvantages:

(a) Possible disturbance of certain mineral—solution equilibria, probably invalidating study of certain ions such as Ca^{2+}, Mg^{2+}, HCO_3^-.

(b) The dilution effect may produce constraints on analytical techniques and accuracies.

(c) It provides no access to isotopic compositions of the pore fluids and sample vacuum distillation has to be used for this purpose.

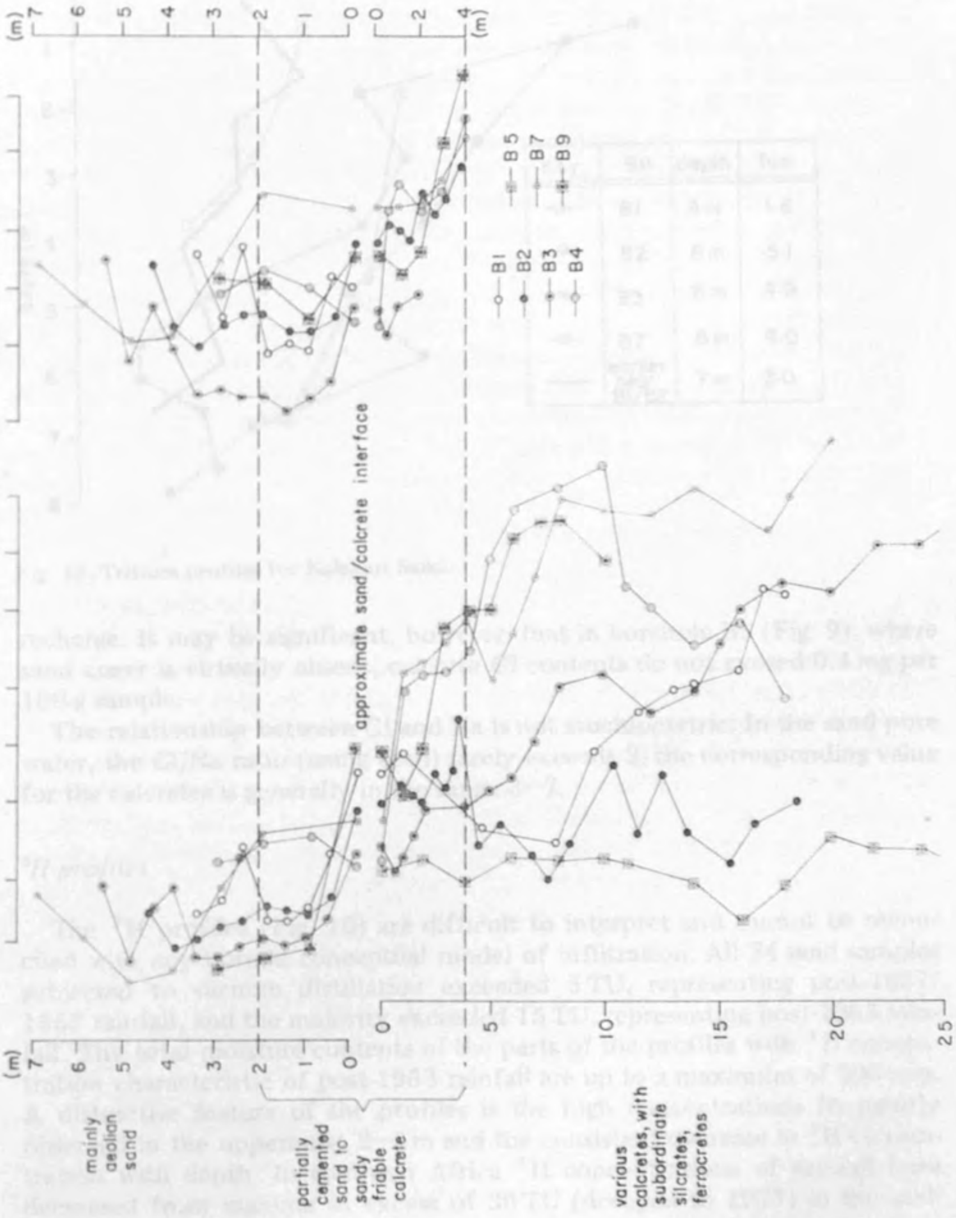
The chemical studies concentrated on Cl determined in the field laboratory by argentiometric micro-titration, supported by some sodium (Na) analyses on return to the base laboratory, using the atomic absorption spectrometer. The analytical results were initially expressed as mg Cl or mg Na per 100-g sample and in the case of the unconsolidated samples converted to mg/l, using the appropriate value of field bulk density.

Cl and Na profiles

The dominant feature of the Cl (and Na) profiles (Fig. 9) is the increasing concentrations with depth, especially in the partially cemented sand and sandy friable calcrete at the base of the Kalahari Sands. The absence of a salt crust at the surface or at any other level in the sands, and the relatively low solute contents measured, imply that some water is periodically flushing downward solutes, which must temporarily accumulate near the surface as a result of evapotranspiration. This process may have been more prominent in the recent relatively wet years.

Unfortunately, no long-term records of the atmospheric fallout of Cl, and other solutes, in the Kalahari are available but it is suspected, from analyses of some recent samples from central Kweneng, that rainfall is likely to have contained 0.05—0.5 mg Cl/l, which represents only 0.02—0.2 $g\,Cl\,m^{-2}\,a^{-1}$. From consideration of the mass balance (Table II), it thus appears that the Cl concentrations in the non-cemented sand are consistent with extremely low *net* rates of downward water movement (certainly less than 5 mm/a and probably less than 1 mm/a). The Cl content of the sand-cover, where more than 4 m in thickness, must represent at very least 50 years' input; although its variability is somewhat surprising. The fact that the Cl concentrations in the lower parts of the sand profiles generally exceed 100 mg/l also suggests that there has been little recent groundwater recharge, because this value is considerably higher than that normally encountered in underlying aquifers.

The Cl contents of the various calcretes and their contained moisture were also determined, in the main from air-flush chip samples. Representative moisture contents were not, of course, obtainable from such samples. The Cl contents were generally many times higher than those of the overlying sand, though in view of the more localised nature of any groundwater movement through these materials, such results could reflect the process of calcrete formation and not, of necessity, the absence of active groundwater


Cl (mg/l)
20
50
100
200
500
1000
Cl (mg/100 gm sample)
0·1
0·2
0·5
1·0
2·0
5·0
10
20
(m)
7
6
5
4
3
2
1
0
0
2
4
(m)
0
5
10
15
20
25
(m)
mainly aeolian sand
partially cemented sand to sandy friable calcrete
various calcretes, with subordinate silcretes, ferrocretes
approximate sand/calcrete interface
B1
B2
B3
B4
B5
B7
B9

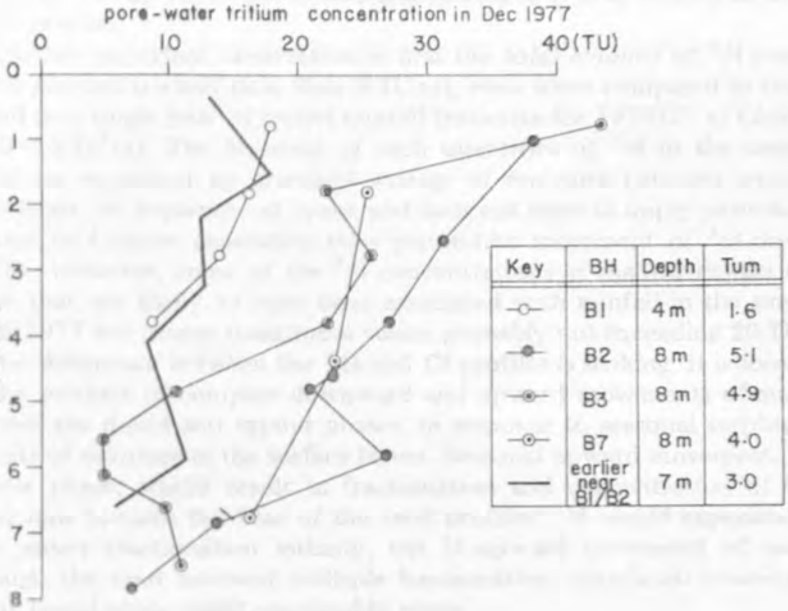


Fig. 10. Tritium profiles for Kalahari Sand.

recharge. It may be significant, however, that in borehole B5 (Fig. 9), where sand cover is virtually absent, calcrete Cl contents do not exceed 0.4 mg per 100-g sample.

The relationship between Cl and Na is not stochiometric. In the sand pore water, the Cl/Na ratio (using epm) rarely exceeds 2, the corresponding value for the calcretes is generally in the range 3–7.

^3H *profiles*

The ^3H profiles (Fig. 10) are difficult to interpret and cannot be reconciled with any normal conceptual model of infiltration. All 24 sand samples subjected to vacuum distillation exceeded 5 TU, representing post-1957/1958 rainfall, and the majority exceeded 15 TU, representing post-1963 rainfall. The total moisture contents of the parts of the profiles with ^3H concentration characteristic of post-1963 rainfall are up to a maximum of 200 mm. A distinctive feature of the profiles is the high concentrations frequently observed in the uppermost 2–3 m and the consistent decrease in ^3H concentration with depth. In southern Africa ^3H concentrations of rainfall have decreased from maxima in excess of 30 TU (decayed to 1977) in the mid-

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Fig. 9. Pore-water chloride profiles for Kalahari Beds (October–December 1977).

1960's to 15–20 TU in the 1970's and cannot be readily related to the form of the profiles.

Another important observation is that *the total amount of* ^{3}H *contained in the profiles is small* (less than 5 TU m), even when compared to that contained in a single year of recent rainfall (estimate for 1976/77 at Letlhakeng is 10–12 TU m). The presence of such quantities of ^{3}H in the sand-cover might be explained by transient storage of moisture between wetter and drier years, or sequences of years, and does not need to imply periodic small volume infiltration generating slow piston-like movement of ^{3}H down the profile. However, some of the ^{3}H concentrations at shallow depths exceed those that are likely to have been associated with rainfall in the preceding 1976/1977 wet season (maximum values probably not exceeding 20 TU).

The difference between the ^{3}H and Cl profiles is striking. It is thought to be the product of complex downward and upward movements of moisture, in both the liquid and vapour phases, in response to seasonal surpluses and deficits of moisture in the surface layers. Seasonal upward movement, via the vapour phase, would result in fractionation and concentration of Cl and other ions towards the base of the sand profiles; ^{3}H would experience only very minor fractionation initially, but if upward movement of moisture through the sand involved multiple fractionation, significant concentration in the liquid phase could conceivably occur.

CONCLUDING REMARKS

While some doubts remain about the interpretation of certain aspects of each body of data (meteorological, hydrophysical, chemical and isotopic) presented in this paper, taken collectively they suggest it would be imprudent to assume that diffuse groundwater recharge will be actively occurring through a Kalahari sand-cover of more than ~4 m depth in areas with annual rainfall regimes similar to, or less favourable than, that of central Kweneng. It seems likely that any short-term excess rainfall will be temporarily stored in the sands and utilised in subsequent dry seasons by the vegetation-cover of bush and grass. Indeed this moisture store probably accounts for the existence of the relatively abundant vegetation of much of the region.

In those parts of the Kalahari where the sand is thinner, excess rainfall will occur in some years, and groundwater recharge and/or localised surface runoff will develop, depending on the detail of the shallow geology and the character of the calcrete.

In the context of groundwater evaluation and planning for large-scale development, it is recommended that "resource mining" *must* be assumed, unless the existence of extensive, near sand-free tracts can be demonstrated from aerial photographs, satellite imagery and ground survey. The presence of active recharge to any deep aquifers in such areas should be confirmed, wherever feasible, by isotope and chemical analysis of first-strike water-table samples and by closely-monitored pilot development of the groundwater resources.

The tentative conclusion drawn in this paper could be confirmed using soil physics instrumentation to monitor temporal variations in soil water tension and moisture content in the Kalahari Sand cover. However, such work would be technically and logistically difficult to sustain in Botswana field conditions; for the present it would be advisable to restrict this approach to detailed study, at a few sites, of changes during a single wet season. Comparative hydrophysical, chemical and isotopic profiling of the sand cover in one area in the north of the country and another in the southwest, with mean annual rainfalls of ~ 550 and ~ 350 m, respectively, is also recommended.

ACKNOWLEDGMENTS

This research work formed part of the Botswana Government GS10 Project financed by the Ministry of Overseas Development (now Overseas Development Administration), London. The paper is published by permission of the Permanent Secretary, Ministry of Mineral Resources and Water Affairs, Gaborone and the Director, Institute of Geological Sciences, London.

Dr. B.Th. Verhagen of the University of Witwatersrand, Johannesburg, kindly advised on and supervised the laboratory measurements of tritium and radiocarbon.

Helpful encouragement or discussion from P.L. Agar, J.B.S. Diphaha, D.R.C. Grey, C.R. Jones, D. Prachett, Christina Skarpe, E.P. Wright and E.G. Youngs is acknowledged. Considerable assistance in the field was given by Jane Baron, Colin Cheney, John Kikele and Charles Jaba.

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CZECHOSLOVAKIA - PRAGUE 5.-11.9.1982

PROOF

IAH International Symposium: Prague, Czechoslovakia: 1982
"Impact of Agricultural Activities on Groundwater"

THE DISTRIBUTION OF AGRICULTURAL SOIL LEACHATES IN THE UNSATURATED ZONE OF THE BRITISH CHALK

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ABSTRACT

In Europe the Chalk constitutes a major source of potable water supply. Its outcrop forms extensive tracts of agricultural land, where the groundwater resources largely originate as infiltrating excess rainfall. Research on the unsaturated zone of the aquifer beneath such cultivated land should allow an assessment of nutrient leaching losses from the associated highly-permeable soils and the prediction of future groundwater quality trends. Pore-water profiles for nitrate, and numerous other constituents, from a site of exceptionally detailed study are presented, and compared to results from sites elsewhere in eastern England, to demonstrate the impact of modern arable agriculture. Environmental isotopes have also been investigated in depth to aid the study. The problems in evaluating the evolution of the unsaturated zone profiles are discussed.

INTRODUCTION

General Background

In the last few years, a number of papers have been published reviewing the progress of contining British research into the impact of agricultural practices on groundwater quality (Foster & Young, 1979 & 1980; Oakes et al, 1981; Foster et al, 1982). Their conclusions can be thus summarised:

(a) Modern arable farming practice is leading indirectly to major leaching of nitrate, and other solutes, from the freely-drained soils characteristic of the main aquifer outcrops.

(b) The chemical quality of groundwater supplies pumped from the main aquifers has, in most cases, only recently begun to reflect the radical changes in arable agriculture that were initiated some 20-30 years ago; this the combined result of delayed soil response, a significant or dominant component of slow solute migration in the unsaturated zone and considerable dispersion during lateral flow to production boreholes in the saturated zone.

(c) The detailed model of solute transport in both the unsaturated and saturated zones of the main (porous, fissured, bedrock) aquifers and the significance of in-situ denitrification require clarification by further investigation and long-term monitoring of solute and isotope distributions.

Of greatest, and most immediate, concern are numerous regions of eastern England, where most land is now used for near-continuous cereal cropping sustained by large applications of inorganic fertilisers. A single annual crop, generally sown in October or March, is cultivated without significant irrigation. Rainfall averages 600-800 mm/a, potential evapotranspiration 450-550 mm/a and excess rainfall 150-300 mm/a, the latter generally occurring in the months November-March.

Research Site Conditions

This paper discusses primarily the results of unsaturated zone investigations at a site on the Chalk near Cambridge (known locally as Fleam Dyke). The site is 60 m sq and part of a large flat field, fairly typical of agricultural land on the aquifer outcrop in eastern England, which has been in arable farming for at least 40 years. Fifteen cereal crops were cultivated during the period 1960-80 with inorganic fertiliser applications mainly in the range 60-100 kg N/ha/a, and 40-55 kg/ha/a of both P_2O_5 and K_2O, higher rates being applied in split application to winter-sown cereals. Sugar beet and peas have been the only other crops. Fertiliser application rates are believed to have increased greatly during the period 1950-60 with increasingly frequent cereal cropping and, at this site, have been reduced marginally since 1975. Cambridge is one of the driest parts of eastern England and the site is estimated to have a long-term average excess rainfall of about 170 mm/a. In recent years climatic conditions have been extreme, the prolonged drought which ended in autumn 1976 being following by three unusually wet winters and springs, with, for example, major infiltration occurring as late as May in 1978.

Hydrogeologically the site is on Middle Chalk with a groundwater table not thought ever to rise above 15 m depth. The Chalk is a pure, highly porous, limestone, but at this site, as in much of eastern England, it is slightly more marly and less homogeneous (Fig 1) than the Upper Chalk of southern England. Beneath the thin (0.3 m) cover of loamy calcareous soil, the Chalk is deeply-cryoturbated to a depth of about 2.0 m (Fig 1); the basal part of this structureless zone being exceptionally marly and underlain by a 0.5 m thick harder bed of lower porosity. The exceedingly small pore sizes of the Chalk matrix (Fig 1) mean that hydraulic conductivities are very low (less than 10^{-3} m/d at saturation) and that gravity drainage is almost entirely inhibited, the Chalk matrix remaining very close to saturation below 1.5 m depth, the zone of plant influence. In excavations the Chalk can be seen to be traversed by a large number of high-angle joints, whose net affect is to produce a broken aspect with individual blocks commonly less than 50 mm size. The resulting system of fine fissures is believed to be characterised by apertures of 0.05-5.0 mm.

Investigation Methods

It has not proved feasible to operate suction samplers in the Chalk unsaturated zone and all samples have been obtained by destructive methods. In the case of the Cambridge site, dry percussion sampling with a drive core barrel was employed, but elsewhere air-flush rotary drilling with a lined double core barrel was necessary. All samples were very carefully handled and stored to minimise evaporation and contamination prior to analysis. Pore water from selected depth intervals was extracted by high-speed centrifugation (except in the case of tritium samples where vacuum distillation to complete dryness was preferred) and analysed by a range of automated standard chemical and

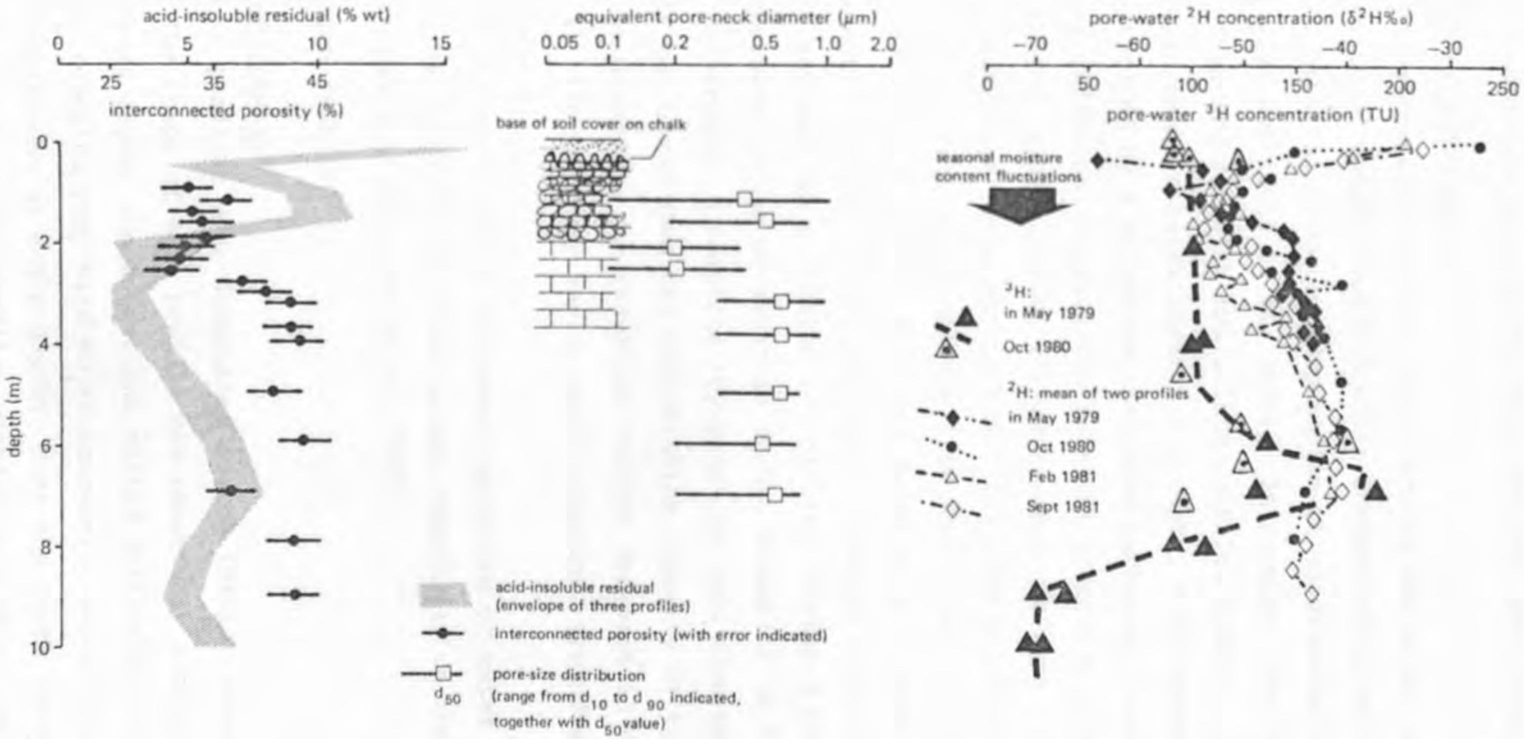

Figure 1: Geohydrological and isotopic profiles of the Chalk unsaturated zone at Cambridge site

isotopic techniques adapted for small volume water samples.

Water & Solute Movement

Soil physics research has also been carried out at the site; in-situ measurements of unsaturated hydraulic conductivity, soil moisture content and potential allowing computation of unsaturated zone water fluxes and pathways (Wellings et al, 1982). In summary, the Chalk unsaturated zone pore water, to which the solute profiles relate, is believed to be relatively immobile below about 1.5 m depth, with downward solute transport controlled by a mechanism involving exchange, through lateral molecular diffusion, between the pore water and mobile microfissure water (Foster, 1975). Thus, intermittently, solutes are eluted from high concentration 'regions' in the matrix and transferred to lower concentration 'regions' along the flow direction. This mechanism is sensitive to variations in rate and duration of fissure flow (a function of intensity of infiltrating rainfall), fissure geometry, matrix porosity and aqueous diffusion coefficient (Barker & Foster, 1981). Non-dispersive solute movement in such a formation is a rather special case. Conversely, a complete 'by-pass' of this slow mode of solute movement can occur when the infiltration capacity of the microfissure system is exceeded, the resulting further decrease in soil moisture potential allowing very rapid, short duration, groundwater flows in the macrofissures.

It should be noted that a different mechanism of water and solute transport may be operative in other areas, especially on the Chalk of southern England (Wellings et al, 1982).

PORE WATER PROFILES

Nitrogen Species

Six NO_3-N profiles were determined during initial investigation in May 1979. The shape of each profile was remarkably similar but laterally, at the same depth, concentrations varied quite widely (Fig 2). The profiles revealed very high NO_3-N concentrations with a 'front' of major proportions at 4-8 m depth. Over the depth range to the base of the front (at 8 m) the profiles contain more than 1100 kg NO_3-N/ha.

Comparable profiles but with generally lower concentrations and deeper fronts (Tab 1) have been observed in numerous arable fields in two other regions of eastern England (Foster et al, 1982).

Evidence for the movement of the profiles during the period May 1979-September 1981 is not conclusive, although little was expected since the infiltration could not have exceeded 260 mm, equivalent to the moisture content of less than 1 m depth of Chalk. The dominant feature is temporal variation of concentration not only in the sub-soil but throughout the uppermost 4-5 m of the profile (Fig 2). This might be attributed to natural lateral site variations and/or to in-situ

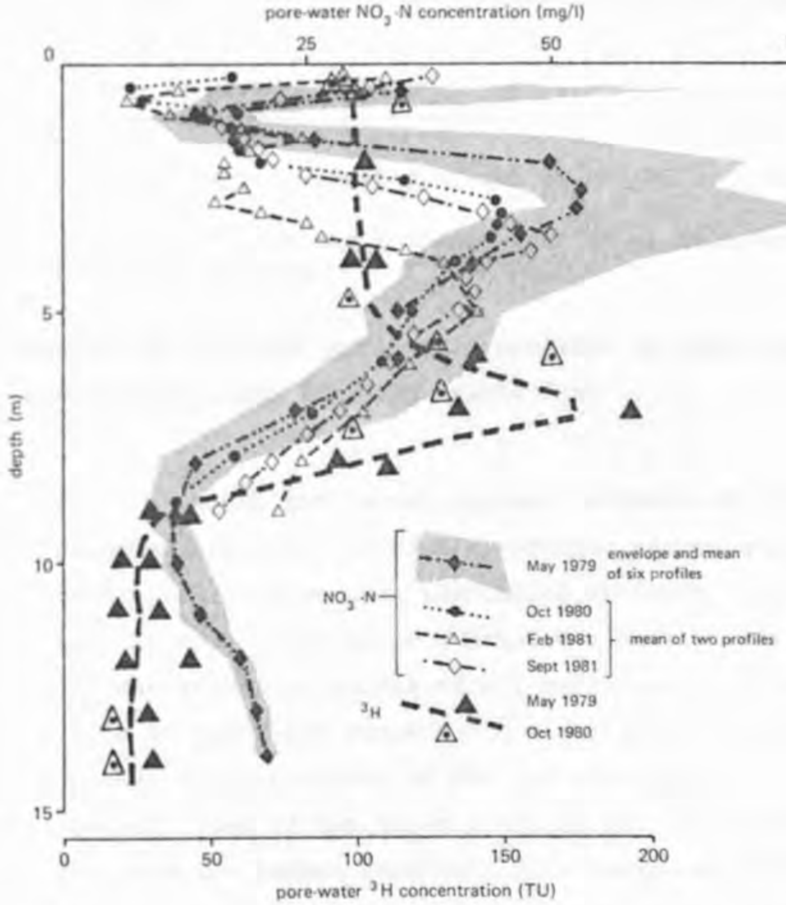

Figure 2: NO$_3$-N profiles of Chalk unsaturated zone at Cambridge site

location (date)	concentration (mg/l)	NO_3-N	SO_4	Cl	Ca
Cambridge† (1979-81)	peak	40-70	170-210	80-140	210-250
	uniform	15	50	40	?
	(at depth)	(8 m)	(12 m)	(6 m)	(9+ m)
North-West Norfolk (1976-79)	peak	20-40	90-160	<100*	110-160
	uniform	15	30	40	80
	(at depth)	(15 m)	(18 m)	(15 m*)	(15 m)
East Yorkshire (1978-79)	peak	<50*	<130*	<80*	<160*
	uniform	15	50	30	90
	(at depth)	(12 m*)	(18 m*)	(15 m*)	(15 m*)

† see Fig 2 & 4 for actual profiles of NO_3-N, SO_4, Cl

* highest concentrations in upper part of profile but peak not clearly defined

Table 1: Summary of chemical pore-water profiles in Chalk unsaturated zone beneath long-standing arable land

denitrification. Although the latter appears unlikely it cannot be discounted, since significant (insoluble) organic carbon and some nitrate-reducing bacteria have been identified at depth in the Chalk unsaturated zone at some other sites (Whitelaw & Rees, 1980). Pore-water NH_3-N concentrations in excess of 0.1 mg/l have been recorded at the research site in the depth range 0-1.0 m and 3.0-4.5 m and must reflect much higher concentrations in the absorbed phase.

Although the overall form of the NO_3-N profiles is broadly consistent with increasing leaching losses resulting from increased post-1960 use of inorganic fertilisers, the depth and magnitude of the peak concentrations are difficult to account for by any relatively simple model of soil nitrate availability and unsaturated zone solute movement.

Environmental Isotopes

The ^{3}H profiles (Fig 2) show the characteristic 'peak' which must have originated from fallout in the spring rain of 1962, 1963 and 1964. However, the 'peak' at this site is at shallower depth (5-8 m) and less defined than at some other sites.

The interpretation of such profiles from three sites on the British Chalk has been comprehensively discussed by Foster & Smith-Carington (1980) and their observations are relevant at this site also. If a non-dispersive ('piston-wise') downward movement of ^{3}H is assumed, post-1961 ^{3}H would be considered to occupy the uppermost 8 m of the Cambridge profiles and would total some 330 TUm, in about 2700 mm of water. Accepting the uncertainty about ^{3}H fallout in the rainfall at this site, it is still only possible to approach a satisfactory mass balance (between the profile ^{3}H and infiltration) if a considerable proportion of summer rainfall penetrates to 2 m depth or more and resides for sufficient time, in contact with the moisture 'buffer' retained at higher tensions, for isotopic and solute compositions to equilibrate (i e: a 'soil moisture store' considerably greater than 500 mm is operative). Even given the operation of this mechanism the ^{3}H concentrations in the upper most 3 m of the profiles are high when compared to those of post-1975 rainfall in eastern England, which only occasionally exceed 100 TU. The reason for this important anomaly is still under investigation.

The overall shape of the profiles from this site, and the difficulty in simulating their major features with any simple model of the input and transport mechanisms, suggest that the downward movement of ^{3}H below a depth of 2-3 m is also somewhat dispersive, with characteristic 'forward tailing' and 'peak retardation' (Barker & Foster, 1981).

The stable isotope ratios (^{2}H/^{1}H and ^{18}O/^{16}O) have also been investigated. Large seasonal fluctuations in the isotopic composition of rainfall have been measured at the site, with isotopically-light rainfall in the winter months, but a fairly constant long-term weighted annual mean is assumed.

The most significant features of the results are:

(a) Apparent discrepancy between the weighted mean composition of recent rainfall ($\delta^2H = -60\ ^0/oo$; $\delta^{18}O = -8.5\ ^0/oo$) and the uniform composition of unsaturated zone pore water (below about 3 m depth), the drainage of a 5 m deep lysimeter on an adjacent grass site and the local saturated zone groundwater (Fig 3).

(b) Variable composition of the uppermost 2-3 m of the profile; the shift in composition from isotopically light in May 1979 to heavy in October 1980, for example, being marked (Fig 1).

The results suggest a mechanism which produces a 'selective' net infiltration of isotopically-heavy water relative to average rainfall and support the concept of rapid penetration of summer rainfall, and mixing with 'stored' soil moisture prior to evapotranspiration, over the uppermost 2 m or so of the profile. At other sites with more clearly defined ^3H peaks small cyclic variations in δ^2H and $\delta^{18}O$, of seasonal origin, occur over some metres depth (Bath et al, 1982), suggesting less mixing in the upper zone.

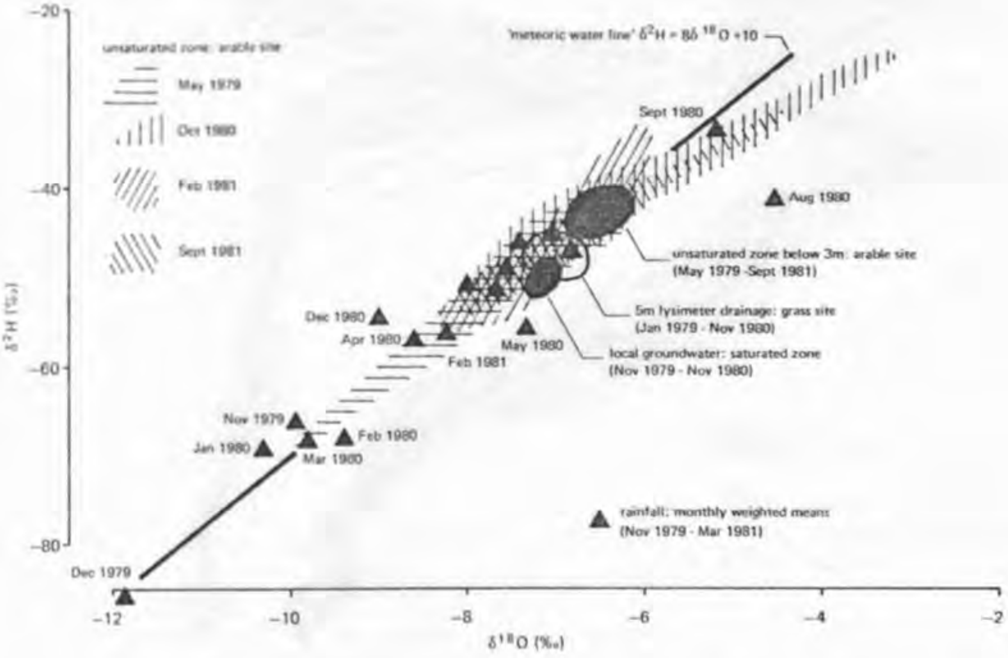

Figure 3: Summary of stable isotope data for Cambridge Chalk site

Chloride

The pore water profiles for a non-reactive, conservative ion, such as Cl also aid the interpretation of solute movement. Botanically, chloride is a non-nutrient, although it may be taken into some root crops (notably sugar beet) and plant saps.

The Cl profiles for the Cambridge site exhibit a similar form to those for NO_3-N, but with a somewhat narrower peak (Fig 4). The Cl fallout in rain leads, after soil concentration, to a groundwater composition of some 15 mg/l and all Cl above this background must be derived from potash fertiliser (almost invariably KCl) and certain other soil treatments.

In common with the NO_3-N and ^3H profiles, when a non-dispersive downward movement is assumed, some problems of interpretation arise and also

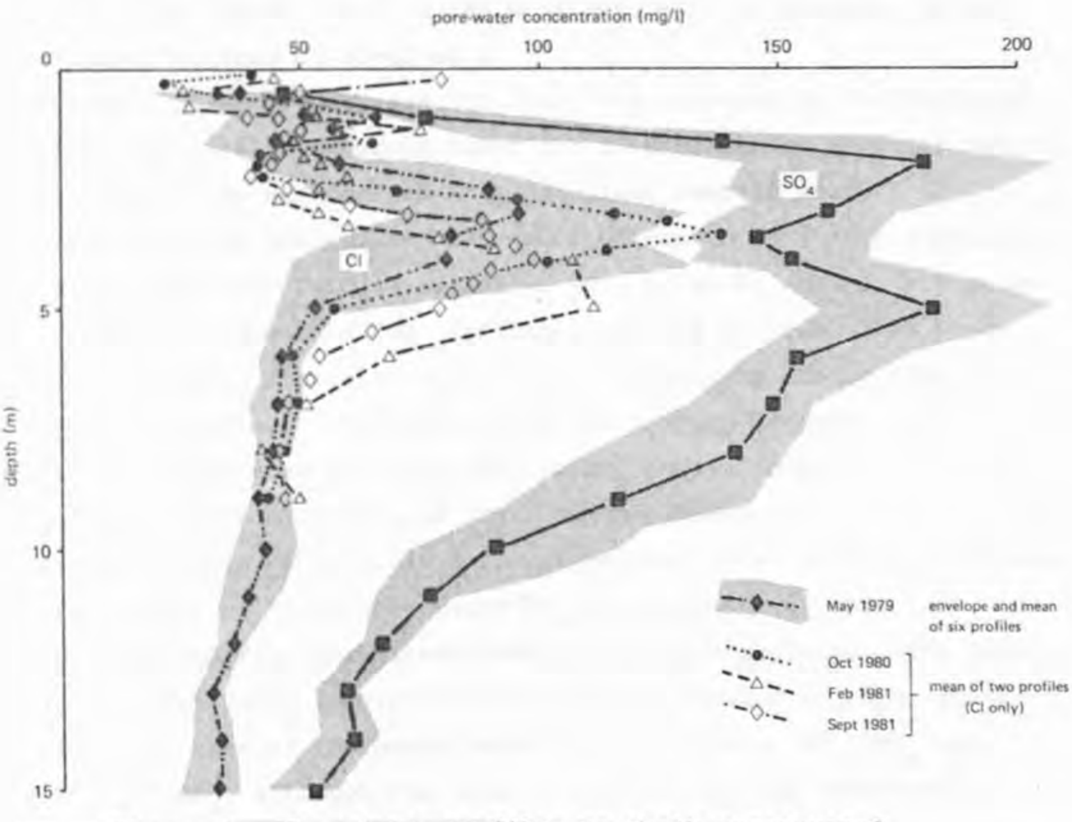

Figure 4: Cl and SO_4 profiles on Chalk unsaturated zone at Cambridge site

argue against this simple model of solute migration:

(a) The mass of Cl above 'rainfall background' to 8 m depth in the profile, (over 1300 kg/ha) is considerably more than the total applied since 1961 in fertilisers, some 900 kg/ha.

(b) The profile shape is not consistent with the historic record of fertiliser applications, particularly in respect of the peak width and magnitude.

Ca-CO_3-SO_4 Equilibria

Very high concentrations of SO_4 in pore water profiles, with a major 'front' in the depth range 5-12 m, have been detected (Fig 4); the Ca profiles are similar to those for SO_4. Comparable profiles have been observed at numerous arable sites in other regions (Tab 1). Although the fallout of SO_4 in rain has increased significantly in recent years, it is still only sufficient at the Camrbidge site to generate groundwater concentrations of 30-40 mg/l.

The unstable parameters pH and HCO_3 were not measured in the Cambridge profiles, but on-site determinations for five boreholes in other regions (whose reliability was confirmed by excellent overall analytical balances) show the unsaturated zone pore waters to be mostly supersaturated with respect to $CaCO_3$ (indices of +0.1 to +0.6) and grossly undersaturated with respect to $CaSO_4$ (indices of -0.8 to -1.9). In these profiles the $CaSO_4$ stoichiometry can be evaluated by subtracting Ca due to $CaCO_3$ dissolution. The approximate correlation between (Ca-HCO_3) and SO_4, their proportions not exceeding Ca-SO_4 equivalence, suggests that $CaSO_4$ is an important source of SO_4. Marine carbonate rock, such as the Chalk, may contain up to 0.05% S by weight, but this is unlikely to have been the source of these pore water SO_4 concentrations. The $CaSO_4$ is probably derived from fertilisers and its rapid dissolution with $CaCO_3$ may account for $CaCO_3$ supersaturation: SO_4 is present in large quantities in some types of inorganic fertilisers, notably $(NH_4)_2SO_4$ and $Ca(H_2PO_4)_2$-$CaSO_4$, although the usage of both types has decreased in recent years. The rate of migration of SO_4 will be influenced by its lower diffusion coefficient and by anionic retention.

element	detection limit (mg/l)	uniform conc.* (mg/l)	profile form		peak conc. (mg/l)
			soil tail	peak (m)	
Na	0.5	20.0	yes	no	-
Mg	0.1	2.5	no	2-5	4.0.
Si	0.1	2.5	yes	no	-
B	0.02	0.35	yes	no	-
K	0.5	0.5 - 2.0	no	no	-
Ba	0.001	0.2	yes	no	-
Sr	0.001	0.5 - 0.6	no	?	1.0
Cu	0.005	0.01-0.03	no	2-5	0.06
Zn	0.01	0.02	no	2-5	0.05
Li	0.005	0.01	no	no	-

* approximate value for two detailed profiles to 9 m in 1981 given, or range where results have considerable scatter without trend

n b: in all samples analysed following elements were below detection limit indicated in parenthesis in mg/l: Pb (0.2), Al (0.1), Mo (0.1), Ni (0.05), Co (0.02), Cd (0.005), Fe (0.005), Mn (0.005), V (0.005)

Table 2: Summary of minor and trace element pore water profiles from Chalk unsaturated zone beneath Cambridge arable site

Minor & Trace Elements

Amongst the profiles for these elements four groups can be distinguished (Tab 2):

(a) Profiles with indications of peak concentrations at depths of 2-5 m similar to Ca and/or SO_4 and/or Cl and/or NO_3-N.

(b) Profiles which 'tail' to uniform concentrations from maxima at the base of the soil.

(c) Elements which exhibit relatively uniform concentrations throughout the profiles.

(d) Elements which do not exceed current detection limits.

Some correlation of Mg, Sr, Zn (and perhaps Cu) with Ca is not surprising since they are characteristically associated with the carbonate phase. Correlation in turn with Cl and NO_3-N, which are largely fertiliser derived, may result from the latter modifying the hydrochemistry (especially pH) of water infiltrating the Chalk surface and allowing greater reaction with carbonate minerals, releasing more Ca, Sr, Mg, Zn and Cu before equlibrium is achieved, or from their presence in fertilisers.
The relatively high concentrations of Ba and B in the uppermost part of the profiles (Tab 2) are probably fertiliser derived, but their migration must have been strongly retarded by adsorption-desorption processes on soil minerals.

CONCLUSION

Large quantities of solutes leached from arable land are present in the unsaturated zone of the British Chalk. The rates of leaching have increased substantially with more intensive cultivation over the last 20 years or so. The pore water profiles presented also demonstrate the complexity of solute transport mechanisms (from the soil through the unsaturated zone) in a fissured microporous limestone, such as the Chalk. These mechanisms need to be better understood if the historic and future evolution of the major fronts of nitrate, sulphate and other solutes are, respectively, to be evaluated and predicted. From the numerous lines of investigation pursued in detail at the Cambridge site it is suggested that:

(a) In the uppermost few metres, the precise depth being a function of the hydrogeological properties of the weathered profiles, solute movement is strongly dispersive, with intermittent rapid downward (and, presumably, near-continuous slow upward) fluxes occurring in summer.

(b) Solutes are eluted from this upper zone and transported downwards by infiltrating excess rainfall, the extent of non-equilibration, or dispersion, being essentially a function of the intensity of infiltration, the matrix hydraulic properties , the fissure geometry and the appropriate diffusion coefficient of the solute concerned. Environmental isotopes have proved a considerable aid in evaluating both the input and transport processes, which can be expected to vary significantly across and between regions.

ACKNOWLEDGEMENT

This paper is published by permission of the Director of the Institute of Geological Sciences and with the encouragement of its Chief Hydrogeologist, John Day. The work was financed by the Department of the Environment and the Natural Environment Research Council. The authors thank their colleagues, Lionel Bridge, Amanda Smith-Carington, Jennifer Cook, George Darling and Adrian Lawrence for valuable assistance.

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The Institution of Civil Engineers

PROCEEDINGS

PART 1

Design and
Construction

PRE-PROOF

Proc Inst Civil Engrs (London) I : Paper No 8550 (1982)

EXPLORATION, EVALUATION AND DEVELOPMENT OF LARGE-SCALE GROUNDWATER SUPPLIES IN THE BOTSWANA KALAHARI*

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ABSTRACT

Unlike some other major semi-arid regions, the Kalahari is not blessed with an extensive prolific aquifer. Large areas are underlain by thick Karoo and Kalahari strata, however, and either may include some consolidated sedimentary formations which form subregional aquifers, possessing sufficient transmissivity for production boreholes to yield 5-15 l/s of acceptable quality groundwater. While such aquifers appear capable of making a significant contribution to the large water supplies required for the region's development, hydrogeological complexity increases the cost of, and reduces confidence in, groundwater resources evaluation. Five main problems are commonly encountered and these are discussed in relation to the case of a 20 Ml/d water-supply for a new mine and associated infra-structure. The interim solution utilising groundwater was achieved inside 3 years at a total capital cost of about US$ 11 M, some 15% of which represented exploration costs, compared to the surface water alternative priced at more than US$ 40 M. The effect which groundwater resource uncertainties have on the approach to technical development and capital investment for mine water-supply is also highlighted.

INTRODUCTION

Background to water supply demand

1) The existence of a major diamond prospect at Jwaneng in southern Botswana was discovered in 1976. By mid-1977 the need for a water-supply of 4.5 Mm^3/a (up to 20 Ml/d during 300 d/a) over at least 20 years, for mine process water and mining infrastructure, had been defined. Only the latter needed to be of potable quality. The economics of such a mining venture are highly dependent upon establishing an adequate water-supply, since the cost and effectiveness of diamond recovery methods vary widely with water-supply availability. The Jwaneng project represented an increase of more than 10% in Botswana's water demand. Groundwater had previously been developed to a short-term capacity of some 10 Ml/d, from the Cave Sandstone for the Orapa-Letlhakane mining complex, but only as a stand-by supply.

2) During 1977 preliminary evaluation of the possibilities of developing surface water resources revealed that:

   (a) The only realistic option involved a pipeline from the Gaborone Dam, over 120 km west, at a capital cost of about US$ 36 M*; the dam would also have to be modified to increase available storage at a further cost of some US$ 10 M, and its use would prejudice future expansion of Gaborone's water-supply.

   (b) The reliability of a surface water storage scheme could not be assessed with any confidence until 1981, at the very earliest, because of meagre hydrological records.

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* all costs are in US$ on dates implied in text, when the Botswana Pula was valued at about US$ 1.25 and UK£ 0.55

3) Thus groundwater appeared the only means feasible to satisfy the mine's water demand of 1-3 Ml/d for construction and pilot operation during 1978-81, building up to 15 Ml/d in the early years of full-scale operation from 1982 onwards. It was possible that, if necessary, a conjunctive use of surface and groundwater resources could be implemented some 3 years after the reliability of a surface water scheme had been adequately evaluated.

Geohydrological setting of southern Botswana

4) Across much of southern Botswana (Fig 1) the Kalahari is underlain by the Karoo system (of Carboniferous-Jurassic age), within which useful subregional aquifers may be present in the Ecca and Cave (Stormberg) sandstones. The geology of the Karoo system is very complicated and has only been elucidated locally during mineral exploration. The complex stratigraphy, sedimentology and structure of the Ecca Series reflect a continental basin environment of deposition. Later, during the Stormberg, more uniform conditions of sedimentation prevailed and, in consequence, the stratigraphy of the Cave Sandstone is less complex. Unfortunately, however, this formation does not appear to be characterised by as high transmissivity and storativity as some Ecca sandstones and completion of efficient production boreholes is also more difficult. The overall geohydrological picture is further complicated by late-Karoo volcanism and by the surficial blanket of Kalahari Beds (Fig 1). No thick Middle Kalahari aquifers, like those in parts of Namibia (Worthington, 1977) appear to be present.

5) In southern Botswana, the Kalahari Beds (of Cretaceous to Recent age) rarely exceed 40 m thickness except in occasional pre-Kalahari buried channels, and comprise a sequence of essentially aeolian sands, calcretes and related deposits. The remarkably flat sand-covered plain has very variable, high intensity rainfall, averaging 250-550 mm/a (Fig 1) and occurring mainly in the hot wet season (December-March) when potential evaporation reaches 8 mm/d. For the most part, the region is sufficiently vegetated

to stabilise the sand cover and only in the extreme southwest do true desert conditions prevail. Despite high rainfall intensities, surface run-off is localised and rare, although some water stands quite regularly in pans. The existence of 'fossil' valleys must be a relic of historic wetter periods.

Scope of groundwater investigations

6) In 1977 a groundwater feasibility study was initiated over 100 km radius from the projected mine to assess the prospects of obtaining the required water-supply for a minimum of 7 years, with priority on an area of about 3200 km^2 of the Karoo margin some 20-70 km north (Fig 2). This area is fairly remote, being 85 km from the nearest all-weather road and 140 km from an airport or railhead. Although its broad stratigraphy was known from some 20 cored boreholes for coal exploration, very little hydrogeological data were available.

7) The positive results of this study in respect of an area of central Kweneng some 30-50 m distant, where Ecca Sandstones occur at relatively shallow depth, led to an intensive staged investigation of a smaller area of some 1200 km (Fig 2), to evaluate the groundwater resources and to plan groundwater development. Existing abstraction totalled only some 0.7 Ml/d for livestock watering and village water-supply. A timetable of the investigations, with a breakdown of costs, is given in Table 1. The principal methods of hydrogeological exploration and groundwater resources evaluation utilised are summarised in the following paragraphs.

8) Surface geophysical surveys

Two techniques were employed, gravimetric and magnetic. The gravity results were used in an attempt to delineate the major tectonic features and to define the configuration of the underlying (pre-Cambrian) basement, composed in this area of highly-indurated sediments with widespread doleritic intrusions. The magnetic results were complementary where the basement was apparently doleritic, but were also used to search for any late-Karoo intrusions. Some 22 north-south traverses of varying lengths, totalling about 710 km, were surveyed with prismatic compasses. Geophysical stations for gravimeter and magnetometer readings were established every 200 m along each traverse and accuracies better than 0.1 mgals and 2 gammas respectively achieved. Electric resistivity soundings were not pursued because of the potentially complex and time-consuming data interpretation associated with highly-variable Karoo lithologies, but it should be recognised that both geoelectric (Worthington, 1977) and seismic techniques might have been employed with some success.

9) Drilling programme

The main programme involved drilling at 39 discrete sites (Fig 2). Combined air-hammer/rotary drilling machines were used throughout, equipped with a compressor/booster system capable of delivering up to 0.4 m^3/s (850 cfm) at 3.1 MPa (450 psi), with a limiting capacity of 260 mm diameter 'completions' to 150 m and 200 mm 'open-hole' to 350 m. At each site a single exploratory/trial borehole was put down initially and the following data were collected: geological strata record, incremental airlift yield during drilling, geophysical formation logs by electric self-potential, single-point resistivity, natural gamma and bulk density (gamma-gamma) techniques with, where justified, (short-duration) step-test pumping. Additionally, government groundwater research work has included parallel drilling programmes with:

(a) Five cored boreholes at certain of the above sites (Fig 2) to improve stratigraphical correlation and to provide samples for laboratory testing of aquifer properties.

(b) Power augering and coring of the Kalahari Beds to study their stratigraphy and to generate soil, rock and water samples for physical, chemical or isotopic analyses.

10) Hydrogeological pumping tests

At 12 of the above sites (Fig 2) further boreholes were drilled to produce suitable conditions and proper control for the conduct of steady-rate hydrogeological pumping tests, mainly of 2-5 days' duration. At a further 11 sites (Fig 2) steady-rate pumping tests without observation boreholes were conducted to permit the estimation of transmissivity. During such testing, geophysical flow logs (micro-conductivity, differential temperature and impellor flowmeter) were run at some sites in an attempt to establish the presence of any major fissure-flow horizons. Systematic water sampling for chemical analyses was also carried out.

11) Mathematical aquifer modelling

A mathematical model was used to aid groundwater resources evaluation, to establish the sensitivity of such evaluation to errors in estimation of certain critical parameters and to guide wellfield design. The finite difference method of discretization was used, with alternating-direction, implicit, iterative procedures of solution to an acceptable convergence for the selected time increments. The area selected for modelling (Fig 2) was 56 km by 40 km; data files on the basic aquifer hydraulic parameters and boundary conditions being established on a 1 km grid and progressively upgraded during the investigation programme.

12) While the above methods represent a 'relatively advanced package' in the field of groundwater resource exploration and evaluation, they are all accepted techniques. This paper, therefore, does *not* describe them in any detail *nor* does it report their results systematically. The main objective is to appraise how far such methods were successful in quantifying the groundwater resources of a previously little-explored area with complex geohydrological conditions, given the prevalent time constraints and budget controls. Five principal hydrogeological problems were encountered and each is examined in subsequent sections.

PRINCIPAL HYDROGEOLOGICAL PROBLEMS

Exploration for major aquifers

13) Since the various formations within the Ecca Series were known to have been deposited in basin and basin-margin environments, it was believed from the outset that basement configuration, together with major tectonic structures, could be highly significant in the exploration for important aquifers.

14) On completion of the surface geophysical surveys, conducted largely during the feasibility study and at the first stage of the main investigation, Bouger gravity (Fig 3) and total magnetic intensity maps were produced. These data were digitised and subjected to spatial wavelength filtering by computerised techniques to produce upward continuation and second derivative maps, thus enhancing the study of the larger basement features and of the shallow smaller geophysical anomalies respectively. Specific traverses and anomalies of interest were also subjected to two and three dimensional modelling to aid interpretation; a density contrast of 0.5 gm/cm^3 being assumed between the Karoo sediments and the basement. Two main southern basins, separated by a NNE-SSW basement ridge, were defined (Fig 3), bounded to the north by a major regional WSW-ENE fault system with a variable net downward throw to the north in excess of 150 m. All fault systems are likely to be reactivated basement features; a frequent direction of faulting in the area being WNW. In general Karoo strata are wedged and faulted out southwards against the rising basement complex.

15) The drilling programme for the feasibility study (over 3200 km^2) included 18 sites to explore the geohydrological conditions in areas of differing geophysical signature. This led to the following main conclusions:

(a) The widespread occurrence on the basement ridge, and in much of the southeastern basin, of a sandstone sequence possessing transmissivity (T) frequently in excess of 400 m^2/d; the major aquifer apparently being a coarse arkosic sandstone within the Upper Ecca, containing remarkably fresh $Ca-HCO_3$ groundwater.

(b) The existence of useful sandstone aquifers, also containing low salinity groundwater but with lower T (up to 200 m^2/d, but frequently less than 100 m^2/d) over wider areas.

(c) The presence of Ecca sandstones regionally downdip and to the north of the regional fault system, containing fresh $Na-HCO_3$ groundwater under high confining heads beneath thick Beaufort Shale (Fig 4).

16) In subsequent drilling programmes, attention was focussed on the aquifers of the two southern basins and their boundaries. The density of drilling sites over the central part of the exploration area was increased from 1 per 50 km^2, at the end of the feasibility study, to more than 1 per 20 km^2. The results can be summarised as follows:

(a) The groundwater contained by the Ecca sandstones is encountered at depths from 60-140 m and extends to depths of up to about 300 m, with the piezometric surface generally at about 40-60 m bgl.

(b) Over much of the basement ridge and the relatively shallow southeastern basin, the main water strikes are in the Upper Ecca (Masope) Formation, with additional aquifers in the underlying Middle Ecca Group (Fig 4). The lowermost 20 m or so of the former are generally by far the most permeable and the groundwater in this (Lower Masope) aquifer is, in practice, frequently confined (at 15-30 m head), by immediately overlying finer-grained, less permeable strata.

(c) In the deeper southwestern basin, the Masope Formation is absent (Fig 4); the main aquifer is a thick (30-150 m) sequence of Middle Ecca sandstones, which, as in the north, is overlain by a confining bed of Beaufort Shale.

(d) At only one site, No 32 in the southwestern basin (Fig 3), was groundwater of significantly high salinity encountered at depth in the Middle Ecca sandstones.

Evaluation of aquifer characteristics

17) Hydrogeological pumping test data (Table 2) from the southwestern basin showed fully confined responses but over the rest of the main investigation area the behaviour was much more complex (Fig 5). Most sites exhibited responses similar to the 'leaky confined' type, perhaps artificially enhanced by the penetration of solid lining tubes, with subsequent signs of 'delayed-yield' at some sites and pronounced directional anisotropy in certain instances. The responses were compatible with the concept of a major Lower Masope aquifer receiving induced leakage from overlying less permeable strata, and possibly also from below.

18) There were also indications that, in some cases, the situation is yet more complex. Excess, or increasing, groundwater heads at depth, of up to a few metres, were quite frequently observed in the Middle Ecca Group, and static borehole water-levels must often be composite. In such instances, the initial rate of pumping test drawdown will be governed by well storage alone and the transmissivity of the aquifer horizon possessing the excess head (Fig 5). If, as will be the case, the latter is small in relation to that of the Lower Masope aquifer, then the excess component of the composite static water-level will behave as a 'dead' head and be rapidly depleted until drawdown has reached the piezometric surface of the Lower Masope. Estimation of its magnitude was attempted by analysis of step pumping tests. Some of the observed (minor) changes in groundwater chemistry of discharge samples during pumping tests probably reflect the existence of excess heads at depth (and others the development of induced leakage).

19) Laboratory testing of borehole core samples from 5 sites (Fig 2) showed the interstitial horizontal permeability of the sandstones to be generally in the range 0.01-1.0 m/d. The wide variation in lithology makes selection of representative samples from unit core intervals difficult and although some sandstones (notably the Lower Masope) do appear to possess sufficient permeability to permit major intergranular movement of groundwater, an important and perhaps major component of the total T (in the high T areas) must be associated with fissures of some nature. Since high T is areally widespread, these fissures are not necessarily of tectonic origin, and many are likely to be bedding-plane joints enlarged by water movement. Detailed descriptive logging of borehole cores showed coarse friable arkosic sandstones at the base of the cyclic units of sedimentation, with many cavities resulting from the decomposition and removal of part of the feldspathic matrix probably being responsible for the relatively high formation T. The SiO_2 concentrations of the groundwater (30-60 mg/l) are higher than those generated by quartz dissolution alone and suggest that silicate alteration is taking place. Fissures were ubiquitous throughout the profiles and in the coarser zones included cavities up to 50 mm diameter, aligned parallel to the bedding.

20) In heterogeneous and fissured aquifers it is not sufficient to know only the magnitude of transmissivity. The depth and thickness of the main permeability developments are more important than the overall saturated thickness, since they directly relate to the heads that can be utilised in groundwater abstraction and therefore to the behaviour of individual production boreholes. Major groundwater inflows into pumping boreholes are normally associated with minor variations of electrical conductivity and/or temperature of the borehole fluid column, which can be logged using sufficiently sensitive equipment, and estimates of vertical flow rates below the pump can be made by flowmeters, giving a semi-quantitative indication of productive zones.

However, the maximum completion diameter for trial production boreholes resulting from the drilling technique used (170 mm and latterly 210 mm), imposed a serious constraint on the application of the above methods, since it was insufficient to allow access for the borehole flow logging probes, when pumping plant of appropriate capacity was installed. From the important evidence of the incremental airlift yield during drilling, it is tentatively concluded that highest permeability is associated with the Lower Masope, where this is present, but this could not be confirmed.

Establishment of lateral aquifer continuity.

21) Stratigraphic and lithologic correlation between boreholes in the Ecca Series is extremely difficult, because of repeated cycles from coarse to fine sandstones, siltstones and carbonaceous shales, marked facies variation and frequent tectonic disturbance. The question of the extent of lateral continuity of aquifer horizons arises.

22) Areas of shallow gravimetric (Fig 3) and magnetic gradients appear to reflect general continuity in broad geological terms, but not necessarily of aquifer horizons themselves. While numerous faults, probably of small throw, are postulated from the surface geophysics, it is not clear whether these will enhance or diminish local formation transmissivty on a consistent basis. A few prominent, but small, magnetic and gravimetric anomalies, which might have represented localised post-Karoo intrusions, were carefully analysed to determine most likely geometry. In each case their depth appeared too great to represent an intrusion into the aquifer system and at one site this was confirmed by drilling.

23) Perhaps the most important indication of hydraulic continuity is the fact that in 12 hydrogeological pumping tests no indication of lateral 'barrier' (impermeable or low permeability)

boundaries was recorded, but the complex hydrogeological conditions at many sites somewhat reduces confidence in their interpretation. The prominent basal arkosic sandstones of the Masope Formation were positively identified over a fairly wide area (Fig 4); correlation being aided considerably by geophysical formation logging, especially natural gamma. However, doubts remain about the continuity of the main aquifer units and the hydraulic relation between the Lower Masope of the southeastern basin and the thick Middle Ecca of the southwestern basin can only be speculated upon.

Likelihood of current groundwater replenishment

24) Although some groundwater replenishment associated with surface run-off may occasionally occur east of the area under consideration, the magnitude of any diffuse recharge from modern rainfall is regarded as a more critical question. Basic meteorological statistics for central Kweneng are sparse, but suggest that infiltration to depths of more than 2 m could occur occasionally during wet seasons, possibly at a mean rate of 25-35 mm/a during 1961-77. However, in areas where the sand cover is deep, this moisture will be retained and, during subsequent dry seasons, may be largely or totally lost by evapotranspiration.

25) A research programme was carried out to improve knowledge of the Kalahari Beds in central Kweneng (Foster *et al*, 1982) **and to study** the fate of this moisture. The results can be summarised:

(a) The Kalahari Sand proved generally to be 4-9 m in thickness, highly uniform and fairly well sorted, with a median grain size of 0.18 mm.

(b) Field moisture contents at the end of the (1977) dry season were low, uniform in distribution (Fig 6); it appearing that the moisture storage capacity of a 4 m deep sand profile would only be exceeded following an exceptional sequence of rainfall events.

(c) Tritium (^3H) profiles (Fig 6) were difficult to interpret and could not be reconciled with any simple infiltration model. Many samples exceeded 15 TU, representing post-1963 rainfall, and the total profile moisture content exhibiting such levels was around 200 mm, and the highest ^3H concentrations were in the uppermost 2-3 m and decreased consistently in depth and the total profile ^3H was less than 5 TU m, small even compared to a single year's fall-out in recent local rain.

(d) The dominant feature of chloride (Cl) profiles (Fig 6) was increasing concentrations with depth, especially towards the base of the Kalahari Sands. While the absence of a salt crust implied that some water had been periodically flushing solutes, the profiles were consistent with *extremely* low *net* rates of downward movement, ceertainly much less that 5 mm/a and the total Cl content of the sands, where more than 4 m thick, represented much more than 50 years' atmospheric input. The fact that concentrations in the lower parts of the sand profiles generally exceeded 100 mg Cl/l also suggested little or no recent groundwater recharge, because this value was higher than that of most groundwaters in the underlying aquifers.

26) Most Ecca groundwaters in central Kweneng have remarkably low salinity to surprising depth, with Cl concentrations being mainly in the range 50-100 mg/l. The chemistry of groundwaters appears to relate to the basins from which they derive (Fig 7), calcium bicarbonate groundwaters in the southeastern basin with increasing sodium, as a result of cation exchange on shale minerals, in the southwestern basin and to the north of the major WSW fault system. Pumped groundwater samples from the southeastern basin mainly recorded very low tritium concentrations (less than 1 TU), suggesting no definite post-1956 water present, and radiocarbon determinations in the range 50-65% mc, indicating groundwater ages of 2,000-4,500 years BP, or perhaps significantly younger.

27) Groundwater levels are generally below the base of the Kalahari Beds and the area possesses no identifiable groundwater discharges. Hydraulic gradients are extremely low, generally less than 0.0005 in a westward direction, and unlikely to represent a groundwater flow of more than 2 Ml/d per 10 km flow frontage.

28) In the context of groundwater resource planning, it would thus be imprudent to assume that recharge will occur as a result of present-day rainfall, unless near sand-free areas can be demonstrated. Such conditions are believed to occur only locally in central Kweneng. Therefore, any large-scale groundwater development must be regarded, for the present, as resource 'mining'. The philosophical question as to whether fresh 'fossil' groundwater in a semi-arid region should be abstracted for use as mine process water is not discussed here. However, since it is only economically practical to 'mine' a proportion of the total groundwater storage, development need not threaten village and cattle-post water-supplies, although remedial action will be required in certain instances.

Estimation of unconfined storage coefficient

29) At 8 of the 12 sites for which hydrogeological pumping tests were conducted, 'confined' or 'leaky confined' groundwater level responses were recorded (Table 2), with values of confined storage coefficient (S) mainly in the range 0.001-0.0001. Because of the relatively small confined head in most areas, except for the deepest parts of the southwestern basin, the total amount of groundwater in 'confined' storage is estimated to be only about 6300 Ml, compared with a water demand exceeding 4500 Ml/a. In the absence of groundwater recharge, therefore, aquifers are expected to become unconfined, and/or drainage of leakage beds to occur, at virtually all production borehole sites within the first few years of pumping. The apparent equilibrium produced by the 'leaky confined' response will, in the absence of groundwater recharge, also be relatively short-

lived. The mean unconfined storage coefficient (Sy) of the top 10 or 20 m of the saturated zone of the main aquifer horizons will, therefore, be critical in determining the groundwater resources and the long-term behaviour of a wellfield.

30) At 4 pumping test sites, suggestions of a 'delayed-yield' unconfined response were recorded (Table 2) and some gravity drainage of the uppermost part of the aquifer appears to have occurred; analyses of these data tentatively suggest an Sy of 0.01-0.03. In order to obtain more representative values it would be necessary to produce larger drawdowns in the unconfined aquifer over wider areas, which at the investigation stage would have required a group of production boreholes continuously pumping at a high steady rate for a number of months, with groundwater being discharged to waste through a relatively long, temporary pipeline to avoid recirculation. This was considered impractical and undesirable.

31) Indirect methods of estimating Sy based on laboratory testing of core samples were, therefore, introduced. Some 155 determinations of interconnected porosity (Ø) by the liquid resaturation method were made on sandstone samples taken every 1.0-2.5 m from the saturated interval of 5 cored boreholes; a mean value of 0.16 was obtained (Fig 8). Only a proportion of Ø will, in practice, be drained by gravity and contribute to Sy. This proportion will depend upon the pore sizes and, with certain reservations, can be estimated from measurements of pore-size distribution or from (less time-consuming but more subjective) centrifuge simulation tests. Some 10 of the former tests and 25 of the latter were undertaken on samples selected to represent the range of sandstone porosities and lithologies. The results suggest (Fig 9) that most of the sandstones with Ø of over 0.15 should have an Sy in excess of 0.05 and occasionally in excess of 0.10. However, some lower porosity sandstones, with hydraulic conductivities of less than 0.01 m/d, are characterised by much finer grain-size distributions and can be expected to possess an Sy of 0.01-0.05.

32) For the Lower Masope aquifer of the southeastern basin, Ø and Sy are expected to be at the higher end of the measured range, but it must be noted that this formation is only about 20 m thick and the possibility that shale horizons could inhibit gravity drainage of the sandstones must not be overlooked. Some 40% of the saturated formation thickness is composed of shales, but considering only the main aquifer horizons this proportion is significantly smaller. A value for Sy of 0.01 was thus selected as a conservative estimate for the sandstones in question. It is hoped that, at least locally and during certain periods of abstraction, values exceeding 0.05 will be experienced

APPROACH TO GROUNDWATER DEVELOPMENT

State of resources evaluation

33) The uncertainty about the average value of unconfined storage coefficient,and to lesser degree about continuity of the main aquifer horizons and current groundwater recharge, reduce confidence in the groundwater resources evaluation. The sensitivity of resource estimates to errors in storage coefficient and aquifer boundary conditions was examined using a computerised, finite-difference, mathematical model (Fig 10A). For an assessment of high confidence, the following worst-case assumptions were made:

(a) S and Sy to average 0.0003 and 0.01 respectively,

(b) neglect any 'leaky' storage from saturated strata overlying the Lower Masope aquifer in the southeastern basin,

(c) treat as impermeable boundaries, the main WSW fault system and the limits of the exploration area in all other directions,

(d) no active groundwater recharge either within the area modelled or across its lateral boundaries.

34) Operation of this model for various wellfield layouts demonstrated the availability of an absolute minimum of 7 years' supply for the projected mine, with relatively modest drawdowns in the'unconfined' storage (Fig 10B). Such a supply was considered sufficient to justify the cost of developing the appropriate wellfield, particularly since it would enable the mine to be brought into production at the earliest feasible date. Using more optimistic hydrogeological assumptions, it appeared that the mine could be supplied from groundwater for 20 years and possibly a lot longer.

35) Given the complexity of the hydrogeological conditions, it is not possible to assess groundwater resources with higher precision or greater confidence until the response to some large-scale abstraction has been observed. In particular significant dewatering of the southeastern basin will be required before estimates of Sy can be refined. Some 3 years of full-scale operation*, with comprehensive monitoring would yield much improved data on all hydrogeological parameters, with the possible exception of active groundwater recharge. In unison with this approach, parallel decisions on future water-supply planning and investment, including those related to the possible development of surface water storage and conjunctive use, have been deferred until 1985.

Production wellfield design and construction

36) In addition to the problems limiting confidence in groundwater resources evaluation, two additional factors affect the number of production boreholes, and the wellfield layout, needed to produce the required yield in the long-term:

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* to the end of 1981 abstraction totalling some 1200 Ml for pilot mining operations has produced no unexpected responses

(a) The degree of internal continuity of the main aquifer horizons within the areas of groundwater development in the southeastern and southwestern basins.

(b) The distribution of permeability with depth and the possibility of rapid non-linear reduction in transmissivity with drawdown in the main aquifer horizons.

The wellfield design must, therefore, be conservative and flexible, so that any loss of yield at individual production boreholes can be compensated by drilling additional boreholes at intermediate sites along wellfield pipelines, without necessitating major redesign.

37) A number of wellfield layouts were run on the mathematical aquifer model with printouts of total drawdown and of drawdown in the 'unconfined' storage after operation for approximately 1, 7 and 20 years. The layout selected (Fig 10B) takes into account the above considerations, and that of spreading and minimising the predicted drawdown in the 'unconfined' storage throughout the proven area of high transmissivity aquifers together with the need for standardising production borehole design. It comprises 16 production boreholes of either 1.5 Ml/d or 1.0 Ml/d maximum capacity, and allows for the number of production boreholes to be increased up to 24 without reducing spacing to less than 2 km, should excessive drawdown and concomitant loss of yield occur at any sites.

38) A comparative study of possible pumping plant for the production boreholes suggested that line-shaft turbine pumps (powered by surface motors) have certain disadvantages when compared to electric submersible pumps:

(a) Borehole verticality tolerances are more critical, if excessive strain on the line-shaft is to be avoided.

(b) They are not as compatible with the range of pumping duties resulting from the continuously-falling groundwater levels anticipated; this is likely to lead to higher maintenance costs.

(c) They have higher operating costs as a result of line-shaft losses.

Thus electric submersible pumps were preferred, despite marginally higher capital cost resulting from the need to drill production boreholes of larger diameter. Production boreholes had to be completed at 300 mm diameter to 150 m, the predicted maximum depth for the pump suction, and at 210 mm below that depth, with screens against the main producing horizons. Drilling at diameters sufficient for these completions is close to the technological limits of the air-hammer method and significant problems were encountered, which necessitated the abandonment of 2 production boreholes*. Unfortunately no other large-diameter drilling technique appeared practical, given the site conditions and time constraints.

39) The total *capital* cost of groundwater supply development, including project investigations, production borehole drilling, pumping plant installation, electricity supply, access roads, pipeline laying and monitoring work is about US$ 11.4 M, somewhat over 50% of which is the cost of the external pipeline and associated works. The unit overall (capital plus running) cost of untreated groundwater at the mine is calculated to be nearly US$ 0.5/m^3, assuming a discount **rate of 10% and a 20-year** wellfield life with some up-grading during the first 10 years. This latter cost is not very sensitive to errors in drawdown estimation because of the comparatively deep static groundwater levels.

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* this, in turn, required the up-grading of maximum pumping capacity at certain sites, but the overall development philosophy remained viable

CONCLUDING REMARKS

40) In areas of complex or little understood geology, exploration drilling programmes with a borehole density in the range 1 per 50-100 km^2, over a broad search area defined by economic and geological criteria, are required if the presence (or absence) of important subregional aquifers is to be confidently established. Surface geophysical surveys should be used to guide site selection but may not allow a significant reduction in the number of boreholes required, at least, at the initial exploration stage. Before embarking on major surface geophysical surveys for hydrogeological purposes it is worthwhile evaluating the relative effectiveness and likely cost-benefit of the various techniques available directly, by comparative field tests.

41) The disadvantages of groundwater development from such aquifers, for large-scale water supplies, primarily arise from the difficulty of accurately assessing the size of the two resource components - storage and recharge. A relatively-advanced 'package' of investigation techniques should allow a preliminary evaluation of the groundwater resources. However, it is well to recognise that, for the refinement of such an evaluation, carefully-monitored pilot development schemes are likely to be more effective than continuing investigations, which beyond a given level will arrive at a situation of diminishing returns.

42) The time at which to commence development must depend heavily upon the distance between the demand centre and the groundwater resource, and on the rate of growth of the water demand, since these factors will largely determine the initial capital cost of development and, therefore, the minimum resource required to justify development. Fairly soon after the initiation of groundwater investigations it should be possible to establish a mathematical aquifer model, which can be progressively upgraded as investigation proceeds. If realistic worst-case values for the relevant hydrogeological parameters corresponding to the state of knowledge of the groundwater system are selected, the model can be used to assess the minimum available resource and to steer subsequent investigation.

ACKNOWLEDGEMENTS

Much of the work to which this paper refers was undertaken on behalf of De Beers (Botswana) Mining Co Pty Ltd and the Government of the Republic of Botswana by Anglo-American Corporation and their consultants, Wellfield Consulting Services Pty Ltd. The senior author is acting as adviser to that government and is funded by the British Overseas Development Administration under their technical cooperation arrangements. The paper is published by permission of De Beers (Botswana) Mining Co Pty Ltd, the Ministry of Mineral Resources and Water Affairs, Gaborone, and the Director of the NERC Institute of Geological Sciences, London. The authors are indebted to many people associated with the Debswana Jwaneng Mine Project and, also, the Anglo-Botswana GS10 (Underground Water Resources Evaluation)Project: especially Martyn Marriott, Felix Mokobi, 'Neil' Evans, Alan Sobbott, John Martens, Peter Agar, Paul Spray and John Farr.

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Geophysics : 42 : 838-849

stage	duration	area (km^2)	surface geophysics (line km)	drilling sites	pumping tests		costs US $M*		
					step only	steady rate with(out) OBs	supervision	drilling	TOTAL
Feasibility Study	Apr 1977- Oct 1977	3200	140	18	11	5(0)	0.28	0.26	0.54
Government Research (part of parallel programmes)	1977-78	1200	0	(5 + 8)	0	2(0)	0.13	0.18	0.31
Stage I Investigation	May 1978- Dec 1978		450	15	12	5(6)	0.51	0.31	0.82
Stage II Investigation	Feb 1979- Jul 1979		120	6	5	0(5)	0.12	0.06	0.18
TOTAL			710	39	28	12(11)	1.04	0.81	1.85

* all costs refer to dates indicated; the Botswana Pula is valued at about US $1.25 and UK £0.55

Table 1: Timetable, scope and cost of groundwater investigations.

site no.	general location	no. of OBs	pumping rate (l/s)	total test duration (d)	terminal drawdown (m)*	T (m^2/d)	(S) Sy	response/ boundary
6	seb	3	9	13.0	4	500	1.10^{-2}	DY
13	seb	2	11	2.0	20	680	(3.10^{-4})	LC$^{\emptyset}$
14	seb	1	5	2.0	8	320	(3.10^{-3})	LC
16	br	1	8	4.5	7	190	2.10^{-2}	DY
17	br	3	19	6.8	1	1000+	(2.10^{-4})	LC
18	swb	1	11	2.4	11	440	(1.10^{-4})	C
20	out	1	11	5.0	8	140	(1.10^{-3})	LC
23	br	1	14	2.0	14	400	(3.10^{-4})	LC$^{\emptyset}$
27	seb	1**	10	4.7	17	600	(1.10^{-3})	LC$^{\emptyset}$
28	seb	1	11	3.3	2	1000+	3.10^{-2}	DY
29	br	1**	15	5.4	14	1000+	2.10^{-2}	DY
30	swb	1	15	2.6	6	580	(3.10^{-4})	C

KEY:
seb in southeastern basin
swb in Southwestern basin
br on basement ridge
out outside central area of investigation

* of trial production borehole, including variable well-loss component
** shallow observation borehole also installed

C confined response
DY with delayed-yield (indication of gravity drainage)
LC with indication of induced leakage
$\emptyset$ analysis much complicated by 'dead' head

Table 2: Summary of hydrogeological pumping tests

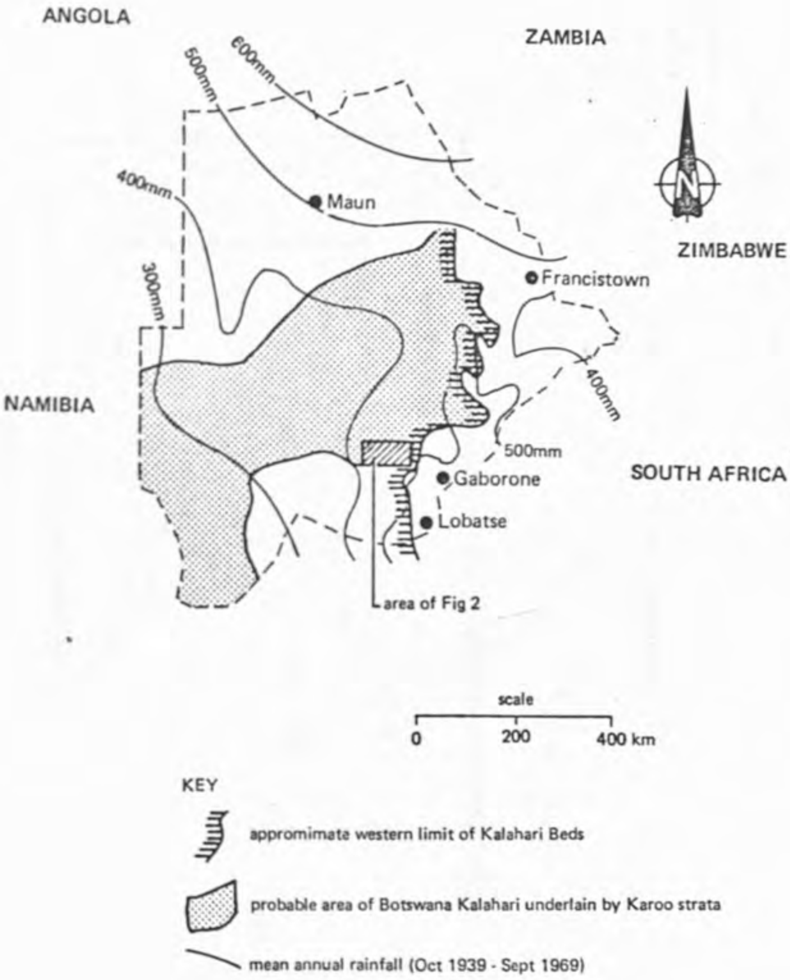

Fig 1. Botswana: location of investigations

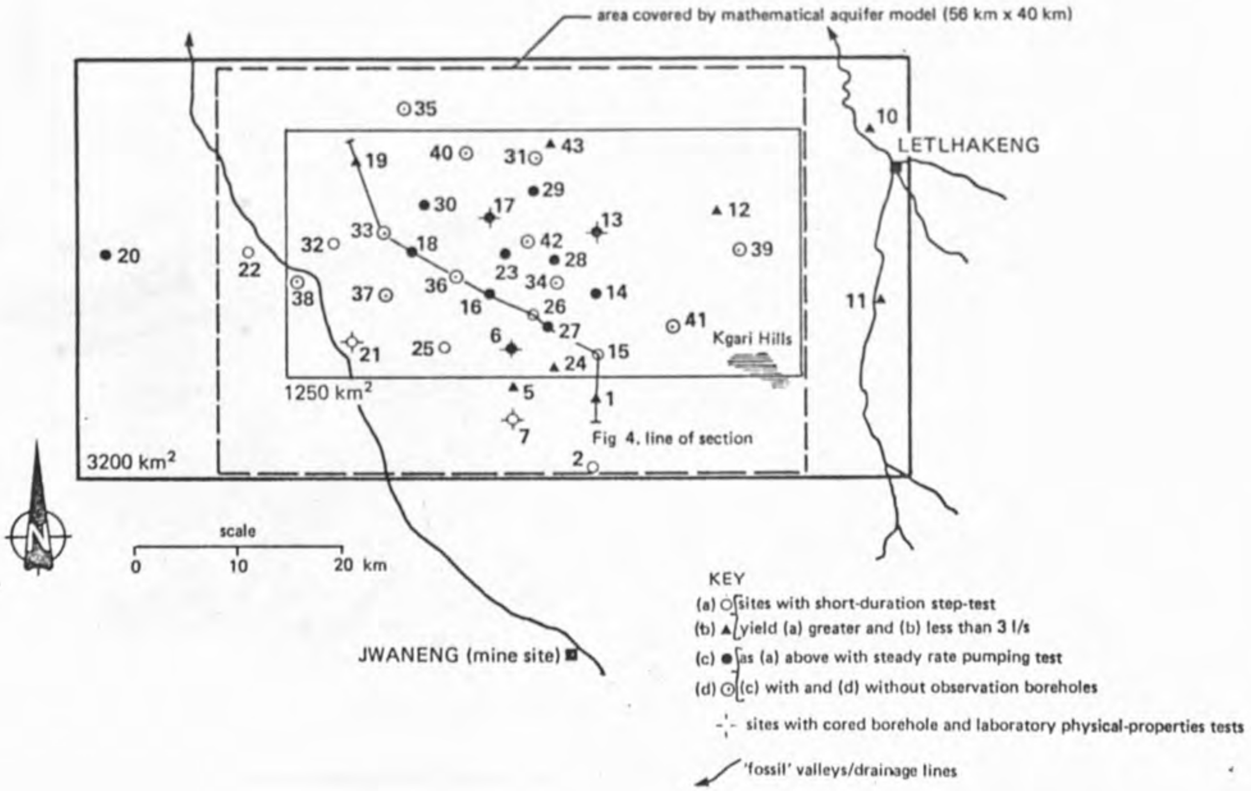

Fig 2. Central Kweneng: location of investigation area and sites

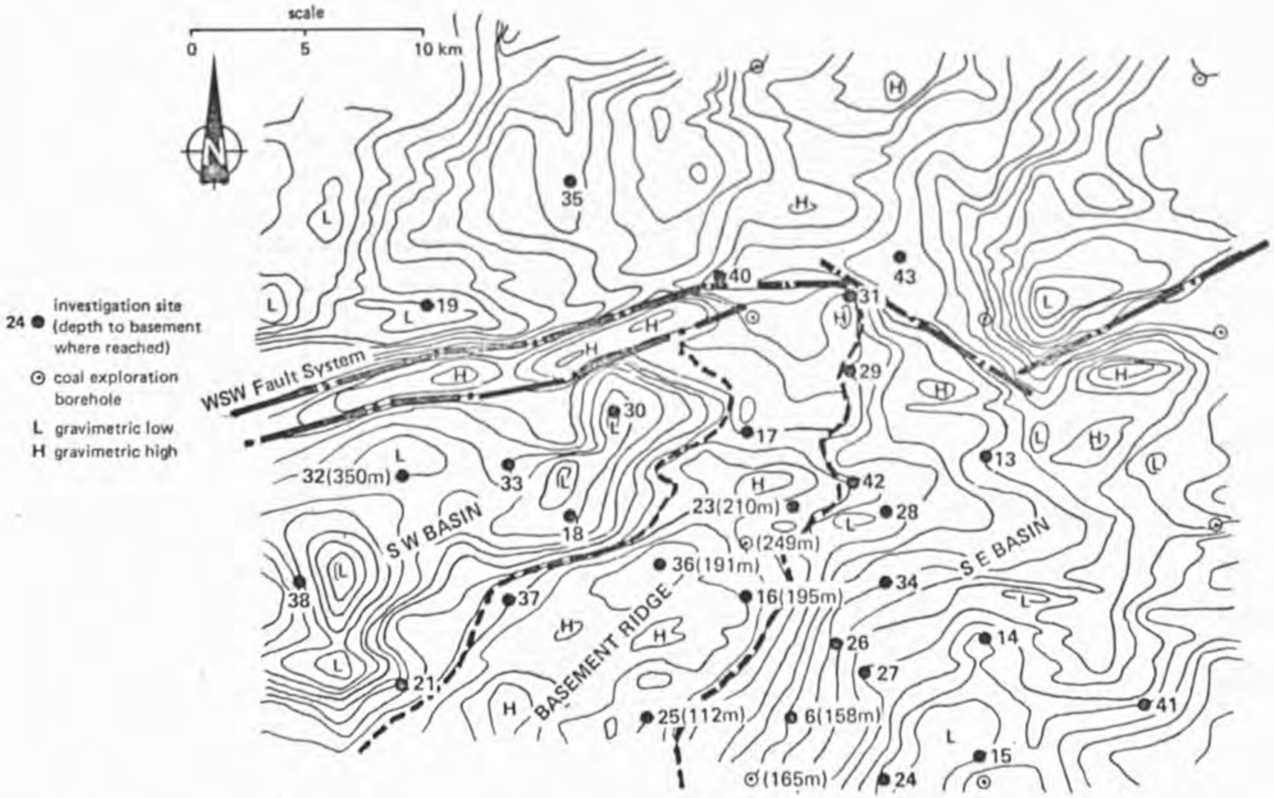

Fig 3 Bouger gravity map for the central part of investigation area

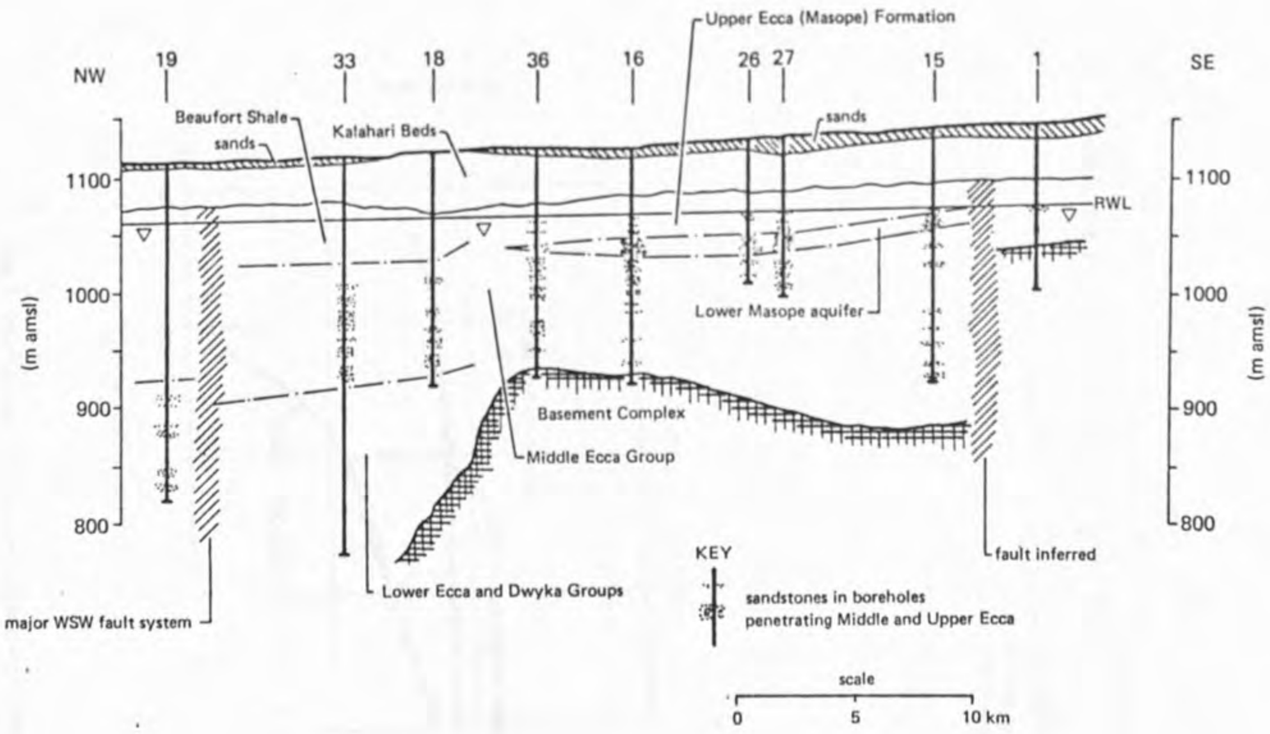

Fig 4 Hydrogeological cross-section with tentative correlation (vertical exaggeration approx. x 50)

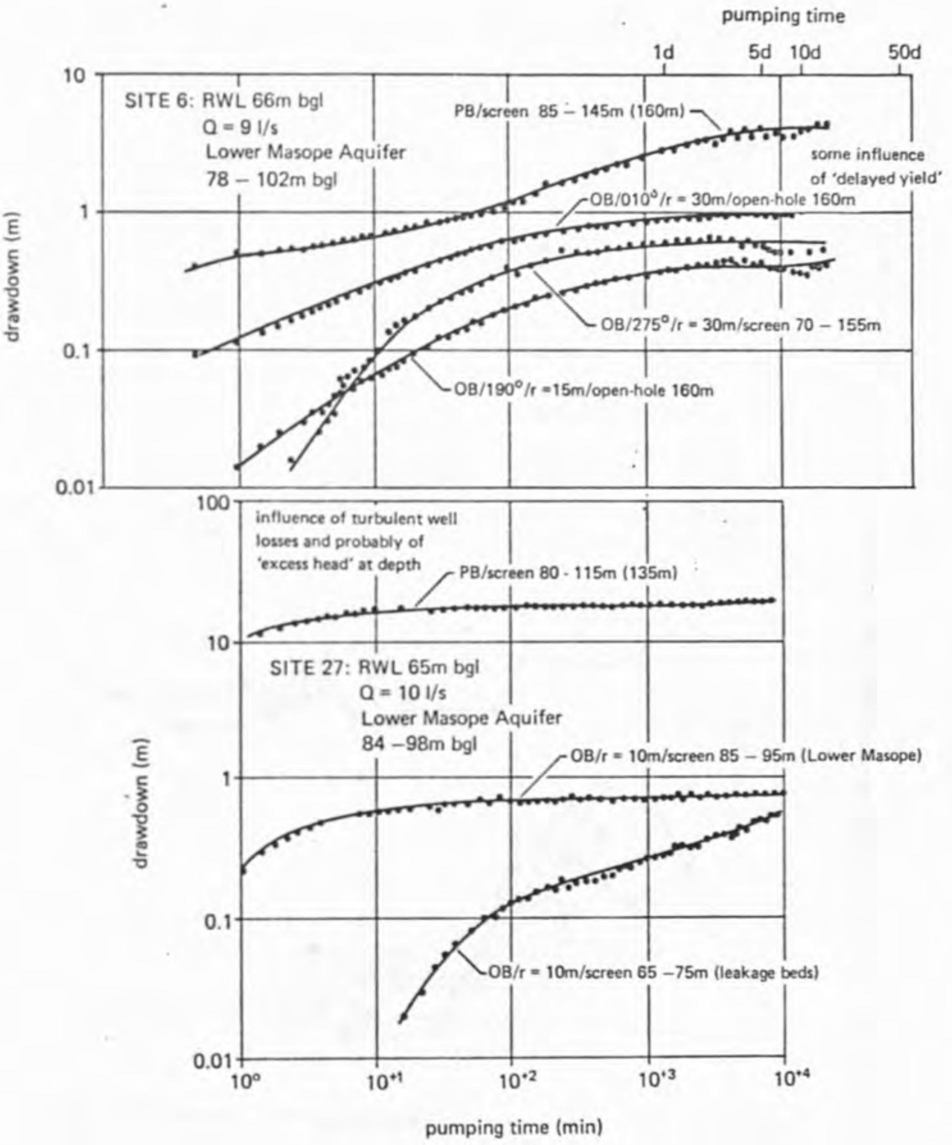

Fig 5. Selected data from hydrogeological pumping tests

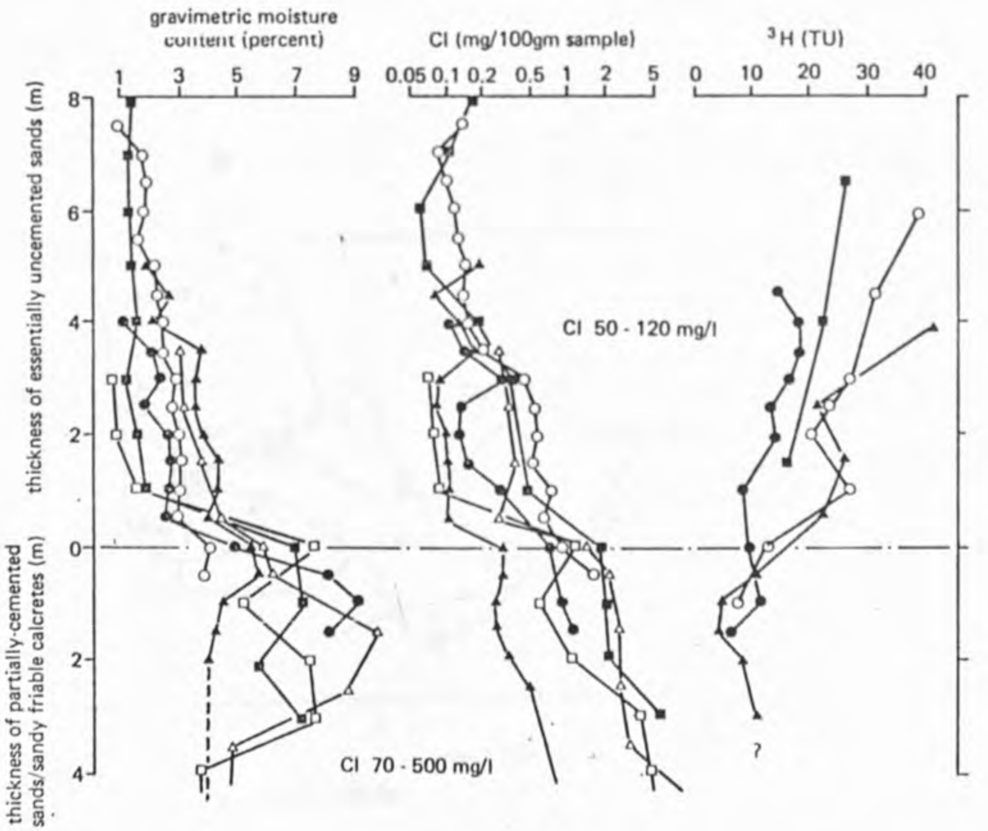

Fig 6. Moisture content, pore-water chloride and tritium profiles for Kalahari sand-cover (Oct - Dec 1977)

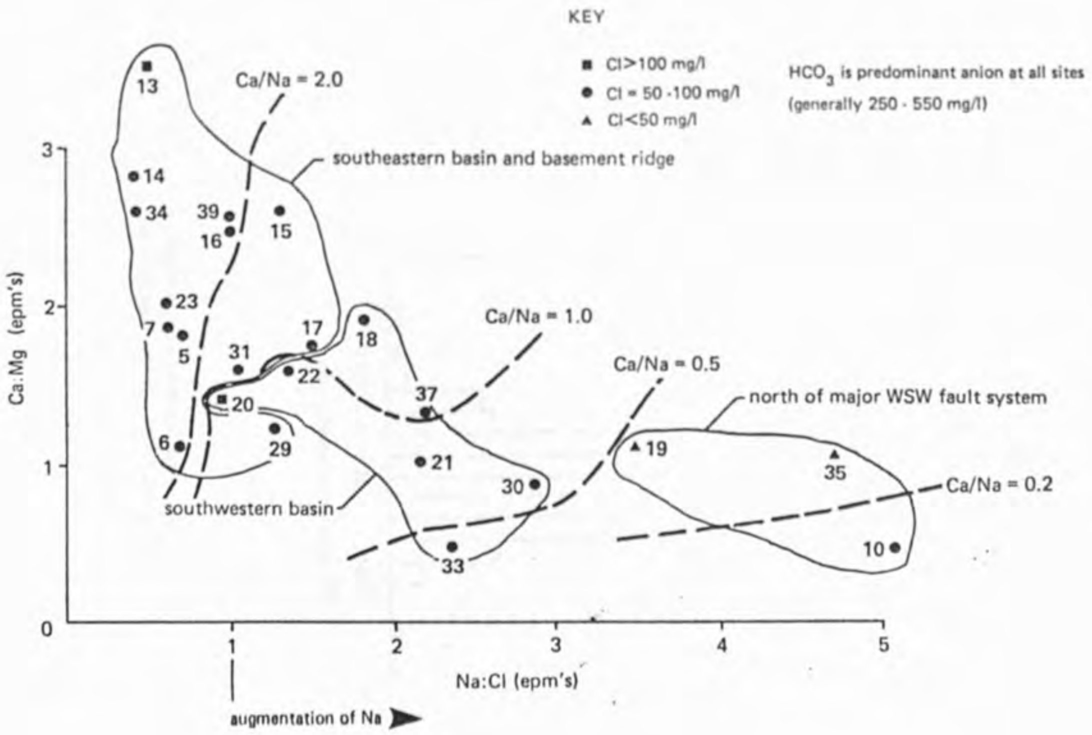

Fig 7. Summary of chemical characteristics of Ecca groundwaters

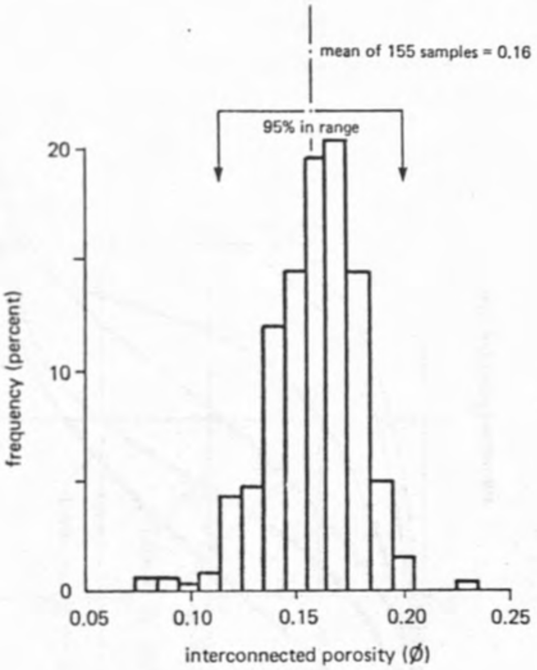

Fig 8. Porosity histogram for Ecca sandstones
(cored boreholes at sites 6, 7, 13, 17, and 21, saturated interval only)

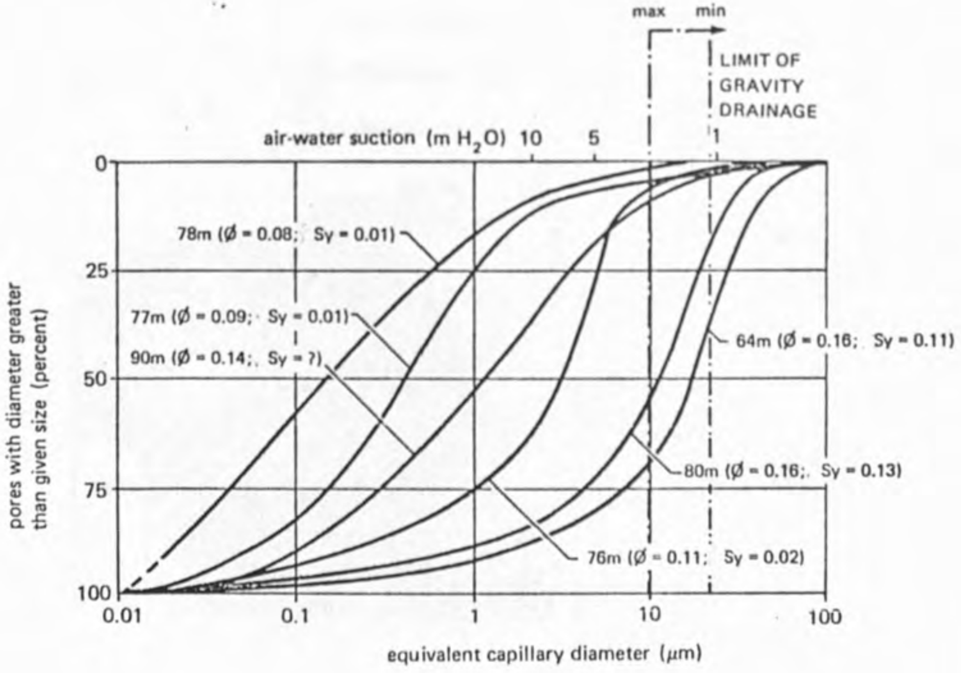

Fig 9. Selected pore-size distributions for Ecca sandstones (samples from site 13)

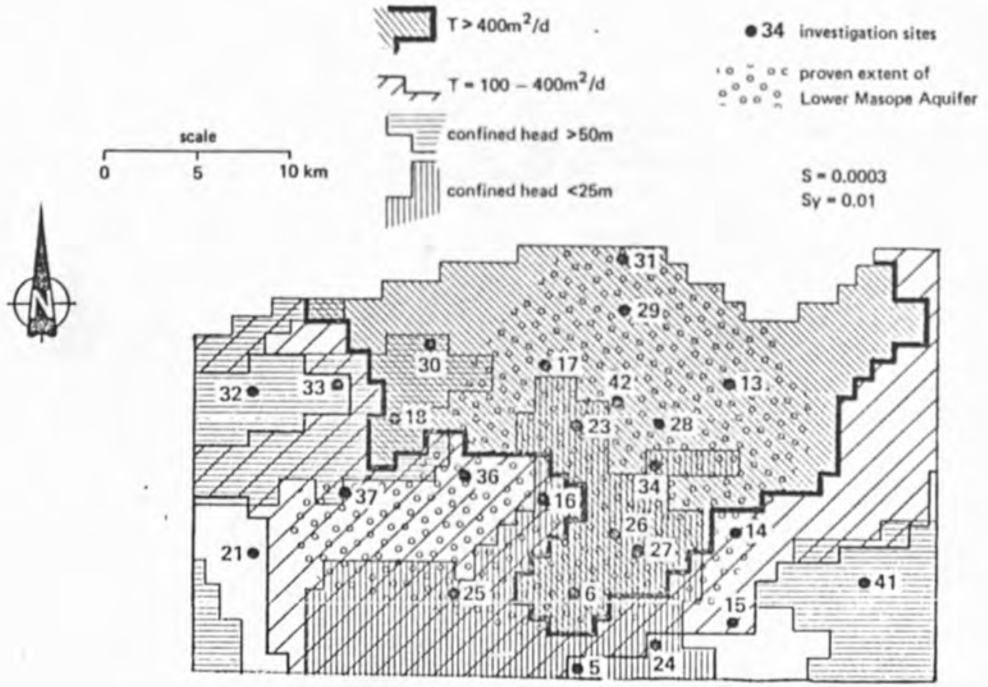

Fig 10A. Mathematical aquifer model-summary of worst-case hydrogeological parameters

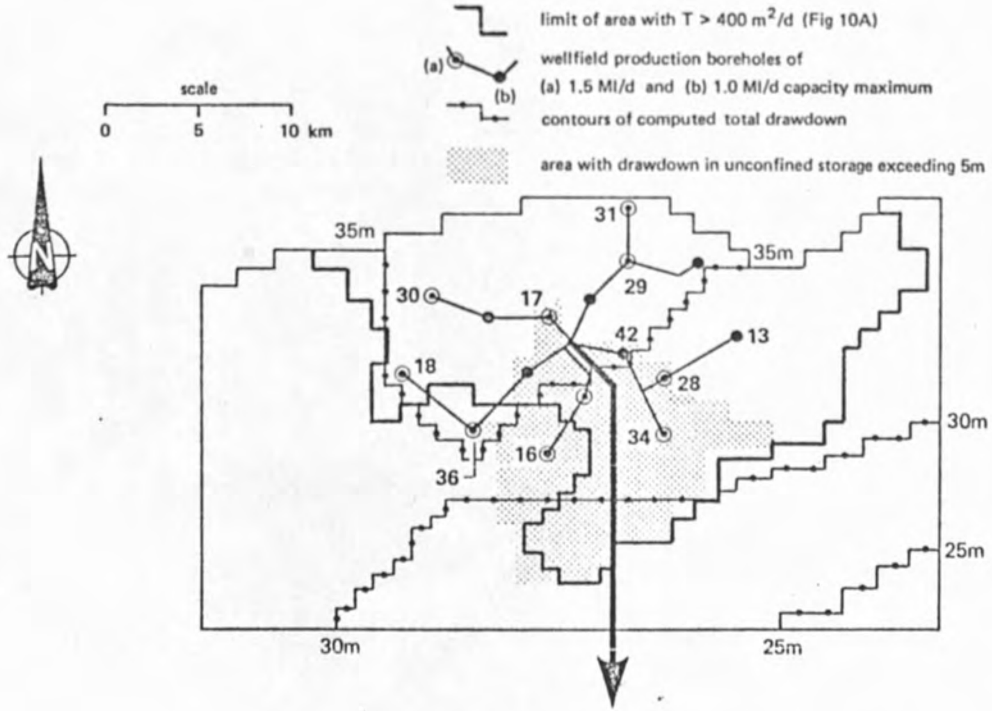

Fig 10B. Mathematical aquifer model-worst-case estimates for drawdowns after about 7 years abstraction (15 Ml/d for 300 d/a)

(6)

Studies in Environmental Science 17

QUALITY OF GROUNDWATER

Edited by

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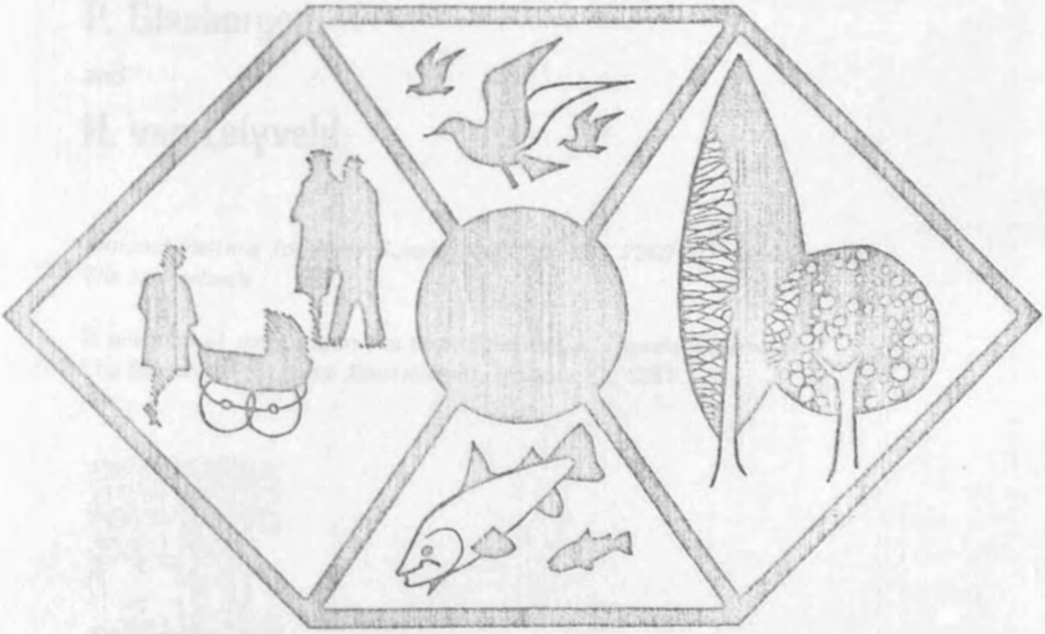

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Studies in Environmental Science 17

QUALITY OF GROUNDWATER

Proceedings of an International Symposium, Noordwijkerhout, The Netherlands,
23–27 March 1981

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A selection of these papers has been published as a special volume of
The Science of the Total Environment, Volume 21, 1981

ELSEVIER SCIENTIFIC PUBLISHING COMPANY
AMSTERDAM – OXFORD – NEW YORK 1981

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Quality of Groundwater, Proceedings of an International Symposium, Noordwijkerhout, The Netherlands, 23–27 March 1981, W. van Duijvenbooden, P. Glasbergen and H. van Lelyveld (Eds.), *Studies in Environmental Science*, Volume 17

THE EFFECTS OF FARMING PRACTICES ON GROUNDWATER QUALITY IN THE UNITED KINGDOM

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ABSTRACT

During the period 1975 to 1980, research in the United Kingdom has produced a large, and possibly unique body of data on the distribution of solutes derived from agricultural land in the major British aquifers. Unsaturated zone pore-water quality profiles demonstrate a clear relationship between the concentrations of certain solutes, especially nitrate, and farming practice. High concentrations of nitrate, often in excess of WHO recommended limits, are characteristic of areas of arable farming, whilst low concentrations are generally found beneath permanent grass or woodland. Mathematical models have been developed which simulate the vertical distribution of mobile solutes, notably nitrate and tritium, at a number of sites.

High concentrations of nitrate and other solutes have also been measured in the saturated zones of aquifers whose recharge areas are formed by arable farmland. The spatial distributions and temporal variations in concentrations suggest control by the hydrogeological properties and geometry of the aquifers. For some catchments it has been possible to use fully-mixed cell models to predict changes in groundwater nitrate concentrations.

INTRODUCTION

Groundwater provides about 30 per cent of water supplies in Britain, the two principal aquifers being the Chalk and Triassic Sandstone. Groundwater is generally of high quality but, in recent years, an increasing number of sources in the Chalk, Triassic Sandstone and other aquifers have shown rising nitrate levels, especially in eastern England (refs 1,2). In some cases nitrate concentrations in water supply sources have exceeded the World Health Organisation lower limit of 11.3 mg NO_3-N/l. The situation concerned the British water industry and led to the initiation of programmes of field and laboratory investigation by the Water Research Centre (WRC), the Institute of Geological Sciences (IGS) and, latterly, the Regional Water Authorities, with the objectives of:

Reprinted from *The Science of the Total Environment*, 21 (1981) 17–30

(a) determining the extent of nitrate contamination of the unsaturated and saturated zones of the British aquifers,

(b) evaluating the mechanisms and rates of movement of potential pollutants, derived from the land surface, through the unsaturated zone to the water table, and through the saturated zone to pumping wells or springs,

and

(c) estimating future trends in groundwater nitrate concentrations on both the local and regional scales.

Work on these major research programmes is still continuing. This paper describes the techniques used and reviews the principal results to date, discussing first the unsaturated, and secondly the saturated, zones.

SOURCES OF NITROGEN INPUT TO GROUNDWATER

The inputs of nitrogen to aquifers may be by direct discharges from agricultural wastes or sewage effluent, or from leaching through agricultural soils. The contribution from agricultural soils is, by and large, much greater than that from effluent discharges, though the latter may be important in certain areas.

Nitrogen losses from the soil/plant system may be divided into gaseous losses, removal by the crop and leaching. The soils developed on the outcrops of the principal aquifers are well drained. Under arable regimes such soils remain well aerated and losses by denitrification appear to be small, whilst mineralisation of organic nitrogen is promoted. However, compaction of the soil under permanent grass may lead to anaerobic conditions with denitrification in the lower soil layers (ref. 3). The rate of removal by crops is variable (ref. 4) but a mean value of about 50 per cent of the applied fertiliser nitrogen has been suggested (ref. 5). Under British climatic conditions it is probable that a proportion of the remaining applied fertiliser is assimilated by weeds and microflora during the growing season.

The rates of application of inorganic fertilisers to root crops and cereals currently range from 90 - 200 kg N/ha (ref. 6), having increased by between 5 and 10 times during the past 35 years. The use of organic fertilisers is now limited, though the spreading of sewage sludge and slurries from intensive stock rearing units is practised locally, principally onto grass.

The mineralisation of soil organic nitrogen following the ploughing of established grassland has been proposed as another important source of the nitrate lost from agricultural soils by leaching (ref. 6). The potential quantity of nitrogen available for mineralisation may be several thousand kg per hectare (ref. 7). Measurements made at a WRC experimental plot on a 60 cm deep Chalk soil profile in Sussex, at which ploughing of virgin grassland first occurred in April 1978, have indicated that more than 200 kg N/ha of soluble nitrate was leached from the fallow soil during the winter of 1978-79 compared with less than 5 kg N/ha from beneath a grass covered plot.

The conversion of pasture to arable land has been a marked feature of British agriculture during the past 100 years. At the turn of the century about 30% of the land area was under arable cultivation and about 40% under grass. A major increase in arable acreage, to nearly 40% of the land area, occurred in the 1940s, while the grass acreage fell to about 30%. It is noteworthy that the increase in arable land was concentrated principally on the thin upland soils of the Chalk recharge areas.

UNSATURATED ZONE RESULTS

More than 100 boreholes at more than 20 localities (Fig. 1) have been drilled so as to cover the range of differing land use situations and meteorological conditions encountered across the outcrops of the major British aquifers. Most of the boreholes were continuously cored and special drilling methods were employed to avoid sample contamination. Pore waters for chemical analysis were extracted by high speed centrifugation and were analysed using standard autoanalyser techniques. Samples for tritium determination were extracted by vacuum distillation, enriched, and measured by scintillation counting.

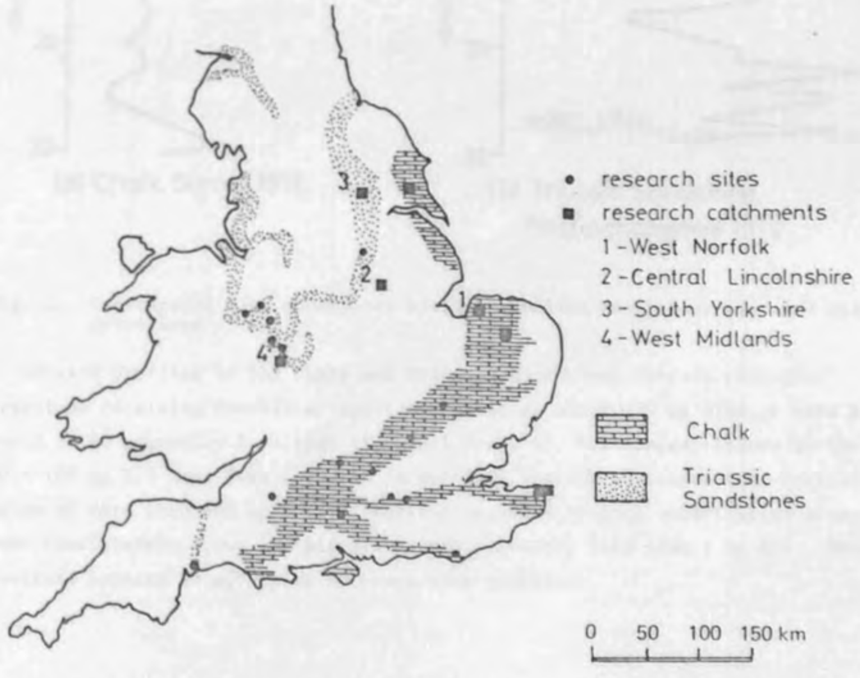
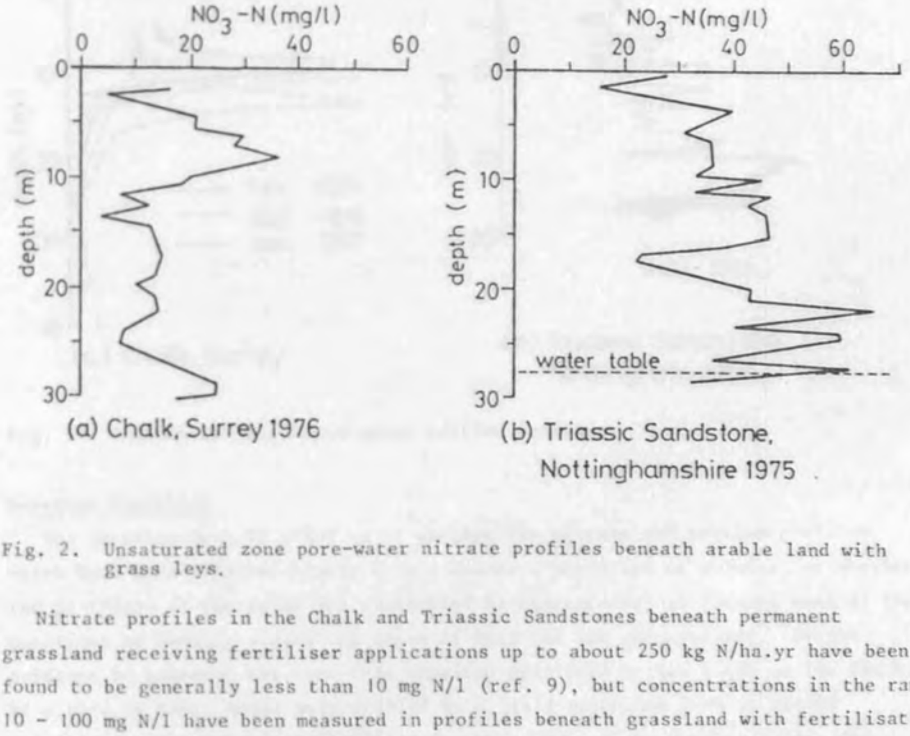


Fig. 1. Location of main research sites and catchments.

Nitrate Profiles

High nitrate concentrations (often >20 mg N/l) in the interstitial water of the unsaturated zone were invariably encountered beneath arable farming regimes. Relatively smoothly varying nitrate profiles were found to be characteristic of sites on the Chalk under continuous arable regimes with consistent fertiliser application rates (ref. 8). Sinusoidal variations of nitrate concentration with depth have been found beneath Chalk sites at which arable cropping is periodically interrupted by grass leys (Fig. 2a), this being most apparent at sites with long term (4 - 7 year) leys (ref. 6). The nitrate profiles beneath arable and arable/ley regimes in the Triassic Sandstones (Fig. 2b) have been found to follow a similar pattern, but to show more rapid and irregular variations with depth. This may be attributed to the modifying effect of the greater heterogeneity of the Triassic Sandstones when compared with the Chalk.



(a) Chalk, Surrey 1976

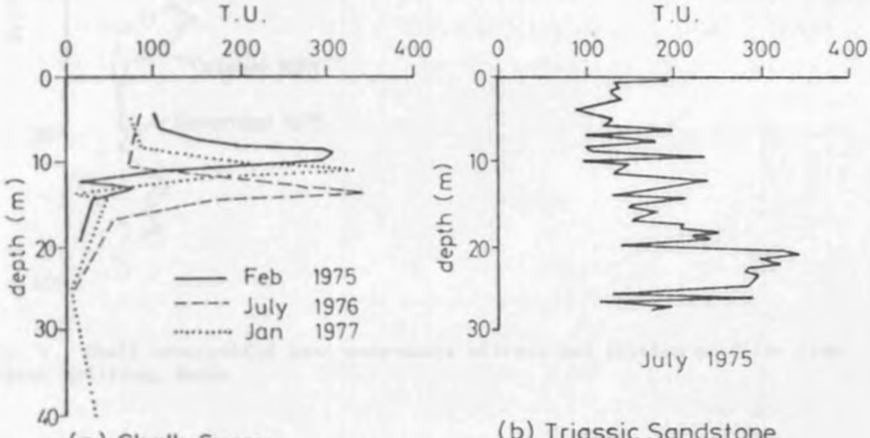
(b) Triassic Sandstone, Nottinghamshire 1975

Fig. 2. Unsaturated zone pore-water nitrate profiles beneath arable land with grass leys.

Nitrate profiles in the Chalk and Triassic Sandstones beneath permanent grassland receiving fertiliser applications up to about 250 kg N/ha.yr have been found to be generally less than 10 mg N/l (ref. 9), but concentrations in the range 10 - 100 mg N/l have been measured in profiles beneath grassland with fertilisation rates of more than 400 kg N/ha. Profiles measured beneath unfertilised grassland have consistently shown low nitrate values, commonly less than 1 mg N/l. Established woodland appears to give rise to comparable profiles.

Tritium Profiles

At many sites tritium profiles have been measured. In the Chalk (Fig. 3a) the peaked form of the profiles is generally comparable with that determined for the Upper Chalk of Berkshire in 1968 (ref. 10), with peak concentrations apparently recording the position of infiltration during the winters of 1963-64 and 1964-65 when thermonuclear tritium in rainfall reached maximum values. Profiles measured in the Triassic Sandstone aquifers (Fig. 3b) are less well defined than those from the Chalk, but indicate peak concentrations at depths of about 20 metres in the late 1970s.



(a) Chalk, Surrey

(b) Triassic Sandstone, Nottinghamshire

Fig. 3. Unsaturated zone pore-water tritium profiles.

Repeated Profiling

The question must be posed as to whether the nitrate and tritium profiles which have been measured result from a downward migration of solutes, or whether the positions of the peaks are controlled by hydrogeological factors such as the positions of bedding planes and zones of high and low permeability. Direct evidence of movement has come from repeated drillings at two sites on the Chalk. At a site in Kent, holes were drilled in a field which has been in arable cultivation since the early 1900s in November 1975 and in October 1978. The nitrate and tritium profiles (Fig. 4) indicate a downward movement of about 2 m which is consistent with the low infiltration of this area. At two sites in Norfolk, however, profiling in February 1976, March 1977 and November 1979 has failed to reveal a comparable, consistent downward movement.

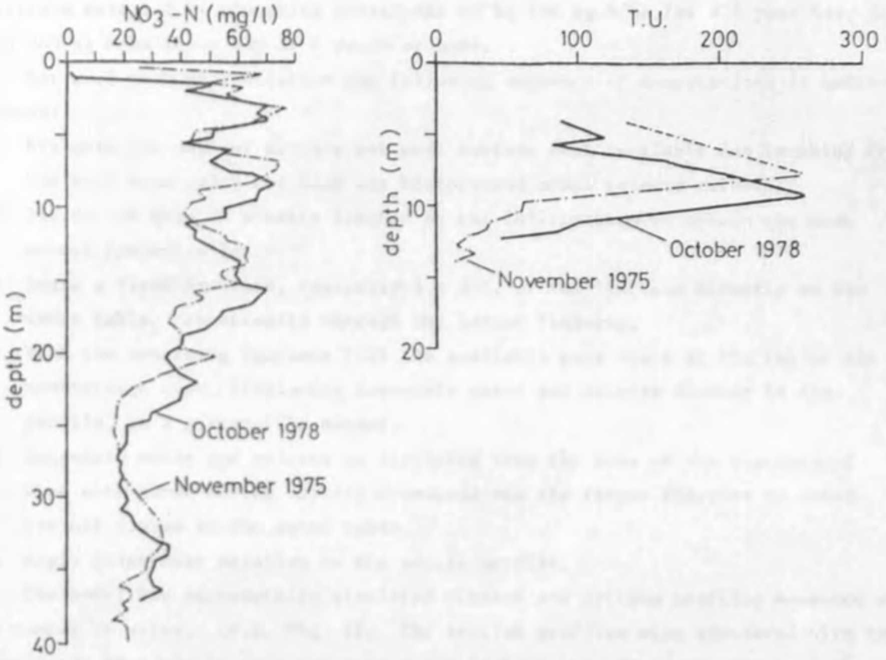


Fig. 4. Chalk unsaturated zone pore-water nitrate and tritium profiles from repeat drilling, Kent.

Data Interpretation

At many of the arable sites there appears to be a good correlation between the measured concentration in the pore water and the mass of unaccounted-for fertiliser nitrogen when expressed as a mean concentration in the residual rainfall. This relationship has been embodied in a model of vertical transport of nitrate through the unsaturated zone (ref. 11).

The mass of nitrogen released each year in the soil layers for uptake by infiltrating water was assumed to depend on present and antecedent field use and fertiliser application. Kolenbrander (ref. 5) has estimated that for root crops and cereals 50 per cent of the applied fertiliser becomes available as organic material for mineralisation, and it was assumed in the model that this quantity leaches from the soil zone. Not all of this material is available in the year of application. Using Kolenbrander's work as a basis, it was assumed that mineralisation takes place over a three-year period. A major contribution to nitrate leaching comes from the ploughing of grassland. By matching the model results to the observed nitrate profiles in a number of boreholes it was possible to estimate the mass of nitrate released by ploughing grasslands to be 100 kg N/ha for a 1 year ley, increasing to 280 kg N/ha for a ley of 4 years or more.

For each year of simulation the following sequence of computations is undertaken:

1 Evaluate the mass of nitrate per unit surface area available for leaching from the soil zone using the land use history and model release rules.
2 Divide the mass of nitrate leached by the infiltration to obtain the mean annual concentration.
3 Route a fixed fraction, typically 5 - 10%, of the leachate directly to the water table, conceptually through the larger fissures.
4 With the remaining leachate fill the available pore space at the top of the unsaturated zone, displacing downwards water and solutes already in the profile, in a piston-like manner.
5 Aggregate water and solutes so displaced from the base of the unsaturated zone with those moving rapidly downwards via the larger fissures to obtain the net fluxes at the water table.
6 Apply dispersion equation to the solute profile.

The model has successfully simulated nitrate and tritium profiles measured at a number of sites. (e.g. Fig. 5). The tritium profiles were simulated with inputs estimated by a simple soil moisture model to take account of the seasonal fluctuation of tritium in rainfall. Despite the ability of models of this type to simulate some observed profiles, the mechanisms of the water and solute movement in the unsaturated zone are not fully understood (refs 12,13,14), and require further investigation. The assumed rules for the release of nitrate from agricultural soils may also require some refinement.

SATURATED ZONE

The research methods used in the investigation of the saturated zone included (a) pore-water profiling for nitrogen species, major ions, some trace elements and certain isotopes (principally tritium) using similar sampling techniques to those described for the unsaturated zone, (b) field pumping tests, borehole flow logging and laboratory core analysis to establish the aquifer hydraulic properties and groundwater flow pattern, and (c) installation and operation of groundwater monitoring/sampling networks to determine temporal variations in groundwater quality.

Selected results from four research catchments will be presented here. Three of the catchments are located in eastern England, and, in each case more than 80% of the aquifer outcrop area is long-standing arable land receiving inorganic fertiliser. The fourth is a predominantly arable catchment in central England, in which inorganic fertilisation is supplemented by sewage spreading to selected areas.

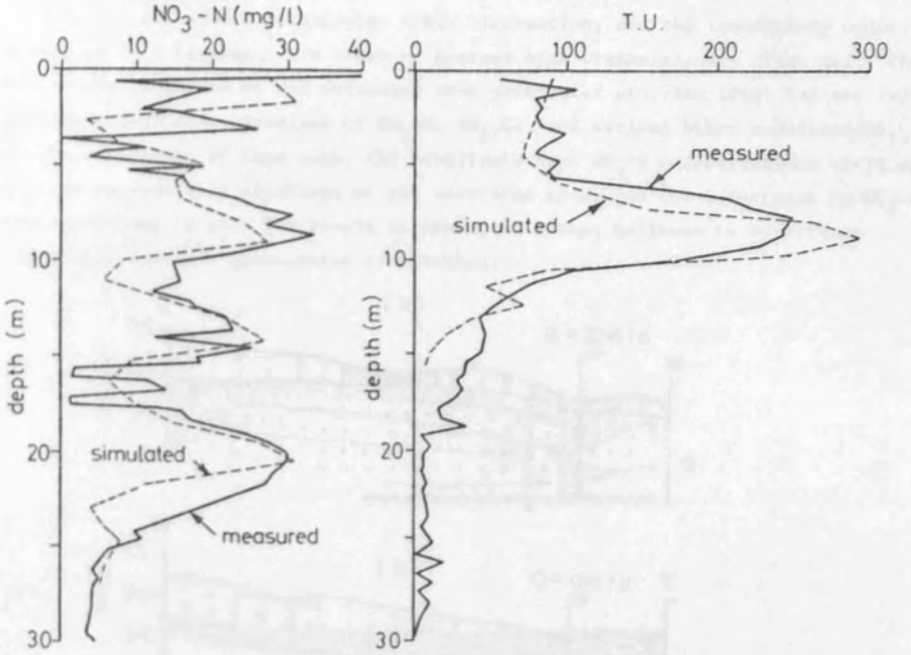


Fig. 5. Simulation of Chalk unsaturated zone nitrate and tritium profiles, Hampshire.

The three aquifers involved (the Chalk, Jurassic Limestone and Triassic Sandstone) are porous bedrock formations, but there are some significant differences in their hydraulic properties (Table 1).

	Laboratory Tests			Field Tests		
Aquifer	K_H	T_i	Ø	T_t	Sy	Saturated Zone Flow Regime
Chalk	0.001	<1	0.30	500+	0.01	fissure
Jurassic Limestone	0.0001	<1	0.20	500+	<0.01	fissure
Triassic Sandstone	2.0	300	0.25	400	0.10	intergranular (minor fissure)

K_H	intergranular horizontal conductivity (m/d)
T_i/T_t	calculated intergranular/field transmissivity (m^2/d)
Ø	porosity
Sy	specific yield

TABLE 1

Aquifer hydraulic properties

Chalk of West Norfolk

The zone of natural groundwater table fluctuation, and the immediately underlying strata in this catchment are known to possess high transmissivity (Fig. 6a). The distinctive features of the saturated zone pore-water profiles (Fig. 7a) are (a) variable, high concentrations of NO_3-N, SO_4, Cl, and various other constituents, in the upper part of that zone, (b) relatively high NO_3-N concentrations (8-15 mg/l) through considerable thickness of the saturated zone, and (c) a decrease in NO_3-N concentrations to very low levels at depth, in a zone believed to be without significant natural groundwater circulation.

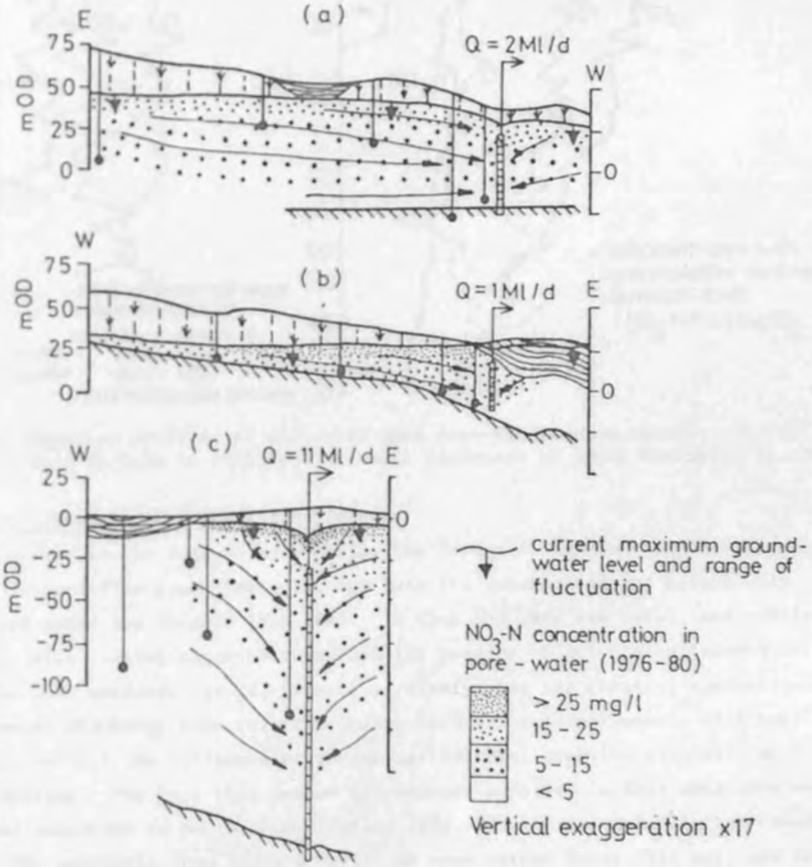


Fig. 6. Simplified sections of (a) Chalk of West Norfolk, (b) Jurassic Limestone of Central Lincolnshire (c) Triassic Sandstone of South Yorkshire.

Careful monitoring of purpose-drilled observation boreholes completed over restricted depth ranges has shown the mobile (fissure) groundwater at depth also to have significantly lower NO_3-N, SO_4, Cl and Ca concentrations than the large (intermittent) fissure flows in the zone of seasonal groundwater table fluctuation. Pumped groundwater supplies currently display only slight seasonal variations in the range 13 - 15 mg N/l.

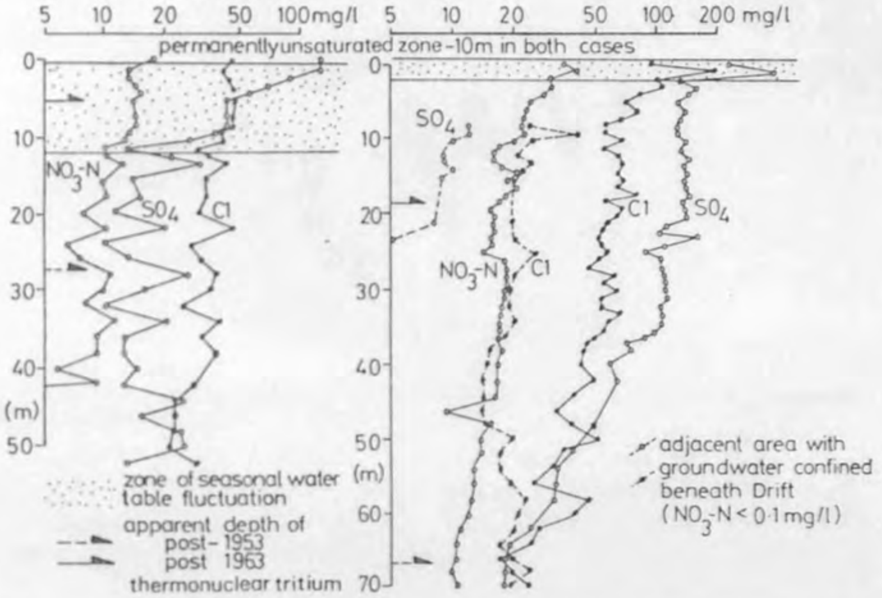


Fig. 7. Chemical profiles of saturated zone pore-waters from outcrop area of (a) Chalk of West Norfolk in 1976, (b) Triassic Sandstone of South Yorkshire in 1980.

Jurassic Limestone of Central Lincolnshire

Comparable to the West Norfolk Chalk, the Jurassic Limestone aquifer is of the porous fissure-flow type (Table 1), but both its unsaturated and permanently saturated zones are thinner (Fig. 6b). It thus has very low total, and mobile, water storage, with limited capacity to retard the passage of soluble pollutants derived from the land surface. It is, therefore, likely that the chemical composition of groundwater discharge from this catchment, both natural and pumped, will more directly reflect the influence of recent agricultural practice than will most groundwater systems. The fact that pumped groundwater supplies in this area show marked seasonal variation in NO_3-N concentration (Fig. 8), and in various other constituents (e.g.: SO_4 currently from 110-150 mg/l), to some extent bears this out, and these data are of especial interest for that reason. Some caution is required in interpreting the data, however, because (a) the pumping well is located down gradient from the main spring discharges in the catchment, (b) groundwater pumping ceased for extended periods in 1979 and 1980, and (c) the monitoring has a relatively short time-base through a sequence of unusual climatic episodes. Nevertheless, the data give cause for serious concern about the possibility of a still rising trend in NO_3-N concentrations, possibly as a result of increased leaching losses following

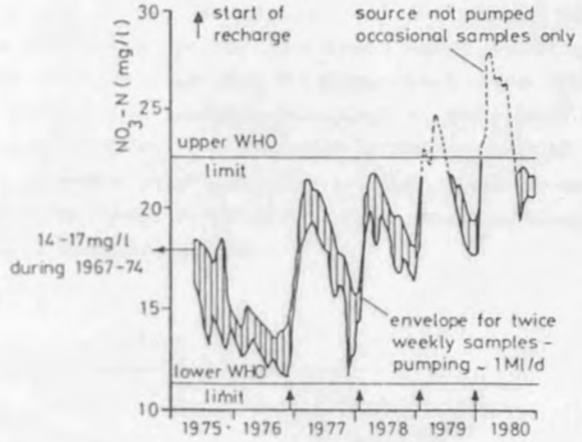


Fig. 8. Nitrate concentration of groundwater discharge from Jurassic Limestone, Central Lincolnshire.

recent minor increases in fertiliser applications on some arable crops or of a long-continuing slow adjustment of soil nitrogen levels to earlier major changes in arable farming practices during the 1960s.

Triassic Sandstone of South Yorkshire

This catchment is distinct in being underlain by a thick porous sandstone in which intergranular flow appears to dominate (Table 1), and having little, if any, natural groundwater circulation, most of the flow having been induced since major groundwater abstraction commenced in 1968 (Fig. 6c). The aquifer outcrop/intake area is largely utilised for high-yield cereal farming.

Nitrate concentrations in pumped groundwater supplies rose rapidly quite soon after initial development, and currently stand at 10 - 14 mg N/l. Moreover, cored boreholes beneath the outcrop area show deep penetration of elevated concentrations of NO_3-N, SO_4 (Fig. 7b), and certain other major ions (Ca, Cl, Na) and trace elements (Mg, K, Ba, Sr, B). Very high concentrations at shallow depth beneath the groundwater table give cause for concern and the regime of groundwater flow and pollutant dispersion is still under investigation.

Groundwater underlying adjacent areas covered by low permeability, lacustrine (Drift) deposits (Fig. 6c) exhibits a marked contrast in quality (Fig. 7b), but is expected to be, for the most part, of considerably older age. Exploitation of this storage as a source of low nitrate groundwater supplies has recently commenced and detailed monitoring is being undertaken to determine the response of the system.

Triassic Sandstone of West Midlands

The aquifer outcrop area is relatively drift-free and intensively farmed. Flows in this catchment are predominantly intergranular, but nitrate profiling to depths of greater than 100 m below the water table has revealed strong stratigraphic contro on solute movement in the saturated zone. Higher nitrate concentrations, up to 20 mg N/l, were associated with the major flow horizons within a 60 m thick coarse, conglomeritic sandstone just below the water table. The areal distribution of nitrate in groundwater is dominated by the discharge of about 5000 m^3/d of sewage to grassland in an arable/ley rotation, within an area of nearly 2 km^2 (Fig. 9a). The sewage is spread by a pipe system and allowed to seep into the soil through ploughed channels.

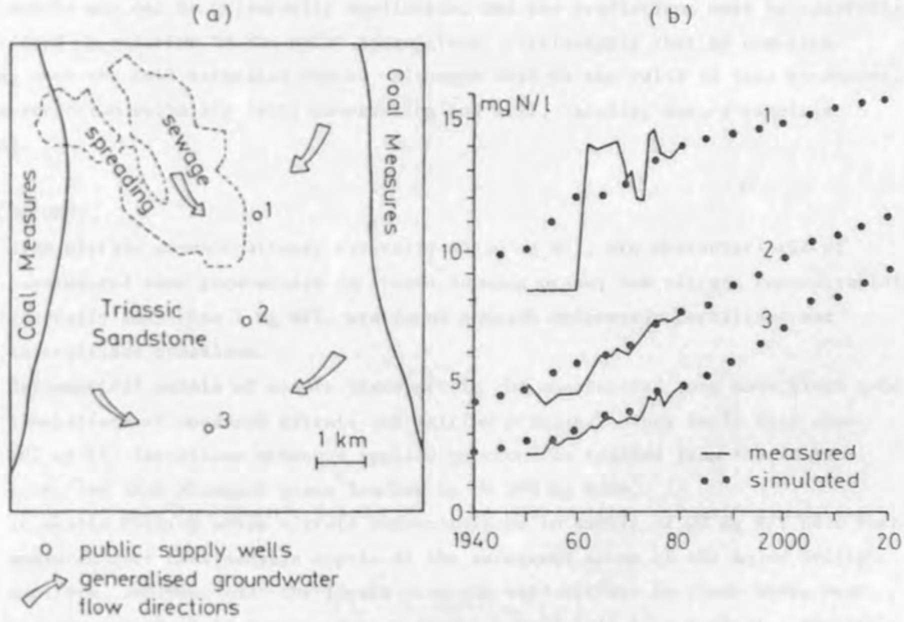


Fig. 9. Triassic Sandstone of West Midlands; catchment characteristics and measured and simulated nitrate concentrations in pumped discharges.

Nitrate concentrations in discharge from the three major pumping stations in the catchment are rising (Fig. 9b), and a groundwater quality model has been built to provide predictions of future trends. The model used the same rules for the release of nitrate from agricultural soils as the unsaturated zone model, the nitrate in the sewage effluent being treated in the same manner as inorganic fertiliser additions. The model utilised flows calculated from a groundwater flow model to route nitrate through the saturated zone, and nitrate fluxes across the water table were calculated from the time series of nitrate leached from the soil zone by applying lags dependent on the unsaturated zone thickness and infiltration rate. In this catchment the rate of movement of nitrate through the unsaturated zone was estimated to be between 1 and 2 m/yr. Nitrate concentrations in the saturated zone were calculated with a fully-mixed cell model which assumes complete mixing of nitrate over the full saturated depth (ref. 11). The model predictions of nitrate concentration in discharge from the major pumping stations compare well with measured values (Fig. 9b), and imply that equilibrium with current agricultural activity has not yet been established.

Similar models have been sucessfully applied to Chalk catchments. However, such models may not be universally applicable, and the predictions must be carefully considered in relation to the model assumptions, particularly that of complete mixing over the full saturated depth. Although that is not valid in this catchment, the abstraction wells are fully penetrating and will, locally, ensure complete mixing.

CONCLUSIONS

1 High nitrate concentrations, typically 15-50 mg N/l, are characteristic of unsaturated zone pore-waters in arable farming areas; low nitrate concentrations, generally less than 5 mg N/l, are found beneath moderately fertilised and unfertilised grassland.

2 Mathematical models of solute transport in the unsaturated zone have given good simulations of measured nitrate and tritium profiles. They imply that about 50% of the fertiliser nitrogen applied to crops is leached from the soil zone, and that ploughed grass leaches up to 280 Kg N/ha.

3 In arable farming areas nitrate concentrations in excess of 20 mg N/l have been measured over considerable depths of the saturated zones of the major British aquifers, implying that the inputs from the land surface in these areas must have contained similar mean concentrations over fairly long periods. Beneath confining strata nitrate concentrations are generally low.

4 Models of solute transport in the saturated zone have been successfully applied to some catchments, and have indicated that, in general, nitrate concentrations will continue to rise for some time before stabilising.

ACKNOWLEDGEMENTS

This paper is published by permission of the Director of the Water Research Centre, Medmenham Laboratory, and the Director of the Institute of Geological Sciences. Part of the work was funded by the Department of the Environment. Active participation of the Anglian, Severn-Trent, Southern and Yorkshire Water Authorities is gratefully acknowledged.

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Studies in Environmental Science 17

QUALITY OF GROUNDWATER

Edited by

W. van Duijvenbooden
P. Glasbergen
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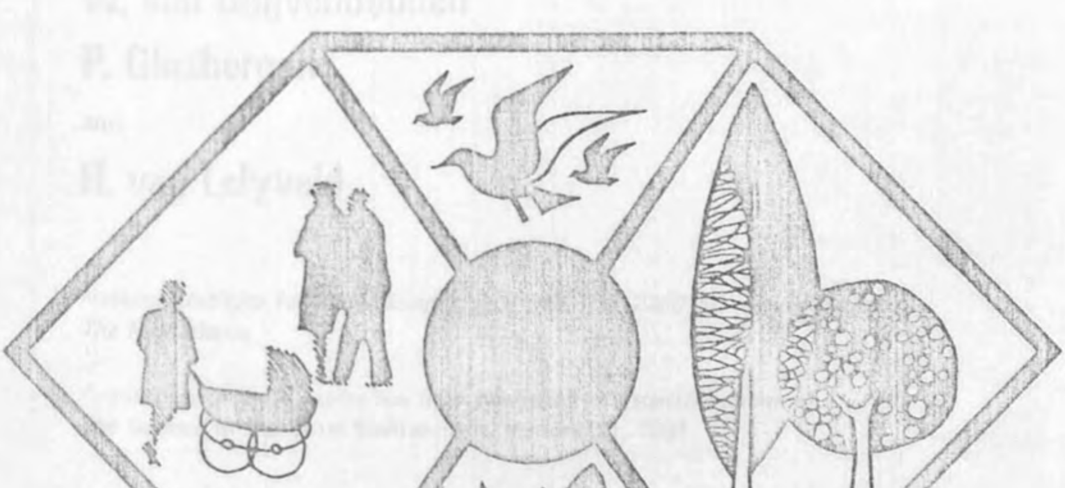

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Studies in Environmental Science 17

QUALITY OF GROUNDWATER

Proceedings of an International Symposium, Noordwijkerhout, The Netherlands,
23–27 March 1981

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A selection of these papers has been published as a special volume of
The Science of the Total Environment, Volume 21, 1981

ELSEVIER SCIENTIFIC PUBLISHING COMPANY
AMSTERDAM – OXFORD – NEW YORK 1981

Quality of Groundwater, Proceedings of an International Symposium, Noordwijkerhout, The Netherlands, 23–27 March 1981, W. van Duijvenbooden, P. Glasbergen and H. van Lelyveld (Eds.), *Studies in Environmental Science*, Volume 17

THE NEED FOR AN INTEGRATED APPROACH TO WATER-SUPPLY AND SANITATION IN DEVELOPING COUNTRIES

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ABSTRACT

During the coming decade much greater emphasis will be placed in developing countries on groundwater exploitation for drinking water-supplies and on unsewered sanitation. In certain hydrogeological conditions these low cost technologies may be in conflict and an integrated approach is required to avoid new pollution hazards. This paper briefly reviews the factors influencing the survival and migration of faecal bacteria and viruses in groundwater systems, assesses the threat of chemical pollution, and identifies the critical factors in the evaluation of groundwater pollution risk.

INTRODUCTION

The period 1981-90 has been adopted by the UN General Assembly as the International Drinking Water Supply and Sanitation Decade. The goal of this decade is that all people should have access to an adequate water-supply and a satisfactory means of excreta disposal in order to reduce the incidence of water and excreta related diseases. Groundwater is widely used, and will be increasingly developed, since it is normally the cheapest and safest source of untreated potable water in developing countries. It has also been established that unsewered (on-site) sanitation can provide adequate service levels for excreta disposal at substantially less cost than mains sewerage systems (ref. 1).

CLASSICAL RESEARCH ON UNSEWERED SANITATION

The natural soil profile has long been recognised as an effective system for wastewater disposal. The detailed studies of some early researchers (refs. 2 - 4)

Reprinted from *The Science of the Total Environment*, 21 (1981) 53–59

are directly relevant because they relate to broadly comparable excreta disposal units (latrines). Most investigations were restricted to situations where excreta were discharged directly into the saturated zone (fig. 1); lateral migration of faecal bacteria did not generally exceed 10 m in the groundwater flow direction, although a broader plume of chemical contamination could be detected over much larger distances. The extent of bacteriological pollution was observed to reduce with time, concomitant with the formation of a crust on latrine walls as a result of pore clogging. In unsaturated soils faecal bacteria were rarely found to penetrate more than 1.0 m below a latrine. These results suggested 15 m as the safe lateral separation between groundwater supply installations and excreta disposal units; a guideline which has been very widely adopted by public-health engineers. A serious limitation of the studies, however, is that they sampled restricted ground conditions; essentially sandy formations with mean grain sizes and saturated groundwater flow velocities of less than 300 μm and 1.0 m/d respectively.

Not all hydrogeological environments are equally effective for effluent purification. Under certain conditions, in unconfined (water-table) aquifers, latrines may represent a serious pollution risk to groundwater, and thus to neighbouring water-supply installations, such as boreholes, wells and springs, and sometimes also to water reticulation mains subject to intermittent depressurisation. On the other hand, if aquifers are essentially confined or semi-confined (fig. 1), or where thick unsaturated zones of unconsolidated strata are present above unconfined aquifers (fig. 1), a 15 m separation may be too conservative. For various social reasons the minimum practicable separation will often be desired. This paper constitutes the synopsis of a major desk study on the subject, interpreted in the light of field experience (ref. 5).

MICROBIAL MIGRATION IN GROUNDWATER SYSTEMS

Role of soil-unsaturated zone in effluent purification

It is considered that infiltration into, and through, the unsaturated zone affords the first line, and by far the most important line, of defence against pollution for underlying aquifers from which groundwater supplies may be drawn. The performance of most latrines depends primarily on the ability of the soils and rocks of the unsaturated zone to accept and to purify sewage effluent: functions which may be in conflict and relate, either directly or indirectly, to the hydraulic characteristics.

The unsaturated zone contains continuously varying proportions of water and air; the moisture content and the unsaturated vertical hydraulic conductivity being a function of the prevailing moisture potential or tension (fig. 2). Some sands and sandstones have relatively large pores which drain abruptly at quite low tensions, in contrast to clays and siltstones whose water is strongly

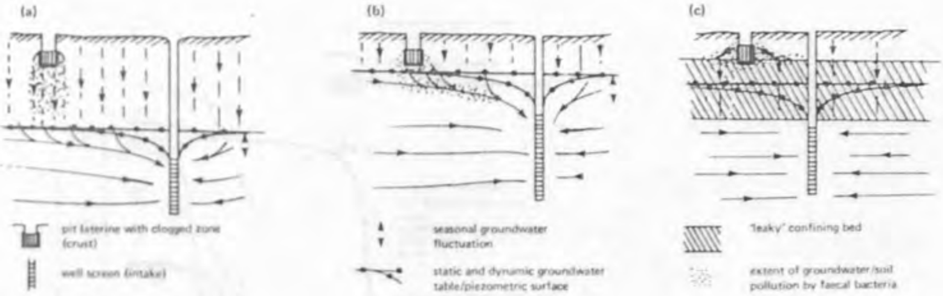

Fig. 1. Sketch sections illustrating typical pollution regimes: unconfined aquifer with (a) deep and (b) seasonally shallow groundwater table and (c) semi-confined aquifer.

retained in very fine pores. Most consolidated rocks, and some clays, contain sub-planar voids (normally known as fissures), which will also only contain (and conduct) water at very low tensions (fig. 2). In consequence, unsaturated vertical hydraulic conductivity often decreases dramatically with reduction in moisture content and groundwater flow rates in the unsaturated zone do not normally average more than 0.3 m/d. However, under conditions of heavy artificial hydraulic loading or of high intensity infiltrating rainfall, in fissured formation, they may be much higher.

When latrine effluent enters the unsaturated zone, pore clogging develops at the infiltration surface as a result of (a) changes in soil structure caused by cation exchange and swelling of clay minerals, (b) blockage of soil pores with filtered solids, (c) deposition of slimes through bacterial activity and (d) precipitation of insoluble metal sulphides, deoxygenated conditions developing after ponding has become established (ref. 6). Although pore clogging may result in the failure of some latrines, due to surfacing of effluent, the crust performs important roles: (a) it acts as a very effective filtration (straining) medium for faecal bacteria (size 0.5 - 5.0 μm), which are eliminated by antagonistic anaerobes, and (b) by reducing the effective infiltration rate per unit area it ensures that the moisture potential, in the unsaturated zone below, remains relatively high, thereby greatly reducing its vertical hydraulic conductivity, increasing its groundwater residence time and minimising the possibility of preferred (rapid) flow in aggregated clay soils and fissured rocks.

Passage through the crust results in the elimination of a very large proportion of the faecal bacteria in latrine effluent, but populations are so high (probably 10^9/100 ml) that significant numbers still enter the unsaturated zone. Surface adsorption on mineral surfaces, with degradation by other (aerobic) bacteria, is believed to be the predominant elimination process here and is

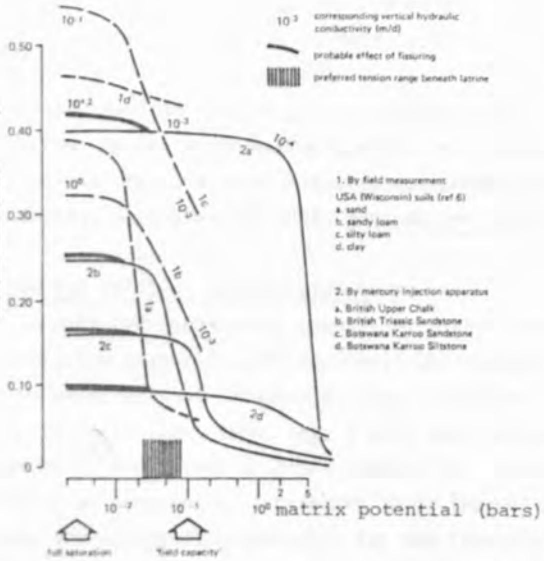

Fig. 2. Moisture content as a function of matrix potential (tension).

enhanced when liquid movement occurs only in the smaller pores of the soil/rock with maximum media-liquid contact.

Prediction of the survival time of faecal bacteria in subsurface environments is complicated by the many controlling factors: moisture content, temperature, acidity, together with organic/nutrient levels and antagonistic microbial populations. In soils, faecal coliforms generally survive less than 60 days, with t_{90} (time for 90% population reduction) normally less than 15 days, but under cool, moist, alkaline conditions a hardy residual fraction may survive for many months. In groundwater, exceptional survivals of over 100 days have been reported, but bacterial half-life in well and laboratory groundwaters is mainly in the range 0.3 - 1.0 d, that is t_{99} less than 11 days (ref.7).

Viruses (0.01 - 0.1 μm diameter) are the smallest excreted pathogens and differ fundamentally from bacteria in that (a) they consist of inert particles (of ribonucleic acid) that cannot replicate outside a living host, (b) their infective dose may be orders of magnitude less, and (c) they are too small to be removed by porous medium filtration. Retardation of virus penetration into the sub-surface is thus dependent almost entirely on adsorption (ref. 8), the rate of which will vary with viral strain but increases with soil acidity. The factors controlling subsequent elimation are not well understood but degradation by aerobic bacteria is probably the dominant process. Longest survivals are likely in anaerobic, low temperature, environments, and $t_{99.9}$ of 2 - 100 days are reported. Viruses can become desorbed from soils, especially following heavy rainfall. It is also important to note that viruses may sometimes be isolated from samples containing no detectable faecal bacteria indicator organisms, especially in anaerobic environments.

Most of the reported incidences of microbiological contamination of groundwater, resulting from the use of unsewered sanitation, are associated with areas of thin soil cover (less than 3 m) over fissured non-porous bedrock or areas of high (less than 3 m depth), or seasonally high, groundwater table.

Attenuation and dilution in saturated zone

Since in most hydrogeological conditions (other than close to pumping boreholes in relatively low transmissivity aquifers) the hydraulic gradient is very shallow, it might be expected that groundwater flow velocities in the saturated zone would invariably be small (less than, say, 2 m/d) and that protection of water-supply installations in unconfined aquifers against pollution from excreta disposal units could readily be obtained by increasing their lateral separation.

However, the processes responsible for the fixation of excreted pathogens (primarily adsorption) will, in most cases, be much less active than in the unsaturated zone, and the population of aerobic bacteria to affect their eventual elimination will be greatly reduced. Moreover, few aquifers are, in practice, uniform. Permeability heterogeneity will often be present, sometimes on a gross scale as in some stratified alluvial sequences and in many limestones. The presence of highly-permeable groundwater flowpaths of relatively small cross-sectional area results in groundwater velocities often exceeding 10 m/d, reaching 100 m/d or more in many fissured aquifers and 1 km/d or more in some karstic limestones. Physical (hydraulic) dispersion, the phenomenon primarily responsible for dilution of pollutants in groundwater flow systems, is also difficult to predict and costly to investigate. Thus, in many hydrogeological environments, increasing lateral separation is not a very manageable method of increasing protection against faecal groundwater pollution. Even where reliable, it must be recognised that the separation will have to be increased in large increments, say, to 25 or 50 m, and this will only be feasible in low density settlements (substantially less than about 100 people/ha).

A striking feature of the published work on lateral microbial pollution travel in the saturated zone is that migration is governed predominantly by groundwater flow velocity; appearing to be equivalent to the flow distance during a period of no more than 10 days. This implied (or apparent) survival time is much less than many reported experimental survivals, but the latter probably refer to higher initial populations, less dispersion and less antagonistic environments. The largest recorded distance of microbial travel in unconsolidated (non-fissured) strata is 920 m, for bacterial and viral tracers in coalluvial gravels (ref. 10).

NITRATE POLLUTION PROBLEM

The introduction of unsewered sanitation schemes will, almost inevitably, lead to nitrate contamination in underlying unconfined aquifers, except where the groundwater system is naturally anaerobic. Human waste contains about 5 kgN/cap/a, in the form of ammonium and complex organic compounds, both of which can be expected to be rapidly converted to (highly mobile) nitrate under aerobic conditions. Heavy nitrate pollution can be expected in some cases (eg.ref. 9). The factors controlling its severity will be (a) population density, (b) the proportion of nitrogen lost from the latrine directly by denitrification, (c) dilution by local groundwater recharge and regional aquifer throughflow, (d) any denitrification in the groundwater system itself.

CONCLUDING REMARKS

In view of the complexity of the factors involved, and the potential importance of rather detailed considerations, it would be desirable to treat each settlement or site on individual merit when assessing the faecal pollution risk associated with unsewered sanitation. However, the economics and logistics of low cost sanitation schemes are such as to preclude the routine use of hydrogeological field investigations and, in practice, a classification of hydrogeological environments is required as the basis for new guidelines.

The classification must identify under which conditions a separation of 15 m between water-supply installation and excreta disposal unit (a) can be reduced to 10 m, or even 5 m, (b) is acceptable, (c) may involve significant risk and increasing separation to 25 or 50 m accompanied by monitoring of pilot schemes is advisable, and (d) involves high risk and specialist advice should be sought, since modified excreta disposal units or redesign/relocation of water-supply installations may be required. It must be workable with data readily available to public-health engineers from records normally held locally in government offices/agencies, or that they can collect on site following a simple manual. The principal parameters involved have been identified as (a) degree of confinement and character of the aquifer horizons from which groundwater supplies are drawn, (b) thickness and nature of the unsaturated zone, and (c) latrine hydraulic loading.

A preliminary classification in the form of an algorithm has been drawn up using these parameters (ref. 5) but further data are required for its consolidation and extension. Such data could best be collected by detailed field research and/or routine monitoring associated with pilot on-site sanitation schemes.

ACKNOWLEDGEMENTS

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The Quarterly Journal of Engineering Geology

Volume 14 No. 1 1981

Encompassing Engineering Geology and Hydrogeolog

THE QUARTERLY JOURNAL OF ENGINEERING GEOLOGY

Vol. 14, no. 1 1981 Price £13.50

Annual subscription: £45 (UK), £54 (Overseas), $135.00, $U.S. (North America); single numbers all issues £13.50 ($34 U.S.A.); double numbers £24.00 ($68 U.S.A).

Contents

Published for
THE GEOLOGICAL SOCIETY
BURLINGTON HOUSE,
PICCADILLY, LONDON W1V 0JU
by
BLACKWELL SCIENTIFIC PUBLICATIONS LTD.
OSNEY MEAD
OXFORD, 0X2 0EL
and printed by
THE UNIVERSITIES PRESS (BELFAST) LTD.
ALANBROOKE ROAD, BELFAST BT6 9HF, NORTHERN IRELAND

Q. J. eng. Geol. London, 1981 Vol. 14 pp. 17–24. Printed in Northern Ireland

A diffusion exchange model for solute movement in fissured porous rock

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Summary

A model of solute movement in an idealized, fissured, porous medium, involving diffusion exchange between mobile fissure-water and immobile pore-water, is formulated mathematically and solved numerically for a range of values of the input parameters. The insight gained into this mechanism of solute movement is of relevance in predicting the migration of the more soluble pollutants in the major British aquifers, and is of particular significance to the interpretation of the distribution of tritium and nitrate in the unsaturated zone of the Chalk beneath arable land.

Introduction

Background to model development

An understanding of the mechanisms of solute movement in groundwater systems is a fundamental aspect of hydrogeology and is of particular practical significance in the context of pollutant migration. Bedrock (consolidated) aquifers form a most important group in which the hydraulic conductivity (permeability) is predominantly associated with fissure development, but in many of these aquifers the rock matrix itself may possess significant porosity. For the purposes of this paper such formations have been termed fissured porous media. An excellent example is the Chalk in Britain, and the group includes a substantial number of other limestone and sandstone aquifers.

For the Chalk and other comparable porous media, Foster (1975) suggested that a major component of solute movement was controlled by a mechanism involving solute exchange, through lateral molecular diffusion, between mobile fissure water and (relatively) immobile matrix, or pore, water; the mobile fissure water eluting solute from high concentration regions in the matrix and transferring it to regions of lower concentration along its direction of flow. This was of especial significance when interpreting the distribution of thermonuclear tritium and pollutants, such as nitrate, in the unsaturated zone of the Chalk and when predicting the rate of lateral migration of pollutants in the saturated zone of the aquifer (Foster 1976). It has been suggested (Oakes 1977) that such a mechanism would conform to the mathematical theory describing the chromatographic process, with instantaneous equilibrium between the mobile and stationary water, and, in the case of the Chalk's unsaturated zone, it has gained acceptance by British hydrogeologists (Young *et al.* 1976; Downing *et al.* 1978, 1979; Reeves 1979).

Scope of paper

The primary reason for the construction of the mathematical model, described in this paper, was to give a detailed insight into the behaviour of this diffusion exchange mechanism for solute transport in fissured porous media, and to establish the extent to which the 'chromatographic' equilibrium approximation was valid. The model has been further developed to aid the interpretation of tritium, nitrate and other solute profiles of pore-waters from the Chalk's unsaturated zone (Fig. 1), but not at this stage to simulate their profiles, which are extremely complex in detail.

The model

Description

The migration of solutes in fissured porous media will be primarily controlled by the average geometry of the fissure system, assuming the rock matrix has relatively homogeneous properties. A substantial problem that arises in modelling, however, is to characterize this system by as few parameters as possible, while endeavouring to retain all the essential features of its behaviour. The geometry selected (Fig. 2) was intended to be the simplest that would retain such features.

Fissures (joints) were taken to be semi-infinite planar openings (of width w) at a uniform spacing, a, dividing the porous rock-mass into blocks. Because of the periodicity of this geometry, only a single, repeating, two-dimensional unit need be considered (Fig. 2). The fissures are assumed to be saturated with water which, having entered the system (at $y=0$) with known solute concentration, $f(t)$, passes down them at a velocity, u, with negligible dispersion in the y direction. The lateral gradient of solute concentration in the fissures is assumed to be negligible and, at each depth, this concentration is assumed to be equal to

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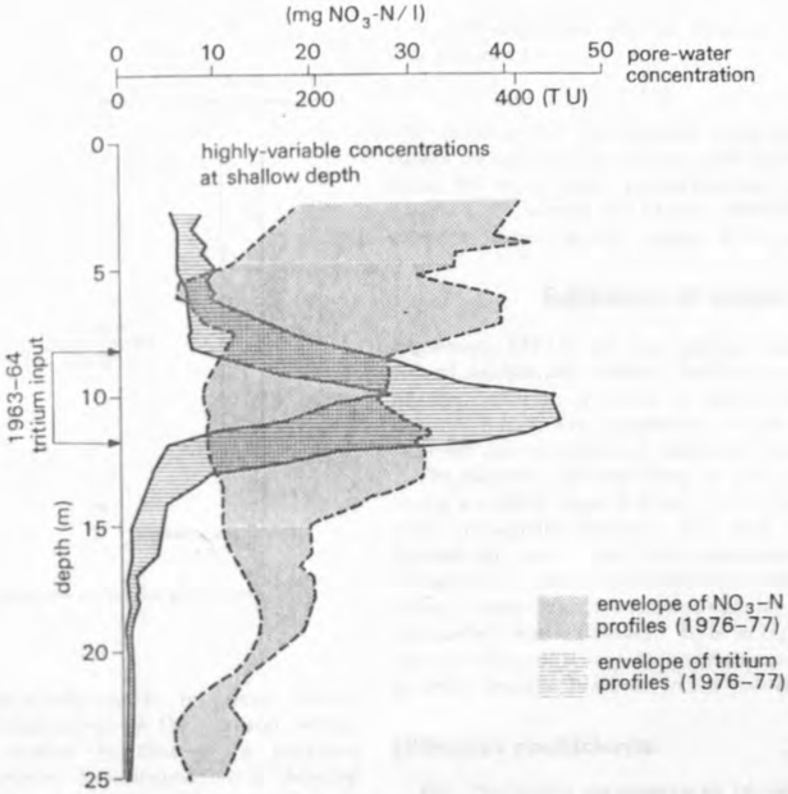

FIG. 1. Summary of nitrate and tritium profiles in the unsaturated zone of the Chalk beneath long-standing arable land in West Norfolk.

that in the matrix pore-water at the surface of the block (i.e. at all points with $x = 0$).

The rock matrix was taken to be a homogeneous medium of porosity ϕ, which is fully saturated with immobile pore-water. The solute moves through the saturated porous matrix in the x direction only (perpendicular to the fissures) by aqueous molecular diffusion, according to Fick's law, with a diffusion coefficient D. The initial solute concentration in the pore-water of the matrix is a known function of depth only, $g(y)$.

The simplification of ignoring vertical diffusion in the matrix was considered justified since, in practice, hydrodynamic dispersion in the fissures (not included in this model) would probably over-shadow vertical diffusion.

Mathematical formulation

Let $c(x, y, t)$ be the solute concentration per unit volume of fluid at time, t. Given the above assumptions, this function will be the solution of the following equations:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \quad \text{in} \quad 0 < x < a/2. \tag{1}$$

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial y} = \frac{2\phi D}{w}\frac{\partial c}{\partial x} \quad \text{at} \quad x = 0. \tag{2}$$

$$\frac{\partial c}{\partial x} = 0 \quad \text{at} \quad x = a/2. \tag{3}$$

$$c(0, 0, t) = f(t). \tag{4}$$

$$c(x, y, 0) = g(y). \tag{5}$$

Equations (1) and (2) represent conservation of mass in the matrix and the fissure, respectively. Equation (3) expresses the fact that, due to symmetry, there can be no net movement of solute across the centre of a block. Equations (4) and (5) define the initial conditions.

The 'Chromatographic' approximation

The only condition for which Foster's (1975) diffusion exchange mechanism has been evaluated is that in

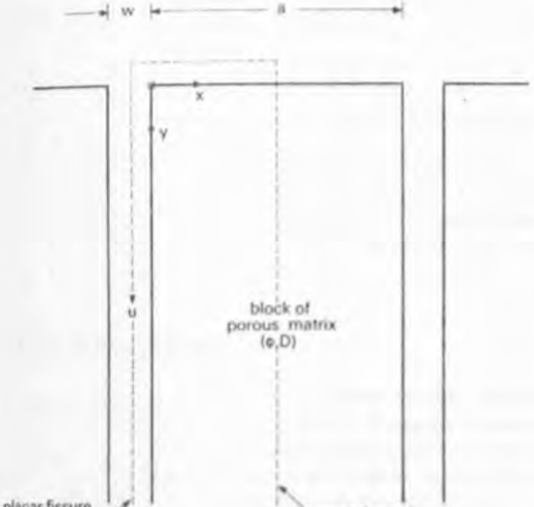

FIG. 2. Definition of model geometry.

which the diffusion coefficient is, in effect, infinite (Oakes 1977). The behaviour of the fissured porous medium is then similar to that of a partition chromatographic column. It is instructive to develop this limiting case of the present model, particularly in the context of interpreting field data from the unsaturated zone.

Consider the evolution from an initial profile, g(y). If D is infinite, solute exchange between the stationary pore-water and mobile fissure-water will be instantaneous and the solute profile will move downwards (in the y direction) without distortion, according to:

$$c(x, y, t) = g(y - V_\infty t) \quad \text{for} \quad y \geq V_\infty t,$$

where

$$V_\infty = u \frac{w}{(\phi a + w)} \tag{6}$$

is the velocity of movement of the undistorted profile. (A rigorous proof of this result can be obtained from Equations (1)–(5)). From the geometry of the model, the amount of infiltration (I) per unit area in time (T) is expressed by:

$$I = \frac{1}{(1 + a/w)} \int_0^T u \, \mathrm{d}t$$

or, using Equation (6):

$$I = \frac{(\phi a + w)}{(a + w)} \int_0^T V_\infty \, \mathrm{d}t.$$

This integral is the distance (X) that the profile moves in time (T) and, since (in all practical cases) a is orders-of-magnitude greater than w, this latter equation reduces to:

$$X = I/\phi. \tag{7}$$

The question that immediately arises is for what finite values of diffusion coefficient (D) does Equation (7) cease to be a good approximation; the values for tritium (^3H), nitrate (NO_3) and chloride (Cl) being of especial interest in the context of the present paper.

Behaviour of model

Equations (1)–(5) do not appear capable of being solved analytically without further excessive simplifying assumptions. In order to study the behaviour of the model they were, therefore, solved numerically for selected combinations of values for the parameters.

The porosity (ϕ) was fixed at 0.35 throughout; this being a typical value for the Chalk, the formation of most immediate interest. The flow velocity in the fissures (u) was fixed, also somewhat arbitrarily, at 1.0 m/d in many of the numerical solutions, but sensitivity to increases (to 5.0 m/d) in this most significant parameter was examined. It is accepted that much higher values of u may be appropriate, in many areas, at some fissured horizons in the saturated zone.

Diffusion coefficients

The laboratory measurement of aqueous diffusion coefficients in porous media presents numerous practical difficulties and the only attempt, known to the authors,* to make a measurement on saturated Chalk was reported by Oakes (1977), who quoted a value for Cl of 1.3×10^{-9} m^2/s (presumably at room temperature). This value appears anomalously high when compared to other published data. Stoessell & Hanor (1975) reported D for Cl in saturated, epoxy-cemented sand ($\phi = 0.3$) to be in the range $3\text{–}5 \times 10^{-10}$ m^2/s (at 35°C) and Barraclough & Nye (1979), in experiments on soil blocks with 30–35% water-saturated porosity, obtained values in the range $3\text{–}7 \times 10^{-10}$ m^2/s (at 25°C); D clearly decreasing as moisture content is reduced below full saturation.

No corresponding results are known for NO_3*, although this ion has a similar self-diffusion coefficient in water to that of Cl (Parsons 1959; Erdey-Gruz 1974). The ratio of the matrix-diffusion coefficient to the self-diffusion coefficient depends on parameters that will, in general, vary from one solute to another (Nye 1966); however, column experiments (Mercer & Hill 1976, 1977) suggest that NO_3 and Cl behave similarly in powdered Chalk and Chalk soils.

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* Since this paper was completed, values of D ranging from 0.4×10^{-10} to 3.0×10^{-10} m^2/s have been measured for NO_3 and Cl (at 20°C) in a variety of saturated Chalk samples with different porosities (Mercer, E. R.; personal communication).

The self-diffusion coefficient of ^3H has been measured by Mills (1973), who gave values of 1.3×10^{-9}, 1.7×10^{-9} and $2.2\times10^{-9}\,m^2/s$ at 5°, 15° and 25°C, respectively. These results illustrate the sensitivity of D to temperature; interpolation gives a value of about $1.5\times10^{-9}\,m^2/s$ at 10°C, the average temperature of groundwater in Britain.

Considerable uncertainty must remain as to the appropriate values of D for ^3H, NO_3 and Cl in saturated or near-saturated Chalk at 10°C, and variation over the whole range 10^{-9}–$10^{-10}\,m^2/s$, at least, must be considered possible.

Fissure geometry

It is very difficult, also, to make *in situ* measurements of fissure aperture (width), although some idea of the sizes of the blocks separating joints and fissures can be obtained by direct observation in excavations and by televisual examination of borehole walls. For the Chalk in Britain, variation of a and w in the range 2–10 cm and 0.2–1.0 mm, respectively, were initially considered. It is recognized that, in the unsaturated zone, fissures of the above range of aperture will conduct water only at low negative potentials (suctions) and a fissure system with smaller values of a and w may also play an important role in the flow of water; whereas, in the saturated zone, values of a and w may exceed the maximum values considered (Foster & Milton 1974; Reeves 1979; Foster & Smith-Carington 1980).

Profile characterization

During most of the use of the model the initial solute concentration in the matrix $g(y)$, was taken to be a Gaussian function, since this can be characterized by just two parameters, magnitude of peak (C_0) and standard deviation (S_0): normally the values $C_0=1$ and $S_0=20$ cm were used. The surface input concentration was taken to be zero [i.e. $f(t)=0$] for the results reported below.

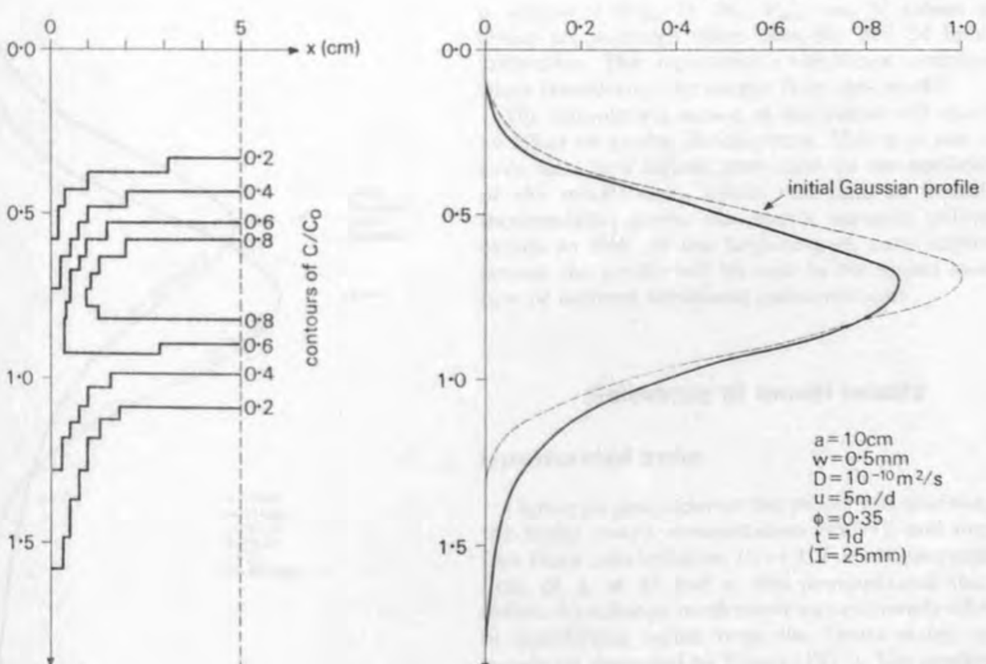

FIG. 3. Concentration contours within the porous matrix block and the corresponding mean concentration profile (Eq. 8).

As the flow of water in the fissure proceeds, the concentration across the matrix slab at any depth becomes a function of x (Fig. 3). Of main interest is the average value:

$$\bar{c}(y, t) = \frac{2}{a}\int_{0}^{a/2} c(x, y, t)\,\mathrm{d}x. \tag{8}$$

as this gives the best approximation to the results obtained from borehole core-sampling. Since, to greater or lesser extent, all the distributions become non-Gaussian (Fig. 3), the rates of movement of both the peak (V_{max}) and the mean ($\bar{V}$) of the distribution, $\bar{c}(y, t)$, were determined.

Output from model

For a given geometry ($a = 2$ cm, $w = 1$ mm, $\phi = 0.35$), the sensitivity of profile development to variation of D is illustrated by Fig. 4; these model runs assumed $u = 1$ m/d over a time interval of 2 days. It is evident that a slow downward movement of solute results, but that while the original Gaussian distribution is essentially preserved for the larger value of D (10^{-9} m^2/s), for the smaller value (10^{-10} m^2/s) the peak remains almost stationary and a marked 'forward tail' develops. This sensitivity is further evaluated in Fig. 5 for two geometries (which are probably not unrealistic for the Chalk); the rate of movement of the peak and mean of the distribution being compared to the corresponding value for the 'chromatographic approximation case' (V_{max}/V_∞ and $\bar{V}/V_\infty$). It is evident that these ratios depart rapidly from the unity asymptote as values of D decrease below about 10^{-9} m^2/s and, at the same time, the peaks of the distributions lag increasingly behind the means.

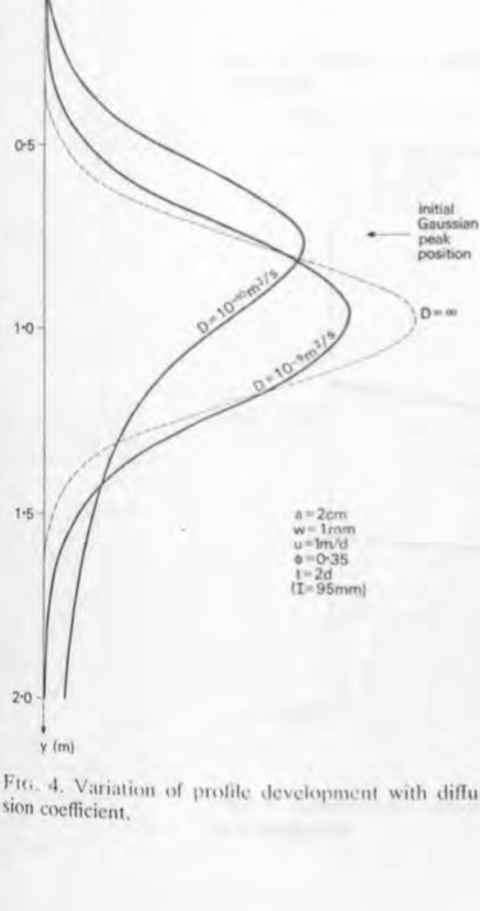

FIG. 4. Variation of profile development with diffusion coefficient.

In the range of D under special consideration (10^{-9}–10^{-10} m^2/s), these effects are even more pronounced if u is increased to 5 m/d (Fig. 5): profile development clearly being highly sensitive, also, to variations in the rate of water flow in fissures.

It is further apparent that for given values of u, and D, the extent of the departure from the 'chromatographic approximation' increases with increasing w, but to a lesser extent with increasing a (Fig. 6).

It must, however, be noted that V_{max} is not constant throughout the initial period during which infiltration is simulated (Fig. 7); the V_{max} and $\bar{V}$ values given above are averages taken over the first 24 hours of infiltration. This represents a significant complication when considering the output from this model.

The intermittent nature of infiltration will also have an effect on profile development. This may not, however, lead to a serious restriction on the applicability of the model since solute will tend to equilibrate (horizontally) across the matrix between infiltration events so that, at the beginning of each infiltration period, the profile will be near to the model assumption of uniform horizontal concentration.

Relevance of model results

Unsaturated zone

During its development the model was also run with the initial matrix concentration $g(y) = 0$ and the surface input concentration $f(t) = 1$. For certain combinations of a, w, D and u, this demonstrated that the diffusion exchange mechanism was extremely effective in transferring solute from the fissure water to the matrix, as suggested by Foster (1975). The mechanism also provides a ready explanation of how solutes (and pollutants) present in the unsaturated zone in the matrix of fissured porous media migrate across near horizontal (bedding-plane) discontinuities. Moreover, the model is, at the same time, compatible with the

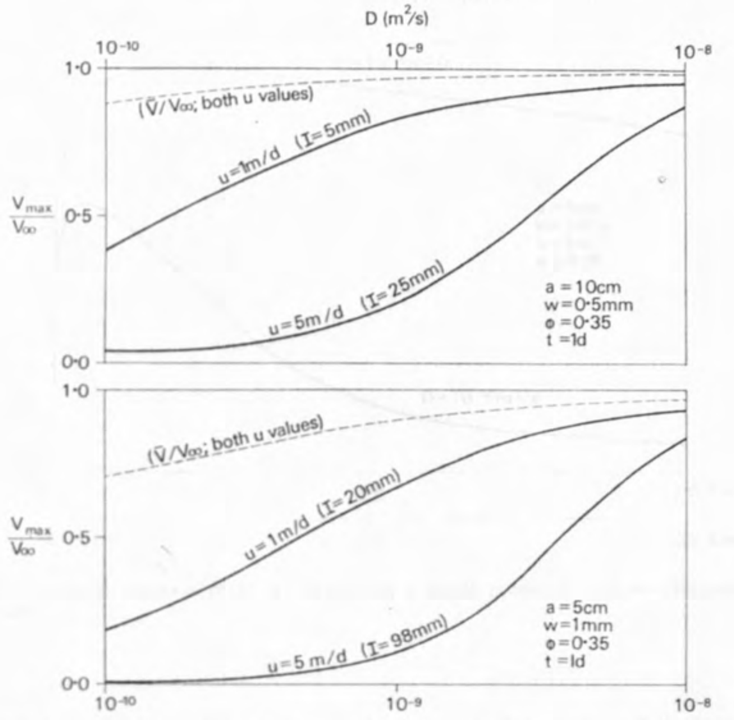

FIG. 5. Variation of profile velocity with diffusion coefficient for two geometries.

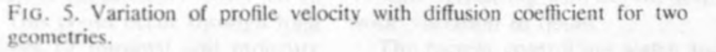

FIG. 6. Approximate variation of V_{max}/V_{∞} with geometry for a given diffusion coefficient.

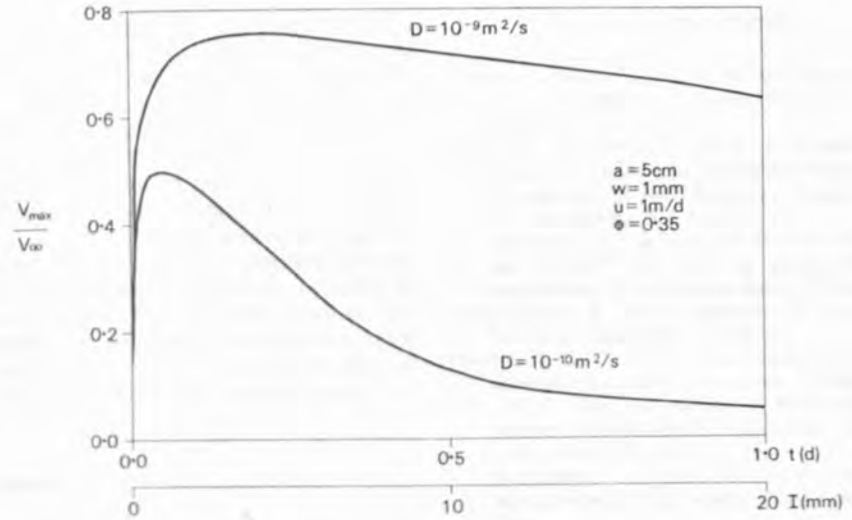

FIG. 7. Temporal variation of peak velocity for a single geometry and two diffusion coefficients.

rapid penetration of pollutants from the land surface to the water-table, which is occasionally observed in fissured porous media. This could occur through high hydraulic loading at times of minimal soil moisture deficit (following high intensity rainfall or some kind of artificial irrigation), when fissures of larger aperture (w) would be expected to conduct groundwater flow at relatively high velocity (u) with only minor attenuation by the matrix.

The natural ^{3}H profiles from the Chalk's unsaturated zone (Fig. 1) are remarkable for the preservation, with only minor dispersion, of the peak associated with rainfall and infiltration in the springs of 1963 and 1964. The ^{3}H input concentration of infiltration and the behaviour of ^{3}H in the soil are both uncertain and it should be noted that a significant by-pass of this slow mode of downward ^{3}H movement exists (Foster & Smith-Carington 1980). Nevertheless, as far as the slow mode is concerned, the preservation of this peak implies that the uppermost 10 m or so of the Chalk's unsaturated zone (at least) contains a fissure system characterized by such values of w, u and a that $(V_{max}/V_{\infty}) \rightarrow (\bar{V}/V_{\infty}) \rightarrow 1$, for the operative value of D. Even so, the existence of small 'forward tails' on the peak would be expected from the results of the model. Although difficult to distinguish in the field data from the effect of complexity in surface input concentrations, such 'forward tails' have been identified but were not attributed to this process (Smith *et al.* 1970).

The NO_3-N profiles for the Chalk's unsaturated zone from beneath long-standing arable land appear to possess a characteristic shape (Fig. 1), with concentrations decreasing with depth, despite exhibiting fairly wide variation in detail.

The factors controlling water and solute movement in the uppermost 2–3 m of the unsaturated zone (where highly variable concentrations with depth and time have been observed) are complex and include:

(a) The existence of high negative potentials (suctions) exerted by the matrix of the Chalk, as a result of reduced moisture content, in summer and early autumn.

(b) Some upward movement and direct uptake of water and nutrients from depth by plants, in late spring and summer.

It is known that initial soil drainage in autumn always contains very high solute concentrations (especially of NO_3-N) and because of the prevailing suctions these will enter the Chalk's matrix at shallow depths. The much larger volume of winter and early spring drainage has, in general, relatively low solute concentrations and would be expected to elute solutes from the (then saturated) shallow matrix of the Chalk by the diffusion exchange mechanism.

The initial conditions selected for the numerical solutions of the present model and the results obtained (Figs 4–7) are most appropriate for the evaluation of this process, but it should be noted that w, u and a will vary with depth in the unsaturated zone. Profile development will be very sensitive to diffusion coefficient and significant differences in the behaviour of ^{3}H and NO_3-N could be concomitant upon their differences in D (Figs 4–5). Moreover, the sensitivity of the results to D and to u also suggest that it is possible for a quasi-steady state NO_3-N peak, with a pronounced 'forward tail' to become established at shallow depth beneath arable land, because of insufficient time for elution to proceed very far during each winter's infiltration sequence. Profiles of the observed characteristic shape could have developed in this way. If this were the case, it would imply substantially lower rates of leaching of nutrients from arable land than might at first seem apparent, and give less cause for concern about the long-term future of groundwater quality of the Chalk; nevertheless, NO_3-N concentrations are likely to continue to rise. Final interpretation must await the results of sequential re-drilling in selected arable fields over a period of more than 5 years.

Saturated zone

The saturated zone of fissured porous aquifers may commonly be characterized by higher fissure-flow velocities (in excess of 10 m/d), particularly close to the water-table in unconfined aquifer situations and more generally near to pumping boreholes. In carbonate aquifers, like the Chalk, fissure apertures are often enlarged by solution.

Thus the results from the present model (Figs 5–6) suggest that:

(a) Once having entered the Chalk matrix, by some mechanism, solutes (pollutants) could take a very long time to be completely eluted out.

(b) Conversely, newly-introduced solutes (pollutants) in the fissure water may not be significantly attenuated, in their horizontal movement, by the diffusion exchange mechanism.

Moreover, the results of tracer experiments using water-soluble non-reactive salts to evaluate groundwater dispersion coefficients are likely to produce results varying with the local hydraulic gradient, since this will control fissure-flow velocity and in turn the extent to which the diffusion exchange with the matrix will occur.

ACKNOWLEDGMENTS. The paper is published by permission of the Director of the Institute of Geological Sciences (NERC). Financial support from the Department of the Environment and the Natural Environment Research Council are gratefully acknowledged.

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(9)

Journal
of

Hydrology

Elsevier Scientific Publishing Company
Amsterdam – Oxford – New York

Journal of Hydrology, 46 (1980) 343—364 343
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THE INTERPRETATION OF TRITIUM IN THE CHALK UNSATURATED ZONE

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(Received July 25, 1979; accepted for publication September 12, 1979)

ABSTRACT

Foster, S.S.D. and Smith-Carington, A., 1980. The interpretation of tritium in the Chalk unsaturated zone. J. Hydrol., 46: 343—364.

Pore-water tritium profiles from the Chalk unsaturated zone are presented and the problems and limitations in their interpretation are evaluated in detail. A new model of the physicochemical behaviour of tritium in the soil zone is proposed, which can account for the quantity and distribution of thermonuclear tritium observed at shallow depths in the unconfined Chalk aquifer. The mechanisms of solute movement through the Chalk unsaturated zone are also discussed.

INTRODUCTION

Background to paper

The relevance of thermonuclear tritium (^3H) to groundwater studies on the *unsaturated zone* of the British Chalk was first demonstrated by the far-sighted work of Smith et al. (1970), and Smith and Richards (1972). They recovered uncontaminated cores and determined the tritium distribution in pore water beneath sites in Berkshire (October 1968) and Dorset (September 1970). The tritium profiles at both sites had very clearly defined peaks of over 500 TU[*1] at depths of 4 and 7 m, respectively (Fig.1). After allowing for radioactive decay[*2], these peaks could only have originated from fallout in the spring rainfall[*3] of 1963 and 1964, following a period of frequent thermonuclear weapon testing. Only 15% and 5% of the total thermonuclear tritium present at the respective sites had reached depths of more than 12 m. The profiles were inter-

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[*1] The unit of tritium concentration used in this paper, which is defined as one ^3H atom per 10^{18} atoms of all hydrogen species and represents a radioactivity of $3.2 \cdot 10^{-3}$ pCi/ml.

[*2] The half-life of tritium is approximately 12.3 yr.

[*3] The term rainfall is used in this paper for all forms of precipitation; snowfall not being a significant process in the hydrology of lowland Britain.

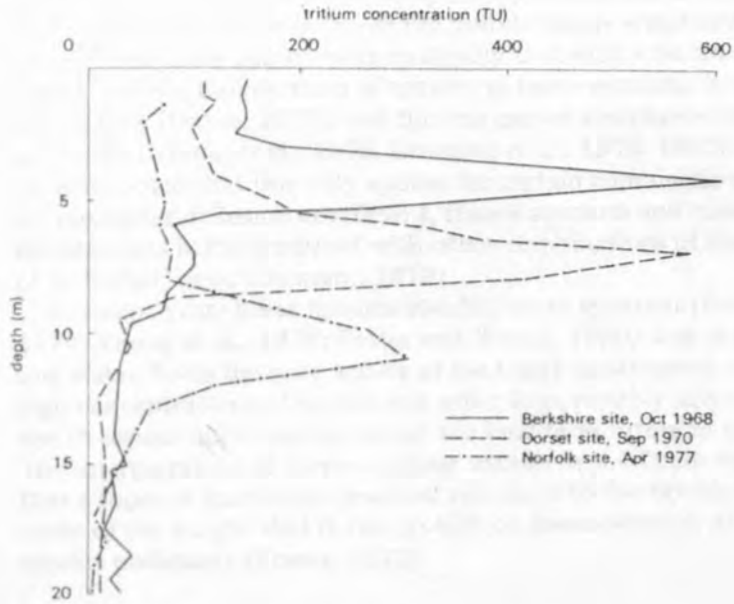

Fig. 1. Selected tritium profiles for Chalk unsaturated zone.

preted as indicating that most of the infiltration was moving downwards by *interstitial piston flow* at average rates of about 1 m/yr. It was also noted that the tritium input from infiltration (using excess rainfall calculated from meteorological data and correlated/observed values for tritium concentration in British rainfall) was not sufficient to account for the tritium recovered in the cores, and it was postulated that the classical method of computing infiltration might be over-estimating evaporation rates and/or that significant infiltration of summer rainfall was occurring.

These results had important implications for the estimation of groundwater resources, for water-quality management and for pollution protection in the important Chalk aquifer, from which 15–20% of national water supplies are abstracted.

Despite moderate-to-high porosity (mainly in the range 0.15–0.45, according to region and horizon), the Chalk matrix has very low permeability (rarely exceeding $5 \cdot 10^{-3}$ m/day). Thus it was widely believed that downward groundwater movement through the unsaturated zone (like the horizontal flow in the saturated zone below) occurred mainly or exclusively in the frequent fissures, joints and other discontinuities of the rock mass (Foster and Crease, 1974). The tritium profiles appeared to contradict this concept. However, the exceedingly small pores (mainly less than 1 μm diameter) mean that gravity drainage of the Chalk matrix is almost entirely inhibited (Price et al., 1976), and within most of the *unsaturated zone* it must remain very close to full saturation. Foster (1975) thus postulated that relatively rapid unsaturated groundwater flow could occur in fissures, but with the downward movement of tritium (and other solutes) being largely retarded as a result of exchange by molecular diffusion between the mobile fissure water and the static pore water. It has been shown mathematically that such a mechanism can produce similar vertical distributions of tritium to those resulting from interstitial piston flow (Oakes, 1977), and this has gained acceptance by British hydrogeologists (Young et al., 1976; Downing et al., 1978, 1979). Nevertheless it must be noted that this only applies for certain combinations of matrix porosity, molecular diffusion coefficient, fissure aperture and spacing; quite different distributions being produced with other combinations of these parameters (J.A. Barker, pers. commun., 1979).

In recent years it has become steadily more apparent (Foster and Crease, 1974; Young et al., 1976; Foster and Young, 1980) that at shallow depths below arable fields the pore waters of the Chalk unsaturated zone contain very high concentrations of nitrate and other ions, notably sulphate. This has given rise to serious apprehension about the long-term future of groundwater quality. The interpretation of thermonuclear tritium in the Chalk unsaturated zone is thus a topic of immediate practical relevance to the British water industry, because of the insight that it can provide on the movement of troublesome water-soluble pollutants (Foster, 1976).

Scope of paper

The importance of the topic has necessitated a *thorough* reassessment of all the factors that enter, or might enter, into the evaluation of the mass balance for thermonuclear tritium. Of particular interest is the interpretation of the proportion of the total tritium input involved in the slow mode of movement down to the water table, and the nature and degree of any "bypass" of this route.

In addition to a reconsideration of the original data from the Berkshire and Dorset sites (Fig.2), *new* data are presented and analysed from the following investigations:

(a) Multiple profiling of adjacent sites, mainly in arable land use, on the West Norfolk Chalk during 1976–1977.

(b) Re-drilling of the original Dorset site on permanent rough grassland in 1977.

All the profiles from Norfolk (Fig.3A), which are 0.1–10 km apart, show remarkable lateral uniformity. Tritium profiles with single pronounced peaks have also been found at numerous other sites on the Middle/Upper Chalk of southeastern England* with sufficiently thick unsaturated zones (Foster and Young, 1980). The relative magnitude and depth of the TU peaks are broadly

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*The relevance and interpretation of tritium profiles in the hydrogeological study of Chalk areas with a known capping of *low-permeability* residual soils, glacial drift, or Tertiary deposits, from which localised surface runoff often occurs, are *outside* the scope of this paper.

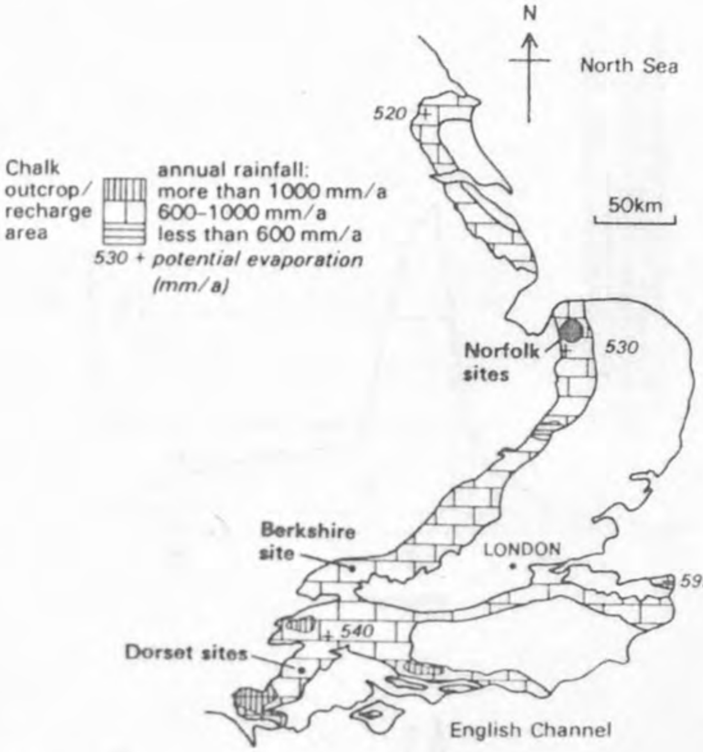

Fig. 2. Location and climate of investigation sites.

consistent with what might be expected, after allowing for radioactive decay and considering both the mean infiltration rate and the Chalk porosity in the areas concerned. However, it should also be noted that substantial differences between tritium profiles from closely adjacent sites drilled at comparable times are known from two areas, and various other minor anomalies have been observed in certain profiles.

Investigation methods

The majority of samples were obtained by dry, percussion drilling with a 0.45 m long, 100-mm diameter, drive core barrel. In order to obtain satisfactory samples from the somewhat harder and more cemented Chalk in Norfolk, air-flush rotary drilling with a lined double core barrel was required at depths greater than 15–20 m. Mechanically-excavated trenches were also used for obtaining samples at shallow depths and studying the weathering profiles of the Chalk rock mass. A comparison of laboratory results between the three sampling methods showed good agreement.

All samples were carefully handled and stored to eliminate, or to minimise,

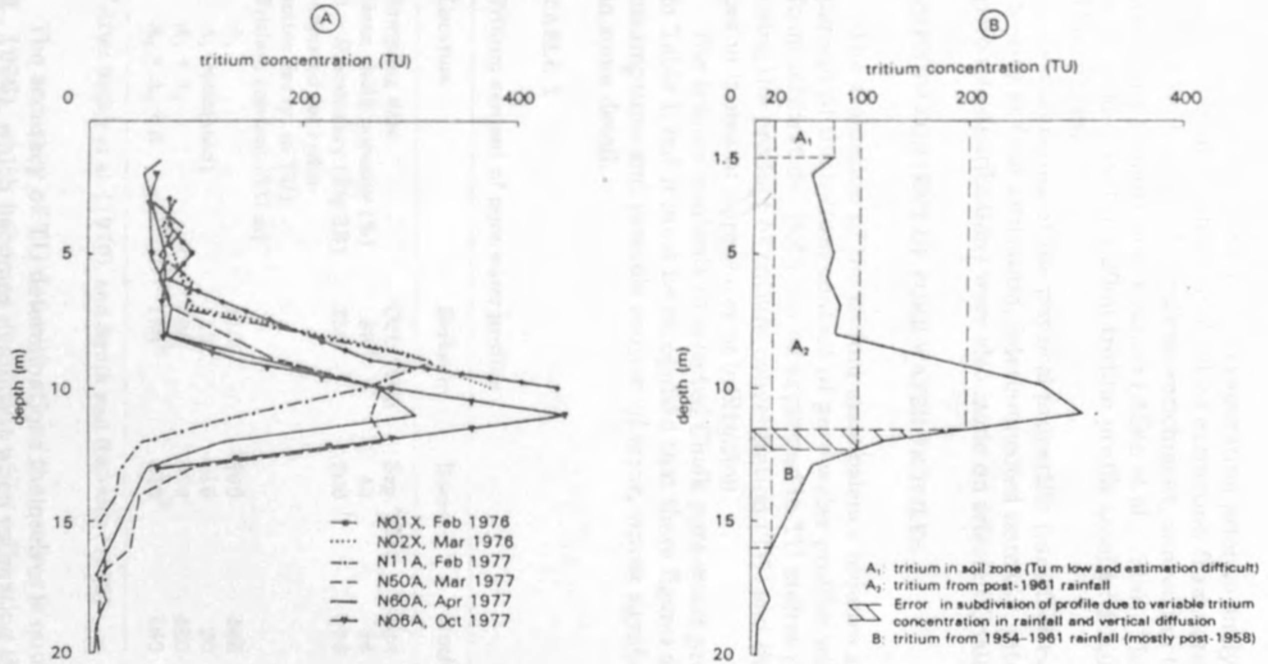

Fig. 3. Tritium profiles for Norfolk sites and their analyses.

pore-water contamination or evaporation prior to analysis. The determination of the tritium content involved its extraction from cores by distillation to complete dryness, electrolytic enrichment, conversion to ethane and measurement in a proportional counter (Allen et al., 1966). The overall sampling and analytical costs for a 20-m tritium profile totalled £ 2,000–2,500 at 1977 U.K. prices.

Measurements of the physical properties (moisture content by weight, bulk density at field saturation, interconnected porosity, intergranular permeability, pore-size distribution) were also made on selected Chalk samples.

TRITIUM CONTENT OF PORE-WATER PROFILES

The evaluation of the tritium mass balance requires a detailed, critical comparison of the tritium content of pore-water profiles with the tritium input from infiltration. Both can be expressed in TU metres (TU m); this unit being the product of tritium concentration (TU) and the respective volume per unit area of pore water or infiltration.

The tritium contents of selected Chalk pore-water profiles (Fig.1) are given in Table I, but it must be recognised that these figures are subject to several assumptions and possible sources of error, whose significance must be analysed in some detail.

TABLE I

Tritium content of pore-water profiles

Location	Berkshire	Dorset	Norfolk (N60A)
Sampling date	Oct. 1968	Sep. 1970	Apr. 1977
Mean chalk porosity (%)	38*	43	36
A_2–B boundary (Fig.3B) (adjusted for radioactive decay; in TU)	250	200	150
Tritium content (TU m)			
A_2	510	760	460
A_1 (estimated)	15	10	20
$A_1 + A_2$	520	770	480
$A_1 + A_2 + B$	730*	810*	560

*After Smith et al. (1970), and Smith and Richards (1972).

The accuracy of TU determinations themselves is quoted at ± 10% (Allen et al., 1966), which becomes significant when estimating the TUm associated with the principal peak in the profiles. The determinations were performed on lithologically-representative core samples of 0.3 m length for every 0.5 m, 1.0 m, or, occasionally, 2.0 m of borehole depth. Any variation in pore-water concentration in the rock mass, for example that with distance from joints or other discontinuities, would thus be averaged. The concentrations in the un-

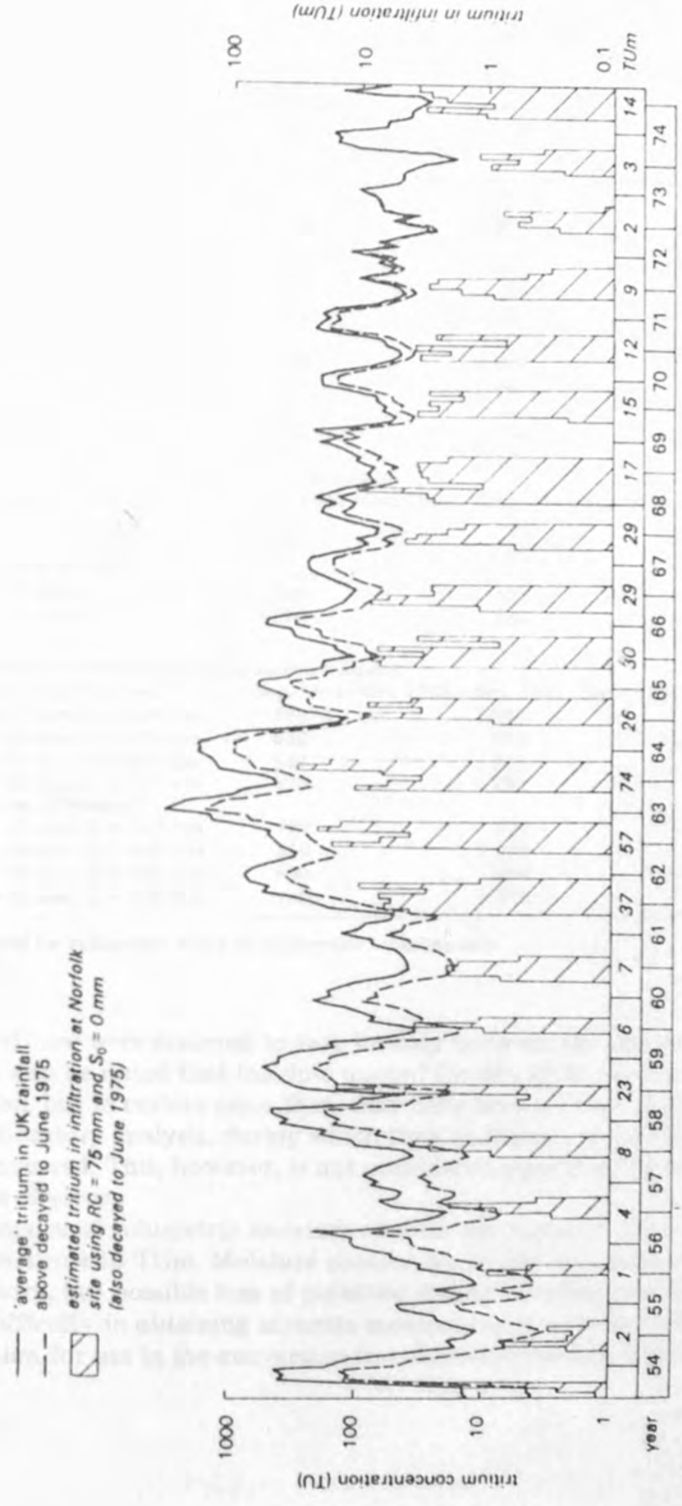

Fig.4. Long-term variation of tritium in rainfall and infiltration.

TABLE II

Tritium input from infiltration

Location	Berkshire	Dorset	Norfolk
(A) Summary of basic meteorological and tritium data:			
Period of analysis	Sep. 1961—Oct. 1968	Sep. 1961—Sep. 1970	Sep. 1961—Apr. 1977
Mean annual rainfall (mm)	740	880	700
Mean annual infiltration (mm):			
RC = 75 mm	240	410	230
RC = 25 mm	280	450	280
Total rainfall (mm)	5,360	8,040	10,920
Total infiltration (mm):			
RC = 75 mm	1,700	3,680	3,650
RC = 25 mm	1,980	4,060	4,420
Total TUm in rainfall*	2,140	2,230	1,700
Peak TU in rainfall*	2,470	2,220	1,540
(B) Estimation by method of Smith et al. (1970):			
Total TUm in infiltration*:	Sep. 1961—Oct. 1968	Sep. 1961—Sep. 1970	Sep. 1961—Apr. 1977
RC = 75 mm (S_e = 0)	450	700	330
RC = 25 mm (S_e = 0)	490	760	430
Peak TU in infiltration*:			
RC = 75 mm (S_e = 0)	1,050	880	610
RC = 25 mm (S_e = 0)	1,050	880	1,250
(C) Estimation using revised soil-moisture model:			
Total TUm in infiltration*:	Sep. 1961—Oct. 1968	Sep. 1961—Sep. 1970	Sep. 1961—Apr. 1977
RC = 25 mm, S_e = 500 mm	690	1,040	610
RC = 25 mm, S_e = 300 mm	650	990	580
RC = 75 mm, S_e = 300 mm	540	840	430
RC = 25 mm, S_e = 100 mm	500	790	460
Peak TU in infiltration*:			
RC = 25 mm, S_e = 500 mm	790	870	650
RC = 25 mm, S_e = 300 mm	840	1,070	830
RC = 75 mm, S_e = 300 mm	820	990	620
RC = 25 mm, S_e = 100 mm	780	1,170	1,150

*Corrected for radioactive decay to appropriate sampling date.

sampled core were assumed to vary linearly between the sampled lengths. It should also be noted that the date quoted for any given profile is that of sampling, but in certain cases there may have been a delay of some months before laboratory analysis, during which time additional radioactive decay would have occurred. This, however, is not considered significant in relation to other sources of error.

Estimates of volumetric moisture content are required to convert the TU measurements to TUm. Moisture content by weight was measured in the field laboratory, but possible loss of moisture during sampling/handling together with difficulty in obtaining accurate measurements of bulk density at field saturation for use in the conversion to volumetric content lead to the possibility of a ± 15% error. However, the physical properties of the Chalk are such that, in situ, the pores will everywhere remain close to full saturation, except in the uppermost metre or so of the profile. Thus porosity measurements can also serve for volumetric moisture content; these were made by the water resaturation method, with an estimated accuracy of ± 10%.

Subdivision of profiles

To attempt an evaluation of the tritium mass balance, it is necessary to attribute the pore-water tritium content down to some depth as being derived from infiltration during a known period. Implicit in this approach is the assumption that the downward movement of tritium in the profiles concerned has conformed to an *apparent* piston flow.

In view of the major rise of TU in rainfall during the spring of 1962 (Fig.4 and Table IIA) it is thought most practical to treat all the tritium above the base of the corresponding peak in the groundwater profiles as post-1961 in origin. However, the selection of this depth boundary is somewhat arbitrary (Fig.3B), and, in the case of the broader peaks of recent profiles, is aggravated by vertical diffusion. This may lead to errors of ± 25 TUm. An alternative approach is to attempt to integrate all of the thermonuclear tritium in the profiles, including the lower levels derived from 1954–1961 rainfall, but this involves a similar element of subjectivity in deciding the position of the lower depth boundary. Additionally, although the tritium content in the soil and Chalk-derived drifts is low, it is difficult to estimate accurately because of highly variable physical properties (Table III).

TABLE III

Summary of physical properties of soil—rock profiles

Location	Dorset	Norfolk
Soil drift cover:		
Lithological description	brown calcareous earths	brown (calcareous) earths over sandy glacial drift
Thickness (m)	0.3–0.5	0.5–2.5
Acid residual (%)	?	2–60 (locally)
Field bulk density (g/cm³)	?	1.8–2.2
Estimated volume moisture content at field capacity (%)	15–20	15–20
Chalk:		
Depth to base of Chalk zone V* (m)	3	3–5
Acid residual (%)	0.5–2.0	1.0–2.5
Porosity (%)	40–47	30–40
Field bulk density (g/cm³)	1.9	2.0
Moisture content (% by volume)	? 40–47	30–40

*Deeply weathered "structureless" Chalk, as defined by Ward et al. (1968).

TRITIUM INPUT FROM INFILTRATION

The estimates of the tritium input function used by Smith et al. (1970) were derived by summing the products of monthly excess rainfall, computed by the classical Penman—Grindley method with a RC*[1] of 75 mm, and the "average" correlated/observed tritium concentrations in British rainfall. Similar data extended and decayed to June 1975 are shown in Fig.4. The TUm in post-1961 infiltration estimated in this way, and in each case integrated and decayed to the date of sampling at the corresponding site, are given in Table II, (*B*). In Norfolk, as in Berkshire (Smith et al., 1970), such estimates are not nearly sufficient to account for the corresponding TUm in the pore-water profiles (Table I), despite ample TUm in the rainfall itself [Table II, (*A*)]; nor are the infiltration volumes capable of displacing the main tritium peak to the observed depths. These anomalies led to a more detailed consideration of all the factors affecting the estimation of tritium input from infiltration. In Dorset, however, the deficit of TUm in post-1961 infiltration is only minor [Tables I and II, (*B*)].

Reliability of tritium data for rainfall

The data on TU in British rainfall have been produced from several different sources. For the period 1953—1958 the British values were derived by correlation from measurements for Ottawa (Canada), and for 1956—1964, a particularly critical period, from measurements for Valentia (Ireland). TU determinations on British rainfall began in 1965, and the average British values given (Fig.4) are the arithmetic mean of results from up to five sites, after the elimination of any results suspected of contamination from those sites near to nuclear power stations.

Statistical analyses of the monthly data from two of the longest-standing British monitoring stations (Orfordness and Milford Haven) together with those for Valentia*[2] were carried out to investigate the spatial variation of tritium in rainfall. Student's *t*-tests showed the undecayed TU at all three stations to be significantly different (Table IV); Valentia having the lowest TU and Orfordness the highest. It is suspected that the former is subject to a much higher degree of oceanic dilution than the British stations. Using linear regression analysis only moderate correlation coefficients (r^2) are obtained (Table IV), and because, for the peak 1962—1964 period, considerable extrapolation is required to estimate monthly TU in rainfall at the British sites from that at

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*[1] The root constant, which is related to the soil moisture deficit at which actual evaporation rates fall below potential, for the soil—plant system concerned.

*[2] Because of a systematic difference in laboratory calibration, all the British values quoted in this paper should be multiplied by a factor of 0.89 to conform with international standards; this factor was taken into account when undertaking statistical comparisons with the Valentia data.

TABLE IV

Results of statistical analyses of data on tritium in post-1965 rainfall

Stations compared			Valentia/Orfordness	Valentia/Milford Haven	Milford Haven/Orfordness
TU	monthly values[*1]	t	11.42 (S)	5.90 (S)	7.27 (S)
		r^2	0.78	0.80	—
TUm	monthly values[*1]	t	0.01 (NS)	0.35 (NS)	1.78 (NS)
		r^2	0.23	0.29	—
TUm	yearly totals[*2]	t	0.82 (NS)	0.48 (NS)	1.40 (NS)
		r^2	0.82	0.87	—

Calculated t is compared with tabulated t-values of 1.98 and 2.20 for monthly and yearly time base, respectively, for 95% level of significance; S indicates significant difference between sites and NS indicates no significant difference.

[*1] For months where TU available for all sites.

[*2] TU interpolated for months when not available.

Valentia, the accuracy of any data generated will be uncertain and subject to wide confidence limits. The regression equations obtained:

$$\mathrm{TU}_{\mathrm{Orfordness}} = 1.89\ \mathrm{TU}_{\mathrm{Valentia}} - 4.26$$

and

$$\mathrm{TU}_{\mathrm{Milford\ Haven}} = 1.47\ \mathrm{TU}_{\mathrm{Valentia}} - 10.22$$

appear to give greater values for the 1963 rainfall maximum than those published as the British "average".

It was considered that the total TUm fallout in rainfall might be more constant spatially, TU varying inversely with rainfall. Statistical analyses showed that, although monthly TUm did not appear to be significantly different, high scatter in the data caused extremely low correlation coefficients (Table IV), and no useful regression equations could be produced. The correlation between sites increases dramatically, however, when longer periods of analysis are considered. Thus on a yearly time base the TUm in fallout is spatially quite uniform, any temporal variations in local TU distribution and rainfall incidence being averaged out. However, yearly totals of TUm are only of limited use for the present purpose.

In conclusion, the average values for TU in British rainfall (Fig.4) are subject to serious limitations and must only be treated as a general indication of the scale of temporal variations that occurred. Amongst the sites under consideration, it is likely that both Berkshire and Norfolk would have experienced above "average" TU values, although no simple relationship can be anticipated. There is substantial uncertainty over the TU and TUm in rainfall during the critical period 1962–1964, although it remains absolutely certain that the bulk of the TUm in infiltration must have been derived from rainfall during this period. The subsequent variations in TU and TUm in rainfall are better understood and will be useful for future studies of temporal change in porewater tritium profiles.

Computations using meteorological data

There will be errors in the measurement and computation of the basic meteorological data (rainfall and potential evaporation), and it is also accepted that rainfall may be subject to some spatial variation between the investigation site and the nearest gauging station. However, their effect on the computation of long-term infiltration is likely to be small.

Lysimeter experiments (R. Kitching, pers. commun., 1978) and water balance studies (e.g., Headworth, 1970) suggest that the RC for short-rooted vegetation could be reduced from 75 mm to perhaps as low as 25 mm. However, the use of a single root constant for arable farmland may not adequately represent the change in the regime of evaporation after harvest. Some lysimeter measurements and the monitoring of the shallow groundwater table at one of the Norfolk sites during 1976–1978* (Fig.5A and B) supports the hypothesis that the RC certainly does not exceed, and is probably substantially less than, 75 mm. The reduction of RC to 25 mm would have the effects of reducing the computed soil moisture deficit to zero earlier each year, increasing the infiltration by about 10–20% allowing larger displacement of the main tritium peak and producing a significant increase in the TUm in infiltration, particularly in 1963 when maximum concentrations in rainfall occurred [Table II, (*B*)]. However, this factor alone cannot nearly account for the apparent deficit in TUm estimated in infiltration against that measured in pore-water profiles, except in Dorset.

There is some evidence from groundwater level hydrographs for infiltration of summer rainfall to the Chalk, following certain intense storms. On occasions such infiltration appears to occur without the soil moisture deficit being satisfied (and therefore is not taken into account by classical calculations based on meteorological data). Such events are likely to be associated with the highest TU in the yearly rainfall cycle (Fig.4), but in recent years at least, the associated rises in groundwater level in Norfolk (Fig.6) and Dorset have never exceeded 0.05 m and may include a component of barometric fluctuation, known to occur in unconfined Chalk observation boreholes during storms. Even assuming a high value for Chalk specific yield (2%), the amount of infiltration involved would only produce an additional input of 3–4 TUm in Norfolk during the period 1964–1977. It is believed that summer infiltration occurs because of the cracking of the clay soil cover, but it only results in recharge of the Chalk aquifer in the very *small* percentage of the land surface underlain *directly* by solution pipes or exceptionally large fissures. Elsewhere

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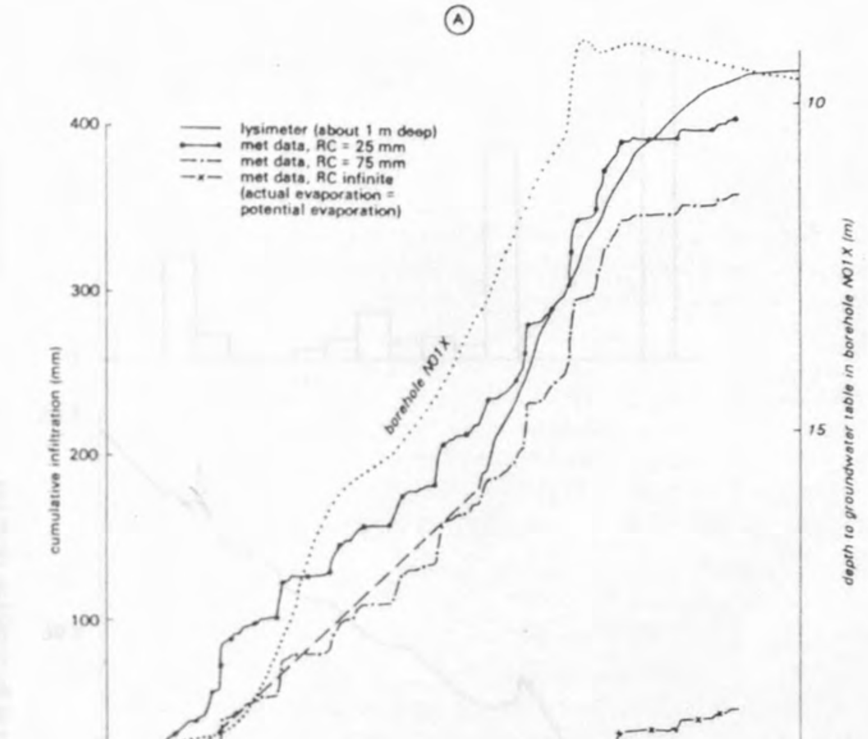
*It should be noted that the period 1976–1978, included a sequence of rather unusual meteorological conditions — the end of the worst British drought of the 20th century in October 1976, followed by the extremely wet winter of 1976–1977, and the wettest spring–summer for many years in 1978.

Fig.5. Comparison of computed and observed infiltration in Norfolk during: (A) 1966–1977; and (B) 1977–1978.


A
lysimeter (about 1 m deep)
met data, RC = 25 mm
met data, RC = 75 mm
met data, RC infinite (actual evaporation = potential evaporation)
cumulative infiltration (mm)
400
300
200
100
0
borehole N01X
depth to groundwater table in borehole N01X (m)
10
15
20
Oct
Nov
Dec
Jan
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B
300
200
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cumulative infiltration (mm)
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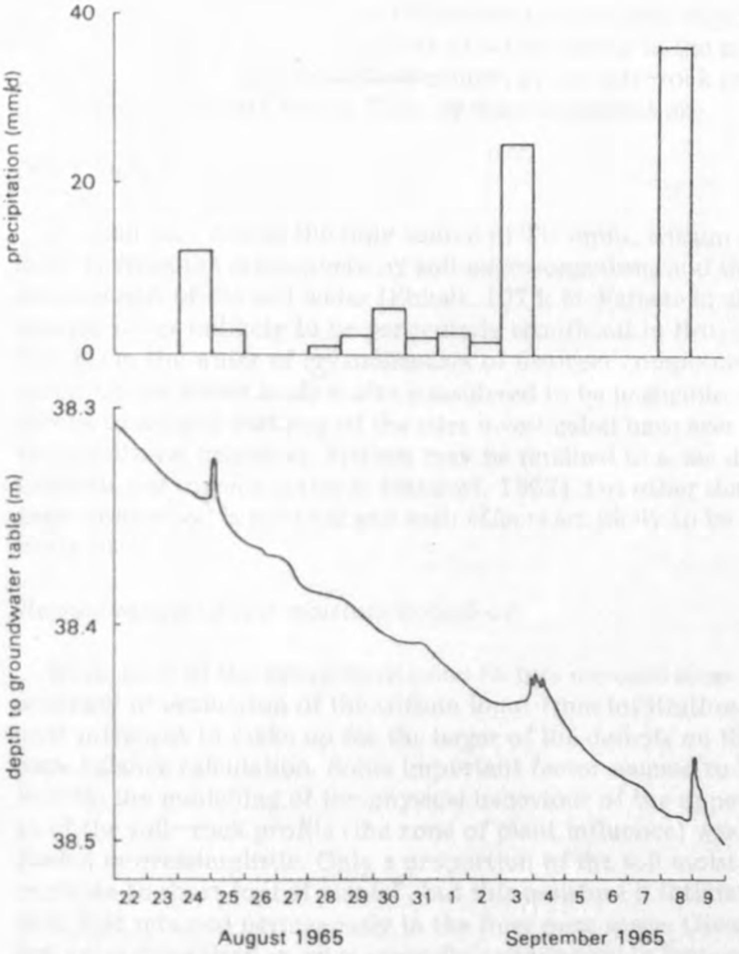

Fig.6. Minor recharge to Norfolk Chalk from summer rainfall.

there would be no potential for any short-term excess rainfall to be drawn laterally into such features, because of the prevailing high pore-water suctions; thus averaged over the entire land area this phenomenon results in almost negligible infiltration.

Some other factors which might affect the TU of rainfall, evaporation and infiltration, should also be mentioned. While there is no isotopic enrichment of water during transpiration through plants (Zimmermann et al., 1966), a degree of fractionation (preferential evaporation of non-tritiated water) occurs during evaporation from bare soil. Although this condition arises on arable land for up to eight months each year, the overall enrichment of TU in the soil water is unlikely to be more than 2%. This is negligible, bearing in mind that the total evaporation during the non-growing season is unlikely to exceed

150 mm. The actual TU in rainfall incident at soil level may be modified by plant interception and by recycling of water vapour in the microclimate. The presence of any deeper root development in the soil—rock profile could lead to a disproportionate loss of TUm by evapotranspiration.

Other factors

Rainfall may not be the only source of TU input; tritium may be taken up directly from the atmosphere by soil micro-organisms and then oxidised to become part of the soil water (Ehhalt, 1973; McFarlane et al., 1978), but this process seems unlikely to be particularly significant in British field conditions. The TU in the water of crystallization of fertiliser compounds (applied in large quantities to arable land) is also considered to be negligible. There is also no record to suggest that any of the sites investigated have ever been subjected to agricultural irrigation. Tritium may be retained to some degree on clay minerals and organic material (Stewart, 1967), but other than in the soil zone, their proportion is minimal and such effects are likely to be unimportant in chalk itself.

Revised model of soil-moisture behaviour

While each of the above-mentioned factors imposed some limitation on the accuracy of evaluation of the tritium input from infiltration, they did not appear sufficient to make up for the larger of the deficits on this side of the mass balance calculation. Some important factor seemed to have been overlooked; the modelling of the physical behaviour of the uppermost metre or so of the soil—rock profile (the zone of plant influence) was, in particular, regarded as oversimplistic. Only a proportion of the soil moisture in this zone is available to short-rooted plants*, but this moisture is intimately associated with that retained permanently in the finer pore space. Given the relatively low evapotranspiration rates generally experienced in Britain, it is highly probable that much of the *summer* rainfall resides in the soil zone for sufficient time to allow TU equilibration with the soil moisture, by vertical hydraulic dispersion and lateral molecular diffusion.

Thus a revised soil moisture model was introduced in which the TU of the soil moisture at the end of each month is given by:

$$T_s = [T_{s-1}(S_0 - S_{s-1}) + T_R R]/(S_0 - S_{s-1} + R)$$

where S_0 is the limiting size of the soil moisture store (i.e. the field capacity); S_{s-1} and T_{s-1} are the antecedent soil moisture deficit and TU in the store, respectively; R is the rainfall; and T_R its average TU. The evaporation and any

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*The low values of RC, which appear appropriate, suggest that short-rooted vegetation cannot draw water from Chalk pores of much less than about 0.6 μm, that is against suctions of more than 5 atm. (50 m of water).

infiltration occurring during the month in question are assumed to have a TU equal to T_s. The TUm input is $T_s I$, where I is the infiltration.

For the calculation of infiltration the classical Penman—Grindley method, applied to the *daily* meteorological data is retained. It is recognised that, ideally, values of T_s should also have been computed on a daily basis, but because of the afore-mentioned uncertainties over the precise values of T_R, the additional computation hardly seemed justified.

The physical character of the soil—rock profile will control S_0 and it is estimated, from physical properties (Table III), that the top metre has a moisture content at field capacity of 300—350 mm at the Dorset sites and 150—200 mm at the Norfolk sites. The Berkshire site is similar to those in Dorset. If the next 0.5 m of the profile could be included it would increase the above values to 500—550 and 300—350 mm, respectively, and thus values for S_0 of 100, 300 and 500 mm must be considered.

A somewhat similar model to that developed here was suggested by Andersen and Sevel (1974), but it only allowed the *monthly excess* of rainfall over actual evaporation to enter and mix with the soil moisture storage; this seems less realistic, at least under British conditions. Even the proposed model departs from physical reality because:

(a) it fails to take account of interception, that is the water stored on the wetted surface of plants and evapotranspired directly from them during and immediately following rainfall;

(b) it neglects the effect of any small upward water flux from below the soil zone (which may occur under certain conditions in drier summers) on the TU in the soil moisture store;

(c) the depth of penetration and residence time of summer rainfall in the soil zone will vary widely and the assumption of total equilibration throughout this zone will not always hold.

A number of different combinations of S_0 and RC have been evaluated, using meteorological data for each of the three sites under consideration and the average TU in British rainfall decayed to the appropriate date. The computation was started in September 1960 with the initial T_s in the soil moisture store set at 160 TU before decay. The revised model produces very much larger tritium inputs in infiltration (Table II, (C)] because some of the tritium in summer rainfall, which possesses the highest TU each year (Fig.4), is retained in the soil moisture and enters infiltration in the subsequent autumn—winter. The store acts as a buffer, and the fluctuations of TU in the soil moisture, and therefore in infiltration, are much more subdued and lag behind the widely-varying concentrations in rainfall (Fig.7). The increased autumn inputs (when T_s is greater than T_R) tend to be partially counteracted by reduced inputs in spring (when T_s is less than T_R), but once a high TU has built up in the store a long time is required for it to dissipate. The behaviour of the store thus also explains the fact that the TU at shallow depth in pore-water profiles is commonly observed to be higher than the TU in the winter rainfall of the immediately preceding years.

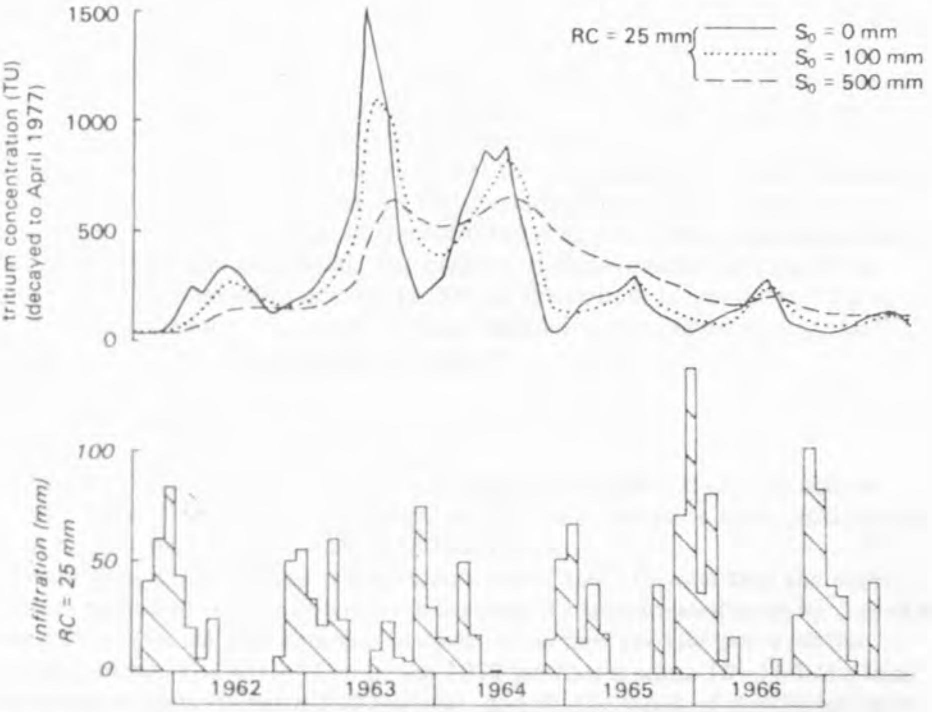

Fig.7. The effect of soil moisture mixing on tritium concentration in infiltration (Norfolk sites). The TUm input is the production infiltration is the product of tritium concentration and infiltration.

INTERPRETATION OF TRITIUM PROFILES

The combination of S_0 and RC selected to model a given Chalk site must be capable of producing the time distribution of TU and TUm in infiltration apparently implied by its tritium profiles (after allowing for the effects of radioactive decay and of minor vertical diffusion) and, in particular, account for the magnitude and width of the main tritium peak.

In general terms, the larger the S_0, the greater is the total TUm in infiltration but the less peaked is the distribution of TU with time. However, the timing of the last infiltration in 1962—1963 and the first in 1963—1964 (Fig.7) is the critical factor in determining which model produces the highest peak TU in infiltration [Table II, (*B*) and (*C*)]. In the presence of a soil moisture store, the effect of variation in RC is also not straightforward, because it influences not only the timing and magnitude of autumn infiltration but also the size of the summer soil moisture deficits.

The uncertainty about the distribution of TUm in rainfall, especially during 1962—1964, preclude the confident selection of a single combination of S_0 and RC as the best-fit model for any given site. The significant difference in the original mass balance anomaly between Dorset and Berkshire or Norfolk is, in all probability, essentially a reflection of differing degrees of departure of the actual TU in rainfall from the "average" British value. On the balance of the available data, the most appropriate model for all sites would appear to have an S_0 of 100—300 mm and RC of 25—50 mm.

Adoption of such a model implies that the TUm observed in the Chalk pore-water profiles down to the base of the thermonuclear tritium peak may represent a smaller proportion of the total input in post-1962 infiltration than has been previously estimated. The balance of the available data could be interpreted as suggesting that up to 20% of the *tritium* is transported by a preferential (more-rapid) flow of water, involving some type of "by-pass" of the slow route of downward movement.

Temporal changes in profiles

Reliable interpretation of tritium in the Chalk unsaturated zone also requires study of the temporal changes in profiles at the same sites, particularly with respect to the movement of tritium peaks.

Redrilling and sampling at the Dorset site in 1977 showed that the main tritium peak had moved downwards through the unsaturated zone by 3.5—4.0 m since 1970 (Fig.8), but detailed analysis of the new profiles poses certain complications. The total TUm in the 1977 profiles is some 10—15% *less* than the appropriately decayed 1970 profile, despite the input of significant quantities of tritium during the period 1970—1977. In the case of the original (lower) site, groundwater levels in recent years have occasionally risen above 10 m b.g.l. (below ground level) and could have washed some tritium out of the unsaturated zone profile but this *certainly* could not have occurred at the adjacent upper site, where, because of the higher elevation, groundwater levels have never risen above 15 m b.g.l. During September 1970—July 1977 the infiltration in the area is estimated to be 2780—3130 mm (depending on the root constant employed). If an apparent piston displacement of the tritium peak was occurring as a result of *all* infiltration, the peak would have been expected to move down by 6.5—7.3 m; the observed movement was *less than* 60% of that expected. The proportion of infiltration associated with the slow mode of downward movement* (by whatever physicochemical process) is thus further questioned.

In the analysis of the Berkshire profile, Smith et al. (1970) interpreted the proportion of the total TUm that had penetrated in advance of the main peaks to depths of more than 12 m as being a measure of the component of preferential rapid fissure movement. This approach is questionable since it is

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*It would be valuable if unsaturated zone pore-water chemical profiles (perhaps Cl or Na) beneath untreated non-agricultural land could be used for a complementary analysis of this proportion, but sensitivity of this method to small errors in the estimation of mean solute concentration in rainfall appear to preclude its confident application.

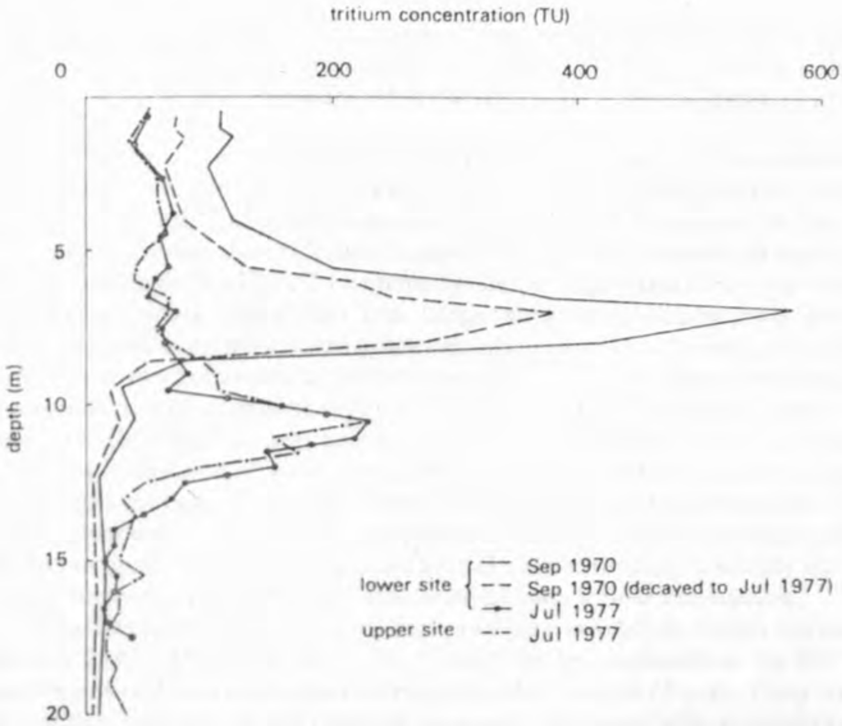

Fig.8. Temporal variation of tritium profiles in Dorset.

highly probable that some part of any rapid component will have passed down fissures not intersected by the investigation borehole and/or have reached the water table.

Probable physical mechanism for by-pass flow

Foster (1975) showed that the effectiveness of the Chalk matrix in retarding the rate of downward movement of tritium and other solutes in water-filled fissures would decrease with increasing fissure aperture, due to the larger fluid volumes involved and the faster rate of fluid movement, which would make lateral molecular diffusion less effective. However, except at very low suctions, fissures of larger aperture would remain air-filled and not be conductive.

Scotter (1978) has demonstrated that very rapid preferential movement of solutes in soils can be expected to occur in cracks and pores with a characteristic size exceeding 0.1—0.2 mm but that such voids would only conduct water in near-saturated soil (i.e. at negative potentials (water suctions) of less than about 0.2 m). It is likely, therefore, that the slow mode of downward tritium movement is associated with water transport in the microfissures and largest pores of the Chalk, whose characteristic size are in the range 0.01—0.2 mm. Such voids are unlikely to represent more than 1% of the Chalk by volume and probably produce a saturated vertical hydraulic conductivity of up to 10^{-2} m/day.

After the most intense rainfall, the infiltration capacity of this system is likely to be exceeded, suctions will fall concomitantly and positive potentials will develop locally allowing horizontal groundwater movement to the macrofissures (of greater than 0.2 mm in aperture). The distribution of macrofissures in shallow Chalk is difficult to quantify, but in many areas they are likely to occur at a spacing of less than 1 m. Larger structures, such as pipes, although of widespread occurrence, are much less abundant. Unsaturated groundwater flow in the macrofissures is probably too rapid to allow significant lateral molecular diffusion of tritium into the Chalk matrix. Temporal variation in operative flow mechanism, according to rainfall intensity, will cause wide variation in the rate of water-table response to infiltration. Apparent rates of downward movement well in excess of 20 m/day have been recorded. The bacteriological contamination of groundwater supplies, which not infrequently occurs in areas of thick Chalk unsaturated zone after high-intensity excess rainfall, is further evidence for the existence of such a flow mechanism.

Variation in the proportion of high-intensity rainfall in Dorset between the periods 1962—1970 and 1970—1977 might be the explanation for the slower movement of the tritium peak during the latter period (Fig.8). (Any analysis of rainfall intensity in this context, however, is unavoidably subjective; spatial variation in the macrofissuring and temporal variation in antecedent meteorological conditions combine to preclude the choice of any specific rainfall intensity above which rapid by-pass flow will occur.) Another cause could be that physical properties (fissure aperture and frequency) change with depth.

The presence of a preferential rapid component of downward flow dependent on the intensity of excess rainfall would have significant implications for the interpretation of the behaviour of other solutes in the unsaturated zone. The availability of ions for leaching from agricultural soils varies with time, maximum concentrations being likely to occur in the first autumn drainage, and also in any drainage in late spring. During the main winter period, when the probability of high-intensity *excess* rainfall is greatest, the concentration of agricultural leachates is likely to be relatively low. This factor could be of considerable significance in the overall interpretation of the Chalk groundwater nitrate problem.

CONCLUSIONS

(1) The introduction of a more realistic conceptual model of the behaviour of tritium in the soil fully accounts for the large amounts of thermonuclear tritium in the Chalk unsaturated zone.

(2) At any given location, uncertainties over the limiting size of the soil store in the new model and over the TUm in rainfall during 1962—1964 com-

bine to exclude an adequate evaluation of the mass balance for tritium pore-water profiles.

(3) Individual profiles cannot be interpreted with sufficient precision to question or to qualify the standard hydrometeorological models for the calculation of excess rainfall.

(4) The TUm recovered in the pore-water profiles probably represent a smaller proportion of the total TUm input from infiltration than was previously believed. An important component of preferential rapid downward movement of tritium (and other solutes) could occur by some by-pass mechanism associated with macrofissures that only conduct water in response to high intensity excess rainfall. It is in the evaluation of these unsaturated zone processes that Chalk pore-water tritium profiling finds its most valuable application.

(5) Long-term investigation of the temporal changes in pore-water tritium profiles at individual sites will be required before unsaturated zone models to predict solute movement can be adequately calibrated.

ACKNOWLEDGEMENTS

This paper is published by permission of the Director of the Institute of Geological Sciences. The following colleagues are thanked for their assistance and interest: Lionel Bridge, Alan Cripps, John Barker and Michael Price.

Financial support from the Department of the Environment and the Natural Environment Research Council are gratefully acknowledged, as are the work of A.E.R.E. Harwell Laboratory in performing the tritium determinations and of the Meteorological Office in providing processed data.

The authors had valuable discussions with J.H. Bell (Institute of Hydrology), R.A. Otlet (A.E.R.E. Harwell Laboratory), H.J. Richards (Central Water Planning Unit) and D.B. Smith (Natural Environment Research Council). L.A. Greene (Anglian Water Authority) assisted in the promotion of the field work.

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The Institution of Civil Engineers

PROCEEDINGS

June 1980
Volume 69

Research and Theory

Proc. Instn Civ. Engrs, Part 2, 1980, **69**, June, 281–293.

8316 The pollution hazard to village water supplies in eastern Botswana

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Concern about groundwater pollution has been aroused by observations in many village water supply boreholes of nitrate concentrations far in excess of recommended limits. A hydrogeological and hydrochemical study in the environs of a selected borehole, aimed at evaluating the causes and mechanisms of pollution, is described. Pit latrines are shown to cause a major build-up of nitrogeneous material in the surrounding soil and weathered rock, from which nitrate is leached intermittently by infiltrating rainfall. Moreover such installations can also present a risk of groundwater pollution by faecal bacteria. The study illustrates the need for integrated planning, based on a sound appreciation of local hydrogeological conditions, when developing low-cost village water supplies and sanitation, if serious new public health hazards are to be avoided.

Introduction

Water supply situation in eastern Botswana villages

During the past few decades there has been a steady improvement in public health throughout eastern Botswana, effected by the drilling of water-supply boreholes,[1] the introduction of low-cost sanitation and the elimination of the use of surface watercourses. Similar conditions exist in the rural population centres of many developing countries, and are the target of the United Nations' development programmes for the 1980s.[2]

2. Groundwater is normally the safest source of untreated potable water in developing countries, but regular monitoring of chemical and bacteriological quality at individual water-supply boreholes is frequently beyond the capacity of local professional and financial resources.

3. Recently many important villages in eastern Botswana were found to have polluted groundwater. A sampling and analytical programme[3] showed the nitrate concentrations in most public water-supply boreholes within urban limits to exceed World Health Organisation drinking water standards: below 100 mg NO_3/l preferable and above 200 mg NO_3/l unacceptable. In certain instances concentrations were grossly in excess of these levels. The problem has been shown to be persistent and widespread.

4. The potential health implication for infants of ingesting excessive nitrate

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Written discussion closes 15 August, 1980, for publication in *Proceedings*, Part 2.

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concentrations in drinking water has been a topic of continuing medical attention[4–9] and the possible effects on adults of high nitrate intakes over long periods is a subject of growing medical concern.[10] The presence of high groundwater nitrate concentrations, if derived from organic sources, may be associated with intermittent bacterial pollution and would normally warrant careful monitoring.

Geohydrological setting of eastern Botswana

5. Over most of eastern Botswana the Kalahari sand cover, which mantles the remainder of the country, has been removed by erosion and pre-Cambrian basement formations exposed. Minor aquifers are developed in the weathered zone and/or in the underlying fractured/jointed bedrock. Groundwater movement takes place almost exclusively through any open fissures, which may be sparse because of infilling by clayey weathering products. Groundwater levels are usually relatively shallow (less than 30 m), aquifer transmissivities low (less than 50 m^2/d) and borehole yields small (less than 2 l/s), but with deep cones of pumping depression.

6. Eastern Botswana has an average rainfall of about 500 mm/a and, with thin, albeit clayey, soils and frequent bedrock exposures, diffuse groundwater recharge occurs fairly regularly in most wet seasons (November–March). The region is hilly and there is substantial runoff in (locally influent) ephemeral streams. There are few perennial streams, fed by groundwater discharge.

7. In most areas the chemical quality of unpolluted groundwater is good and the total dissolved solids and chloride concentrations are relatively low.

Scope of research

Methods of investigation and objectives

8. The study was aimed at establishing the causes and mechanisms of pollution of village water-supply boreholes, and at considering possible remedial action. It involved a detailed evaluation of the factors controlling water and pollutant movement in the unsaturated and saturated zones around a selected water-supply borehole.

9. Three investigation/observation boreholes, at 15-25 m radius from the water-supply borehole (Fig. 1), were drilled to about 10 m below the water-table using power augering and air-flush cored rotary or hammer percussion techniques. They were lined with perforated plastic casing and developed by pumping until their discharge cleared. Soil samples were collected at every 0·5 m. A series of auger holes for sampling the soil and weathered rock was also drilled.

10. The main methods of investigation were

(*a*) test pumping of the water-supply borehole, using the existing plant, at a constant rate of 1 l/s, groundwater levels being measured and electrical conductivity/temperature logs run
(*b*) chemical and bacteriological analyses of water samples collected from the saturated zone
(*c*) nitrate and chloride analyses on soil samples
(*d*) chemical tracer experiments.

The timing of the investigations is shown in Fig. 2; most of the analytical work was performed in a field laboratory.

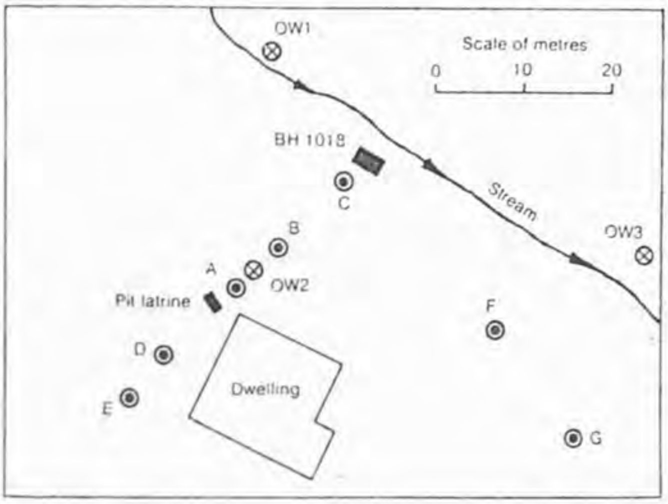

Fig. 1. Detailed site plan

Groundwater conditions in study area

11. Borehole BH 1018 (Fig. 3) was in a major village with a population of about 20000, had a nitrate concentration of more than 500 mg/l and, until 1977, was the primary source of water for a nearby hospital.

12. The study area is in an embayment of an escarpment (Fig. 4) of Waterberg sandstone and shales and is underlain by talus and weathered Basement Complex granite gneisses. Soils are dark, clayey, 0–3 m thick and grade downwards into weathered rock. The area is transected by a stream which rises in the Waterberg hills and is impounded by a small dam about 150 m upstream of BH 1018. The stream is gaining in its upper reaches, base flow being maintained for some of the year, but in the study area it apparently becomes losing.

13. Pumping test analysis shows the weathered granitic aquifer to have a transmissivity of only 15–20 m^2/d with a storage coefficient of up to 0·01. Some natural or induced recharge from the adjacent stream is present but its proportion must be minor or intermittent because it could not be detected as a boundary in the pumping test.

14. The direction of regional groundwater flow is away from the escarpment, in common with that of the surface drainage, but because of the low aquifer transmissivity is of only small magnitude. The hydraulic conditions and low pumping rate will limit the flow frontage intercepted by BH 1018 to within 100 m of the borehole.

15. A survey of potential pollution sources within a 100 m radius of BH 1018 was made. About one in four households has a pit latrine (a popular and growing form of low-cost sanitation in Botswana), which is normally shared.

16. The area surveyed had 30 pit latrines used by about 200 people. The nearest pit latrine to BH 1018 was 25 m distant (Fig. 1), hand-dug to about 2·5 m deep and floored by weathered bedrock with the local water-table 3·0 m

below its base. It was constructed before the water-supply borehole. Additionally, although outside the 100 m radius of BH 1018, there are about 300 people at the hospital, some of the effluent of which enters the reservoir impounded by the dam; this reservoir overflows into the stream which flows past BH 1018.

Groundwater quality in saturated zone

Hydrochemical

17. The electrical conductivity logs showed the presence of groundwater stratification in observation boreholes OW1 and OW2, with abrupt increases from about $800\ \mu\Omega^{-1}$ to more than $2000\ \mu\Omega^{-1}$ at 6 m and 8 m depth respectively. The groundwater in OW3 had a uniform conductivity of $800\ \mu\Omega^{-1}$. On pumping, the lower conductivity water was depleted and the stratification quickly disappeared. Various pumped and depth samples were collected for full chemical analyses. These analyses (Table 1) confirmed the observation (Fig. 5) and showed the deeper, higher conductivity, layer to be comparable chemically

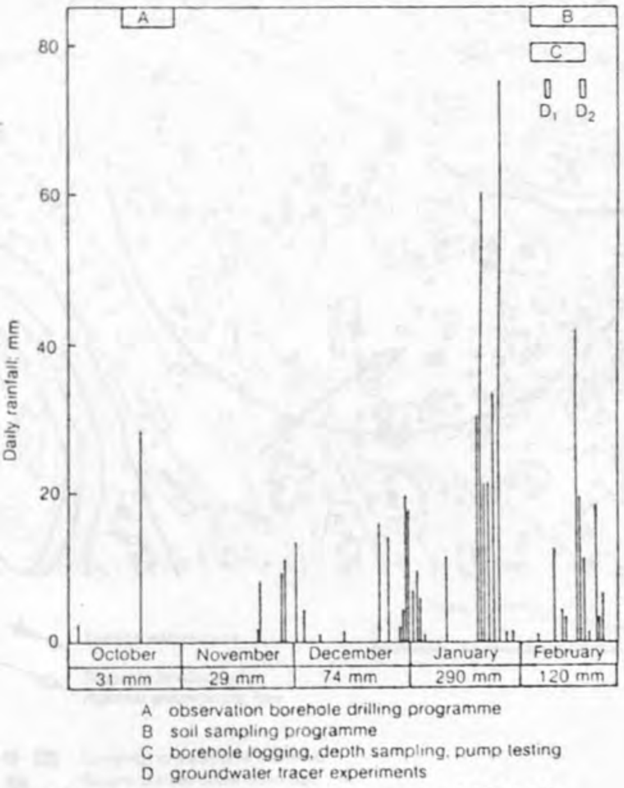

Fig. 2. Timing of field investigations during wet season of 1977–78

Fig. 3. General plan of study area

Fig. 4. Settlement pattern in study area

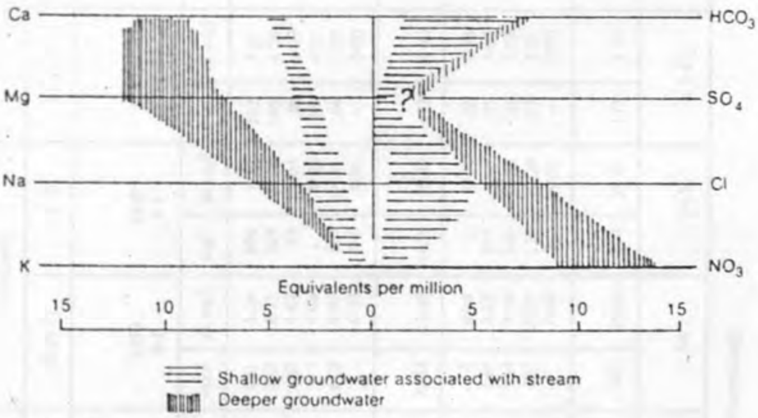

Fig. 5. Stiff diagram summarizing groundwater chemistry

Table 1. Full chemical analyses of groundwater samples

Sample (depth)	BH 1018 (pumped)				Stream (surface)				OW1 (4 m)		OW1 (10 m)		OW2 (6 m)		OW2 (10 m)		OW2 (22 m)		OW3 (6 m)	
Date	21.10.77		3.2.78		21.10.77		3.2.78		2.2.78		2.2.78		2.2.78		2.2.78		2.2.78		2.2.78	
Electrical conductivity,	2450		2800		1085		335		880		2340		1070		2550		2350		960	
pH	8·1		6·5		8·0		8·1		7·3		7·0		7·4		6·3		6·5		7·5	
Units	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l
HCO_3	321	5·26	396	6·49	222	3·63	105	1·72	491	8·05	500	8·20	172	2·82	222	3·64	340	5·57	78	1·28
Cl	238	6·73	294	8·29	145	4·08	35	0·99	35	0·99	190	5·36	177	4·99	276	7·79	278	7·84	100	2·82
SO_4	80	1·67	93	1·94	38	0·80	28	0·58	26	0·54	—	—	—	—	81	1·69	—	—	22	0·46
F	0·7	0·04	*	0·00	0·6	0·03	*	0·00	*	0·00	*	0·00	*	0·00	*	0·00	*	0·00	*	0·00
NO_3	614	9·90	874	14·11	16	0·26	39	0·64	51	0·83	568	9·16	37	0·60	600	9·78	680	10·97	284	4·63
NO_2	*	0·00	0·6	0·01	*	0·00	0·5	0·01	*	0·00	0·2	0·00	61	1·33	15·0	0·33	7·6	0·17	0·1	0·02
Sum of anions	1254	23·60	1658	30·84	422	8·80	207	3·94	603	10·41	—	—	—	—	1194	23·23	—	—	484	9·21
K	2	0·04	2	0·04	22	0·55	17	0·44	36	0·92	34	0·87	20	0·51	7	0·18	8	0·21	4	0·10
Na	144	6·28	102	4·44	85	3·68	19	0·83	26	1·13	99	4·31	77	3·35	91	3·96	101	4·39	39	1·70
Ca	174	8·69	240	11·98	41	2·06	30	1·50	100	4·99	180	8·98	80	3·99	230	11·48	230	11·48	90	4·49
Mg	122	10·03	150	12·34	25	2·09	12	0·99	44	3·62	88	7·24	28	2·30	100	8·23	100	8·23	28	2·30
NH_4	*	0·00	0·1	0·01	*	0·00	0·3	0·01	0·1	0·01	0·1	0·01	3	0·17	*	0·00	0·1	0·01	*	0·00
Sum of cations	442	25·04	494	28·81	173	8·38	78	3·77	206	10·67	401	21·41	208	10·32	428	23·85	439	24·32	161	8·59
Ionic balance	−3·0%		+3·4%		+2·4%		+2·2%		−1·2%		—		—		−1·3%		—		+3·5%	

* Not determined.

with the water supply from BH 1018, and the lower conductivity layer to resemble stream water in certain respects. The latter similarity must reflect the presence of influent seepage from the stream, but the fact that lower conductivity groundwater was rapidly depleted suggests that the seepage must be small and perhaps intermittent.

18. The deeper layer appears to be representative of groundwater in the general area. It is heavily polluted with nitrate (invariably exceeding 500 mg/l) and also has high chloride, sodium, calcium and magnesium concentrations. The samples from borehole OW2, which was adjacent to the pit latrine, also contain high concentrations of nitrite and some ammonium.

19. In the nitrate-rich groundwater, the increased calcium and magnesium content is not balanced by a proportionate increase in bicarbonate, but more likely by nitrate itself. This is probably due to nitrate being leached from the soil-weathered rock in an acidic form, and hence dissolving some of the carbonate present. There is a good correlation (a coefficient of 0·92) between excess Ca + Mg ($-HCO_3$) and NO_3 when they are expressed as equivalents; analyses of samples pumped from other water-supply boreholes in the same village were used when this hypothesis was tested.

Bacteriological

20. Samples were collected from the water-supply borehole and from the observation boreholes for bacteriological examination; taps and a depth sampler were sterilized by flaming in methanol before sampling. Total and faecal coliform counts were made on each sample in the field laboratory using a standard membrane filter technique.

21. *Escherichia coli* occur in enormous numbers in the excreta of man and animals and their presence in water is indicative of recent faecal pollution. However, they cannot be used as a quantitative measure of faecal pollution nor of the presence of pathogenic micro-organisms. The philosophy is that if faecal contamination of water is present, then pathogens may also be present. Other coliform organisms are more widely distributed in nature and may gain access to water from non-faecal sources, e.g. soils and plants.

22. The bacteriological tests (Table 2) showed gross faecal pollution in observation boreholes OW1 and OW2; there were lower *Escherichia coli* counts in BH 1018 and OW3. Nevertheless, the water supply from the former would be classified as suspicious to unsatisfactory because the sampling was very limited.

Table 2. Bacteriological tests on groundwater samples

Sample (depth)	BH 1018 (pumped)		OW1 (10 m)	OW2 (pumped)	OW2 (6 m)	OW2 (10 m)	OW3 (pumped)
Date	26.10.77	10.2.78	3.2.78	26.10.77	3.2.78	3.2.78	26.10.77
Escherichia coli/100 ml	9	1	200	13	350	80	2
Total coliforms/ 100 ml	*	127	500	*	1000	500	*

* Not determined.

There had been little previous bacteriological examination of village borehole water supplies in Botswana. Regular measurements or routine monitoring, especially during and after heavy rainfall, are required to establish the extent and regime of bacteriological pollution at any given site.

23. Since the work described here was done, a preliminary study of the pollution of borehole water supplies by faecal bacteria has been carried out in the same village; the results are alarming.[11] Gross faecal pollution has been found to be general, frequently pathogenic species have been identified and, in certain instances, these appear to be strains which are resistant to many common antibiotics.

Contamination of soil and unsaturated zone

24. The mobile field laboratory was equipped with a refrigerated centrifuge with special bucket liner assemblies for extracting pore fluid from geological samples. It was used in the determination of the nitrate and chloride content of soil and weathered rock. A modification to the normal centrifuge method[12] incorporating an elutriator was developed because low soil moistures did not generally permit the recovery of sufficient pore fluid. Known small volumes (15–20 ml) of deionized water were added to soil samples (of about 150 gm) after they had been packed in the centrifuge liners; recovery of the elutriate was 30–80%. Experimental recovery of solutes which were added artificially to samples suggests that the error introduced by this method of sample handling does not exceed ±20%.

25. The samples of elutriate were stoppered and refrigerated until they were analysed in batches for chloride and nitrate by argentiometric microtitration and the colorimetric sodium salicylate method respectively. The results were expressed in terms of milligrams of leachable ion per kilogram of moist sample (ppm by weight). The soil NO_3-N content determined may include other nitrogen species present in the soil and oxidized by the elutriation/centrifugation technique; this possibility is considered in the interpretation of the results.

26. The locations of the seven auger holes A–G used for soil sampling are shown in Fig. 1; four additional auger holes H–K were drilled in and outside the village at sites remote from all potential pollution sources to determine background concentrations. High concentrations of NO_3-N and Cl (10–2000 and 10–400 ppm respectively) were found in the soil samples from auger holes A–E, which were drilled close to the pit latrine, whereas the samples from auger holes F and G, which were about 40 m distant, recorded only background concentrations (2 ppm NO_3-N and 4 ppm Cl). The highest NO_3-N and Cl concentrations were in general immediately above the rock head (Fig. 6); the higher concentrations found around auger hole E are probably due to preferential drainage.

27. Nitrate is a stable ion; it is generated from oxidizable forms of nitrogen by infiltrating rain-water and leached from soils during the wet season. Assuming a field bulk density of 1·3, the total mass of readily oxidizable nitrogen in a column of soil reaching from the surface to the rock head for the sites in the immediate vicinity of the pit latrine (auger holes A–E) has been calculated to be 0·1–0·5 kg N/m^2. This shows that the contaminated soil zone, which extends at least 15 m either side of the pit latrine, represents a major source of nitrate contamination to groundwater supplies.

28. The nitrogen content of human excreta is believed to be about 5 kg/man per year; thus the total nitrogen discharged to the soil within 100 m radius of

water-supply borehole BH 1018 (discounting the hospital further upstream) would be 1000 kg N/year. Assuming a mean nitrate content of 600 mg/l for this borehole and that, when in use it operated throughout the year for five hours a days at 1 l/s, the discharge would represent about 900 kg NO_3-N/year.

Groundwater tracer experiments

Unsaturated zone

29. The transit time between the pit latrine and the adjacent observation borehole (OW2) was measured by the injection of 20 l of lithium chloride solution (approximately 2500 mg Li/l) into the pit latrine during the pumping test in February 1978. After injection, samples were collected regularly from the observation borehole throughout the subsequent 20 hour period. Lithium was chosen because it is a safe, mobile ion, and its background level of occurrence is very low.

30. The first sample collected from borehole OW2 had a concentration of lithium of more than five times the background level (Fig. 7). Subsequent samples showed a steady decrease in lithium concentration and after about nine hours the concentration was at its normal level. Most of the tracer thus reached the water-table in less than 25 minutes; as the bedrock between the pit latrine and borehole OW2 (Fig. 6) was fissured, recharge took place rapidly. The experiment thus demonstrated the high risk of faecal bacterial contamination of groundwater via pit latrines.

Saturated zone

31. The transit time between boreholes OW2 and BH 1018 was determined by the injection of 2 l of the concentrated lithium chloride solution and monitoring appearance of the tracer by frequent sampling (Fig. 7). During the first 200 minutes the lithium concentration in the discharge from BH 1018 remained

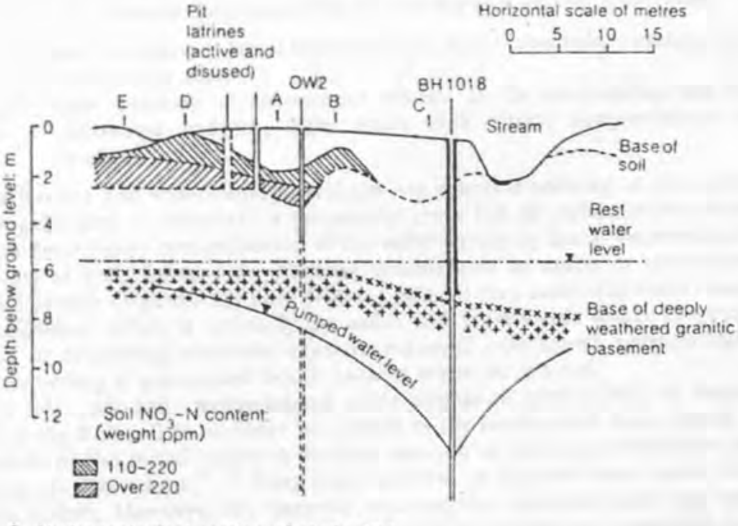

Fig. 6. Hydrogeological section of study area

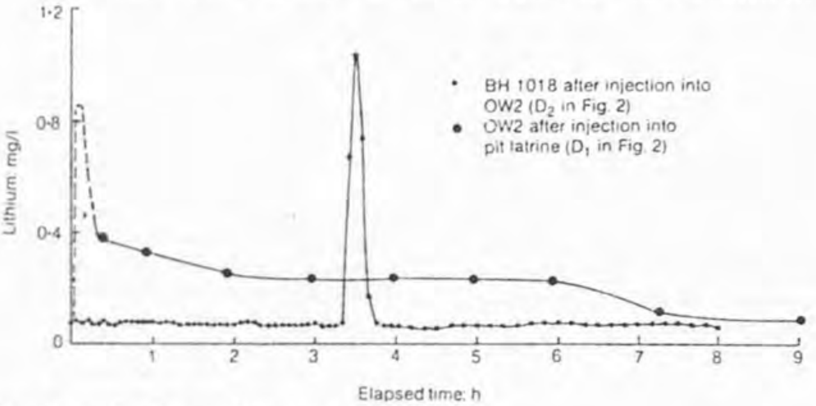

Fig. 7. Results of groundwater tracer experiments

at 0·08 mg/l; it peaked at 1·05 mg/l in the sample collected after 210 minutes and dropped to 0·08 mg/l again after 230 minutes. A sample taken from the observation borehole after completion of the test showed that there was still a plentiful supply of lithium in the water at depth, suggesting that the flow of the tracer out of the borehole had occurred only at isolated fissure-flow horizons. The total transit time from the pit latrine to the water-supply borehole was thus less than 235 minutes: a further demonstration of the pollution hazard involved.

Conclusions

32. The study clearly establishes the serious groundwater pollution hazard represented by pit latrines in hydrogeological environments such as those widely encountered in eastern Botswana. This hazard has two distinct components

(*a*) rapid transport of faecal bacteria to the water-table before natural elimination can occur
(*b*) major build-up of nitrogenous effluent in the surrounding soil and weathered bedrock, from which high nitrate concentrations are leached.

If pit latrines and water-supply boreholes are closely associated in this type of hydrogeological environment a potentially grave risk to public health results. Intermittent heavy contamination of the water-supply by faecal bacteria can be anticipated and nitrate concentrations considerably in excess of the absolute World Health Organisation limit (100 mg NO_3/l) may occur. For these reasons groundwater, which is normally the safest and most viable source of potable water in developing countries, must be managed with sound hydrogeological understanding if serious new health hazards are to be avoided.

33. All soils and unconsolidated strata appear to remove 90% of bacteria within the first 1–2 m of water movement in the unsaturated zone, almost regardless of the initial bacterial loading, because of mechanical filtration and biological elimination.[13–15] They thus represent an effective waste water treatment system. However, any bacteria reaching the saturated zone may move substantial distances down any hydraulic gradient, normally in a thin sheet close

to the water-table.[16–18] As viruses are smaller than bacteria, it is generally believed that those strains that can resist changes in environment may be more persistent and mobile in groundwater systems.[18–20]

34. In bedrock fissure-flow formations, bacteria and viruses can be especially mobile.[21] A serious outbreak of infectious hepatitis in a small town in the USA has been attributed to rather similar conditions to those described in this Paper.[22] Even in low-transmissivity basement aquifers like those in eastern Botswana, in which natural mass movement is very slow, relatively rapid groundwater flow without significant bacterial filtration may take place at certain horizons over radial distances of at least 25 m and up to perhaps 100 m, given the steep hydraulic gradients imposed during pumping. In the absence of hydrogeological data, it has been recommended that the distance between a properly-constructed shallow well and a pit latrine founded in deep soil should be at least 30 m.[18,23]

35. There are many small—mostly ephemeral—streams in villages in eastern Botswana. They normally generate some influent seepage, because frequently they flow directly on weathered bedrock, and when they pass close to water-supply boreholes they represent an additional bacterial and chemical pollution hazard; however, they are unlikely to have high nitrate concentrations. In general it is inadvisable to site new water-supply boreholes close to such watercourses.

36. The most realistic long-term solution is the progressive relocation of public water-supply boreholes in unpopulated areas with reticulation to standpipes in the villages and chlorination of any remaining doubtful sources. Such a policy is now gradually being implemented in eastern Botswana. However, it must be recognized that small-scale chlorinators are unlikely always to operate effectively in developing countries. Source protection must, therefore, form the primary counter-pollution measure. Pollution protection areas should be established, as a priority, around all new water-supply boreholes.

37. To eliminate direct pollution an area of at least 5 m radius around boreholes should be fenced to exclude people and animals from entering and paved so as to direct surface drainage away from the borehole. Solid lining tubes should be effectively grouted at the surface and taken to a depth below the zone of seasonal water-table fluctuation.

38. To reduce pollution via the aquifer certain restrictions should be enforced over a much larger area; these include a ban on the construction of pit latrines, septic tanks and so on (and, therefore, effectively on habitation), the storage of chemicals and oil, and the location of livestock pens. The size of this area should be dictated by local groundwater conditions (e.g. aquifer transmissivity, hydraulic gradient, groundwater flow regime, the presence of any confining strata and thickness of the soil and unsaturated zone). However, in practice adequate hydrogeological data and expertise may not always be available. Although far from ideal, it is considered that the pollution hazard would be greatly reduced in the groundwater conditions normally encountered in eastern Botswana by the establishment of pollution protection zones of 200 m radius around each water-supply borehole.

Acknowledgements

39. The study was financed from the funds of an Anglo-Botswana technical co-operation project. This Paper is published by permission of the Directors of

the Institute of Geological Sciences in London and the Geological Survey Department, Botswana.

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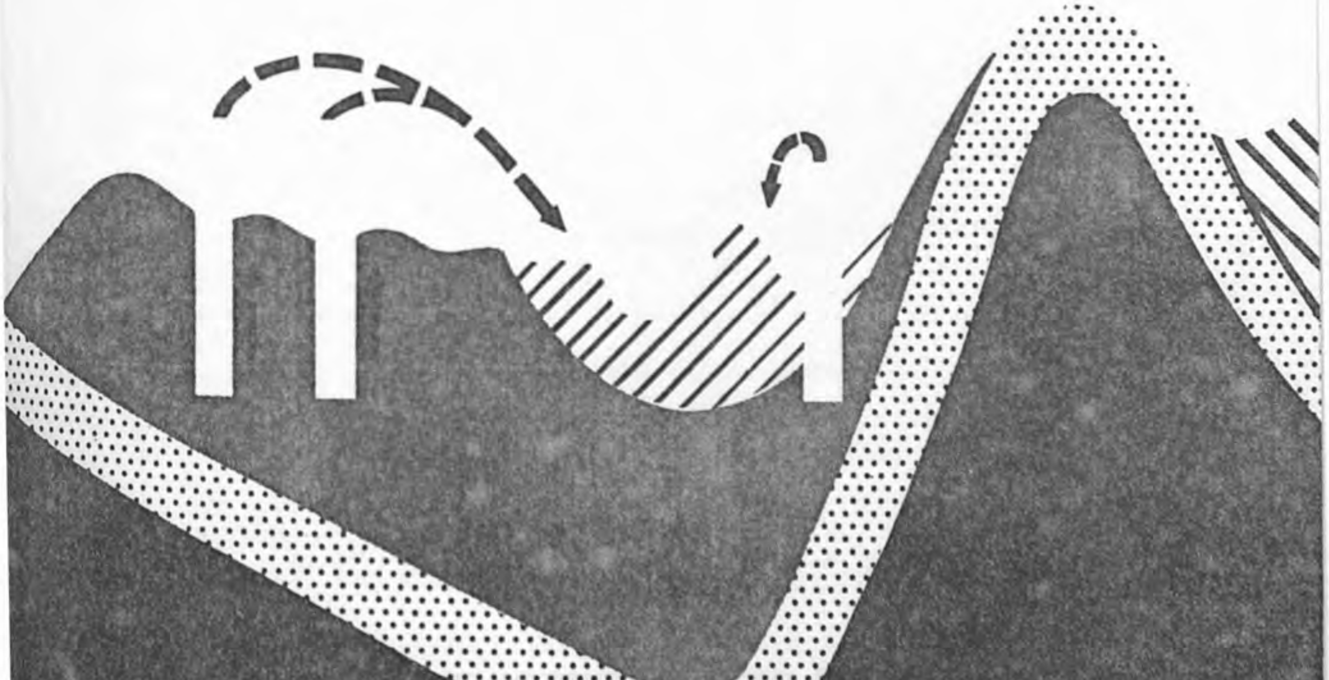
WATER RESOURCES a changing strategy?



WATER RESOURCES

a changing strategy?

Proceedings of the Conference held in London
2–5 October 1979

THE INSTITUTION OF CIVIL ENGINEERS
LONDON 1980

Water resources have a vital role to play in national development. Engineers, however, are faced with a wide range of problems in selecting water resources and timing their introduction and in their management. These problems arise from the uncertainties of forecasting demand, from the problem involved in determining the reliability of water resources and from the constraints posed by social, economic, environmental and health factors.

The papers and discussions contained in this book examine how these problems are being resolved and whether strategies of water resource developments are being changed to overcome them in the developed and developing countries.

ISBN: 0 7277 0097 9

Contents

The role of water resources in national development

Assessment of need for water resource development

Water resource development—Part A

Water resource development—Part B

Operational aspects of water resources

Water quality and environmental aspects

Financing water resource development

S.S.D. FOSTER *(Institute of Geological Sciences)* I wish to comment primarily on Papers 9 and 11, in relation to which I wish to amplify certain points on the subject of regional groundwater resources development, but as a groundwater specialist I am repeatedly confronted with a scarcity of basic data and am thus concerned to some degree with Paper 8 also.

From the outset I consider it worthwhile to define what we mean by a regional (or major) aquifer system and would be interested to learn the Authors' opinions. Do we draw the line at systems having mean transmissity in excess of 50 (or perhaps 100) m^2/d and hydraulic continuity over more than 50 or 100 km^2?

Now aquifers with lower transmissivities and of more limited extension would be classed as local or minor; nevertheless, on a world-wide basis and taken collectively, they should continue to be of great importance as a (direct) source of water-supply, both for human consumption and animal watering. However our strategy towards them is I think, in most cases, unlikely to change radically - though more effort must go into source pollution protection and groundwater quality conservation, and some rationalization of abstraction may be desirable in certain instances.

In relation now to the major groundwater systems, those benefitting most from a regional or basinwide approach to resource development, a vital prerequisite is a clear understanding of the exploitable storage, as Mr Rofe has clearly reminded us (Paper 9, paragraph 10). At the same time it must be recognized that the determination or estimation of the storage coefficient pertinent to a particular set of operational conditions (groundwater levels etc) is probably the most important, yet thorny, problem in practical groundwater science. This applies to all aquifer types, with the possible exception of karstic limestones and some basaltic formations whose storage resources are normally insignificant when compared to their throughflows. In the overall evaluation of groundwater resources, the problem of storage coefficient selection is often compounded with numerous uncertainties generally associated with the estimation of the long-term average rate of aquifer replenishment.

Although I agree with Mr Rofe that we in Britain must have been amongst the first to gain practical knowledge in the application of new concepts for the combined use of surface and groundwater resources (Paper 9/paragraphs 12 and 17), I do not think we should be too complacent. Recent experience has clearly shown that we had, and probably still have, a lot to learn about groundwater storage in our major aquifers (refs 1, 2 and 3), despite the fact that they have been exploited as a major source of public water supply for more than a century.

Now if we turn our attention away from Britain, we find that hydrogeologists and groundwater engineers are confronted, additionally, with a number of far more immediate problems including

(a) the almost invariable scarcity or poor quality of water-supply borehole records, and in particular the general absence of well-documented operational experience;
(b) reluctance to face the cost and/or the time-delay involved with adequate investigation and research;
(c) the required rates of scheme implementation are not normally compatible with systematic development;
(d) constraints on investigation and development imposed by the limitations of drilling equipment and pumping plant available locally;
(e) inability to sustain, or lack of interest in, routine data collection;
(f) an organizational and legal framework that may prevent the implementation of more effective policies in water resource development and management.

As the Authors of Paper 11 have pointed out (Paragraph 1.4): 'the disadvantages of groundwater development arise mainly from the difficulty of accurately assessing the size of the resource (storage and replenishment) and the possible consequences of over-development'. Bearing this and the above problems in mind, I would strongly advocate the following strategy towards groundwater resources in the developing countries:

(a) new developments should proceed on a clearly structured or staged basis, gathering information for the design of the later stages from those preceding - recognizing that in the groundwater business 'the proof of the pudding is in the pumping;
(b) the size of the initial stage should be decided using computerized mathematical modelling to assess the sensitivity of resource estimates to errors in storage coefficients and recharge rates, including the interaction of realistic worst case values for these and other problematic parameters;
(c) developments should, as far as possible, use locally manufactured or assembled hardware and be designed for simple maintenance;
(d) every effort should be made to make adequate provision for the routine monitoring of pumping rates, groundwater levels/salinity.

All of this will inevitably mean a slowing-down of the rate of development: a change in emphasis from development to management. In advocating this one is normally in a situation of attempting to frustrate the goals of politicians and social planners! But in the groundwater field there is still room for further enlightment of administrators ('client education' as consultants would call it), and if one reckons on the number of abandoned wells and boreholes around the world, I consider this course preferable to the loss of investment - and, perhaps worse, of hope - that will inevitably follow as a result of accidental, uncontrolled, over-abstraction.

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MR S.S.D. FOSTER *(Institute of Geological Sciences)*

Professor Bradley has emphasized the need for ever closer collaboration between the engineering and health professions if the best results of water developments are to be achieved and their associated health hazards minimized.

I would like to illustrate this need in relation to low cost schemes for the improvement of village water supply and sanitation - a most topical subject in view of the recently announced UNDP target for the 1980s and one touched upon by other Authors (Paper 3, para. 16; Paper 12, para 11).

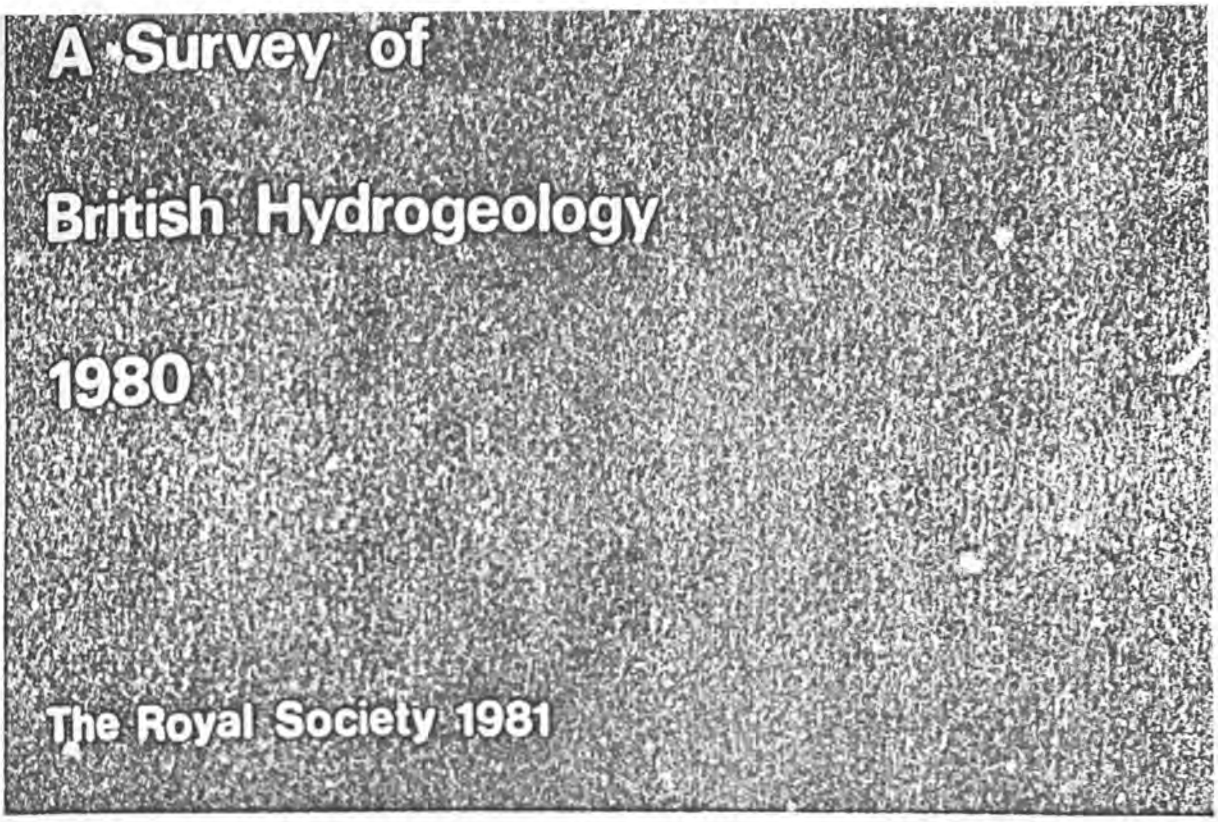
In the 'villages' of eastern Botswana the last two decades have seen steady improvement in public health brought about by, amongst other factors, the progressive construction of water supply boreholes and sanitary installations (generally pit latrines) and consequent elimination of the dependence upon surface watercourses. Recently, however, the nitrate concentrations in public water supply boreholes within the urban limits of many villages has been shown to exceed WHO recommended limits, in certain instances grossly with levels greater than 50 mg NO_3-N/l not being uncommon. In general these boreholes draw small water supplies (less than 2 l/s) from weathered, fissured, bedrock aquifers of low transmissivity (less than 50 m^2/d), whose relatively shallow water tbales (often less than 10 m bgl) are recharged in almost every wet season, as a result of the high intensity rainfall and thin soil cover.

During 1977-78 I directed a detailed research programme to evaluate the mechanisms of ground water pollution, the results of which will be published shortly . It was shown that the close association of pit latrines and water supply boreholes in this type of hydrogeological environment can lead to serious new health hazards, the goundwater pollution having two distinct componenets: (a) a major build up of nitrogeneous effluent in the soils and weathered bedrock surrounding the pit latrines, from which high nitrate concentrations are intermittently leached; and (b) the rapid transportation of fecal bacteria populations to the water table before natural elimination can occur.

The gross bacterial contamination is particularly alarming since groundwater is normally regarded as the safest source of untreated potable water in developing countries. In the instance studied, a transit time from a pit latrine to a water supply borehole, 25 m distant, was demonstrated to be less than 4 hours. I understand that a broader survey has now shown gross fecal pollution of village water supply boreholes to be widespread; pathogenic species having been frequently identified and, in certain instances, these are said to be strains exhibiting resistance to many common antibiotics.

This example illustrates the need for a sound appreciation of local hydrogeological conditions when planning this type of low cost public health orientated water development. It also demonstrates the need of integrated planning of both the water supply and sewage disposal aspects aspects.

In general for eastern Botswana, the most realistic long term solution to the groundwater pollution problem would be the progressive relocation of public water supply boreholes in unpopulated areas, with reticulation to standpipes within the villages themselves. For the type of reasons mentioned in paragraph 14 of the Paper, chlorination cannot be regarded as the primary counter-pollution measure. Source protection areas must be established around all new water supply boreholes to prevent settlement and to ban other potentially polluting activities. The size of these areas ought to be dictated by local groudnwater conditions, but in any event, for most situations in eastern Botswana, they should include at minimum the area within 100 m radius of each borehole.



A Survey of British Hydrogeology 1980

The Royal Society 1981

(12)

47-59 Foster S S D & Young C P
Effects of agricultural land-use on groundwater quality
with special reference to nitrate

also previously published in :

a) Bull BRGM (2:III) 3 : 245-256 (1979, in French)

b) UNESCO-IHP Studies & Reports in Hydrology 30 : II : 268-282
(1980, abridged version with different title)

BULLETIN DU
BUREAU DE
RECHERCHES
GEOLOGIQUES ET
MINIERES
DEUXIEME SERIE

SECTION III
N° 3 - 1979
(245-256)

ISSN 0300-936 X

Hydrogéologie britannique : progrès récents

TRIMESTRIEL

Foster S S D & Young C P

Consequences de l'utilisation agricole des sols sur la qualite de l'eau souterraine et notamment sur sa teneur en nitrate

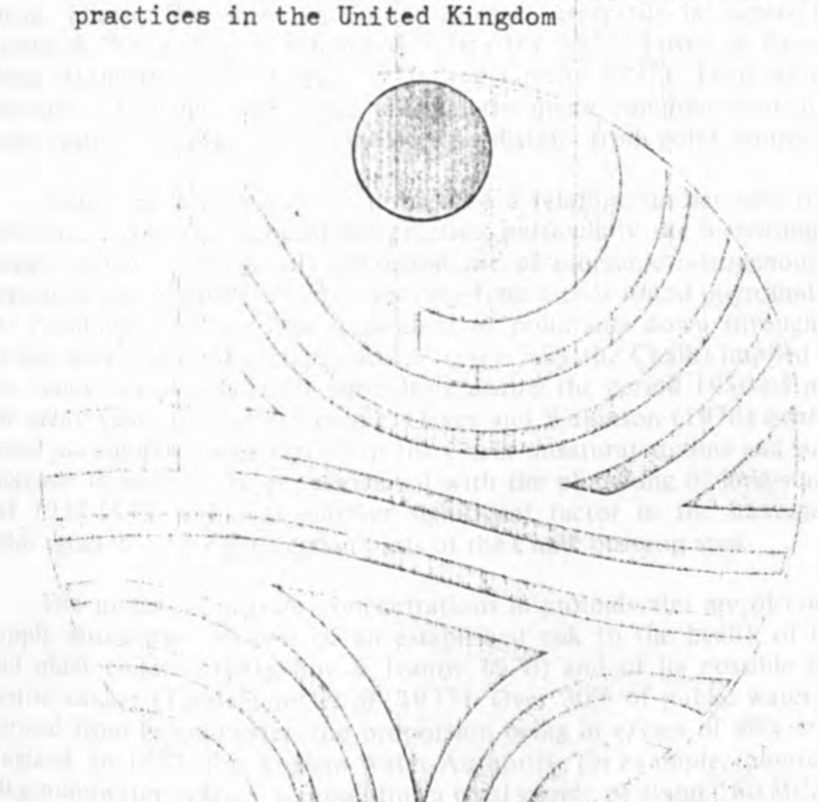
Studies and reports in hydrology 30

Aquifer contamination and protection

Project 8.3 of the
International Hydrological
Programme

Prepared by the
Project Working Group,
R. E. Jackson, Chairman
and General Editor

(268-282) Foster S S D & Young C P
Groundwater contamination due to agricultural land-use
practices in the United Kingdom



unesco (Paris) 1980

EFFECTS OF AGRICULTURAL LAND-USE ON GROUNDWATER QUALITY WITH SPECIAL REFERENCE TO NITRATE

S.S.D. Foster* & C.P. Young**

ABSTRACT

Groundwater provides over 30% of potable water supplies in Britain. It is mainly derived from the Chalk and Triassic Sandstone formations, which occur widely as unconfined and semi-confined fissured aquifers (with significant primary porosity), the recharge areas of which form extensive tracts of valuable agricultural land. Nitrate (NO_3-N) levels in many sources, particularly in eastern England, are now considerably above 10 mg/l though, in many cases, there is no obvious point source of pollution. In consequence, two national research programmes are in progress and their interim results are summarized. Very high NO_3-N concentrations (over 20 mg/l) have been widely observed in the interstitial water of the unsaturated zone beneath arable farmland. Their implication for future groundwater quality is discussed in the light of probable rates of pollutant transport and of possible attenuating processes.

INTRODUCTION

Background to British research

Although instances of individual wells and boreholes producing nitrate-rich groundwater (with more than the current lower WHO limit for NO_3-N of 11.3 mg/l) have been recorded at least since the end of the 19th century (Whitaker 1908), the contamination could be confidently assigned in the majority of cases to nearby discrete or point sources, such as cess pits, leaking sewage mains or farmyard drainage. In recent years, however, an increasing number of examples of high and/or rising nitrate levels have been reported from Chalk, Triassic Sandstone and other aquifers, especially in eastern England (Davey 1970, Greene & Walker 1970, Satchell & Edworthy 1972, Foster & Crease 1974, Severn-Trent Water Authority 1976, Foster 1976, and Greene 1977). Their widespread distribution in outcrop or recharge areas suggested that the major component of nitrate input to groundwater systems was derived from diffuse, as distinct from point, sources.

Foster and Crease (1974) postulated a relationship between rising nitrate concentrations and changes in agricultural practice, particularly the increasingly regular cropping of cereals sustained by greatly increased use of inorganic nitrogenous fertilizers. They also expressed serious apprehension over long-term trends found in groundwater sources, because the possibility of very slow movement of pollutants down through the unsaturated zone to the water table of certain aquifers (especially the Chalk) implied that the full effect of the major changes in arable agriculture during the period 1950-65 might not be perceived for many years thereafter. Young, Oakes and Wilkinson (1976) confirmed the presence of major accumulations of nitrate in the Chalk unsaturated zone and suggested that the major increases in arable acreage, associated with the ploughing of long-standing grassland during the 1939-1945 war, was another significant factor in the increased leaching of nitrate from agricultural land in certain parts of the Chalk outcrop area.

The increasing nitrate concentrations in groundwater are of concern to public water-supply authorities because of an established risk to the health of infants (Comley 1945) and older children (Petakhov & Ivanov 1970) and of its possible role in the etiology of gastric cancer (Tannebaum *et al.* 1977). Over 30% of public water-supplies in Britain are derived from groundwater, the proportion being in excess of 80% in parts of south-eastern England. In 1973, the Anglian Water Authority, for example, inherited a situation in which 50 groundwater sources, representing a total supply of about 160 Ml/d, already had recorded NO_3-N concentrations in excess of 11.3 mg/l (Greene 1977).

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Scope and status of British research

Growing awareness of the groundwater nitrate problem in the 1970s led to the commissioning of two major national programmes of hydrogeological research – one at the Water Research Centre (WRC) and the other at the Institute of Geological Sciences (IGS) – to establish in detail the effects of agricultural land-use on groundwater quality; the Central Water Planning Unit of the Department of the Environment co-ordinated the work.

The objectives of the programmes are:

(a) To determine the extent of nitrate pollution in the principal aquifers, primarily in their unsaturated zones;

(b) To evaluate the mechanisms and rates of movement of potential groundwater pollutants, derived from the land surface, through the unsaturated zone;

(c) To estimate future trends in nitrate concentrations.

Dedication of a substantial proportion of the total research effort on the unsaturated zone was justified because of its critical importance (as a consequence of the relatively high porosity and specific retention of the principal British aquifers) in the estimation of future trends and the almost complete lack of published work on unsaturated zone groundwater chemistry.

The WRC and IGS research, beginning late in 1974 and 1975 respectively, involves extensive borehole drilling programmes. The former primarily comprises drilling and sampling, on a nationwide basis (figure 1), at selected sites (such as experimental farms) with detailed historical landuse and fertilizer application records. The latter involves detailed drilling, sampling and monitoring of small groundwater catchments to public water-supply sources already displaying a substantial nitrate problem; two such catchments have been investigated to date (figure 1).

As both programmes are still in progress, the interpretation of results presented here is, to some degree, interim. An essential part of the research programmes was redrilling of the unsaturated zone at selected sites after a hydrologically significant period, say four or five water years. To date, investigation has also been limited almost entirely to the outcrop or recharge areas, that is the unconfined aquifers; no systematic study has yet been made of the fate of nitrate migrating down-dip into confined aquifers.

INVESTIGATIONS OF CHALK AQUIFER AND THEIR RESULTS

Chalk aquifer

The Chalk is the most important British aquifer. Geologically, it comprises a uniform sequence of very fine-grained, pure white limestones composed predominantly of the remains of planktonic organisms with variable, often scant, calcite cementation (Hancock 1975). Hydrogeologically, the formation has very low interstitial permeability (generally less than 10^{-3} m/d), despite moderate-to-high porosity (mainly in the range 0.20–0.40, according to region and horizon), because of its exceedingly small pore diameters (Price, Bird & Foster 1976). Borehole water supplies thus depend upon joints and fissures; these are generally well-developed beneath the outcrop area (Foster & Milton 1974, Owen & Robinson 1978), where individual borehole yields of more than 20 l/s for 5 m drawdown are commonplace. The outcrop area represents the principal recharge zone for groundwater resources and also forms extensive tracts of rich agricultural land.

Continuous sampling of the Chalk with minimal chemical contamination has been achieved to depths of about 70 m. Samples from mechanically-excavated trenches and from continuous flight augers (100 mm diameter) were cut during preliminary investigation at some sites, but the majority of samples were obtained by dry percussive drilling with a drive core barrel (0.45 m long, 101 mm diameter). In order to obtain satisfactory samples from the harder, more cemented chalks of north-eastern England, air-flush rotary drilling with a lined (triple) core barrel is required at depths greater than 15–25 m. All samples were carefully handled and stored to eliminate or minimize pore water contamination or evaporation (Gray *et al.* 1977, Foster *et al.* 1977) prior to centrifuge extraction of their interstitial water (Edmunds & Bath 1976).

The pore water samples (generally of 10–30 ml) thus extracted were analysed for nitrate and other nitrogen species by standard methods adapted for small volumes on the autoanalyser. In some cases, other anions together with the suite of major cations were determined, the latter on a spectrophotometer. Determination of the tritium content of the interstitial water involved its extraction from cores by distillation to complete dryness, electrolytic enrichment, conversion to ethane and measurement in a scintillation counter (Allen *et al.* 1966). Measurements of some physical properties and limited biochemical studies on core material were undertaken. For the research catchments, various devices for monitoring and sampling soil drainage and mobile groundwater have been installed.

Unsaturated zone

In more than 60 boreholes, the vertical profiles of nitrate concentration in the interstitial water from the Chalk unsaturated zone have been shown to be closely related to the history of agricultural practice on the overlying land. Lateral variation in the overall shape of nitrate profiles, that is between boreholes drilled in the same year within the same field, is considered to be relatively slight, although in detail there is likely to be substantial variability (figure 2).

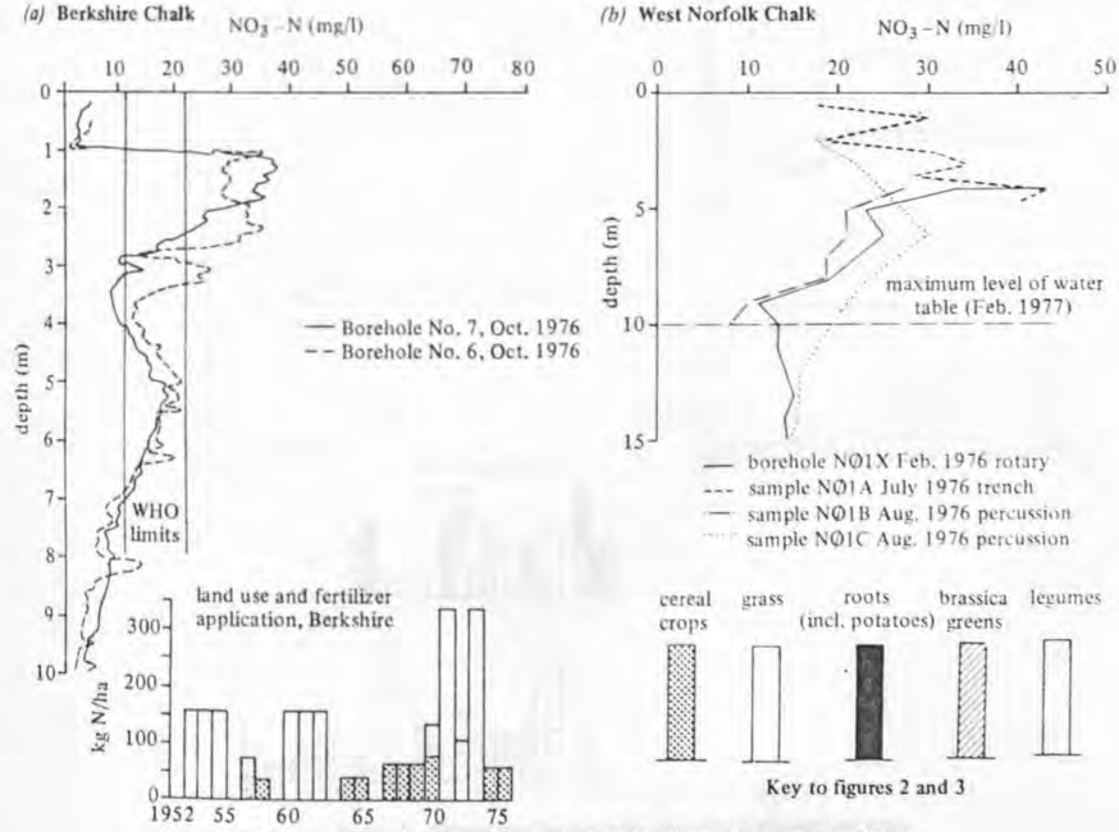

Figure 2. Comparison of nitrate profiles in single fields, illustrating lateral variation.

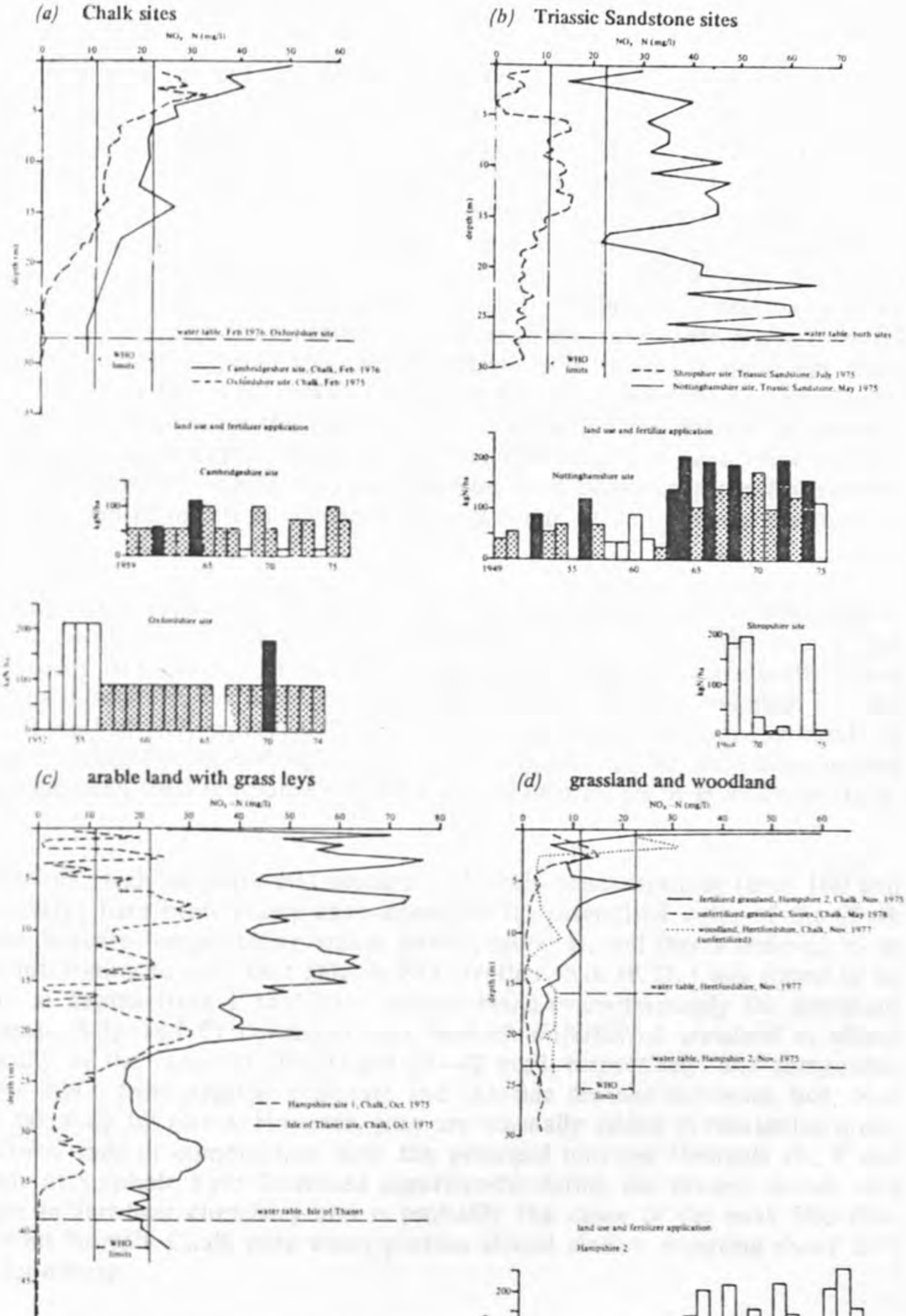

Figure 3. Nitrate profiles beneath sites with different land uses.

Concentrations of NO_3-N in excess of 11.3 mg/l, either continuously or intermittently, have been measured in the pore water profiles from beneath *all* the arable and arable/grass-ley sites that have been investigated. At many sites, the NO_3-N concentrations have exceeded 22.6 mg/l at numerous depths and individual values well in excess of 50 mg/l have been frequently encountered. The profiles beneath sites, subject to long-term, essentially-continuous arable farming, normally appear to be relatively smooth with nitrate concentrations decreasing with depth (figures 2(*b*), 3(*a*)), but those at which arable husbandry has been frequently interrupted by grass-leys are more sinuous (figure 3(*c*)); in some cases, low concentrations may be reached at depth within the unsaturated zone though, in others, relatively high concentrations continue to the water-table. Carbohydrates have been detected at depths of up to 55 m at concentrations of about 0.1 mg/kg dry chalk (Young & Hall 1977) and this may imply a potential for microbial reduction of nitrate. However, bacteriological studies on the West Norfolk Chalk could not detect the presence of any denitrifying genera at depths below 2 m (Foster *et al.* 1977); until more positive evidence has been gathered, the conservative assumption must be made in profile interpretation that no reduction of nitrate is occurring, or will occur, at depth in the unsaturated zone.

In sharp contrast to arable sites, pore water profiles from beneath areas of permanent unfertilized vegetation, such as rough grassland, downland and woodland, have been found to be characterized by NO_3-N concentrations mainly below 5 mg/l, and frequently below 1 mg/l (figure 3(*d*). Long-term fertilized grassland has been found to be underlain by pore waters with 5–10 mg/l of NO_3 nitrogen (figure 3(*d*)), except where abnormal amounts of inorganic nitrogen fertilizer (over 500 kg nitrogen per hectare each year) have been applied or where fields have been used temporarily for the storage of manures or as intensive stock-pens.

In West Norfolk, high sulphate and moderate chloride concentrations (over 100 and 50 mg/l, respectively) have been widely encountered in the interstitial water of the Chalk unsaturated zone beneath long-standing arable fields (figure 4), and this is believed to be the norm. It is interesting to note that SO_4 or NO_3 (rather than HCO_3) was found to be the *major* anion at depths from 1 to 10 m, calcium being overwhelmingly the dominant cation. In contrast, SO_4 and Cl concentrations beneath unfertilized grassland at inland sites were typically in the range of 20–50 and 15–40 mg/l, respectively, and compatible with the known input from rainfall. Sulphate and chloride are not nutrients, but, to a degree, may be taken-up by plants. However, they are normally added in substantial quantities to agricultural soils in combination with the principal nutrient elements (N, P and K). The amounts of sulphate have decreased significantly during the present decade as a result of changes in fertilizer chemistry and is probably the cause of the peak SO_4 concentrations in West Norfolk Chalk pore water profiles almost always occurring about 3–7 m below those for nitrate.

The practical relevance of tritium (^3H) as a natural tracer in groundwater studies in the Chalk unsaturated zone was first demonstrated by Smith *et al.* (1970) who determined its distribution at a site in Berkshire in 1969 (figure 5). The existence of a clearly-defined peak at a depth of around 4 m was interpreted as indicating that about 85% of the infiltration was moving downwards by interstitial piston flow at the surprisingly slow rate of about 0.8 m/a since, after allowing for radioactive decay, the ^3H values observed in the peak (about 600 TU) could only have originated from rainfall during the springs of 1963 and 1964. Similar ^3H profiles, with a single pronounced peak (always of more than 200 TU) at depths between 5 and 14 m, have been found at *all* sites on the Middle/Upper Chalk (with sufficiently thick unsaturated zones) so investigated during 1975-77 in the course of the current research programmes. The peak concentrations and the depths to the peaks (see figure 5 and table 1) are broadly consistent with expectation, after allowing for radioactive decay and considering the average local infiltration rate. However, instances of significant differences in ^3H profiles from adjacent sites at comparable times are also known.

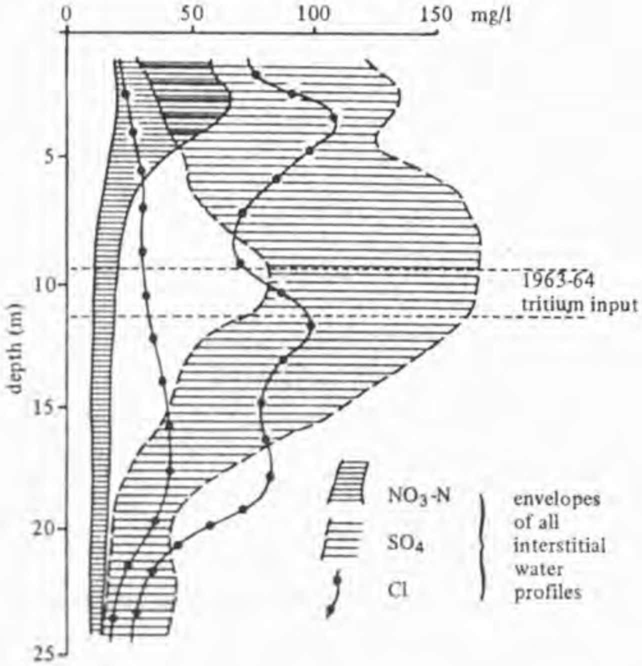

Figure 4. Partial summary of chemical profiles of interstitial water for Chalk unsaturated zone beneath arable sites in West Norfolk.

Moreover, careful study of individual profiles reveals that a confident evaluation of the mass ^3H balance is not always possible for a variety of reasons, and suggests that reliable interpretation will have to await the collection of a number of time sequences of ^3H profiles for selected sites (Foster & Smith-Carington 1980). Available data, for sites on the Hampshire and Dorset Chalk, confirm that the tritium peak is moving slowly downwards though, at the Dorset site, there is some doubt as to the proportion of the total tritium input involved in the slow component of movement. *This is a critical question.*

The mechanism by which water and solutes move downward through the Chalk unsaturated zone also remains a subject of uncertainty and controversy. The exceedingly small pore diameters (mainly less than 1 μm) mean that gravity drainage is almost entirely inhibited and that, *even within the unsaturated zone*, most of the Chalk matrix remains very close to saturation (Price, Bird & Foster 1976). In view of the observed frequent vertical jointing, Foster (1975) postulated that relatively rapid infiltration and groundwater flow in unsaturated zones may occur with ^3H (and other solutes) diffusing between the mobile 'fissure' water and the almost-static pore water. This general concept has been extended by Young, Oakes & Wilkinson (1976) and Oakes (1977) who demonstrated that such a mechanism could, under certain conditions, produce a similar vertical distribution of solutes to interstitial piston flow. The detailed picture is likely to be complex and to involve combinations of mechanisms. Obviously the ultimate aim must be to produce a satisfactory mathematical modol of unsaturated zone solute transport, starting with tritium and extending to include nitrate and other constituents of interest. If this were possible, it would generate, by way of calibration, an evaluation of the rates of leaching of nitrate from permeable agricultural land with various husbandries and, given assumptions as to future climate and cropping practice, a prediction of future nitrate concentrations reaching the water-table. Modelling of the sites on the Hampshire Chalk (Young, Oakes & Wilkinson (1976)) has provided satisfactory simulation of unsaturated zone profiles of nitrate, chloride and tritium. Simulations have been achieved of some other Chalk sites but these require modifications to the model. The model assumes that a high proportion of the solutes are transported via the slow component of flow and that no nitrate reduction occurs. Preliminary investigation of the presence of nitrogen-transforming bacteria in Chalk indicates that denitrification is slight and restricted to the upper few metres of rock.

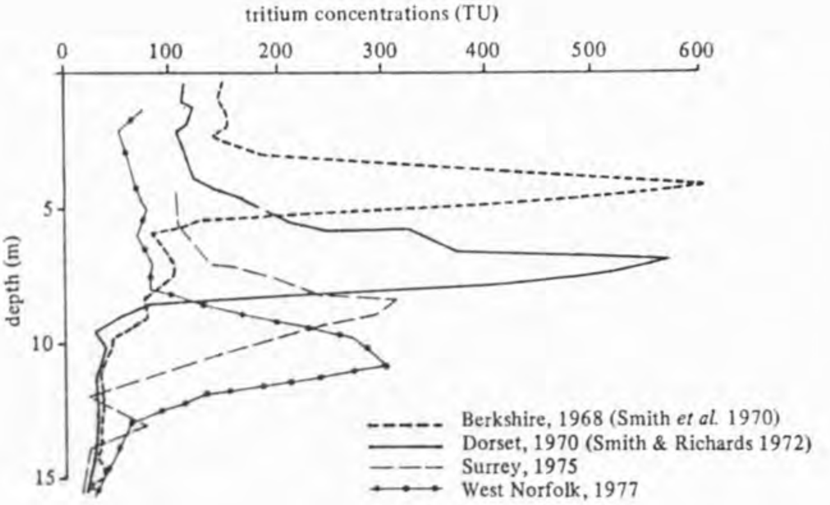

Figure 5. Selected tritium profiles for Chalk unsaturated zone pore-water samples.

Table 1. Depths below ground level to peak tritium concentrations in the Chalk

location	no. of boreholes	sampling date	depth to peak (m)	long-term average effective rainfall (mm) assuming 75 mm root constant
Cambridgeshire	1	1976	5	130
West Norfolk	5	1976/77	9 – 12	160
Isle of Thanet	1	1975	7.5	200
Oxfordshire	1	1975	7.5	210
Surrey	2	1975/77	8 – 11	240
Hampshire	1	1975	8 – 11	315
Sussex	1	1977	12.5	330

Saturated zone

In the research catchment on the West Norfolk Chalk, three cored boreholes were drilled to about 50 m below the water-table to facilitate chemical and isotopic analyses of interstitial water and thus establish the extent to which storage and/or reduction of nitrate might delay or attenuate the migration of high concentrations reaching the saturated zone. Some risk of contamination of pore water samples from depth with mobile groundwater in overlying major flow zone existed, but it is believed that the effect was minimized by the core drilling and handling procedures employed.

The distinctive features of the profiles obtained (figure 6) are:

(a) Variable and often high concentrations of all constituents in the upper part of the zone of seasonal water-table fluctuation, where downward moving solutes must come into intermittent contact with horizontal groundwater flows;

(b) Relatively high NO_3–N concentrations (8–15 mg/l) through a considerable thickness of the permanently saturated zone, suggesting that inputs from the land surface in

long-standing entirely arable areas must have contained similar mean concentrations over fairly long periods;

(c) Decrease of the NO_3–N concentrations to low or very low levels below the Plenus Marl, because of the absence of significant groundwater circulation at this depth and/or of denitrification.

(Similar distributions of nitrate in the saturated zone have been measured in the Chalk in Sussex and on the Isle of Thanet, but at one site in Surrey nitrate concentrations were reduced to low levels at about 20 m below the water table).

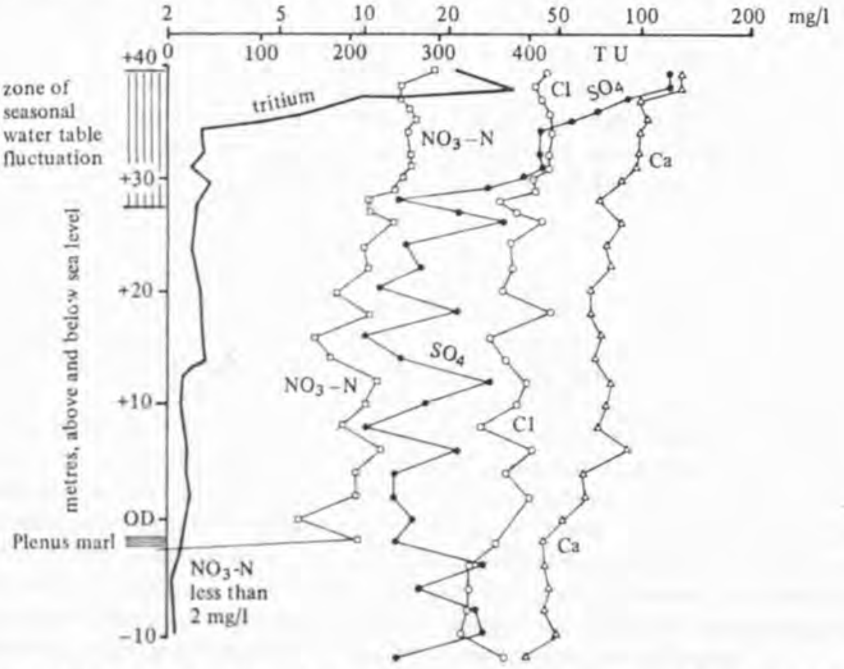

Figure 6. Chemical and isotopic profiles of saturated zone interstitial waters from individual boreholes in West Norfolk Chalk.

By way of comparison, careful and regular sampling from observation boreholes of different depths in the West Norfolk catchment have shown the deeper of the major groundwater flows to contain 11–13 mg/l of NO_3–N. Following heavy infiltration in February 1977, the zone of water table fluctuation filled with groundwater containing 17–21 mg/l of NO_3–N, although it is extremely unlikely that the actual infiltration from the soil had anything like this level of nitrate. An adjacent water-supply borehole, normally producing groundwater with 12–15 mg/l of NO_3–N, peaked to 17 mg/l in February 1977. The levels of other chemical constituents in this borehole are: SO_4, 35–50 mg/l; Cl, 30–40 mg/l; Ca, 105–135 mg/l.

Other aquifers

Triassic Sandstone

The Triassic Sandstone, which outcrops mainly in central and northern England (figure 1), is composed of consolidated, red, in part pebbly, sandstones of continental deposition. Extensive areas of the outcrop are mantled by glacial deposits; where this cover is absent, weathering to depths of 10 m or more is common. As dry percussive coring was generally impractical because of the formation lithologies, continuous flight augering was employed for shallow exploratory boreholes, and air-flush rotary core drilling for deeper boreholes. The handling, storage and pore water extraction techniques were similar to those used with Chalk cores, but the majority of samples were deep-frozen to prevent drainage.

The general relationship between land use and pore water nitrate profiles observed at Chalk sites is repeated in the Triassic Sandstone: NO_3-N concentrations in the range 10–50 mg/l are characteristic of arable land (figure 3(*b*)), while levels of 10–20 mg/l and less than 5 mg/l have been measured beneath fertilized and unfertilized grassland, respectively. The high degree of vertical anisotropy, resulting from the sedimentary character of the sandstones, was found to be reflected in the form of the interstitial water profiles. Lateral variability in the Sandstones, when compared to the Chalk, was responsible for the lack of close correspondence in shape of adjacent profiles from individual arable sites. Determination of reliable ^3H pore water profiles in the unsaturated zone has been restricted by the low moisture content of the rock and the difficulty of obtaining satisfactory cores without the use of a drilling fluid; those that have been determined (Brereton & Wilkinson 1977) have shown irregular forms, with maxima in the range 200–300 TU at depths of around 20 m. This suggests a more rapid (and possibly less uniform) rate of downward movement than in the Chalk.

Cored boreholes to depths of 150 and 200 m were drilled in a Staffordshire valley, close to boreholes producing groundwater having NO_3-N levels of 7–8 and 3–4 mg/l. The saturated zone profile from the former site (figure 7(*a*)) showed high NO_3-N concentrations between 40–90 m depth, while concentrations of 6–10 mg/l were measured at the latter site (figure 7(*b*)) to a depth of about 60 m. Lithological examination of the cores from both sites showed that the higher concentrations were confined to the Bunter Pepple Beds and geophysical borehole logging revealed that the main groundwater flows occur within this part of the Triassic sequence. Tritium determinations showed the groundwater moving through the Bunter Pepple Beds, at both sites, to be significantly younger than that in the underlying Lower Mottled Sandstone, suggesting the nitrate to be of relatively recent origin. A survey of land use in the groundwater catchments contributing to each pumped borehole showed a greater proportion of arable cropping in the catchment of the source producing the higher nitrate concentration groundwater.

Jurassic Limestone

Research is being undertaken on a groundwater catchment in the Lincolnshire Limestone, the land use of which has been about 90% arable since the 1930s or even earlier. The presence of some massive cementstones and numerous marl bands within the Limestone

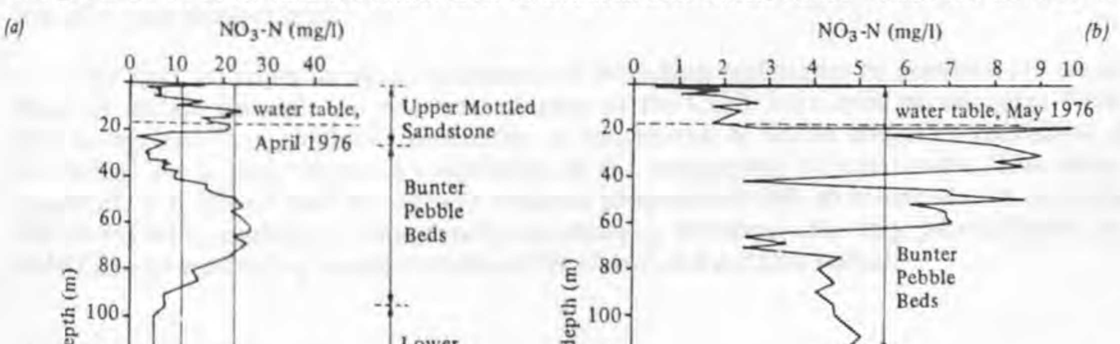

Figure 7. Nitrate profiles of saturated zone interstitial waters from boreholes in the Trianic Sandstone, Staffordshire.

sequence causes many perched water-tables and significant lateral groundwater movement, above the regional water-table, following major infiltration. This invalidates an analytical approach to the vertical profiles of interstitial water chemistry, though most of the more porous lithologies throughout the formation were found to have high or very high pore water nitrate concentrations.

The formation and its permanently saturated zone rarely exceed 30 m and 10 m thickness, respectively; in consequence, the aquifer has very low storage, both in respect of total and mobile water content. It is thus probable that the overall groundwater system more nearly approaches equilibrium with current arable farming practice than do other groundwater systems. It is therefore of considerable interest that the groundwater produced by the water-supply borehole tapping the catchment exhibits marked seasonal fluctuation in the concentration of nitrate and other constituents; NO_3–N and SO_4 peaking at about 22 mg/l and 150 mg/l and falling during the groundwater recession to 12–16 mg/l and 110–130 mg/l, respectively.

CONCLUDING REMARKS

Prior to the 1970s, hydrogeological factors were often ignored in groundwater quality investigations, especially when such investigations were limited to pumped sampling. In particular, no study of physical and chemical processes in the unsaturated zones of aquifers had been attempted.

The current British research programmes have produced a substantial and possibly unique body of data on the unsaturated zone, especially of the Chalk. They are bringing about a realization of the great influence of agricultural practice on groundwater chemistry and of the extent of the build-up of nitrate and other solutes beneath arable farmland.

If the physico-chemical behaviour of these solutes is similar to that of tritium, the rates of leaching from arable fields appear to have increased substantially since 1963–64. In West Norfolk, for example, the Chalk pore waters above the ^3H peak at 10 m depth are estimated to contain the following concentrations of SO_4 and Cl: 600–1000 kg/ha, 2000–4500 kg per hectare and 1000–2400 kg per hectare corresponding to average losses of at least 40–70 kg (nitrogen) per hectare per year, 150–350 kg (sulphate) per hectare per year and 70–180 kg (chloride) per hectare per year. The sinuous pore water nitrate profiles beneath arable/grass-ley sites suggest that significant quantities of nitrate are released and lost after ploughing-in grass.

The first attempts at using mathematical modelling techniques to simulate the movement of nitrate through the unsaturated zone of the Chalk have been encouraging. While it is recognized that confident prediction of movement of solute under all conditions is dependent on a more detailed knowledge of the mechanism of unsaturated flow solute transport, it is hoped that the current research programmes will go a long way to resolving the outstanding problems. Time-dependent changes, however, can only be established by redrilling and resampling at selected sites after elapse of a suitable period.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the collaboration of the Anglian, Severn-Trent and Southern water authorities in joint studies and the assistance of other water authorities in data collection. Isotope analyses were carried out by the Harwell Laboratory of the United Kingdom Atomic Energy Authority. Part of the work described has been funded by the Department of the Environment. This paper appears by permission of the Directors of the Institute of Geological Sciences and of the Water Research Centre.

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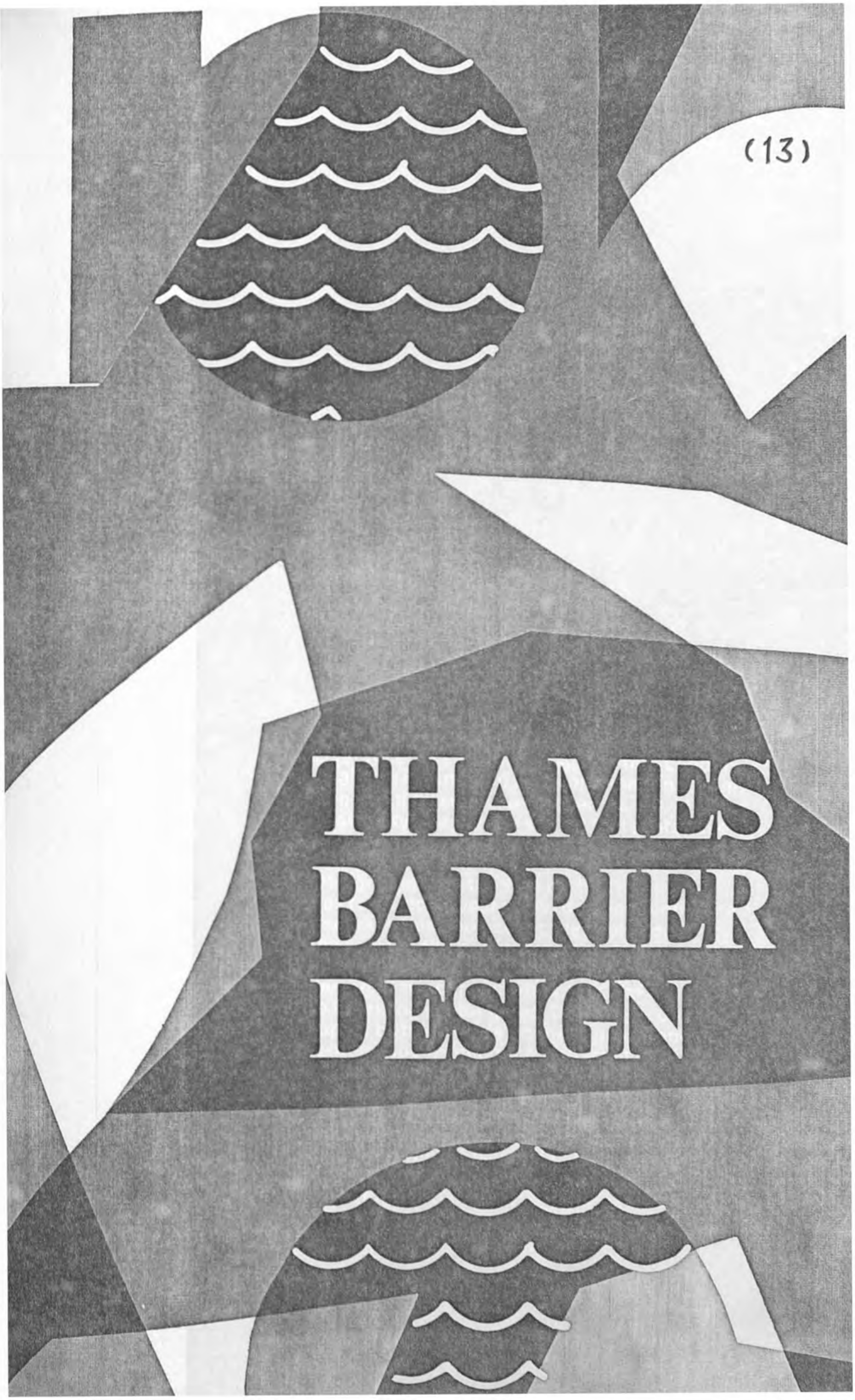

THAMES BARRIER DESIGN

Over recent years the possibility that London might be innundated by a combination of high tide and tidal surge has moved from a possibility to a danger so real that protective measures have become essential.

Design and construction of the Thames Barrier has required intensive and detailed work. The papers in this book cover the background to the project, the geotechnical and environmental concerns, and all aspects of the design of the barrier, with particular reference to the rising sector gates. Discussion on the papers both expands on these points and raises further aspects of concern to engineers and environmentalists.

Participants at the conference included representatives from many disciplines including architects, administrators, mechanical and electrical engineers, and experimental workers.

ISBN : 0 7277 0057 X

THE INS

THAMES BARRIER DESIGN

Proceedings of the conference held in London
on 5 October, 1977

THE INSTITUTION OF CIVIL ENGINEERS, LONDON, 1978

Contents

The problem

The site

The solution

MR S.S.D. FOSTER and MR A.C. CRIPPS (Institute of Geological Sciences)

14. The results of the investigations[4-7] referred to in paragraph 17 of Paper 4 pertain primarily to the operation of the tidal barrier rather than its design, but they may also have some implications for construction. (Details of the location and construction of the boreholes used for the investigations in Woolwich Reach are given in Fig.7 and Table 1.)

15. Along Woolwich Reach tidally-induced fluctuations in pore-water pressure are observed over substantial distances from the river in the more permeable formations: the Flood Plain Terrace Gravel and the Chalk (Figs 8 and 9). The Thanet Sand whose permeability is 1-2 orders of magnitude lower, partially confines the Chalk groundwater on the northern bank and probably only exhibits tidal fluctuations in pore-water pressure close to the river bank and to its contacts with the more permeable formations both above and below (Fig.5 of Paper 4).

16. The transmission of diurnal changes in head in a tidal river to adjacent groundwater systems is a function of two essentially distinct processes: transfer through the river bed and river bank to the groundwater system and propagation away from the river, laterally through the groundwater system.

17. In the ideal case of perfect hydraulic communication between a tidal river and any permeable strata into which it has channelled, the tidal ratio (TR*) beneath the river bed would be 1.00; but the presence of any low-permeability, compressible deposit in the river bed would tend to reduce this ratio substantially. The observation of considerable damping (TR = 0.39) and measurable time-lag (3-10 mins) in the response of piezometer 24B (Fig.8), which is sealed through the river bed into the Flood Plain Terrace Gravel of 24 m offshore from the southern bank of the river, is an illustration of the considerable 'impedance' of the river bed deposits.

18. Propagation away from the river will be a function of the hydraulic properties of the groundwater system and of any confining strata.[6, 8, 9] The observation of a sizeable tidal fluctuation (TR = 0.11) in observation borehole W7 (Fig.8), 110 m from the southern bank of the Thames, is a reflection of the high permeability coefficient and low specific storage of the confined groundwater system in the Flood Plain Terrace Gravel.

* The ratio between the response of the groundwater system and the corresponding diurnal change of tidal head in the river.

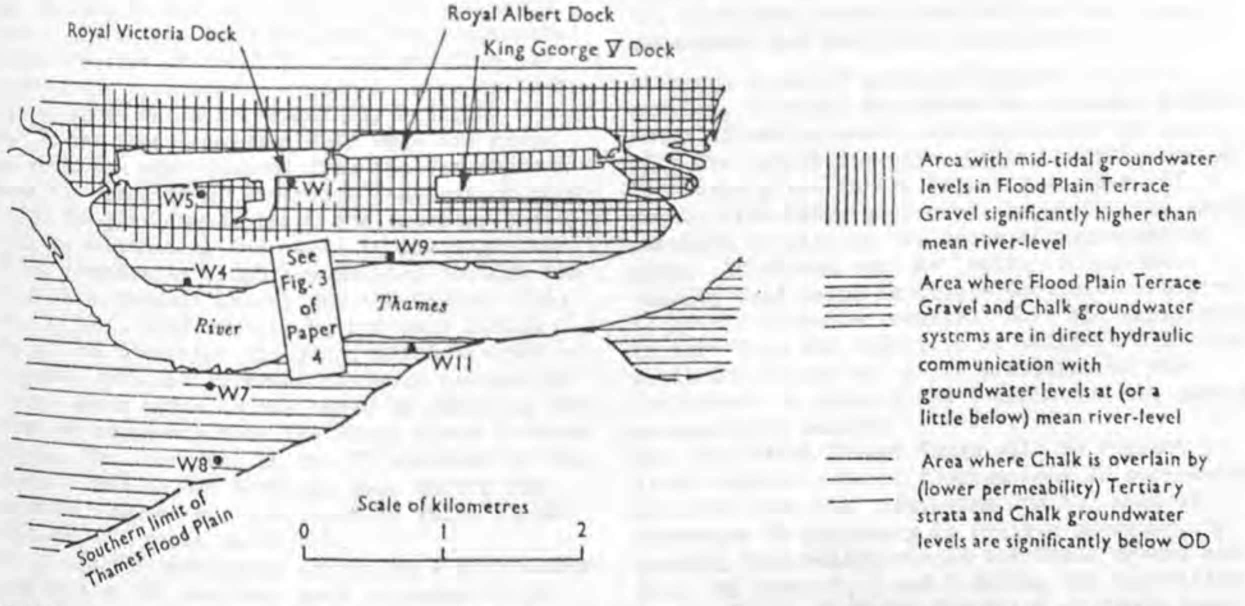

Fig.7. Thames Flood Plain in Woolwich Reach - general location map with groundwater conditions

Table 1. Summary of construction, location and tidal response of observation boreholes and piezometers

Borehole No.	Borehole Type†	Geological formation*	Distance from river wall	Distance from edge of dredged channel	TR**	Time lag (mins)** at low tide	Time lag (mins)** at high tide
North Bank							
W4	O	FPTG	60	250	0.17	c 80	10
W5	O	FPTG	660	880	0.08	c130	c120
W12A	O	FPTG	12	260	0.19	70	5
W12B	O	sCK			0.15	c130	c 60
W13	O	FPTG	45	290	0.15	c 90	20
48	P	sCk	110	360	0.13	?	45
52A	P	sCk	19	270	0.18	c110	20
52C	P	dCk			0.09	c160	c100
South Bank							
W7	O	FPTG	110	300	0.11	30	c130
W8	O	FPTG	650	840	0.01	c 80	c100
W11	O	FPTG	75	250	0.25	c 50	25
W14A	O	FPTG	9	130	0.25	25	10
W14B	O	sCk			0.26	20	5
W15	O	FPTG	52	170	0.21	30	20
24B	P	FPTG	-24	95	0.39	10	3
30	P	FPTG	165	285	0.14	40	30
53	P	sCk	16	80	0.49	15	10
54	P	FPTG	54	120	0.42	25	10

† O Observation borehole completion; P piezometer completion

* FPTG Flood Plain Terrace Gravel; sCk(dCk) shallow (deep) Chalk

** data apply to a single moderate spring tide in 1972; some variations have been observed with fortnightly tidal cycle and with season

19. In analysing the TR data for Woolwich Reach, it was considered pertinent to express distances of observation boreholes and piezometers from the nearer edge of the main dredged channel (or dredged anchorage) and not from the river frontage. The data are then sufficiently ordered (Fig.10) to permit confident use of the analytical theory[8] for predictive purposes. The fact that the log TR-distance data can be extrapolated to the origin suggests that the 'impedance' to the transfer of tidal fluctuations from the river to the groundwater system is more or less zero in areas which are regularly dredged.

20. It was thus concluded that when the river bed sediments were removed from the foreshore areas (by dredging of diversion channels or excavation for pier foundations, for example) there would be substantial increases in the magnitude of the groundwater tides transmitted through the Flood Plain Terrace Gravel and the Chalk. This was, in fact, confirmed to be the case during the initial diversion dredging, which started in September 1974 and diverted the main navigation channel about 100 m to the north by removing the river bed sediments from the Flood Plain Terrace Gravel. The increases in the TR observed in the gravel strata on the northern bank during the succeeding months are indicated in Table 2, and compared with those predicted.

21. A similar phenomenon affecting a more extensive area on the southern bank is expected to occur following the planned diversion of the main navigation channel to the south, so as to pass between the piers currently under construction. The side-effects of the transient increases in pore-water pressure during high tides could include:

(a) increased peak flow to the drains protecting non-waterproofed buried structures
(b) increased maximum hydrostatic uplift on tanked sub-surface structures
(c) decreased overall stability of the river embankment and the flood plain cover.

Although no major problems appear likely to develop, it would be prudent to keep the groundwater situation under continuous observation.

22. The values for permeability coefficient of the Chalk given in the Paper (paragraph 57) could, from hydro-geological knowledge, be easily exceeded locally by one order of magnitude or more. In strata such as Chalk, rising and falling head tests in single boreholes are prone to give unreliable results. Have the experiences to date from the operation of wellpoints in the Chalk for relief of uplift pressures on the cofferdams at piers 8 and 9 borne out the quoted permeability values?

23. The basal Thanet Sands will be subject to large tidally-induced fluctuations in pore-water pressure from the underlying Chalk. Will it therefore be necessary to relieve pressure, by pumping from wellpoints in the Chalk around the sites of piers 1, 2 and 3 during the excavation in the Thanet Sand for formation of their foundations and emplacement of the cofferdams?

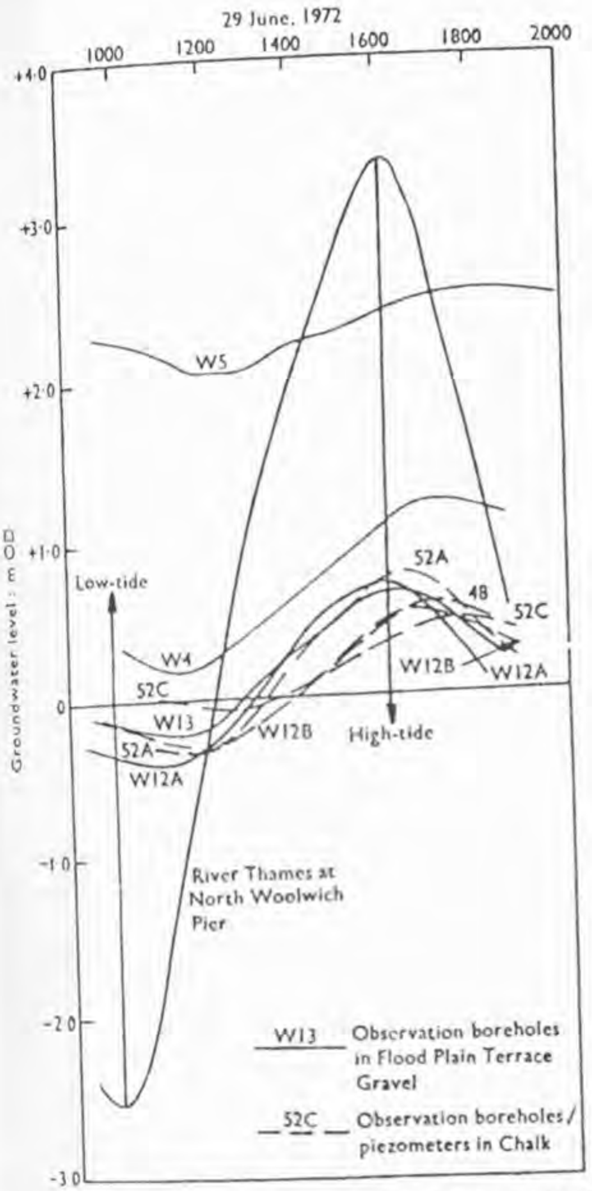

Fig.8. Groundwater response to diurnal tidal fluctuation along Woolwich Reach (North Bank)

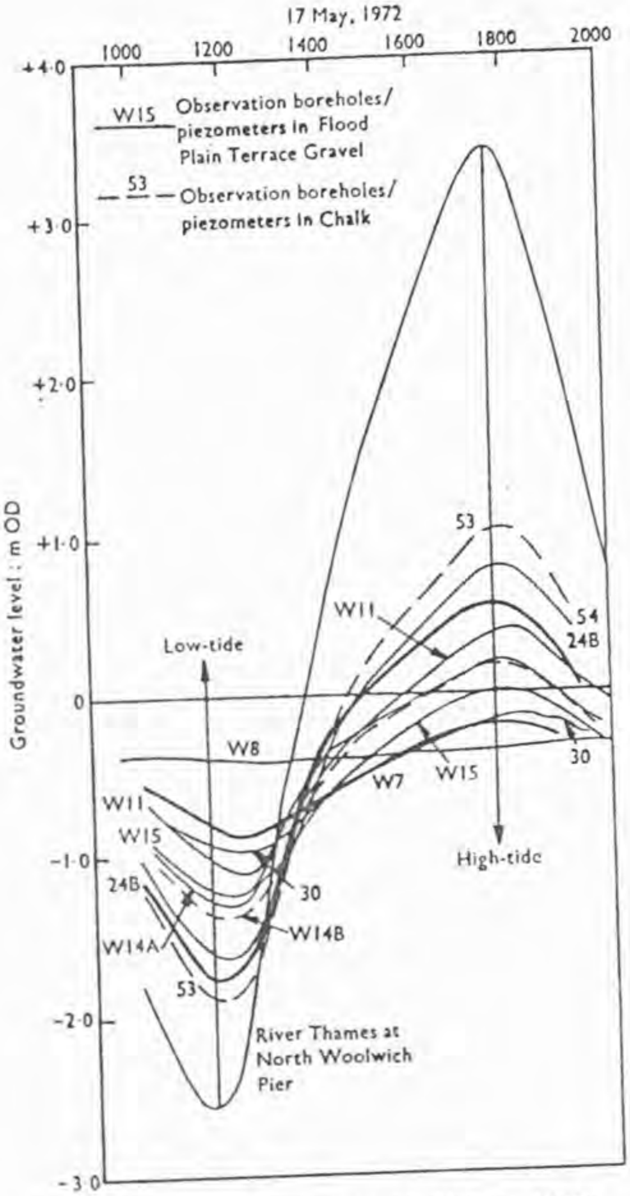

Fig.9. Groundwater response to diurnal tidal fluctuation along Woolwich Reach (South Bank)

24. A survey of the chemistry of groundwaters along Woolwich Reach, based only on pumped samples, was also undertaken by the Institute of Geological Sciences.[6] Such samples may not reflect fully the chemistry of the most aggressive groundwaters present in situ, as a result of dilution from other inflow levels into the borehole concerned. Most of the groundwaters appeared to have fairly high chloride and sulphate concentrations (2000-3500 and 100-750 ppm respectively) but were not markedly acidic. However, a sample from borehole W13 (on the northern bank of the barrier site) had about 2500 ppm SO_4^{2-} with a pH of 4, and lenses of a similar groundwater could be present elsewhere locally. The existence of groundwater of this quality is attributed to previous disposal of industrial effluents to the ground near the site - this was also the case at a site in West Bromwich where spectacular attack of the concrete linings of a new main drainage tunnel was reported.[10]

25. On the subject of costs (paragraph 68), what proportion of the estimated total cost of the structure (at 1972 prices) was represented by the site investigation? How does this proportion compare with that for other major river and marine engineering works? Does the figure quoted include the staff costs of the consulting engineers for supervision and interpretation of the site investigation?

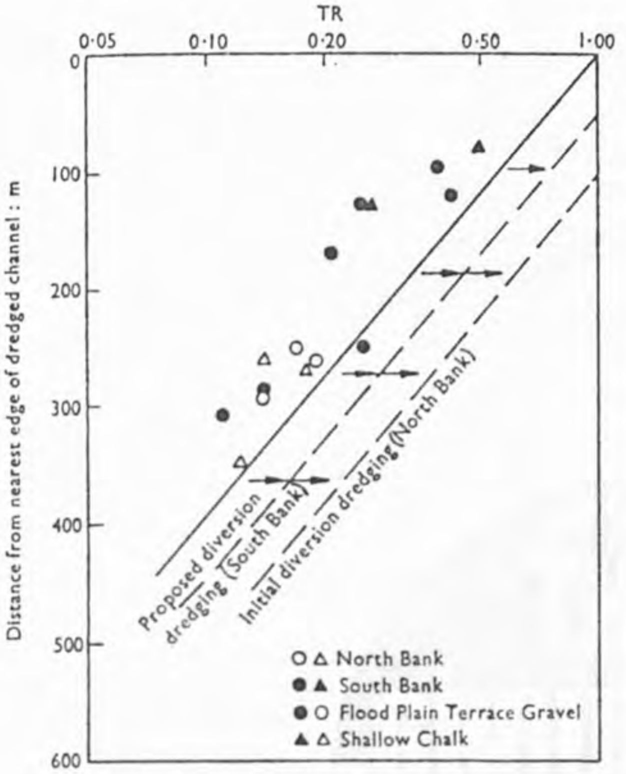

Fig.10. Analysis of propagation of groundwater tides

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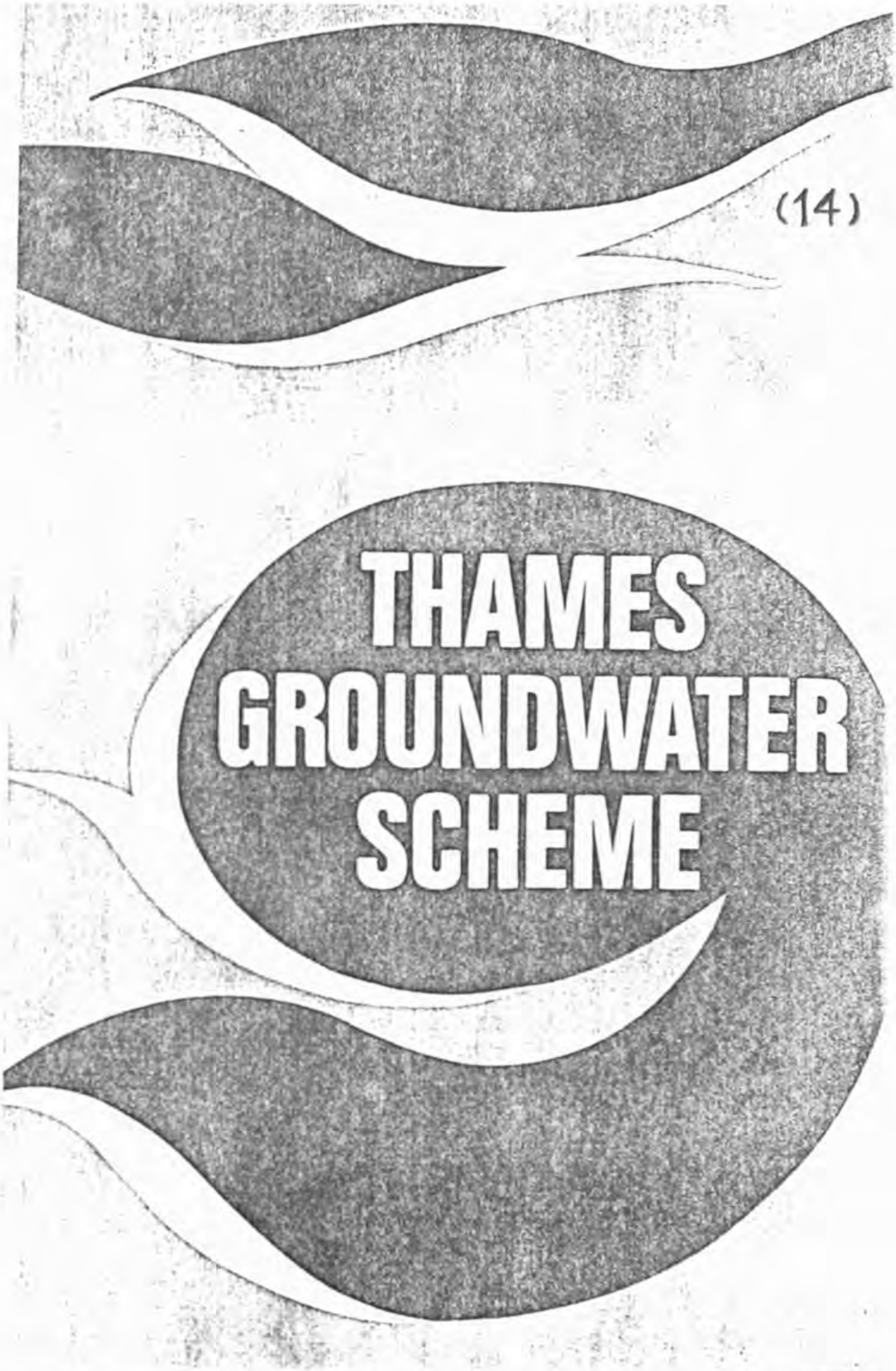

THAMES GROUNDWATER SCHEME

The Thames Groundwater scheme is the first large scale regional project to augment stream flow by groundwater. These papers provide the earliest full report, from the proposal in the late 1940s to date. This period has been one of massive development of knowledge of the properties and behaviour of groundwater, and of comparable developments in computer technology which enabled sophisticated modelling techniques to be devised. Research undertaken in connection with the Thames scheme has contributed to these developments and the conference provides an invaluable record of the problems encountered and the means by which they were solved.

ISBN: 0 7277 0060 X

THAMES GROUNDWATER SCHEME

Proceedings of the conference held at Reading University on 12-13 April, 1978

THE INSTITUTION OF CIVIL ENGINEERS
LONDON, 1978

Contents

ACKNOWLEDGEMENT

The authors are indebted to Thames Water Authority (and in particular the Director of Operations, Eric C Reed, DFC, C.Eng, FICE, FIMunE, FIWES, MBIM and the Director of Planning, Dr Colin Sinnott, BSc, PhD, C.Eng, MRAeS, FSS, MBIM) for permission to publish these papers.

Mr S.S.D. Foster (Institute of Geological Sciences, London)

As a research hydrologist, it is my opinion that, the evaluation of chalk groundwater storage is the central issue for the Thames Groundwater Scheme. One should not lose sight of the fact that the underlying objective of the scheme (and other similar schemes at various stages of investigation and development in the catchements of the rivers Great Ouse, Itchen, Waveney, Dorset, Avon, and Hull) is the controlled exploitation of natural groundwater storage in the chalk. But how much is understood about this storage?

Clearly Thames Water Authority have learnt a lot and some of the lessons have been less than favourable: paragraphs 18 and 22 of Paper 2 are probably the most significant of the Proceedings. Reductions of original estimates of the relevant operational values for both transmissivity and storativity of 70% are indicated, and coupled with a 50% reduction in effective aquifer thickness. This represents a 4 fold reduction (from 910 to 225 mm) in the estimated average unit storage of the unconfined chalk aquifier at drought. This new figure of 225 mm implies that the ratio between the drought storage and the mean annual recharge of the groundwater reservoir is less than 1. How far in terms of rate and duration will it remain economic to develop storage for river regulation from a reservoir of these characteristics?

The Institute of Geological Sciences has had some opportunities to conduct detailed research on chalk and during 1974-77 published results of investigations at sites in East Yorkshire (ref. 1.2, 1.3), South Norfolk (ref 1.4) and mid-Hampshire (ref. 1.5). These investigations suggested that

(a) Almost all of the transmissivity is invariably associated with only a few fissures, and these are frequently sub-horizontal in disposition and impart a substantial degree of radial uniformity in the aquifier's response to the pumping of individual wells.

(b) The rest of the Chalk has surprisingly low in situ permeability (normally less than 1 m/d) and some storage (up to 0.5%), both probably associated with micro-fissures and occasional larger pores in the rock matrix.

(c) The transmissivity and storativity will fall-off dramatically with decreasing groundwater level, a large proportion of the permeability and storage of the unconfined aquifier being located within the zone of natural seasonal water-table fluctuation.

(d) High transmissivity appears to be due to the solution enlargement of fissures, which shows a general tendency to increase down groundwater flowlines to a maximum in the areas of current groundwater discharge.

(e) Large-scale geological structure and geomorphological history appear to be the dominant controls on permeability development with the influence of detailed stratigraphy and tectonics being relatively limited and localized. These results led to a personal concept of the type of feature most commonly responsible for much of the permeability and groundwater flow in the Chalk, Fig. 1.5.

It is relevant to introduce some detail from the investigations on the Hampshire Chalk (ref. 1.5). These included the use of water injection tests on packed-off sections of a 120 mm cored borehole, which had previously been pumped clean, logged to evaluate borehole inflows and inspected by closed-circuit television. The injection tests were carried out with a double inflatable packer assembly carried on 63 mm diameter drill casing, permitting relatively high injection rates for small head losses. A pressure transducer was incorporated within the assembly to permit direct and accurate measurement of injection pressure in the test zone. In all, sixteen zones were tested covering the borehole interval from 17-75 m bgl. In fifteen of these sixteen zones (including some in which borehole logging techniques suggested minor flow levels) only very low injection rates proved possible even when high injection pressures were applied (Fig. 1.6) indicating in situ impermeabilities in all cases of less than 3 m/d and in most cases less than 1 m/d. In the remaining zone of 3.7 m in length a transmissivity of over 200 m^2/d was computed from the injection test results and inspection of this zone revealed just one single, near horizontal, fissure. The value of 200 m^2/d represents only a minor proportion of the total transmissivity at this site; the bulk of which must be located above 17 m bgl. It was not possible to conduct reliable water injection tests above this level because the borehole required support from lining tubes.

The revised scheme of variation of Chalk aquifier parameters, given in Paper 2, is likely to be much closer to reality than were the original values. I would question however

(a) The validity of the concept of effective aquifier thickness itself, in a formation like the Chalk in

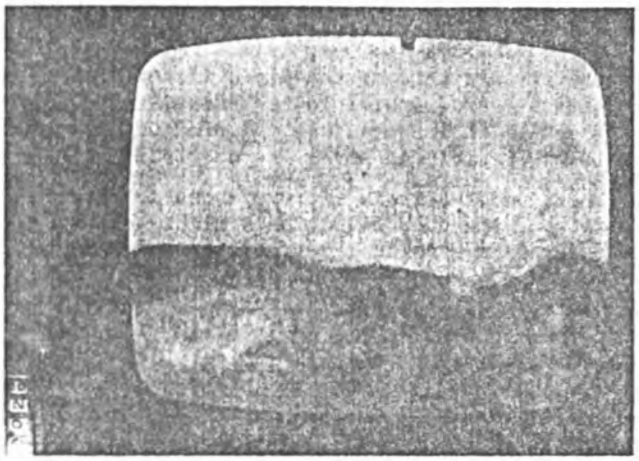

Fig. 1.5 Borehole TV view of a fissure in a borehole in the Chalk of Hampshire. The screen diagonal represents approximately 37 mm

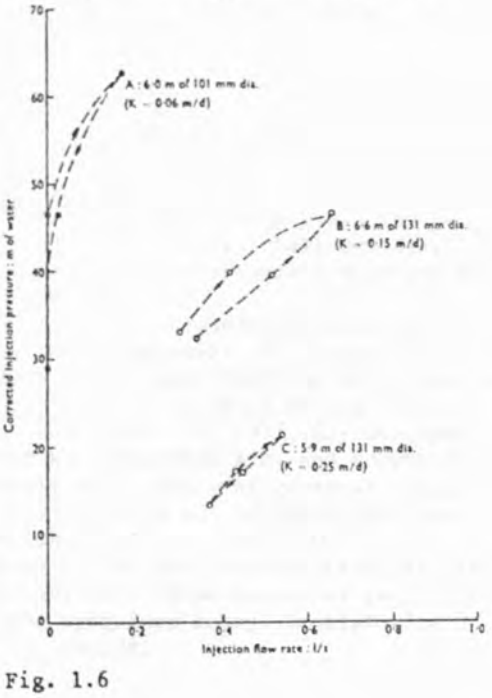

Fig. 1.6

which the major fissures may be of very infrequent distribution.

(b) If gravity drainage of the micro-fissures and the occasional larger pores in the rock matrix, (i.e., the bulk of the theoretically exploitable storage) would be possible at levels remote from major fissures.

(c) Whether, under certain circumstances in the pumped condition, the unconfined Chalk might not behave regionally as a multi-layered leaky aquifier system, whose full evaluation would require measurements of pressure and flow within individual major fissures.

To control Chalk groundwater effectively, we must understand it. In the past we have probably tried to get by with insufficient basic hydrogeological research on its fundamental properties. There is still room for such research in the future. All too often in groundwater engineering, unjustified and unverified assumptions on aquifier storativiity have been made, and believed because they allowed superficially acceptable calibration of analogue and digital models. Such calibration, perhaps to relatively insensitive parameters, has often discouraged futher investigation of the properties concerned (ref. 1.6).

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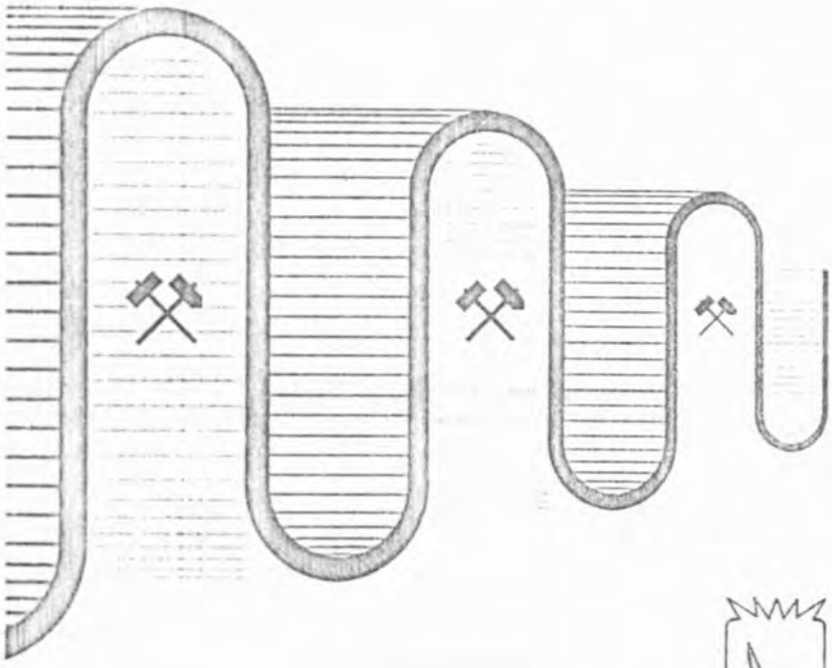
EL AGUA EN LA MINERIA Y OBRAS SUBTERRANEAS.

WATER IN MINING AND UNDERGROUND WORKS.

L'EAU DANS LES MINES ET TRAVAUX SOUTERRAINS.



GRANADA-ESPAÑA

SIAMOS-1978

Asociación Nacional de Ingenieros de Minas.
Consejo Superior de Colegios de Ingenieros de Minas.

Editor Científico:

Prof. R. Fernández-Rubio, Dr. Ingeniero de Minas

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Diseño de Portada:

Sr. D. J. Fernández Lorca

Publicado en base a los textos enviados por los autores
Published on the basis of the papers presented by the authors

ISBN 84-500-2798-5 (nº general)
ISBN 84-500-2799-3 (Volumen I)
ISBN 84-500-2800-0 (Volumen II)

Depósito Legal GR. 351 - 1978

Impreso en:

Talleres ARTE
Prieto Moreno 6
Maracena (Granada)

BRITISH EXAMPLES OF A HYDROGEOLOGICAL APPROACH TO THE EVALUATION OF DRAINAGE PROBLEMS IN SUBSURFACE ENGINEERING

Foster, S. S. D.* & Price, M.**

ABSTRACT : Projects involving subsurface engineering have increased steadily, both in number and complexity, during the present decade. During site investigation, failure to identify the potentially difficult problems that arise from the presence of groundwater in highly permeable strata can, and often does, lead to costly delay and/or re-design during construction. The hydrogeological approach to the collection and evaluation of groundwater data differs, in both philosophy and techniques, from that normally used in civil and mining engineering site investigations. The value of such an approach is discussed, citing a number of recent British examples.

RESUME : Pendant la décade actuelle les projets en relation avec le génie civil souterrain ont augmenté peu à peu, aussi bien en nombre qu'en complexité. Dans la recherche correspondante du sous-sol, les erreurs d'identification des difficultés potentielles qui découlent de la présence d'eau souterraine dans des formations de grande perméabilité, peuvent, comme il arrive souvent, conduire à un retard onéreux et/ou à des variations du projet. L'application de concepts hydrogéologiques à l'acquisition et à l'évaluation de données d'eau souterraine, diffère dans sa philosophie et ses techniques de la méthodologie habituellement utilisée dans les recherches du génie civil et des mines. On discutera l'utilisation de ces concepts, à partir d'exemples britanniques récents.

RESUMEN : Durante la década actual los proyectos relacionados con la ingeniería subterránea han aumentado paulatinamente, tanto en número como en complejidad. En la correspondiente investigación del subsuelo, los errores al identificar las dificultades potenciales derivadas de la presencia de agua subterránea en formaciones de alta permeabilidad, pueden ocasionar, y de hecho ocasionan, un retraso oneroso y/o variaciones de proyecto. La aplicación de los conceptos hidrogeológicos a la adquisición y evaluación de datos, relativos al agua subterránea, difiere en su filosofía y sus técnicas de la metodología normalmente utilizada en las investigaciones de ingeniería civil y minería. Se discute el valor de estos conceptos, en base a ejemplos británicos recientes.

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1. INTRODUCTION

The presence of geological formations of high permeability* at a site in which underground works are planned to extend below the piezometric surface, poses special engineering problems. These problems relate both to the construction phase and to the permanent design. Their solution will generally involve:-

(a) groundwater lowering by a variety of pumping techniques (involving the abstraction of large quantities of groundwater) to produce either soil/rock drainage or to reduce hydrostatic uplift,

(b) groundwater exclusion by construction of a cut-off to an impermeable stratum, or by reduction in soil/rock permeability, using grouting or groundwater freezing methods,

or some combination of these techniques.

Realistic evaluation of the costs** of the various options has to be made to select the most effective design. This requires detailed information on the occurrence and movement of groundwater at the site. Such data are also vital in the planning of construction work. All too often unexpected groundwater conditions are encountered during the course of construction; this can be very costly when it occurs on the critical path of a major project. Even when simple empirical solutions such as short-term wellpoint dewatering or a crash programme of grouting are available, their implementation may not be compatible with site conditions or project timing.

The types of problem posed by the presence of highly permeable strata differ considerably from those associated with subsurface engineering in saturated strata of low permeability, where drainage or exclusion of groundwater is not a major problem and more important issues include the assessment of stability and settlement. Civil and mining engineering site investigation techniques, based on the classical theories of soil and rock mechanics, are well developed to handle the latter types of problem. The collection and evaluation of groundwater data in permeable formations, however, is an aspect of site investigation which appears to have been rather neglected.

On the other hand, hydrogeological science has developed rapidly in the past 20-30 years, primarily in relation to the need for improved methods in the exploration, development and management of groundwater resources. The authors claim that the adoption of a hydrogeological approach to engineering groundwater problems, both in the philosophy and the techniques of investigation, is attractive from a number of points of view.

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* with general or local hydraulic conductivity exceeding, say, 20 m/d

**capital and running costs must be distinguished and the cost of temporary works during construction included

2. FEATURES OF THE HYDROGEOLOGICAL APPROACH

(A) PHILOSOPHY

A basic feature of the hydrogeological approach to the collection and evaluation of groundwater data is that it treats the groundwater at the site of the proposed engineering works not in isolation, but in the context of the hydrogeological system to which it pertains. To understand the groundwater conditions at a given site, it is necessary to appreciate the major controls on the system as a whole and, in the case of permeable strata, this may involve direct investigation some kilometres beyond the limit of the site itself. This is because the boundaries and recharge of the groundwater system, rather than its hydraulic properties, will be the dominant factor in determining long-term drainage quantities. For example, an excavation in a highly permeable formation (K greater than 100 m/d) of limited area (say less than 10 km^2) would be confronted with a major groundwater problem during construction, but after large quantities of groundwater had been drained from storage, the subsequent pumping requirement would be limited.

In humid climates the piezometric surface of a groundwater system may show large natural variation, seasonally, following infiltration of rainfall. The variations will be particularly pronounced in fissured bedrock formations characterised by low specific yield, such as the British Chalk, where seasonal water-table fluctuations in the outcrop areas frequently exceed 10 m and sometimes 20 m. Man-made influences on the piezometric surface, such as those due to the pumping of adjacent water-supply boreholes, must also be taken into account during site investigation, especially if these boreholes may be shutdown during part of the year, causing recovery of groundwater levels. Thus it is important that the collection of groundwater data is not limited to a single occasion, and it is highly desirable in certain cases to collect data for a period of at least one water-year, using continuous monitoring equipment.

The hydrogeological approach to the evaluation of groundwater data requires a full understanding of the related groundwater system. It will therefore include an assessment of the effects on groundwater resources of proposed groundwater drainage at the site of underground works and of the disposal of drainage waters. Such effects might include:-

(a) Unnecessary loss of valuable groundwater resources and, in particular, regional lowering of the water-table which could reduce the yield of water-supply boreholes.

(b) Changes in groundwater quality, prejudicing the water-supply function of the aquifer.

(B) TECHNIQUES

The quality of groundwater data collected during many civil and mining engineering site investigations is often poor, commonly being recorded from boreholes as drilling advances. If data collection is restricted to such measurements there is risk of misinterpretation of the groundwater conditions and of missing important points of detail. Hydrogeological methods would introduce a more rigorous approach to the collection of groundwater level data, involving the use of carefully designed and installed observation boreholes and/or piezometers, whose water levels would be regularly or continuously measured over as long a period of time as possible.

In a short paper of this type, no attempt will be made to detail hydrogeological techniques, on which there is substantial literature. Only those aspects where application of such techniques could be especially useful in civil and mining engineering site investigations will be identified.

Single borehole techniques* for the estimation of the hydraulic conductivity of permeable strata are normally used in civil and mining engineering site investigation. The limitations of such tests must be recognised. Their results may be highly dependent on ground disturbance caused by the drilling process itself, and underestimation of permeability may result from the presence of a drilling smear on borehole walls. Hydrogeological method always requires a borehole to be cleaned-out before permeability testing, and even before static water-level measurement. In the few instances where pumping tests with observation boreholes are conducted for civil and mining engineering purposes, the approach is unnecessarily empirical. The application of non-equilibrium methods of pumping-test analysis, now standard practice in hydrogeology (Kruseman & de Ridder, 1970; Lohman, 1972; Walton, 1962), is more attractive and likely to yield more satisfactory values for the formation hydraulic properties. At the same time, these methods permit evaluation of the influence on the groundwater system of nearby boundaries, such as rivers, which will greatly modify its response to pumping, whether for dewatering or for water-supply purposes. It must be recognised that drawdown in pumping wells includes a component of well losses, which must be identified during analysis. In hydrogeology great care is paid to the design of pumping tests, and in particular to the degree of penetration of pumping wells and observation boreholes; failure to do this can easily lead to highly erroneous results.

At engineering sites on those bedrock formations of sedimentary and volcanic character, which allow significant regional fissure flow of groundwater, the level and thickness of the main fissured horizons

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*rising or falling head tests and, occasionally, water injection tests in sections of boreholes isolated by packers will be a most critical factor. Conventional permeability testing is not sufficient to determine this and, in hydrogeology, supplementary methods of investigation have been developed, involving laboratory testing of core samples (Lovelock, 1970; Price, 1977) and geophysical borehole flow logging (Tate et al, 1970, Tate & Robertson, 1975). It is known that groundwater inflows into boreholes are normally associated with variations of electrical conductivity and/or temperature of the borehole fluid column: such variations may be small (less than 0.05°C and 1 µmho/cm) but are detectable using sufficiently sensitive geophysical logging equipment. The changes of temperature and conductivity in a pumped borehole which occur with the change from static to dynamic conditions will normally indicate the main levels of groundwater flow. The vertical flow rate to the pump may be measured by impeller and heat-pulse flowmeters (for high and low velocities respectively). Although the hydraulics of borehole flow are complex, these measurements, when carefully interpreted, can indicate the relative contributions from various levels in the borehole and therefore the main fissured horizons. Such methods are valuable for the investigation of formations where most of the fissures are subhorizontal, but of limited value where fissure flow is localised in occasional vertical joints and faults; here it is necessary to resort to surface and between-borehole geophysical techniques, the results of which cannot be quantified in hydraulic terms.

For complex groundwater problems, hydrogeological data analysis often includes computerised mathematical modelling. The use of such models may not be restricted to interpretation but can also be useful at the investigation stage, in assessing the sensitivity of the problem to variation of the relevant parameters.

3. BRIEF CASE HISTORIES ILLUSTRATING HYDROGEOLOGICAL APPROACH

(A) URBAN MOTORWAY TUNNEL

Current awareness of the need to conserve land resources and the urban environment is causing transportation routes (highways, railways) and major services to go underground. The associated engineering works are frequently bedevilled by the presence of groundwater in strata of high permeability.

For example, there is a project to construct a 6-lane highway of nearly 2 km length in a cut-and-cover tunnel at a site in south-eastern England. The geological conditions along the line of the motorway tunnel were determined by standard site investigation and soil survey and are summarised by a detailed longitudinal section (Fig 1). In this case the strata of high permeability are the Upper Glacial Gravel

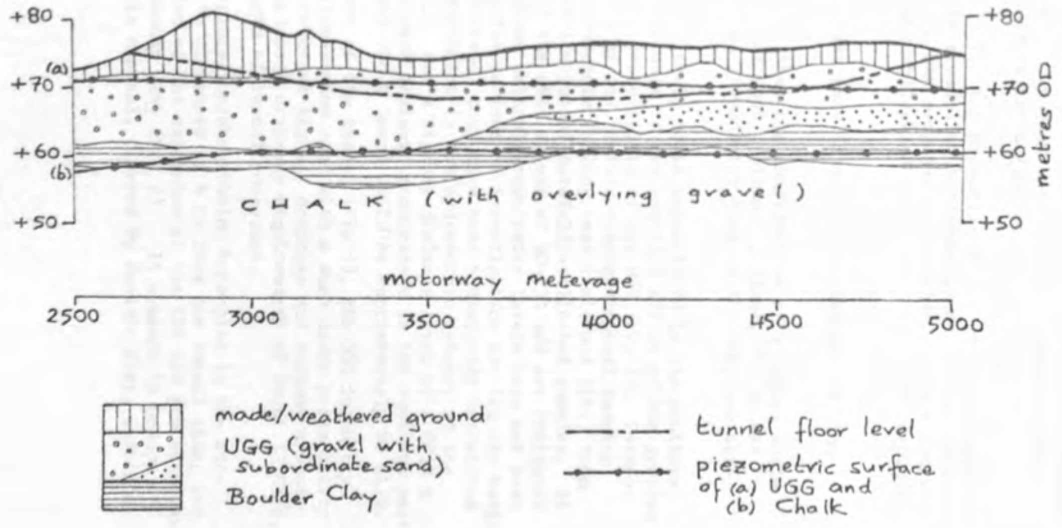

Fig 1: Longitudinal geohydrological section of motorway tunnel
(vertical exaggeration X 20)

(UGG) and the Chalk; the latter represents the major aquifer of the region with a piezometric surface of about +60 m OD at the site. The initial site investigation showed some indications of a groundwater body in the UGG, perched well above the regional Chalk piezometric surface by the intervening Boulder Clay. Further evaluation was not possible because groundwater data were only collected during drilling in this initial site investigation.

The authority responsible for the promotion of the road construction programme decided to seek specialist hydrogeological advice. Supplementary site investigation was proposed and mounted, using a hydrogeological approach to the collection and evaluation of the groundwater data.

The investigation, which was carried out in two phases, had the following outcome:-

(a) The initial suspicion that the construction of a tunnel would be confronted by significant drainage problems, due to the existence of a perched groundwater body in the UGG, was confirmed.

(b) Great difficulty was likely to be encountered in the southern part of the tunnel because of the combined effect of the greater thickness and higher permeability of the UGG (Fig 1). Permeability was estimated by (i) limited hydrogeological pumping tests, (ii) single-borehole falling head tests and (iii) from the grain-size distribution of carefully-collected samples. At the southern end of the site values of 50-250 m/d are indicated for the UGG. Maximum natural groundwater levels have not been experienced during the periods of investigation but (on the basis of fluctuations observed) they have been tentatively correlated from observation boreholes in the hydrometric network of the surrounding region. For a highway drainage level of + 68.0 m OD, the associated peak drainage requirement in the southern part of the tunnel (about 700 m long) would be approximately 60 Ml/d.

(c) In the northern part of the tunnel (Fig 1), the UGG is partly represented by a fine-medium sand with a much lower permeability (3-10 m/d). The relevant highway drainage and maximum groundwater levels suggest peak drainage requirements of about 12 Ml/d, for the 1000 m length of tunnel concerned.

(d) The drilling of exploration/observation boreholes in the surrounding area, up to distances of 4 km from the tunnel site, has permitted definition of the extension of the UGG and its associated perched groundwater body (Fig 2). It appears to occupy a secondary asymmetric channel, floored by Boulder Clay, within a

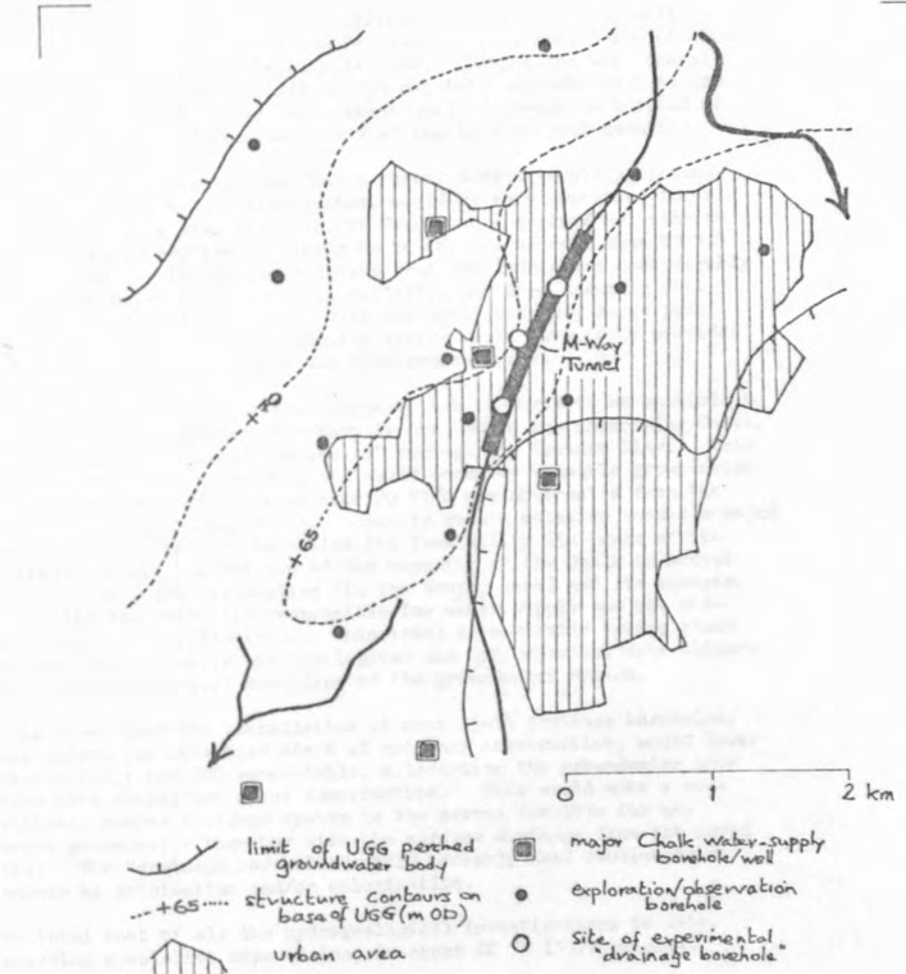

Fig 2: Hydrogeological location of motorway tunnel

much larger channel in the Chalk bedrock, about 4-6 km wide and filled with a variety of superficial deposits. The overall surface extension of the UGG is about 14 km^2, some 3 km^2 of which is built-up and artificially drained. Taking the mean annual infiltration from rainfall as 250 mm, this suggests that in the long-term the drainage requirement would decrease to a total of less than 8 Ml/d, ie. about 10% of the initial peak quantity.

Preliminary evaluations show that a tunnel design involving groundwater exclusion, by whatever system, would be very expensive for a structure of this size and that, if feasible, a drained solution to the groundwater problem is likely to be cheaper by more than £M 1.0 (1977 prices). The design motorway drainage levels are considerably below local sewer and stormwater outfalls, and even assuming that the existing system could cope with the predicted very large peak drainage flows, a permanent pumping system would have to be provided with associated high running and maintenance costs.

The hydrogeological conditions suggest that it ought to be possible to drain the perched groundwater body in the UGG to the underlying Chalk, by constructing "drainage boreholes" through the Boulder Clay. This solution would be inexpensive and would conserve valuable groundwater resources in an area in which over 20 Ml/d are abstracted from the Chalk for public supply alone. Clearly such a solution needed a major field trial in order to establish its feasibility (in terms of its ability to drain the UGG and of the capacity of the Chalk to accept the recharge), its reliability (in the longer term) and its acceptability (to the authority responsible for water supply and the prevention of water pollution). This trial is currently taking place and involves intensive hydrogeological and hydrochemical data collection, and mathematical modelling of the groundwater system.

It is hoped that the installation of some 25-35 drainage boreholes, long before the scheduled start of motorway construction, would lower substantially the UGG water-table, alleviating the groundwater problems both during and after construction. This would make a conventional pumped drainage system to the sewers feasible for any excess groundwater together with the surface drainage from the paved area. The "drainage boreholes" would probably need routine maintenance by acidisation and/or chlorination.

The total cost of all the hydrogeological investigations to date, including specialist supervision, is about £K 70 (1977 prices).

(B) ACCESS WAYS TO DEEP COAL MINES

Britain has large deposits of coal, which have been exploited since the beginning of the industrial revolution. The exposed Coal Measures were developed first, followed by those buried at shallower depth, and today the exploitation of new deposits usually involves extracting coal from beneath a thick cover of younger sediments. These sediments commonly include large thicknesses of Permo-Triassic Sandstones, which are highly permeable and constitute a major national aquifer.

The groundwater in the Permo-Triassic formations is not usually in hydraulic communication with mine workings in the Coal Measures because of impermeable strata in the intervening Upper Carboniferous or Lower Permian. However access shafts and drifts* for coal removal must frequently pass through the Permo-Triassic Sandstones.

For example, the National Coal Board in Britain was faced with the problem of driving a drift for about 300 m through Permo-Trias Sandstones, 50-60 m thick and including the highly permeable Bunter Pebble Beds, to meet extended workings at an existing mine (Grieve, 1973). One of the early shafts at the mine was reputed to have had groundwater flows at the construction face of up to 35 l/s. A public water-supply pumping station, about 600 m from the colliery, was pumping an average of 1.6 Ml/d from the Permo-Trias and an abandoned mine shaft was pumped at more than 1.0 Ml/d for industrial use at the colliery itself (Fig 3), so the water-bearing capacity of the sandstones was well established. Hydrogeological advice was therefore sought for the assessment of the hydraulic properties of the Permo-Trias at the site and so facilitate selection of the most suitable method of excluding water during construction and design of the drift lining.

In the first stage of the hydrogeological investigation, two boreholes were drilled and a pumping test carried out, using BH2 as the pumping well and BH1 for observation (Fig 3). This test indicated a transmissivity in excess of 2000 m /day, but later in the test the effect of at least one hydraulic barrier boundary (believed to be a known fault, the Eastern Fault in Fig 3) was detected. Two more observation wells (BHs 3 and 4) were drilled and further pumping tests carried out. The striking feature of these tests was the failure of Bh 4 to respond to pumping, despite cleaning and development. This was attributed to the presence of a second barrier boundary between BHs 2 and 4 (the conjectural Western Fault in Fig 3). It thus appears that, coincidentally, the line of the proposed drift lies between two hydraulic barrier boundaries. In practical terms this means that

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* an inclined access tunnel

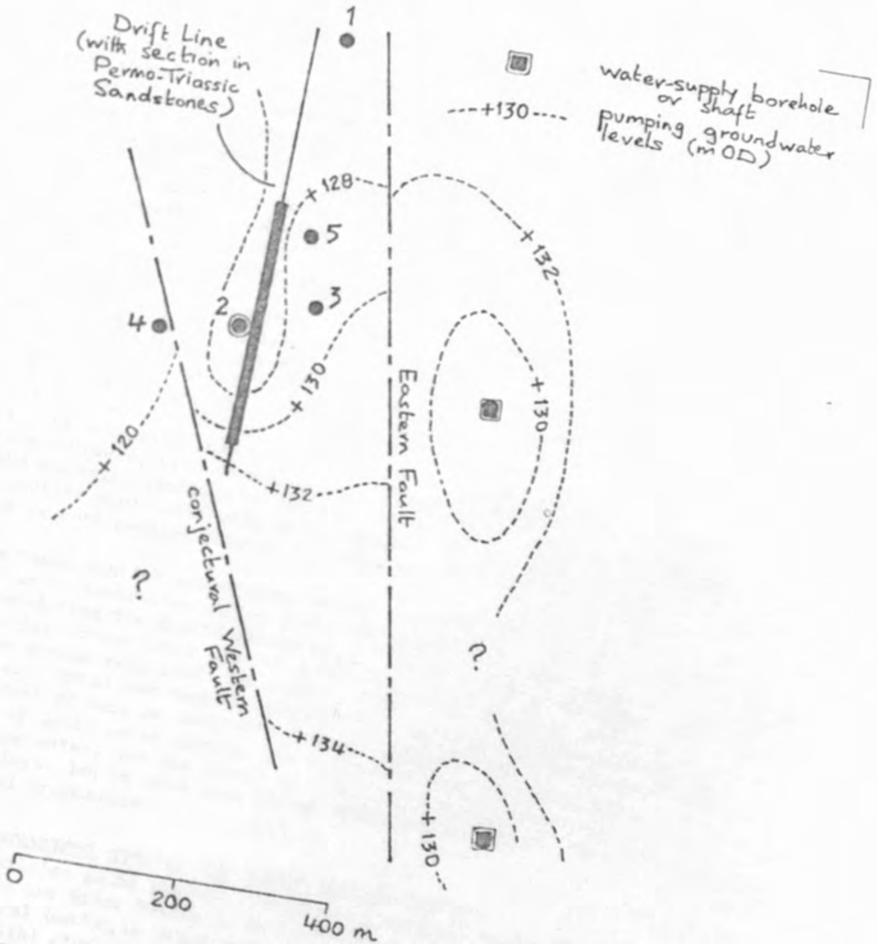

Fig 3: Hydrogeological location of mine drift

dewatering of the Permo-Trias by means of specially-drilled abstraction boreholes becomes feasible and preferable to grouting or to groundwater freezing, although complete re-location of the drift in more favourable geological conditions is also under consideration.

A second problem involved the sinking of a pair of access shafts through about 90 m of Permo-Triassic Sandstones overlain by 20 m of Quaternary Clays, for development of a new mine. Again, the options available for groundwater control were freezing, grouting or dewatering. A hydrogeological test programme was devised which included the drilling of a cored pumping well and an observation borehole. Laboratory tests were carried out on the core material for the determination of intergranular properties. On site a 5-day pumping test at an abstraction rate of 13.5 l/s was carried out and supplemented by geophysical borehole flow and formation logging.

The laboratory measurements, on samples taken at 2 m intervals in the cored borehole (Fig 4), indicated a mean intergranular permeability of about 0.8 m/d, corresponding to an intergranular component of transmissivity of about 70 m^2/d. The pumping test suggested that the total transmissivity was about twice this value; the implication that some fissure flow must account for the difference was supported by the flow logging investigations. Pumping test analysis was straightforward, with no boundaries or leakage being detected and the sandstone being confined by the overlying clays. During dewatering, the aquifer would obviously become unconfined, and laboratory measurements on core samples indicated a specific yield of about 0.18.

Given these aquifer properties, it was apparent that the amount of water to be abstracted during construction would be more than could be pumped from the shafts themselves. It was calculated that a dewatering scheme could only be successful if a ring of boreholes was drilled around each shaft to create a 'dry' cone in which work could proceed. Total abstraction rates up to about 200 l/s were predicted. The effect of such an abstraction on the aquifer, which is an important source of local water supply, the difficulties of disposing of the discharge water, and the danger of troublesome settlement of the overlying clays, led in this case to the abandonment of dewatering as a practical proposition.

(C) ENVIRONMENTAL STUDIES FOR THAMES BARRIER PROJECT

A multi-million pound project to construct a tidal flood-prevention barrier on the River Thames in Woolwich Reach, some 10 km downstream from Central London, is being carried out. A number of related environmental studies of the river estuary and the flood plain were commissioned. These included a survey of the groundwater conditions in the Lower Thames Flood Plain and an assessment of the relationship between the river and the groundwater system in the area, in special

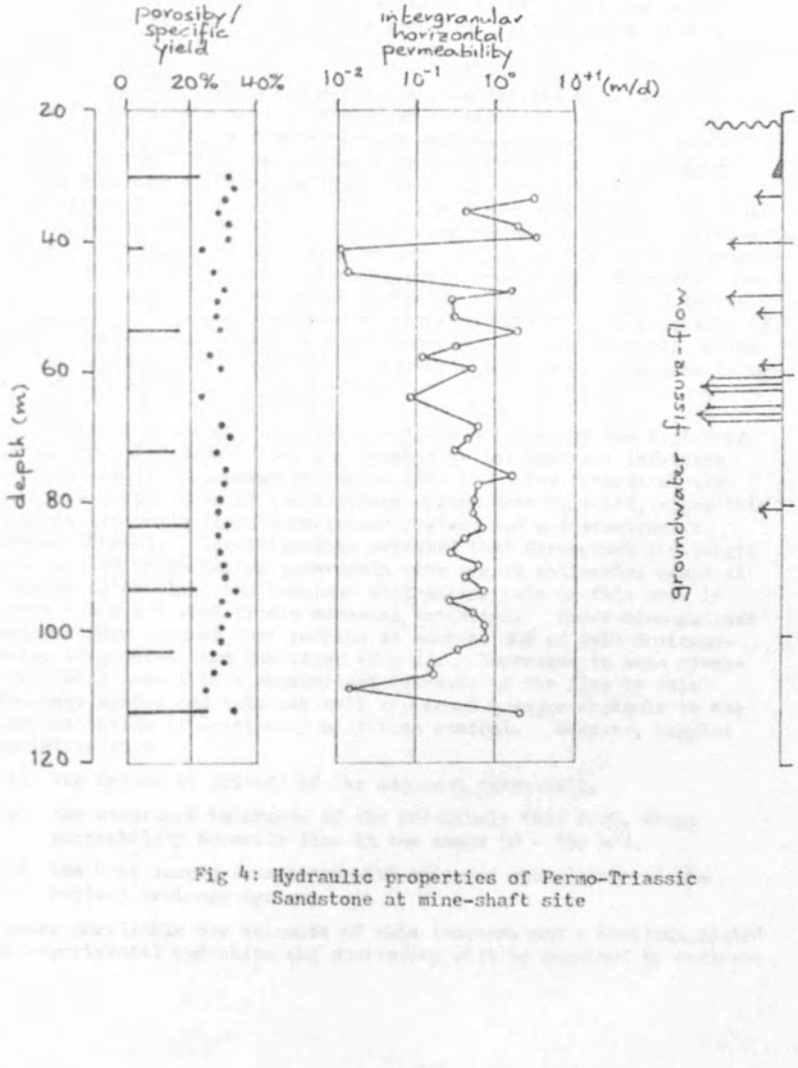

Fig 4: Hydraulic properties of Permo-Triassic Sandstone at mine-shaft site

relation to the construction of the barrier and its operation for half-tide control (involving a long-term increase of mid-tidal river level of 1.2 - 1.5 m throughout Central London). Although this study does not directly concern the construction of subsurface engineering works, some of the results illustrate well the need for a hydrogeological approach if the groundwater problems related to subsurface structures are to be understood.

Over 60 shallow observation boreholes were drilled in an area of the Flood Plain Terrace Gravel (FPTG) extending up to 15 km from the barrier site, and their water levels were monitored, with float-operated recorders housed in manholes beneath pavements, during a 1-2 year period (Foster, 1971). The results were related to information on the riverwalls and on the drainage arrangements within major subsurface structures (Fig 5). To varying degree the riverwalls cut-off hydraulic communication between the river and the FPTG groundwater and the creation of extensive paved areas, with stormwater sewers for road-and-roof drainage, has virtually eliminated natural infiltration from rainfall over much of the Flood Plain. Additionally in the Central London area, two very important man-made controls on the shallow groundwater regime can be recognised - one on each bank (Gray & Foster, 1972).

On the north bank, the permanent drainage measures of the District/Circle Line Underground Railway constitute the dominant influence over the shallow groundwater regime (Fig 5). Few records of the design and operation of the drainage system have survived, since this was the capital's first underground railway and was constructed around 1866-69. Investigations revealed that throughout its length the railway track has an underdrain with pumped collecting sumps at regular intervals; the combined abstraction rate in this area is about 6.8 M l/d with little seasonal variation. Order-of-magnitude calculations suggest that perhaps as much as 90% of this drainage-water originates from the river (Fig 6). Increases in mean river-level will result in a concomitant increase in the flow to this drainage system and this may well represent a major obstacle to the implementation of continuous half-tide control. However, complex variation in:-

(a) the degree of cut-off of the adjacent river-wall,

(b) the saturated thickness of the relatively thin FPTG, whose permeability normally lies in the range 50 - 150 m/d,

(c) the head losses associated with entry of groundwater to the railway drainage system,

render unreliable any estimate of this increase and a cautious period of experimental operation and monitoring will be required to evaluate

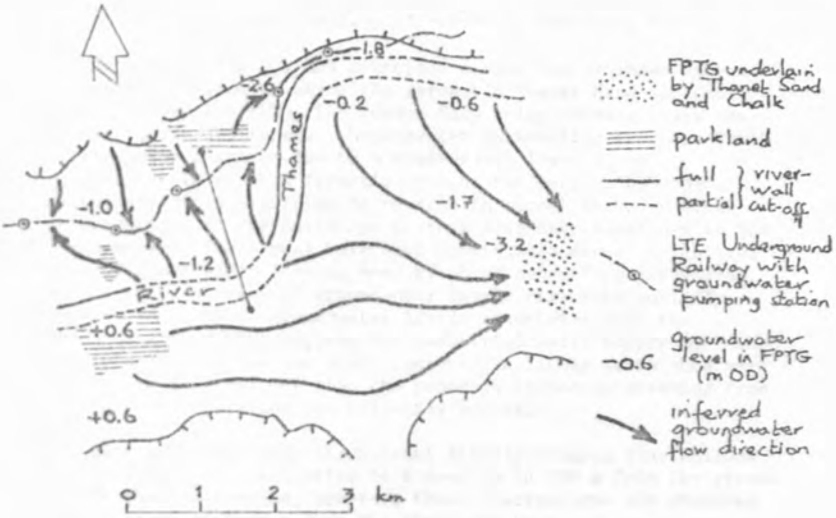

Fig 5: Groundwater flow regime in the Thames Flood Plain of Central London

Fig 6: Hydrogeological section from the River Thames to the LTE Underground Railway

(line of section in Fig 5; vertical exaggeration X 35) the severity of the problem. The factor of safety with respect to pumping capacity, at each of the principal pumping stations, appears to be about 4.0, but the present state of the drains themselves is not known. Similar drainage systems exist in other sections of the older, shallow underground railway elsewhere in the Flood Plain.

On the south bank (Fig 5), the principal subsurface drainage appears to be towards the area in which the permeable Thanet Sand and Chalk directly underlie the FPTG, the London Clay being absent; here the FPTG is virtually dewatered. Groundwater abstraction from the Chalk for water-supply purposes led to a progressive lowering of groundwater levels in that formation during the period 1890-1940, though the effect is beginning to reverse in recent years. Since a high proportion of the buildings in this area have basements in the FPTG, and many of these must have been constructed since the initial lowering of groundwater levels, many of these subsurface structures are likely to be at risk if groundwater levels rise substantially. However the recovery of groundwater levels associated with the cessation of groundwater pumping for industrial water supply (because of quality deterioration and other factors) is likely to be much more significant in this respect than the probable increases stemming from proposed barrier operation for half-tide control.

In the Central London area, significant tidally-induced fluctuations in groundwater level are limited to a zone up to 100 m from the riverbank. Further downstream, however, these fluctuations are observed over much larger distances from the river due to:-

(a) the deeper base of the FPTG and the reduced cut-off of the river-wall,

(b) the thickening cover of alluvial silts and clays which confine the FPTG groundwater system (Fig 7).

The transmission of diurnal head changes in a tidal river to adjacent groundwater systems is a function of two essentially distinct processes:-

(a) Transfer through the riverbed and riverbank, which may, in the presence of a compressible low-permeability riverbed deposit, reduce the tidal ratio[*] (TR) greatly,

(b) Propagation laterally away from the river, which will be a function of the hydraulic properties of the groundwater system and those of any confining strata.

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[*] ratio between the response of the groundwater system and the corresponding diurnal change of tidal head in the river

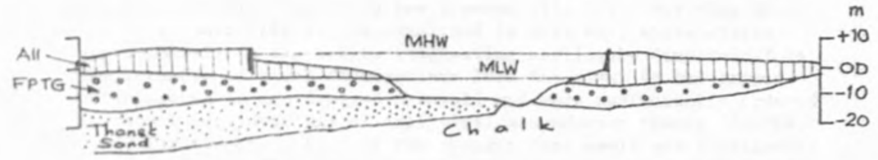

Fig 7: Geological conditions across the River Thames in Woolwich Reach (vertical exaggeration X 5)

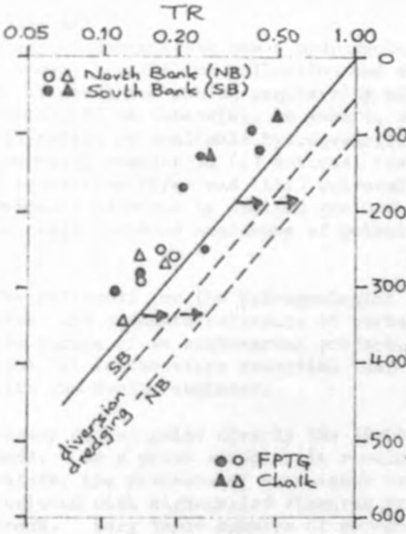

Fig 8: Analysis of the propagation of groundwater tides from the River Thames in Woolwich Reach

In analysing the groundwater TR data at the barrier site(Woolwich Reach)it was thus necessary to express distances of observation boreholes and piezometers from the nearer edge of the main dredged channel and not from the river frontage, since substantial thicknesses of riverbed deposits are present (Fig 7). The "log TR - distance" data (Fig 8), rationalised in this way, extrapolated approximately to the origin (suggesting negligible "impedance" to the transfer of tidal fluctuations from the river to the groundwater system in the dredged channel) and were sufficiently ordered to permit confident use of analytical groundwater theory (Ferris, 1963) for the prediction of the changes that would occur following the dredging of diversion channels and excavation for pier foundations associated with barrier construction. The predicted substantial increases in the magnitude of "groundwater tides" (Fig 8), were in fact first recorded in the winter of 1974, when dredging diverted the main navigation channel some 100 m to the north by removing the riverbed sediments from the FPTG. A similar effect is expected to occur on the south bank following the second planned diversion dredging, and the influence on any existing subsurface structures in the area is being kept under careful observation.

4. CONCLUDING REMARKS

The preceding examples demonstrate how a hydrogeological approach can, in certain cases, benefit the collection and evaluation of groundwater data at civil and mining engineering sites. At the present time however, it is impossible to ensure, and not easy to promote, the utilisation of available hydrogeological expertise. This expertise normally resides in (i) national research organisations, (ii) specialist consulting firms and (iii) universities. Improvements in undergraduate lectures in applied geology for civil and mining engineers could increase awareness of potential groundwater problems.

In turn it can be difficult for the hydrogeologist to appreciate fully the technical and economic relevance of certain groundwater conditions to the design of an engineering project. If involved in site investigation, it is therefore essential that he should work in close liaison with the design engineer.

It is also necessary to recognise clearly the limitations of hydrogeological methods. As a prime example, it remains difficult to establish, or refute, the presence of occasional zones of permeability development associated with high-angled fissures in otherwise nearly impermeable bedrock. Very large numbers of boreholes would be needed for an exhaustive investigation. It is unrealistic to expect that sufficient funds will be available to elucidate every relevant subsurface feature before proceeding with construction. The specialist must assess, while investigation proceeds, what features affecting design and construction could conceivably exist but may not have been identified. A decision can then be taken on whether it is necessary to investigate further the risk of such possibilities. In certain cases the related problem can be overcome during construction with little additional expense, providing the possibility of its existence was foreseen at the outset and contingency plans laid.

In any event we should guard against a stereotyped approach to site investigation —— whether or not it involves hydrogeological work. In subsurface engineering every site should be considered individually, with careful thought about what the site investigation needs to discover.

ACKNOWLEDGEMENTS

This paper is published by permission of the Director of the Institute of Geological Sciences and with the encouragement of its Chief Hydrogeologist, Mr John Day. Various colleagues, especially Michael Bird, John Chilton and Alan Cripps, are thanked for their assistance in the original investigations.

The work described was carried out in Britain respectively for the DoT Eastern Road Construction Unit, the National Coal Board and the Greater London Council, who are thanked for their support of the work and agreement for its presentation.

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The Institution of Civil Engineers

PROCEEDINGS

December 1977
Volume 63

Research and Theory

Proc. Instn Civ. Engrs, Part 2, 1977, 63, Dec., 803–817

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Evaluation of a semi-confined Chalk aquifer in East Anglia

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About 4000 km^2 of East Anglia are underlain by a semi-confined Chalk aquifer: semi-confined in the sense that it is buried beneath a variable suite of glacial deposits which, to varying degree, confine its groundwater and reduce recharge rates from infiltration. The aquifer is a major source of water supply. It exhibits outwardly unpredictable variation in borehole yield behaviour but there has been little field research into the causes. This Paper describes an investigation at a site of public water supply abstraction in south Norfolk, and has numerous implications for the development and management of groundwater resources in much of the surrounding region.

Background

Since the early 1950s the semi-confined Chalk aquifer at Rushall (9 km east-north-east of Diss in south Norfolk (Fig. 1)) has been increasingly exploited for public water supply. Development has involved the drilling of six boreholes, and their completion as pumping wells, in a triangular site of about 800 m side; four are currently in use. All these boreholes are 400–600 mm in diameter and were completed by surge pumping and, with the exception of number 2, by acid treatment.

2. The boreholes show substantial variation in yield-drawdown characteristics (Fig. 2), numbers 3 and 5 being notably inferior. Additionally, the yields of individual boreholes have deteriorated with time (e.g. number 1 in Fig. 2). Across the region as a whole, the yields of large diameter boreholes in Chalk are normally in the range 10 l/s for 30 m drawdown to 25 l/s for 10 m drawdown.[1] Despite their close proximity and superficially similar construction, the yields of the Rushall boreholes vary from considerably below average (number 3) to well above average (number 6) (Table 1), although they do not reach the exceptional yields for small drawdowns recorded locally around Norwich and Ipswich.

Geological setting of the Rushall site

3. The concealed surface of the Chalk of much of central East Anglia is dissected by a network of buried channels, frequently narrow and often deep.

Written discussion closes 15 February, 1978, for publication in *Proceedings*, Part 2. Mr Foster will give a talk based on this Paper, entitled 'The hydrogeological evaluation of Chalk aquifers' to the East Anglian Association at the Angel Hotel, Bury St Edmunds on 18 January, 1978, at 7 p.m.

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Fig. 1. East Anglia: sub-division of the Chalk aquifer

Woodland[2] described these features as 'buried tunnel valleys' and regarded them as sub-glacial in origin.

4. The Rushall site (Fig. 3) is close to the edge of a buried valley, a tributary to the Waveney system.[2] The depth of the Chalk surface varies by as much as 23 m across the site, from +9 m OD in borehole 6 to − 14 m OD in borehole 3.

5. Away from the line of the buried valley at Rushall, the Chalk is overlain by 25–35 m of glacial deposits (Fig. 4), which in upward sequence comprise

- (*a*) well-sorted sands and sandy gravels, probably representatives of one of the East Anglian Pleistocene crags
- (*b*) a complex Boulder Clay series with rapid lateral and vertical changes in lithology, including consolidated silty clays, silts, numerous fine silty sands and rarer gravels.

The fill of the buried valley is recorded as being predominantly hard, dark grey silty clays with subordinate sand and gravel, suggesting post-Crag sub-glacial formation. About 2–3 km south-east of the Rushall site, on the limb of the East Suffolk syncline, the general level of the buried Chalk surface drops steadily and the thickness of the overlying Crag increases substantially (Figs 3 and 4).

6. At the surface the Rushall site is relatively flat, being on the broad interfluve between the valleys of the Pulham Stream to the north and the River Waveney to the south (Fig. 4).

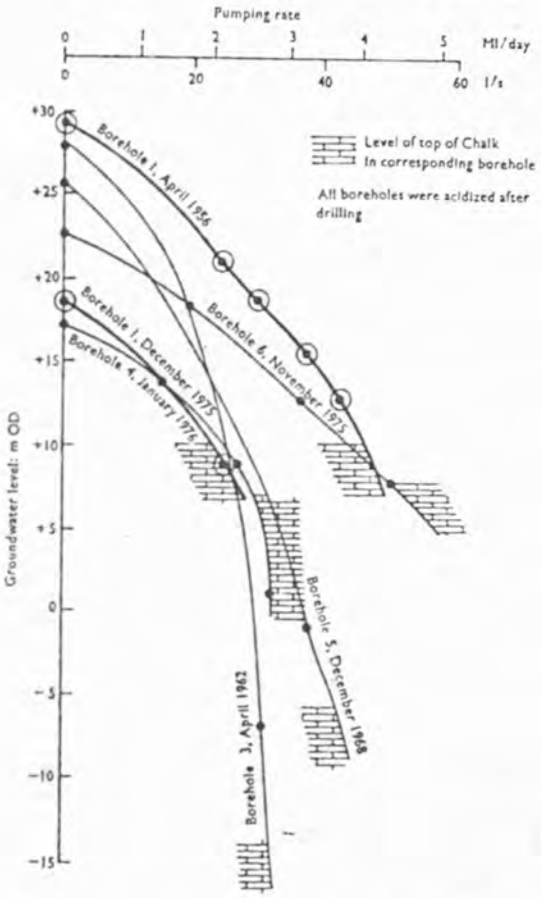

Fig. 2. Yield–drawdown characteristics for Rushall pumping boreholes

Table 1. Rushall production boreholes; drawdown comparison for yields of 25 l/s and 40 l/s

		Borehole 1	Borehole 3	Borehole 4	Borehole 5	Borehole 6
Drawdown (in metres) for pumping rate of	25 l/s (2·2 Ml/day)	10	19	9	14	6
	40 l/s (3·5 Ml/day)	17*	†	15*	30	11

* No longer obtainable. † Never obtainable.

Geophysical investigation of Chalk groundwater flow

7. During 1975–76 comprehensive borehole flow logging investigations were undertaken at Rushall in some of the production diameter boreholes (numbers 1, 3, 4, 5 and 6 in Fig. 5) and in the purpose-drilled observation boreholes of 150 mm diameter (numbers 7A and 8A in Fig. 5). The methods used are described in part by Tate *et al.*[3]

8. Groundwater inflows into boreholes are normally associated with variations of electrical conductivity and/or temperature of the borehole fluid column. Such variations, although sometimes small (less than 0·01degC and 1 μmho/cm), may be logged using sufficiently sensitive equipment.[4] The changes of the temperature/conductivity logs from the rest condition during the onset of pumping normally indicate the main levels of groundwater flow.

9. Measurements of the vertical flow rate to the pump can be made by impeller and heat-pulse flowmeters for high and low velocities respectively. Although the hydraulics of borehole flow are complex, the measurements when carefully interpreted can indicate the relative contributions from various levels

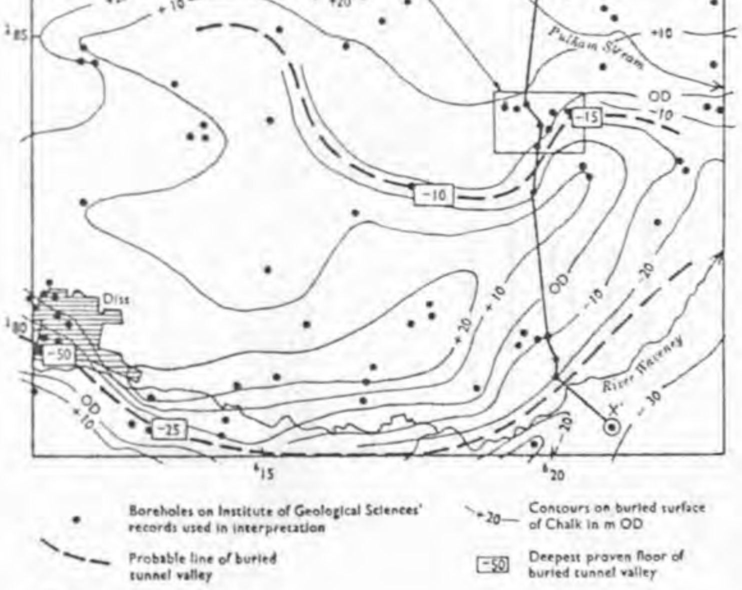

Fig. 3. South Norfolk: hydrogeological location map

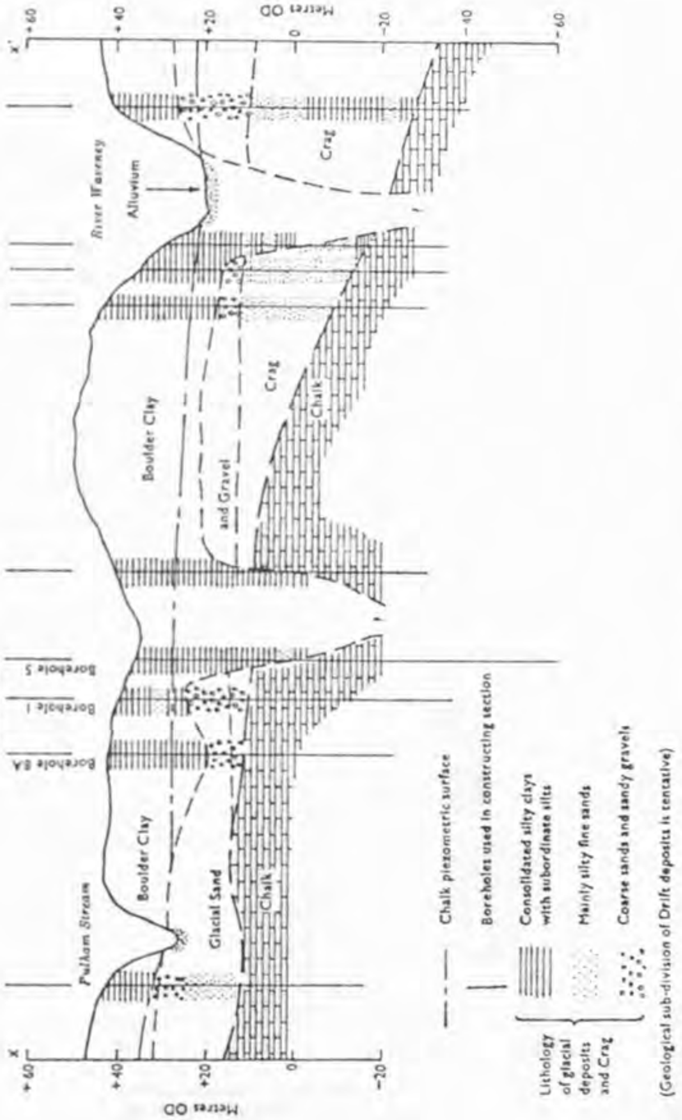

Fig. 4. Hydrogeological cross-section of Rushall site (vertical exaggeration ×45–50)

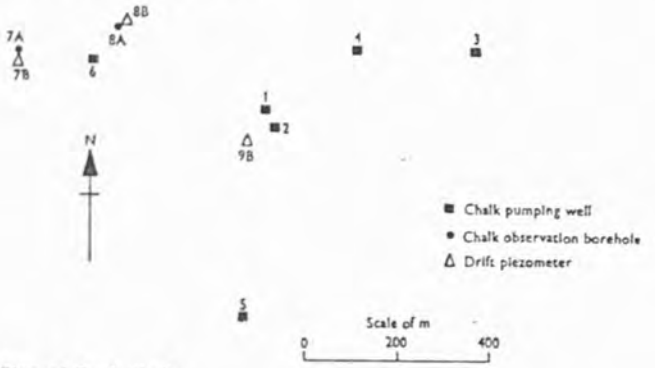

Fig. 5. Plan of Rushall site

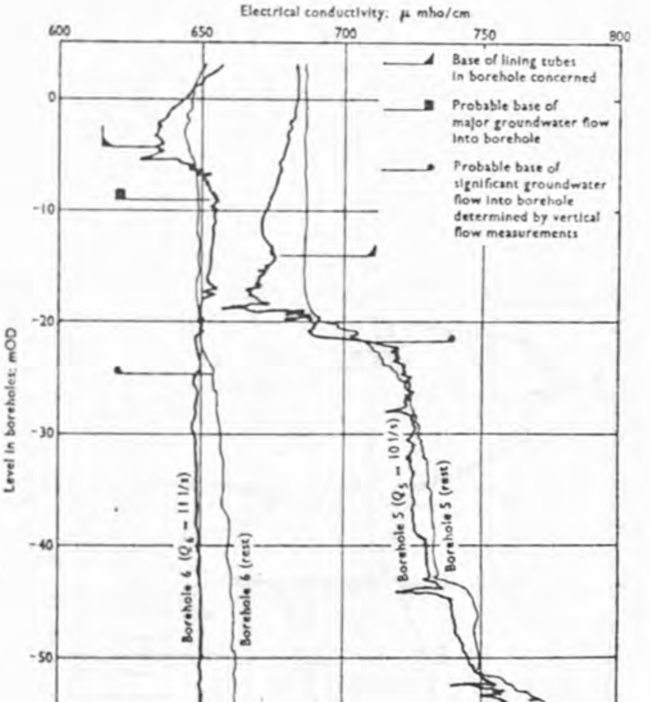

Fig. 6. Selected electrical conductivity logs of Rushall boreholes in rest and pumping conditions, boreholes 5 and 6

in the borehole (i.e. the productive zones of the aquifer). The normal configuration for flow logging is with the pump at the minimum depth necessary to sustain a low pumping rate, and at a depth which does not conflict with anticipated flow levels. Under such conditions in 500–600 mm dia. boreholes, pumping rates of more than about 2 l/s should produce, in their upper sections, vertical flows characterized by Reynolds numbers of over 4000 and with blunt rough-turbulent velocity distributions. For boreholes of 150 mm diameter the corresponding pumping rate will be about 0·6 l/s. In the lower sections of boreholes below the major inflows, laminar vertical flow with parabolic velocity distribution is likely to prevail. When both flow regimes are uniform, semi-quantitative interpretation of flow logs is possible with some confidence, but a major complication arises opposite, and for some diameters above, major groundwater inflows where grossly non-uniform vertical flows may develop.

10. At Rushall the conductivity log proved to be the more diagnostic for flow investigation; selected results are given in Figs 6 and 7. In borehole 6 (Fig. 6) the onset of pumping gives rise to a strong inflow of slightly lower conductivity water from near the base of the solid lining tubes (−4 m OD) down to −7 m OD, with indications of minor inflows below the latter depth. Measurements of vertical flow to the pump, operating at 11 l/s and situated within the solid lining tubes, showed a sevenfold decrease in velocity by about −7 m OD and a further fourfold reduction by about −22 m OD, strongly suggesting that the bulk of the yield is derived from above the former level and that probably no more than 5% originates from below the latter. Borehole 1 behaved similarly (Fig. 7).

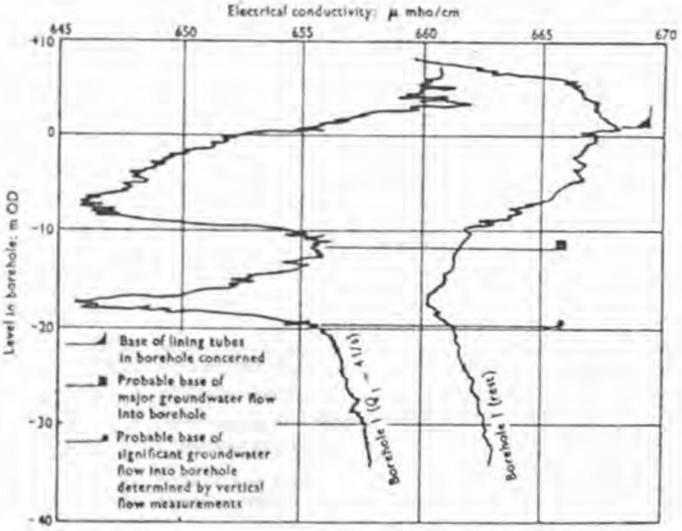

Fig. 7. Selected electrical conductivity logs of Rushall boreholes in rest and pumping conditions, borehole 1

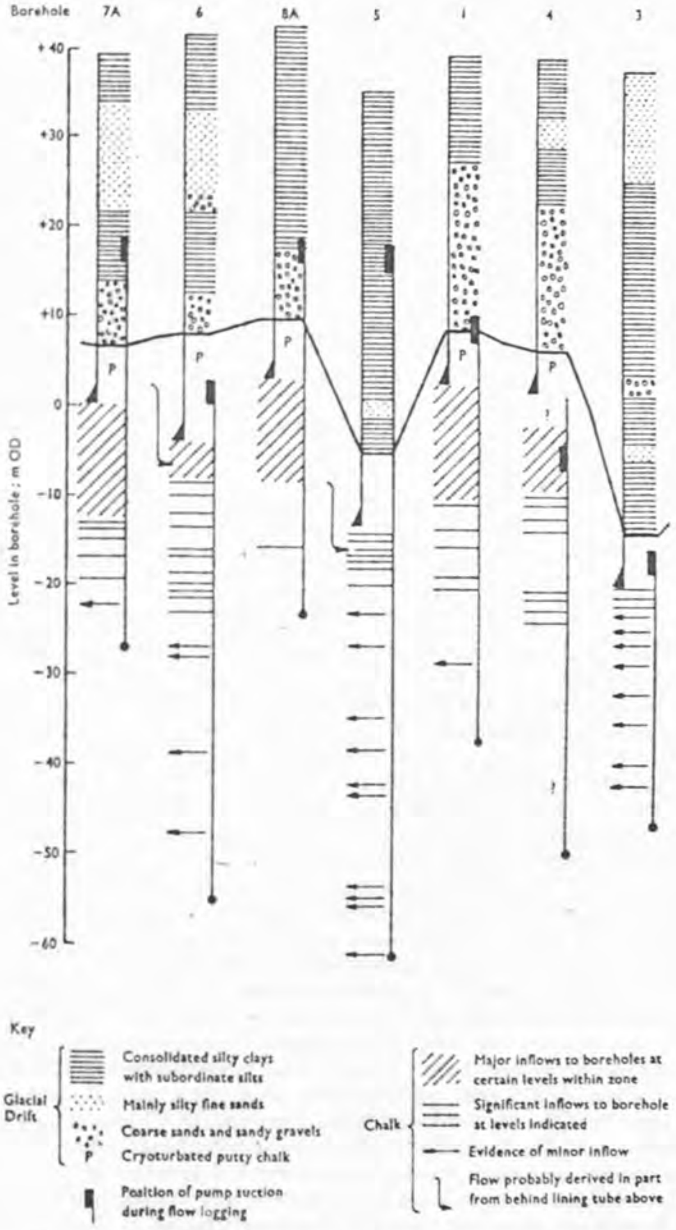

Fig. 8. Rushall boreholes: summary of Chalk groundwater flow levels and glacial drift lithologies

11. Borehole 5, on the edge of the buried valley, has a distinctive conductivity log (Fig. 6), with more saline (higher conductivity) groundwater at depth. The flow levels are again clearly marked by conductivity changes with the onset of pumping, but in this case the flow logging suggests that the minor inflows below −21 m OD are proportionally more important than in boreholes 1 and 6.

12. The overall results of the geophysical investigation of groundwater flow are summarized in Fig 8. Although the Upper Chalk alone is estimated to be over 200 m thick at the Rushall site and many of the boreholes penetrate to −40 m OD or more, the bulk of the groundwater flow to Chalk boreholes is concentrated above −20 m OD and largely above −10 m OD. Although the distribution of groundwater inflow to boreholes may be influenced to a degree by the positioning of pumps, it is suggested also that the bulk of the permeability development in the Chalk is above −10 m OD, with no highly permeable horizons below −20 m OD. Recently, the fact that substantial thicknesses of the Chalk aquifer have very low in situ permeability has been independently demonstrated at sites in Hampshire using water injection tests in cored boreholes.[5] The inferior yield–drawdown characteristics of boreholes 3 and 5 at Rushall thus appear to be due to the absence or erosion of most of the highest permeability chalk in the buried valley. The implication is that the development of high permeability, presumably due to the solution on near-horizontal discontinuities of the rock mass by naturally circulating groundwater,[6] must in substantial part geologically pre-date the formation of the buried tunnel valley.

Interpretation of aquifer test pumping

13. Systematic pumping tests were carried out in November–December 1975 by pumping boreholes 6 and 2 in turn and observing the aquifer response by monitoring the water levels in all other boreholes in Chalk. Three piezometers in the glacial deposits (7B, 8B and 9B in Fig. 5) were also measured regularly throughout the tests. Steady pumping rates of 18 l/s, 37 l/s and 49 l/s were used in the case of borehole 6 and 24 l/s was used for borehole 2. In order to satisfy the operational needs of Rushall pumping station, boreholes 3 and 4 were pumped at a steady combined rate of about 55 l/s (4·7 Ml/day) from some weeks before the start of test pumping until some weeks after its completion. This is not believed to have significantly affected the aquifer testing.

14. An example of the data collected is given in Fig. 9. The most prominent feature of all the test data is a rapid trend to equilibrium caused by marked recharge effects. The non-equilibrium observation borehole responses, for the test around borehole 6 (Fig. 9), conform tolerably to the leaky confined model[7,8] and suggest aquifer properties of about the following magnitudes: transmissivity 500 m^2/day, storage coefficient 10^{-3} and leakage factor 600 m.

15. The regional groundwater flow in the Chalk is known to be directed generally eastwards under a hydraulic gradient of less than 0·003% and is therefore unlikely to exceed 1·5 Ml/day per 1 km of flow frontage. It thus could not be the major source of rapid recharge observed in the high rate (49 l/s, 4·2 Ml/day) pumping test. The recharge is interpreted as induced downward leakage from the overlying Crag sands. The confining bed appears to be the 2–5 m thick layer of putty chalk (a glacial cryoturbation product) between the base of the Crag sands and the main body of the Chalk formation (Fig. 8). The existence of leakage is corroborated by the behaviour of a piezometer in the Crag (8B),

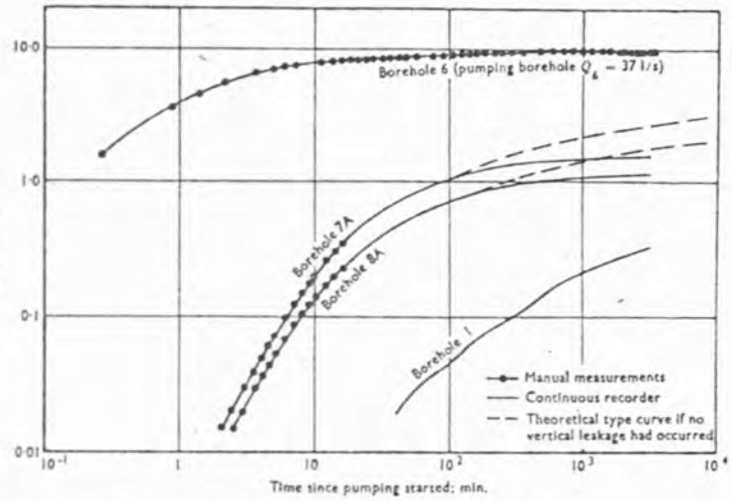

Fig. 9. Example of non-equilibrium pumping test data

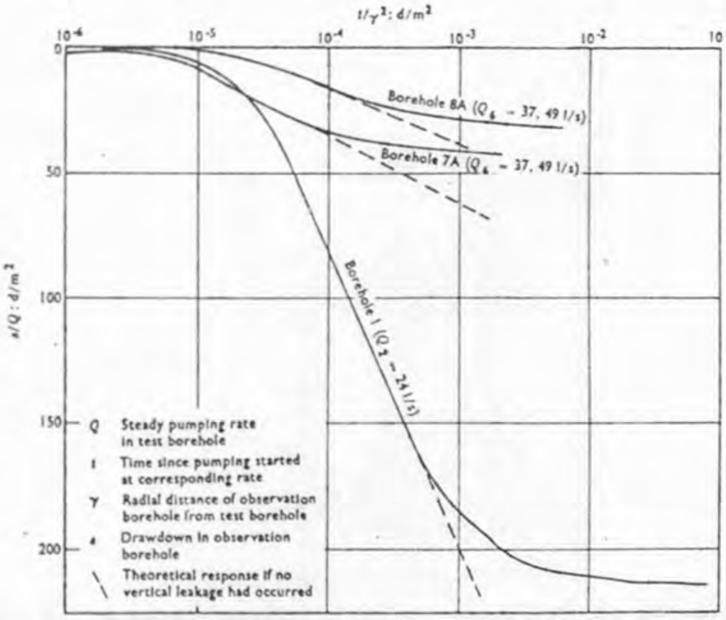

Fig. 10. Comparative plot of non-equilibrium pumping test data from Rushall site (November–December 1975)

which responded to pumping but to a smaller degree and less rapidly than in the adjacent Chalk observation borehole (8A) with the same pre-test water level. The shallower piezometers (7B and 9B) in the more sandy horizons of the Boulder Clay series recorded significantly (3–6 m) higher pre-test heads than those in the underlying Chalk, but showed no response to pumping throughout the test period.

16. The relationship between the pumping rates from borehole 6 and the corresponding observation borehole drawdowns was strictly linear, confirming a laminar flow regime in the aquifer at distances of 100 m and more from the pumping well. Similar behaviour has been observed for an unconfined Chalk aquifer.[6]

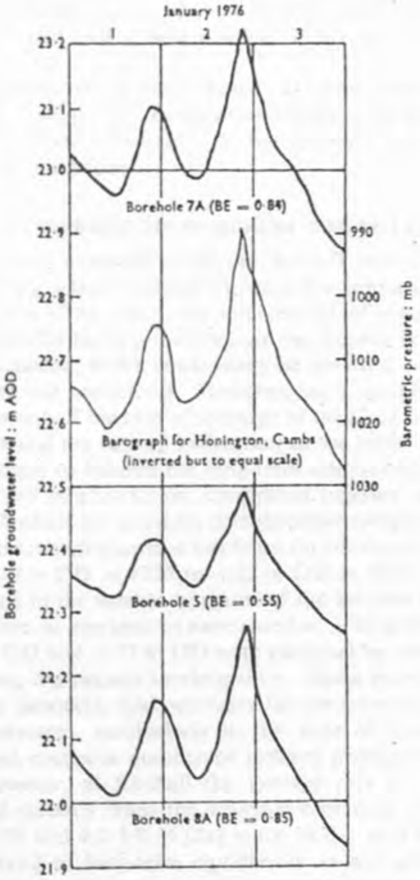

Fig. 11. Barometric response of selected Rushall boreholes (BE barometric efficiency)

17. Despite the relatively good yield–drawdown characteristics of borehole 6, evaluation of the theoretical drawdowns attributable to radial groundwater flow through the aquifer alone to a well of equal nominal diameter suggests that it may be only 55–65% efficient. The well losses appear to result mainly from the partial lining out of the most productive zone of the Chalk (Fig. 8). Slotting of the bottom 6 m or so of the solid lining tubes should have reduced losses and increased efficiency.

18. The more limited data from the test around borehole 2 have been plotted on an equal dimension basis (Fig. 10) to facilitate comparison with those from the test on borehole 6. A threefold or fourfold reduction in T is apparent with a slower rate of development of induced vertical leakage. However, the possibility of turbulence affecting the observation borehole response here cannot be completely ruled out, as it is only 30 m from the test borehole and there are insufficient data to prove laminar aquifer flow. Further reduction in T occurs along the centre of the buried valley, where values appear to fall well below 100 m^2/day.

19. As might be expected, the Rushall boreholes show marked response to barometric fluctuations (Fig. 11). Barometric efficiency is in most cases very high, but lower in the case of borehole 5; the reason is not understood. (Data for borehole 3 are not available.)

Evaluation of vertical leakage from glacial deposits

20. The rapid equilibrium achieved in all the Rushall boreholes after the start (or re-start) of pumping was interpreted as being due primarily to induced downward leakage from the Crag sands, the interception of regional groundwater flow in the Chalk aquifer being of only minor significance in this process. (This is an important conclusion, which could easily be missed if comprehensive hydrogeological data were not collected.) However, such equilibrium will be sustained in the long-term only if the rate of recharge of the Crag from the overlying Boulder Clay series and the rate of infiltration to the latter formation at the surface are both sufficient to balance the long-term abstraction.

21. The historical record of abstraction, considered together with recovery water level data, for the Rushall site provides corroborative evidence. It shows (Fig. 12) that the Chalk piezometric surface has fallen (at boreholes 1 and 2, for example) from above +30 m OD in 1950 to +23 m OD in 1975. Moreover, shallow groundwater levels in the sandier horizons of the Boulder Clay appear, from local drainage practice, at one time to have stood at +30 m OD to +35 m OD but levels of +26 m OD and +27 m OD were recorded by piezometers 9B and 7B respectively during the present investigation. Some permanent fall in groundwater level is both inevitable and necessary for the economical development of groundwater resources, particularly in this type of hydrogeological environment, otherwise an excessive number of isolated production boreholes would be required. However, at Rushall the average rate of groundwater abstraction has increased steadily from the equivalent of only 1·6 Ml/day in 1960 to 3·4 Ml/day in 1970 and 4·5–5·0 Ml/day since 1973. It is therefore not possible to establish a trend of long-term equilibrium at any given pumping rate from the historical record. If, in the long term, abstraction grossly exceeds replenishment, groundwater levels will fall, drawdowns will increase or borehole yields reduce. Failure of boreholes would be gradual as the cone of depression

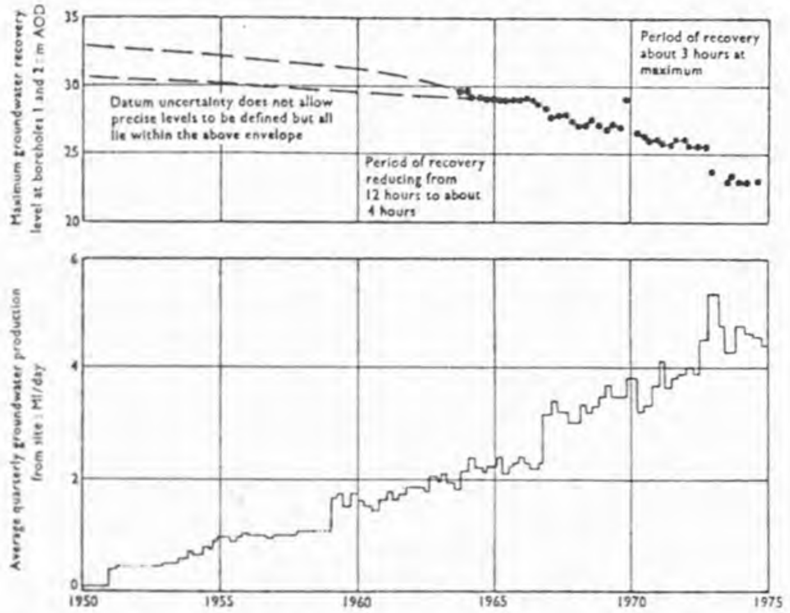

Fig. 12. Historic groundwater abstraction and recovery levels for Rushall site

would tend to expand, thus intercepting more aquifer throughflow and inducing additional leakage. Equilibrium at a reduced abstraction rate would eventually be established.

22. The fall in the Chalk piezometric surface over the years, has reduced available aquifer drawdown and the yields of individual boreholes, for example borehole 1 between April 1956 and December 1975 (Fig. 2).

23. Many approaches to the evaluation of deep groundwater recharge from excess rainfall are possible but, because of the lithological complexity of the Boulder Clay, none will be precise. From determination of the groundwater component of river flow in the Waveney at Needham, the average natural long-term recharge to the Chalk aquifer over the entire catchment was put at 40–50 mm/a.*[1,9] The corresponding figure for excess rainfall exceeds 150 mm/a* and it is probable that additional deep recharge is thus being induced by groundwater development. Such figures give an indication of the order of resources (0·1–0·4 Ml/day per km^2) available in the long-term from induced downward leakage in the area considered. The extent to which these resources can be developed from a single borehole or localized source, such as Rushall, will depend on the transmissivity of the Chalk aquifer. Correspondingly higher rates of abstraction can be sustained in the short and medium term because of the very large volume of groundwater storage in the glacial deposits.

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* This assumes, perhaps questionably, that no long-term climatic change is occurring.

Conclusions

24. For the Rushall Chalk there is little evidence to suggest useful permeability, in the context of water supply development, below about −20 m OD. The zone of highest permeability appears to be 10 m and more above this level and almost directly below the formation's buried erosion surface. This condition has been observed widely in East Anglia,[10] although at many locations there is evidence of some flow of fresh groundwater down to about −40 m OD. In general it appears that there is little to be gained by drilling water supply boreholes deeper than −20 m OD. In view of the probable permeability distribution, however, it is strongly recommended that any lining tubes required for support in the Chalk should be slotted from as near the top of the formation as possible, to avoid accidental exclusion of groundwater from the zone of highest permeability.

25. In East Anglia the so-called buried tunnel valleys[2] appear to constitute poor sites for chalk groundwater development, because the zone of enhanced chalk permeability will often have been eroded during their formation; under certain circumstances it is possible that they may act as partial barriers to groundwater flow. Boreholes into such valleys are likely to provide poorer yields for higher drawdown, need to be of greater depth and require longer lengths of solid casing. However, when the fossil valleys are traced downstream their character changes radically[2] and a different hydrogeological condition almost certainly will apply. Where a true buried tunnel valley[2] directly underlies part of a major present-day valley, the position will also be more complex. Woodland[11] and Ineson[12] suggest that, in general, the Chalk was higher yielding (and thus possessed higher transmissivity) beneath major valleys than beneath the higher ground. High chalk permeability is probably associated with solution during long-term natural circulation of fresh groundwater;[6,13] thus where these valleys are the focus of major groundwater discharge permeability is likely to be highest. However, drilling water supply boreholes into those parts of present alluvial tracts underlain by buried tunnel valleys should be avoided anyway. Moreover, the transmissivity of the Chalk away from the present valleys may have been underestimated by studies of the variation in borehole yield alone, since many more well-constructed, high-demand boreholes are located, for one reason or another, in valleys, introducing a bias into statistical data.

26. The rapidity with which equilibrium is established in boreholes in Chalk at Rushall after the start, or re-start, of pumping could, in the absence of other data, easily be misinterpreted. It has been shown to be due to induced downward leakage from the basal glacial sands and gravels (the Crag, in the case of Rushall). Similar pumping test behaviour has been reported at sites in the Tas Valley to the north of Rushall[14] and is likely over large areas of the semi-confined aquifer (Fig. 1). There is strong evidence from the Rushall site that such equilibria may be relatively short-lived and that in the longer term the sustainable yield of a site will depend on the average rate of induced leakage throughout the entire thickness of the glacial deposits and their rate of replenishment from excess rainfall.

27. Despite the semi-confined conditions of groundwater storage, the hydrogeological environment should prove favourable to schemes for augmentation of river flow from groundwater storage in drought or for conjunctive use of surface and groundwater. This is because the induced leakage should

allow seasonal over-abstraction of groundwater and at the same time greatly retard the rate of spread of interference effects to the areas of groundwater discharge and, therefore, to river flow.

Acknowledgements

28. The investigations described were carried out by the Institute of Geological Sciences in collaboration with the Anglian Water Authority to form a basis for decisions on the future operation and management of the Rushall pumping station and the development of water supplies in the surrounding area. They were suggested by Mr T. K. Tate of the Institute of Geological Sciences, Hydrogeological Department, and promoted by Mr K. Rowe, Divisional Engineer of the Anglian Water Authority, Norwich Water Division, to both of whom the Authors are most indebted. Much assistance on site was given by Mr A. M. Robinson and Mr E. Sharpe of the Anglian Water Authority and Mr M. J. Bird and Mr W. G. Darling of the Institute of Geological Sciences. This Paper is published by permission of the Director, Institute of Geological Sciences.

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October 1977
Volume 81 - Number 980
Regd. ISSN 0043-1168

Water SERVICES

RESOURCES, SUPPLY, SEWAGE & EFFLUENT

(17)

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RESOURCES, SUPPLY, SEWAGE & EFFLUENT

AN INDUSTRIAL NEWSPAPERS PUBLICATION

OCTOBER 1977 Vol 81 No 980

ISSN 0043-1168

Published and © 1977 by

Fuel & Metallurgical Journals Ltd.,
Queensway House,
2 Queensway, Redhill,
Surrey RH1 1QS

Telephone: Redhill 68611
Telex: 948669

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Technical articles of full page length, or over, appearing in *Water Services* are indexed in *British Technology Index*

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PRINCIPAL CONTENTS

REGULAR FEATURES

December feature

The subject for the December feature is Water and Sewage treatment. The editor would be pleased to receive articles and information on this subject and these should be sent to the Redhill office by 10 November latest.

Chalk permeability—a study of vertical variation using water injection tests and borehole logging

by M Price, A S Robertson and S S D Foster*

Introduction

The continual rise in the demand for water in Britain, together with the growing threat to groundwater resources posed by waste disposal, sewage effluent and the intensive use of agricultural fertilisers, makes it increasingly desirable to understand in detail the natural mechanisms of groundwater movement and storage. This paper describes a new approach to the in-situ study of the hydraulic properties of the Chalk. The Chalk aquifer plays an essential role in the nation's water supply both directly, through groundwater abstraction, and indirectly because of the large contribution which Chalk groundwater makes to the flows of some of our major rivers.

English Chalk generally has a high transmissivity, which is attributable to the presence of fissures in an otherwise relatively impermeable rock mass (Ineson, 1962; Tate *et al* 1970). It has long been recognised that the fissures may be more strongly developed at particular levels, but recent work (Foster and Milton, 1974; Foster and Robertson, in press) has shown that these levels may perhaps be controlled by hydrological rather than lithological factors. It also appears that in many cases a few near-horizontal fissures are responsible for most of the total transmissivity; in the unconfined Chalk, a high proportion of the water bearing capacity being concentrated within the zone of seasonal fluctuation of the water table (Foster, 1975).

The manner in which the permeable horizons of the Chalk are developed and distributed with depth will greatly influence the behaviour of wells and springs deriving water from the unconfined aquifer, particularly during long periods of dry weather when the water table falls to unusually low levels.

An investigation was mounted to study the vertical variation in horizontal permeability in an unconfined Chalk aquifer within an area being investigated for river flow augmentation (see acknowledgments). The techniques used were water injection testing, core analysis and borehole flow logging. The last-named is a proven hydrogeological tool for the investigation of flow levels but one which can only yield at best semi-quantitative information on permeability. As in previous work, it was used to define the levels of water movement in the formation and to provide an estimate of their relative importance.

It was expected from the outset that injection testing would indicate the presence of very permeable zones but would probably not yield quantitative permeability values for these horizons, because of the difficulty of injecting water at sufficiently high flow rates. The intention was to obtain numerical permeability values for the less permeable zones, believed to make up a substantial thickness of the Chalk, and to derive values for the most permeable horizons by comparing the injection measurements with bulk values derived from pumping tests. Laboratory core analysis provided permeability values for unfissured Chalk; by comparing these with injection test results it was possible to estimate quantitatively the contribution of fissures in the less permeable horizons.

Borehole construction

Two boreholes (B and C)† were drilled on the Chalk outcrop in Hampshire about 2km apart. In each case a 300mm diameter hole was drilled using a percussion rig to about 5m below ground level, and 250mm diameter steel casing was inserted and grouted with cement/bentonite grout. Percussion drilling was then continued at 250mm diameter to the approximate depth of the water table (Table 1) where coring commenced at 101mm diameter leaving a 131mm hole. In borehole C, core diameter was reduced to 75mm from a 101mm hole at a depth of about 45m. Injection tests were carried out as the holes were deepened; on completion of core drilling and testing, the boreholes were reamed to 200mm diameter to facilitate flow logging and TV inspection. Subsequently, C was reamed to 250mm diameter to 12m and 200mm abs casing (perforated below the water table) inserted, because the upper part of the borehole wall appeared unstable.

Throughout the programme, mains water (abstracted from the Chalk) was the only drilling and injection fluid used.

Water injection testing

Injection testing took place in B and C as core drilling progressed. The standard form of the test used in civil engineering site investigation was employed (Louis and Maini, 1970; Muir-Wood and Caste, 1970), in which a length of the borehole above the temporary base was isolated by an expanding rubber packer carried on drill pipe and inflated using compressed nitrogen. The packer was

Table 1 Details of Boreholes B and C

Borehole	*B*	*C*
Site name	*Abbotstone*	*Itchen Down Farm*
NGR	SU 558 349	SU 546 334
Ground elevation	92.3m a OD	62.6m a OD
Rest water level (Feb 1976)	26.8m bgl	10.2m bgl
Depth at which coring commenced	25.5m bgl	12.0m bgl
Cored depth	79.3m bgl	81.1m bgl
Reamed depth	85.0m bgl	82.0m bgl

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*Hydrogeological Department, Institute of Geological Sciences, Exhibition Road, London SW7 2DE.

† *Borehole A was drilled subsequently. See footnote page 608.*

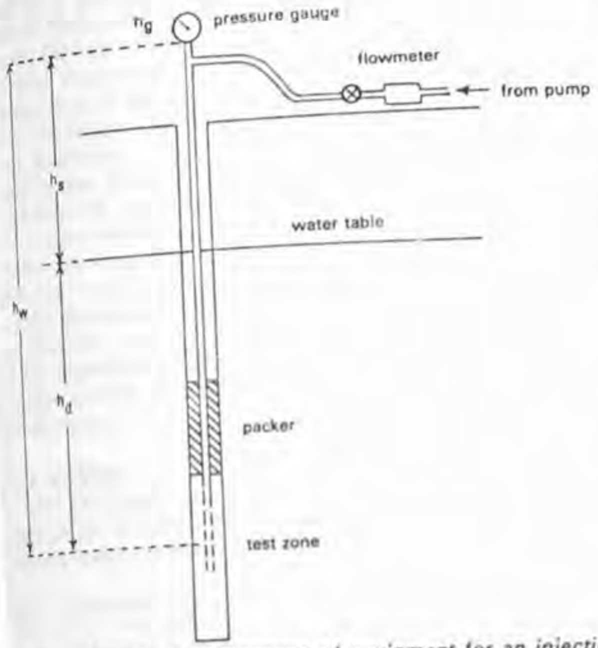


Fig 1 Generalised arrangement of equipment for an injection test.

normally located 5 to 6m above the base of the hole and a test carried out each time the hole was deepened by 5 to 6m so that, with a few exceptions, the borehole was tested completely, in stages, between the water table and final depth.

Water was injected into the test zone through the drill pipe, using a Mono D62 surface pump. Flow rate was measured with an integrating flow meter and pump injection pressure with a pressure gauge mounted on top of the drill pipe (Fig 1). If this pressure is h_g metres head of water, the friction loss in the drill pipe is h_f, and the other symbols are as identified in Fig 1, then the effective injection pressure at the test zone, H_e, is

$$H_e = h_g + h_w - h_d - h_f \qquad (1)$$

$$\text{or } H_e = h_g + h_s - h_f \qquad (2)$$

This form of water-injection test was used because the equipment is readily available and the technique used and understood by most site-investigation contractors. It was realised, however, that there would be difficulties in its use for the hydrogeological investigation of high permeability strata. Typical site investigations for, say, dam foundations, involve measuring the permeability of relatively impermeable rocks, usually with the water table near surface (so that h_s is small). Although high injection pressures are used, they produce only small flow rates, so that h_f is also small and H_e corresponds closely to h_g.

In the case of the unconfined Chalk aquifer much higher permeabilities are probable and commonly (as in this case) the water table is at considerable depth. In consequence of the latter h_s will be large and H_e may be very different from h_g. In zones of high permeability the high flow rates necessary to cause a measurable pressure at the gauge, even if they are attainable, will cause large friction losses. This is particularly so if internal upset drill pipe is used for injection, as in this case. It is possible to make estimates of the head losses but considerable errors may occur where very high flow rates and long pipe runs are involved (Dick, 1975). The friction losses and errors could be substantially reduced by using pipe with internal flush coupling if available, but it would seem advantageous to measure H_e directly by means of a pressure transducer in the test zone.

Provided that steady-state laminar-flow injection conditions can be achieved, that the formation around the test zone is homogeneous and isotropic and that the test zone length (l) is much greater than the borehole radius (r), then the permeability K of the formation around the test zone can be calculated from the formula

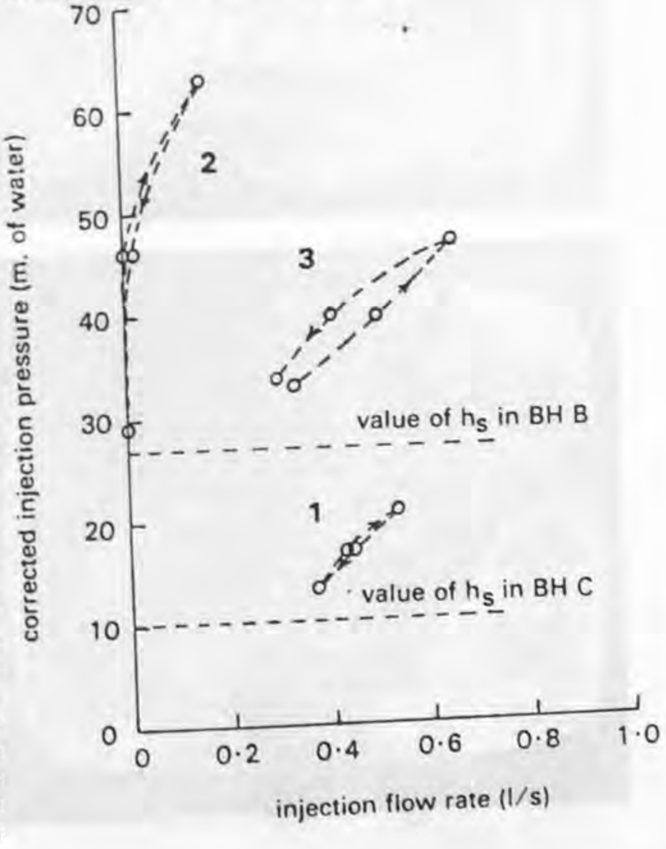
$$K = \frac{Q(\ln l/r)}{2\pi H_e l} \qquad (3)$$

where Q is the injection rate. The usual procedure is to increase h_g in three equal increments, measuring the corresponding values of Q at each step, and then to decrease h_g in similar steps, again measuring Q. When plotted as a graph of H_e against Q the five resultant points should lie on a straight line. Marked non-linearity or hysteresis indicates a departure from the ideal condition, possibly caused among other factors by the onset of turbulent flow in the formation, packer leakage, scouring or closing of a fissure, or by enlargement of a fissure as a result of H_e exceeding the overburden pressure. The shape of the curves provides valuable information on the nature of the departure from the idealised conditions. In impermeable ground it is easy to increase H_e in nearly equal steps because H_e approximates to h_g; in permeable strata with high injection rates it is not.

Fig 2 shows examples of pressure/flow rate curves from tests in both boreholes. Curve 1 shows an almost 'ideal' result—the pressure/flow relation-

continued on page 606

Fig 2 Pressure-flow curves for borehole injection tests. Curve 1 is from C, 14.0 to 19.9m bgl. Curve 2 is from C, 63.1 to 69.1m bgl. Curve 3 is from B, 38.7 to 45.3m bgl.



ship is a straight line through the origin and the lack of hysteresis indicates no change of conditions during the test. Curve 2 shows the results of a test in which the permeability of the formation apparently increased with increasing test pressure: again there is no significant hysteresis, that is to say the effect was reversible. It might have been caused by the effective test pressure exceeding the local overburden pressure and so temporarily forcing a fissure open but is more likely a result of leakage past the packer at high pressure. Curve 3 exhibits, to a minor degree, both non-linearity and hysteresis, the latter indicating a slight decrease in apparent permeability during the course of the test. All of the curves show a bunching of the measured points in the high pressure region, because testing at effective heads less than h_i was not possible.

Core analysis

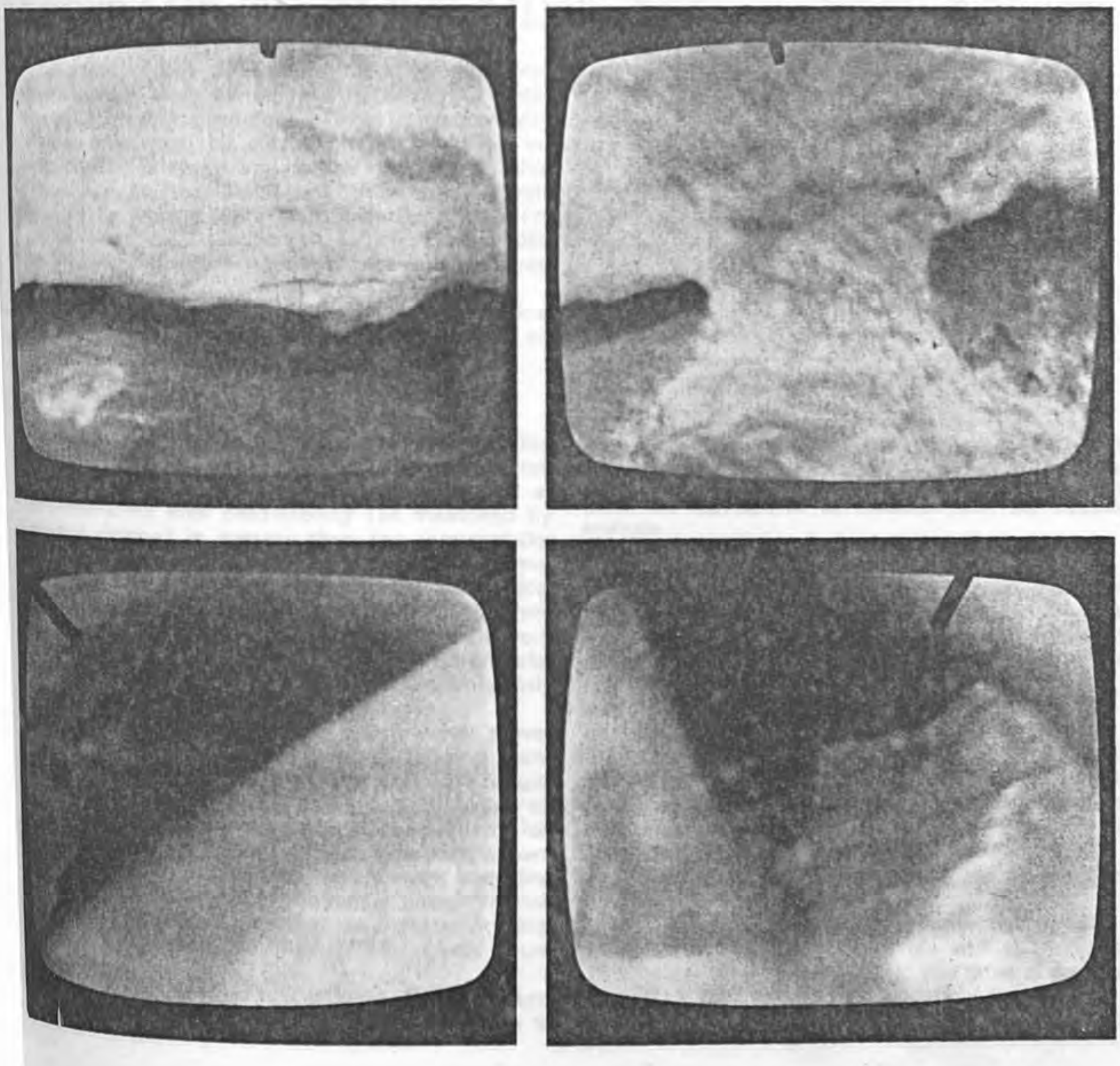
After each core run had been described, samples were taken at about half-metre intervals for subsequent measurement of physical properties. From each sample a test plug (25mm diameter core) was cut, approximately 25mm long, with its axis horizontal (*ie* perpendicular to the borehole axis). Additionally, a vertically oriented plug was cut from every tenth sample. The permeability of each test plug was measured using a gas permeameter with nitrogen as the test fluid (API, 1956). An empirical correction (Klinkenberg, 1941) was then applied to the results to produce an estimated liquid permeability, which was corrected for density and viscosity to yield an intergranular hydraulic conductivity to a non-reactive liquid with the properties of water at 10°C.

Borehole logging

Borehole geophysical measurements were of two main types—those measuring directly properties of the rock strata around the boreholes and those measuring properties of the water within them. Only the water measurements will be discussed in detail in this paper.

Under rest (non-pumping) conditions, the water column in a Chalk borehole reaches an apparent

Plate 1 Television photographs (radial view) of fissure horizons in B. In each case the top of the borehole is indicated by the black mark. Top left and top right: Fissure horizon 29.2m below ground level. Screen diagonal represents approximately 37mm. Bottom left and right: Fissure horizon 35.7m below ground level. Screen diagonal represents approximately 30mm.



equilibrium with the free water in the surrounding Chalk. Changes in the temperature or electrical conductivity of the water column can be detected with a sensitive temperature/conductivity sonde (Tate and Robertson, 1975) and usually occur at levels where water is entering or leaving the borehole. Such a level indicates the presence of relatively high permeability combined with a difference in hydraulic head. The head difference is frequently brought about because the borehole connects strata which are relatively permeable, are separated by less permeable material, and which contain water under slightly different total heads. The borehole thus provides an artificial conduit for vertical flow to take place between these strata. Pumping from the borehole will alter the head distribution and may accentuate other levels of entry. The definition of levels of movement from a single log is often difficult and for this reason it is usual to make a series of logs under different hydraulic conditions, such as at the start and the finish of pumping from the borehole. Changes in flow velocity above and below a level of water movement can give an indication of the relative importance of that fissure, but not an absolute value of its permeability contribution. The problems of centralising the flowmeter below a pump and of avoiding errors caused by non-uniform turbulent flow in what is essentially a rough walled pipe subject to side entrance effects, mean that the relative results are at best only semi-quantitative.

Temperature and conductivity logging and flow measurements were carried out in B and C under rest and pumping conditions. These measurements were supplemented by closed circuit television inspections of B above and below the water table (Plate 1). All the significant flow entry levels detected by logging were identified as fissures (of various forms) by TV inspection which also revealed the presence of other openings above the water table.

Natural gamma, gamma-gamma and electrical resistivity logs were made to provide information on stratigraphy and lithology.

Results

Injection test and core-analysis permeability (hydraulic conductivity) results for B are presented in Fig 3 and for C in Fig 4. It will be seen that at all horizons the total permeability (as measured by injection testing) is greater than the intergranular permeability measured in the laboratory. The permeability results obtained in the laboratory are typical values for unfissured Upper and Middle Chalk from Southern England (Price *et al*, 1976). It appears from the core analysis measurements that the intergranular permeability of the Middle Chalk is significantly lower than that of the Upper Chalk.

The most important levels at which water movement was detected by the borehole logging techniques are also shown in Figs 3 and 4; an example of the way in which these levels are indicated on the logs is shown by the electrical conductivity log incorporated in Fig 3. Only one log has been shown for clarity, but in practice the levels were identified by studying a set of logs obtained under varying conditions; Fig 4 also incorporates a resistivity log, which defined the Upper Chalk-Middle Chalk boundary.

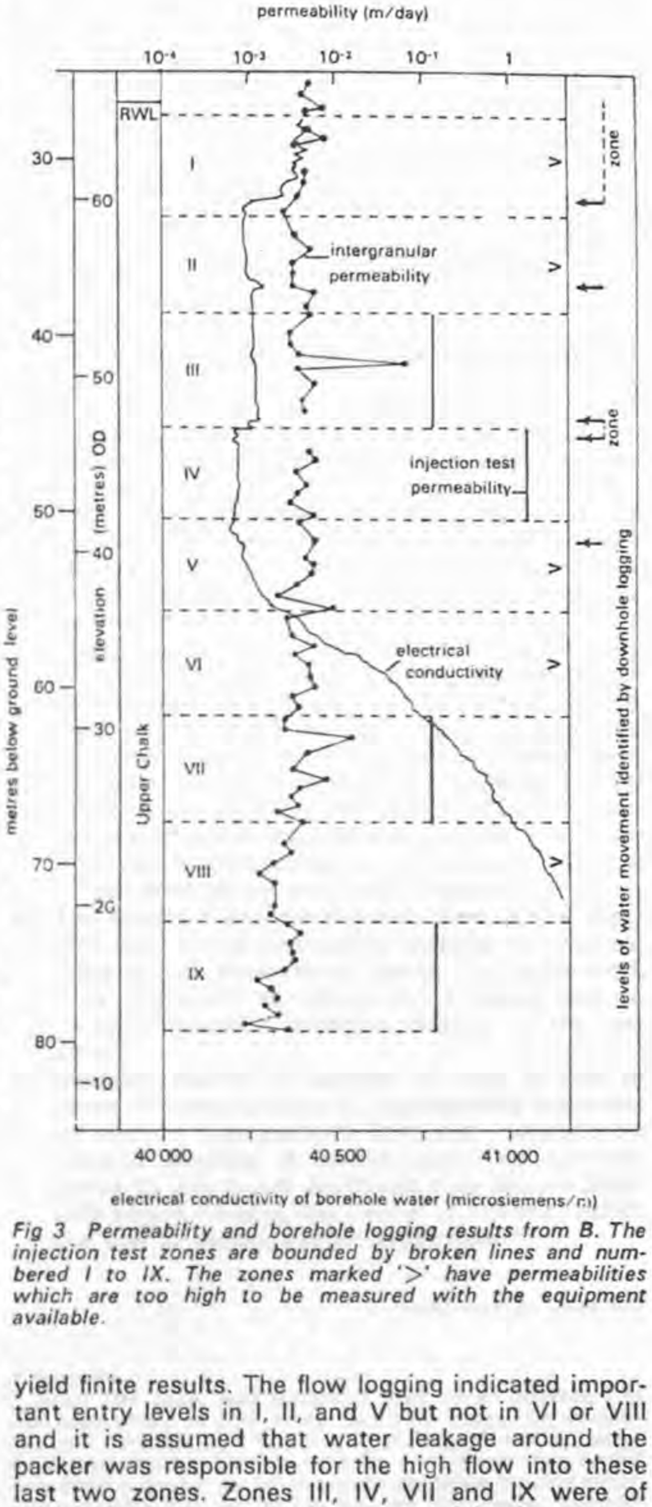


Fig 3 Permeability and borehole logging results from B. The injection test zones are bounded by broken lines and numbered I to IX. The zones marked '>' have permeabilities which are too high to be measured with the equipment available.

In B (Fig 3) injection test zones I, II, V, VI and VIII were apparently too permeable for the tests to yield finite results. The flow logging indicated important entry levels in I, II, and V but not in VI or VIII and it is assumed that water leakage around the packer was responsible for the high flow into these last two zones. Zones III, IV, VII and IX were of sufficiently low permeability for an injection test to be successful. The only water movement levels in these zones were detected by logging between 44.5 and 45.5m below ground level and it seems probable that these levels did not give rise to high injection rates because they represent minor permeability contributions, fall on the boundary between zones III and IV and were partly covered by the packer during testing.

In C (Fig 4) flow logging detected a zone of inflow between the water table and approximately 15m below ground level (bgl); this interval could not be tested with the packer assembly because of the presence of temporary drill-casing. Only two other

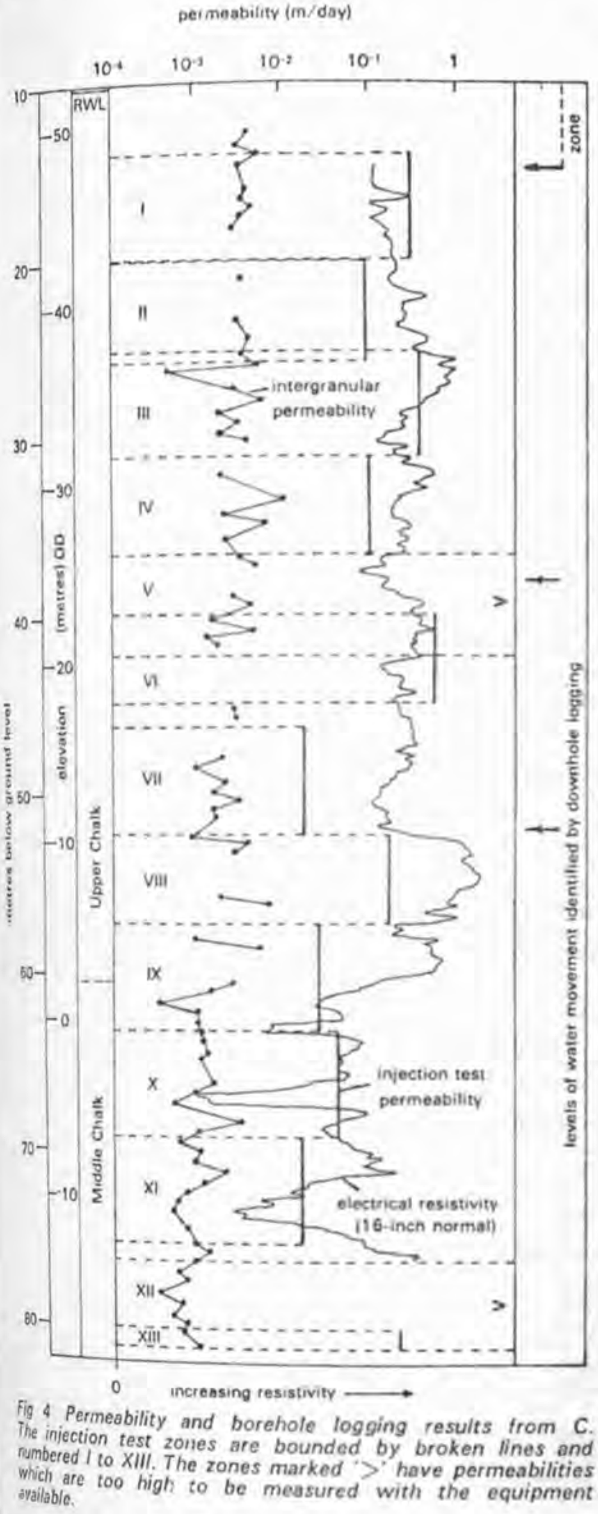


Fig 4 *Permeability and borehole logging results from C. The injection test zones are bounded by broken lines and numbered I to XIII. The zones marked '>' have permeabilities which are too high to be measured with the equipment available.*

inflow levels were detected by logging; a major one at about 38m bgl, corresponding to the high permeability test zone V, and a less pronounced level at about 52m bgl. The latter level again falls exactly on the boundary between two test zones. The only anomaly in C is the high permeability result obtained from test zone XII, which on the flow logging evidence contains no significant flow level. The core from this zone contains several high-angle fractures and it it is possible that flow occurred from the test zone around the packer through near-vertical fissures.

Generally, the boreholes were not cleaned out prior to injection testing, and it is accepted that the permeability may have been reduced by drill cuttings clogging fissures. It is always difficult to separate regional (aquifer) properties from local (borehole) effects, and it was particularly desired not to locally enlarge fissures by pumping. The use of water rather than mud as drilling fluid and the wide variations in permeability which were recorded suggest that clogging by drilling cuttings was not significant.

Conclusions

Five principal conclusions were drawn from this study:

1) A large number of the zones tested by water injection, forming a significant thickness of saturated Chalk at these sites, have very low total permeability.
2) This total permeability is usually at least ten times higher than the intergranular permeability as measured in the laboratory, indicating the likelihood of some minor fissuring throughout the interval studied.
3) The zones which do not have low permeability generally contain prominent fissures which can be identified by borehole flow logging techniques. Their permeabilities are too high to be measured with the water injection equipment which was available. Comparison with the result of a short pumping test at site C indicates that for the interval tested more than 99 per cent of the transmissivity is contributed by no more than 12m or 17 per cent of the saturated thickness.
4) The standard site-investigation form of the injection test is not particularly suitable for applications in high permeability strata. For future work it is important to reduce head losses and to measure injection pressure directly in the test zone.*
5) Injection testing in isolation is likely to lead to errors in interpretation. It is particularly important to confirm that packers have not inadvertently covered fissures. It would clearly be advantageous to drill to full depth and then log the borehole before carrying out packer work: this implies the use of double-packer assemblies.*

continued on page 610

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* *Footnote*

Since this paper was written, a third cored borehole (A) has been drilled to 85m in the Candover Valley. On completion the borehole was pumped clean, logged and inspected by closed circuit television. Injection testing was then carried out, using a double packer assembly to isolate the test zones. The assembly was carried on BX size drill casing (approximately 63mm internal diameter), permitting high injection rates for relatively small head losses. A pressure transducer was incorporated into the assembly to permit direct and accurate measurement of the pressure in the test zone.

Because the Chalk around the upper part of the borehole was extensively fissured and broken, necessitating the use of slotted casing, it was not possible to test above 17m bgl (the water table is approximately 2m bgl). Between 17m and 75m bgl, 16 zones were tested, covering virtually the whole of this interval. The logging and closed circuit television information was used to select smooth areas of the borehole against which to seat the packers. In 15 of the zones, the permeability was less than 3m/d; in the remaining zone it averaged about 60m/d over a zone length of 3.7m. This zone contained a well developed horizontal fissure. The borehole logs indicate that similarly high permeabilities are to be expected in the lined part of the borehole, above 17m bgl.

Acknowledgments

The investigations described in this paper complement groundwater resource (river flow augmentation) studies being carried out in the Candover Valley, Hampshire by the Southern Water Authority. The Institute and the authors would like to thank the SWA for negotiating access and planning consents and for arranging water supplies for drilling and testing, as well as for supplying a wealth of general information on the area. Particular thanks are due to Derek Giles, Howard Headworth and Merfyn Hewins. We are also grateful to landowners and farmers for permission to drill and test on their land; special mention must be made of the considerable co-operation which we have received from Mr J R Burge of Itchen Down Farm. The core drilling and water injection testing were carried out by Soil Mechanics Ltd.

Finally, we are grateful to several colleagues at IGS, especially T K Tate, Michael Bird and Keith Murray, for assistance with the field and laboratory work which this study has involved.

The work has been carried out under the general supervision of Mr J B W Day, chief hydrogeologist, and the paper is published by permission of the director, Institute of Geological Sciences.

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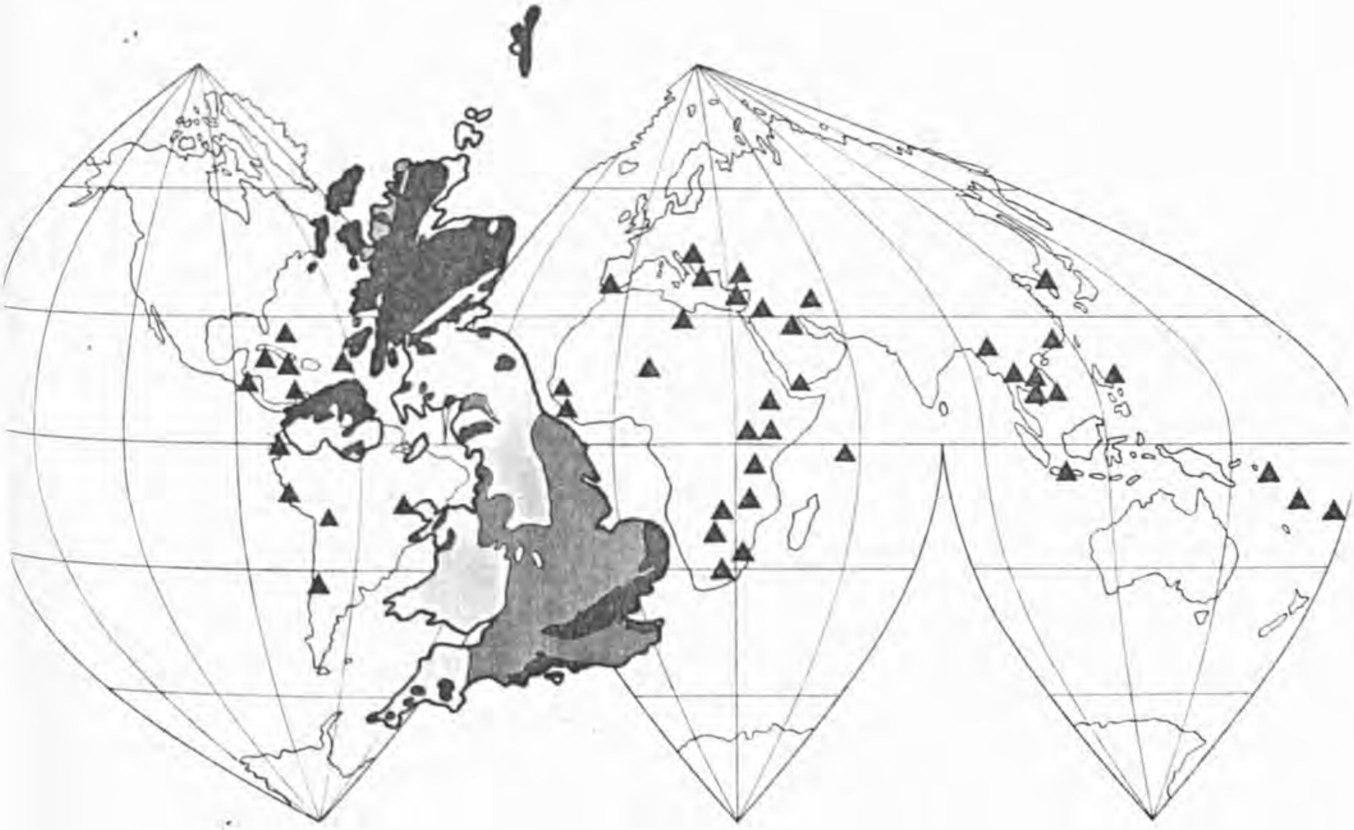
INSTITUTE OF GEOLOGICAL SCIENCES

Groundwater storage in Fife and Kinross - its potential as a regional resource

REPORT No. 76/9



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Report No. 76/9

Groundwater storage in Fife and Kinross - its potential as a regional resource

S. S. D. Foster, W. G. N. Stirling and I. B. Paterson

London: Her Majesty's Stationery Office 1976

It is recommended that reference to this report be made in the following form:

Foster, S.S.D., Stirling, W.G.N. and Paterson, I.B. 1976. Groundwater storage in Fife and Kinross - its potential as a regional resource. *Rep. Inst. Geol. Sci.*, No. 76/9, 21 pp.

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ISBN 0 11 881251 3

PREFACE

The investigations described here were carried out on behalf of the Scottish Development Department, who funded part of the work, within the framework of a research contract financed by the Department of the Environment.

The work was undertaken prior to the administrative reorganisation of the water industry in Scotland and accordingly, the organisations referred to in the Report are those who collaborated with, or provided data to the Institute, rather than their successors. Publication is with permission of the former Fife and Kinross Water Board, though the opinions expressed are those of the authors and not necessarily those of the Board. The authors were grateful for the interest and support of Mr R.J. Cameron Stobie, Engineer/Manager, and Mr D. Crombie, Deputy Engineer, of the Board.

The valuable assistance of the following staff of the Institute or Board is acknowledged; Mr M.J. Bird, Mr M.A.E. Browne, Mr A.C. Cripps, Mr J. Gibson, Mr D. Gregg, Mr K.H. Murray, Mr L.D. Purdie, Mr T.K. Tate and especially Miss A.S. Robertson for her work on the geophysical investigations of borehole flow.

Hydrological data on the Eden River system were provided by the Tay River Purification Board and on Loch Leven by the Forth River Purification Board. Mr J.A. Reid, Hydrologist to the former of these Boards is thanked for some most helpful discussions. Meteorological data were obtained from the Meteorological Offices in Edinburgh and Bracknell.

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1 February 1976

Summary

A thick regional aquifer has been identified within the Upper Old Red Sandstone sequence of Fife and Kinross, extending from the eastern rim of the Loch Leven basin for a distance of more than 25 km on the southern side of Stratheden to beyond Cupar. The bulk of the sandstone in the main aquifer has moderate intergranular permeability (greater than 1 m/d) and porosity (over 20 per cent), and also exhibits significant fissure permeability. Laboratory studies suggest over 15 per cent specific yield under gravity drainage.

Production boreholes yielding at least 40 l/s for less than 25 m drawdown can now be sited with some confidence. Conventional large-scale groundwater abstraction for continuous perennial water supplies must nevertheless be considered as undesirable at the present time, because of interference with surface water systems leading to problems of sewage dilution and amenity conservation.

In view of the hydraulic properties of the main aquifer, its hydrological regime and its very large fresh water storage, however, there are good prospects for intermittent abstraction of large volumes of groundwater from limited areas for use in conjunction with existing and future upland reservoirs, particularly at times of drought and peak demand, without causing undue interference. A 20 Ml/d pilot development scheme is proposed to confirm feasibility. The economic advantages of exploiting the groundwater resources of Stratheden are so attractive, no matter how the economic parameters of the various source options are varied, that the possibility of large-scale development should not be neglected.

Sommaire

On a identifié un aquifère épais régional dans la séquence de vieux grès rouge supérieur de Fife et Kinross. De la marge de l'est du bassin de Loch Leven il s' étend plus de 25 km à la côté du sud de Stratheden jusqu'au delà de Cupar. La plupart du grès dans l'aquifère principal possède une perméabilité intergranulaire moyenne (plus de 1 m/d) et une porosité moderée (plus de 20 pour cent), et elle montre aussi une perméabilité importante par fissures. Des études dans la laboratoire suggèrent un rendement spécifère de plus de 15 pour cent par drainage par gravité.

Maintenant il est possible de fixer avec quelque degré de confiance les emplacements de trous de sonde, produisant au moins 40 l/s avec moins de 25 m rabattement. L'extraction conventionelle sur un grand échelle, d'eau souterraine pour l'approvisionnement constant d'eau doit être considerée à present, cependant, comme peu désirable à cause de son influence sur les systèmes d'eau au surface, ce qui peut causer des problèmes en la dilution des égouts et la protection d'agréments.

Cependant, en considération des attributs hydrauliques de l'aquifère principal, de son régime hydrologique, et de son très grand capacité d' emmagasinage d'eau douce, on pourrait bien procéder à l'extraction intermittente de grandes quantités d'eau souterraine de zones limitées, pour s'en servir conjointement avec des réservoirs montagnards actuels ou futurs, surtout pendant des périodes de sécheresse ou de consommation maximum, sans provoquer trop de dérangements. Afin de confirmer sa practicabilité on propose un projet d'essai de 22 Ml/d. Les avantages économiques de l'exploitation des ressources en eau souterraine de Stratheden ont tant d'attraits, de n'importe quelle manière que les paramètres économiques des sources facultatives soient variés, que la possibilité de développement sur une grande échelle ne doit pas être negligée.

Zusammenfassung

Man hat einen massigen örtlichen Grund wasserleiter in der alten, roten Obersandsteinfolge von Fife und Kinross identifiziert. Diese Folge reichtvom östlichen Rand vom Loch Leven Becken mehr als 25 km weit auf der südlichen Seite von Stratheden weiter als Cupar. Das Hauptteil vom Sandstein im Hauptgrundwasserleiter hat mässige interkörnige Permeabilität (grösser als 1 m/d) und Porosität (mehr als 20 Prozent) und zeigt auch wichtige Spaltpermeabilität. Laboratoriumsarbeit gibt zu verstehen, dass es einen bestimmten Ertrag von mehr als 15 Prozent unter Schwerkraftentwasserung gibt.

Man kann num mit fester Überzeugung Produktionsbohrlöcher placieren die wenigstens 40 l/s für weniger als 25 m Senkungstrichter liefen. Trotzdem muss man gewöhnliche grosse Grundwasserabstraktion für ununterbrochere langdauernde Wasserporgungen im Augenblich als unerwünscht betrachten, weil die Störung von Erdoberflächewassersystemen zu Problemen von Abwasserverdünnung und Annehmlichkeitsschutz führt.

In Hinblick auf den hydraulischen Besonder heiten des Haupt grundwasserleiters, auf den hydraulischen Wasserstandsverhältnissen und auf dem hydrologischen Süsswasser speichern, gibt es aber gute Aussichten für periodische Abstraktion von viel Grundwasser aus beschränkten Gebieten für Gebrauch zusammen mit existierenden und kommenden Oberlandstanbecken, besonders zu Dürrezeiten und Höchstnachfrageperioden, ohne über massige Störung zu verursachen. Ein 20 Ml/d Versuchsprojekt der Entwicklung wird beabsichtigt, um die Möglichkeit zu bestätigen. Die ökonomischen Vorteile der Benutzung von den Grundwasser mitteln von Stratheden sind so vorteilhaft, ganz gleich wie man die ökonomischen Parameter von der verschiedenen Quellensauswahlen ändert, dass man die Möglichkeit von grosser Entwicklung nicht ausser acht lassen darf.

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ILLUSTRATIONS

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Groundwater storage in Fife and Kinross - its potential as a regional resource

S.S.D. FOSTER, W.G.N. STIRLING, AND I.B. PATERSON

Background

REGIONAL WATER SUPPLY SITUATION

In 1973 the total water demand of the region under consideration was 114 Ml/d and growing at a rate close to the national average of 2½ per cent per annum (Scottish Development Department, 1973). Should such a growth rate be sustained, demand would be expected to double by the end of the century.

The bulk of the total developed resources of the Fife and Kinross Water Board is represented by a complex of impounding reservoirs on the upper part of the River Devon; the other major source at present is the Glenfarg Reservoir (Fig. 1A). Prior to the drought experienced throughout eastern Scotland in 1971-1974, the combined reliable yield of all existing sources was put at 110 Ml/d; the major reservoirs storing over 14 000 Ml. Precipitation during 1971-1974 was only 80 per cent of the long term average and in 1973 was less than 70 per cent, total reservoir yield being reduced to about 90 Ml/d. The supply deficit was offset somewhat by the drilling of four exploratory boreholes and by emergency appeals, but some restrictions were experienced and the storage of upland reservoirs was excessively depleted.

By 1977, development of potential upland catchment areas will be almost complete with the construction of the Castlehill Dam in Glendevon, the fifth impounding reservoir in this catchment, together with a treatment works. This will augment available supplies by some 29 Ml/d at an estimated cost of £4.2 million (1974 prices). Forward plans to the turn of the century include a 67 Ml/d intake on the River Earn, to augment the existing Glenfarg source, which, together with another major treatment works, are estimated to cost a total of £4.3 million (1974 prices) and to involve heavy routine pumping costs.

HISTORY OF GROUNDWATER DEVELOPMENT

In 1960 Dr J.E. Richey (consulting geologist) reported that there was a prospect that comparatively shallow boreholes in the Upper Old Red Sandstone of the Loch Leven basin and Stratheden would produce good yields of groundwater for public supply, which would require minimal treatment. Subsequently the Institute of Geological Sciences prepared a more detailed report on the area.

In 1972, faced with an extreme drought and a serious shortage of source capacity, the Fife and Kinross Water Board decided to drill four, 300 mm diameter and 120 m deep, exploratory production boreholes; two in the vicinity of Loch Leven (at site 2 in Fig. 1B) and two in the Eden Valley (at sites 5 and 6 in Fig. 1B). After test pumping and commissioning, these boreholes proved to have a combined yield of 10 Ml/d, exceeding expectations and suggesting much greater potential. In addition the groundwater quality proved suitable for direct injection into the regional trunk mains without treatment beyond simple chlorination.

GEOLOGICAL SETTING

The main topographical feature of the area is the tract of low ground formed by the Loch Leven basin and Stratheden. It is flanked on the north by the Ochil Hills and on the south by Benarty and the Lomond Hills (Fig. 1B). Stratheden, which trends north-eastwards and has a maximum breadth of about 8 km, is drained by the River Eden. The Loch Leven basin, which is separated from Stratheden by a low divide about 5 km north-east of Kinross, is drained by the River Leven.

The low ground is underlain by Upper Old Red Sandstone strata which in general dip to the south-east (Fig. 2). Both the underlying lavas and associated sediments of the Lower Old Red Sandstone and the largely shale-sandstone sequence of the Lower Carboniferous above, appear generally to be of much lower permeability.

Locally along the margin of the Ochil Hills, the basal conglomerates of the Upper Old Red Sandstone rest upon the underlying lavas at outcrop, but this northern boundary is probably for the most part faulted (Figs. 1B and 2). If so, published estimates of the overall thickness of the series (Geikie, 1900; Chisholm and Dean, 1974) are considerably too low and the thickness may exceed 1200 m. On Benarty and the Lomond Hills the overlying Lower Carboniferous strata have been intruded by a large quartz-dolerite sheet. It is possible also that the major fault downthrowing the Carboniferous rocks to the south of the Lomond Hills extends north-eastwards to unite with the Dura Den Fault (Chisholm and Dean, 1974), which forms the southern margin of the Upper Old Red Sandstone outcrop east of Cupar (Fig. 1B).

The Upper Old Red Sandstone is generally concealed by a veneer of boulder clay, which is overlain in the area around Loch Leven and in much of Stratheden by extensive spreads of sand and gravel of glacial origin. The thickness of this drift sequence is not known in any detail, but locally may exceed 10 m. It is possible that the boulder clay is unbroken throughout the Loch Leven area, but in Stratheden the sand and gravel are known to rest directly upon bedrock at numerous localities.

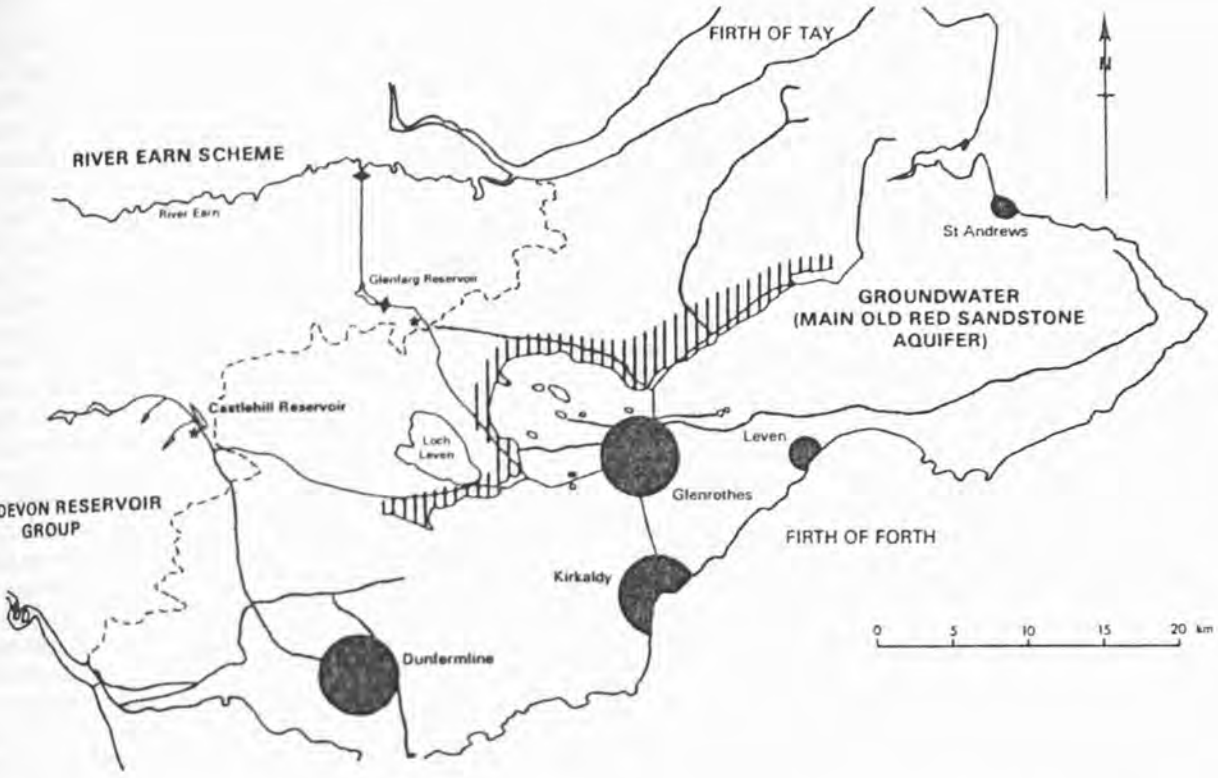

Fig. 1A. Introductory map with location of existing and proposed future water-supply sources

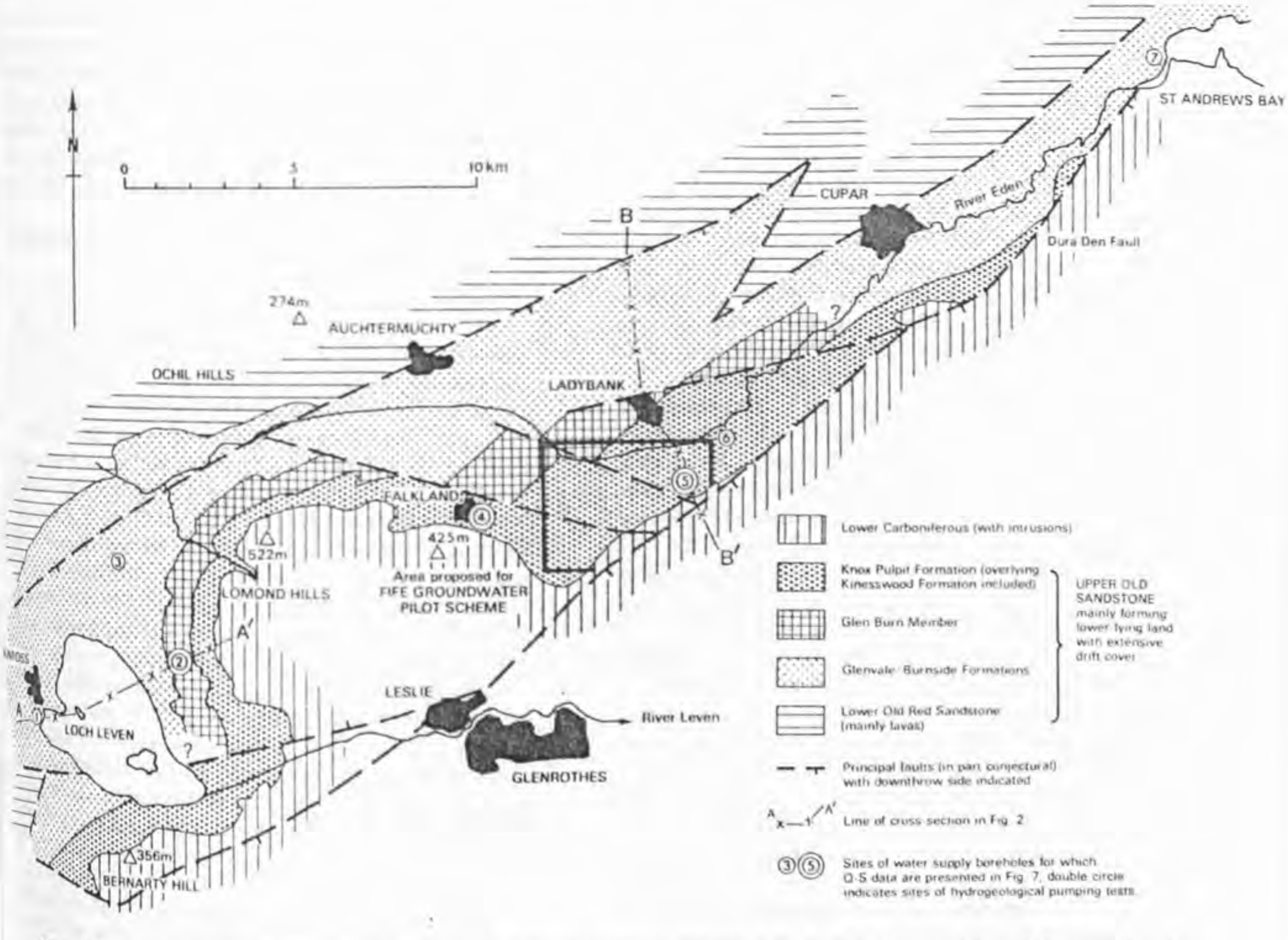

Fig. 1B. Introductory map with simplified bedrock geology of Eden Valley and Loch Leven basin

OBJECT AND SCOPE OF REPORT

In the light of the successful drilling in the Upper Old Red Sandstone in 1972-1973, the Institute of Geological Sciences was invited by the Scottish Development Department to undertake a hydrogeological reconnaissance of the Loch Leven and Stratheden areas with the objective of determining whether the groundwater of the Upper Old Red Sandstone could be regarded as a regional resource.

From the outset the form of the available riverflow hydrographs of the Eden indicated a significant groundwater component and that substantial infiltration and throughflow were present in the Upper Old Red Sandstone. There were no data available on natural fluctuations in groundwater level, prohibiting any attempt at a groundwater balance. Moreover, taking into account the likely forms of future groundwater development, it was considered more important to establish in some detail the permeability and storage characteristics of the main groundwater reservoir and to assess the general nature of the groundwater flow regime and its relationship to the surface water system. Most effort was directed to these ends.

In this report the results of these investigations, carried out for the most part in 1974, are summarised and discussed in relation to potential schemes of systematic development of groundwater resources. A specific recommendation for a 20 Ml/d groundwater pilot scheme to prove the feasibility and to evaluate any side-effects of heavy groundwater abstraction from limited areas during restricted periods is presented. Such a resource could be developed for conjunctive use with existing upland reservoir storage, considerably extending the combined net yield of both sources.

Character of Groundwater Reservoir

INVESTIGATION TECHNIQUES

Numerous methods of investigation were deployed in order to advance rapidly knowledge of the geological and hydraulic characteristics of the Upper Old Red Sandstone.

Hydrogeological pumping tests were organised at three sites (2, 4 and 5 in Fig. 1B), in each case with a single observation borehole. The tests were only of a reconnaissance nature but the application of standard analytical methods for non-equilibrium drawdown data (for example, as summarised by Walton, 1962; Lohman, 1972) gave values for the overall transmissivity of those strata penetrated and an indication of the storage and boundary conditions of the groundwater system (Table 1). Interpretation was extended by determination of the major levels of groundwater inflow into most of the boreholes concerned, using differential temperature and conductivity logging techniques and heat-pulse or impeller flowmeter measurements (Tate and others, 1970). In some cases the associated geological features were identified by direct inspection with a closed-circuit underwater borehole television camera.

At the Falkland and Kettlebridge sites (4 and 5 in Fig. 1B), the observation boreholes were purpose-drilled and core samples were obtained throughout. In addition a cored exploratory borehole was drilled at Mawcarse (Site 3 in Fig. 1B). The core samples were tested in the laboratory for intergranular permeability, porosity, pore-size distribution and centrifuge specific yield. Special emphasis was placed on the latter two parameters to establish the extent to which the sandstones were likely to drain under gravity.

The cored boreholes greatly supplemented existing information on the lithology of the Upper Old Red Sandstone and allowed some assessment of the frequency of horizontal discontinuities. Geophysical formation logs (electrical resistivity, spontaneous potential and natural gamma) were run to establish their value in local and regional correlation (Fig. 3A and 3B).

DEFINITION OF PRINCIPAL AQUIFER

The Upper Old Red Sandstone comprises the following subdivisions, based on the work of Chisholm and Dean (1974):

4) Kinnesswood Formation
3) Knox Pulpit Formation
2) Glenvale Formation (including
   the Glen Burn Member at top)
1) Burnside Formation.

The Burnside and much of the Glenvale Formation consist primarily of red-brown, medium grained, well cemented, fluviatile sandstone with subordinate beds of conglomerate (especially towards the base) and of silty mudstone. The strata penetrated by the Mawcarse borehole are typical of these formations (Fig. 3A) and have a porosity (ϕ) of 10 to 20 per cent and mean intergranular permeability (k_H) of about 0.2 m/d with the most permeable horizons reaching 1 m/d. The sandstones of the uppermost 150 to 180 m of the Glenvale Formation are distinctive, however, being mainly yellow or pale-brown in colour and generally friable. For convenience they are here referred to the Glen Burn Member.

The Knox Pulpit Formation, of which the strata encountered in the Falkland borehole are believed representative (Fig. 3B), is about 225 to 250 m thick and consists mainly of cream, fine to medium grained, cross-bedded sandstone, weakly cemented by calcite, with subordinate flat or ripple-laminated beds. The coarser grained cross-bedded units appear to be more permeable and porous (k_H and ϕ more than 0.5 m/d and 20 per cent respectively), but their spatial distribution is not known.

The uppermost 50 to 60 m of the Upper Old Red Sandstone is similar in properties to the Glen Burn Member but also contains discontinuous beds of calcareous nodules ('cornstones'). These strata are known as the Kinnesswood Formation, which as a result of its position and very narrow outcrop is only of minor hydrogeological significance.

During the course of the present reconnaissance, it became apparent that the upper part of the Upper Old Red Sandstone formed the main aquifer of the region and was of

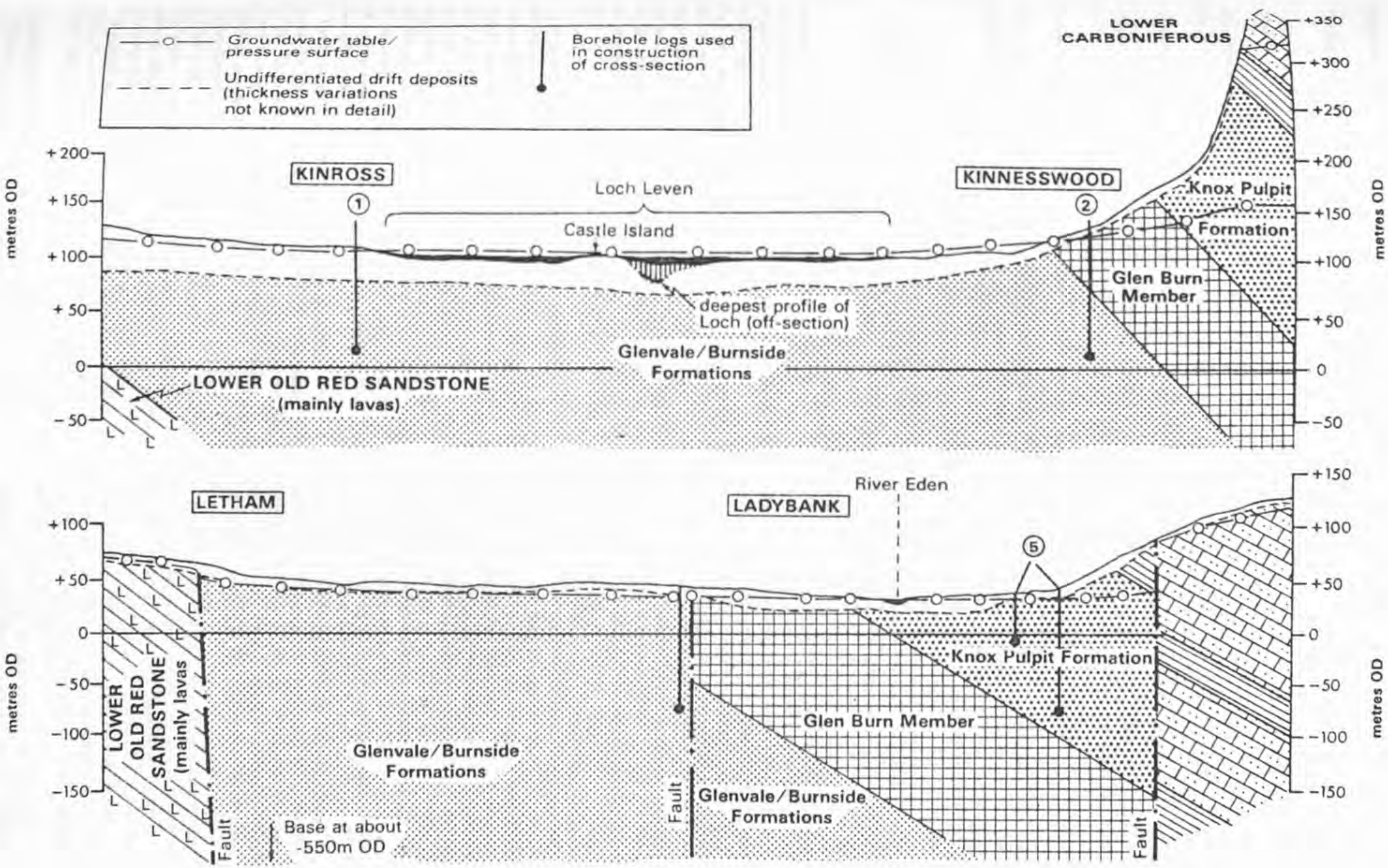

Fig. 2. Hydrogeological cross-sections of Upper Old Red Sandstone (lines of section given on Fig. 1 B.)

Table 1. Summary of results of reconnaissance field pumping tests on Upper Old Red Sandstone.

Pumping test site	KINNESSWOOD(2)	FALKLAND(4)	KETTLEBRIDGE(5)
Geological formation	Glen Burn Member (largely)	Knox Pulpit Formation	Knox Pulpit Formation
Date	March 1974	September 1974	October 1974
Groundwater level (m AOD)	128	55	36
Testing rates (l/s)	12, 25, 38	8, 15	33
Observation boreholes	One at 120 m, equally penetrating	One at 150 m, equally penetrating	One at 350 m, partially penetrating
Transmissivity (m^2/d)	250	200	150
Dominant hydraulic boundary	Barrier at more than 800 m, (?) feather edge of Glen Burn Member	Recharge at 200 to 500 m; probably from culverted river in town	Recharge at 300 to 600 m; streambed recharge of 10 to 20 l/s from Kettle Burn
Groundwater storage conditions	Unconfined, covered but pumping test S (10^{-4}) indicates self-confinement	Unconfined, covered; S_y indeterminate in pumping tests because of early effects of boundaries	

much greater water supply potential than the lower part. This conclusion emerged from comparison of the results of investigations in the Knox Pulpit Formation at Falkland (site 4 in Fig. 1B) with those in the Burnside Formation at Mawcarse (site 3 in Fig. 1B). In addition to the difference in porosity and intergranular permeability (Fig. 4), difference in jointing and fissure-permeability development lead to a transmissivity of about 150 to 250 m^2/d in the case of the former and less than 50 m^2/d in that of the latter.

The lower boundary of the main aquifer is somewhat uncertain, but is tentatively placed at the base of the Glen Burn Member on the basis of the results of investigations at Kinnesswood (site 2 in Fig. 1B). Pumping tests and geophysical borehole flow logging here showed relatively high transmissivity (250 m^2/d), with the larger part of the groundwater yield (50 to 80 per cent) being derived from the upper 50 to 60 m of strata, which are thought to belong to this member.

The principal aquifer is thus believed to comprise the Glen Burn Member and the Knox Pulpit Formation. It has a narrow outcrop on the lower slopes of the Benarty and Lomond Hills and dips south-eastwards beneath the Lower Carboniferous rocks, which occupy the higher ground (Fig. 2A). East of Falkland (Fig. 1B), the aquifer subcrop beneath the drift expands considerably and extends all along the south side of Stratheden (Fig. 2B), narrowing again and disappearing east of Cupar where these formations are downthrown on the south side of the Dura Den Fault.

AQUIFER HYDRAULIC PROPERTIES

The Knox Pulpit Formation has received most detailed investigation at the Falkland and Kettlebridge sites in Stratheden (4 and 5 in Fig. 1B). At Falkland some 30 per cent of the overall transmissivity of 200 m^2/d appears to be represented by intergranular permeability, with the cross-bedded units from 30 to 40 m below ground level contributing about 30 m^2/d (Fig. 3A). Fissure permeability, which contributes the larger part of the overall transmissivity, is thought to be principally developed in the uppermost 10 to 15 m of the saturated zone.

At Kettlebridge more extensive geophysical borehole flow investigations were possible and these showed that about 60 per cent of the groundwater yield was derived from a restricted level around 5 m AOD (Fig. 5). There were minor inflows from fissures and from the horizons of higher intergranular permeability throughout the borehole to its base at 75 m below OD. Television inspection showed that at most levels where inflows had been identified in the flow logging, low-angle fissuring was present. Since this fissuring did not exceed 30° to the horizontal, it could well have been associated with bedding and cross-bedding features, the dip of the formation itself being about 10°. There were occasional levels at which such fissuring was identified but where no significant groundwater inflow appeared to occur.

At both Falkland and Kettlebridge positive recharge boundaries in the groundwater flow system were detected (Table 1), apparently associated with minor naturally-losing streams descending from the hills to the south. This complicated the determination of the storage coefficient or specific yield of the apparently unconfined aquifer.

In view of the importance of specific yield in assessing the feasibility of certain types of

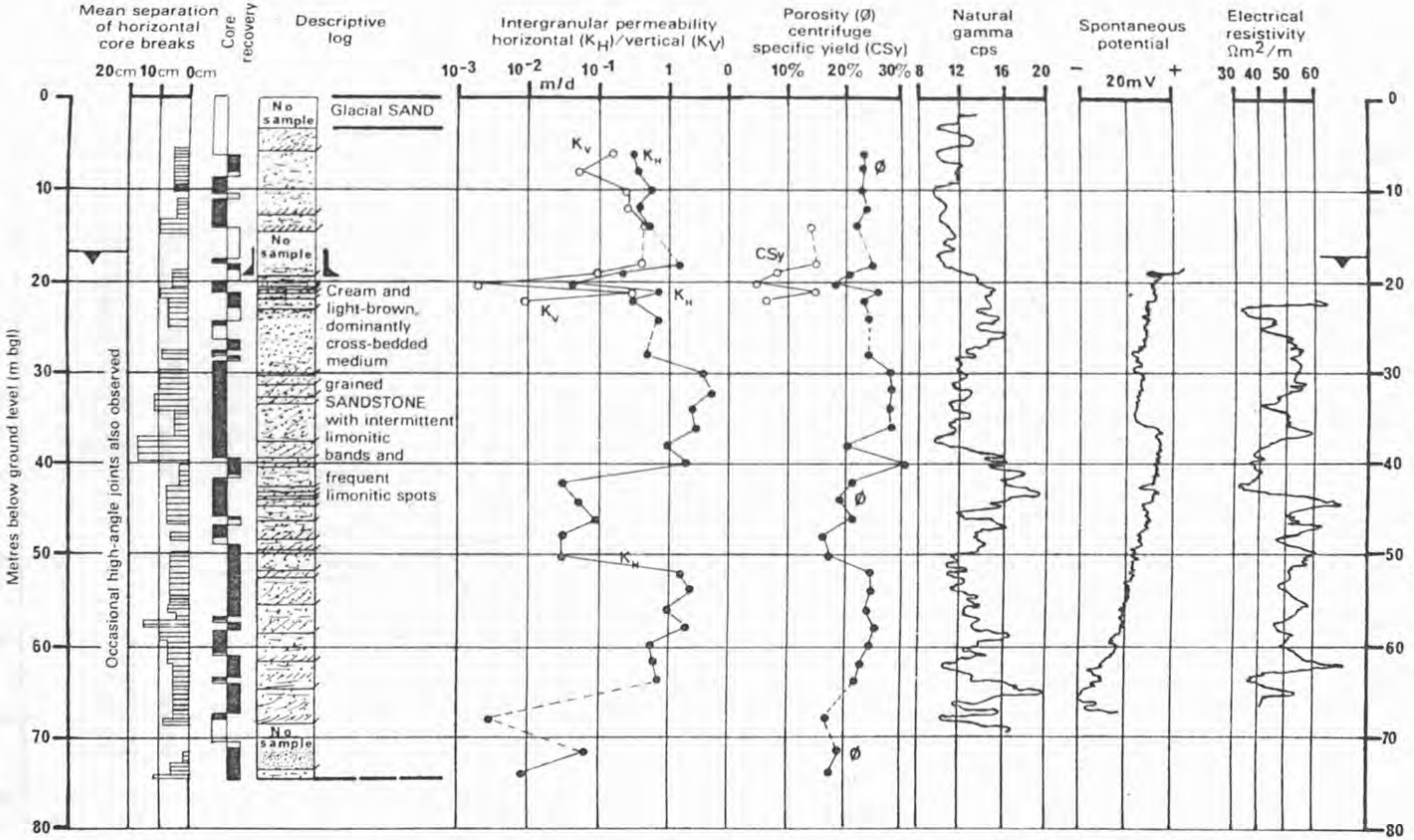

Fig. 3A. Borehole logs with interstitial aquifer properties - Falkland (4)/Knox Pulpit Formation

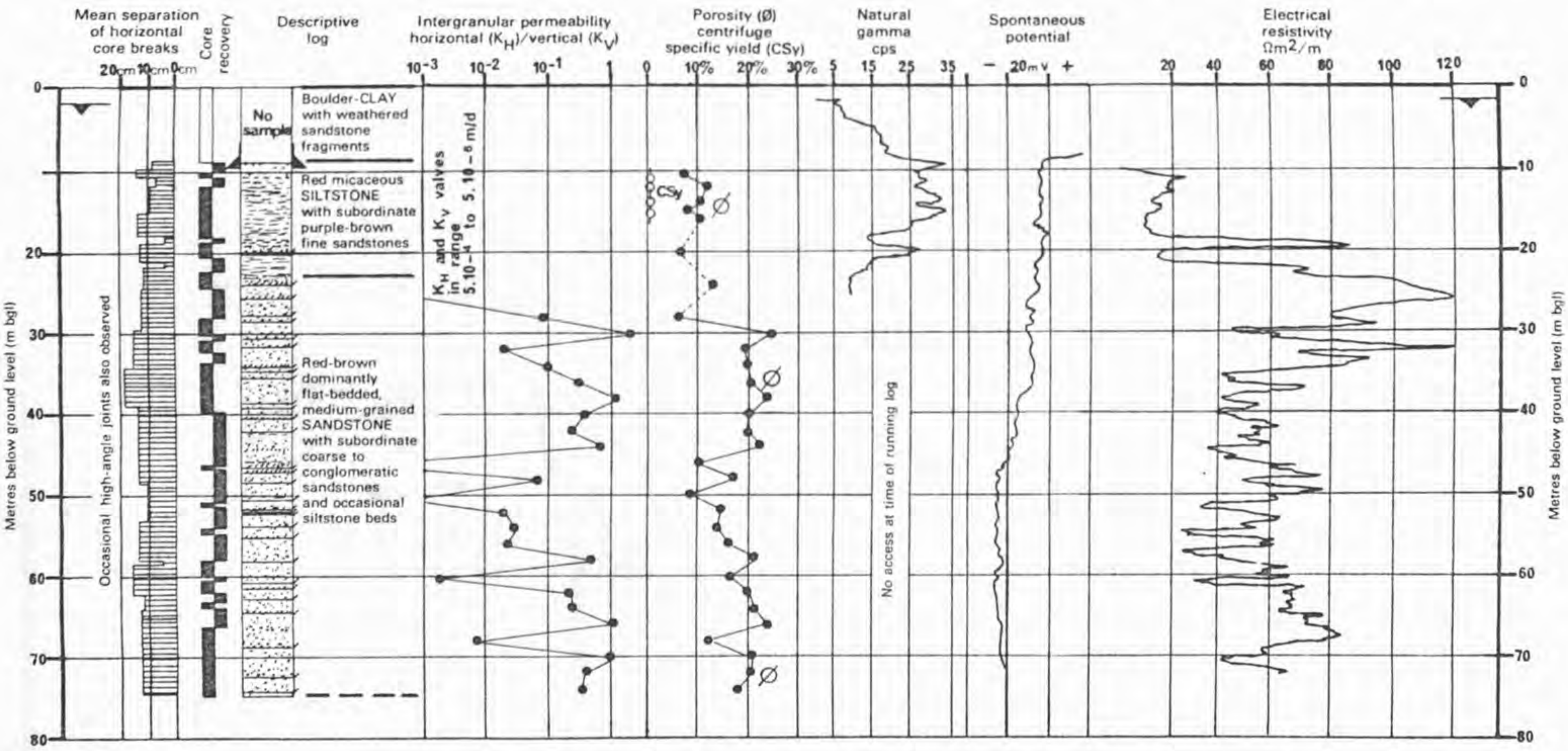

Fig. 3B. Borehole logs with interstitial aquifer properties - Mawcarse (3)/Glenvale-Burnside Formation

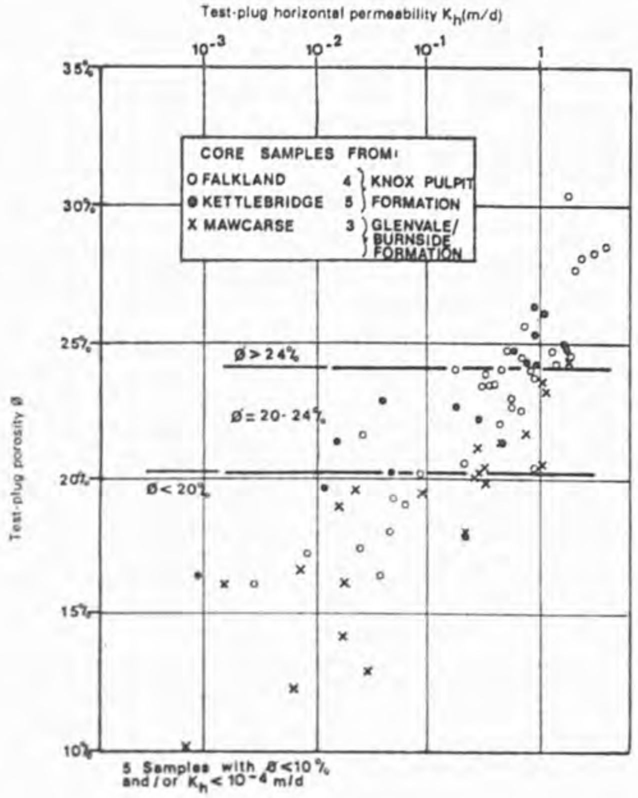

Fig. 4. Permeability/porosity relationship for laboratory samples

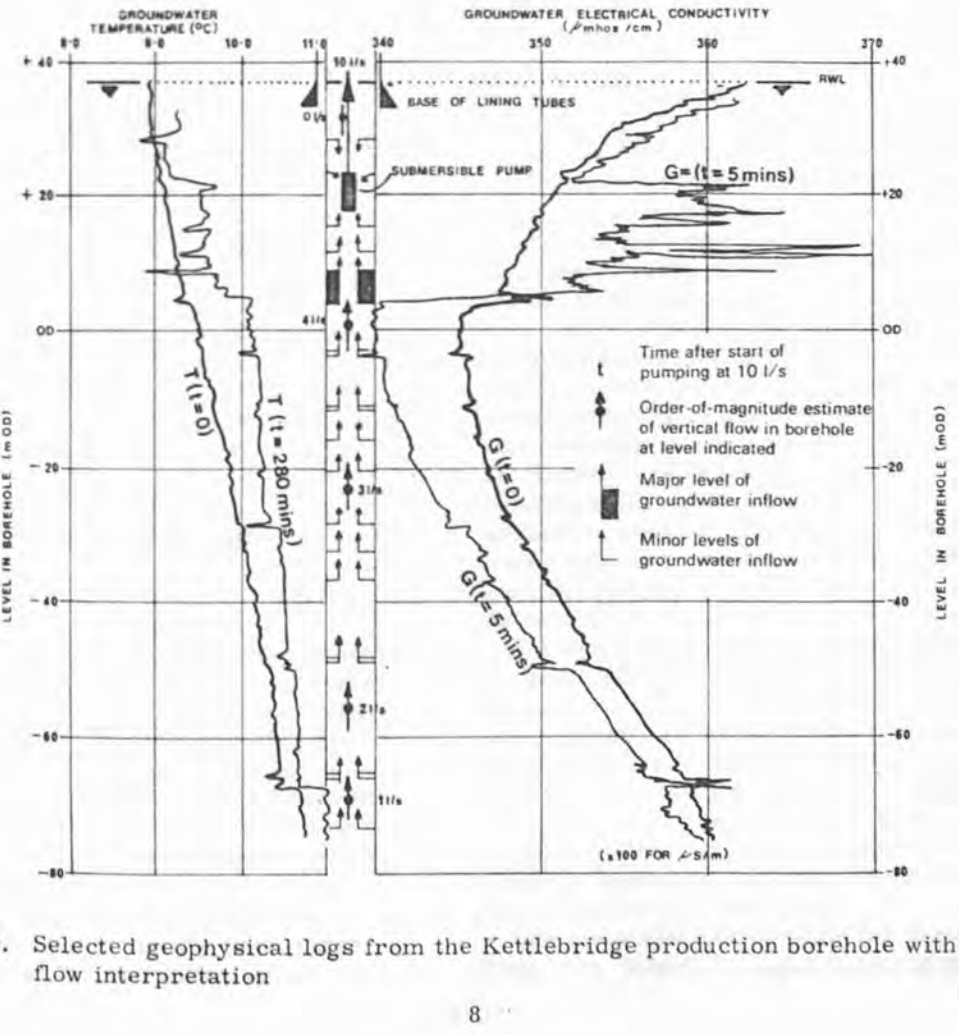

Fig. 5. Selected geophysical logs from the Kettlebridge production borehole with associated flow interpretation

groundwater development, detailed investigation of the pore-size distribution of the Knox Pulpit sandstones was made in the laboratory using the mercury-injection method. Fifteen core samples from shallow levels in the saturated zone of the Falkland and Kettlebridge sites were selected to represent the range of porosities present (Fig. 4). The results (Fig. 6) suggest that 60 to 80 per cent of the porosity of those sandstones with ϕ over 20 per cent, are likely to drain under gravity. Specific yields of over 12 per cent, and probably over 15 per cent, would be expected for such horizons. It should be noted, however, that the lower porosity sandstones (ϕ under 20 per cent) were much more variable in their pore-size distributions and in certain cases might have specific yields of less than 5 per cent (Fig. 6).

BOREHOLE YIELD CHARACTERISTICS

A comparative plot of the available yield-drawdown characteristics of production boreholes in the Upper Old Red Sandstone (Fig. 7) reflects strongly the hydrogeological division between the upper and lower part of the series discussed above. In the lower part of the sequence no yield of over 10 l/s has been recorded despite drawdowns in excess of 20 m (sites 1, 3 and 7 in Fig. 1B), whereas all five production boreholes drilled to date in the principal aquifer have very similar and far superior Q-s relationships (Fig. 7).

In addition the boreholes in the main aquifer have shown significant improvement with continuous pumping (Fig. 7), due presumably to development of the fissures and to increase in effective diameter; this, however, may also be accompanied by a minor sand pumping problem.

The present characteristics show yields of over 40 l/s for drawdowns of less than 25 m and suggest that increased yields might be obtained from larger diameter boreholes, in which higher capacity pumps could be installed. These may, however, not be economic especially if the borehole yield characteristics 'breakaway' at larger drawdowns. In the case of the Kettlebridge borehole for example, the results of the geophysical flow logging (Fig. 5) lead one to expect that the Q-s relationship will fall off rapidly for drawdowns in excess of 30 m, corresponding to the level of major fissure inflow.

Hydrogeology of Stratheden and Loch Leven Areas

GROUNDWATER FLOW REGIME

The very limited data on natural groundwater levels in the Upper Old Red Sandstone are interpreted in Fig. 8; this picture is thought to be representative of the 1971-1974 droughts and overall fluctuations are probably only of the order of 1 to 4 m. It should be noted however, that minor perched water tables may also be present at some localities on the higher ground along the southern flank of the valley.

The natural recharge of the groundwater reservoir is believed to originate from three sources (Fig. 9); a) direct infiltration of precipitation at the outcrop, b) small losing-streams descending from the hills flanking the valley, particularly on its southern side, which are fed both by surface run-off and springflow from minor bodies of perched groundwater in the Carboniferous rocks, c) precipitation infiltrating the more permeable drift deposits (much of this, however, may enter shallow groundwater circulation and be discharged). The existence of relatively recent recharge to the main aquifer is confirmed by the levels of thermonuclear tritium in the Kinnesswood and Kettlebridge sources (in all cases over 35 TU and in the case of the Kinnesswood No. 1 borehole increasing from 46 TU to 67 TU through the winter of 1973-1974).

The mean long-term average annual precipitation for Stratheden exceeds the potential evaporation by about 330 mm and in the upper part of the Eden catchment and in the Loch Leven area, heavier rainfall means that this figure approaches 500 mm (Table 2). On the East Fife coast it is probably nearer 200 mm. With the complex groundwater recharge regime however, it is impractical to attempt to evaluate directly the various sources and an assessment of volume of groundwater in natural circulation has to be approached from knowledge of the groundwater discharge.

SURFACE WATER/GROUNDWATER RELATIONSHIPS

The groundwater level contours in Fig. 8 show the general directions of subsurface drainage. In the central and western part of Stratheden, the major component of groundwater flow is directed towards the River Eden with a subordinate component of underflow parallel to the river itself. Downstream at Cupar, where the valley has narrowed somewhat, the groundwater underflow is probably only of the order of 1 to 2 Ml/d (0.01 to 0.02 cumecs) and insignificant in relation to the riverflow. In the upper part of the catchment, at the Gateside river gauging station for example, the groundwater underflow is about 3 to 5 Ml/d (0.03 to 0.06 cumecs) and in drought conditions may well approach the riverflow; explaining the relatively small groundwater component of total river discharge at this station, when bearing in mind that 60 to 70 per cent of its catchment area is formed of Upper Old Red Sandstone (Table 2). The large proportion of underflow renders this station unsuitable for water balance calculations despite its homogeneous geological character and limited extension.

In Stratheden the major component of lateral groundwater flow leads to the development of important groundwater discharges on the lowest lying ground, in hollows and along the lower reaches of the tributary streams, where the drift deposits are thinnest, and to a lesser extent directly through the bed of the Eden (Fig. 9). It is likely that land drains have eliminated many seepage areas and that they conduct groundwater discharge to the Eden River.

The riverflow hydrographs for the Eden (Fig. 10) reflect the significance of groundwater

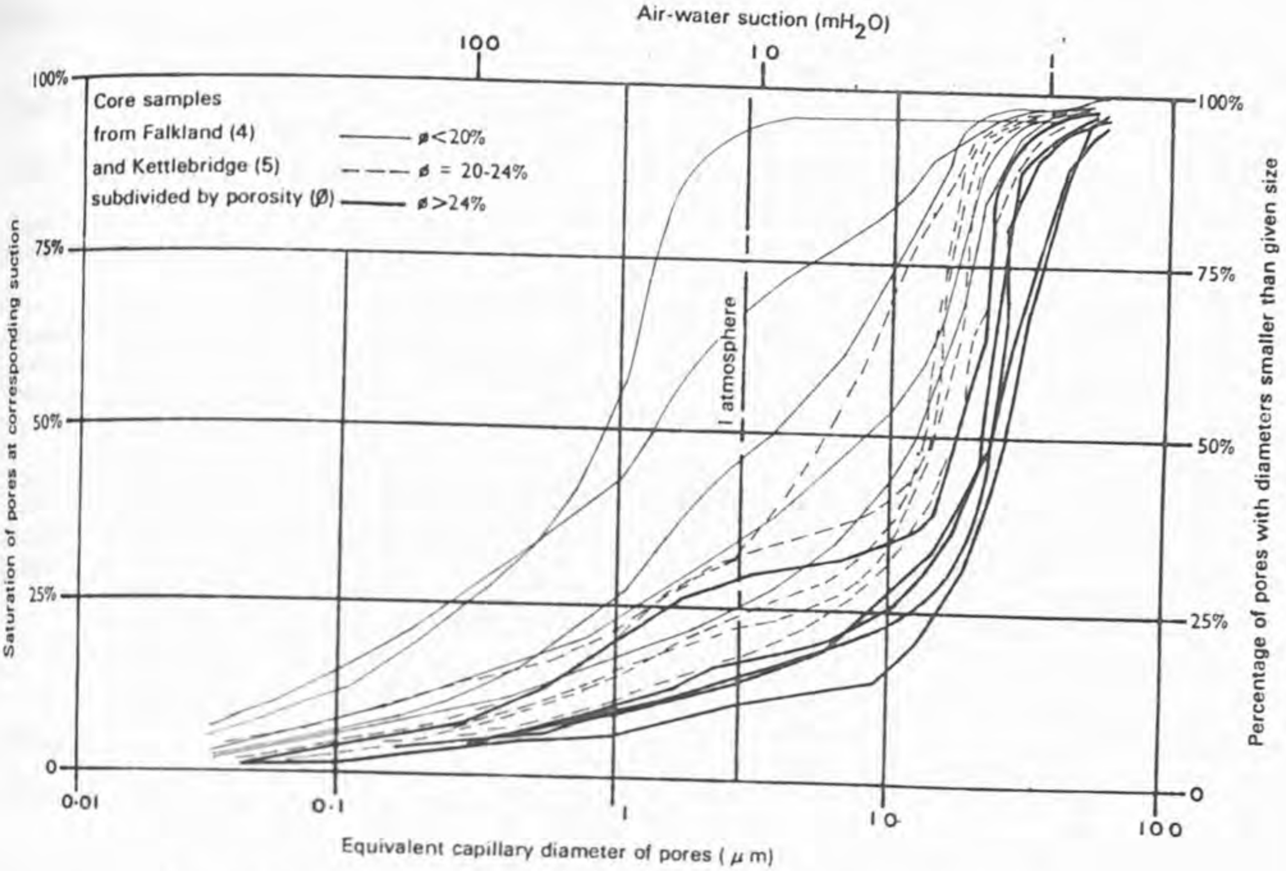

Fig. 6. Pore size distribution of Knox Pulpit Formation sandstones

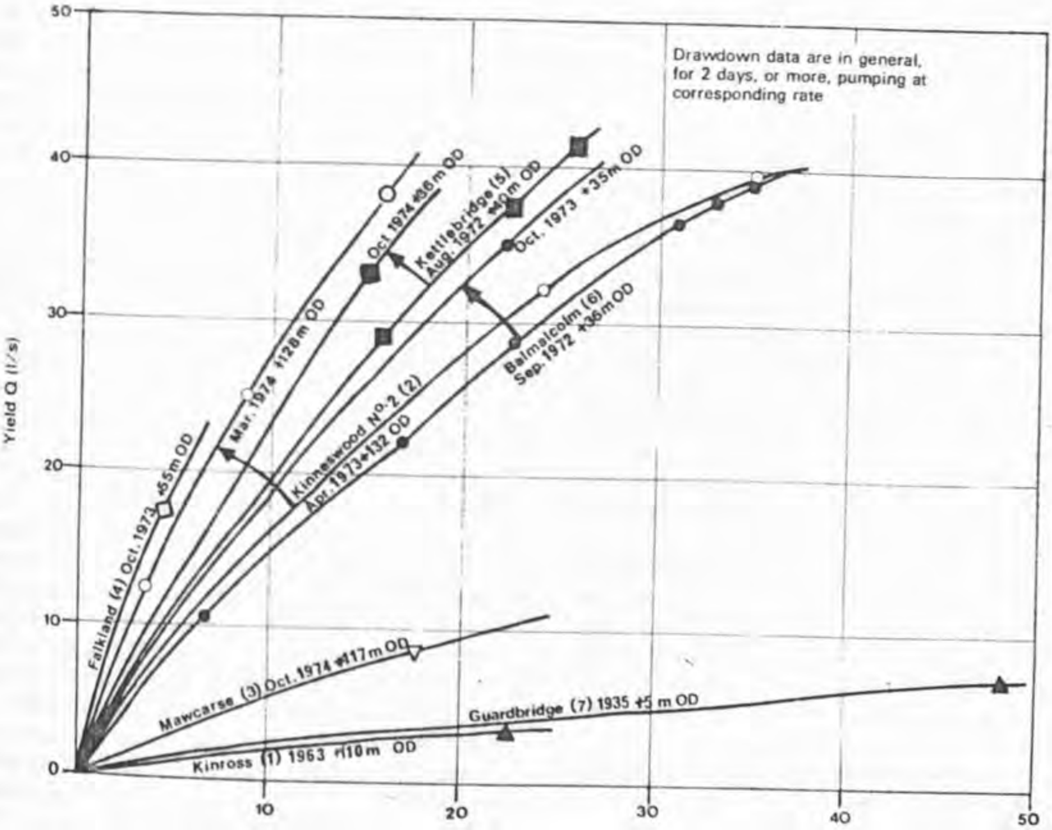

Fig. 7. Yield-drawdown characteristics for Upper Old Red Sandstone boreholes

Table 2. Summary of riverflow analysis and corresponding meteorological data.

Eden subcatchment		KEMBACK	GATESIDE
Surface catchment area (km^2)		307	21
Upper Old Red Sandstone sub-surface catchment area (km^2)		126	15
Groundwater component of riverflow (Ml/a) (determined by base-flow separation, percentage of total riverflow in parenthesis)	1968 - 1969	51 000 (40%)	-
	1969 - 1970	46 000 (59%)	-
	1970 - 1971	53 000 (50%)	-
	1971 - 1972	44 000 (44%)	2 500 (34%)
	1972 - 1973	32 000 (65%)	1 900 (45%)
Precipitation (mm/a) (Kemback taken as average of Leuchars, Pitlair, West Hall and Gateside gauges)	1968 - 1969	796 e	-
	1969 - 1970	703 e	-
	1970 - 1971	627 e	-
	1971 - 1972	637	730
	1972 - 1973	475	588
	long-term (1931 - 1960) mean	795	940
Mean potential evaporation (mm/a)		465	440 e

e - estimated because corresponding data are incomplete.

flow in the catchment hydrology by the relatively steady low flows. Both the Kemback and Gateside hydrographs appear to comprise three principal components with recession constants of 0.25 and greater, about 0.02 and 0.003: k, the recession constant, being defined by the equation $Q = Q_0 e^{-kt}$ (Barnes, 1939). The former represents surface run-off, mainly from the steeper areas of Lower Old Red Sandstone lavas in the north-west of the catchment and of Lower Carboniferous rocks in the south-east (Fig. 8). The latter would definitely appear to be discharge from the deep groundwater flow system of the Upper Old Red Sandstone. The intermediate component is more difficult to ascribe to a specific physical run-off process but may also be groundwater from shallow circulation systems in the more permeable of the drift deposits.

A separation of the major groundwater component of riverflow derived from the Upper Old Red Sandstone can be made with reasonable confidence (Fig. 10) and a conservative estimate of its volume during the period of available riverflow data appears in Table 2. Above Kemback the groundwater discharge varied from 32 000 Ml in the hydrological year 1972-1973 to 51 000 Ml in 1968-1969 and the discharge never fell below 69 Ml/d (0.8 cumecs) even in extreme drought. When viewing the data in Table 2 it should be borne in mind that the precipitation in Stratheden for the entire period 1969-1973 was considerably below the long term mean and in 1972-1973 was only 60 per cent of average, and that hearsay evidence suggests that over extensive areas of the Upper Old Red Sandstone the minimum water table in 1973 was considerably below average, possibly by as much as 2 m, implying that some 15 000 Ml of the total baseflow could have been derived from groundwater storage. Concurrent changes in soil moisture also affect water balance calculations, but it is still certain that over much of the Upper Old Red Sandstone a large proportion of the excess rainfall (of 330 mm) infiltrates and such infiltration is supplemented by natural stream-bed recharge.

The groundwater divide between the Eden Valley and the Loch Leven basin can be defined on the basis of the groundwater level contours (Fig. 8) and differs only slightly from the surface water divide. The groundwater flow regime in the Loch Leven basin is not fully established. It is suggested that, as a result of the more extensive and perhaps unbroken boulder clay cover on the lower lying ground, groundwater recharge will be largely restricted to the boulder clay-free eastern and northern flanks of the basin. Therefore it must be limited and is not likely to exceed 8 per cent of the total water balance of the loch, whose mean inflow is 121 000 Ml/a (Smith, 1973). Most of the groundwater discharge appears to be at springs and seepage areas feeding minor streams flowing into the loch, though there is a possibility of some direct discharge through its bed at the sites of kettle-holes, where the thickness of the boulder clay must be greatly reduced (Fig. 2A).

GROUNDWATER CHEMISTRY

There are only limited analyses available on the chemistry of the Upper Old Red Sandstone groundwaters and all refer to pumped water samples. The most complete data are from the sites developed for public supply (Table 3). In addition occasional partial analyses are available for four further boreholes in the Loch Leven

Table 3. Summary of chemistry/quality of major public water supply sources in Upper Old Red Sandstone during 1972-1974.

Chemical constituent (all results in mg/l)	BALMALCOLM (6)				KETTLEBRIDGE (5)				KINNESSWOOD Nos. 1 & 2(2)			
	max.	min.	mean	no. of samples	max.	min.	mean	no. of samples	max.	min.	mean	no. of samples
Total hardness (as $CaCO_3$)	203	196	202	37	229	214	220	29	155	136	142	42
Total alkalinity (as $CaCO_3$)	134	126	130	34	161	138	157	30	116	94	104	42
Calcium (Ca)	45	38	40	27	38	29	32	24	40	34	38	36
Magnesium (Mg)	27	23	25	27	36	32	34	24	14	10	12	36
Sodium (Na)	7.9	6.1	7.8	11	11.2	7.7	8.7	14	-	-	5.5	7
Potassium (K)	2.0	1.4	1.7	11	1.9	1.6	1.7	14	-	-	1.6	7
Chloride (Cl)	20	15	17.6	29	36	16	21	18	12	9	10.5	24
Sulphate (SO_4)	49	42	44	6	46	35	38	10	19	15	17	3
Iron (Fe)	0.15	<0.01	0.03	20	0.1	<0.01	0.02	19	0.06	<0.01	0.02	27
Manganese (Mn)	0.09	<0.01	0.01	15	<0.01	-	-	-	0.01	-	-	-
Nitrate (as NO_3-N)	6	4	5	26	8	3	5	28	5	3	4	40
Phosphate (PO_4)	0.05	<0.01	<0.01	23	0.1	<0.01	0.03	17	0.37	<0.01	0.20	35

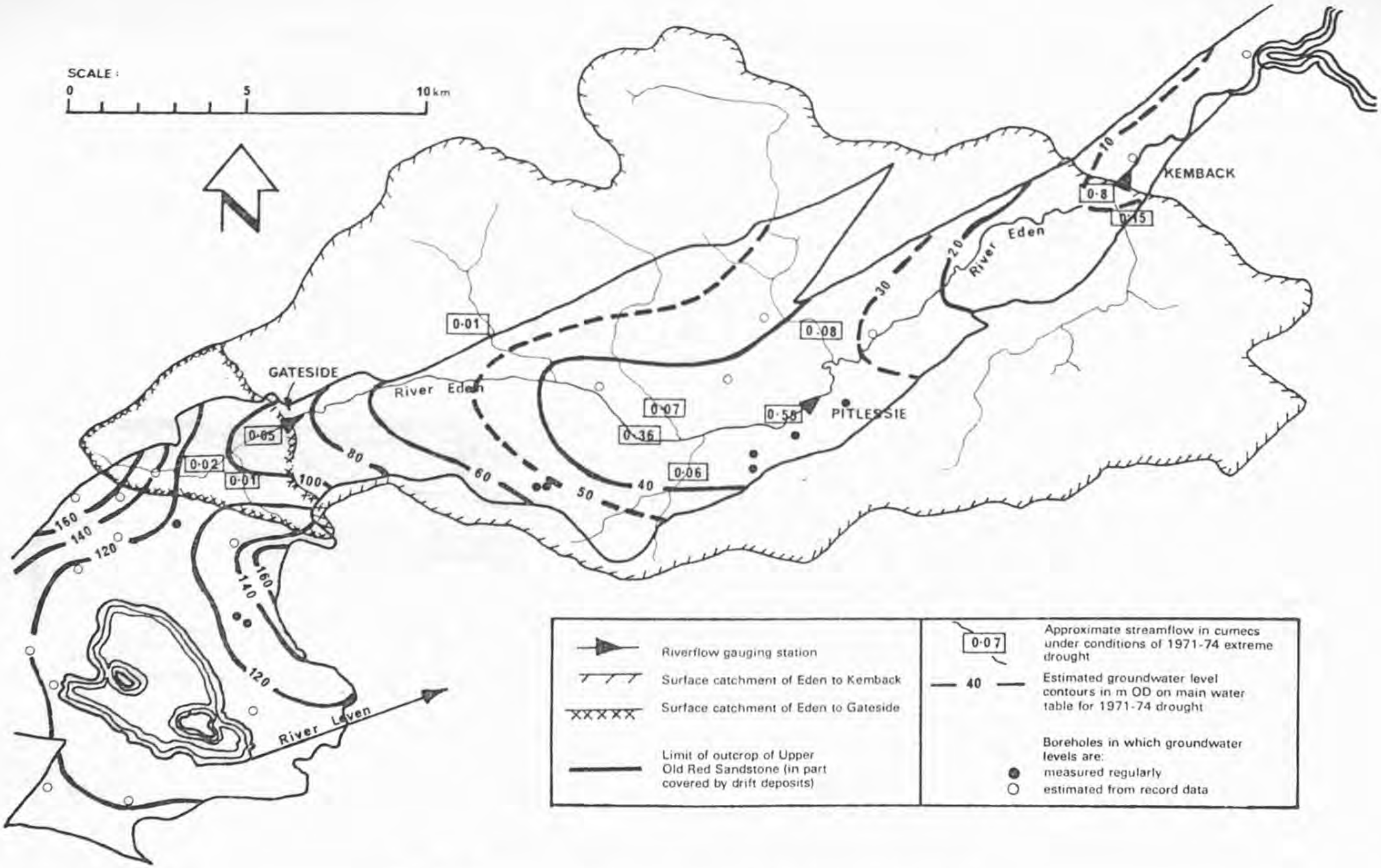

Fig. 8. Reconnaissance groundwater level and streamflow data

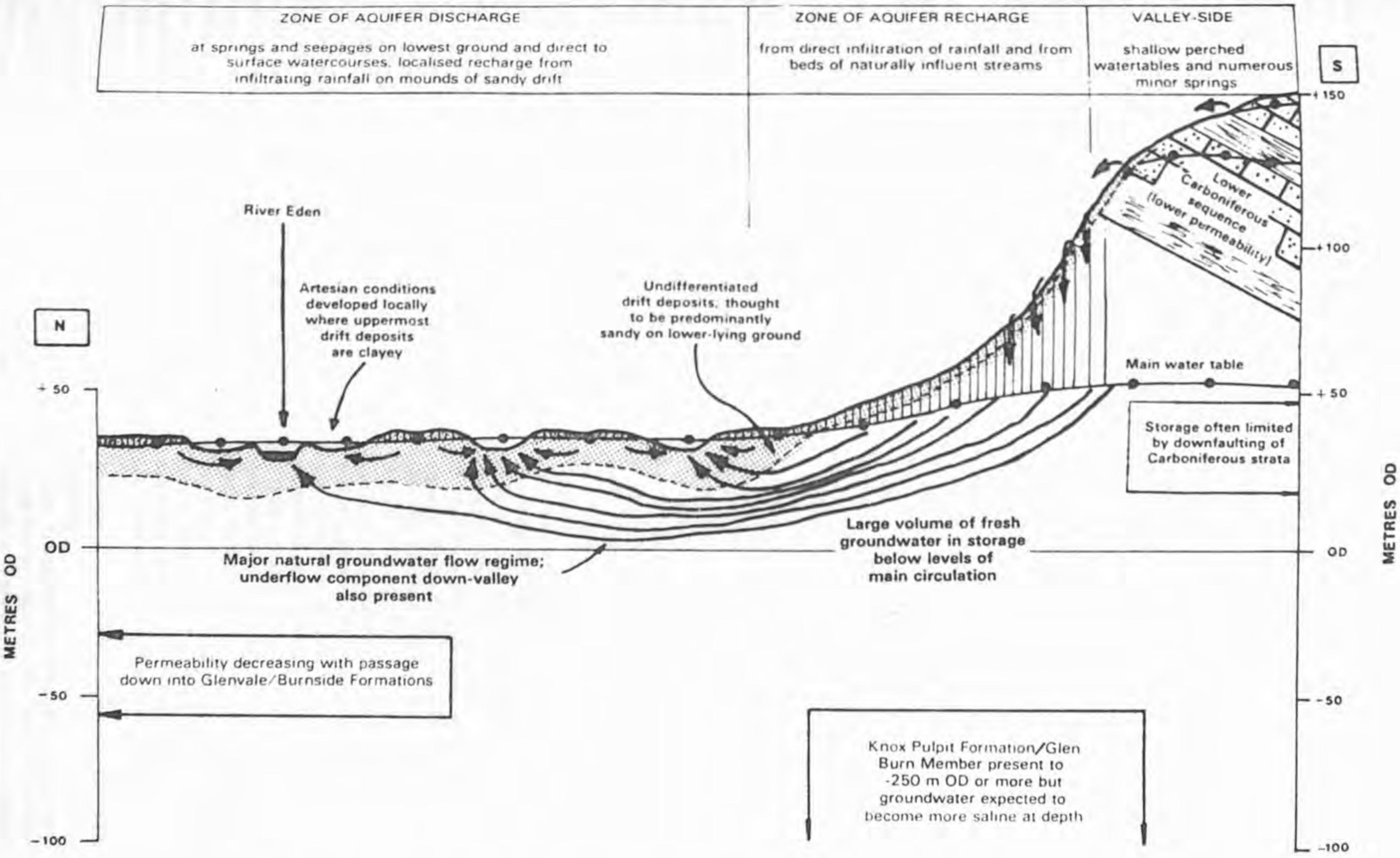

Fig. 9. Schematic section of Eden Valley illustrating aquifer recharge and discharge regime

basin and five in Stratheden.

In general groundwaters appear to have good inorganic and organic quality, but are moderately hard. The total hardness is notably higher in the Kettlebridge/Balmalcolm sources than at those in the Upper Eden Valley and Loch Leven basin (for example, Falkland and Kinnesswood) and is apparently caused by 10 to 20 mg/l higher Mg^{++}, 5 to 10 mg/l Cl^- and 20 to 25 mg/l SO_4^{--}. This may reflect a greater proportion of streambed recharge in the case of the former and the fact that the overlying basal Lower Carboniferous strata have a much wider outcrop.

There is limited evidence to suggest a general increase in dissolved constituents downstream of Cupar, where most of the groundwater is held in confined storage. In a groundwater reservoir extending to considerable depths below present sea level, the presence of increasingly saline water at depth must be expected (Fig. 7). Conductivity logging at the Kettlebridge site, however, proved fresh groundwater at least to below -75 m OD.

Groundwater Resources: Evaluation and Development

PERENNIAL SUPPLY OR CONJUNCTIVE USE?

The preceding sections have demonstrated the existence of an important regional aquifer, which permits substantial abstraction from individual boreholes and possesses major storage. How should this resource best be developed?

In Stratheden conventional groundwater development for perennial supply (baseload sources) will involve some reduction of low flows in the Eden, no effluent being generated because the main area of water demand is outside and well to the south of the catchment. Interest in the low flow of the Eden is primarily for dilution of sewage effluents (Scottish Development Department, 1972), pending construction of two new treatment works for Cupar (Springfield) and for the Auchtermuchty/Falkland/Ladybank area. Currently there is substantial river pollution locally in drought.

Since the flow of the Eden in extreme drought is over 40 Ml/d at Pitlessie and almost 70 Ml/d at Kemback (Fig. 8), there would appear to be some capacity for groundwater development as base-load sources (perhaps up to a total of 10 Ml/d), bearing in mind the exceptionally economical water supply produced. Moreover internal use of groundwater, perhaps involving deliberately induced recharge from the Eden for industry in the Cupar area for example is to be encouraged providing the effluent returned to the river is of tolerable quality. However, the large-scale perennial development of groundwater resources for export from Stratheden would not appear desirable until such time as the quality of sewage effluent discharged to the river is improved.

Similar arguments apply to the Loch Leven basin, where the water interests include loch conservation and amenity and those of industry on the River Leven, whose discharge is regulated by the loch. Here, however, a limited perennial groundwater development of 10 Ml/d would, at the outside during an absolute drought of 100 days duration, represent a fall of only 0.07 m in loch level - this compared to a mean annual fluctuation of about 0.4 m (Smith, 1973).

Such restrictions on perennial groundwater development do not eliminate the possibility of large-scale exploitation of the groundwater resources. The Knox Pulpit Formation in particular is known to have very large volumes of fresh groundwater in storage (probably 500 to 750 $Ml/km^2/5$ m of saturated thickness). The problem is how to develop this storage while minimising interference with riverflow. Consideration of the hydraulic properties of the main aquifer in Stratheden (T and S of the order of 150 m^2/d and 0.15 respectively), its distribution and its discharge suggests that there is a good prospect of being able to abstract relatively large volumes of groundwater from storage for restricted periods in limited areas without much interference with the surface flow. Should this prove feasible in areas close to trunk mains the boreholes could be used conjunctively with upland reservoirs. Given sufficient mains capacity, this would allow an increased rate of off-take from the reservoirs in the wetter months, drawing increasingly on the groundwater storage in drought (that is, operating the boreholes as a trough-filling source).

In every case there would probably be almost total interception of the groundwater discharge to the river system (Fig. 9) in the vicinity of the well field, but this may not involve more than about 5 Ml/d and could perhaps be made good by compensation boreholes. The most critical aspect of this type of development would be the degreee of interference beneath the bed of the Eden itself during the maximum required period of pumping (estimated to be about 150 days) and the risk of diminishing riverflow by inducing riverbed recharge. Providing that under heavy pumping the aquifer has a storage coefficient nearer 0.15 than 0.01 and that the well-field is situated over 1 km from the river, the chance of riverflow depletion by this mechanism would appear slight (Fig. 11), also bearing in mind that the vertical permeability in the vicinity of the riverbed is likely to be much lower than the horizontal permeability of the aquifer. Intermittent groundwater development for conjunctive use is further discussed below, in relation to the proposed groundwater pilot scheme.

It is possible that a small well-field could be developed in the east or south of the Loch Leven basin to augment low flows in the River Leven for restricted periods. Further investigation would be required to evaluate the time lag in the spread of interference laterally and vertically to loch and river and thus to establish feasibility.

FIFE (KINGSKETTLE) GROUNDWATER PILOT SCHEME

The prospects of obtaining a high yield from groundwater storage for limited periods in drought are good and it is recommended that a pilot scheme be developed to confirm the

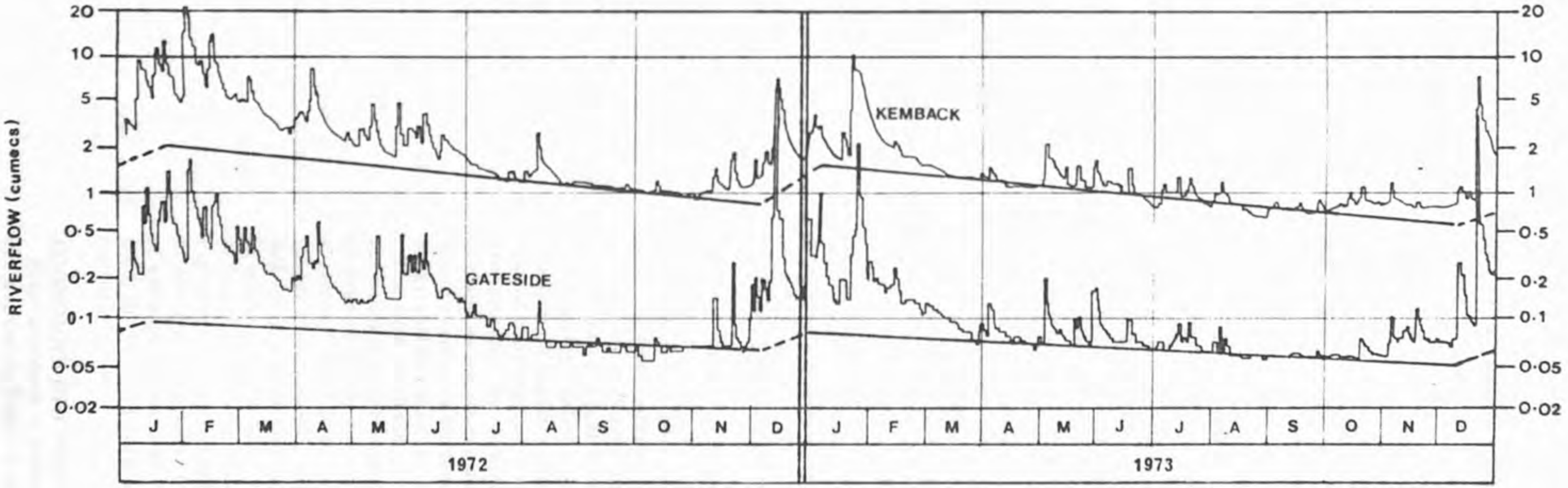

Fig. 10. River Eden hydrographs for 1972-1973 drought with separation of major groundwater component

feasibility and to determine the degree of interference with the River Eden. A major exploitation of groundwater resources should be staged and have a research component as the cost of complete investigation prior to any development may be excessive.

The simplest and most economical area in which to develop a pilot scheme is at Kingskettle (Fig. 12), utilising the existing production boreholes in the vicinity.[1] A further three production boreholes, at a spacing of 300 to 500 m (Fig. 11), would need to be drilled and commissioned (at a cost of £75 000, 1974 prices) to reach the minimum practicable pilot scheme yield of 20 Ml/d. The success of the scheme, the interference with the surface water courses and other side-effects would be assessed through the hydrometric network detailed in Fig. 12: this network is estimated to cost some £25 000 (1974 prices).

The absolute maximum draught on aquifer storage of 3000 Ml (20 Ml/d for 150 days) derived from an area of about 10 km^2 would require 300 mm of infiltration for replenishment, but of course, it would not be abstracted every year.

If the pilot scheme were successful there would exist the possibility of further development of a similar type along the southern flank of the Eden Valley in the direction of Falkland. In the event of unacceptable diminution of riverflow, three of the pilot scheme boreholes could probably be operated as base-load sources retaining the other two as an emergency stand-by.

EXPERIENCE AND ADVANTAGES OF GROUNDWATER USE

After two years experience of operating the existing Upper Old Red Sandstone boreholes, during which time over 2000 Ml of groundwater have been abstracted, a number of points can be confirmed.

1. It is acceptable to the majority of consumers without dilution and superior in quality to partially treated water from upland reservoirs, which have occasioned frequent consumer complaints in the past.
2. The injection of groundwater directly into trunk mains after simple chlorination has raised no serious sediment or growth problems.
3. In spite of increasing cost of electrical power, groundwater was produced at a total cost of less than 1.3 p/m^3 when bulk imported water was costing 4.6 p/m^3.

In general the development of groundwater resources, when available, has many significant advantages.

1. An installation may be designed and constructed rapidly (in much less than 12 months in a case of emergency) and, in Scotland, is subject to only the minimum of statutory control.
2. A borehole source may be sited on a plot less than 10 m square and with modern electric submersible pumps the entire installation can be unobtrusive with only a small surface cabinet capable of housing the power-supply controls and instrumentation for an entire group of boreholes.
3. Groundwater development in its simplest form of direct injection into existing trunk mains involves the least unit capital commitment, only 25 per cent of that required for a pumped river intake scheme with treatment, like the proposed River Earn project, and 15 per cent of that required for an upland impounding reservoir with treatment works; for this reason it is the ideal form of stand-by capacity suited to 'mothballing' and recommissioning as need arises.
4. The development of a major borehole project can proceed gradually at a similar rate to the growth of demand (this is a positive advantage given a programme of concurrent research and appraisal of the spacing and location of boreholes and of interaction with riverflow).
5. Groundwater storage is more reliable than riverflow in extreme droughts and represents a major resource under such conditions which, given installed borehole capacity, can be used to protect the consumer from their effects.
6. The existence of a complex of boreholes in the Eden Valley would open up the possibility of providing a concentrated 'freshet' of discharge to the river for a short period to combat heavy spot pollution or to conserve fishing interests.

At the same time it must be recognised that upland impounding reservoirs have some definite advantages over borehole sources, namely, their ease of operation, normally requiring neither power (therefore being immune from power cuts and fuel shortages) nor a high degree of telemetry control. Moreover the effect of inflation on capital costs, and in particular the cost of construction, may make it preferable to proceed with the construction of the next major surface water source and to develop the groundwater resources conjunctively when the main construction phase is complete.

The Fife and Kinross Water Board have upland impounding reservoirs with a total reliable yield of over 90 Ml/d, feeding gravity distribution systems. Most of the major catchments are 'under reservoired', that is, with average rainfall there will be considerable overflow running to waste. At the same time, storage capacity is insufficient to sustain the yield in years of repeated drought. Exploiting groundwater storage in drought conditions could enable an increase of perhaps 25 per cent in the rate of off-take from the upland reservoirs during periods of normal rainfall.

ECONOMICS OF GROUNDWATER DEVELOPMENT

Four schemes of possible source development are set out in Table 4 and their capital commitment compared; the attractiveness of groundwater

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[1] A new production borehole in the area has encountered significant organic groundwater pollution, including phenols. This appears to derive from earlier effluent disposal of a now non-existent gasworks. The yield of the borehole however, is most encouraging (50 l/s for 6 m drawdown). The extent of the pollution needs to be established however and a method of control or elimination designed before proceeding with the proposed pilot scheme.

Table 4. Details of water supply schemes with capital commitment comparison (1974 prices).

Scheme	Design Yield (Ml/d)	Pumping Head (m)	Additional Pipeline length (km)	Capital Cost (per Ml/d capacity)	Asset Life Total Cost (per Ml/d capacity)	Life Annuity Commitment(%)	Remarks	
1. CASTLEHILL UPLAND RESERVOIR on River Devon with pumping to treatment works for direct supply to existing mains	30	60	Nil	£0.129 m (100%)	£0.858 m	100%	Under construction, commission planned in 1977	
2. RIVER EARN INTAKE pumping to existing impounding reservoir, enlarged outlet and secondary pumping to new treatment works and trunk mains	68	230	25	£0.069 m (54%)	£0.258 m	30%	Legal stages in hand, consultant commissioned	
3. KINGSKETTLE GROUNDWATER PILOT SCHEME chlorination and pumping to existing mains	11	150	Nil	£0.078 m (60%)	£0.114 m	13%	Base load with 100% stand-by	Boreholes for about 6 Ml/d already available but not all commissioned
	23			£0.039 m (30%)	£0.057 m	7%	Conjunctive use; seasonal load, no stand-by	
4. EXTENSION SCHEME 3 including chlorination, trunk main telemetry	23	150	14	£0.116 m (90%)	£0.232 m	27%	Base load with 100% stand-by ?riverflow diminution acceptable	Requires hydrogeological research programme in 3 to assess feasibility
	45			£0.058 m (45%)	£0.116 m	14%	Conjunctive use; seasonal load, no stand-by	

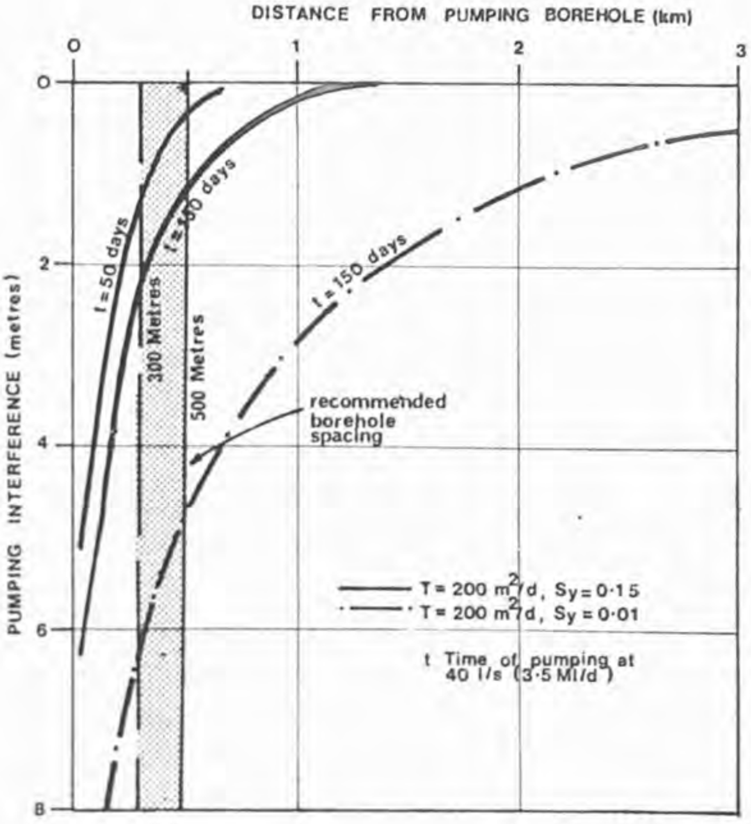

Fig. 11. Theoretical pumping interference effects in an idealised aquifer

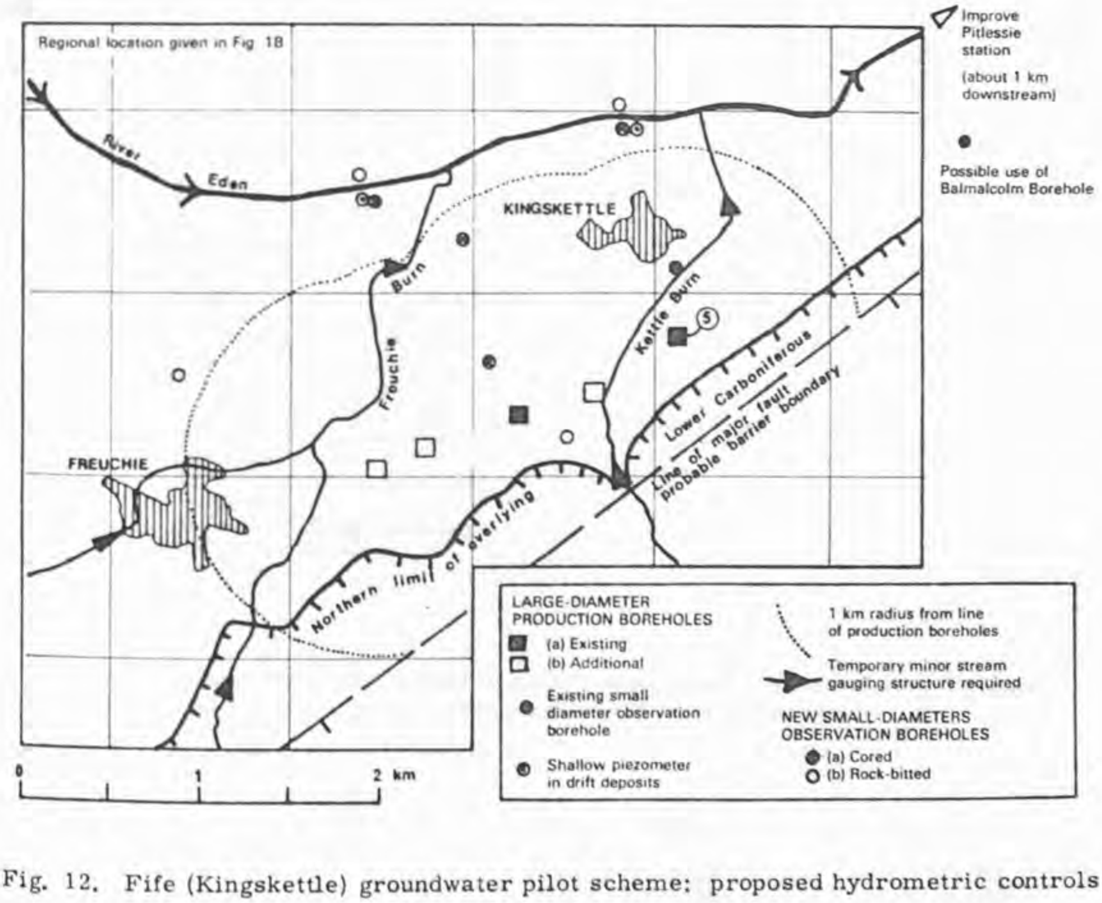

Fig. 12. Fife (Kingskettle) groundwater pilot scheme: proposed hydrometric controls

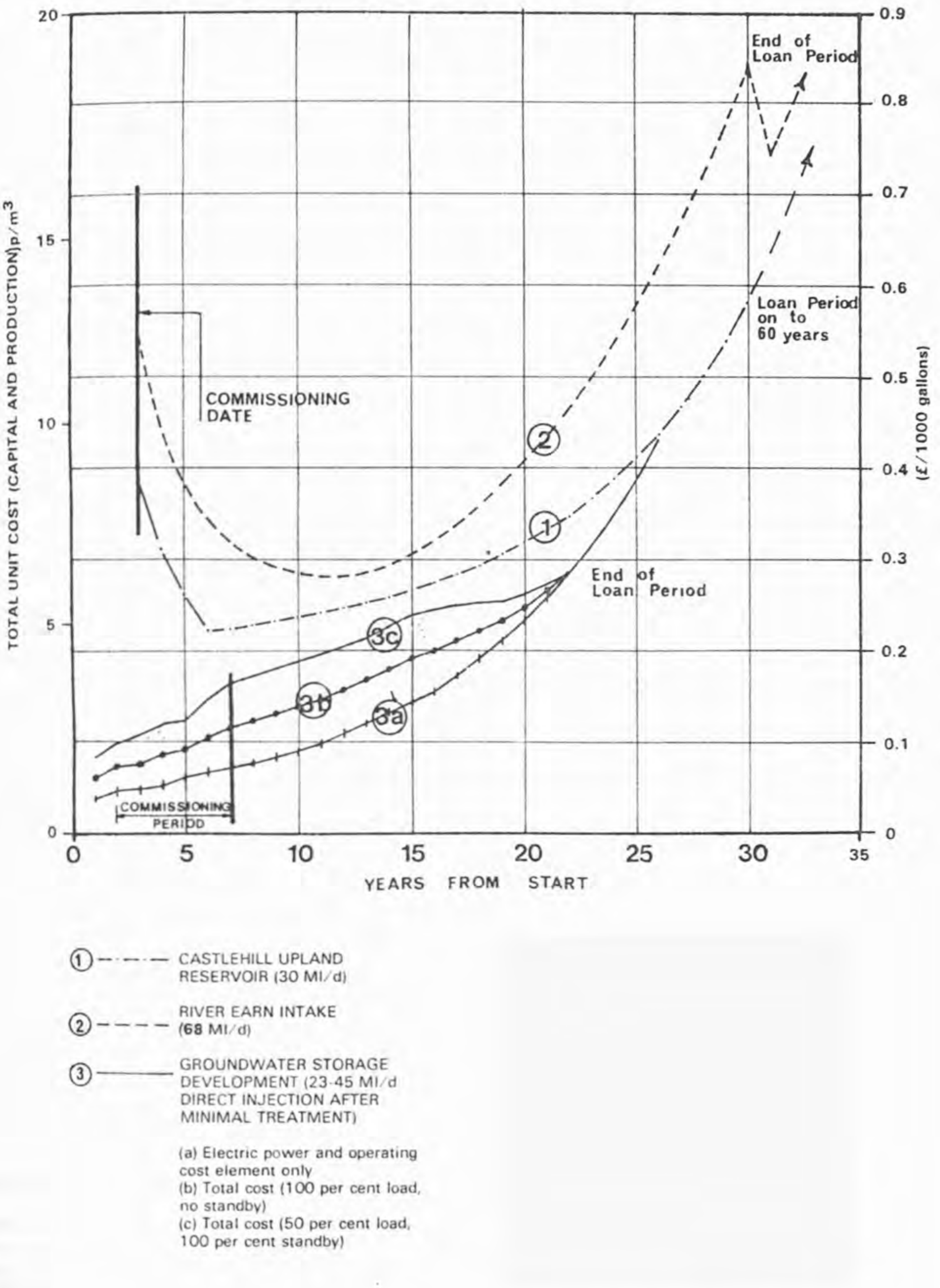

Fig. 13. Comparative unit cost projections for major water-supply schemes (see Table 4 for details of scheme and p. 21 for assumptions used in calculations)

development in this respect is evident. It is however important to consider both capital and running costs. In Fig. 13 the total unit cost of water from three of the schemes is compared in a real operational situation. Demand has been assumed to increase by 4.5 Ml/d annually up to the capacity of each scheme. Arguable assumptions made in calculating the capital element are as follows: an average borrowing rate of 12 per cent p.a. spread over 60 years for the dam, 30 years for other works and 15 years for boreholes, electrical and mechanical installations; power costs to rise at 25 per cent p.a. up to 1976 and at 7½ per cent p.a. thereafter; labour costs to be restricted to rise at 10 per cent p.a. with increased use of automation; chemicals, materials and other running cost items to rise at 15 per cent p.a.

It should be appreciated that with so many assumptions, Fig. 13 must be considered with caution, as an attempt to build into cost comparisons the impact of various parameters and to take account of the proportions of capital, power and maintenance costs in each type of scheme. Its usefulness might be extended using a computer to examine the effects of variation in the key parameters.

FINANCIAL CONCLUSIONS

The short financial life (15 years) of a borehole installation coupled with an engineering life expectancy of over 25 years, makes groundwater an attractive proposition, particularly in this era of shortage of loan capital and high interest rates.

Operational costs are represented largely by electric power and, while comparatively high, are uncommitted and reduce to nil at any time when boreholes are on stand-by.

The low standing charge of less than £3300 p.a. per Ml/d capacity compares favourably with that of the River Earn Intake Scheme, which at comparative rates will amount to £4300.

In spite of high power costs, groundwater directly injected into existing mains is cheaper than any other source under consideration over a 25 year period (Fig. 13). The extended groundwater scheme (Table 4) if feasible, would produce cheaper water at all times than the Earn Intake Scheme, primarily because of the lower pumping heads and simpler treatment involved.

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Dd. 496322 K8

Printed in England for Her Majesty's Stationery Office
by Unwin Brothers Limited, The Gresham Press,
Old Woking, Surrey

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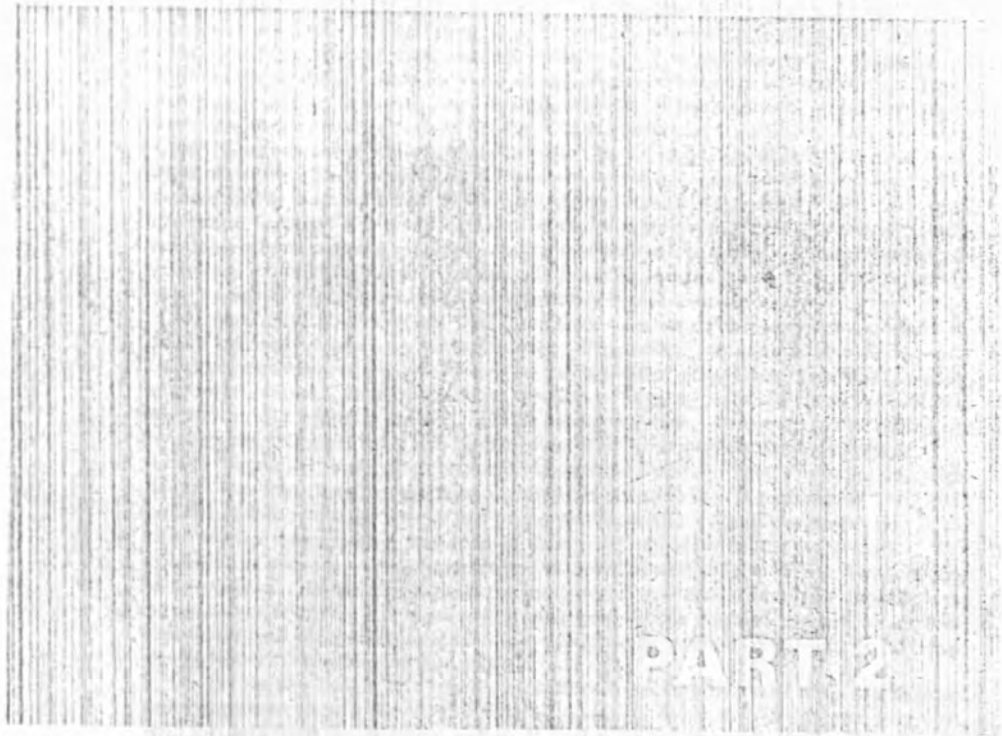

PART 2

Proc. Instn Civ. Engrs, Part 2, 1976, 61, Dec., 849–850

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DISCUSSION

A numerical model for pumping test analysis

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Mr S. S. D. Foster, Institute of Geological Sciences

I welcome the appearance of a numerical technique of pumping test analysis. It should provide a more flexible approach than the multitude of mathematical extended type-curve methods currently competing for application by practising groundwater engineers and hydrogeologists. By allowing the sensitivity of response to variation of numerous parameters to be tested, it is particularly relevant to complex field situations.

48. In their preoccupation with the precision of T values, however, I wonder if the Authors are in danger of losing sight of the primary objectives of the hydrogeological pumping test in water resources evaluation. In two of the sources of data used—those dealing with the pumping tests at Dalem, The Netherlands[10] and on the East Yorkshire Chalk[11]—the position was clearly spelt out: 'An average T of about 2000 m²/d is the most accurate answer possible . . . a higher degree of accuracy is only an illusion and is not consistent with the (overall) lithological character of the aquifer'[10] and 'The more important function of a good hydrogeological pumping test is that of providing (independent) evidence on the general hydraulic response of the aquifer, its confinement and boundary parameters, rather than that of obtaining precise T values . . . the former are more critical in predicting long-term (regional) response to pumping'.[11]

49. It should also be noted that these tests were essentially at, what the water industry currently regards as, research level. Frequently, pumping tests used in water resources exploration are constrained to much smaller expenditure and, consequently, to poorer control. In such cases no amount of juggling with the data, by whatever technique, will produce unique, reliable interpretations. In these circumstances the hydrogeologist's experience will be critical in arriving at meaningful conclusions.

50. The really important conclusion to emerge from the East Yorkshire investigations[11] was that there was a major variation in permeability and storage of the Chalk aquifer in depth, a major proportion of the total flow and a significant proportion of the total storage being within the zone of seasonal fluctuation of the water-table. This condition is proving to be characteristic of most, if not all, the British Chalk water-table aquifers. In the language of the modeller, T and S will be highly dependent on groundwater level.[12] The numerical model used by the Authors did not incorporate this factor and their interpretation must therefore be open to question: its proposed development in this direction is welcomed.

51. In the low water-table test the time drawdown data from the observation boreholes appear to show a decrease in T with decreasing distance from the pumping well, with the data from the pumping well itself giving the lowest result of all. The T value quoted in reference 11 (700–1300 m²/day) reflects this apparent variation, whereas that given by the Authors (500–620 m²/day) seems to be weighted towards the pumping well data. I suggest that their value is essentially attributable to a zone of higher per-

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Paper published: *Proc. Instn Civ. Engrs*, Part 2, 1976, 61, June, 281–296.

meability Chalk at around − 15 m OD—which is probably responsible for transmitting the bulk of the groundwater in the vicinity of the pumping well, but that in the outer parts of the cone of depression the lowest part of the zone of seasonal water-table fluctuation (which is also of very high permeability) remains saturated and also plays a significant role in the aquifer response.

52. The Authors place considerably more reliance on the analysis of drawdown data from the pumping well than would most field hydrogeologists, despite the fact that major manipulation of model boundary conditions is required. Is such reliance justified in view of the hydraulic complexity of the turbulent groundwater flow entering pumping wells? In certain cases for example, cascades develop in Chalk wells.

53. I was also surprised by the low value of k_z/k_r used by the Authors. Values of 0·01–0·10 are usually considered to be more typical of the type of aquifer concerned. How sensitive was the model response to this parameter?

Dr Rushton and Mr Chan

The tolerances quoted in the Paper for the transmissivity of (for example) 1680 ± 50 m²/day may appear to be too stringent, but they do indicate the narrow range of transmissivities which give acceptable agreement between the numerical model and the field results. It is recognized that this narrow tolerance does not appear to be consistent with the lithological character of the aquifer, but unfortunately the aquifer response is often very sensitive to the parameter values. A consequence of this is that when these aquifer parameters are used in a numerical model of the regional groundwater flow, then differences between the predicted and actual heads are almost certain to occur.

55. As regards the control of the pumping test, a great advantage of the numerical method is that it is suitable for analysing both tests with good control and also tests with poor control such as those in which the discharge rate from the borehole is not maintained at a constant value. For instance, a 14 day test, done years ago to investigate the yield of an aquifer, has been used to deduce values of the aquifer parameters, although the pump broke down on several occasions. Indeed, the failure of the pump, which can be modelled in the numerical technique, gave much useful information.

56. Variations in permeability and storage coefficients with depth have now been included in a study of pumping tests in the chalk of the Berkshire Downs.[13] This has produced significant differences in the time-drawdown curves. The inclusion of a variable permeability and storage coefficient in the Etton test would undoubtedly have added to the interpretation of the field data.

57. As regards particular details of the Etton test, the quoted transmissivity value of 560 m²/day is determined primarily from the data at observation wells and therefore follows the normal practice. The different values obtained in reference 11 almost certainly arise because the effect of the water contained within the well was ignored. After the aquifer parameters had been estimated using the data from the observation wells, the aquifer behaviour in the vicinity of the abstraction well was examined. In this instance, for adequate agreement between the numerical model predictions and the abstraction well data, the permeability in the vicinity of the abstraction well was increased and no head losses appeared to occur due to any high velocities or cascades. The ratio k_z/k_r has a significant effect only in the vicinity of the abstraction borehole; as there are no observation boreholes in that region it is not possible to deduce the magnitude of this ratio from the test results. Thus a ratio of $k_z/k_r = 0{\cdot}01$ would give equally acceptable results.

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12. Foster S. S. D. Discussion on Storage. In *Engineering hydrology today*. Institution of Civil Engineers, London, 1975, 128–129.
13. Rushton K. R. and Chan Y. K. Pumping test analysis when parameters vary with depth. *Ground Water*, 1976, 14, 82–87.

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INSTITUTE OF GEOLOGICAL SCIENCES

Hydrological basis for large-scale development of groundwater storage capacity in the East Yorkshire Chalk

REPORT No. 76/3

HMSO £1.15 net

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Report No.76/3

Hydrological basis for large-scale development of groundwater storage capacity in the East Yorkshire Chalk

S. S. D. Foster and V. A. Milton

London: Her Majesty's Stationery Office 1976

The Institute of Geological Sciences was formed by the
incorporation of the Geological Survey of Great Britain
and the Museum of Practical Geology with
Overseas Geological Surveys and is a constituent body
of the Natural Environment Research Council.

It is recommended that reference to this report be made in the following form:

FOSTER, S. S. D., AND MILTON, V. A. 1976. Hydrological basis
for large-scale development of groundwater storage capacity in the
East Yorkshire Chalk. *Rep. Inst. Geol. Sci.*, No. 76/3, 71 pp.

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ISBN 0 11 881235 1

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PREFACE

The work described was carried out in the Institute of Geological Sciences under the general direction of its Chief Hydrogeologist, then Mr. D. A. Gray, whose personal knowledge and interest in the area promoted investigation. The authors had the assistance and advice of numerous colleagues, particularly those who contributed the appendixes and also Mr. R. W. Gallois, Dr. K. G. Jeffery, Mr. M. Morgan-Jones, Mr. J. G. O. Smart, Mr. T. K. Tate and Mr. C. J. Wood.

The IGS observation boreholes were drilled by Holst & Co. Ltd of Leeds, and the cooperation of the East Riding County Council Highways Department in agreeing to their construction at roadside locations is acknowledged.

The survey was undertaken prior to the administrative reorganisation which followed the implementation of the Water Act, 1973. Accordingly, the organisations referred to in the Report are those who provided facilities, operated equipment or collaborated with the Institute's staff during the course of the study, rather than their successors.

In addition to their initial interest in the work the former Yorkshire River Authority are thanked for the provision of basic data, support and discussion in the field activities and for the implementation of the programme of re-opening of sealed wells and boreholes to gain access for water-level measurement.

The interest of Mr Harold Ackroyd, the Engineer to the former East Yorkshire (Wolds Area) Water Board has resulted in the collection of a considerable body of valuable hydrogeological data on the Chalk of the area. The collaboration of his deputy, Mr. R. I. Crease, and staff greatly aided the field activities.

Other public bodies willingly provided the pertinent data in their possession and the interest and cooperation of some of the private owners of wells and water-supply boreholes in the region was gratifying.

Kingsley Dunham
Director

Institute of Geological Sciences
Exhibition Road
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1 March 1975

Dr A. W. Woodland succeeded Sir Kingsley Dunham as Director on 1st January 1976

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Summary

A geological and hydrological analysis of the catchment of the River Hull to Hempholme Lock has been undertaken through both data and field study. This area includes much of the Yorkshire Wolds, whose Chalk has been shown to be an exclusively fissure-flow and largely fissure storage aquifer with marked variations of permeability and storage with depth below the water table. The boundary between the water table aquifer of the Wolds outcrop and the confined groundwater system underlying the Hull Valley coincides with a 'buried coastline', which produces a narrow, but hydrologically important, zone of extremely high permeability in the subsurface.

The Chalk aquifer has ample groundwater resources, both in terms of storage and recharge, to meet the forecasted water supply deficit of Kingston-upon-Hull to the year 2001. This is evident from consideration of aquifer volume and specific yield and examination of the long term average discharge of the River Hull at Hempholme Lock, over 80 per cent of which represents natural discharge (springflow) from the Chalk groundwater reservoir.

Problems are encountered, however, in formulating a practical and efficient method of developing these resources; that is, in manipulating the aquifer storage to regulate its throughflow. The prevailing hydrological regime and the distribution of existing water supply sources impose the dominant restrictions. Environmental considerations and amenity interests will be a further constraint. Augmentation of low flows on the River Hull is required to allow an increase in the perennial intake of the existing treatment works at Hempholme Lock. Possible schemes to sustain a flow of 115 Ml/d (70 Ml/d over and above the lowest recorded flow) by abstraction from groundwater storage are presented and the hydrogeological factors affecting their economics are discussed. Analysis of the last decade of riverflow data indicates that augmentation would be needed on average for between 45 and 80 days per year but that in the most extreme of recent droughts (1964-1965) a continuous period of operation of 225 days would have been required. The combination of hydrogeological conditions suggests that, wherever river augmentation boreholes are sited, interception of natural discharge from the aquifer will be a much more critical factor than subsequent recirculation through bed losses from the surface watercourses.

Sommaire

Une analyse géologique et hydrologique du bassin d'alimentation du River Hull à Hempholme Lock a été entreprise par l'étude de données et par des travaux pratiques. Cette région comprend une grande partie des Yorkshire Wolds où on a déjà démontré que le calcaire est une aquifère dans lequel la circulation passe exclusivement par des fissures et la rétention est principalement dans des fissures avec des variations prononcées de perméabilité et de rétention selon la profondeur de la nappe aquifère. La limite entre l'aquifère de l'affleurement dans les Wolds et le système resserré d'eau souterraine sous le Hull Valley coincide avec une ligne de côte enterrée, qui produit une zone étroite, mais hydrologiquement importante, de pérmeabilité extrêmement haute sous la surface.

Quant à la rétention et l'alimentation, l'aquifère dans le calcaire possède des ressources assez abondantes en eau souterraine, pour combler le déficit prévu dans la provision d'eau pour Kingston-upon-Hull jusqu'à l'an 2001. Ceci se manifeste si on tient compte du volume et du rendement spécifique de l'aquifère et du débit moyen à long terme du River Hull à Hempholme Lock dont plus de 80 pour cent représente le débit naturel (provenant des sources) du réservoir d'eau souterraine dans le calcaire.

On rencontre, cependant, des problèmes dans l'élaboration d'une méthode pratique et efficace de développer ces ressources; c'est à dire pour agir sur l'aquifère afin de régler l'écoulement. Le régime hydrologique régnant et la distribution des sources d'eau actuelle imposent les restrictions dominatrices. Des considérations de l'environnement et des agréments du lieu imposeront encore de contraintes. Il est nécessaire d'augmenter les débits bas du River Hull pour permettre l'accroissement de la prise pérenne de l'usine de traitement à Hempholme Lock. On présenté des projets possibles pour soutenir un débit de 115 Ml/d (en plus du débit le plus bas que l'on a signalé) par l'extraction d'eau souterraine, et on discute les facteurs hydrogéologiques qui les affectent de point de vue économique. On a analysé les données du débit du fleuve pendant les dix derniers ans, ce qui indique que l'augmentation serait nécessaire en moyen pendant 45 à 80 jours par an, mais que pendant la sécheresse récente la plus sévère (1964-1965) on aurait dû opérer sans cesse pendant 225 jours. La combinaison de conditions hydrogéologiques suggère que, n'importe où les trous de

sonde pour augmenter le débit sont situés, l'interception du débit naturel de l'aquifère sera un facteur beaucoup plus critique que la récirculation subséquente des pertes du lit des cours d'eau au surface.

Zusammenfassung

Eine geologische und hydrologische Analyse von der Stauung von Fluss Hull bis zum Hempholme Lock wird sowohl durch Daten als auch Aussenarbeit unternommen. Dieses Gebiet schliesst viel von den Yorkshire Wolds ein, dessen Kreide nachweislich ein ausschliessender Spaltestromungs- und grössenteils Spaltelagerungs-Grundwasserleiter ist. Dieser Grundwasserleiter hat bemerkbare Unterschiede von Permeabilität und Lagerung der Tiefen entsprechend unter der Grundwasser oberfläche. Die Grenze zwischen dem Grundwassersustem, das unter dem Hull Valley liegt, passt zu einer "verborgenen Küstenlinie", was eine enge, aber hydrologisch wichtige Zone von äusserst hoher Permeabilität unterhalb der festen Erdoberfläche herstellt.

Der Kreidegrundwasserleiter hat genügende Grundwassermitfel, sowohl in Form von Lagerung als auch von Widerfüllung, das vorhersagte Wasserdefizit von Kingston-upon-Hull zum Jahre 2001 zu erfüllen. Dieses ist zu sehen von der Überlegung vom Grundwasserleiter volumen und besondere der langfristigen Mittelwasserführung vom River Hull bei Hempholme Lock, wovon mehr als 80% natürliche Wasserführung (Quellenführung) vom Kreidegrundwasserstausee schildert.

Trotzdem betrifft man Probleme, wenn man versucht, eine praktische und wirksame Methode zu formulieren, diese Mitfel zu entwickeln: das heisst, das Grundwasserleiterspeichern zu manipulieren, um den Durchfluss zu ordnen. Die herrschenden, hydrologischen Verhältrisse und die Verbreitung von bestehenden Wasserversorgungsquellen bilden die entscheidenden Einschränkungen. Umweltrücksichtsnahmen und Annehmlichkeitsinteressen bilden eine weitere Beschränkung. Vergrösserung von den niedrigen Wasserführungen auf dem River Hull ist nötig, um eine Vergrösserung in der langdauernde Einnahme von die existierenden Behandlungswerken bei Hempholme Lock zu erlauben. Man beschreibt mögliche Pläne, eine Wasserführung von 115 Ml/d (70 Ml/d ausserdem die niedrigste dokumentierte Führung) durch das Abstraktion aus Grundwasserspeichern. Man bespricht die hydrogeologischen Faktoren, die dessen Finanzen beeinflüssen. Analyse vom letzten Jahrzehnt von Stromführungsdaten zeigt, dass Vergrösserung im Durchschnitt zwischen 45 und 80 Tage pro Jahr nötig wäre, aber dass in der grössten letzten Trockenheit (1964-1965) eine ununterbrochene Arbeitsperiode von 225 Tagen nötig gewesen wäre. Die Zusammenstellung von hydrogeologischen Verhältnissen lässt denken, dass, wo auch immer Flussvergrösserungsbohrlocher sich befinden, die Verhinderung von natürlicher Wasserspende von Grundwasserleiter, ein viel entscheidenderer Bestand als folgende Wiedercirkulation durch Schichtverlüste aus den Oberflächlichen Wasserläufen sein wird.

Hydrological basis for large-scale development of groundwater storage capacity in the East Yorkshire Chalk

S. S. D. FOSTER AND V. A. MILTON

Introduction

BACKGROUND

The current water supply situation in the Kingston-upon-Hull area, and forecasts of its future demand, require the assessment of all potential sources of major supplies in the adjacent regions. Moreover a major increase in the water requirements of North Humberside could result from the creation here of a new urban development (Yorkshire Ouse and Hull River Authority, 1969).

The immediately adjoining area is dominated by the highly permeable Chalk formation. It is present over an area of some 1800 km^2 in East Yorkshire. Over its outcrop, about half of that area, drainage is almost entirely subsurface. The discharge from the Chalk groundwater system contributes the bulk of the flow in the River Hull, the principal perennial watercourse of the region.

The present state of development of the groundwater resources of the East Yorkshire Chalk for Humberside water supplies is irrational from a number of hydrological viewpoints. Consideration and investigation of the hydrological regime has played little part in the process of development, which has been piecemeal as a result of the historical growth of water resources organisation.

Further large scale development must be designed with a thorough understanding of the relevant components of the natural hydrological regime, since certain detailed points in the relationship between the Chalk groundwater reservoir, its natural discharge and the surface watercourses could prove critical. Schemes conceived in partial knowledge of the controlling hydrological factors could be prone to great inefficiency or excessive and unsuspected interference with existing water users and water-based amenities.

The field investigations described in this report were carried out during 1970-1972. All previous work has been considered and available data assessed. Particular attention has been paid to the data that has accumulated in the period 1952-1972, which post-dates the only previous systematic evaluation of this aquifer (Gray, 1952).

GENERAL REGIONAL HYDROLOGY

In East Yorkshire, as in other carbonate rock terrains, the main elements of the overall hydrology are determined by the regional stratigraphy and geological structure, since they control the position of the permeable rock outcrop, its confining bed of low permeability and therefore the location of the recharge and discharge areas of the groundwater system.

The Yorkshire Wolds are the topographic expression of a crescent-shaped Chalk outcrop and stretch uninterrupted from the Humber Gap in the south to the cliffs of Flamborough Head (Fig. 1). They form an undulating thin-soil covered upland area (Plate 1) dissected by many broad dry valleys, the largest of these being the Great Wold Valley. The elevation of most of the Wolds ranges from 60 to 150 m OD. It increases towards the north-west, where it is generally above 125 m OD and reaches a maximum of 246 m OD; here the dry valleys also differ being narrower, more deeply dissected and having abrupt terminations at their heads.

The limit of the Chalk is marked by significant escarpments facing the Vale of

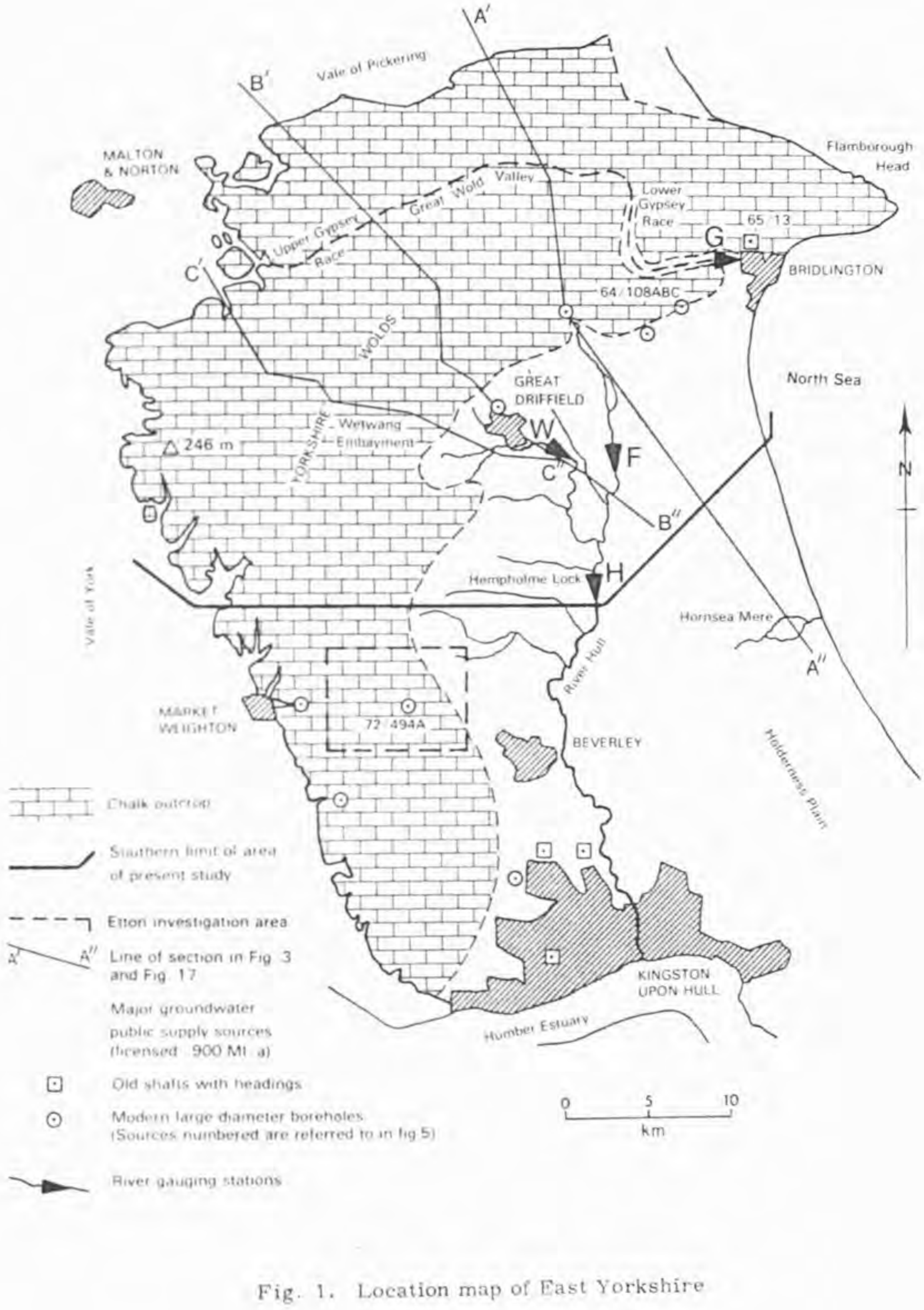


Fig. 1. Location map of East Yorkshire

Pickering to the north and the Vale of York to the west. The Chalk dip slope passes beneath a complex series of mainly low permeability glacial and alluvial deposits, when traced southwards and eastwards into the Hull Valley and Holderness. The former has a floor of alluvial deposits at a general elevation of 1 to 5 m OD characterised by tracts of poorly drained peaty soils, known locally as carrs.

The Chalk formation is generally highly permeable and its outcrop drains so freely as to make it virtually devoid of surface water, except for a few intermittent watercourses and the occasional pond. The drainage of the entire outcrop area is subsurface and, by virtue of the general geological structure, directed mainly eastwards or southwards towards the lower lying areas of the Hull Valley. The position is complicated somewhat in the north both by direct subsurface flow towards the North Sea and by the intermittent development of a Chalk-water-table river, the Lower Gypsey Race, flowing down the Great Wold Valley (Fig. 1). Over limited areas the Chalk formation drains towards its escarpment giving rise to numerous small contact springs contributing to the Derwent river system.

Around the perimeter of the Hull Valley the Chalk aquifer discharges in numerous sizeable springs which form both the main source of the River Hull and its various minor tributaries. The Hull, contained by earth embankments to prevent or reduce flooding of the lowest lying land, flows southwards (Fig. 1) to enter the Humber Estuary near the city centre of Kingston-upon-Hull. It is tidal to Hempholme Lock, about 24 km or so above this point. A complex network of land-drainage cuts (dykes) augments the natural drainage system throughout the valley of the Hull and greatly modifies the area of the river's surface catchment.

The extreme east and south-east of East Yorkshire is occupied by the Holderness Plain (Fig. 1), a glaciated lowland area of irregular relief (6 to 18 m OD). The glacial deposits attain a maximum thickness of about 45 m and are dominated by a series of boulder clays, which are thought to form a continuous low permeability blanket covering the underlying Chalk throughout the area (Catt and Penny, 1966) and over large distances from the coast beneath the bed of the North Sea (Kent, 1967). The recharge to and available exits from the confined Chalk groundwater system are thus restricted and its circulation almost negligible. At surface along much of the North Sea coast south of Bridlington, the Boulder Clay forms low cliffs and drainage in most of Holderness is inland. The subsoils are often heavy and relatively impermeable and the spread of agriculture led to the widespread development of a complex system of artificial cuts draining to the Humber, with pumping stations to generate flows.

The average annual precipitation (1916/50) of East Yorkshire varies from 630 mm in Holderness to 870 mm on the higher Wolds, with only minor differences between the totals for any given month or season (Yorkshire Ouse and Hull River Authority, 1969). Winter and summer rainfall differ in character and intensity in the sense that the latter tends to be associated more with thunderstorms and is not dependent on moist westerly airstreams nor is it orographic in distribution. The proximity to the North Sea and intermittent exposure to cold north-easterly airstreams results in a significant proportion of the annual precipitation falling as snow; annually there are on average 15 to 25 days with snow lying, depending on altitude.

Unlike rainfall, temperature and other climatic parameters do show moderate differences between seasons and lead typically to a considerable excess of evapotranspiration over precipitation in the months of May, June, July and August and near balance in March, April and September (Yorkshire Ouse and Hull River Authority, 1969). An overall picture of summer and autumn soil moisture deficits thus emerges.

REGIONAL WATER RESOURCES SITUATION

About 75 per cent of the people of East Yorkshire live on North Humberside; Kingston-upon-Hull has a population of about 300 000, and over 375 000 if its outer suburbs are included. Of the towns, only Bridlington and Beverley (Fig. 1) have more than 20 000 inhabitants but the former is swelled by tourism, particularly during summer weekends. There are several smaller towns and many villages and whilst rural depopulation is occuring in the north of the region, many of the villages in the south are expanding with the growth of commuting to the Kingston-upon-Hull area.

Kingston-upon-Hull is a major commercial and fishing port and has a wide range of industries, the most notable of which are pharmaceutical, chemical, food processing and preserving. Industrial demand, both for cooling and process water, has always been a large item in the total requirement of the North Humberside area and one which, over the past 25 years, has increasingly fallen on the statutory water undertaking. Elsewhere industry is for the most part agriculturally based.

In an area including the urban and industrial zones of North Humberside and much of Holderness the statutory undertaking for water supply rests with the Kingston-upon-Hull CBC. Its sources include three major Chalk-groundwater pumping stations with extensive adits situated on the fringe of the urban area (Fig. 1) and a modern intake works on the River Hull at Hempholme Lock. Their estimated combined drought yield is, perhaps optimistically, put at 120 Ml/d (Yorkshire Ouse and Hull River Authority, 1969). The history of water supply development for the City has been described by Jones (1955) and that in East Yorkshire as a whole by Aylwin and Ward (1969). Humberside has by British standards something of a history of water shortages; their effects have been at best inconvenient, at worst insanitary and disruptive (Jones, 1955).

An essentially rural area of about 100 000 inhabitants stretching from Bridlington across to the southern part of the Vale of York, is supplied by the East Yorkshire (Wolds Area) Water Board. Their sources comprise a scattered network of mainly modern large diameter boreholes with an estimated combined drought yield of about 50 Ml/d; a number of those abstract from the Chalk of the Hempholme catchment (Fig. 1) but in general result in the generation of an effluent to the Hull. In the remainder of the region, the north-western part of the Wolds, the Ryedale Joint Water Board has a number of small sources and is responsible for public supply.

The bulk of the land area is used for agriculture. Both in the Wolds and in much of Holderness arable farming predominates but dairying is dominant in the Hull Valley. Woodland is restricted to relatively small areas on some of the larger estates. Recent years have seen both large increases in the number of pigs and poultry in East Yorkshire with the development of intensive rearing units and the spread of large scale market gardening through the south of the region under the stimulus of the Humberside food industry. Agricultural water supplies have been traditionally dealt with on a private basis, by the sinking of wells and drilling of boreholes. However the increased dependence on spray irrigation, to sustain certain types of agriculture and for intensive growing under glass, poses a new water supply problem. Spray irrigation demands can be high and fluctuate enormously on both a daily and seasonal basis. They are thus difficult and costly to meet from a public-supply distribution network but likely to increase and continue to be concentrated around their present centre in the south of the region. This area is without reliable surface sources of supply and its groundwater resources are already heavily developed to meet public and industrial demand.

The principal water based amenity in East Yorkshire is angling on the River Hull and its tributaries, parts of which are jealously preserved trout streams of excellent standard. Change in river regime or quality may affect the fish but comparatively little is known of the essential needs of the non-migratory types concerned (Yorkshire Ouse and Hull River Authority, 1969).

The estimation of future demand guides the scale of required development and has been defined by the Yorkshire Ouse and Hull River Authority (1969) and the Water Resources Board (1970). The Water Resources Board (1970) estimated that the deficit for the North Humberside area in respect of public water supply would be 23 Ml/d by 1981.

Future growth of industry and population is likely to be centred on Humberside but the interaction of such factors as movement and other uncertainties in population prediction, changing character of industry and its water use and improvements of recirculation technology all complicate forecasting. Demand also tends to be held in balance by increasing cost or deteriorating quality. Moreover little is known about the savings that might be introduced from the prevention of leakage and more widespread metering to discourage wastage.

Since a significant proportion of the water used by public supply undertakings is supplied to industry, the rising trend of industrial consumption has to a certain extent been taken into account in the estimated deficit. However, increased demand by direct industrial abstraction, together with that for spray irrigation already mentioned, could aggravate problems in the Kingston-upon-Hull/Beverley area (Yorkshire Ouse and Hull River Authority, 1969).

Beyond 1981 demand depends much on the national policy towards any new Humberside development, its location, size and whether it will be based on high or low water demand industries. A figure of 78 Ml/d has been estimated for the deficit of Kingston-upon-Hull in 2001 and a further 135 Ml/d has been arbitrarily allocated for Humberside development (Yorkshire Ouse and Hull River Authority, 1969). In the foreseeable future it thus appears that the need for concentrated large scale developments of water supply (say in excess of

20 Ml/d) will only arise from the demands of the North Humberside area. Elsewhere in East Yorkshire there are likely to be regular demands at scattered locations for supplies possibly up to 10 Ml/d, but more normally of the order of 2.0 Ml/d or less.

PREVIOUS WORK

There has been little systematic or quantitative work on the hydrology and groundwater resources of the East Yorkshire Chalk, considering that it is one of the major aquifers of the country and recognising its significance to the water supply of the city of Kingston-upon-Hull through many decades. This is in part explained by lack of pertinent data on groundwater levels and riverflow and the reluctance to face the cost and organisation of monitoring them. Attempts at developing groundwater supplies, both successful and unsuccessful, were very poorly documented prior to about 1950 and since then have not always been used to full advantage in furthering knowledge of the hydrology and hydraulics of this major aquifer.

Of the studies done before the Second World War, those of Mortimer (1879), Fox-Strangways (1906) and Lapworth (1933) are worthy of mention. Mortimer drew together the writings and notes of East Yorkshire's early well sinkers and started to piece together a picture of the overall regime of recharge and discharge of the Chalk aquifer, the gross variations in the quality of supplies and the danger of intrusion of estuarine water on Humberside. He drew a hydrogeological cross-section of the Wolds showing the approximate position of the water table in January 1877 and discussed the conditions leading to the severe drought of 1874, which required the deepening of wells throughout the area. Lapworth's work (1933) was more comprehensive; he presented the first known groundwater level map of the area with the aim of establishing the directions of groundwater flow to guide future water supply problems and postulated without many supporting facts, an element of stratigraphical and structural control of Chalk groundwater movement. He suggested that the poor quantity and quality of supplies from the Holderness Chalk were due to extremely sluggish natural circulation of the groundwater in this area.

In the immediate post-war period the subject received more attention but most of the work suffered from lack of active field investigation and reliable data on the hydrological parameters. Versey (1948) and Green (1950) gave some useful descriptions of local hydrogeological conditions but their approach to the evaluation of groundwater resources was not sufficiently refined to give more than a general indication of their magnitude. Waters (1949) considered that the development of groundwater supplies in East Yorkshire had been so great since the report of Lapworth (1933) as to make it obsolescent except for the purely geological aspects. Hainsworth (1950) defined the principal problems of water management at that time to be the determination of the maximum reliable yield of and groundwater flow frontage to three large municipal pumping stations in the vicinity of Kingston-upon-Hull, and the risk of further encroachment of estuarine water.

As has been mentioned, Gray (1952) made the only previous evaluation of the Chalk aquifer of East Yorkshire based on systematic hydrogeological field and data study. He considered meteorological, riverflow, and groundwater level fluctuation data and delineated catchments and saline intrusion areas by field measurement. Deficiencies in certain parts of the data limited the study to a reconnaissance level. Essentially the report was the starting point for the present work.

CONSTRAINTS ON DEVELOPMENT

In the North Humberside area the only source of water of adequate quality for most purposes, the Chalk aquifer, is already heavily developed and has been so for many years. By far the largest abstractions are those of the public water supply undertaking but significant quantities of water are also pumped, perennially by industrial users and seasonally for horticultural spray irrigation. The groundwater resources balance for the 'chalk block' south of the latitude of Hempholme Lock shows that there is little room for further development throughout this area (Foster and others, in press).

Among the side effects of the existing groundwater development are the perennial drying-up of all dip-slope Chalk streams from the Humber northwards to beyond Beverley (Fig. 1) and, in the old industrial area of Kingston-upon-Hull, the encroachment of saline water, apparently from the Humber.

A method both of relieving the pressure on this part of the aquifer and allowing further development would be its artificial recharge. One attractive possibility would be to pipe excess spring and early summer flows from the River Hull at Hempholme Lock and the Holderness land-drainage system (if quality allowed) and recharge them at the Chalk outcrop in the southern Wolds. Such a scheme is likely to present considerable technological problems and would require extensive feasibility and economic studies. At the present time therefore it would appear preferable to redistribute abstraction from the Chalk for public supply purposes, by development elsewhere in the aquifer at rates in excess of estimated deficits. This would reduce the competition for water in the critical Humberside area and should allow further demands by industrial users and for spray irrigation to be more easily met by direct abstraction.

Most of the flow of the River Hull at Hempholme Lock (80 to 85 per cent) originates as natural groundwater discharge from its Chalk catchment, which extends over a major portion of the Yorkshire Wolds. Any perennial development of Chalk groundwater involving consumption or export from this catchment, in the end will lead to a comparable reduction in the Chalk-derived baseflow at Hempholme Lock. In late summer and autumn Chalk baseflow represents almost the total riverflow, which under severe drought conditions (1964-1965) is less than 50 Ml/d (0.6 cumec)

The above factor together with the commissioning of the Tophill Low river intake works at Hempholme Lock in 1965, impose the dominant constraint on future water supply development. The current capacity of the treatment works is 55 Ml/d but the legally prescribed minimum residual flow is 45 Ml/d. The raw water storage reservoirs, of 1680 Ml capacity, cushion the impact on the supply situation of the reduction in river intake when flows fall below 100 Ml/d (1.2 cumec).

It is possible that engineering measures or reappraisal in respect of Beverley sewage disposal, Hull navigation and other interests below Hempholme Lock, could allow a revision of the prescribed flow and make a larger part of the lowest flows available for water supply purposes. However in conditions of severe drought (as those in 1964-1965), even reduction of the prescribed flow to zero would not allow the works to operate at full capacity.

The provision of additional water supplies to Humberside by perennial abstraction from the Chalk of the Hull-Hempholme catchment thus appears uneconomic under present conditions because of the considerable capital investment represented by the Tophill Low intake, treatment and storage facilities and the distribution network centred upon them. Further factors operating against reduction of the dry weather flows in the River Hull include the strong angling interests and those of navigation and general amenity.

In consideration of possible schemes for development of the large volumes of Chalk groundwater storage in the catchment to Hempholme Lock, augmentation of low river flows must be taken as the first priority (Yorkshire Ouse and Hull River Authority, 1969). To be successful any scheme will have to attain a degree of regulation on the flow in the Hull by manipulation of the storage levels in the Chalk and control over its rates of natural discharge. In general and theoretical terms, this method of development has been excellently dealt with by Ineson (1970) and is essentially an exploitation of the time-lag characteristics and vast storage of major groundwater reservoirs.

In relation to water quality, schemes involving Chalk groundwater are likely to provide a somewhat 'harder' supply than those taken directly from upland reservoirs but not significantly different from many lowland river intake works. The existing sewage effluent load of the Hull above Hempholme Lock is low and given normal precautions no quality problems are likely to arise; the apparent onset of nitrate pollution of Chalk groundwaters in East Yorkshire (Foster and Crease, 1974) however, may ultimately be troublesome.

DESIGN FACTORS FOR DEVELOPMENT

In view of the desirability of rationalising the overall abstraction from the Chalk aquifer to reduce competition for groundwater supplies in the north Humberside area, the facility to augment the lowest flows in the River Hull by a significant increment, of the order of 70 Ml/d, would be most attractive. It might be preferable to phase any scheme, but a substantial rate of initial development would be required for it to be measured and proved adequately during field trials.

The effect of a successful development of 70 Ml/d would be to reduce radically the possibility of the flow in the Hull ever falling below 115 Ml/d, that is, to permit an intake of 70 Ml/d at the Tophill Low Waterworks even during severe droughts.

Since the long term mean daily discharge of the Hull at Hempholme Lock is 320 Ml/d, about 80 to 85 per cent of which is Chalk derived, a development of the above scale represents the regulation of about 40 per cent of the total long term throughflow of the Chalk aquifer in this catchment. It is thus clear that detailed consideration of the rates and processes of infiltration and evapotranspiration and the recharge phase of the groundwater cycle are not of primary importance in the design and evaluation of possible schemes for development. This aspect of the hydrology becomes of major importance in discussing the ultimate yield of the Chalk aquifer. During investigation for and development of any scheme much more should be learnt about all aspects of the hydrology of the Chalk aquifer and consequently the scheme itself should furnish the most useful data with which to assess the possibilities, technicalities and economics of further development. Recharge will be directly evaluated because of its direct relationship to aquifer throughflow, storage levels and rates of natural discharge.

Any scheme for development will involve groups of large diameter Chalk boreholes pumping water intermittently through pipelines to a selected point in the upper reaches of the River Hull, or possibly directly to the Tophill Low Waterworks. Critical choice of locations would be required to achieve maximum, and perhaps even tolerable, efficiency in operation. Excessive expense could be involved in using engineering works to control certain processes in the naturally developed hydrological cycle.

The principal hydrogeological factors that would appear to affect the choice of location and type of development are as follows:

1. The character of the groundwater reservoir, its storage space and boundary conditions.
2. The detailed groundwater conditions in the zone of natural aquifer discharge or overflow.
3. The degree of hydraulic communication between the surface watercourses and the underlying groundwater system.

There exists considerable knowledge and data, albeit rather scattered, that bear on these factors. They receive detailed examination and synthesis in this report and have been amplified through field investigation. A review of the geology of the East Yorkshire Chalk is included, distinguishing and describing those aspects which are of potential relevance to its properties and behaviour as a major groundwater reservoir. In the Hull-Hempholme catchment however there are still significant data deficiencies, particularly in respect of controlled hydrological pumping tests.

It is assumed that a development of the postulated scale will be simulated and guided by a digital model of the regional aquifer. Such a model would assist in prediction of the efficiency and side-effects of proposed schemes. It could be up-dated as development proceeds and new data are generated, becoming both a water-management tool and of considerable use in assessing possible further developments. Some further investigation of aquifer properties and boundary conditions is, however, required to calibrate and refine the model sufficiently for the former purpose.

Geological Character of Groundwater Reservoir

CHALK STRATIGRAPHY AND LITHOLOGY

The Chalk of East Yorkshire comprises a highly uniform sequence of sediments with a maximum thickness in excess of 420 m. Almost the entire sequence, in terms of total thickness, is represented by pure white limestones. Microscopically these limestones are seen to be composed of a matrix of plates of minute spheroidal organic bodies (coccoliths) less than 0.1 to 4 μm in diameter in which occasional larger particles, mainly comminuted macrofossils and microfossils, are embedded (Black, 1953). The absence of terrigenous material from most horizons is notable, exceptional conditions of marine sedimentation in Upper Cretaceous times being indicated.

The sequence of limestones is broken only occasionally by primary marls rarely more than 50 mm in thickness; up to 10 marls may be present in a re-defined middle division of the Chalk (Wood, C. J., personal communication) and at least that many again in the division below. More frequent breaks in the sequence are associated with secondary features, particularly flint bands and stylolites with their associated marls. The stratiform bodies of flint, as distinct from the isolated masses, vary from 50 to 300 mm in thickness and have two types of occurrence, nodular and tabular. The high density of stylolitic solution features in the East Yorkshire Chalk is most striking; individual stylolites typically affect bands of the formation up to 300 mm in thickness. Their origin and associated changes in rock physical properties, and their density of occurrence in the available exposures are discussed in Appendixes A and B respectively.

The subdivision of the East Yorkshire Chalk and the stratigraphic validity of existing subdivisions remains a subject for study and discussion. The lithological subdivision recognised during the original geological survey of the entire area (Dakyns and Fox-Strangways, 1886) related to the presence or absence of flints alone and is of doubtful value even for litho-correlation. Wright and Wright (1942) have made the most complete attempt to date to establish a palaeontological subdivision and recognised 10 zones differing somewhat from those used in southern England because of the distinct aspect of the Chalk fauna. They placed the exposures in about 100 quarries and pits within their zonal sequence. Current biostratigraphical research (Wood, C. J., personal communication) indicates, however, that correlations between zones of the same name in East Yorkshire and southern England may require re-assessment. Moreover confident correlation between any given localities in East Yorkshire itself should await the establishment of key stratigraphic sections relevant to the whole area.

In this respect it is noteworthy that the primary marls appear to be extraordinarily persistent. Individual seams and bands, sequences of bands and their relation to certain other primary sedimentary features such as Inoceramus shell beds, have proved most valuable in correlation in Norfolk (Ward and others, 1968). In East Yorkshire they have been used to correlate over 55 km between the Flamborough Head section and that in the Humberside quarries; correlations over hundreds of kilometres southwards may be possible (Institute of Geological Sciences, 1971).

At present, however, it is still only practical to recognise one subdivision of the Chalk; this is the original Lower Chalk of Dakyns and Fox-Strangways (1886), which is bounded above and below by the Black Band and the Red Chalk respectively. Both are lithologically distinctive and chronologically significant; the Black Band being the thickest (200 to 450 mm) and darkest primary marl in the entire Chalk sequence and the Red Chalk a strongly coloured and much condensed sequence, 1.5 to 7.5 m in thickness. It should be noted also that Jefferies (1963) has questioned the age of the former in relation to its suggested equivalent, the Plenus Marl, further south.

The Lower Chalk itself is somewhat distinctive because of the general absence of flints, the frequency of primary marls and the presence of a much higher proportion of non-calcareous impurities, including clay minerals and glauconite, which impart pale-grey, green and pink colouring to certain horizons. It is not of primary interest from the hydrological viewpoint being only 18 to 38 m thick and, except on the lower part of the escarpment, buried beneath much greater thicknesses of the Middle/Upper Chalk.

Not much can be said of the hydrologically important Chalk sequence above the Black Band beyond that it is highly uniform and includes the mapped Middle and Upper Chalk divisions of Dakyns and Fox-Strangways (1886). Its total thickness is considerable but the actual thickness present at any given locality is, of course, largely dependent on erosion. Recent work suggests substantial sedimentary variations in thickness here, as in the Lower Chalk (Institute of Geological Sciences, 1971). Flints are generally thought to become much less frequent in occurence above a horizon in the middle of the Hagenowia rostrata Zone of Wright and Wright (1942), some 135 to 185 m above the Black Band. Throughout this report subdivision of this sequence has been avoided where possible. When reference to the existing lithological or palaeontological divisions is made, the reservations outlined above apply.

Electrical resistivity logging of water-filled boreholes has been applied to the Chalk of the London Basin both for stratigraphic correlation and identification (Gray, 1965) and also for hydrogeological formation evaluation (Tate and others, 1971). For the Chalk formations resistivity has been shown to relate closely to intergranular porosity (Edmunds and others, 1973); the high resistivity/low intergranular porosity bands are suggested to be those of greatest fissure permeability. In East Yorkshire it has only been possible to log 25 boreholes to date. The Lower Chalk is readily distinguished by its relatively low resistivity, typically not exceeding 100 ohm m. However the limited saturated intervals logged and the absence of control boreholes as yet preclude stratigraphic correlation through the entire sequence.

The values of formation resistivity for much of the thick Middle/Upper Chalk sequence frequently exceed 250 ohm m, particularly in its lower part, with an apparent tendency for increase in the north and west of the region. These values are higher than those of even the hardest 'chalk rock' beds in southern England (Gray, 1965), but comparable with much of the North Lincolnshire Chalk. The generally harder and denser aspect of the northern Chalk, in relation to its better known stratigraphic equivalent, is significant in the hydrological context. It has been attributed to more extensive recrystallisation and secondary pore-space cementation by calcite (Hancock and Kennedy, 1967); it is however still less than in most limestone formations and Hancock (1963) has speculated on possible sedimentary and diagenetic reasons.

HYDRAULIC PROPERTIES OF ROCK MATERIAL

At the outset of the present investigation, the rock material of the Chalk aquifer was thought to possess low permeability (Ineson, 1962) and have moderate porosity, though rarely exceeding a value of 0.20 (Gray, 1952). The latter, while being appreciable, is considerably lower than that of samples from most horizons of the Chalk in southern England, except the well known 'hard' bands such as the Melbourne Rock (Edmunds and others, 1973). The limited

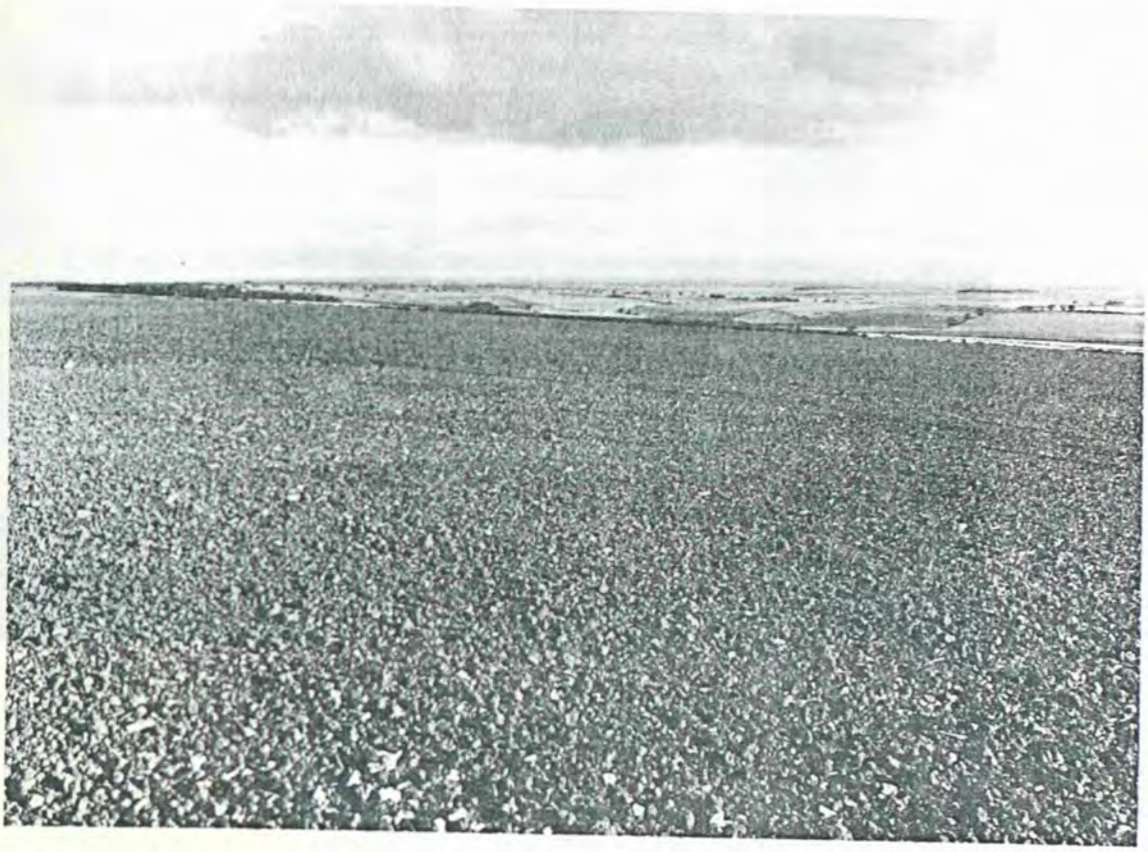


Plate 1a. Topography of the Yorkshire Wolds; looking south-east across Wetwang Embayment towards Hull Valley

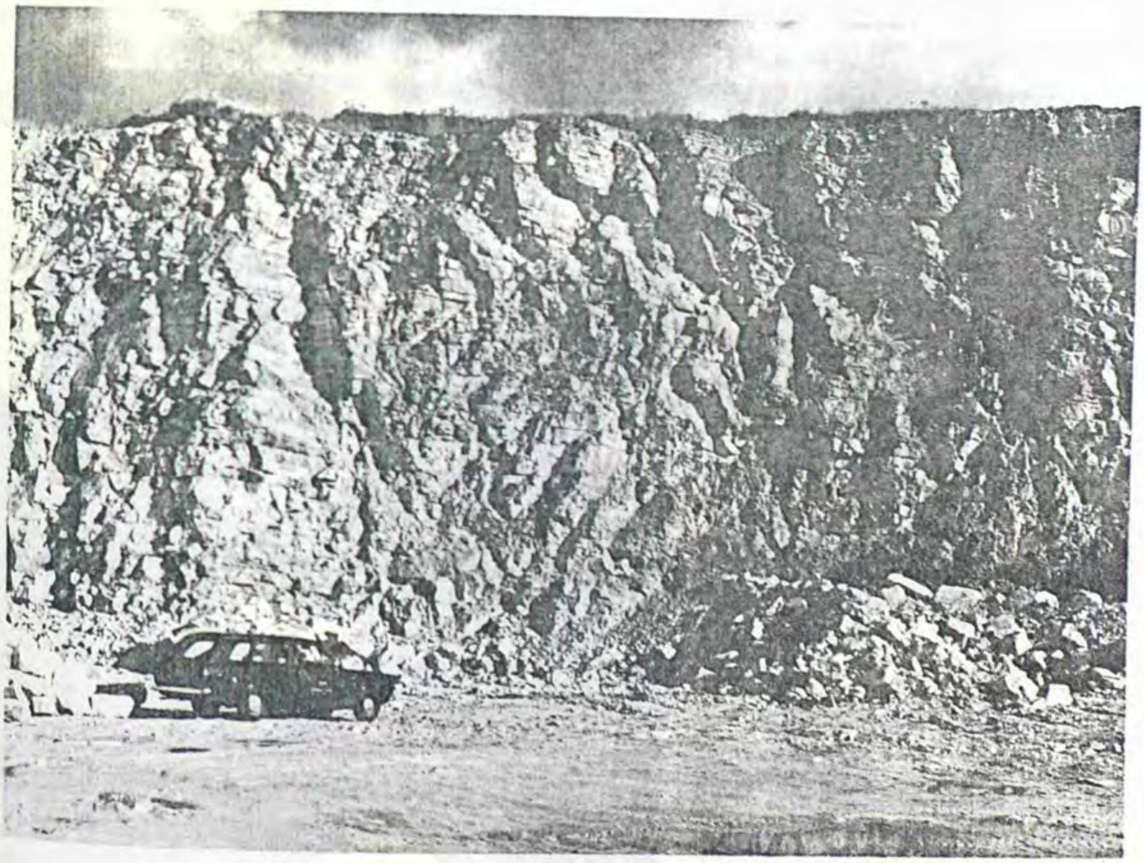


Plate 1b. East Yorkshire Chalk; quarry exposure at Ruston Parva showing characteristic jointing

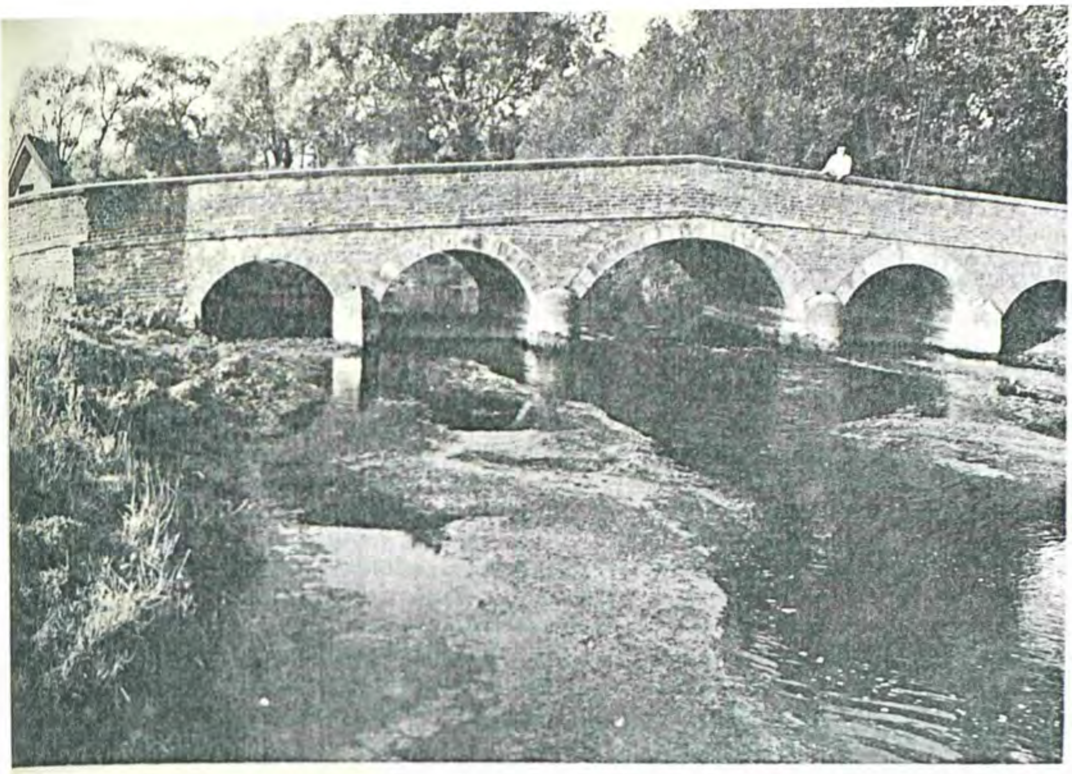
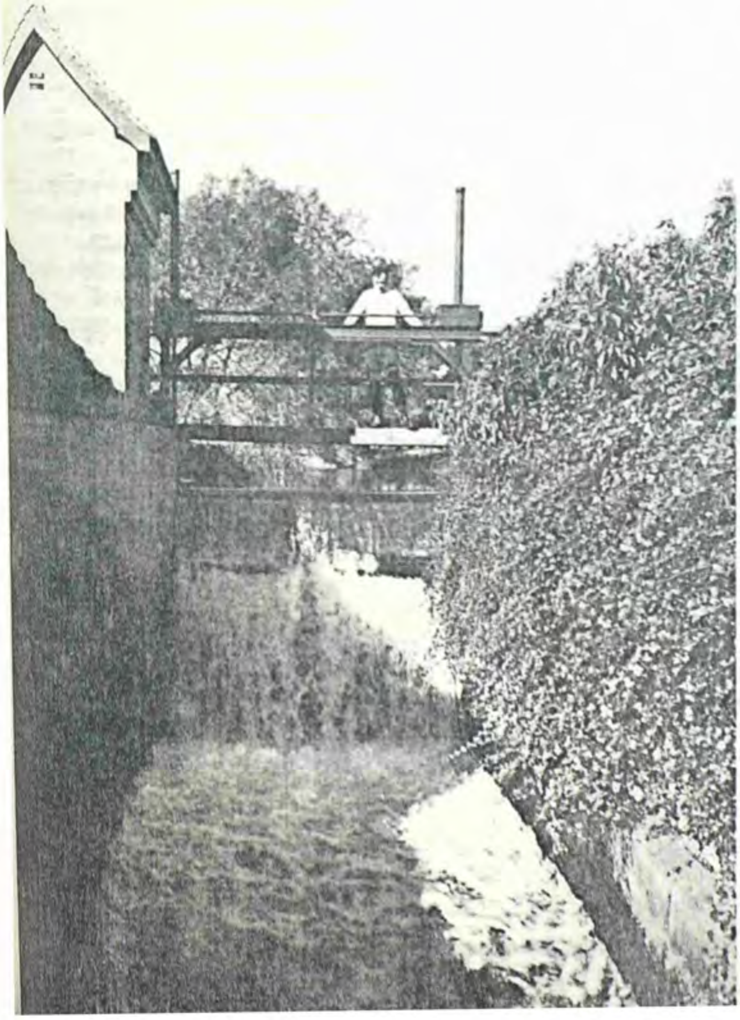


Plate 2a. West Beck at Wansford Bridge; looking upstream at gauging flume beneath bridge under low flow conditions

Plate 2b. Foston Beck at Foston Mill; weir used for flow gauging with recorder housing adjacent



programme of laboratory work carried out on borehole samples in connection with this investigation (Appendix A) confirmed these points. While weathering and the presence of stylolites both had measurable effect on the physical properties, extremely low intergranular permeabilities prevailed. The implication is of exceedingly small grain size and pore channel radii.

According to Ineson (1959a/ discussion of 1960; 1962), pore water should not be ignored in the groundwater hydraulics of the Chalk's saturated zone. However the introduction of laboratory centrifuge specific yield tests suggests that, in East Yorkshire, gravity drainage of chalk pore water is unlikely to be of more than minor significance in computations of mass flow and mass storage (Appendix A). Values of sample specific yield in the range 0.001 to 0.009 were obtained with a mean of only about 0.002.

It is concluded that the East Yorkshire Chalk is almost purely a 'fissure flow' aquifer with the bulk of the pore water constituting 'physically immobile' storage. Flow and storage of groundwater in the saturated zone must occur in the physical discontinuities of the rock mass (joints and less regular fissures, solution openings, fractures and cavities). Permeability, and therefore saturated flow regionally and around individual pumping boreholes is controlled by the configuration of such discontinuities with respect to the external or applied head.

JOINTING IN THE CHALK

The geometry of jointing and its local and regional variation are of considerable significance in the study of the Chalk aquifer. The existing literature contained little mention of jointing and no facts. A limited survey, using conventional geological field methods, was thus undertaken to obtain a quantitative description of the jointing and secondary structures (Appendix B) The distribution of suitable quarry exposures, both geographically and stratigraphically, is not regarded as sufficient for a comprehensive study. Difficulties were also experienced in the definition of sampling criteria and in actually making the measurements. Nevertheless some significant observations of potential relevance to the water-bearing properties of the Chalk were made and are recapitulated here.

The origin of the joint system, its relationship to the tectonic structure of the area and the modifying effect of superficial influences are complex subjects. They are touched upon briefly in Appendix B but were deliberately avoided in favour of a directly descriptive approach, because of data inadequacies and the uncertainty of extrapolation.

In most quarries the first impression of the East Yorkshire Chalk (Plate 2) is that of a fairly massive bedded limestone dominated by frequent multi-directional steeply inclined major joints and even larger numbers of minor joints. Rapid weathering had added to the number of discontinuities present. On closer study, the major inclined jointing frequently appeared to form a system of apparently conjugate high angle sets (greater than 50° to the horizontal). Certain orientations, north-west and east-north-east, are frequently dominant but generally a sufficient number of directions appears to be present to prevent any marked overall anisotropy in the horizontal plane, although exceptions were observed. Moreover the variation between neighbouring quarries implies a measure of local influence, perhaps related to superficial factors, that makes extrapolation into unexposed areas impossible.

The density of major inclined jointing is relatively high and does not vary greatly. On the somewhat subjective basis of counting the inclined joints present in horizontal 30 m sections of the measured faces, densities of the order 0.7 to 1.3 per metre were typically recorded. Given their multi-directional aspect, the overall communication between individual joint openings should generally be unrestricted.

The near-horizontal physical discontinuities include bedding and secondary separation planes and some systematic joints apparently unrelated to bedding. In the exposures measured, they varied in overall density of occurence from 0.6 to 3.6 per metre in the vertical plane and were generally less frequent than the stylolites.

An important observation was that the secondary features (stylolites with their associated marls and flint bands) were in general traversed by the major inclined joints. It appears therefore that such features are not generally capable of reducing the vertical permeability of the rock mass sufficiently to produce local perching or self-confinement within the Chalk groundwater body; this is not in agreement with the observations of Versey (1948). The same may not be true of the thicker primary marls, which may have sealed the joint planes by deformation.

In practice the relevance of the field observations on jointing depends on the answers to three difficult questions.

1. How far is the joint pattern at depth (below

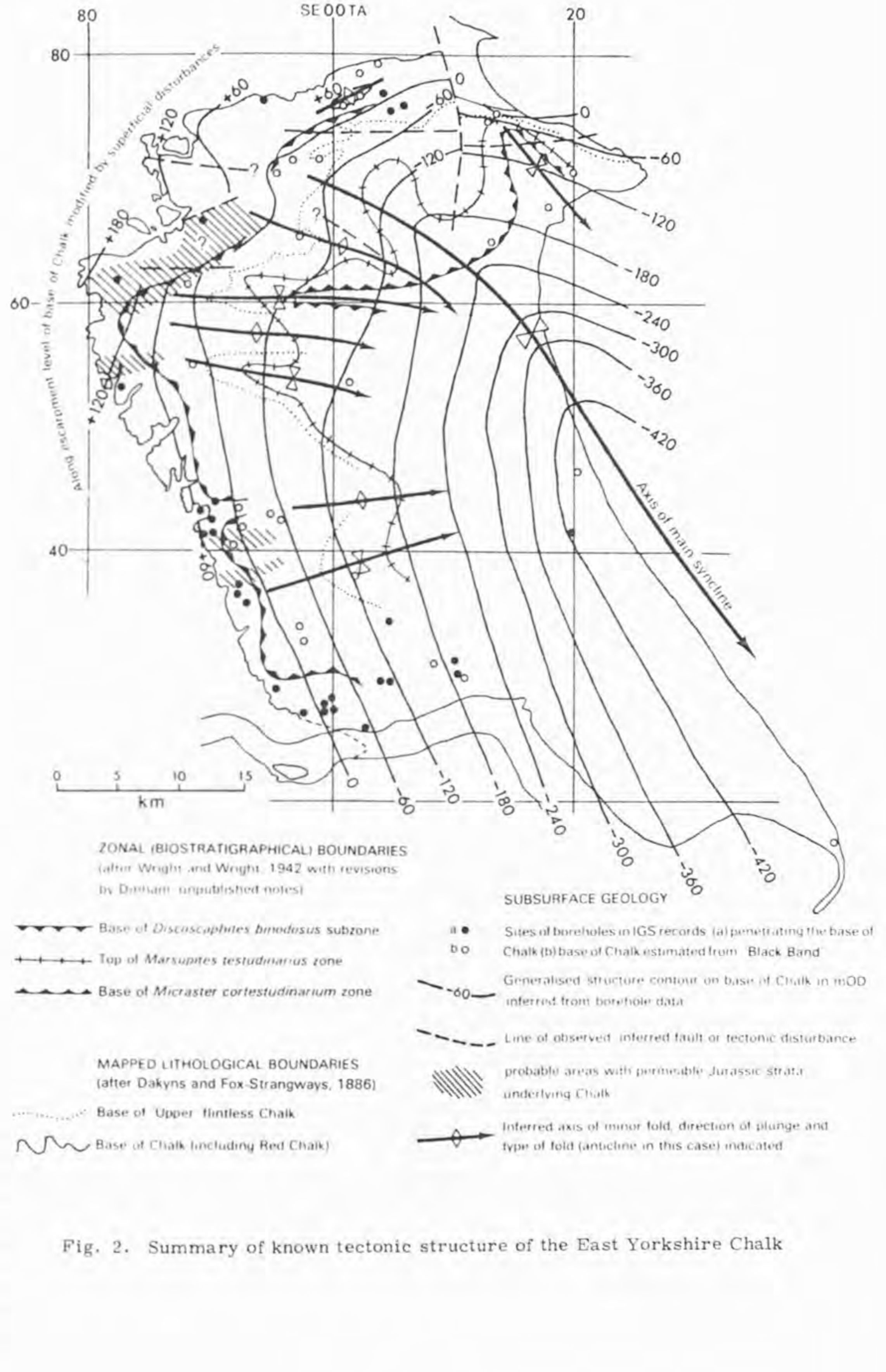


Fig. 2. Summary of known tectonic structure of the East Yorkshire Chalk

the water table) a simple extension of that seen at the surface?

2. How rapidly does reduction in the opening of non-vertical joint planes occur with depth and increasing overburden pressure and does it occur preferentially in certain directions?

3. To what extent have the joint openings at certain depths been modified by solution and other processes?

To the authors' knowledge 1 and 2 have not been answered by systematic investigation in this or any comparable formation and cannot be evaluated with surface geophysical techniques. In respect of 3, large solution features (karst) are not known in the East Yorkshire Chalk, although some solution has and does occur; it is discussed below in relation to permeability development in the Chalk aquifer.

TECTONIC FEATURES AFFECTING THE CHALK

The Yorkshire Wolds represent the outcrop of an open south-easterly plunging syncline, the general scale of which is defined in Fig. 2 by the structure contours on the base of the Chalk. These contours are based on the borehole evidence available in the Institute's records; estimates based on assumed thicknesses for the Lower Chalk are included where boreholes did not penetrate much beyond the Black Band and coverage is poor. Some 50 km off-shore in the North Sea, the limit of the eastern limb of the syncline has been located by Donovan and Dingle (1965).

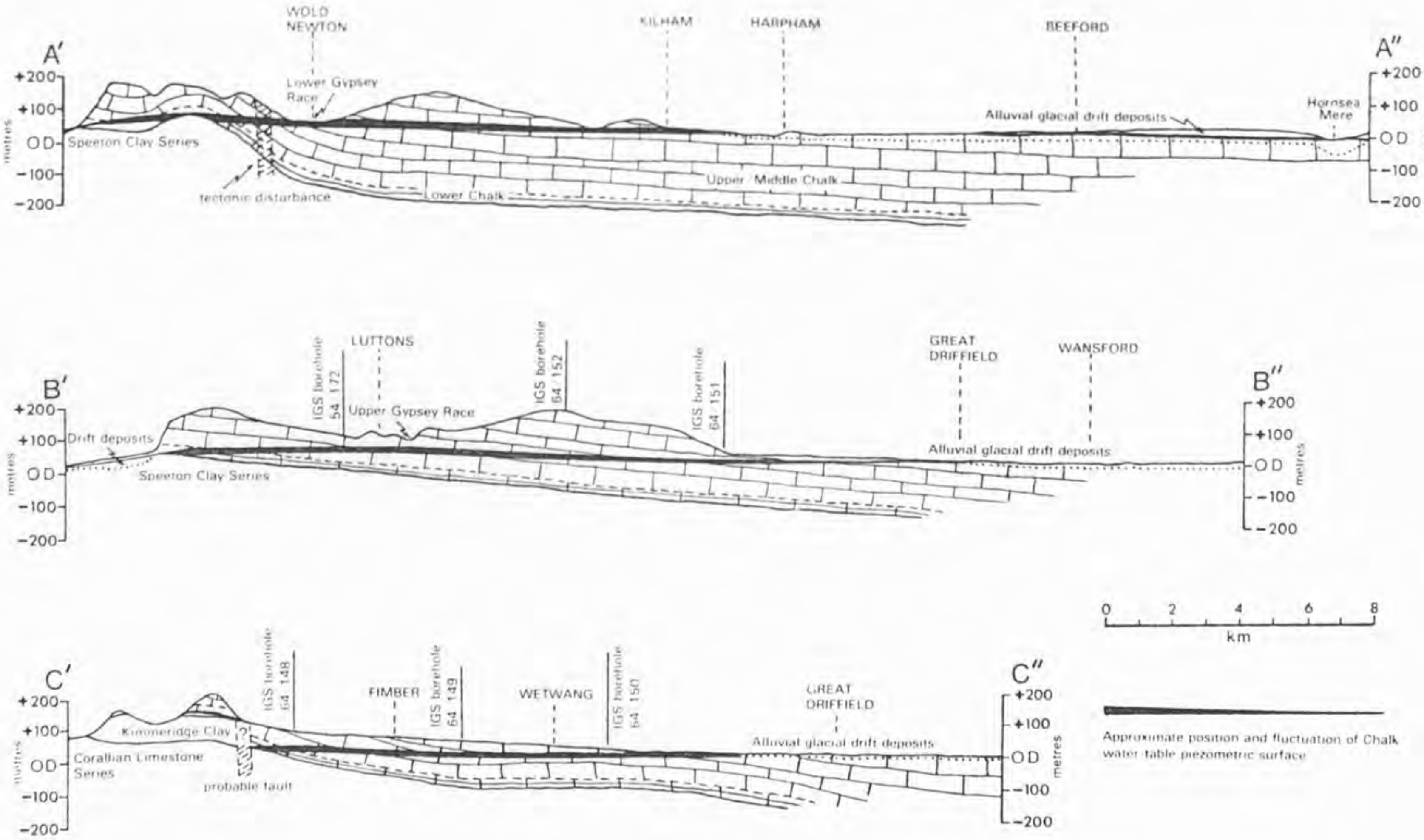
The minor structures within the main syncline are not fully established. In a relatively flat-lying thick sequence the absence of marked lithological changes and uncertainty surrounding the biostratigraphic subdivision, coupled with infrequent exposure in some areas, have to date precluded the detailed mapping of the structure. The series of minor fold axes marked in Fig. 2, which plunge concordantly with the main structure, result from a structural interpretation of the lithological and zonal boundaries indicated. One exception is the Fordon anticline, in the extreme north (Figs. 2 and 3A), which is based on borehole evidence. Some significance would appear to be attached both to the agreement of individual boundaries and to the actual palaeontological boundaries selected (Wood, C. J., personal communication), but it follows from the above discussion that any demonstration of minor structure based on existing biostratigraphical correlation may be open to question. The structure contours in Fig. 2 do not show correspondence with the postulated minor folds, although this could be attributable to insufficient borehole control and the large contour interval consequently adopted.

The dip of the Chalk in East Yorkshire is slight (less than 5° and frequently only 0 to 2°), except locally where tectonic and superficial disturbances are present (Fig. 3). All of the known lines of tectonic disturbance are marked in Fig. 2 but they have little surface expression and can only be seen readily in quarries; it is suspected that many more may be present. Where exposed, these structures often occur in areas of flat-lying strata and consist of very narrow belts of strong folding and fracture apparently without appreciable throw. Most are aligned west-east. The type of associated rock alteration at surface does not appear to include sufficient clay gouge or cemented breccia to impede groundwater movement should these structures be present at depth.

The main north-south disturbance (Fig. 2), the Hunmanby Fault, is distinctive in having considerable vertical and/or lateral displacement revealed by a shift of the escarpment, and is apparently responsible for a comparable displacement in the Great Wold Valley. Its final movement must post-date the west-east disturbances, one of which it noticeably displaces.

In the extreme north-west of the Wolds, evidence from a recently drilled borehole (64/148 in Fig. 3C) suggests that at least one sizeable fault of unknown orientation affects the Chalk near the junction of Thixendale and Burdale. The structure in the area of the north-western escarpment, and to a lesser extent that of the rest of the escarpment, is complicated by extensive superficial movements (Mortimer, 1879).

The existing literature contains much discussion on the influence of possible posthumous movements on pre-existing structural lines in the underlying rocks. Versey (1947) suggested a connection between the west-east Chalk disturbances and the west-north-west fault system of the Jurassic strata in the Howardian Hills, despite the clear unconformity of the Cretaceous succession on these strata south-east of Malton. It is of note that recent work (Kent, 1967; Brunstrom and Walmsley, 1969; Dingle, 1970) implies that this belt of tectonic disturbance may be part of a fundamental structural line of long continued movement stretching from the Pennines for large distances off-shore into the North Sea. If this is the case the structure of the East Yorkshire Chalk, right across the northern part of the Wolds, could be expected to be much more complex than has been indicated (Fig. 2) and this could prove to have significant hydrogeological implications. The thickness variations in the Chalk subdivisions currently


A′
A″
WOLD NEWTON
KILHAM
HARPHAM
BEEFORD
Lower Gypsey Race
Alluvial glacial drift deposits
Hornsea Mere
Speeton Clay Series
tectonic disturbance
Upper Middle Chalk
Lower Chalk
+200
+100
OD
−100
−200
metres
B′
B″
IGS borehole 54/172
LUTTONS
Upper Gypsey Race
IGS borehole 64/152
IGS borehole 64/151
GREAT DRIFFIELD
WANSFORD
Drift deposits
Speeton Clay Series
Alluvial glacial drift deposits
C′
C″
IGS borehole 64 148
FIMBER
IGS borehole 64 149
WETWANG
IGS borehole 64 150
GREAT DRIFFIELD
Kimmeridge Clay
Corallian Limestone Series
probable fault
Alluvial glacial drift deposits
0
2
4
6
8
km
Approximate position and fluctuation of Chalk water table piezometric surface

coming to light may also reflect something of the same influences.

Throughout Jurassic and Lower Cretaceous time, sedimentation in East Yorkshire appears to have been dominated by persistent but intermittent uplift centred along a structurally active belt running approximately west-east across the area north of Market Weighton (Kent, 1955). Marked lateral variations in thickness and facies, overlaps and offlaps are evident at many of the horizons underlying the Chalk escarpment when traced from the Humber at North Ferriby or the North Sea coast at Speeton towards Market Weighton. A full descripton of Jurassic/Lower Cretaceous stratigraphy is not appropriate here and a simplified succession is presented (Table 1). It is recognised that the profound difference and thickness variations in the Jurassic sequence in East Yorkshire north and south of the Market Weighton area (Wilson, 1948) are not represented.

Table 1. Simplified geological succession in East Yorkshire.

Quaternary	Recent alluvium and river gravels	
	Pleistocene Boulder Clay with glacial gravels	
	Disturbed and redistributed chalk	CHALK AQUIFER
Upper Cretaceous	Upper and Middle Chalk	
	Lower Chalk	
Lower Cretaceous	Red Chalk and Carstone	
	Speeton Clay Series	
Jurassic	Kimmeridge Clay	
	Corallian Limestone Series	
	Oxford Clay	
	Kellaways Rock	
	Middle Jurassic oolites and sandstones	
	Upper Lias	
	Middle Lias	
	Lower Lias	
	Rhaetic	

Chalk sedimentation was not dominated by the Market Weighton structure although some mild influence may be present. The base of the Chalk thus oversteps the Lower Cretaceous/ Jurassic strata; this effect being strongest in the Market Weighton area and in the north-west where distribution of Jurassic rocks is affected by the Howardian Hills faults. As a result the Chalk rests on a variety of rock types including all those formations in Table 1 down to the Lower Lias, the maximum overstep occuring at Goodmanham, just north of Market Weighton.

In practice the majority of rocks under the Chalk are virtually aquicludes or have very restricted permeability (Speeton Clay Series, Kimmeridge Clay, Oxford Clay, most of the Lias). They form the lower hydraulic boundary of the Chalk aquifer (Table 1) over large areas, causing a line of contact springs at the outcrop of the junction all along the escarpment and explaining its essential unity as a hydrological system. It should be noted that the Red Chalk and Carstone (a thin ferruginous conglomeratic sandstone only present in a few locations) are included in the Chalk aquifer, although in practice they are of little hydrological significance.

There are however some relatively permeable strata in the Jurassic of the area. Foster (1968) identified three minor aquifers in the Jurassic sequence between Market Weighton and the Humber. Several exist at similar horizons north of Market Weighton. Over limited areas close to the escarpment (Fig. 2) these are probably in hydraulic continuity with the Chalk aquifer, a factor that may influence the position of the Chalk groundwater divide locally. The distribution of the Upper Cretaceous/Jurassic strata beneath the Chalk away from the escarpment is not known in detail. Kent (1967) reports that Jurassic rocks are present at depth throughout East Yorkshire. The possibility of deep groundwater circulation into or out of the area is thus rendered extremely unlikely.

TERTIARY-QUATERNARY MODIFICATIONS

In East Yorkshire there are no strata representing the Tertiary era, during which time the previously described deformation of the Chalk strata, including the folding and tilting of the main syncline, occurred. This was an extended period of uplift and erosion when the escarpment and other essential features of the present topography were developed. The Wolds suffered prolonged denudation and considerable thicknesses of the uppermost divisions of the Chalk were removed from the higher ground. A dip-slope developed in which the

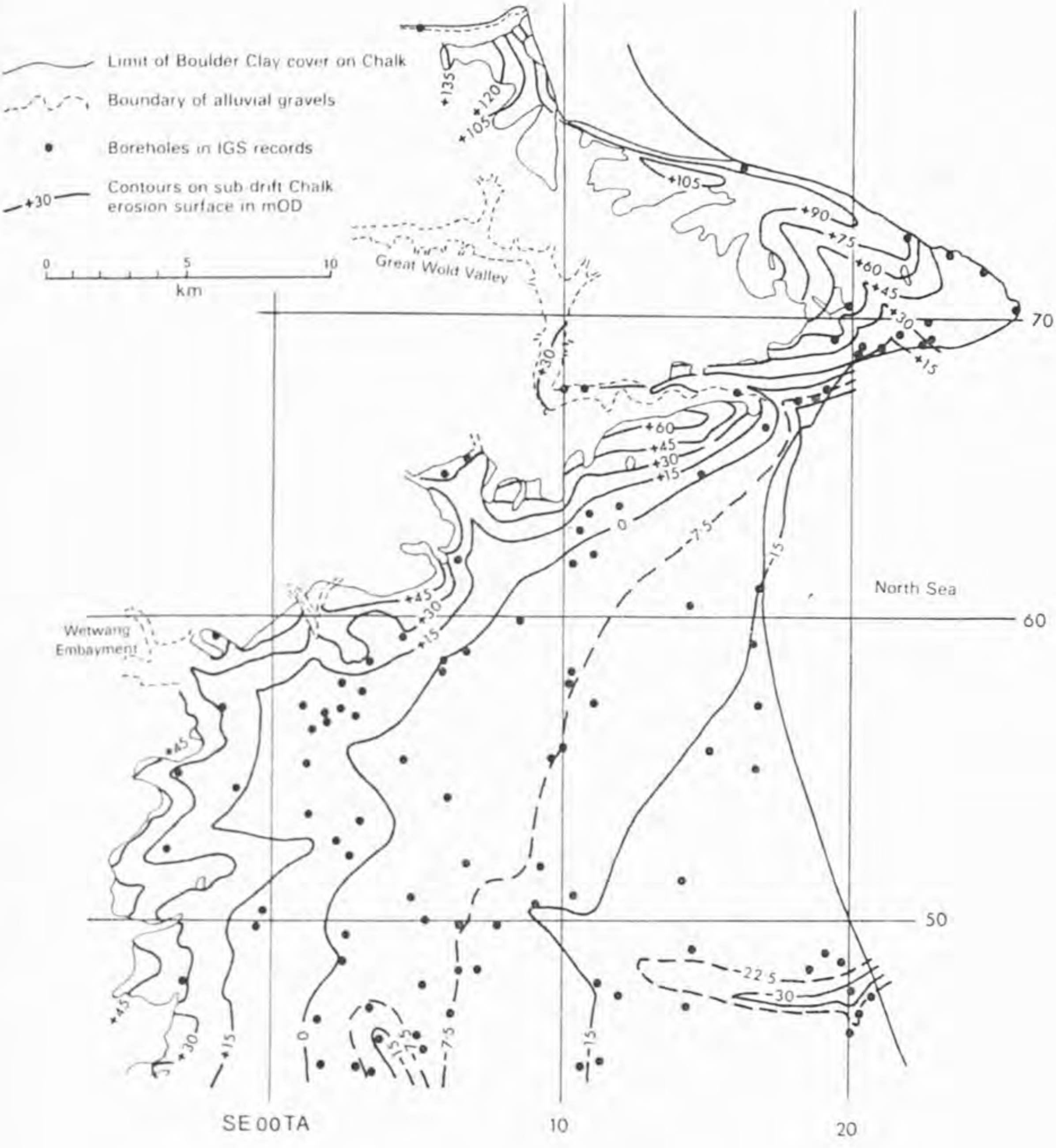


Fig. 4. Structure contours on the sub-Drift Chalk erosion surface

general inclination of the strata is nearly parallel to, but slightly steeper than, that of the land.

The Tertiary topography of the area was then substantially modified by the glacial, interglacial, periglacial and postglacial processes of the Quaternary. During the Pleistocene, extensive composite ice sheets repeatedly moved into the Holderness area abutting against, encroaching onto and probably overtopping the Wolds. Subsequently in Recent geological time, a drainage system developed on the glacial deposits, in response to the immediate postglacial topography, and the current agents of erosion and deposition have initiated further changes.

Quaternary processes have greatly influenced the present hydrological regime. They have affected the Chalk groundwater reservoir directly by the erosion and weathering of its surficial layers at levels now in the saturated zone. Glacial processes also led to the deposition in the lower lying areas of a cover of variable, mainly low permeability, geological materials (the superficial or drift deposits), which confine the Chalk groundwater system, allowing only localised discharge, or restrict rates of precipitation recharge generating surface run-off. The lithological character of the drift cover determines the relationship between the Chalk aquifer and the surface watercourses in areas away from the springheads. Some permeable strata with their own minor groundwater systems are present.

The buried erosion surface forming the top of the Chalk has been contoured from evidence of about 120 boreholes contained in the Institute's records (Fig. 4). Two distinct types of erosional features, an old coastline and some major channels, are revealed.

The old buried coastline runs in the subsurface from north-east of Bridlington all along the eastern flank of the Wolds (Fig. 4) meeting the Humber to the east of Hessle and continuing into North Lincolnshire; locally it reaches the dimension of a buried cliff. Catt and Penny (1966) date the feature to a Pleistocene Interglacial, and suggest that it was associated with a relative sea level of about +1.5 m OD. In the vicinity of the feature, the buried surface of the Chalk has experienced marine erosion and exceptionally high permeability is likely to be associated with deep fissuring and beach deposits. Its level and location are such as to make it potentially of major significance in the regional hydrological regime.

The major buried channel in the Hornsea area (Fig. 4) does not appear to have equal hydrological significance because it is located beyond the limits of the area of large scale natural groundwater circulation. The relationship of this channel, and that in the Bridlington area, to variations in the state of weathering of the buried Chalk surface and in the character of the drift deposits is unknown. Both channels are perhaps of subaerial origin, produced during a period of substantially lower sea level, but could equally be comparable to the buried 'tunnel valleys' in the Chalk of East Anglia (Woodland, 1970) or to the buried 'fjord' at Kirmington in North Lincolnshire. They appear to bear some relationship to the larger dry valleys in the Wolds, whose origin has been attributed to subaerial headward erosion of major springs during the more humid Tertiary/Quaternary periods of higher water table (Lewin, 1969). Subaerial or subglacial meltwater erosion, of a land surface rendered impermeable by permafrost have also been suggested for their origin. However, this dry valley network cannot directly influence the present day hydrogeology of the Chalk, except where the water table is not far below the land surface.

Throughout East Yorkshire the surface layers of the Chalk, whether or not drift covered, have been affected by Pleistocene cryoturbation (frost action) and solifluxion (creep or flow). In many places a layer, up to 12 m thick, of in situ broken up chalk (called 'chalk bearings' by water-well drillers), or a re-distributed chalk-flint gravel, is present. It can be seen in many quarries. Where the surface of the Chalk is buried sufficiently deep for the bearings to occur in the zone of saturation, they may be responsible for gross permeability variation. Local differences in ice action appear to be responsible for replacement of the 'bearings' by an impermeable 'putty chalk' which has been reported in boreholes at a few scattered locations.

The stratigraphy, lithology and distribution of the drift cover in the northern part of the Hull Valley are of equal importance to a detailed understanding of the Chalk hydrology. The most important deposit is the Boulder Clay, considered to be a series of glacial tills or ground moraines of the ice sheets. It is thought to form a continuous cover of the Chalk throughout the Upper Hull Valley encroaching onto the flanks of the Wolds and the higher ground of the Flamborough Peninsular.

Two problems are apparent when attempting to use the published work on the Pleistocene stratigraphy of East Yorkshire for practical hydrological purposes. . Firstly, much confusion surrounds the nomenclature of subdivision; different authors having used the same terms with different meaning. Secondly, most work refers almost exclusively to the excellent coastal exposures in Bridlington Bay and Holderness and at Hessle and not to the main areas of present interest, where exposure is limited to shallow pits.

The most recent and comprehensive work (Catt and Penny, 1966) based its four-fold subdivision on study of the minor variations in grain size and mineralogy of the till matrices, the statistics of erratic occurrence, heavy mineral assemblages, and the field relations of fossiliferous horizons in the better exposures. Because of the uncertainty of the distribution of these units it is not proposed to present their detail. However both the Drab Till, 6 to 12 m thick and the uppermost unit the Hessle Till, up to 5 m in thickness, are thought to be laterally persistent. Their lithologies are strongly influenced by the source of dominant erratic material, which for the Hessle Till is Chalk but for the Drab Till is very variable including significant proportions derived from Triassic and Coal Measures Sandstones. In general all the Boulder Clay can be expected to possess limited but possibly significant permeability, due to sandy 'stringers' and to limited 'fissuring', but very little field or laboratory test data are available.

There has been much discussion on the age and history of the glaciation represented by the Holderness sequence of boulder clays (for example, Bisat, 1940; Catt and Penny, 1966) but it is not of direct relevance here. The deposits of gravel interdigitated locally in the Boulder Clay sequence, about which such a discussion centres, are however of some hydrological significance and may contribute a baseflow to the surface watercourses.

Glacial gravels and sands occur as beds, lenses, channels and ridges, at a number of levels in the sequence, particularly at its top; the geometry and character of the gravel bodies is strongly dependent on their relation to the glacial system as a whole. In East Yorkshire most are outwash complexes, in which the original glacial till has been sorted by the action of meltwater, and ice contact features are relatively rare. Over parts of the Upper Hull Valley, the higher gravels in the sequence form the present land surface although, in the presence of considerable reworking, they are difficult to distinguish from larger spreads of post-Hessle gravel associated with the final retreat of the ice sheets.

The glacial deposits have a cover of alluvial clays and silts, gravelly sands and peat, associated with the development of the current drainage system. The shallow geological conditions in the immediate vicinity of the channel of the River Hull and its tributaries are probably of most interest because they relate to its bank storage, to bank losses into the land-drainage system and to the shallow underflow beneath river gauging stations.

Hydraulic Behaviour of the Chalk Aquifer

INTRODUCTORY REMARKS

At an early stage in the investigation of saturated flow in any carbonate aquifer possessing significant secondary porosity, it is wise to consider the benefit or harm in attempting to attribute it with conventional coefficients of transmissibility (T) and storage (S) (Stringfield and Le Grand, 1969). If the forms of secondary porosity are systematically distributed, even in a gross way, the approximate determination of the basic hydraulic properties of the main elements of the groundwater system, the boundary of each element in depth and space and the hydraulic conditions at those boundaries is fully justified and of considerable value.

The characteristics of the prevailing regime of groundwater flow and storage in the Chalk aquifer have not been established previously at any site in East Yorkshire. Its hydraulic behaviour in the outcrop area was a particular question. Hearsay evidence suggested that, in some areas, flow systems could be restricted to very few discrete conduits and frequent 'perching' might be present, although this was hard to reconcile with the frequency of jointing seen in quarries (Appendix B) and the groundwater level data. The boundary between the zones of aeration and saturation over most of the outcrop seemed to be as clearly defined as in water table storage/intergranular flow aquifers. On drilling boreholes the water generally rises somewhat after first being struck, but this rise was found to be less than 1 m in most cases. There are, however, minor water level fluctuations in response to rapid changes in barometric pressure.

The nature of the groundwater flow regime may most readily be evaluated from a pumping test, given knowledge of the geological conditions in the area concerned and adequate data control through the drilling of observation boreholes. The general reluctance to face the cost of the required type of pumping test at the regional investigation stage, has often meant that such work had to be linked to the development of groundwater resources with consequent restrictions on location.

During the current investigation, an opportunity arose in connection with a scheme to develop further groundwater production from the Etton area. Etton is in the southern part of the Wolds (Fig. 1), outside the Hull-Hempholme catchment. The level of control over experimental conditions during the pumping tests however was in most respects exceptional and the study of the Chalk aquifer in the Etton area has been documented independently (Foster and Milton, 1974).

NATURE OF CHALK PERMEABILITY AND STORAGE

The Etton pumping tests showed the Chalk aquifer capable of quantitative analysis and meaningful approximation by a relatively simple mathematical model. The existence of a laminar (Darcy) flow regime was confirmed, even for high pumping rates at distances down to 125 m from the point of abstraction. No major lateral hydraulic boundaries appeared to be present in the cone of pumping depression and the idea of strong areal anistropy in hydraulic properties, related to jointing and/or the direction of minor dry valleys, was refuted on the evidence from critically sited observation boreholes.

The ordered responses in the observation boreholes during the October 1970 test led to confident application of the established methods of non-equilibrium pumping test analysis (Theis, 1935; Boulton, 1963). The late-time data yielded an average T value of 1000 m^2/d. The analysis for S as always was somewhat more subjective, but a value of the order of 0.005 was indicated and appeared to represent the specific yield (S_y) for the Chalk of this area at the groundwater level in October 1970. Laboratory centrifuge specific yield tests suggest that a significant delayed yield from gravity drainage of pore water is not likely (Appendix A). It is possible however that other sources of longer delayed yield contributions, such as the drainage from microjoints, could be present.

Subsequent test pumping at Etton in April 1971, with a 7 m higher (although not maximum) level of saturation, gave results of about 2200 m^2/d for T. This confirmed the extremely high horizontal permeability of the zone of seasonal water table fluctuation, anticipated from the yield-drawdown characteristics of the original production borehole.

Geophysical borehole flow investigations proved most valuable. In fissure flow aquifers it is not sufficient to know the magnitude of fissure transmissibility but also the three-dimensional distribution of permeability which it represents; the level and thickness of the zones of major permeability development relating directly to the heads that can be utilised in producing borehole yield. Levels of entry of groundwater to the Etton pumping boreholes were restricted. At the near minimum water levels in October 1970, the bulk of the water pumped was derived from a 5.0 to 8.0 m thick zone, the base of which was located 14 and 23 m below OD respectively in the two boreholes at the site. The existence of marked chloride residuals (the products of previous acid treatment) suggest minimal regional groundwater movement from about -29 m OD to the base of the boreholes at -40 m OD and probably below that level. Previous investigations in July 1970, with a somewhat higher water table, had given similar results except that more than 30 per cent of the total pumping rate was derived at or above the pumping water level. It is worth noting that the borehole flow investigations demonstrate that significant groundwater flow occurs, and presumably significant storage exists, below local hydrological base level and below OD but not throughout the thickness of the Chalk formation.

It is concluded that the Chalk aquifer in the outcrop area frequently approximates to a layered moderate-T/low - S_y water table system, whose flow regime will have little in common with turbulent conduit flow systems of karst carbonate terrains. Actual rates of groundwater movement, even under natural hydraulic gradients, however will be relatively fast because of the small cross-sectional area of flow, and could reach 200 m/day. Such a layered aquifer could present difficulties in digital modelling and the reduction in its hydraulic constants with depression of groundwater level will be difficult to forecast.

The conclusions drawn from the Etton pumping tests permit further speculation about the nature of Chalk permeability. The extremely high permeability of the zone of water table fluctuation can probably be attributed to preferential solution increasing the opening on discontinuities in this part of the rock mass, although it is recognised that the development of solution openings is not marked. Other things being equal, the former conclusion has been reached in the studies of a number of carbonate systems (Stringfield and Le Grand, 1969). The factors controlling the initiation of solution openings however are not well understood and the details of their selective development on certain discontinuities are often puzzling (Davis, 1966).

The hydraulics of fluid flow in idealised fractured media show clearly the large influence of a relatively small increase in aperture (opening) due to solution and calculations based on them (Foster and Milton, 1974) are of considerable interest in the interpretation of in situ permeability. Just one fissure with an aperture of 5 mm or more would introduce gross heterogeneity into an aquifer. The areally isotropic behaviour of the Chalk aquifer in the Etton area accompanied by its high permeability probably thus indicates that development of solution permeability is concentrated on horizontal discontinuities, although this is not a unique explanation.

Use of a closed-circuit borehole television camera at Haisthorpe (64/108A in Fig. 1) revealed numbers of horizontal discontinuities that were visibly open and apparently associated with levels of water entry into the borehole during pumping, although the proximity of the 'buried coastline' makes the Haisthorpe site atypical. Numbers of the discontinuities however, were similar to those observed by Ward and others (1968) just above the water table during the direct inspection of walls of large diameter Chalk boreholes at a site in Norfolk. Horizontal 'separation planes' open in places to as much as 10 mm were recorded, bridged and supported by contacts about every 0.2 m.

In the Norfolk boreholes it was observed that, below a maximum of about 14 m below ground level most of the discernible inclined joints were closed tight. The far greater density of inclined joints in the core from of an adjacent borehole (Gallois, R. W., personal communication) suggests that in situ many must be microscopic (that is less than 0.1 mm) in aperture. The same may not hold true for the East Yorkshire Chalk since the rock material is somewhat harder and less ductile. Nevertheless any similar tendency would result in large differences between horizontal and vertical permeability and could be expected to lead to a degree of self-confinement and partially independent flow systems within the aquifer as a whole.

REGIONAL AQUIFER VARIATIONS

The Etton area appears to be in most respects typical of the lower part of the regional Chalk dip-slope and there are no clearly established geological reasons to suggest any gross departures from the 'Etton aquifer model'. Despite the obvious risk of circular argument, there is great temptation, in this as in other limestone terrains (albeit less subject to solution) to attribute the development of high permeability to solution during the long term circulation of fresh groundwater to a given natural base level. If this is the case transmissibility (T) would generally increase towards the natural discharge points on the flanks of the Hull Valley with gradually decreasing values up the dip-slope towards the groundwater divide, because in the former areas the total volumetric flow has been greatest.

In a pilot Chalk groundwater development area in East Anglia, T values of 350 m^2/day are reported on the higher ground with a 2 to 5 fold increase in the main valleys (Backshall and others, 1972). In East Yorkshire even the deepest of the valleys on the Chalk outcrop are nearly all perennially dry. Except in those cases where intermittent discharge occurs (that is, the Great Wold Valley and the Kiplingcotes Valley, north-west of Beverley), there is no reason to suspect that any major variation in aquifer properties are associated with them.

The conditions in the Wetwang Embayment to the immediate hinterland of the major Driffield springheads (Fig. 1) must be exceptional and, as will be seen from the subsequent discussion of groundwater levels and hydraulic gradients, very high permeability is anticipated. Whether the initiation of the major springheads was consequent on high Chalk permeability or on local variation in the drift cover with the Chalk permeability developing subsequently, is not certain.

At times in geological history when a much lower hydrological base level existed, the development of major solution permeability at depth in the Chalk aquifer might be anticipated. The occurrence of a major flow zone at around -20 m OD at Etton, may be associated with the Pleistocene buried channels (Fig. 4), and could be present at equivalent levels throughout the region.

Under the increasing drift cover, down-dip to the east of the River Hull, radical changes in the confinement parameter (S) of the Chalk aquifer are to be expected. At distances of 10 km under cover and throughout Holderness, the limited evidence from water supply boreholes and deep wells suggests a rapid decrease in T also. It is not logical to attribute this low permeability and the presumed tight closure of all joints to overburden pressure. This results from only 20 to 40 m of largely saturated soil and is probably less than that due to the 15 to 100 m of partially saturated rock overlying the Chalk of the saturated zone in the outcrop area, whose T values are very high. The non-development of solution permeability due to absence of long term natural groundwater circulation seems a more likely explanation; the Chalk aquifer being filled by essentially 'dead storage' (that is, by groundwater at lower

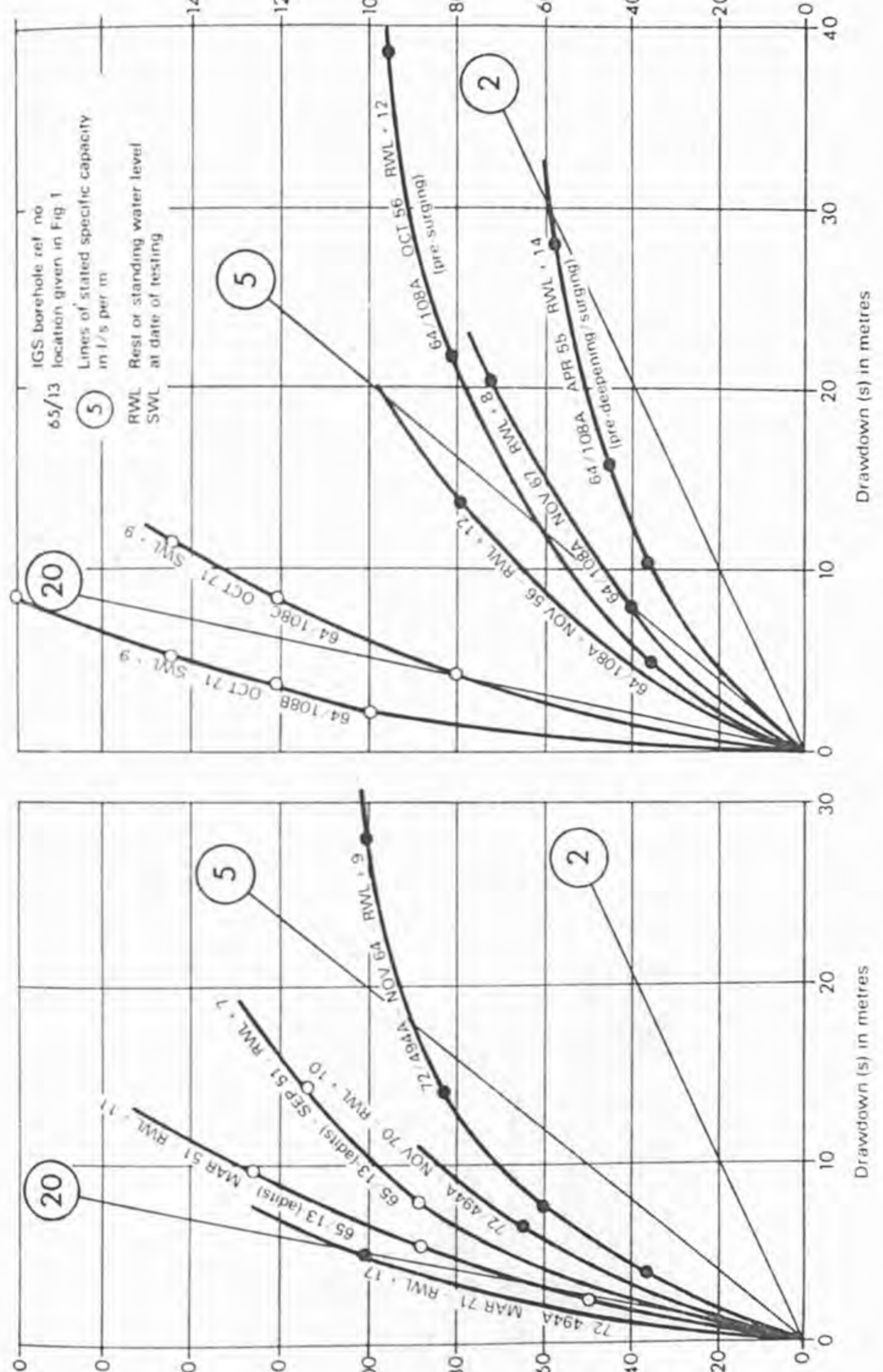


Fig. 5. Chalk borehole yield-drawdown characteristics

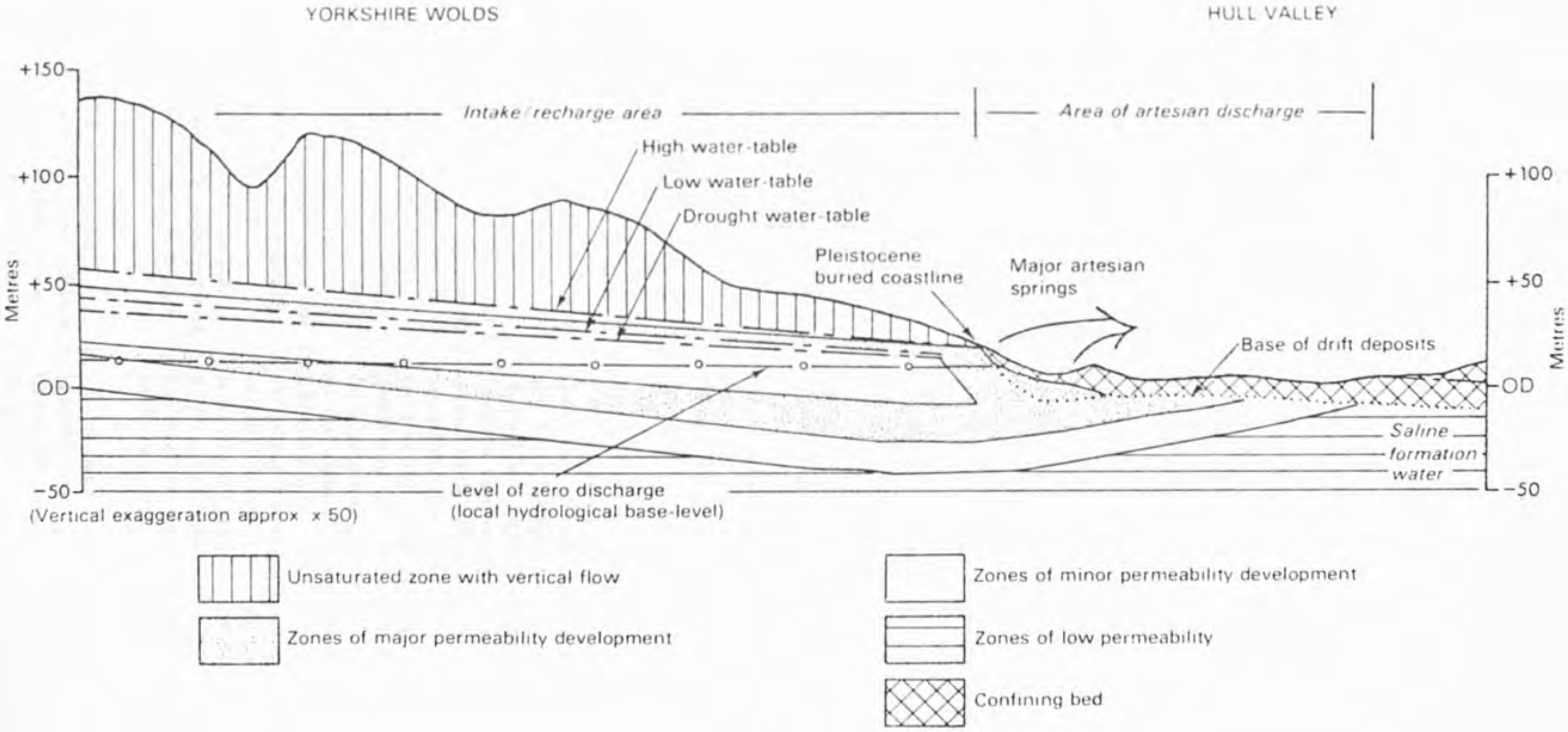


Fig. 6. Schematic interpretation of the hydraulic structure of the Chalk aquifer in East Yorkshire

total hydraulic head than the potential of the natural outlets).

Between the water table aquifer of the Wolds outcrop and the subartesian aquifer in Holderness lies the main area of perennial groundwater discharge; an arcuate zone containing many sizeable artesian springs. This zone is of major significance in the regional hydrology. Despite its transitional position, the aquifer's hydraulic properties throughout the zone may be far from transitional because certain geological factors may exercise overriding control. The presence of the buried Pleistocene coastline together with the surficial layer of cryoturbated chalk result in the possibility that extremely high permeability may be present in this zone over limited areas and saturated depth intervals. The yield-drawdown data from two pumping boreholes at Haisthorpe (64/108BC in Fig. 5) are sufficient to show the locally extremely high aquifer permeability. Unfortunately good observation borehole control was not available for the 1971 testing at the Haisthorpe site, but the limited data collected suggests T values in excess of 5000 m^2/day for the most permeable strip.

An attempt has been made to summarise the postulated variations of the Chalk aquifer in a schematic cross-section (Fig. 6). This is based on the interpretation of the geological conditions and hydrological regime and it has not been possible to confirm by direct testing in the Hull-Hempholme catchment itself. It assumes no major variation in aquifer properties in relation to possible minor folding, lines of tectonic disturbance and Middle/Upper Chalk stratigraphy, points on which there is little direct evidence but which may influence the properties of the Chalk aquifer under certain conditions in other regions (Ineson, 1962).

PUMPING BOREHOLE YIELD CHARACTERISTICS

Records of the behaviour of individual pumping boreholes, either during systematic step-tests (yield-drawdown characteristics) or individual measurements during routine operation (specific capacity data), are more readily available than full scale pumping test data. To a limited extent they furnish quasi-quantitative information on aquifer properties, and considered regionally, on aquifer variations. However they are presented here primarily to give a description of borehole behaviour and to show the restrictions imposed on short term yield as a result of borehole as well as aquifer limitations.

It is useful to consider first exactly what yield-drawdown characteristics represent. Plots of yield (Q) against drawdown (s) may be drawn for any pumping borehole. Strictly each value of s should relate to an equal interval of time after the start of pumping at each steady rate (Q), preferably 24 hours. More commonly an extrapolated 'terminal' or 'apparent equilibrium' drawdown is used. Since true equilibrium is only realised in the specialised condition of constant recharge (in a borehole adjacent to a hydraulically connected river, for example) this is usually a hypothetical concept. Nevertheless the data are of some hydrological value and of considerable use in water supply engineering since they relate directly to the choice of pumping plant and operating conditions.

The Q-s curve for a given borehole depends on the aquifer's hydraulic properties and flow conditions but also includes head losses associated with the entry of water into the borehole and flow to the pump suction (well losses). The latter are commonly non-laminar and result in the final form of the Q-s curve showing strong departures from linearity; for inefficient boreholes they may completely mask the influence of the aquifer's hydraulic properties in determining the overall characteristic. Moreover in fissure flow and other heterogeneous aquifers, the form of Q-s curves for large Q is dependent on the actual levels of entry of the major flows into the borehole. If the pumping water level drops below the principal level of entry, further drawdown may result in little or no additional yield. This phenomenon, amongst others, has been described as a 'breakaway condition' (Ineson, 1959b), by which is meant departure from a series of empirically established Q-s type curves and not just from linearity.

The available yield-drawdown characteristics for water supply boreholes in the Chalk of East Yorkshire (Fig. 5) illustrate the general type of pumping borehole behaviour in this aquifer. Significant variations attributable to known factors can be identified. These variations can occur between different boreholes at the same location, due to large local variation in aquifer properties as at Haisthorpe (cf. 64/108A to 64/108B and C). Seasonal variation in the same borehole can occur due to high transmissibility of the zone of water table fluctuation (for example, 72/494A and 65/13). Improvement can occur in the same borehole due to short term development (64/108A) and also over long periods of time (cf. 72/494A, Nov.'64 and Nov.'70), presumably due to long continued development by solution and abrasion of fissures; deterioration may also occur in some circumstances.

A degree of breakaway from the Ineson (1959b) type curves occurs in a majority of the boreholes at minimum water level conditions. At Etton, breakaway can be positively associated with the principal levels of water entry in the respective boreholes (Foster and Milton, 1974) and the role of the latter in determining the yield-drawdown characteristic cannot be overemphasised.

The specific capacity of a pumping borehole is defined as the ratio Q/s. As in the case of the Q-s characteristic, a specific time (say 24 h) after the start of pumping at the steady rate (Q) should be defined. In practice any time greater than 8 h or so does not produce great variation in the parameter. The potential variation in specific capacity that could arise from single determinations can be seen from consideration of the yield-drawdown characteristics (Fig. 5). These data are for boreholes which are likely, by virtue of their size and function, to be of optimum efficiency and an even greater Q/s variation is possible from poorly developed boreholes. Ineson (1959b) attempted to overcome the variability of Q/s data by using the better defined 'yield for 10 ft drawdown' criteria when attempting to establish a correlation with aquifer properties. However the coarse scale and wide scatter of his correlations limit their usefulness and T values based on such data for the outcrop area of the Chalk aquifer in East Yorkshire (Ineson, 1962) appear frequently to be an order too small. Moreover no such pumping borehole characteristics can be interpreted in terms of the storage and boundary conditions of the groundwater flow regime, which are of major significance in the context of resources evaluation and development.

The available data on specific capacity of water supply wells in the East Yorkshire Chalk should be thus viewed only in a negative way. There are very few locations, on the outcrop or up to 8 km under cover, at which large diameter boreholes have given a specific capacity of less than 2.5 l/s per metre drawdown and there are good prospects of them yielding at least 50 l/s at a specific capacity of more than double that value. Some of the cases of yield failure have been due to constructional reasons but there remain a few instances (for example, at Hutton Cranswick, 5 km south of Great Driffield) which apparently reflect important local variations in aquifer properties.

Detailed Analysis of Hydrological Regime

BASIC DATA ON ELEMENTS OF GROUNDWATER CYCLE

Riverflow is directly measurable, generally to an acceptable level of accuracy. Three permanent and continuously operating river gauging stations were established on the Hull river system during the period 1953-1961 (Table 2 and Plates 3 and 4). The data from them forms the best starting point for a detailed analysis of the hydrological regime and an assessment of groundwater resources. In this report the data for the 8-year period when all the three gauging stations were in operation (1962-1970) is employed for most of the analyses. The (generally weekly) spot-flow determinations on the Gypsey Race at Bessingby Road Bridge were also used but measurement was discontinued during 1968, pending the construction of a permanent flume.

To extend the analysis of riverflow data to a full computation of the groundwater balance requires comparable data on other hydrological parameters, including precipitation, evaporation, the changes in soil moisture and groundwater storage, together with precise definition of the catchment areas, underflow at the gauges concerned, knowledge of water usage and artificial transfers within the catchment. None of the former of these parameters, except precipitation, have been measured to the accuracy of riverflow.

It has been mentioned that the accurate estimation of the input to the Chalk groundwater reservoir is not a prime requisite for the evaluation of a river regulation scheme of the scale envisaged. The deficiencies in evaporation and soil moisture data are thus not critical in the present context. The process of infiltration and recharge to the saturated zone may also be much more complex than might at first sight be imagined. Tritium age determinations were made on pumped water samples and springs from more than 20 locations in East Yorkshire during 1970-1972. Of the eight sampling stations located on the Chalk outcrop only two had tritium levels in excess of 20 T.U. in October 1970 and, even after the winter's infiltration, those sampled in spring 1971 showed no increases (Foster and Crease, 1974). These results could indicate that a large proportion of the water in the saturated zone beneath the outcrop is pre-1953 precipitation and if so, they raise a major question as to the mechanism and rates of groundwater movement in the unsaturated zone. Smith and others (1970) studied the total tritium of Chalk pore water from a cored borehole at a site in Berkshire and concluded that the rate of downward movement in the unsaturated zone was only about 0.9 m/a, that is, the bulk of recharge to the main groundwater body spent more than 18 years in the unsaturated zone during its downward percolation to the water table.

From the outset of the present investigations in 1970 it was clear that the measurement of groundwater levels, particularly in the Hull-Hempholme catchment, was far from adequate. The value of a dense network of observation

Table 2. Hydrometric network in Hull-Hempholme catchment and adjacent areas.

River gauging stations

Station	H River Hull at Hempholme Lock	W West Beck at Wansford Bridge	F Foston Beck at Foston Mill
NGR	TA 080 499	TA 063 560	TA 094 548
AOD(m)	3	5	6
Authority	KuHCBC	YRA	YRA
Type of gauging structure	Two 7 m wide weirs; constant upstream water level: notches for measuring low flows	Compound standing-wave flume	3 m wide rectangular sharp edged weir adjustable to control upstream water level
Comments	Frequently drowned out under high flow conditions; major upstream abstraction by KuHCBC added	Rating intermittently affected by weed growth; some irregularity caused by mill water turbine	Sensitivity at low flows questionable

Groundwater observation boreholes

IGS Ref. No.	NGR	Location	Surface level m AOD	Depth m	Measurement	
					Type	Authority
54/65	TA 083 720	Burton Fleming	38	11	MM	EYWB
54/67	TA 085 773	Hunmanby PS	108.9	82	AR	IGS/YRA
54/125	SE 997 720	Boythorpe Farm, Butterwick	62	23	MM	EYWB
54/134	TA 046 731	Wold Newton	49	14	MM	EYWB
54/135	TA 022 717	Octon Grange Farm, Foxholes	61	23	MM	EYWB
54/171	SE 982 703	Weaverthorpe	70.5	46	AR	IGS
54/172	SE 934 708	Haverdale, Luttons	92.7	53	AR	IGS
64/1	TA 049 612	Nafferton PS	79.9	81	AR	IGS/YRA
64/148	SE 881 616	Burdale	92.1	76	AR	IGS
64/149	SE 918 597	Gameslack, Fimber	62.3	60	AR	IGS
64/150	SE 958 595	Wetwang	42.4	32	AR	IGS
64/151	SE 985 621	Cottam Warren	49.2	46	AR	IGS
64/152	SE 983 664	Honey Hill, Langtoft	162.9	146	AR	IGS
65/15	TA 145 655	Carnaby	26	19	MM/AR	EYWB/YRA

KEY:

MM	manual measurement
AR	automatic recorded
YRA	Yorkshire River Authority
EYWB	East Yorkshire (Wolds Area) Water Board
IGS	Institute of Geological Sciences

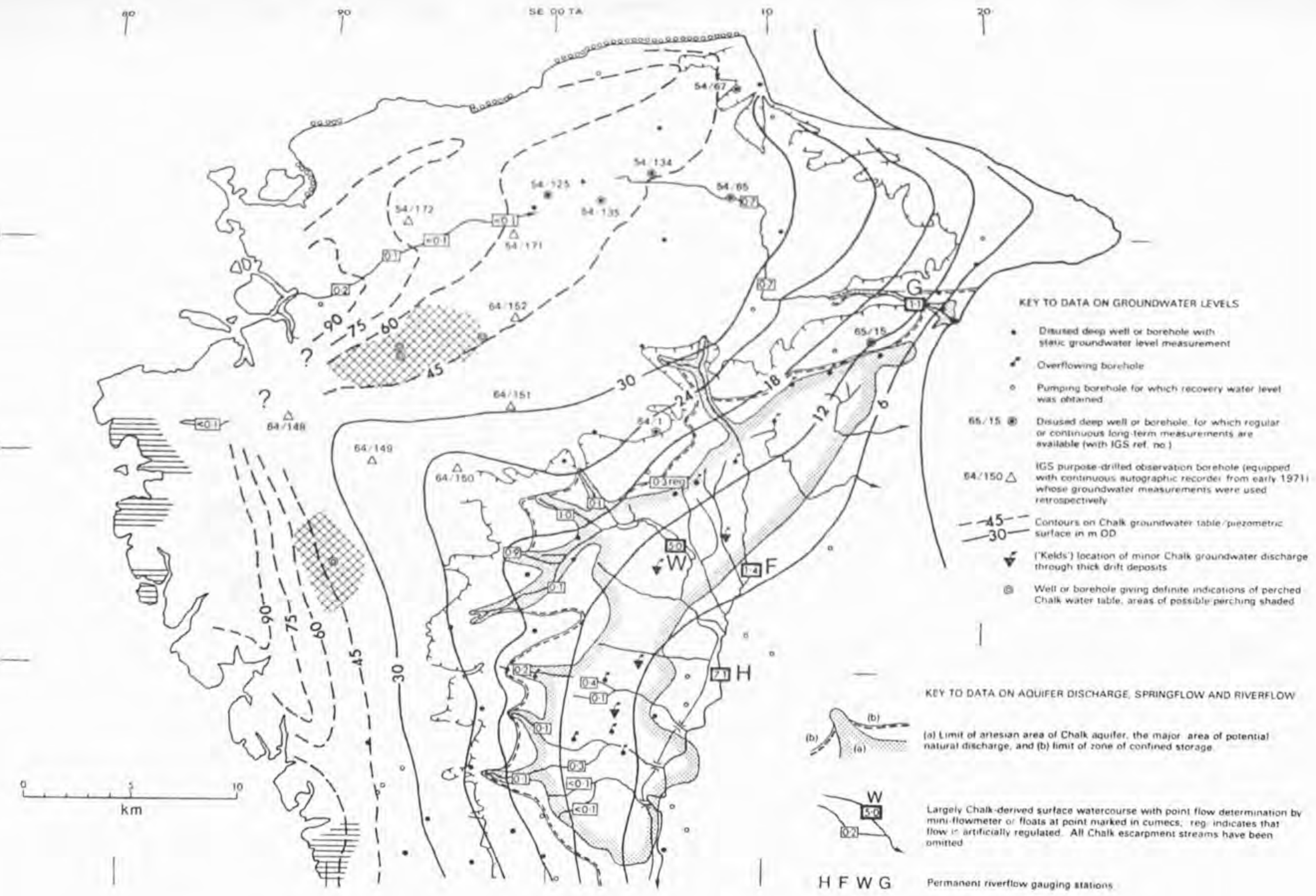


Fig. 7a. Groundwater levels and instantaneous discharge of Chalk aquifer - late March 1970

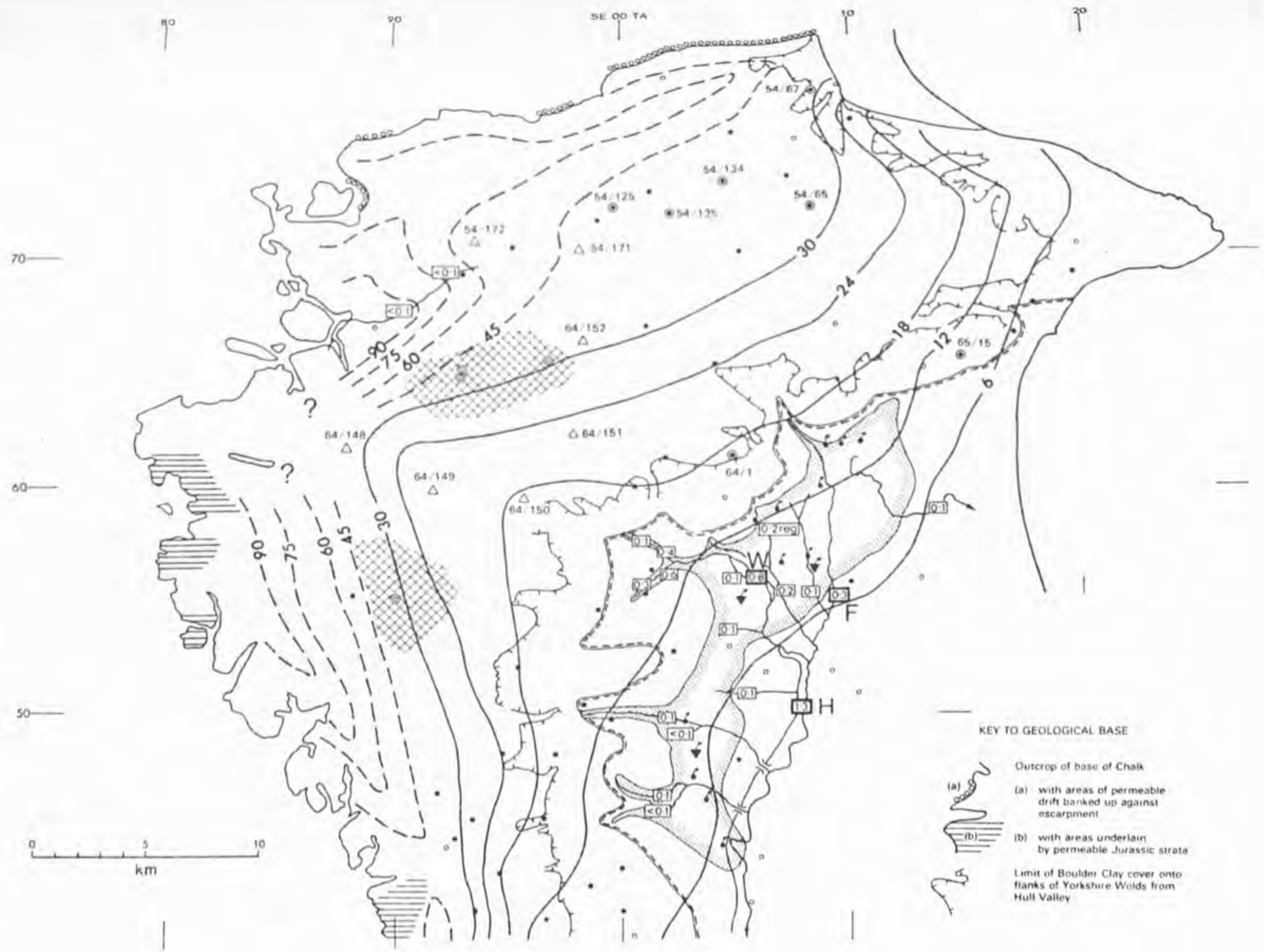


Fig. 7b. Groundwater levels and instantaneous discharge of Chalk aquifer - early October 1970

boreholes for monitoring the variation of groundwater levels in space and time is not limited to the evaluation of changes in groundwater storage. It also enables closer definition of the areas of recharge and discharge, the delineation of groundwater flow directions, the evaluation of aquifer storage conditions and variations in hydraulic properties. Under ideal conditions, analysis can be extended to a full evaluation of the groundwater system by computerised numerical analysis.

The elevation of water in a borehole or well represents the average hydraulic head of the groundwater in that part of the formation with which it is in open communication. The degree of penetration and of communication with the most permeable horizons (for example, the chalk 'bearings') could affect the water level. In practice however, it is unlikely that this will be significant in terms of naturally occuring rates of change in head. Exceptions exist where a definite perched water table is present.

Field work commenced in spring 1970 with an exhaustive reconnaissance of deep wells and boreholes in East Yorkshire; of the 200 selected from the Institute's records over 50 proved accessible for rest water level measurement with an electric probe of 10 mm diameter. Two approaches were initially tried in an attempt to improve coverage. One involved using sites currently licensed for groundwater abstraction where pumping plant did not prevent access and a sufficient recovery period (say 6 h) could be arranged with the owner or operator. The other approach was an attempt to open up selected sealed deep wells and boreholes; although a somewhat slow operation, a reasonable degree of success (over 50 per cent) was achieved and at these sites permanent access for water level measurement was installed.

The chief source of error was inaccuracy in the elevation of measurement datum points. Certain older wells, particularly those that were blocked or collapsed or that comprised a shaft near the water table with a borehole at the base, were likely to record spurious water levels and great care was required if meaningless measurements were to be avoided.

Measurements of Chalk groundwater level were made at all accessible and reliable sites in early April and late October 1970 (Fig. 7). The intention was to investigate the configuration of the water table at high and low saturation within a typical annual hydrological cycle; the conditions at the times of survey can be related to those of 1970 as a whole (Fig. 8) and to more extreme conditions (Fig. 9). It should be noted that the water table configurations are not steady state but near instantaneous pictures of constantly varying conditions of groundwater potential and flow. Some caution must be exercised in their use to compute massflow quantities.

It was evident that there remained poor coverage of groundwater level data and no information on groundwater level fluctuations in a large area (some 100 km^2) of the Chalk outcrop, north-west of Great Driffield. Accordingly the Institute let a contract for the construction of seven observation boreholes, with permanent recorder housings, in the area (Institute of Geological Sciences, 1971). They were completed early in 1971 and the data generated by them (Fig. 10) went some way to meet this serious deficiency.

DISCHARGE REGIME OF THE CHALK AQUIFER

The groundwater level maps permit close definition of the artesian or overflow area of the Chalk aquifer in the Hull Valley (Fig. 7); this corresponds to the potential area of natural discharge in which the groundwater pressure surface is above existing ground level. In practice only the outer limit of this area is shown in Fig. 7 because locally variable topography is associated with the drift deposits. The termination of the artesian area north of Beverley is, as has already been mentioned, the consequence of long standing heavy groundwater abstraction in the area to the south.

A detailed survey of the distribution of natural discharge from the Chalk aquifer was undertaken simultaneously with the measurement of groundwater levels, by examining all watercourses around the perimeter of the Wolds. Flow measurements were made using floats or a mini-flowmeter; work was carried out as far as possible during extended dry periods so that there was minimal interference from recent rain, groundwater discharge alone being measured. The character of the stream-sections readily accessible and the methods of measurement mean however that the accuracy of the figures quoted (Fig. 7) may be no better than ± 30 per cent. Moreover it was not practical to visit every spring or seepage area nor to measure each chalk watercourse at the limit of the artesian area. Nevertheless, the data collected gives a reasonable idea of the distribution of natural groundwater discharge — a major design factor for river regulation schemes.

It can be seen that the discharge from the Chalk aquifer is not uniformly distributed through the artesian area but localised at a number of

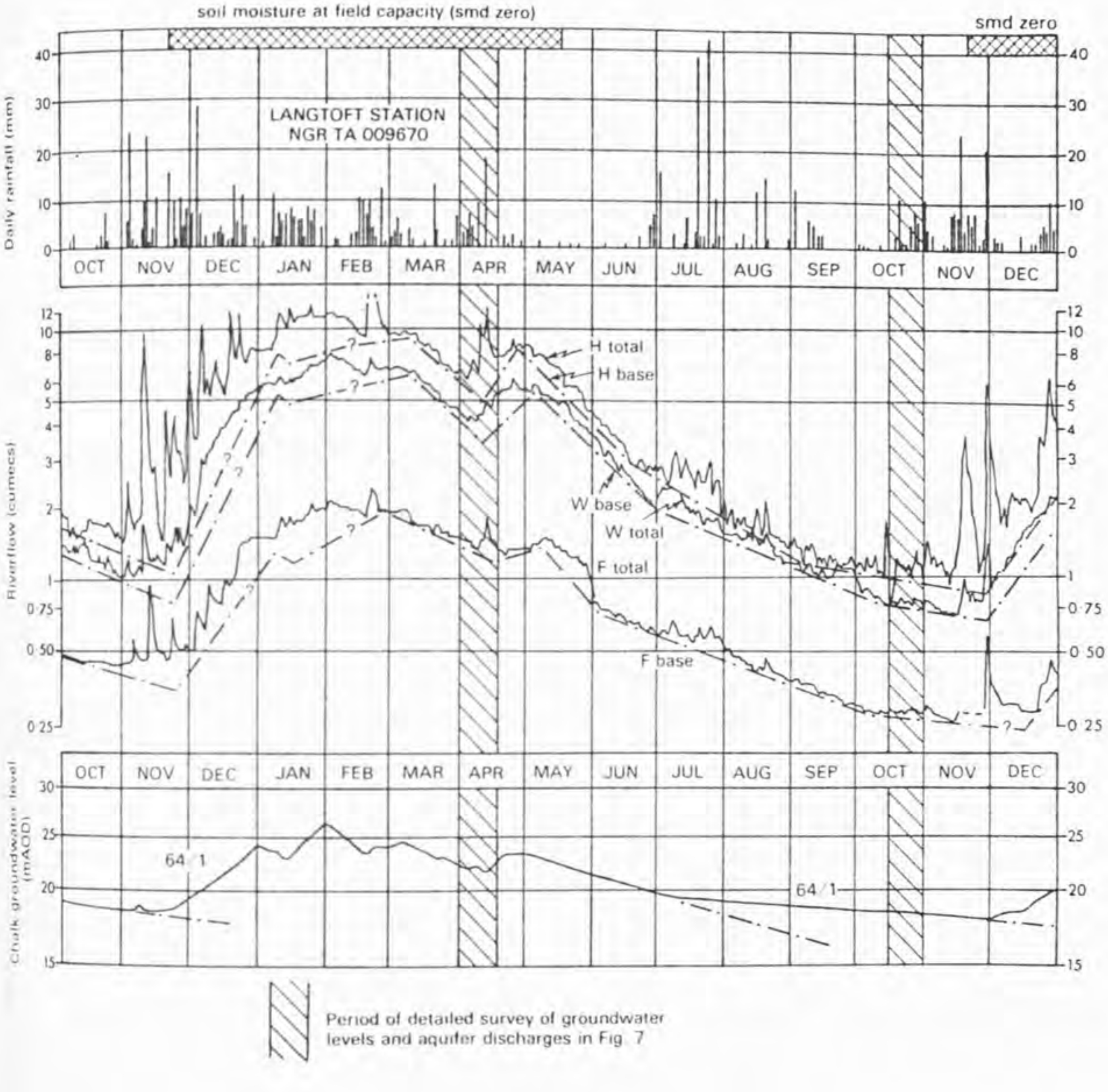


Fig. 8. Riverflow hydrographs and baseflow separation with related hydrogeological data (October 1969 to December 1970)

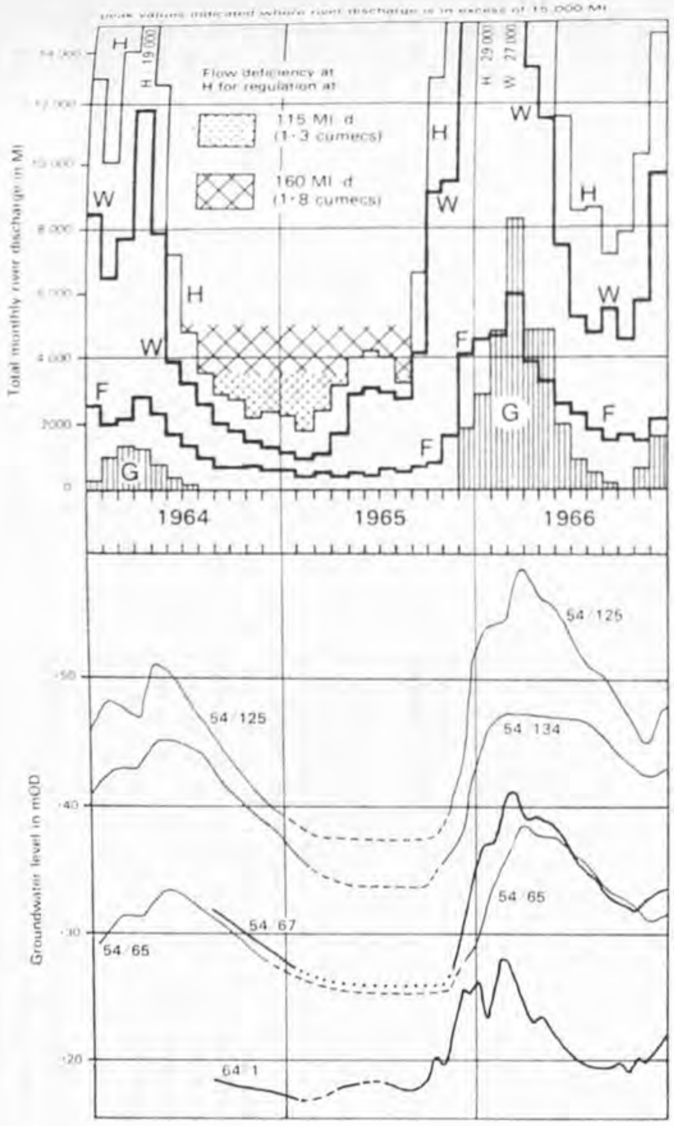


Fig. 9. Riverflow and groundwater level data for conditions of extreme drought (1964-65) and flood (March 1966)

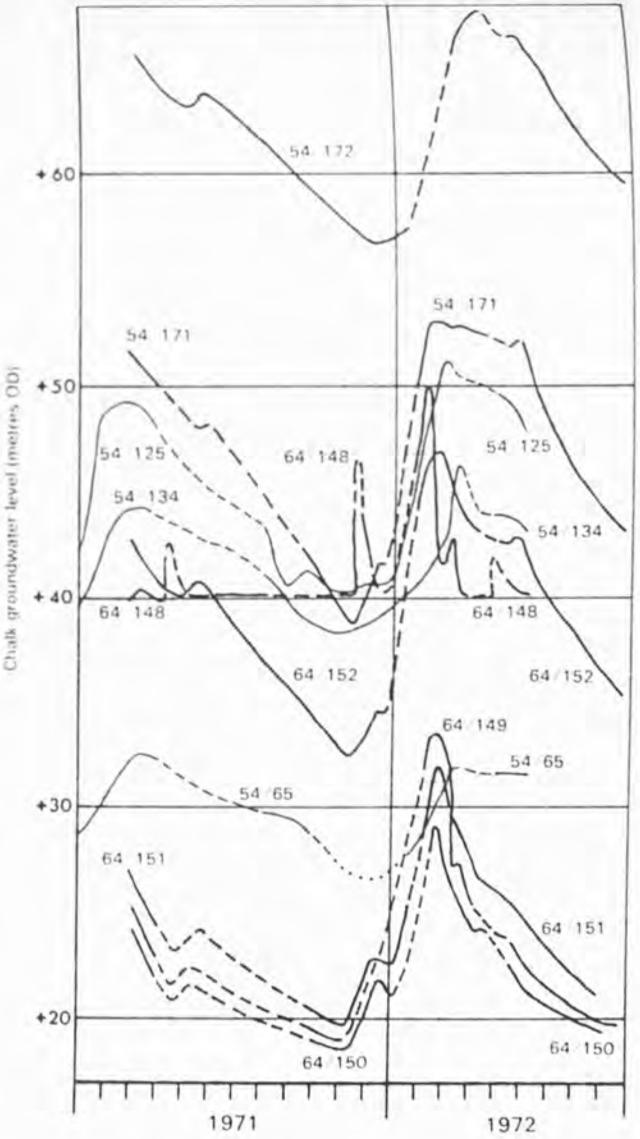


Fig. 10. Chalk groundwater levels in Hull-Hempholme catchment (January 1971 to September 1972)

clearly defined springheads, often associated on the ground with ponds and wooded areas. There are some more dispersed seepage areas, but these no doubt have been reduced in numbers with the spread of land drainage for agricultural purposes. By far the largest springheads are that group to the immediate south of Great Driffield (Fig. 7) forming the source of West Beck, the principal tributary of the River Hull. It is also evident that the bulk of the groundwater discharge or overflow occurs close to the upstream limit of the artesian area, although there are some small artesian springs at distances of up to 5 km under the drift cover (for example, at Blue Keld and Cattlehomes Keld).

It is of some relevance to postulate the origin of the major springs and other discharges and to speculate on the reasons for their localisation. When the present hydrological base level was initially established the groundwater pressure in the confined zone would have probably built up until it became artesian. At that stage discharge would have occurred as soon as there was sufficient artesian head available to overcome the resistance to vertical flow in the most permeable parts of the confining bed. Other things being equal, the first discharge points would be established where the Boulder Clay cover was thinnest and gravel bodies or stringers existed. In areas where the confining bed was of more uniform fine grained material the pressure on the base of the confining bed would further increase until it exceeded the weight of the overlying column of aquiclude. At that point heaving or piping would occur, initiating discharge. Once initiated the springflow process, continuing over long periods of time would probably both increase the solution permeability of the Chalk due to the concentration of flow in these areas and decrease the resistance to vertical flow through the drift by clearance of the discharge passages. Had the density of the confining bed been uniformly greater and its permeability uniformly lower, the Chalk aquifer would have probably filled up to higher groundwater levels and pressures and ultimately formed depression springs on its outcrop, just above the feather edge of the confining bed. In practice this occurs under spring high water table conditions but to very differing degrees in different watercourses (Fig. 7); the increase in groundwater pressure not fully dissipated by increased flow at the perennial springheads initiating new springs and seepages at increasingly higher levels.

The discharge regime of the Chalk aquifer in areas other than the Hull Valley is of secondary significance to this report. A series of contact springs exist all along the escarpment at the junction between the base of the Chalk series and the underlying Jurassic clays. These watercourses were also included in the spring and autumn 1970 surveys. Localisation of springs here is dependant on the superficial disturbances associated with the formation of the escarpment and their effect on the joint pattern of the Chalk. It is further complicated where permeable drift deposits are banked up against the escarpment or where it is underlain by permeable Jurassic strata, since in these areas subsurface outflow from the Chalk groundwater system may occur. The consistent (although low) hydraulic gradient towards the coast in the Flamborough Peninsular suggests that perennial discharge of Chalk groundwater takes place here directly to the North Sea either on the beaches or below low tide level.

Some discharge also probably reaches the North Sea indirectly through the land drainage system of extreme northern Holderness in the area south-west of Bridlington. The strong flows observed on these and other land drains after a long dry period in autumn 1971 suggested that they contained significant quantities of groundwater discharge, probably as the result of the artificial drainage of seepage areas. Chemical analyses of water samples from some land drains showed their chemistry to be almost identical to those of known Chalk waters of the area and while those of several others reflected the presence of agricultural effluent and mixing with other waters, they too could have had a large component of Chalk water, masked by virtue of its low salinity. Unfortunately strontium and fluoride, frequently diagnostic of Chalk waters, are not present at significantly high levels in East Yorkshire and therefore cannot be used for tracer purposes. Those land drains which appeared on the balance of field and hydrogeochemical evidence to have a significant proportion of Chalk baseflow were included in Fig. 7.

One important area of natural discharge of the Chalk aquifer which has not been mentioned so far is the intermittent overflow in parts of the Great Wold Valley, forming the Gypsey Race. The extent of its development varies considerably from season to season (Fig. 7) and from year to year (Fig. 10); the hydrogeology of this watercourse is of considerable significance to the study of the Hull-Hempholme catchment and is therefore dealt with in detail.

HYDROGEOLOGY OF THE GYPSEY RACE

The Gypsey Race has been a subject of considerable local writing, superstition and tradition; 'as the overflowing of the Nile was to the ancients long an enigma, so was the rising

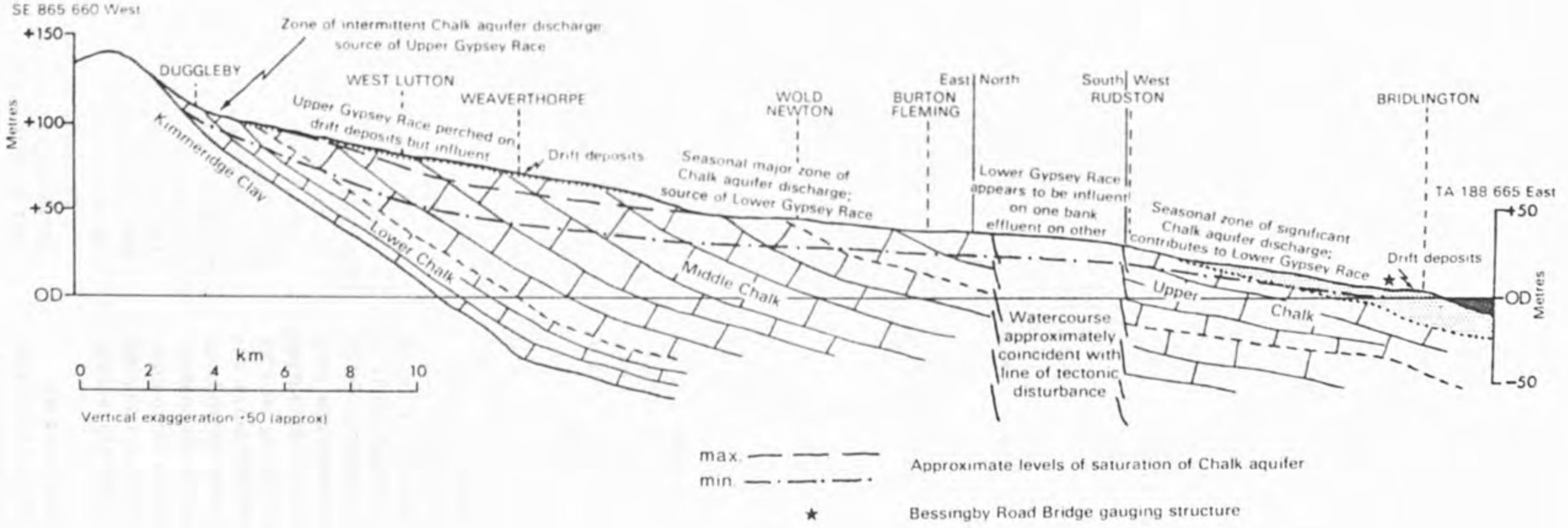


Fig. 11. Schematic hydrogeological profile of the Gypsey Race

of the Gypsies, and may yet be so, even to some of the learned' (Brierley, 1895). As will be seen from its long profile (Fig. 11), it is complex and is not a single watercourse, but two.

The Upper Gypsey Race has its origin in a number of small contact escarpment springs in the vicinity of Wharram-le-Street, which drain the surrounding spurs of the highly incised Chalk escarpment. In this unique case the escarpment springs do not drain towards the Derwent river system but coalesce and flow back onto the Chalk outcrop, as a result of topographical modifications caused by superficial disturbances, such as valley-floor heave.

This upper section of the Gypsey Race, although perched to some degree by the valley floor deposits (flint gravels with interbedded silts), exhibits a consistently influent condition and gradually decreases in flow as a result of leakage to the main Chalk water table (Fig. 11). Under average conditions it has a flow of 0.06 to 0.20 cumecs at Kirby Grindalythe and flows some 10 km or so to Weaverthorpe before finally disappearing as a result of cumulative stream bed leakage. At maximum it may perhaps exceed 0.45 cumecs and flow all the way down the Great Wold Valley to join up with the Lower Gypsey Race. In extreme drought its source springs on the escarpement may dry up. The net hydrological effect of the watercourse is to generate recharge, of perhaps up to 0.1 cumecs (8 Ml/d) maximum, to the Hull-Hempholme catchment and to produce a recharge mound on the Chalk water table (Fig. 7).

The lower main section of the Gypsey Race appears on the other hand to be a conventional water table river (Fig. 11) originating in a number of large depression Chalk springs at various locations on the floor of the Great Wold Valley. It flows to the North Sea at Bridlington Harbour. At highest Chalk water levels, the source springs are located 1 to 2 km west of Wold Newton and further contributory springs occur downstream as far as Burton Fleming. Some of these appear to be localised where quarrying of gravels from the floor of the Great Wold Valley provides a very low resistance discharge path for Chalk groundwater. Further contributory depression springs occur between Rudston and Boynton, although between Burton Fleming and Rudston the river appears to be fairly constant in flow, or locally varying from effluent to influent. In this section its course is diverted from east-west to north-south, the line of the Great Wold Valley apparently being fault controlled.

The available spot flow gaugings on the Lower Gypsey Race have been incorporated in Fig. 9 and, when averaged over long periods, represent a considerable quantity of Chalk groundwater discharge. The gauging site at Bessingby Road Bridge (Fig. 11) also has a large underflow which probably exceeds 0.2 cumecs (17 Ml/d) even in drought.

As groundwater levels recede, the flow at each of the contributory springs decreases and at some stage the upper sets of springs in the vicinity of Wold Newton cease to flow. Flow from those in the Rudston and Boynton area normally persists, although at low rates, for much of the summer but quite commonly in autumn the watercourse dries out completely over the entire length of its lower section. Moreover in certain years when the groundwater levels reach only relatively low maxima, the Gypsey Race may not flow at all in its lowest section or may only flow for a short period from the Rudston-Boynton springs.

During periods of rapidly rising water table complex conditions may exist for short periods in the lower section of the Gypsey Race; for example, it may flow from Wold Newton but disappear between Rudston and Burton Fleming as a result of increase in groundwater levels in one part of the Wolds before another.

As a result of its intermittent character and occasional very large flows (in 1966 exceeding 3.5 cumecs), the Gypsey Race has been extensively canalised.

DELINEATION OF THE HULL-HEMPHOLME CATCHMENT

It is now possible to consider further the delineation of the groundwater catchments to the Hull at Hempholme Lock and to the tributary gauging stations at Wansford Bridge and Foston Mill. Many groundwater catchments undergo major variations in shape and area seasonally or from year to year, in contrast to surface water catchments which are essentially of fixed area and boundaries. Moreover in the case of permeable catchments a considerable body of data on groundwater levels and their fluctuation are required before an accurate delineation of catchment area can be attempted. It is clearly inadequate to assume that the groundwater catchment coincides with the configuration of the ground surface in the outcrop areas of permeable formations.

In practice the precise delineation of the catchment of the Hull at Hempholme Lock is complex both for the above reasons and others. It involves a number of distinct steps (Fig. 12 and Table 3). The boundaries of the lowland surface-water catchment can be drawn directly, given knowledge of land drainage practices

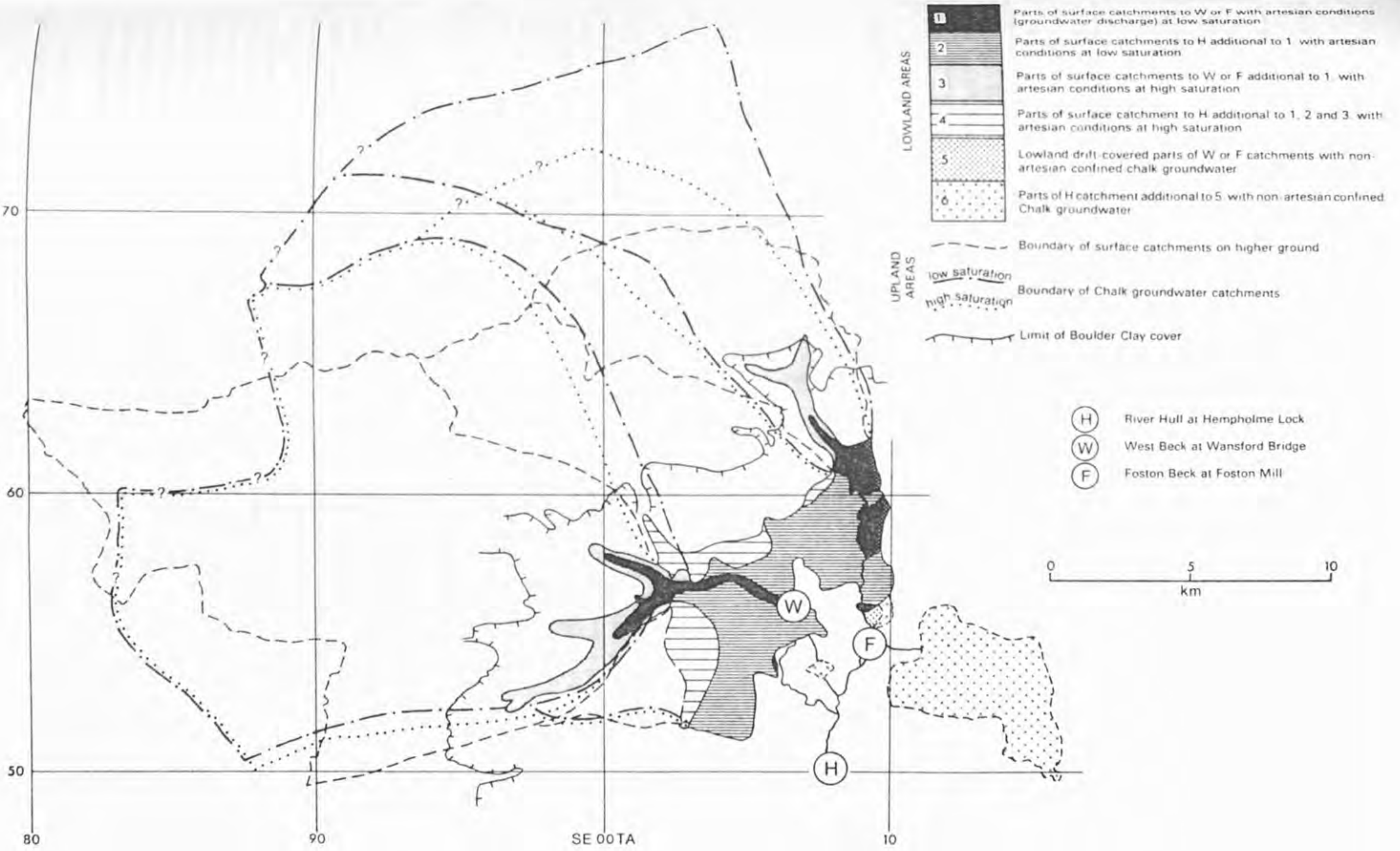


Fig. 12. Delineation of catchments to the permanent gauging stations on the Hull River System

Table 3. Analysis of catchment areas to permanent gauging stations on the Hull River system (in km^2).

Gauging Station	Lowland surface catchment			Upland subsurface catchment				Total catchment area		
	with artesian conditions at		with non-artesian confined conditions	outcrop Chalk + upland Boulder Clay		outcrop Chalk alone		probable combination of surface / sub-surface		based on surface contours for comparison
	low saturation	high saturation		low saturation	high saturation	low saturation	high saturation	max.	min.	
(W) West Beck at Wansford Bridge	3	10	0	239	225	204	197	242	236	192
(F) Foston Beck at Foston Mill	4	7	<1	104	52	93	44	109	60	58
(H) River Hull at Hempholme Lock	35	52	22	434	352	355	288	491	426	378
	areas of surface drainage			areas of largely subsurface drainage		areas of entirely subsurface drainage				

since these have drastically altered the original position. Most of the area is formed of relatively impermeable drift deposits which will generate surface run-off and interflow; only small permeable bodies exist within the drift and none are sufficiently extensive to modify the catchment shape. The West Beck and Foston Beck catchments have extremely small lowland surface drainage components (Fig. 12 and Table 3).

Part of the lowland surface drainage areas lies within the artesian zone of the Chalk aquifer. The next step is therefore to define the sub-surface catchment of the springheads located within this area. This has been attempted by drawing limiting groundwater flowlines from the groundwater contours. Inaccuracies must result because the network of observation boreholes (Fig. 7) was not sufficiently dense to define the detailed distribution of head around the major springs, where an element of radial groundwater flow must be present. The catchment boundaries are summarised in Fig. 12 and major seasonal changes are evident.

The catchment boundary and water divide between the Hull and Derwent river systems is reasonably well established and occupies a relatively constant position, principally as a result of the overall geological structure; over some distance it is formed by a definite geological barrier in the core of the Fordon anticline (Fig. 3A). Some uncertainty however surrounds its position in the extreme north-west because of the complexity of the structure in that area (Fig. 3C) and the underlying permeable Jurassic strata.

The lateral boundary of the Hull-Hempholme catchment to the south is formed by a flowline separating groundwater draining to the tidal and non-tidal Hull; it would appear that this can be drawn with tolerable accuracy (Fig. 7). The north-eastern boundary is much more complex and related to the development of the Gypsey Race. It appears that the Hull-Hempholme and Foston Beck catchments are considerably more extensive after the Chalk aquifer ceases to discharge at the source springs of the Gypsey Race near Wold Newton (Fig. 12 and Table 3). This is not to say that a great deal more water flows south as a result. During the period immediately following the cessation of flow of the Gypsey Race from Wold Newton, the entire area is one of very flat hydraulic gradients as a result of the preceding drainage effect and it takes considerable time for the new base level to become effective.

With the exception of the previously mentioned recharge from the Upper Gypsey Race, there is not thought to be any significant quantity of natural or artificial water transfer across the catchment boundaries; although the lateral boundaries could be influenced by the development of groundwater supplies in their vicinity. Moreover the amount of groundwater abstraction is at present low (7 Ml/d) and there is very little export or consumptive use, or other interference with the natural groundwater cycle. Even in the vicinity of Great Driffield most groundwater abstraction generates an effluent to the Driffield Canal of comparable volume and thus contributes to the flow of the Hull at Hempholme Lock. Such internal catchment usage of groundwater does not have any significant effect on the water resources situation provided that the effluent generated is of tolerable quality and experiences adequate dilution. There is also a minor degree of artificial control on the rate of flow of Nafferton Beck and possibly also of Foston Beck.

It is of importance in the hydrology of the Hull catchment to look more closely into bypass flows and underflows at the main gauging stations. The Beverley-Barmston Drain runs parallel to and along the west bank of the river Hull at Hempholme Lock; its flow is derived from an extensive system of land drains mainly on the east bank in northern Holderness but it also includes some land drains that are suspected of having a Chalk baseflow and it could also act as a drain for the levees of the River Hull itself over considerable distances. There are no reliable data on the flow of the Beverley-Barmston Drain but information on pumpage at Wilfholme Lock suggests that even the relatively low flows could be 0.3 cumecs (25 Ml/d). A significant bypass of the Wansford Bridge gauging structure also appears to exist (Table 4).

Almost all riverflow gauging stations will have a groundwater underflow, commonly with two components; a shallow underflow through the superficial deposits related to the river itself and a deep underflow through a regional aquifer where a major permeable formation is present at depth. The latter is normally the more significant in terms of water balance computations. The magnitude of the deep underflows has been estimated from Darcy's Law, since the hydraulic gradients, cross-sectional areas of groundwater flow and aquifer properties are known or can be assessed with tolerable accuracy (Table 4). In all cases the gauging stations are located 'downstream' of the main discharge area of the Chalk aquifer and the T values, hydraulic gradients and, therefore, underflows are all low. The cross-section of the alluvial channels of the Hull and its tributaries are shallow and narrow and their throughflows are probably negligible.

CHALK AQUIFER ANALYSIS THROUGH RIVERFLOW AND GROUNDWATER LEVEL DATA

The analysis of riverflow and groundwater level data can yield valuable information on the gross behaviour and properties of a permeable catchment. The groundwater catchment of

Table 4. Bypass flows and Chalk groundwater underflows at permanent river gauging stations.

Gauging station	Bypass flows			Chalk groundwater underflow			
	bypass route	bypass flow (Ml/d)	conditions	T value (m^2/d)	Width of flow path (km)	Underflow (Ml/d)	conditions
H	Beverley-Barmston Drain (in part)	up to 25	low flow	150	12	2	Apr. 1970, high flow
						1	Oct. 1970, low flow
W	major relief drain on southern side	5	Oct. 1970, low flow	600	5	5	Apr. 1970, high flow
						3	Oct. 1970, low flow
F	flow diversion to relief drains	?	-	300	3	1	Apr. 1970, high flow
						<1	Oct. 1970, low flow

West Beck at the Wansford Bridge gauge (Fig. 12) is the most homogeneous geologically, has the most constant shape and area and is therefore the most suitable for such analysis.

Horton (1933) and Barnes (1939) found that the components forming a discharge hydrograph, including those derived from a groundwater system, frequently each had a recession that could be approximated by simple exponential relationships of the form, $Q_t = Q_0 e^{-kt} = Q_0 K^t$ where Q_0 and Q_t are the discharge at the beginning of the measurement period and after time t respectively and k and K are known as recession constants. When $\log_{10} Q$ was plotted against t, a straight line relationship resulted in which for one log cycle of Q

$$k = \frac{1}{t \log_{10} e} = \frac{1}{0.43t}$$

In the case of the groundwater component, the total amount of groundwater storage above hydrological outlet or base level (S_t) corresponding to a river baseflow (Q_t) will equal the total potential drainage $S_t = \int_t^{\infty} Q_t dt = \frac{Q_0 e^{-kt}}{k}$

from which, $S_t = Q_t/k$.

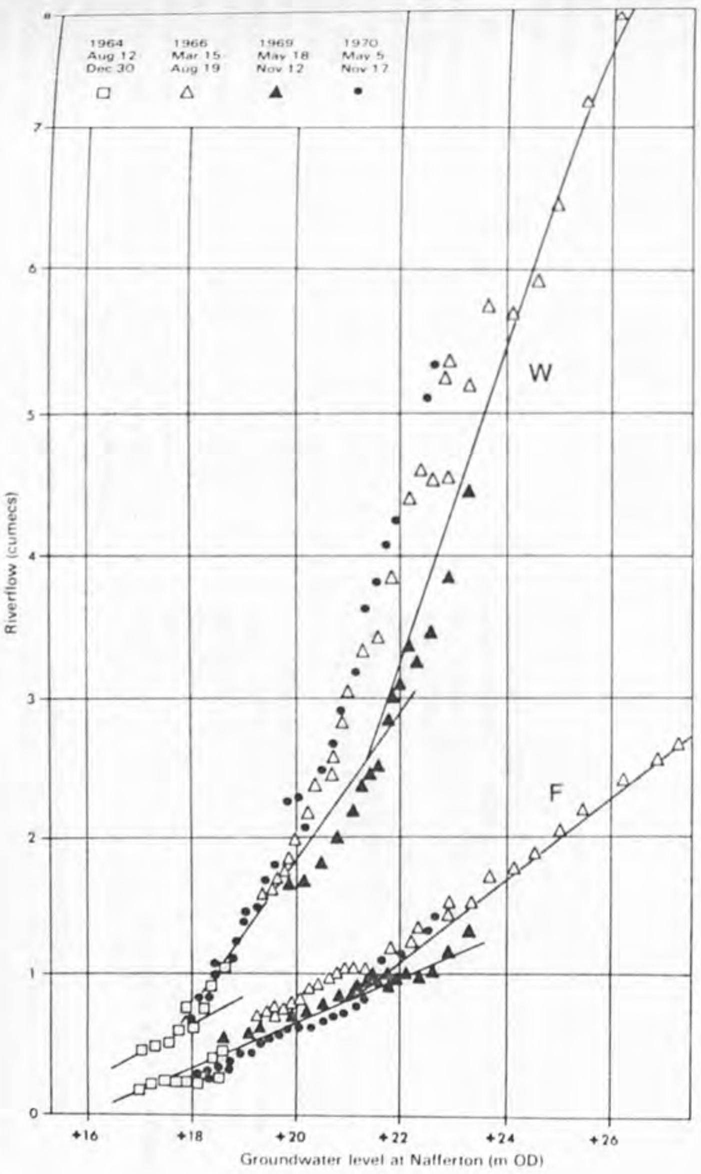
Such a groundwater system can thus be termed a 'linear reservoir' because its rate of natural discharge is directly proportional to its storage and storage levels; it is implicit in the Horton (1933) equation. The relationship appears to hold providing hydrogeological conditions are relatively simple with one extensive, fairly uniform aquifer, negligible direct evapotranspiration of groundwater in riparian areas, absence of major groundwater development, river regulation and significant effluent discharges.

It can be seen (Fig. 8) that no single log-linear relation describes the recession at any one of the three permanent gauging stations on the Hull river system. It is evident however that their recessions can be split into a number of log-linear segments and the analysis of data for those other years in which the recession was not interrupted by repeated large recharge incidents corroborated this point. For each gauge three segments appeared to be present, occurring repeatedly in reasonably closely defined flow ranges (Table 5). In the case of the Hull-Hempholme Lock catchment further steeper log-linear recession elements of higher k, are also present reflecting surface run-off and interflow contributions from the lowland surface catchment (Fig. 8).

The recession of groundwater levels at Nafferton (64/1 in Fig. 8) has a similar form. Moreover when the riverflow data from the two tributary gauging stations for selected years is plotted against Chalk groundwater storage level at Nafferton (Fig. 13), the relationship is certainly not one of a linear storage reservoir type. This is particularly apparent if special attention is paid to the data collected during the extreme drought in 1964-1965. No part of the departure from linearity can be attributed to differences in spring and autumn groundwater evapotranspiration from riparian areas because of their very restricted extent, nor to artifical interferences which are negligible. It appears however that the data could be split into a number of linear segments (Fig. 13); representation of a complex groundwater catchment by a series of linear storage elements being preferred from most standpoints, if at all practical.

The analysis can be extended to compute average values of specific yield (S_y) for each linear storage element in the composite recession (Fig. 13). The computation of the total volume of baseflow during defined periods is a relatively accurate process but errors arise in the estimation of the corresponding changes in groundwater level and to a lesser extent in the estimation of the aquifer catchment area undergoing drainage. Values of 0.010, 0.015 and 0.005 to 0.010 appear to be indicated for the three segments of the recession (Table 6). Furthermore if the existence of a single linear element of aquifer storage between extreme drought groundwater level and hydrological base level is assumed, it is possible to make an estimate of its average specific yield (S_y). A value significantly lower than 0.005, perhaps nearer 0.002, is obtained (Table 6). These results and the overall analysis have been confirmed by the analysis of post-1971 data from the extended observation borehole network in the West Beck catchment (Foster, 1974).

The analysis of riverflow and groundwater level recessions thus appears to corroborate that of the pumping test data in indicating significant layering in the Chalk aquifer's hydraulic properties. It is noteworthy however, that even at extreme drought the total groundwater storage in the West Beck and Hull-Hempholme catchments above hydrological base level alone, is estimated to be over 8000 Ml and 15 000 Ml respectively. It is not unreasonable to expect at least two to three times these volumes to be in storage below base level, given that significant groundwater circulation has been demonstrated below OD at the two sites where geophysical borehole flow investigations have been made.



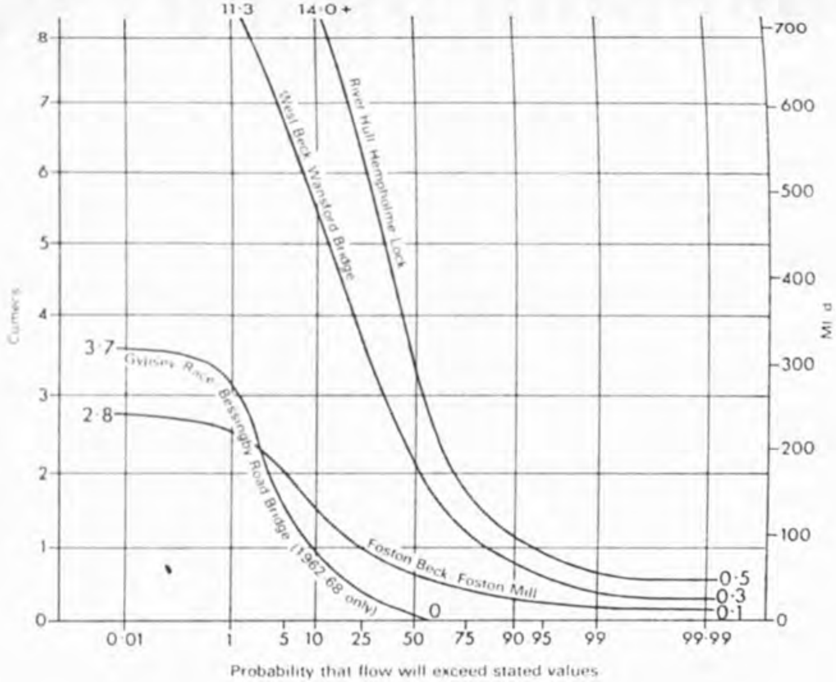


Fig. 14. Flow duration curves during water years 1962-70 for principal East Yorkshire watercourses

Table 5. Summary of riverflow recession characteristics

Measuring station	River Hull at Hempholme Lock		West Beck at Wansford Bridge				Foston Beck at Foston Mill			
Date of data	1964/5	1970	1960	1964/5	1966	1970	1960	1964/5	1966	1970
Recession constant (k) days^{-1}	0.029	0.023	-	0.022	0.018	0.020	-	-	0.018	-
Approximate riverflow in cumecs at inflexion point	3.7	2.8	-	1.8	2.4	1.8	-	-	? 1.0 ?	-
Recession constant (k) days^{-1}	0.015	0.011	0.013	0.009	0.010	0.008	0.009	0.010	0.007	0.009
Approximate riverflow in cumecs at inflexion point	1.3	1.1	0.8	0.6	-	0.7	0.4	0.3	-	0.3
Recession constant (k) days^{-1}	0.004	0.004	0.004	0.004	-	0.004	0.003	0.002	-	0.003

EVALUATION OF RECHARGE TO GROUNDWATER RESERVOIR

The analysis of long sequence riverflow data can be developed to evaluate the recharge to the groundwater reservoir and be used as the starting point in the establishment of an overall water balance for the groundwater phase of the hydrological cycle. As has been mentioned earlier, this is not of primary importance to the schemes for river augmentation from groundwater storage at the rates initially envisaged but pertains to the question of ultimate yield of the Chalk aquifer.

The mean daily discharge data for the three permanent gauging stations on the Hull river system can be analysed to separate the Chalk groundwater component (baseflow) in the total riverflow. In any river or stream sometime after rain ceases, the flow will be sustained by groundwater discharge. Under such conditions the magnitude of the groundwater component is directly measurable, although in certain cases it may originate from more than one groundwater body. The amount of baseflow under flood hydrographs however, has been and remains the subject of much discussion (Barnes, 1939; Ineson and Downing, 1964; Kulandaiswamy and Seetharaman, 1969) and is the main source of error in the determination of the total groundwater discharge. In theory relationships of the types previously described (Horton, 1933; Barnes, 1939) furnish a method of extrapolating back from a known period of baseflow recession to separate the groundwater component in the flood condition. A complication occurs if appreciable surface run-off is present, since the river stage will rise faster than the groundwater-stage, generating bank storage and tending to throttle groundwater discharge; subsequently when the river stage falls the groundwater component will be greater than predicted using the recession curve. All of these factors were considered in the baseflow separations shown in Fig. 8, and the most arbitrary decision that had to be made was found to be the joining of each annual recession to that previous, beneath the rising limb of the hydrograph. This process was refined by detailed study of associated groundwater level data (Fig. 8), but it is still possible that errors could rise to 15 per cent, although are likely to be less than half this figure.

By similar process the Chalk baseflow has been separated from total riverflow at main gauging stations for each water-year in the period 1962/70 (Table 7). It is interesting to note that in every case the baseflow exceeds 80 per cent of the total riverflow and in some cases approaches 90 per cent.

If the catchment area from which the groundwater discharge was derived can be adequately defined and gauge underflows and bypass flows together with artifical interferences

Table 6. Estimation of Chalk aquifer specific yield from river baseflow and groundwater level recessions.

River gauging station	Period of recession analysed			River baseflow (cumecs)		Total baseflow volume (Mm^3)	Groundwater level at Nafferton PS			Estimated mean gwl change in catchment (m)	Area of aquifer in catchment (km^2)	Sy (catchment average specific yield)	K (riverflow recession constant)	
	year	from A	to B	A	B		A (m OD)	B (m OD)	A-B (m)					
W	1966	May 3	Jun 18	4.53	2.55	12.24	23.8	20.7	3.1	5.1	225	0.011	0.015	HIGH WATER TABLE
W	1970	May 8	Jun 12	4.53	2.55	9.54	23.2	20.7	2.5	4.2	225	0.010	0.020	
W	1966	Jul 8	Aug 10	1.98	1.42	4.78	20.1	19.2	0.9	1.5	225	0.014	0.010	INTER-MEDIATE WATER TABLE
W	1970	Jul 4	Oct 3	1.84	0.85	9.06	19.8	18.3	1.5	2.5	225	0.016	0.008	
W	1964-5	Nov 6	Jan 10	0.54	0.43	2.57	17.8	17.1	0.7	1.2	239	0.009	0.004	LOW WATER TABLE
W	1970	Oct 25	Nov 5	0.71	0.65	0.64	18.0	17.7	0.3	0.5	239	0.005	0.004	
F	1964-5	Oct 1	Jan 22	0.28	0.17	2.08	18.1	17.1	1.0	2.1	104	0.009	0.002	
F	1970	Sep 25	Nov 15	0.28	0.23	1.08	18.1	17.4	0.7	1.5	104	0.007	0.003	
W	from drought conditions to hydrological base level			0.40		8.6	17.1	14.6	5000	mainly in higher remote parts of catchment		0.002	0.004	EXTREME DROUGHT CONDITIONS
F				0.17		4.9		15.4	2300			0.002	0.003	
				River baseflow at drought (cumecs)		Calculated groundwater storage above base level (Mm^3)	Drought GWL at Nafferton (m OD)	Hydrological base level (m OD)	Estimated volume of saturated Chalk above base level (Mm^3)					

taken into account, then the annual baseflow component can be expressed as an equivalent effective infiltration or more accurately as the annual rate of recharge at the water table (Ineson and Downing, 1965). The former factors have already been assessed (Tables 3 and 4). For gauge W the error in the estimation of groundwater catchment area could perhaps amount to 10 per cent. It could have significant bypass flows which would result in underestimates of effective infiltration, although all other factors are of little consequence, except possible gauging errors. In the case of gauges F and H, the catchment areas are so variable as to invalidate any such analysis.

In Table 7 the computation of equivalent infiltration is presented for the water-years 1962/70 assuming 100 per cent infiltration of excess rainfall through the upland Boulder Clay. If no infiltration is assumed in such areas, the mean infiltration equivalent is increased from 350 mm (13.7 in) to 390 mm (15.3) in) and the values for individual years in corresponding proportion.

It is of interest to compare these values with those for effective infiltration into the unsaturated zone derived from the meteorological parameters, precipitation (P) and evaporation (E). It has already been mentioned that the process of infiltration and recharge to the aquifer's saturated zone may be complex since the available tritium age determinations pose fundamental questions on the mechanism and rates of groundwater movement in the unsaturated zone. It is thus possible that changes in storage in the unsaturated zone could invalidate comparison between the two former parameters but they do appear to be closely related.

The direct measurement of evaporation is a problem because of the cost and practical difficulties associated with lysimetry and no data exist for the East Yorkshire Chalk. Numerous indirect methods of estimating evaporation exist, through the measurement of associated meteorological parameters and the application of empirical formulae (for example Thornthwaite, 1948; Penman, 1948). Such methods estimate the maximum evaporation that would take place in the given climate from a continuous cover of vegetation with constantly saturated soil, termed the potential evaporation (E_{pot}). In the Hull-Hempholme catchment there are no stations where sufficient numbers of meteorological parameters are measured to compute E_{pot} but average values for the northern part of East Yorkshire are estimated on a monthly basis by the Meteorological Office. The estimation involves both correlation on the basis of sunshine records and empirical correction to average altitude (Ministry of Agriculture, Fisheries and Food, 1967). The data together with the average monthly precipitation, at three representative rainfall stations, are presented for the period October 1962 to September 1970 (Table 8).

Actual, as opposed to potential, evaporation (E_{act}) is limited by availability of soil moisture and is in turn a function of type of vegetation and soil conditions. When soil moisture deficit (SMD) falls to a certain level, given types of plant are unable to draw water to their roots to transpire and thus in extended dry periods E_{act} may be considerably less than E_{pot}. In a study of part of East Anglia, Penman (1950) recognised three general zones defined on a basis of their vegetation, soil and groundwater characteristics. Each zone was attributed a 'root constant' (75 mm, 200 mm and infinity for the short rooted, long rooted and riparian zones respectively), representing the depth of water that would be stored in the root zone at field capacity.

By calculating the excess of E_{pot} over P on a monthly basis and then taking into account SMD through such a system of land zones with fixed root constants Grindley (1967) described a method, adopted by the Meteorological Office, for refining estimates of evaporation. Headworth (1970), working on water-balance computations and the detailed timing of recharge increments to the water table of the Hampshire Chalk, showed that the 75 mm root constant for the Penman short rooted agricultural zone gave too large values for SMD and E_{act}. He suggested that for this zone in Hampshire, a 25 to 50 mm root constant would be more appropriate and discussed the available evidence for and against this value being generally applicable in south-eastern England.

Over 90 per cent of the Chalk outcrop of the Hull-Hempholme catchment would be ascribed to the short rooted agricultural zone. For the purpose of this report it was thought adequate to use a simplified E_{act}/SMD relationship, in which E_{act} equals E_{pot} up to a limiting SMD of 75 mm, bearing in mind the restricted nature of the E_{pot} data and the fact that evaluation of E_{act} is not of major importance at present. The relationship used is approximately equivalent to a root constant in the range 25 to 50 mm. On that basis the monthly computation of actual evaporation and effective infiltration was undertaken (Table 8). It is worth noting that in every case the soil moisture returns to field capacity in the month of or the month before the main rising limb of the groundwater level and riverflow hydrographs. There are however occasional minor recharge incidents visible on the records from autographic recorders in the months of

Table 7. Summary of riverflow data and baseflow separation for principal gauging stations on Hull River system (1962-1970) with derivation of equivalent infiltration.

Water year (Oct-Sept)	H River Hull at Hempholme Lock (Mm^3/a)		$\frac{H_{base}}{H_{total}}$	W West Beck at Wansford Bridge (Mm^3/a)		$\frac{W_{base}}{W_{total}}$	F Foston Beck at Foston Mill (Mm^3/a)		$\frac{F_{base}}{F_{total}}$	$\frac{H_{base}}{W_{base}}$	$\frac{H_{base}}{F_{base}}$	$\frac{W_{base}}{F_{base}}$	Infiltration equivalent to W_{base} (in)
	total flow	base flow		total flow	base flow		total flow	base flow					
1962-63	80.1	-	-	52.6	44.0	0.84	14.7	12.2	0.83	-	-	3.6	7.8
1963-64	118.8	-	-	74.4	61.2	0.82	20.6	17.1	0.83	-	-	3.6	10.8
1964-65	39.4	-	-	26.0	22.0	0.85	6.1	5.5	0.90	-	-	4.0	3.9
1965-66	231.9	-	-	162.6	134.7	0.83	37.2	30.6	0.82	-	-	4.4	23.8
1966-67	149.4	122.4	0.82	92.6	78.4	0.85	24.2	20.8	0.86	1.6	5.9	3.8	13.8
1967-68	118.0	97.9	0.83	73.9	63.7	0.86	19.1	16.5	0.87	1.5	5.9	3.9	11.3
1968-69	212.0	181.2	0.85	140.8	122.4	0.87	39.2	34.3	0.88	1.5	5.3	3.6	21.7
1969-70	172.6	139.6	0.81	115.1	95.5	0.83	31.1	25.7	0.83	1.5	5.4	3.7	16.8
8-year mean	140.3	-	-	92.3	77.6	0.84	24.0	20.3	0.85	-	-	3.8	13.7

June and July and at other times, when a significant SMD almost certainly existed.

These computations of the inflow or infiltration to the groundwater system do not bear direct comparison with those derived from baseflow separation for the outflow, because of changes in the total water in storage at the beginning of each water year. Even assuming that unsaturated zone storage does not vary significantly, a factor on which there is absolutely no data, there can be significant variation in groundwater levels and saturated zone storage and in soil moisture storage, the area of surface water and therefore changes in its storage being negligible.

In practice there are not sufficient data on changes in soil moisture and groundwater levels to attempt a full statement of the water balance including changes of storage. By careful choice of period, however, factors for which there is little data can be eliminated or reduced to minor order. In this connection, minor differences in groundwater levels would not appear to be as significant as those of soil moisture; assuming a specific yield for the Chalk aquifer of 0.01 a 10 m change in groundwater level over the entire catchment represents less water than does a 25 mm change in soil moisture. When comparing the results in Tables 7 and 8 this should be taken into account. It is evident however that the effective infiltration values derived from baseflow separation generally exceed those from meteorological parameters. If no infiltration through the upland Boulder Clay is assumed the differences are quite large. Although the former could have been systematically overestimated, an appraisal of possible sources of error discussed above suggests that probably the reverse is the case, unless important gauging errors are present. The figures derived from meteorological parameters could be in error because of inaccurate potential evaporation data or inappropriate root constant, systematic underestimate or unreliable averages for monthly precipitation. In the case of the former the average altitude used for the Meteorological Office estimates is about 60 m less than that of the Chalk intake area of the Hull-Hempholme catchment and in that of the latter it was noticed that there existed a variation of more than 75 mm between the three individual stations in certain instances in winter and spring.

Previous workers have made approximate estimates of the long term average annual infiltration to the Chalk of the Yorkshire Wolds as follows: Versey (1948) 200 to 330 mm, Green (1950) 305 mm and Gray (1952) 305 mm.

The amount of infiltration or recharge to the Chalk in areas of Boulder Clay cover will depend greatly on the latter's lithology and thickness, as well as on the vertical hydraulic gradients. It is likely to be substantial even under natural conditions on the flanks of the Wolds and could also occur in parts of the Hull Valley outside the artesian area. Gray (1952) allowed an arbitrary 50 mm/a for all areas with less than 9 m of Boulder Clay cover and from studies of East Anglian catchments, Ineson and Downing (1965) derived values varying from 40 to 125 mm.

STATISTICAL ANALYSIS OF RIVERFLOW DATA

Study of the statistics of past flow data for the River Hull and its tributaries is necessary to define the period of and the amount of storage required for flow augmentation and to examine the operating problems.

Flow duration curves are presented for the period 1962 to 1970 (Fig. 14), when all three gauging stations were in continuous operation. It is necessary to consider how representative this flow period is of longer term conditions.

One of the gauges, that on West Beck at Wansford Bridge, has in fact been in operation since 1953 and the flow duration curve for the period 1953 to 1968 (Yorkshire Ouse and Hull River Authority, 1969) has been plotted for comparative purposes (Fig. 15); it appears that the latter period had no more extreme drought than the former but overall had somewhat lower riverflows. In the northern Yorkshire Wolds the average rainfall during 1962/70 was 745 mm/a, almost equal to the 1916/50 average. For the purposes of water resources development it is important to know the maximum departures from the long period flow duration curves and the probability of occurrences of low flows. The flow duration curves for West Beck at Wansford Bridge for the water years 1963/64, 1964/65 and 1966/67 are therefore also presented (Fig. 15). With the moderately short flow record available it is not possible to make flow predictions with a high level of confidence, but the Yorkshire Ouse and Hull River Authority (1969) have generated flow duration curves for the probable one in ten year and one in fifty year drought conditions (Fig. 15).

The correlation of flows in the Hull at Hempholme Lock (H) with those simultaneously recorded at the tributary gauging stations (W and F) is also required in the design of certain types of development scheme and is of general hydrological interest. Simple and partial linear regression analyses were implemented in the

Table 8. Estimation of monthly infiltration from meteorological parameters (1962-70).

Water year	Meteorological parameter		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Annual total
1962-1963	P	in	0.43	2.61	2.00	1.47	1.76	2.79	2.22	1.53	3.55	1.65	4.79	1.63	26.4
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.60	3.05	3.30	3.50	2.50	1.75	18.5
	SMD	in	0.87	0	0	0	0	0	0	1.52	1.27	3	0.71	0.83	-
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.60	3.05	3.30	3.38	2.50	1.75	18.3
	I_{eff}	in	0	1.53	1.89	1.29	1.32	1.76	0.62	0	0	0	0	0	8.4
1963-1964	P	in	1.79	4.54	1.50	1.20	0.91	3.62	1.40	0.85	2.49	1.32	1.59	0.81	22.0
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.80	3.35	3.10	3.65	2.85	1.65	19.2
	SMD	in	0	0	0	0	0	0	0.40	2.90	3	3	3	3	-
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.80	3.35	2.59	1.32	1.59	0.81	14.2
	I_{eff}	in	0.16	4.33	1.39	1.02	0.47	2.59	0	0	0	0	0	0	10.0
1964-1965	P	in	1.25	0.95	2.17	2.74	1.19	1.93	2.55	1.72	1.93	3.51	2.29	5.59	28.3
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.90	2.75	3.30	2.60	2.90	1.20	17.4
	SMD	in	2.55	1.81	0	0	0	0	0	1.03	2.40	1.49	1.60	0	-
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.90	3.05	3.30	2.60	2.90	1.20	17.4
	I_{eff}	in	0	0	0.25	2.56	0.75	0.90	0.65	0	0	0	0	2.79	7.9
1965-1966	P	in	0.92	5.25	4.54	1.76	5.77	0.93	3.39	2.40	2.85	3.03	4.49	1.14	36.5
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.50	3.05	2.90	3.50	2.65	1.35	17.7
	SMD	in	0	0	0	0	0	0.10	0	0.65	0.70	1.17	0	0.21	-
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.50	1.50	2.90	3.50	2.65	1.35	17.7
	I_{eff}	in	0.12	5.04	4.43	1.58	5.33	0	1.79	0	0	0	0.67	0	19.0
1966-1967	P	in	2.53	3.18	2.39	1.89	2.56	1.43	1.38	5.66	0.46	1.20	3.21	2.80	28.7
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.85	2.65	3.70	3.70	2.70	1.65	19.0
	SMD	in	0	0	0	0	0	0	0.47	0	3	3	2.49	1.34	-
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	1.85	2.65	3.46	1.20	2.70	1.65	16.3
	I_{eff}	in	1.52	2.97	2.28	1.71	2.12	0.40	0	2.54	0	0	0	0	13.5
-1968	P	in	3.68	2.80	2.05	1.71	1.87	2.07	1.90	2.32	2.19	3.30	1.65	4.49	30.0
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	2.35	2.80	3.70	3.10	2.10	1.85	18.7

1967-	SMD	in	0	0	0	0	0	0	0.45	0.93	2.44	2.24	2.69	0.05	-			
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	2.35	2.80	3.70	3.10	2.10	1.85	18.7			
	I_{eff}	in	1.54	2.59	1.94	1.53	1.43	1.04	0	0	0	0	0	0	10.1			
1968-1969	P	in	2.76	2.89	3.42	3.61	2.98	2.82	3.16	2.79	3.01	2.34†	0.79†	2.56†	33.1			
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	2.20	2.75	3.50	4.05	2.65	1.75	19.7			
	SMD	in	0	0	0	0	0	0	0	0	0.49	2.20	3	2.19	-			
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	2.20	2.75	3.50	4.05	1.59	1.75	18.6			
	I_{eff}	in	1.91	2.68	3.31	3.43	2.54	1.79	0.96	0.04	0	0	0	0	16.7	8-year mean		
1969-1970	P	in	0.75†	5.20†	3.71†	3.78†	2.66†	2.31†	2.87†	0.31†	0.86†	4.21†	1.59†	1.27†	29.5	29.3	P	in
	E_{pot}	in	0.80	0.21	0.11	0.18	0.44	1.03	2.05	2.95	4.10	3.40	2.80	1.85	19.9	18.8	E_{pot}	in
	SMD	in	2.24	0	0	0	0	0	0	2.64	3	2.19	3	3	-			
	E_{act}	in	0.80	0.21	0.11	0.18	0.44	1.03	2.05	2.95	1.22	3.40	2.40	1.27	16.1	17.1	E_{act}	in
	I_{eff}	in	0	2.75	3.60	3.60	2.22	1.28	0.82	0	0	0	0	0	14.3	12.5	I_{eff}	in

P Mean of monthly precipitation for Birdsall (SE 819650 + 94 m OD) Wetwang (SE 933589 + 67 m OD) and Langtoft (TA 009670 + 79 m OD)
† No data available in these months for Wetwang.
E_{pot} Average potential evaporation estimated by Met. Office for northern part of East Yorkshire (at + 46 m OD).
SMD Soil moisture deficit, limited to a maximum of 3 in (75 mm).
E_{act} Actual evaporation.
Ieff Effective infiltration.

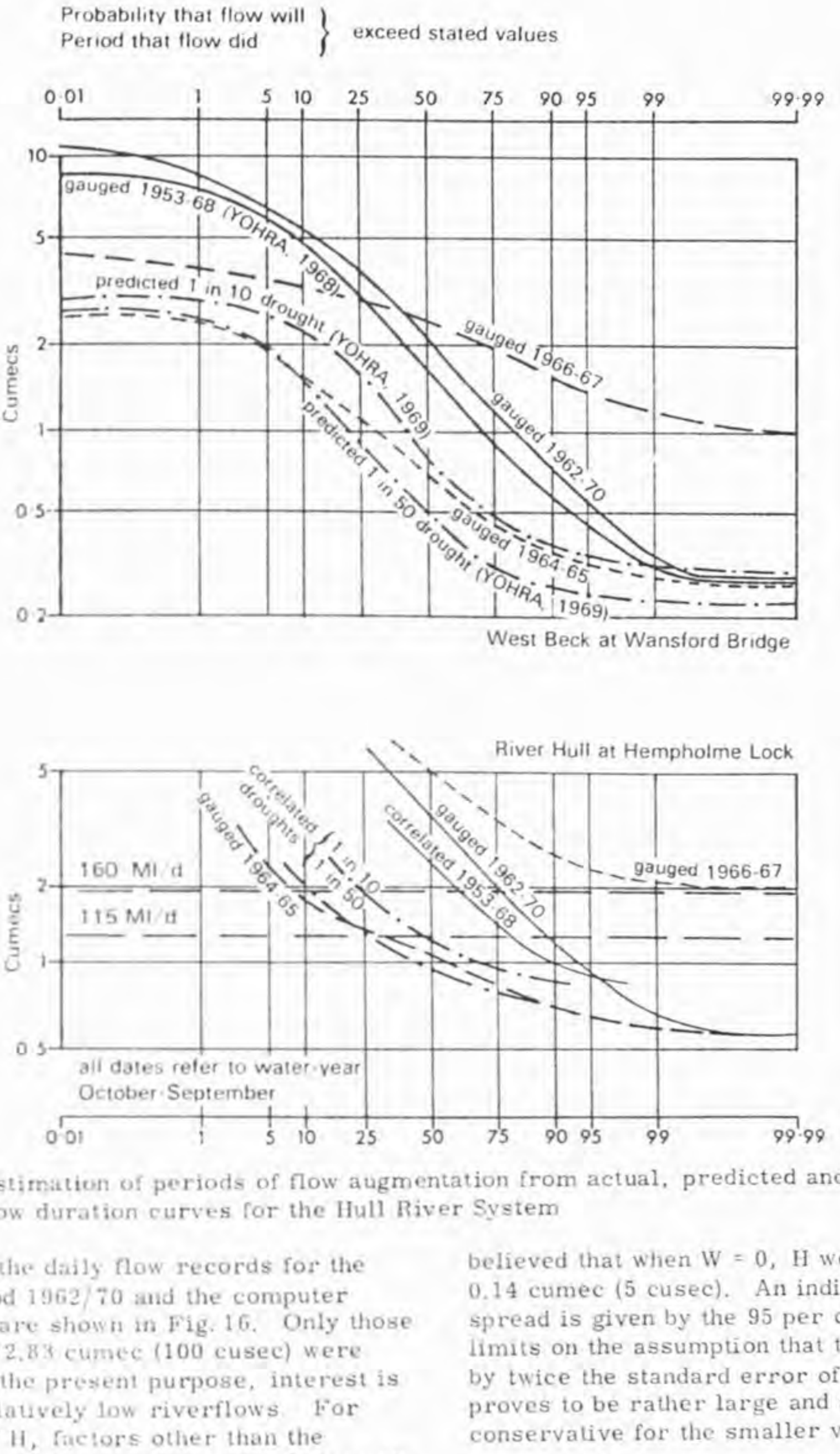


Fig. 15. Estimation of periods of flow augmentation from actual, predicted and correlated flow duration curves for the Hull River System

computer using the daily flow records for the eight-year period 1962/70 and the computer graphic outputs are shown in Fig. 16. Only those records with $H < 2.83$ cumec (100 cusec) were used since, for the present purpose, interest is restricted to relatively low riverflows. For higher values of H, factors other than the tributary flows, such as surface run-off from the lower lying drift covered areas, are likely to become increasingly significant. In all of the analyses the degree of correlation, as indicated by the simple or multiple correlation coefficient, is highly significant although the regression line appears to have been distorted somewhat by the manner in which H was limited. Moreover a non-linear relationship is probably more appropriate for small values of W, since it is believed that when $W = 0$, H would be less than 0.14 cumec (5 cusec). An indication of the spread is given by the 95 per cent confidence limits on the assumption that these are defined by twice the standard error of estimate. This proves to be rather large and appears to be conservative for the smaller values of H and W.

It is also evident (Fig. 16) that there are some occasions when $H < W$ and many instances when $H < W + F$. On further investigation it was found that in the entire daily flow record for the water years 1962/70, the latter condition occurred 15.8 per cent of the time and more than three-quarters of these occurrences were for $H < 2.83$ cumec (100 cusec), that is, relatively low flow conditions. This is surprising since there are some significant inflows to the River Hull above H and below W and F. (The largest is Driffield Canal, which includes Nafferton Beck, but only limited spot-flow determinations are available showing a variation of flow at Snakeholme Lock from 0.25 to 1.50 cumec during 1966/68). It may imply a significant gauging error at either H or W and/or substantial bed and bank losses, perhaps to the Beverley-Barmston Drain; some signs of influent condition of the Hull were noted by Gray (1952). It is thought unlikely that such a condition could prevail in the artesian area of the underlying Chalk aquifer except in specialised circumstances like those of artificial interference for land drainage purposes.

GROUNDWATER CHEMISTRY

To permit examination of the hydrochemistry of the groundwater cycle and to identify any potential groundwater quality problems, pumped samples were collected for chemical analyses in October 1970 from water supply wells and springs along a transect from the Chalk escarpment across the Wolds into the Hull Valley (Fig. 17). Some supplementary analyses were abstracted from the Institute's records, although their reliability and usefulness are variable because of the different laboratories and various purposes concerned. A comprehensive sampling survey was not possible because of the sparseness of pumping boreholes and disused wells accessible for depth sampling over considerable areas of the catchment. Hydrogeochemical studies may also prove of use in the detailed investigation of local groundwater problems; in this area, as has been mentioned, they have been employed to confirm the origin of the baseflow in certain land-drainage channels.

The October 1970 samples were analysed for total dissolved solids (TDS) and the major ions together with potassium (K^+), strontium (Sr^{2+}) and fluoride (F^-); no field measurements such as conductivity, pH, Eh and dissolved gasses were made. The results are presented in two forms (Fig. 17), a graph of absolute concentrations and a trilinear diagram in proportions of equivalents.

It appears that all Chalk groundwaters from the outcrop area are essentially similar in chemistry; hard Ca^{2+}/HCO_3^- waters predominate with carbonate saturation and TDS in the range 250 to 375 mg/l. Minor hydrochemical variations in the Fordon anticline (samples 2 and 3 in Fig. 17) appear to reflect the presence of Jurassic rocks at shallow depths.

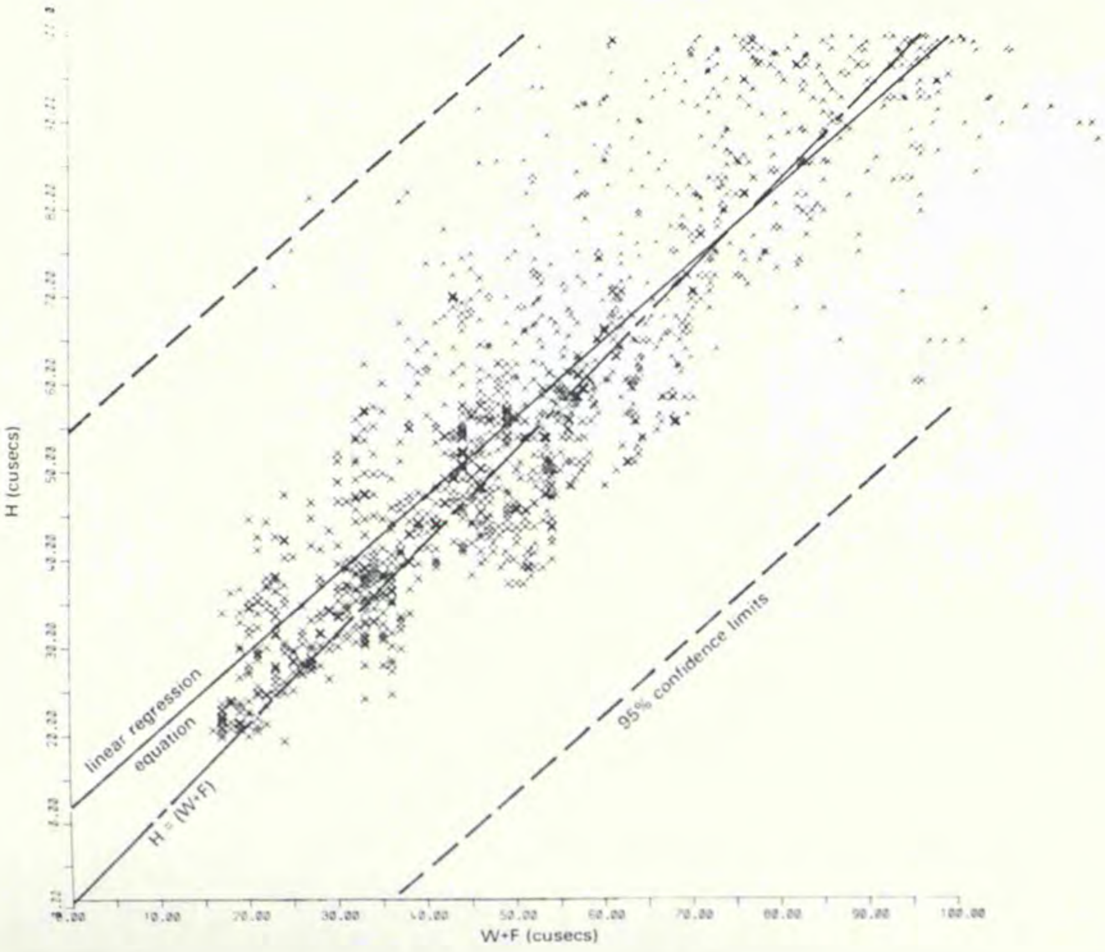
Some important reactions associated with basic changes in the hydrochemical environment occur down-dip in the Chalk aquifer underneath the drift cover, largely as a result of the greatly reduced groundwater circulation and the isolation of the system from the atmosphere. From studies by Ineson and Downing (1963) and Edmunds (1973) one would expect the disappearance of dissolved oxygen and a sharp fall in redox potential (Eh), base exchange (Na^+ for Ca^{2+}) with minerals of the argillaceous confining bed, and beyond this a pH rise and mixing with older formation or connate water. In East Yorkshire all of these changes probably occur but over a short distance and within 10 km down-dip (in Fig. 17 they commence at the location of sample 9 and are complete at and probably well before sample 10). The distribution of the hydrochemical changes presumably reflects the almost total absence of outlets down-dip. Associated changes are sulphate (SO_4^{2-}) reduction, the generation of (H_2S), increased iron with the onset of reducing conditions and the replacement of Fe^{3+} by the more soluble Fe^{2+}, decrease in Ca^{2+} and major increases in Na^+ and Cl^-.

Considering potential groundwater quality problems in development schemes, there is no evidence to suggest the existence of mobile highly saline waters at depth in the Chalk of the outcrop area and no reason to suspect that heavy seasonal overpumping would lead to coning up of groundwater of unacceptable quality from depth.

In the outcrop area the only potential chemical problems come into the category of pollution. In recent years there has apparently been a considerable increase in the concentration of nitrate in Chalk water supplies at a number of widely dispersed locations, as a result of changes in agricultural practice (Foster and Crease, 1974). Levels of NO_3-N have on occasions already exceeded the lower WHO recommended limit (11.3 mg/l) and this could ultimately prove a regional problem. Use of Chalk groundwater for river augmentation however is not in itself likely to worsen this situation since the fertilisation of weeds already results in substantial nitrate removal in the channel of the Hull between its sources and the Tophill Low intakes.

The Chalk aquifer is vulnerable to pollution as a result of the tipping of wastes, particularly where these are deposited in quarries at or near to the water table. Natural groundwater flow rates in the saturated zone have been shown to be fairly high, and could reach 200 m/day, and thus such pollution could spread quite rapidly over large areas.

Any development in the confined zone of the aquifer, particularly downstream of the main



INDEPENDENT VARIABLE	SIMPLE OR PARTIAL LINEAR REGRESSION EQUATION (all in cusecs)	SIMPLE/MULTIPLE CORRELATION COEFFICIENT (r)	STANDARD ERROR OF ESTIMATE (S_H) (cusecs)
W	H = 1.1W + 14.7	0.85	21.3
F	H = 2.9F + 21.0	0.73	21.5
(W+F)	H = 0.9 (W+F) + 12.0	0.79	21.5
W,F	H = 0.88W + 0.92F + 11.9	0.86	10.8

Daily flow data for water-years 1962-70 used; only those records with H<100 cusecs selected (total number: 1250)

All correlations in cusecs (x 0.03 for cumecs)

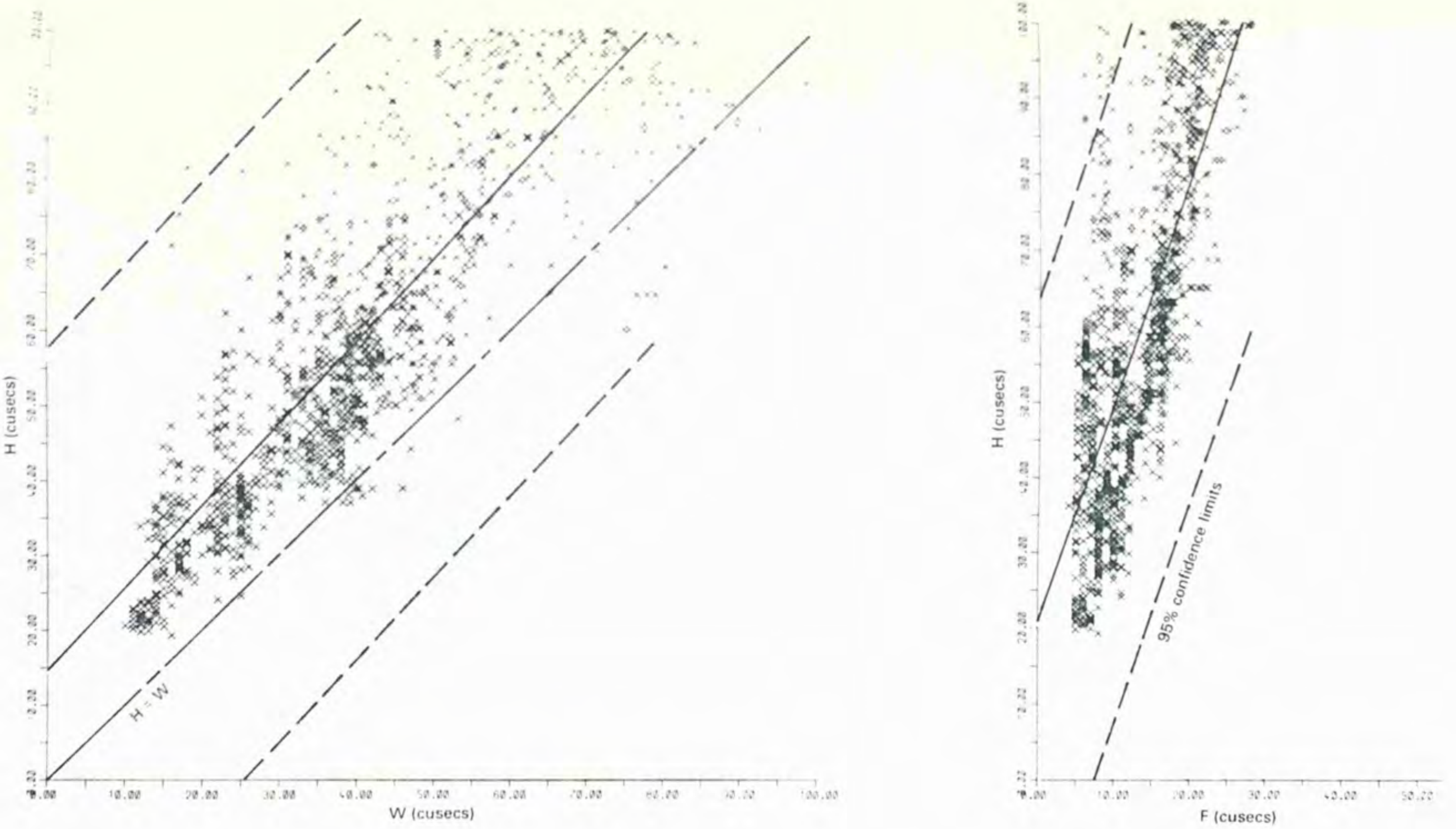


Fig. 16. Computergraphic correlations of riverflow on the Hull and its tributaries

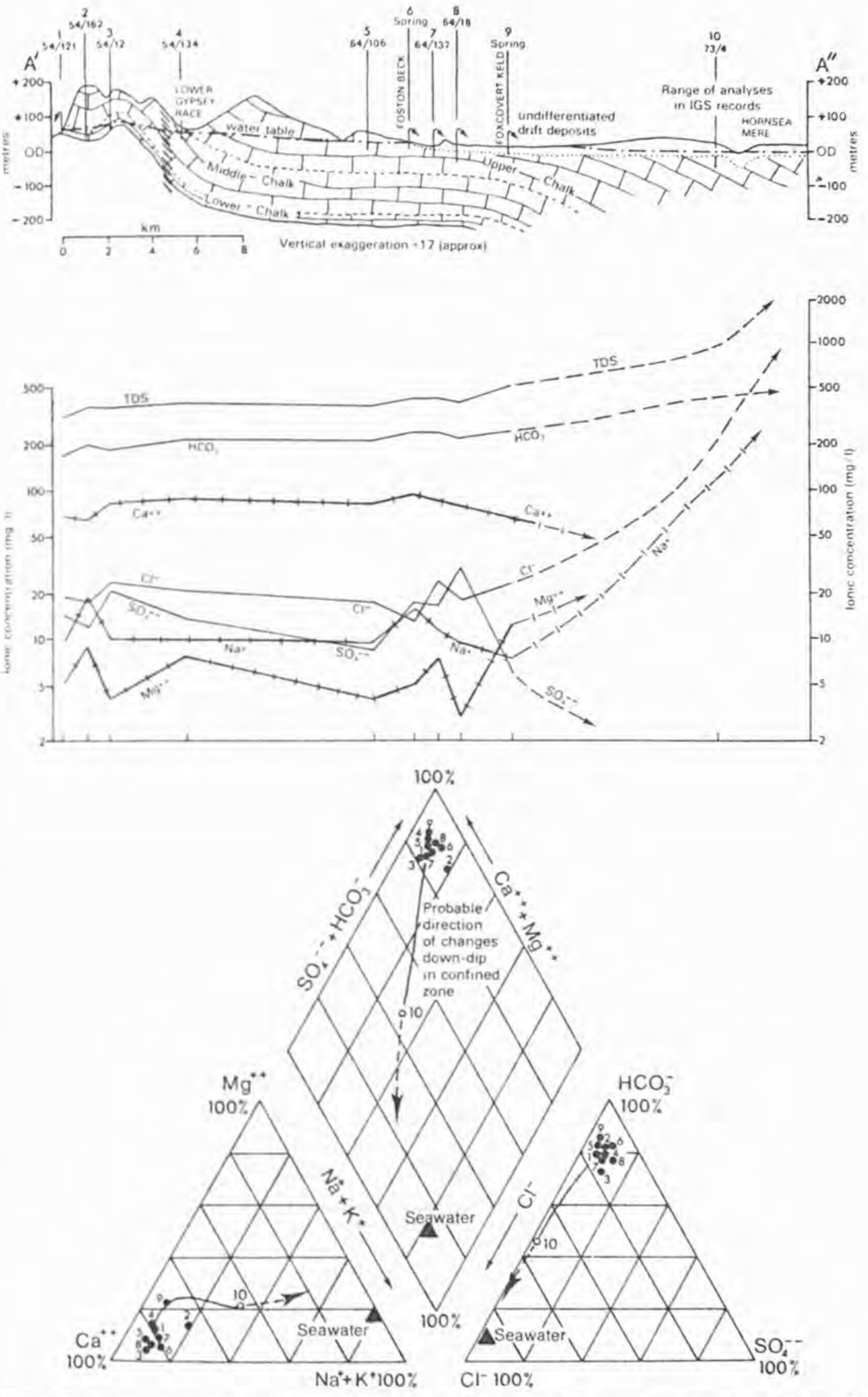


Fig. 17. Cross-section and trilinear diagram illustrating the groundwater chemistry of t Chalk aquifer in East Yorkshire

area of natural groundwater discharge, could encounter significant hydrochemical problems. Firstly the front of the saline Chalk groundwater of Holderness (Fig. 17) could migrate in response to heavy abstraction and secondly the reducing conditions in situ could lead to such problems as the corrosion and deposition of iron and the production of iron-rich water.

Schemes of Development

GENERAL CONSIDERATIONS

The central problem is to obtain the required river augmentation for the minimum cost after taking account of side effects, such as those on existing water users and water-based amenities. The cost of groundwater supplies is relatively very low, but increases for the type of development scheme required, as a result of distance between the source and the consumer and of designing to avoid undesirable environmental interferences. Costing of schemes is outside the scope of this report but among the most important capital and running cost differences between various schemes will be pipeline length, together with the number of boreholes and installed pump capacity to provide the required yield.

An implication of the hydraulic unity of the Chalk groundwater reservoir over large areas is that the effect of abstraction from groundwater storage at one location will in time spread throughout the aquifer; the precise manner of propagation of the interference effects depending on the hydraulic properties and natural flow conditions. In particular the rate of natural discharge at the springheads will at some stage and to some degree be intercepted and bed loss recirculation from the surface water courses may be induced, causing additional depletion of riverflow. If both these types of interference cannot be substantially delayed by strategic

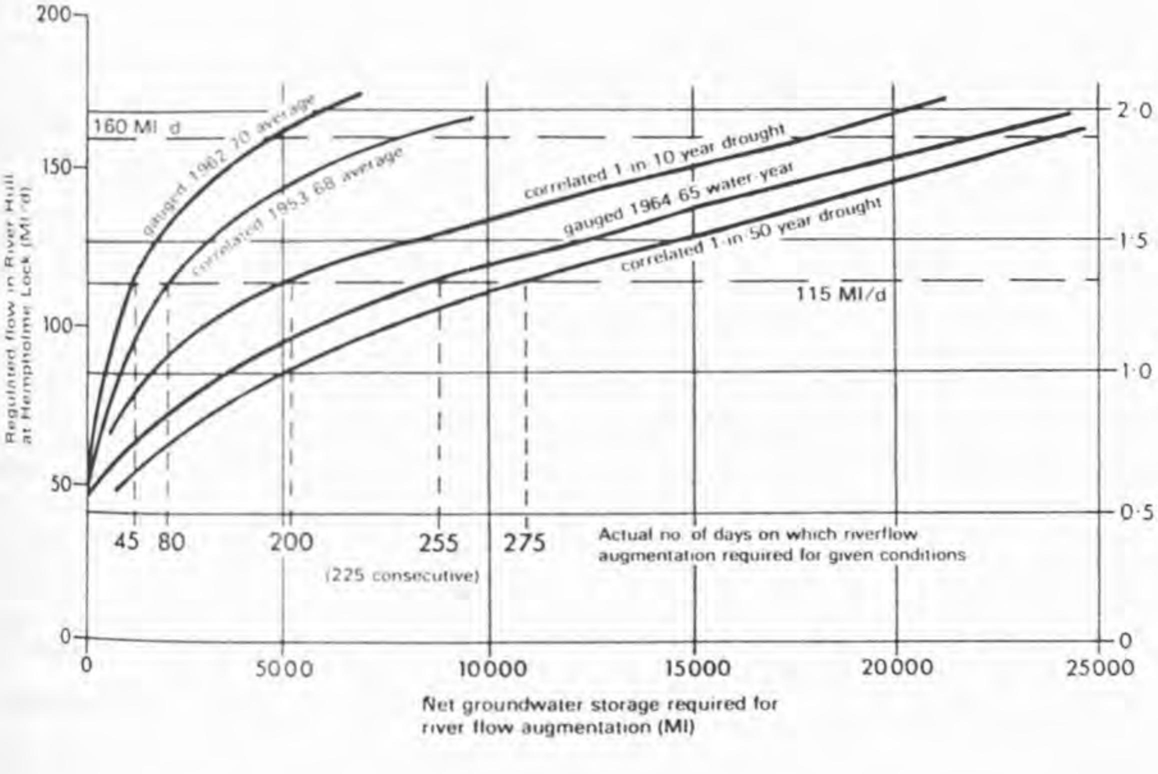


Fig. 18. Estimation of groundwater storage demands to meet regulated flow deficits

siting of the abstraction points, or designed for in some other way, the effective yield of the scheme will be correspondingly reduced. The percentage interception and recirculation will be the measure of efficiency, which in nearly all cases will decrease with operating time (Ineson, 1970); it will ultimately determine how many abstraction boreholes will be required to provide a given net yield. There are conditions in which interception and/or recirculation could be so great as to result in little net augmentation of riverflow and to make augmentation impractical or uneconomic. Under such circumstances the required yield could only be supplied directly by pipeline. Treatment costs for direct supply schemes would be smaller but the maintenance of compensation stream flow from borehole pumpage would present problems except over the lower reaches of the surface water courses.

From the point of view of conservation however, it is worth noting that successful schemes for river regulation using groundwater storage involve minimal environmental disruption because almost the entire works can be subsurface. The increase of low flow is also in the interest of all river users. Given schemes could involve the drying up of some springheads and the uppermost reaches of associated streams (unless stream bed sealing were feasible); this side effect has to be evaluated. Certain schemes could improve the drainage of the lower lying land in parts of the Hull Valley but the decrease in peak flows, resulting from the level of regulation envisaged initially, would not be sufficient to reduce the risk of surface flooding from the Hull.

The possible methods of development of groundwater storage for river augmentation can be divided into two types

1. Direct regulation of the discharge at selected springheads, avoiding as far as possible interference with natural discharge in other parts of the aquifer's artesian zone.
2. River augmentation from groundwater storage in areas remote from the zone of natural aquifer discharge.

In both cases there are many possible locations and distributions for the abstraction boreholes.

OPERATIONAL PROBLEMS

The flow duration curves (Fig. 14) for the Hull at Hempholme Lock show that, during 1962/70, schemes designed to prevent riverflow from falling below 115 Ml/d would be required to operate for about 12 per cent of the time (that is, 45 days per year), typically commencing in mid-August. Some years they would not be required at all. Low flow duration curves, correlated from the Wansford Bridge gauge for the longer period 1953/70 (Fig. 15) suggest that this figure might be on the low side but in any case the average operating period is most unlikely to exceed 80 days per year.

The average condition however does not illustrate the nature of the principal operating problem that will be presented to any river regulation scheme, namely, the striking difference in conditions in the driest years and successive dry years (Fig. 18). For example, during the worst drought of the last decade, the Hull would have required augmentation continually from mid-August 1964 to late March 1965 (a period of 225 days) to maintain a flow of 115 Ml/d at Hempholme Lock; the mean daily discharge over the water year 1964/65 was only equivalent to just over 100 Ml/d.

The question of what should be taken as the worst design-drought arises. Synthetic one in ten year and one in fifty year drought flow duration curves are available for West Beck (Yorkshire Ouse and Hull River Authority, 1969). From these the comparable curves for the Hull at Hempholme Lock have been tentatively generated by correlation (Fig. 15); there is however a risk of spurious interaction between the implicit probability of the original data and the implied probability of the correlation. When compared with the recorded data of 1964/65 the similarity of the required flow augmentation period to that in a one in fifty year drought is, however, to be noted.

The accuracy of the estimate of the longest period of required augmentation is not critical, because of the behaviour of the time of pumping parameter (t) in the laws of radial groundwater flow and spread of interference effects (Fig. 19). However for a sustained flow of 115 Ml/d, it is clearly necessary to consider the degree of interception and recirculation occurring after a pumping period of 200 to 300 days. If the net yield is not to fall-off under such severe conditions it will be necessary to provide a corresponding reserve of groundwater production capacity, boreholes and pumps.

The volumetric increase of demand on groundwater storage for augmentation in dry years is also very marked (Fig. 18), but bearing in mind that a conservative estimate of the total storage in the Hull-Hempholme catchment at extreme drought is about 40 000 Ml, there appears to be ample storage available for augmenting flows to a level of at least 115 Ml/d (1.3 cumec). In practice not all of the pumping capacity of a scheme would be needed immediately after the flow in the Hull at Hempholme Lock dropped below 115 Ml/d. Successive groups of boreholes

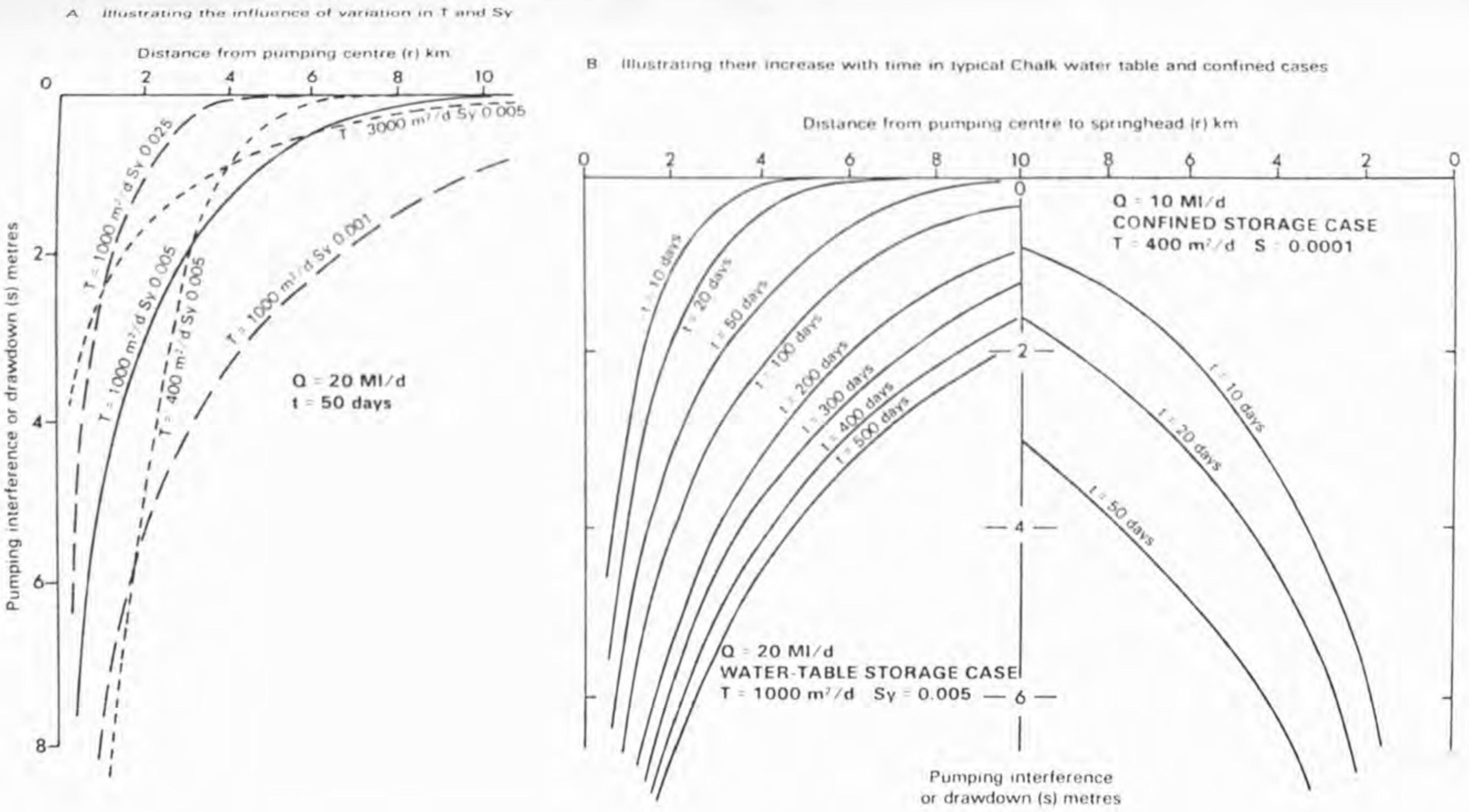


Fig. 19. Prediction of distant interference effects from a pumping centre in an idealised aquifer

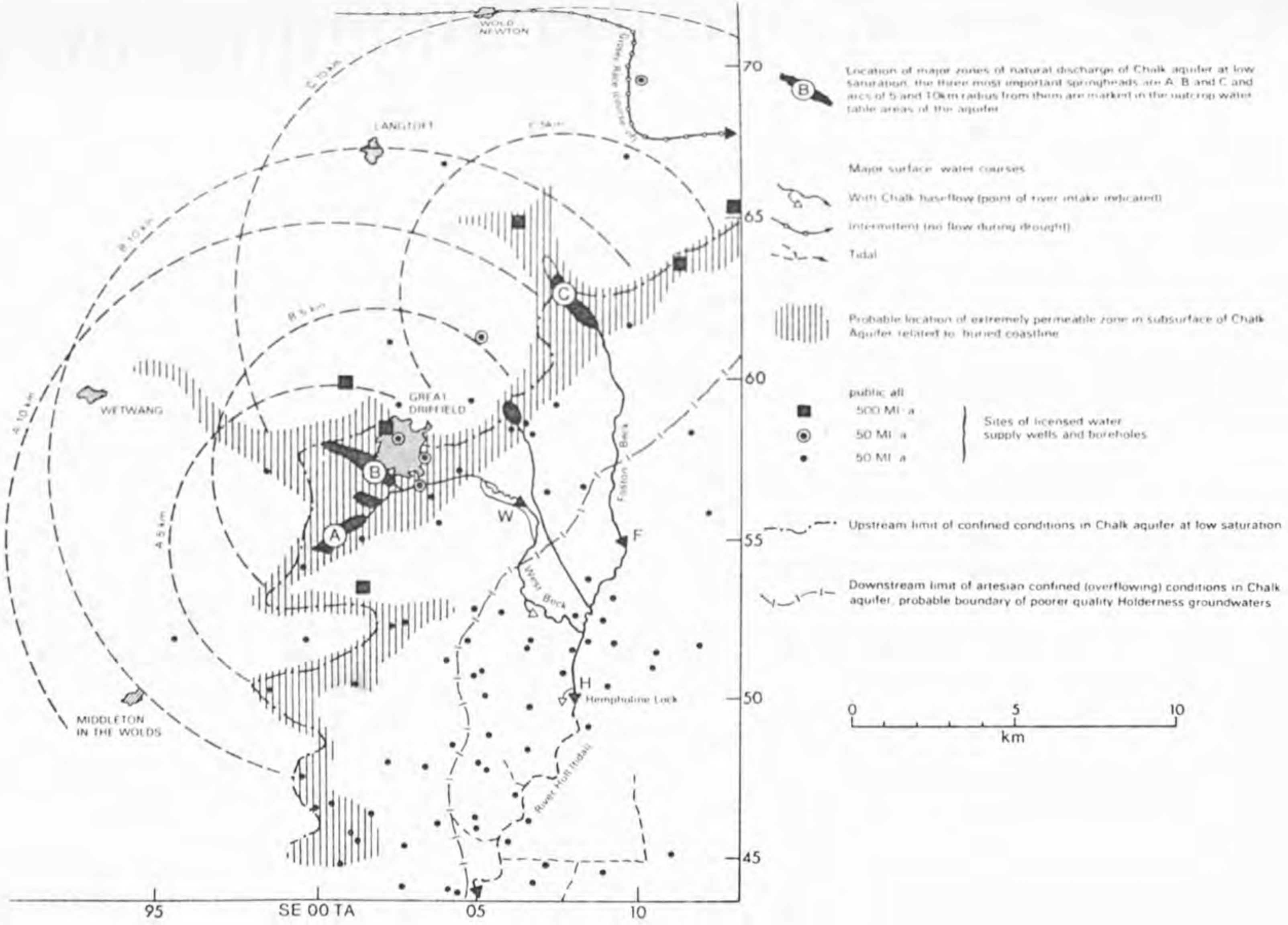


Fig. 20. Sketch map summarising major factors which influence the design, location and operation of river-regulation boreholes

could be switched into production as the drought developed, reducing considerably the total time of, and interference due to, pumping at the maximum rate. Counteracting this will be the effect of development, which itself will tend to delay somewhat the subsequent rising limb of the riverflow hydrograph when recharge occurs. Incidents of mistiming of pumping may also be unavoidable.

The intermittent nature of the pumping means that maintenance can be undertaken during times when the scheme is not required to operate. Stand-by boreholes as such are not therefore required although provision of stand-by pumps would be desirable.

DIRECT REGULATION OF DISCHARGE AT SELECTED SPRINGHEADS

One possible method of development involves the total regulation of the low flow discharges to the River Hull at selected springheads. The close association of the zone of highest aquifer transmissibility and the areas of major springflow has already been mentioned and is illustrated in Fig. 20. It should be relatively simple to site groups of high yielding boreholes in this zone. Pumping interference with the natural discharge of the nearest group of springs would not be delayed for more than a few days and so it would be necessary to pump almost the entire spring discharge plus the net increment above natural riverflow required.

Correlations between the flow of the Hull at Hempholme Lock and the discharge of the selected springhead area are necessary to assess the total groundwater production capacity required, since much of this will be devoted to artificially generating natural springflow. The correlation lines developed by linear regression between the flow of the Hull at Hempholme Lock (H) and its principal tributaries (Fig. 16) are examples of the type of analysis required in this respect. While the degree of correlation is generally high, the spread of data still poses a design problem. It can be seen, for example, that for H = 1.0 cumec the correlated flow is F = 0.14 cumec but the observed spread of data shows that F can contribute 0.31 cumec of this H and there appears a 5 per cent probability that it could contribute as much as 0.57 cumec, although the distribution of the data correlated may make the latter interpretation unrealistic.

The first requirement in respect of borehole location is close grouping; the idea being to reduce to a minimum the interference with all natural springflow except the nearest major springhead; flow from the latter will be largely artificially generated together with the required augmentation increment derived from storage located below local base level.

The highest borehole yields would be likely immediately west and south of Great Driffield (there should be little difficulty in obtaining more than 8 Ml/d per borehole in this area), but a large wellfield would be required to generate the natural springflow which frequently exceeds 60 per cent of the total flow at Hempholme Lock (Fig. 16 and Table 7). For the latter reason it would probably be advisable to locate the augmentation boreholes distant from this area and the most attractive possibility would appear to be close to the Foston Beck springheads between Harpham and Kilham. There is good prospect that high yielding boreholes could be located at close centres in this area also.

While some augmentation from storage would be achieved, considerable apprehension about the direct regulation method stems from the possibility that interference may not be limited to the selected springhead. As a consequence of the exceptionally high Chalk permeability in this area (Fig. 20), the overall efficiency (which from the outset is low in this method) could fall off too rapidly because of interference at distant groups of springs and seepages.

Another distinct disadvantage of this method of development is that the groundwater probably could not be discharged into Foston Beck for a few kilometres downstream, if gross recirculation by riverbed losses was to be avoided. Drying-up of certain lengths of the upper reaches could interfere to some extent with angling and other interests. In general, geological conditions would appear to inhibit or restrict riverbed losses but deep cones of pumping depression and large downward hydraulic gradients would be introduced and this factor would require investigation.

The considerable number of agricultural and domestic supplies readily obtained by boreholes in the artesian area would also experience interference effects and some public supply sources would also be affected (Fig. 20).

Feasibility studies would be necessary; because of the high permeability and known heterogeneity of the Chalk in this area, and the resulting small magnitude of short term interference effects, the trial pumping tests could probably not be undertaken from a single pumping borehole alone. A suitable design for such a study would comprise three closely spaced pumping boreholes (which might ultimately be incorporated into the development scheme proper) with a carefully sited network of observation boreholes at varying distances from the pumping centre. A short duration pumping test using one of the pumping boreholes and observing only the nearest observation boreholes could be used to evaluate the aquifer properties and boundaries in the immediate area and the location of the buried coastline; this would be followed by a pumping test of longer duration whose aims would include the following.

1. The prediction of interference with distant springheads.
2. The determination of the best pipeline discharge point; some specific investigation of the permeabilities of the drift materials in the bed and banks of Foston Beck would also be required in this connection.
3. The evaluation of effects on existing users and the identification of any unanticipated side effects.

Particular attention should also be paid to the yield-drawdown relationships of the boreholes and the likely decrease in yield with falling rest water level and with increasing interference from other boreholes of the group. Geophysical borehole flow investigations would be called for, to evaluate the distribution of permeability and storage with depth in the Chalk aquifer, as this would become increasingly important in determining the yield-drawdown behaviour of individual boreholes and the borehole group with increasing time of pumping. Confident extrapolation of borehole behaviour from the test condition to those of extreme drought will be required, because it will probably not be possible to test under the latter conditions until pilot operation.

RIVER AUGMENTATION FROM REMOTE AQUIFER STORAGE

Direct regulation does not take full advantage of the natural hydrological regime and the hydraulic character of the groundwater reservoir, since relatively large gross groundwater production would be required in relation to the net yield. If the costs of longer pipelines were acceptable, a group of pumping boreholes could be sited in the Wold outcrop area distant from the major springheads. When groundwater is abstracted from storage in these areas there will be a considerable time lag from the start of any given period of pumping until the onset of interception of natural spring discharge; the magnitude of this time lag and therefore the degree of remoteness of the part of the aquifer storage concerned will be a function of the hydraulic properties (T, S_y) of the Chalk aquifer, principally within the intervening area.

Some idea of the influence of T and S_y on the development of a major cone of pumping depression and the magnitude of interference effects at large distances from the centre of pumping can be obtained from Fig. 19. It will be seen that the greater the T/S_y ratio, the more serious will be the interception losses during river augmentation and essentially the less remote is the groundwater storage in the outcrop area. On the other hand, low T conditions will require more boreholes and larger drawdowns to produce a given yield.

The computation of interference effects (Fig. 19) does not allow for the distortion of the cone of depression which would occur as the result of gradual variations in aquifer properties and the existence of natural aquifer throughflow. In practice the cone of pumping depression will expand laterally to intercept a gradually increasing proportion of the throughflow and the amount drawn from storage will be correspondingly reduced, though this reduction will be limited for very high rates of abstraction under drought throughflows.

As has been discussed there is good prospect, throughout the dip-slope outcrop area, of large diameter boreholes yielding 50 l/s (4.3 Ml/d) at specific capacities greater than 2.5 l/s per metre drawdown under low saturation conditions. The choice of location of groups of boreholes will be mainly one of distance from the major springheads (Fig. 20) and the extent to which increasing pipeline length is justified by reduction in interception losses. Clearly the most highly permeable area, the Wetwang Embayment, is to be avoided. The choice of distribution of individual boreholes within a group is essentially that between the exploitation of shallow storage over large areas or deeper storage over limited areas. Dispersal would lead to greater pipeline requirements and would be a less efficient use of the local resources, but the possible reduction in borehole performance when standing water levels are substantially depressed may prove a limitation in the latter case. There are very few licensed groundwater abstractors throughout the area (Fig. 20) and interference with existing usage would be negligible.

Several hydrological factors will be critical to remote storage development. It is thus essential to have a thorough understanding of the aquifer behaviour in the appropriate areas, so that the interference effect at the nearest springheads can be computed for various periods of pumping up to say 300 days. The variation of augmentation period, between the average year and those of extreme drought, also will pose significant design problems to this type of scheme.

The aquifer storage parameter, S or S_y, has major significance in the response to abstraction at distances remote from the centre of pumping (Fig. 19). The difficulty in actually determining representative specific yield values, and the probability of substantial variation of this parameter with groundwater level fluctuations (Foster, 1974), means that preliminary investigations must be well planned and should involve a number of independent methods. Of equal importance is the fact that the amount of interference with a given spring discharge depends upon the size of the pumping interference effect in relation to the head involved in the spring discharge process itself. The head losses and flow regime around groups of major artesian springs or along the line of a spring-fed watercourse are not known in detail for this or any comparable area. The subject remains a practical research requirement in the context of river regulation, involving significant drilling, testing and flow gauging.

If 'Etton type' conditions prevail in the Hull-Hempholme catchment, it appears that the interference effect at a springhead due to pumping 20 Ml/d from a centre 7.5 km distant would be almost negligible after a period of about 50 days but would increase significantly if pumping were continued to 300 days (Fig. 19). For a net augmentation of 70 Ml/d it is thus unlikely that substantial interception of natural spring discharge could be avoided in extreme drought.

An attractive location for this type of development would be in the Rudston-Wold Newton area; it would be necessary to pipe the water some 5 to 10 km to the upper part of Foston Beck and the aim would be to achieve a degree of regulation of this watercourse. Some proportion of the yield however would form a net importation to the Hull-Hempholme catchment at the expense of the Lower Gypsey Race; the abstraction boreholes would be located on the very variable boundary between these two catchments. In the long-term considerable quantities of water (Fig. 9) flow down the Lower Gypsey Race to the North Sea. Except for its amenity value little use can be made of the watercourse because of its intermittent flow. It almost invariably dries out when the spray irrigation demand, one potential use, is greatest. It would probably be feasible to provide a compensation flow below Rudston from the borehole network to satisfy amenity aspects.

An important consideration is the impact of river regulation development in this area on the long term supply situation at Bridlington, to the east. There is a potential risk of sea water encroachment into the Chalk of this area. The current licensed abstraction of the entire 'Bridlington Block' is 8800 Ml/a with usage probably nearer 5000 Ml/a; a considerable production capacity being held in reserve by the East Yorkshire (Wolds Area) Water Board at Haisthorpe. With an average long term infiltration to the Chalk in excess of 300 mm/a, the licensed volume would appear to require a catchment of only some 30 km^2 for recharge.

INVESTIGATION AND DEVELOPMENT PHILOSOPHY

It will be clear from the preceding discussion that there remains insufficient knowledge of certain critical hydrological factors to make a rational choice on the method of development and location of pumping boreholes for a river augmentation scheme.

Considerable cost and time would be involved in the full investigation of these factors and a flexible approach is obviously required. The following programme of feasibility studies, with monitoring at a research level, could be considered as minimal:

1. Two short-duration single-well pumping tests with appropriate observation boreholes in the Wolds outcrop area to assess the degree of remoteness of its storage with respect to the points of natural discharge
2. An investigation of the distribution of head around one or two of the major springs.
3. A short-duration single-well and longer-duration multiple-well pumping test with appropriate observation boreholes in the vicinity of the major springheads, with a view to evaluating the problems associated with direct regulation of their discharge.
4. Some direct investigation of the relationship between the upper reaches of the main Hull tributaries and the underlying Chalk groundwater system to evaluate the scale of riverbed and bank losses under pumping conditions.

Special attention would need to be paid to the more important hydrological factors and parameters which have been discussed in the relevant sections of this report and the fullest use made of the investigation boreholes. If the results of 1 and 2 were sufficiently favourable there would be no need to undertake 3 and 4 and staged development could follow with pilot operation commencing at the onset of the first sufficiently low flow condition for the trial to be a valid one. Some re-design of the existing river-gauging network would probably be required to improve the monitoring of the augmentation flow through the river system to Hempholme Lock.

CONFINED AQUIFER STORAGE

If the confined storage of the Chalk aquifer underlying those parts of the Hull Valley adjacent to Hempholme Lock could be tapped effectively, it could be piped directly to the Tophill Low Waterworks to compensate for any supply deficit resulting from low flows in the Hull.

It is believed that the transmissibility of the Chalk could be as much as an order of magnitude lower in this area than in the main areas of groundwater circulation. Borehole yields are likely to be restricted to a maximum of 2 Ml/d. Unfortunately the confined coefficient of storage is still likely to cause rapid propagation of interference effects (Fig. 19) and there is thus a distinct possibility of significant interference with natural springflow at the flanks of the confined zone.

A factor that could reduce the spread of the cone of pumping depression would be induced leakage from the overlying drift deposits. If this were promoted it would be beneficial in the context of water resources and possibly of land drainage. The possibility of leakage is sufficient to justify further investigation if a short term stand-by supply of up to 10 Ml/d were required, despite the unfavourable results of a previous borehole near Arram (Green, 1950; Jones, 1955). There could, however, be quality problems resulting from the proximity of non-circulating Chalk groundwaters with high total dissolved solids (Fig. 17) and iron corrosion and clogging problems associated with their low redox potential (Eh).

ULTIMATE YIELD OF THE CHALK AQUIFER

The very considerable quantity of water (about 265 Ml/d) represented by the total long term average annual baseflow in the River Hull at Hempholme Lock gives an indication of the potential yield that could be achieved from total regulation. It is already evident however, that the level to which river regulation schemes could be practicably implemented would be limited by hydrogeological and economic factors long before a condition of total regulation was approached. Very widespread interference with the upper reaches of the Chalk watercourses or, on the other hand, excessive recirculation and therefore a very low net yield from each borehole is implied. The volume of groundwater storage required and length of continuous pumping in extreme drought conditions to sustain a flow of say 160 Ml/d will be evident from Figs. 9, 15 and 18.

In the specific proposals for development schemes, some net importation of groundwater into the Hull-Hempholme catchment was suggested by locating the boreholes for river augmentation at or near the eastern boundary of the groundwater catchment. The extent to which this would be tolerable would depend on the degree of interference with the existing public supply boreholes and those of other licensed abstractors, mainly in the Bridlington area. There is little scope for artificially expanding the Hull-Hempholme catchment at the other lateral boundaries and the geological structure makes the groundwater draining to the escarpment springs a small and inaccessible part of the total storage of the aquifer.

Development towards the ultimate yield of the Chalk aquifer and the fullest exploitation of its storage capacity would thus have to involve other methods such as artificial recharge. One attractive possibility has already been mentioned in the context of the Chalk to the south of the Hempholme catchment (Foster and others, in press). In theory it would appear feasible to return excess flows in the River Hull, and possibly the land drainage system of the Hull Valley, as recharge to many parts of the Chalk aquifer. Such schemes would require much more complex technical and economic studies to assess feasibility than those required for a river augmentation scheme and at present are therefore less attractive.

Appendix A: Core Analysis Results from the East Yorkshire Chalk by M. J. Bird

INTRODUCTION

This appendix deals with the core analysis of two sets of selected chalk samples from East Yorkshire. The purpose of this examination was two-fold; primarily to produce data to assist in the hydrological study of the formation and secondarily to determine the effects of stylolites on physical properties of the Chalk.

DISTRIBUTION AND PREPARATION OF SAMPLES

A total of 14 large chalk samples were taken from quarry faces. They were selected, during a survey of joints (see Appendix B), with the intention of covering the range of broadly similar lithologies seen and of stylolitic development. The sampling programme was in no sense comprehensive in either respect. A second set of samples was selected from the limited cored intervals in two observation boreholes drilled by the Institute (64/148 and 64/149 in Fig. 3).

The 14 outcrop samples are believed to comprise eleven from the Upper Chalk, two from the Middle Chalk and one from the Lower Chalk. All 14 borehole samples are thought to be of Middle Chalk. The uncertainties of Middle/Upper Chalk subdivision discussed in the main report however, apply.

Right cylinders of 25 mm nominal length

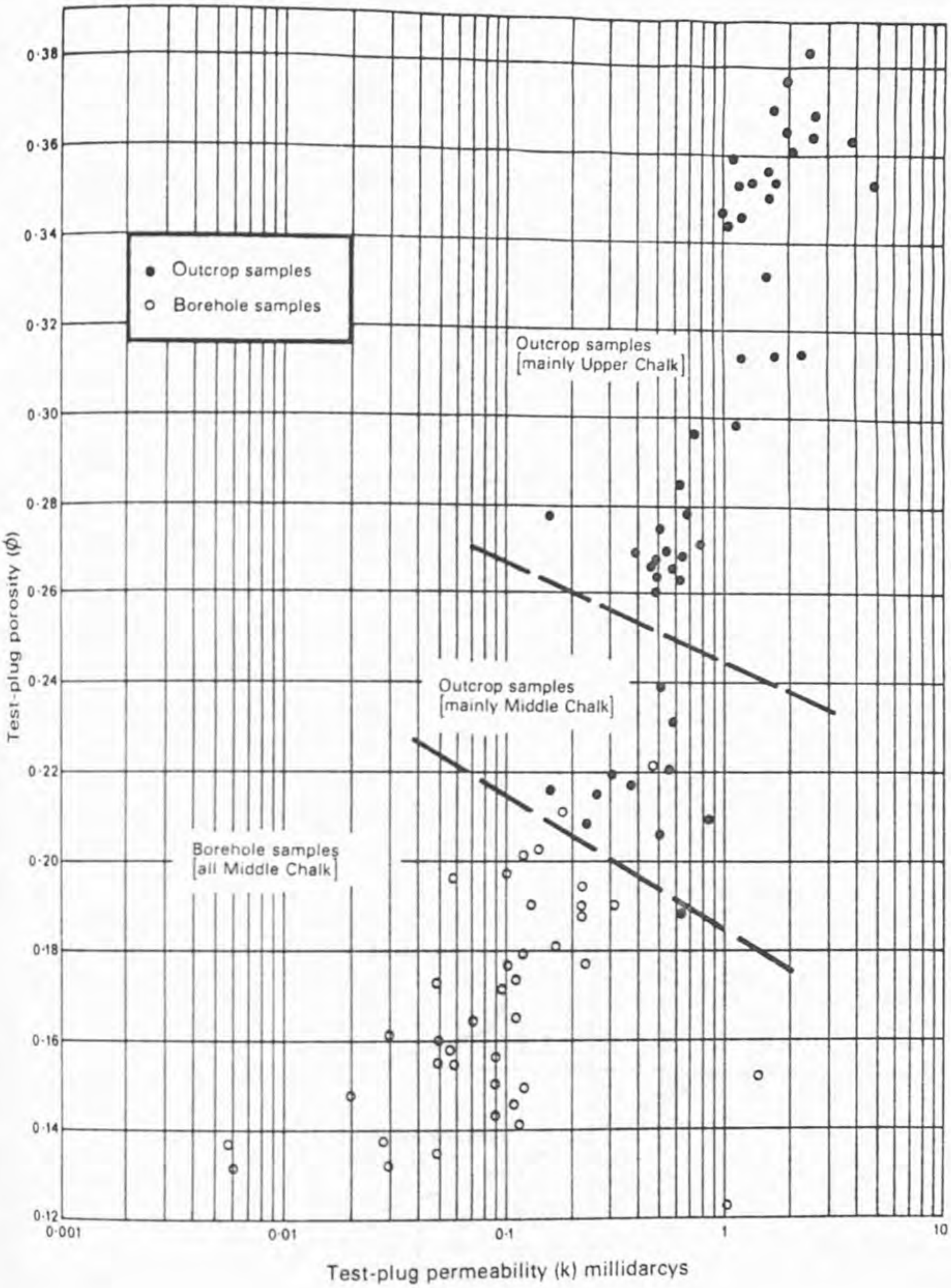
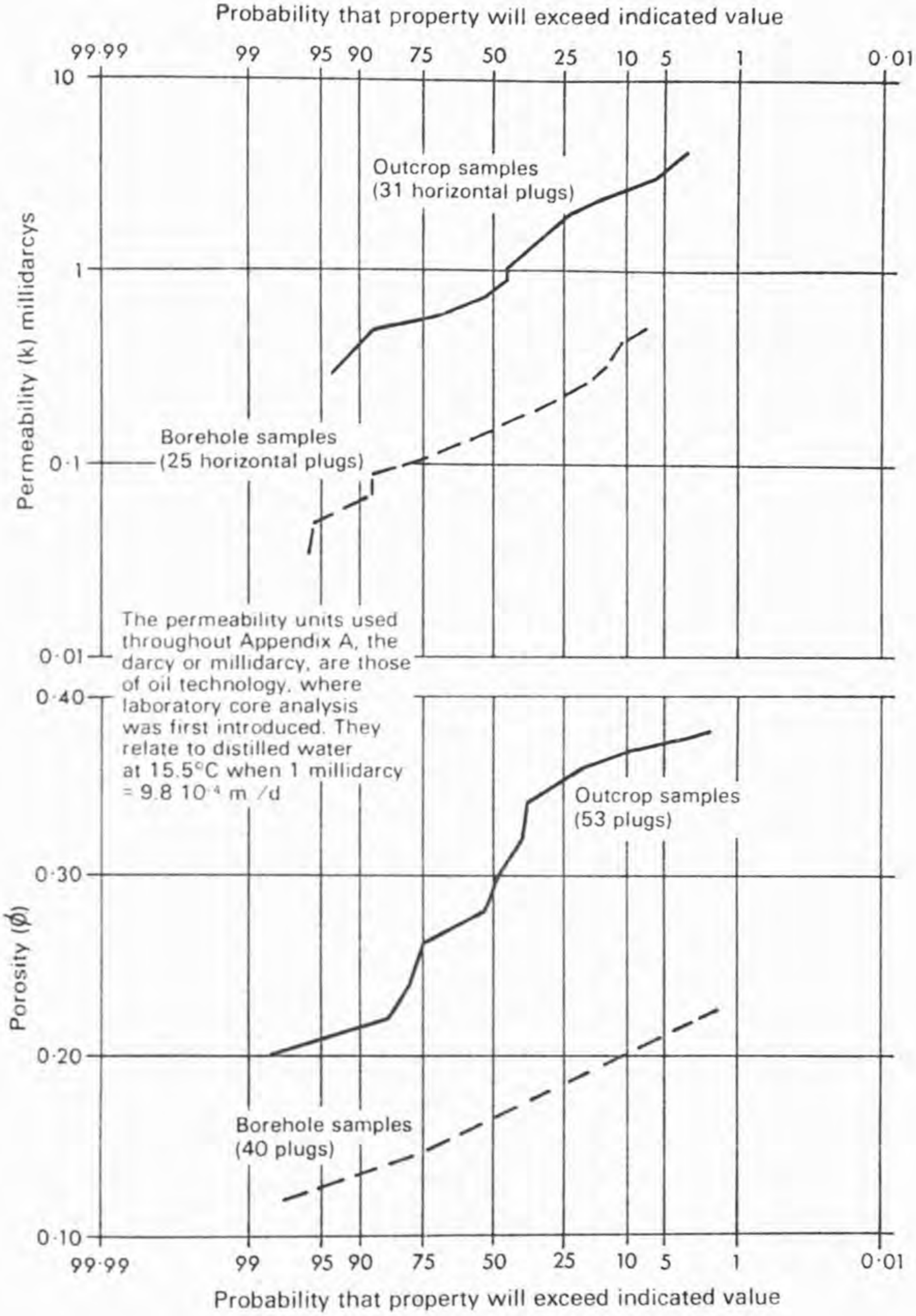


Fig. 21. Laboratory permeability/porosity relationship for samples of East Yorkshire Chalk



The permeability units used throughout Appendix A, the darcy or millidarcy, are those of oil technology, where laboratory core analysis was first introduced. They relate to distilled water at 15.5°C when 1 millidarcy = $9.8\ 10^{-4}$ m /d

Fig. 22. Probability distribution of test-plug permeability and porosity

and diameter were cut from each of the samples in three directions, vertically and in two horizontal directions at 90° to each other. A total of 53 plugs were cut from outcrop samples, 27 containing stylolites and 26 without; 40 plugs were cut from the borehole samples in the same way, of which only six contained stylolites.

METHODS OF TESTING

Permeability tests were carried out in a gas permeameter (American Petroleum Institute, 1956; Lovelock, 1970) using air as the test fluid. The error in reproducibility of the results is of the order of ± 10 per cent. Since some of the permeability values were particularly low, a modification known as the 'burette and soap bubble method' was used. This enabled the measurement of very low flow rates, which could not be determined by the use of a standard rotameter flow gauge. The results were converted into permeability to a non-reactive liquid using a correction function, based on data by Klinkenberg (1941).

The plugs were tested for porosity using the orthodox water resaturation method (American Petroleum Institute, 1960). Accuracy in reproduction of results is ± 5 per cent of the observed value for plugs with an effective porosity of less than 0.12 increasing to more like ± 10 per cent above that value.

The vertical plugs of both outcrop and borehole samples were subjected to centrifuge specific yield tests for determination of gravity drainage properties. Before spinning in the centrifuge, the curved surface of each plug was coated with a thin layer of epoxy resin to prevent lateral drainage from its sides. After coating the plugs were evacuated and saturated as for porosity testing. Batches were then spun in a centrifuge for 2 h at a speed sufficient to exert a pressure of 1/3 atm on the pore water at the mid-point of the test plug. The selection of this particular pressure is at present arbitrary, but is based on similar experimental work relating to alluvial materials (Johnson and others, 1963). Each plug in a batch was of about the same length and weight to ensure that the centrifuge was in balance. The operating speed of rotation (W in rad/s) was calculated using the following equation (Richards and Weaver, 1944).

$$T = \frac{W^2}{2g} (r_a{}^2 - r_b{}^2)$$

in which r_a and r_b are the distances from the base and mid-point of the sample to the centre of rotation during spinning respectively and T is the required tension at the point r_b. After the 2 h test period the plugs were removed from the centrifuge and rapidly weighed giving a 'spun weight' (S_2). By using dry weight (M) and saturated weight (S_1) in addition to pre-determined porosity values ($\emptyset$), figures for centrifuge specific yield (CS_y) can be obtained by using the following equation.

$$CS_y = \emptyset \frac{(S_1 - S_2)}{(S_1 - M)}$$

DISCUSSION OF RESULTS

The intergranular permeability values for all samples are very low; those of the borehole samples being significantly lower than those from the outcrop (Fig. 21). This probably relates to weathering and relief of overburden pressure, although the effect could include actual variation of the Chalk itself. There is 90 per cent probability that the permeability of the outcrop and borehole samples will be less than 3.0 mdarcy and 0.3 mdarcy respectively (Fig. 22). The ratio of vertical permeability (K_v) to horizontal (K_h) is on average less in the outcrop samples than in the borehole samples.

The porosity of most samples was moderately high. The outcrop samples tend to have higher porosity values, although a three-fold division can be seen in Fig. 21; 0.34 to 0.38, around 0.27 and less than 0.24. Of the last group, 8 out of 11 are from the Middle and Lower Chalk whereas 35 out of 38 of the first two groups are Upper Chalk samples. The porosity of supposed Middle Chalk borehole samples is however significantly lower than those from outcrop, although the sampling locations are not strictly comparable. Of the Upper Chalk outcrop groups, those of around 0.27 porosity are noticeably different in hardness and lithology from those in the 0.34 to 0.38 group. This grouping is reflected also in the form of the probability distribution of porosity (Fig. 22).

Centrifuge specific yield values were very low, not exceeding 0.009 and with a mean of only 0.002. In the presence of moderately high porosity they suggest that the diameters of the pore channels are exceedingly small. A fact borne out by the very low intergranular permeability.

INFLUENCE OF STYLOLITES ON PHYSICAL PROPERTIES

Stylolites are features found in many carbonate rocks. They appear as partings between blocks showing interdigitation in the form of columns and sockets. In the East Yorkshire Chalk they are marked by a thin grey layer of clay minerals which produces a jagged dark line in a quarry face or on a machined rock surface.

It is generally considered that these

secondary structures are formed by pressure solution (Dunnington, 1967). Limestones may go into solution on preferential interfaces at depths of burial in the order of 600 to 900 m. Solution will take place at lesser depths where there is free CO_2 present. The process leaves an insoluble residue accumulating as a thin seam at the stylolitic surface. Calculations based on the thickness of this residual layer, relative to the total insoluble material available per unit volume, and the stylolitic amplitude enable estimates of overall diagenetic reduction in thickness of carbonate deposits to be made. Some material must be removed by solution along the stylolite surfaces. However Dunnington (1967) considers that little or no part of the carbonate solution leaves the system and is redeposited in the pore spaces of the adjacent remaining rock, thus reducing its porosity.

Since all the laboratory permeability results are so low, the influence of stylolite development on physical properties must be negligible in the overall context of this report. Further work would be required for systematic study of these features in other contexts. The results showed an overall tendency for plugs with stylolites both parallel and perpendicular to the test flow direction to have higher permeability than comparable non-stylolitic plugs. Closer examination of the results for samples from which stylolitic and non-stylolitic plugs were cut, support this for both the horizontal and vertical directions, but the gross permeability values remain very low. The increase in the vertical direction is presumably the result of microscopic discontinuities formed during the differential vertical movements involved in stylolite formation.

Appendix B: Survey of the Joints and Discontinuities of the East Yorkshire Chalk in Quarry Exposures by C. M. Woodward, BSc and D. K. Buckley, BSc

INTRODUCTION

The geometry of jointing, its local and regional variation are of fundamental significance in the study of any consolidated aquifer. At the outset of investigation in the East Yorkshire Chalk it was clear that the flow and possibly the storage of groundwater must occur in the physical discontinuities of the rock mass.

In the almost complete absence of pertinent existing literature on the occurrence of inclined joints and horizontal discontinuities, this survey of quarry exposures was initiated. Its primary aim was to obtain, fairly rapidly, an adequate quantitative description of the jointing. Conventional geological field methods were used but considerable problems were experienced in the availability of sites suitable for measurement selection of representative measurement samples and in actually making measurements. Other more sophisticated methods could have been employed for the study but many of the same problems would have been met.

The generally high density of discontinuities on all scales in the chalk quarries (Plate 2) led to an immediate impression of random jointing, but despite this, measurement showed the pattern sufficiently well ordered to recognise a system. Jointing, however, is certainly more frequent and less precisely defined in pattern than, for example, in the Carboniferous Limestone (Wager, 1931). The lithology of the East Yorkshire Chalk is relatively homogenous and stratigraphic horizon was not known or expected to be of primary importance in the occurrence of jointing.

In addition to the inclined and horizontal jointing, the other principal secondary features were the ubiquitous stylolitic structures with their associated secondary marls. The average density of occurrence of these essentially stratiform near-horizontal features was measured and their relation to the former observed. Primary marls which are known to be present but were only occasionally encountered, and flint bands, which at some horizons were numerous and persistent laterally, are not dealt with in this survey.

It must be borne in mind that the joint system at depth beneath the water table may not be a simple projection of that measured in the quarry exposures. It is the former that is of most significance in groundwater hydrology. Quantitative accounts of changes in jointing with increasing depth are not known to be available. In a general way it is anticipated that the separation of joints at depth will become less and in the absence of solution, they may be so 'tight' as to approach insignificance in the context of groundwater circulation. Their prominence in quarries may be totally due to the processes of stress relief involved in exposure at the surface. However, it must be borne in mind that very small openings on frequent joints can impart high permeability to a rock mass. This permeability would be a function of joint aperture and orientation.

PROBLEMS IN REPRESENTATIVE MEASUREMENT

Classification of the terms 'joint' and 'fissure' is not satisfactory. Geologists regard large 'open' discontinuities as fissures, particularly where there has been solution, and both small and large closed discontinuities are

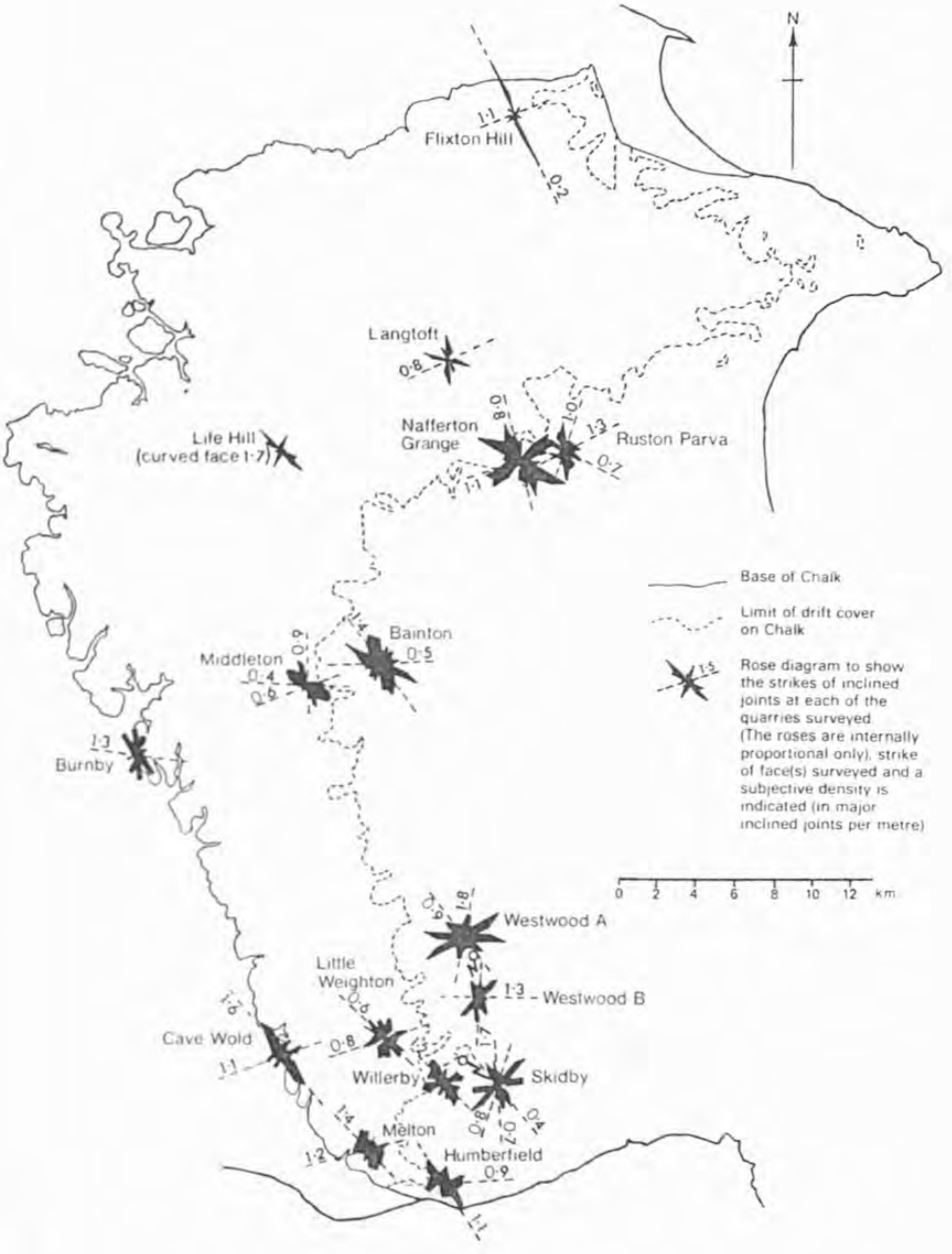


Fig. 23. Summary of joint orientation and density in quarries surveyed

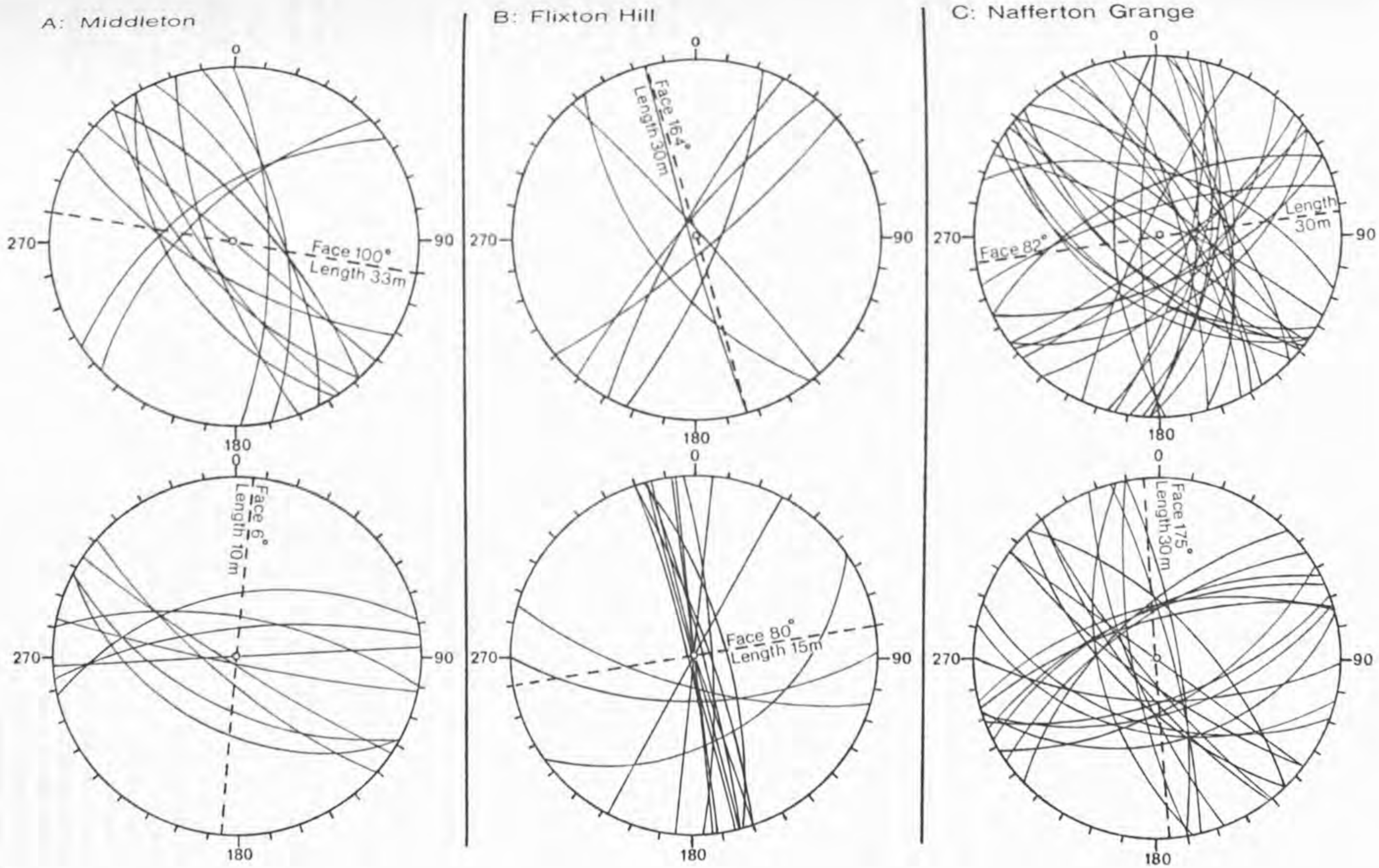


Fig. 24. Joint analysis for selected quarry faces by β-stereograms

commonly termed joints, particularly where the plane of separation is regular and straight. This classification is not followed by all engineers. Fookes and Denness (1969) draw attention to the need for strict definitions. The term 'joint' is used in this report since the structures observed are relatively large, commonly planar, in sub-parallel groups with a regular separation and without marked development of solution features.

The investigation of the joints was carried out by conventional geological methods for field measurement. Certain problems, which were immediately apparent, were those of the selection criteria used to define sampling methods.

In each quarry it was evident that major and minor joints were present and could be measured. The major/minor joint ratio was typically of the order of 1:3. Quantitatively the major joints could probably be regarded as falling into the 100 m^2 (very large), and 1 to 100 m^2 (large) subdivision on surface area, as adopted by Fookes and Denness (1969). The minor joints would be similarly classified as large, though at the lower end of the scale, and occasionally down to 1.0 m^2 in area. The incipient fractures due to weathering were commonly less than 1.0 m^2 in size. However classification based upon surface area of joints, though consistent in application where they are formed by release of residual energy, is not entirely satisfactory for the present purpose. The area of the joint observed being limited by the confines of the exposure, with unknown extension into the quarry face. Despite these limitations, it was comparatively easy to separate major from minor joints on a subjective basis, the former commonly traversing the entire quarry face.

The minor joints were commonly confined to a single bed. They were generally found to be less ordered than the major joints and a complete analysis of minor jointing would have involved a very large number of measurements. It was not undertaken and minor joints are not dealt with further in this report, although their effect on groundwater circulation may be significant.

The location of quarries where an analysis of the joint system was made is shown in Fig. 23 and Table 9. Data from 16 sites were analysed, seven of which lie beneath a thin Boulder Clay cover; about the same number again were visited and found unsuitable. The sites selected, were those with a long high face (and preferably an orthogonal face where available), where weathering was not too far advanced.

For each selected face, the orientation of strike and angle of dip of each major joint plane was measured as accurately as possible. The actual spacing between joints was also measured at some sites. This usually proved difficult or somewhat unreliable because of differing dip directions and the number of joints present in a given length of face was used for convenience as a general indicator of the overall density of inclined jointing in that plane.

The generally high joint density necessitated consideration of the characteristic length for each face; the higher the joint density the shorter the length of face necessary for statistically representative measurement. It was decided to adopt an empirical approach by taking various lengths of the same face, measuring the major joints and plotting them on stereograms. This was done for various faces and it was generally found that where available, a length of about 30 m was sufficient to provide an adequate sample of the face as a whole.

Measurement of orthogonal faces appeared sufficient to include most of the joints present in the entire rock mass, although suitable third and fourth faces to demonstrate this were rarely available. The stereograms of data collected at Middleton and Flixton Hill plotted as β diagrams (Fig. 24), illustrate degrees of contrast between orthogonal faces.

During the survey it became apparent that the quarries suitable for measurment were inadequate, both in number and distribution, for a full regional study of the jointing of the Chalk in East Yorkshire or of that part of it lying in the Hull-Hempholme catchment. Only 6 sites were located in this latter area.

PRACTICAL DIFFICULTIES IN FIELD WORK

During the field investigations difficulties were encountered because of the effect of weathering at even the better exposures. The weathering characteristics of the East Yorkshire Chalk are such that the action of freeze-thaw leads to the rapid development of the large numbers of planar and non-planar closely spaced discontinuities apparent at most outcrops. The degree of weathering at any particular quarry was immediately evident from the condition of the scree. The variation appeared to be principally a function of the time the face concerned had been exposed, its orientation and possibly also variation in rock properties. An attempt was made to exclude weathering effects from the study by selecting the most recently quarried faces, although in some instances the measured face had been exposed for up to 6 years. Local experience of the effect of weathering suggested that large quarried blocks of chalk with retained moisture could be broken

Table 9. Summary of horizontal discontinuities in quarries surveyed.

Quarry (NGR)	Chalk Division and Zone (after Wright and Wright, 1942)	Height of face (m)	Average no. of horizontal discontinuities (per metre)	Average no. of stylolites (per metre)	Remarks
Flixton Hill (TA 046 778)	Middle	8.8	1.3	8.3	Stylolites of very large amplitude present
Langtoft (TA 013 659)	Upper *Marsupites testudinarius*				No measurements face badly weathered
Life Hill (SE 929 616)	Upper *Inoceramus lingua*	5.0		17.7	Insufficient height of face
Ruston Parva (TA 069 616)	Upper *Inoceramus lingua*	17.3	1.2	12.2	Stylolites on small scale
Nafferton Grange (TA 049 612)	Upper *Discoscaphites binodosus*	8.5	0.6	4.8	
Bainton (SE 976 512)	Upper	8.6	2.4	11.2	
Middleton (SE 942 502)	Upper *Hagenowia rostrata*	4.8	few	19.6	Stylolites on very small scale, insufficient height of face
Burnby (SE 858 467)	Lower	4.5		26.0	Stylolites, non-planar and small amplitude, insufficient height of face
Westwood A (TA 020 382)	Upper *Uintacrinus westphalicus*	10.0	3.6	10.0	
Westwood B (TA 025 375)	Upper *Marsupites testudinarius* and *Uintacrinus westphalicus*	10.0	1.6	16.0	
Little Weighton (SE 982 334)	Upper *Hagenowia rostrata*	12.0	very few	30.0	
Cave Wold (SE 930 325)	Middle *Terebratulina lata*	4.3		6.8	Insufficient height of face
Skidby (TA 021 324)	Upper *Hagenowia rostrata*	9.5	very few	20.5	
Willerby (TA 011 314)	Upper *Micraster cortestudinarium*	5.0	few	25.3	Insufficient height of face
Melton (SE 970 278)	Middle *Terebratulina lata* and *Inoceramus labiatus*	14.0	1.0	7.4	Face badly weathered, measurement difficult
Humberfield (TA 015 263)	Middle *Terebratulina lata*	13.0	1.0	10.0	

up by as little as three 'nights' frost. An inherent problem in sampling was the presence of non-planar joints, and the departure of planar joints to curved surfaces. On many faces non-planar joints appeared to be compounded of several planar joints. In these circumstances measurements were taken on the significant component only. Some non-planar joints did not fall readily into this scheme, though fortunately their number was small.

Further problems were the difficulty of access to high faces and the condition of the exposures. The separation between opposing joint surfaces in quarry sections generally proved to be less than 5 mm, except where obviously affected by weathering and blasting. Frequently there was little relief on the quarry faces and it was necessary to use a ladder and to remove adjacent blocks to expose a sufficiently large surface for measurement. This restricted measurement to a height of 3 to 5 m above quarry floor or gallery level, along the 30 m length sampled.

DISCUSSION OF JOINT MEASUREMENTS

The orientation of major jointing at the selected quarries is shown on the rose diagram in Fig. 23, which is the principal end-product of the survey. All joint data were also plotted on stereograms, chiefly in the form of β-diagrams (for example, Fig. 24). However rose diagrams are considered more useful for the purpose of this study where strike orientation is probably more important than dip inclination, which in any case is generally high. The measured density of inclined jointing on the faces surveyed is also recorded in Fig. 23; but while the joint roses are internally proportional they are not all to the same scale because of the differing lengths of faces measured at each site.

Many of the inclined joints measured in the survey formed apparently conjugate sets inclined at more than 50° to the horizontal, quite frequently with their strikes aligned roughly north-west and east-north-east. The former may reflect the influence of the broad regional synclinal structure. Other major joint sets can be recognised locally and are discussed further below. The present survey confirms to some extent the general observation of Versey (1948), who regarded the joint system as comprising three sets, two transverse sets orientated north-west and north-east and an inclined series of unspecified orientation (which make an angle of 30° to the vertical). In general the density of jointing does not vary greatly from 0.7 to 1.3 per metre. Sites having the overall lowest density in all directions (Middleton, Little Weighton and Skidby) would be in the (Upper Chalk) *Hagenowia rostrata* Zone of Wright and Wright (1942). However it is considered that insufficient sites were available in that Zone to draw a general conclusion. No other indication of stratigraphic or lithological control was detected.

The stresses that have been applied to the Chalk strata in East Yorkshire during their geological history include stresses of tectonic origin, associated with deep burial and regional deformation, stresses related to the weight and thrust of the ice sheets during the Pleistocene, and stresses resulting from erosion of overburden and the development of valleys and the escarpment. Price (1959) considered the 'master' and 'regional' (major) joints develop by lateral expansion during regional uplift, releasing the residual stresses of prior tectonic deformation, whose directional aspect determined their orientation. The oblique shear joint system of the East Yorkshire Chalk is consistent with a vertically directed maximum stress.

The chief visual feature of the major jointing is the trellis pattern which it forms on quarry faces together with the scarcity of horizontal or low angle traces of the same system in the orthogonal face. This is a function of the high angle of inclination of the jointing reducing the chance of intersection on the orthogonal face, which probably often approximates to one joint surface of the system. Another feature frequently seen was spear-head shaped blocks of Chalk resulting from the intersection of conjugate sets of high angle joints. Slight displacements along joint planes are very common and thought to be due to the effects of glacial and/or superficial disturbance. It was also noted that several of the joint planes carried slickensides though a study of joint surface features was not undertaken.

While the strikes of the conjugate sets of inclined joints are frequently oriented north-west and east-north-east (for example, at Nafferton Grange and Willerby), many departures from this pattern can be identified (Fig. 23). At some sites there is a tendency towards inclined joint development in many directions (for example, Skidby) but still with some strikes dominating over others. Where one strike direction is strongly developed it usually appears attributable to the influence of local factors, for instance the closeness of the escarpment (at, for example, the Burnby, Cave Wold and Melton sites). Since the same strike directions are seen at dip-slope sites, however, it is possible that an already existing tectonic joint set has been further accentuated by partial release of the stress field associated with the scarp.

The Flixton Hill site is also on the crest of the escarpment but shows joint development almost totally confined in the perpendicular north-northwest direction (Figs. 23 and 24). This could be related to the proximity of the important Hunmanby Fault, or another undefined fault of similar orientation, but there is also an east-west line of tectonic disturbance immediately to the south (Fig. 3).

The joint roses for the Westwood A and B sites (Fig. 23) are less similar than would be expected from their close proximity. Insufficient exposures and geological information are available to suggest local reasons for such diverse rose diagrams. This example clearly emphasises the caution necessary in attempting to draw regional implications from individual scattered locations like those used for the present study.

Despite this variability, it is considered that the results as a whole provide some evidence to support the concept of continuity of the joint system across the outcrop. However, there is little evidence of any significant change in joint pattern reflecting the reputed minor structural elements (Fig. 3).

The relationship of the major inclined jointing to the dry valleys is not straightforward. The latter have been studied in detail by Lewin (1969), who summarised their orientations in each 10 km grid square by rose diagrams, which may be readily compared with the results of the present survey. Dry valleys of north-east orientation dominate and it is important to note that this alignment is against the general slope of much of the terrain, which along with the angular topology suggests a preferential adjustment to the original jointing. The modification of joint pattern due to valley development itself is a complicating factor in any comparison.

STYLOLITES AND HORIZONTAL DISCONTINUITIES

The Chalk of East Yorkshire is characterised by the frequent and persistent development of stylolites and their associated marl seams. They have not been studied or described in detail in this formation but their normal origin is discussed in Appendix A. Most commonly they are near horizontal and parallel to the bedding, as far as this can be discerned, but occasionally occur along inclined planes. They range in vertical scale from just visible to amplitudes of 60 mm. Locally (for example at Flixton Hill), some developments with a height of the order of 1.0 m were observed.

A summary of data concerning the occurrence of stylolites is given in Table 9. From the data collected, stylolite development does not appear to show correlation with stratigraphic horizon. At the four sites assigned to the Middle Chalk, a relatively uniform stylolite density of 6.8 to 10.0 per metre was observed. The 11 sites in the Upper Chalk showed great variability with extremes of 4.8 and 30.0 per metre being recorded at Nafferton Grange and Little Weighton respectively.

In all outcrops it was observed that the joint system cut across both the stylolites and most flint bands. There is thus little reason to suppose that the large numbers of these secondary features could themselves lead to frequent perching or confining within the Chalk aquifer.

The number of continuous horizontal discontinuities, other than the predominant stylolites, were also recorded at each face measured (Table 9); their average density ranges from 0.6 to 3.6 per metre. The term horizontal discontinuities is used and they may in fact be bedding separation planes, but Gallois, R. W. (personal communication) considers that many such features in the Chalk are very low angle shear joints formed at interfaces between a hard indurated bed and either marl bands or marly horizons. The shearing may also have been responsible for the formation of numerous marly wisps observed in the Chalk at many localities.

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Dd. 496303 K8

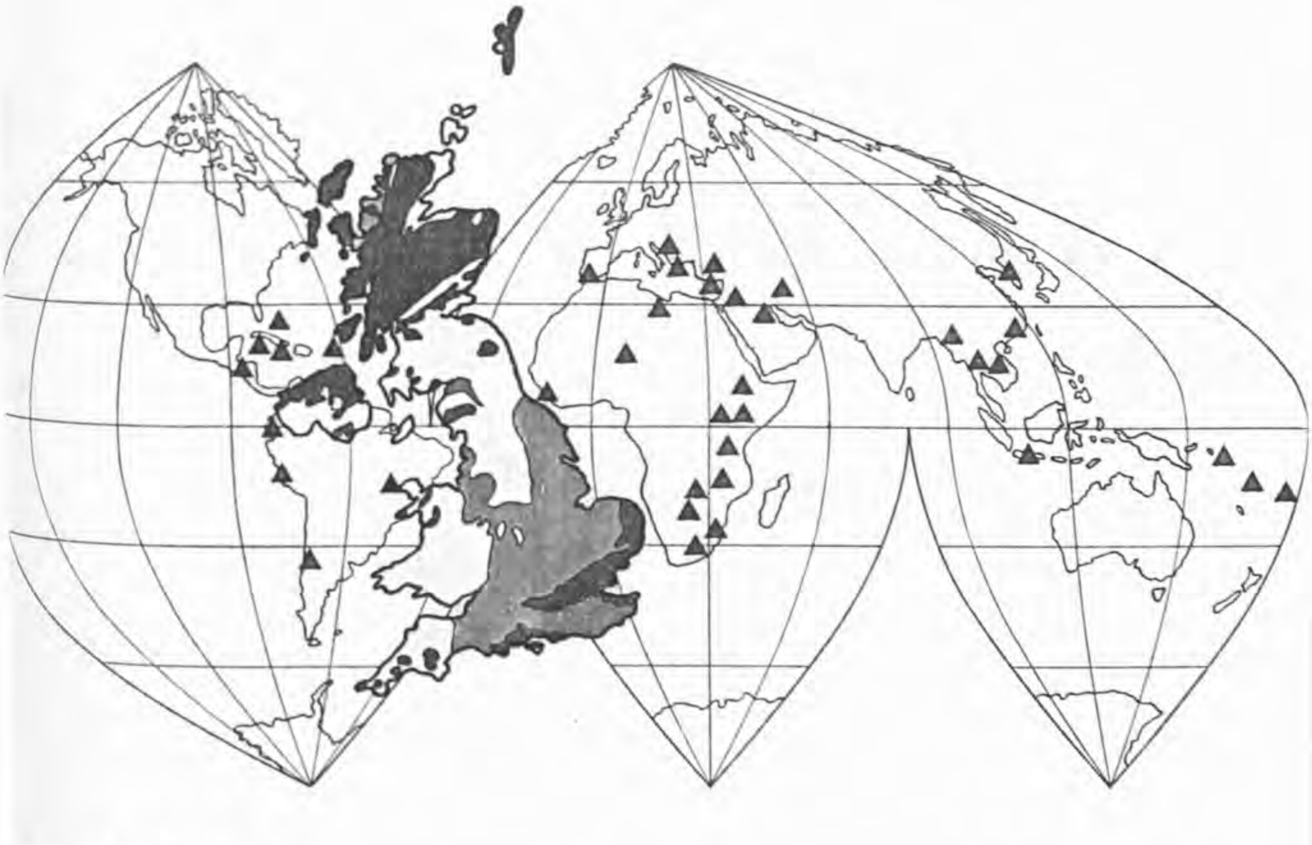
Printed in England for Her Majesty's Stationery Office
by Unwin Brothers Limited, The Gresham Press,
Old Woking, Surrey

NATURAL ENVIRONMENT RESEARCH COUNCIL (21)

INSTITUTE OF GEOLOGICAL SCIENCES

Groundwater resource development and saline water intrusion in the Chalk aquifer of North Humberside

REPORT No. 76/4



HMSO 70p net

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Groundwater resource development and saline water intrusion in the Chalk aquifer of North Humberside

S. S. D. Foster, E. L. Parry and P. J. Chilton

London: Her Majesty's Stationery Office 1976

PREFACE

The work described was carried out jointly by the Institute of Geological Sciences and the former Yorkshire River Authority under the general direction of the Chief Hydrogeologist, then Mr D.A. Gray, and the Water Resources Engineer, Mr K.H. Tattersall, of the respective organisations.

The survey was undertaken prior to the administrative reorganisation which followed the implementation of the Water Act, 1973. Accordingly, the organisations referred to in the Report are those who provided facilities, operated equipment or collaborated with the Institute's staff during the course of the study rather than their successors.

The staff of the former Kingston-upon-Hull CBC Water Department provided assistance in the field investigations and full data on their groundwater sources. Certain private owners and operators of wells and water supply boreholes in the area are thanked for their assistance and collaboration.

Most of the chemical analyses of water samples were undertaken in the laboratories of the Kingston-upon-Hull CBC, and the tritium determinations by the AERE Harwell Laboratories; their services in these respects are gratefully acknowledged.

The geological aspects of the report were discussed with colleagues in the Institute; the advice of Mr J.G.O. Smart, Mr G.D. Gaunt, Mr J.H. Hull and Dr R.T.R. Wingfield is especially acknowledged. It should be recognised that the area is currently being resurveyed and that some geological interpretations in this report may require revision when the work is complete. However, they are unlikely to affect the main conclusions in respect of the groundwater resources.

Kingsley Dunham
Director

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1 March 1975

Dr A. W. Woodland succeeded Sir Kingsley Dunham as Director on 1 January 1976

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Summary

The estimated average rate of long term replenishment (53 000 Ml/a) of the Chalk aquifer in East Yorkshire south of the latitude of Hempholme Lock, exceeded the 1972 actual abstraction (37 000 Ml/a) but was less than the licensed 1972 abstraction (70 000 Ml/a). The major source of error in estimating total replenishment is the infiltration, particularly that through the upland boulder clays. Some 75 per cent of the total abstraction is for public water-supply and is concentrated within 2 to 8 km of the Humber.

In years of severe drought there is a draught of over 19 000 Ml on aquifer storage. Adverse side-effects are falling groundwater levels, reductions in well yields, competition between abstractors and, in the south, risk of increased saline intrusion. The main saline intrusion front is in Kingston-upon-Hull, with a minor front developing intermittently at Hessle. The quality of the Dunswell source, on the other hand, appears to be intermittently threatened by saline palaeo-groundwater from beneath Holderness.

It is remarkable, bearing in mind the size and distribution of abstraction, the saline intrusion is not considerably worse. This appears to be due to rapid natural reductions in aquifer transmissivity towards the Humber and Holderness. The present situation does not justify an immediate cutback in abstraction or specific engineering works to control saline intrusion. A progressive redistribution of major groundwater abstraction, however, is strongly recommended as the most efficient method of groundwater resources management.

Sommaire

Le débit moyen évalué du remplissage à long terme (53 000 Ml/a) de l' aquifère crayeux en East Yorkshire, au sud de la latitude de Hempholme Lock, a depassé en 1972 l'extraction véritable (37 000 Ml/a) mais il n' a pas atteint l'extraction autorisée (70 000 Ml/a). La source majeure d' erreur dans l'évaluation du remplissage total est l'infiltration, surtout celle à travers des argiles à blocaux aux hautes terres. De l'extraction totale, environ 75% est pour la provision publiqué et elle se concentre dans 2.8 km de la Humber.

Pendant les années de sécheresse sévère l'extraction se monte à plus de 19 000 Ml provenant de l'aquifère. Par conséquent les riveaux d'eau souterraine tombent, le rendement des puits est reduit, la concurrence parmi les extracteurs, et le risque d'intrusion saline augmentent. Le front principale d'intrusion saline est dans Kingston-upon-Hull, avec un front de moindre importance qui se montre par intervalles à Hessle. D'autre part la qualité de la source à Dunswell semble être menacée par intervalles par l'eau saline paléo souterraine de dessous Holderness.

Tout en considérant l' étendue et la distribution de l' extraction, il est remarquable que l'intrusion saline n'est pas beaucoup plus importante. Ceci semble être attribuable aux réductions naturelles rapides dans la transmissibilité vers la Humber et vers Holderness. La situation actuelle ne justifie pas une réduction immédiate de l'extraction, on des travaux mécaniques spécifiques pour régler l'intrusion saline. On recommende fortement, cepandant, la redistribution progressive de l'extraction majeure d'eau souterraine parce que c'est la méthode la plus efficace de régler les ressources en eaux souterraines.

Zusammenfassung

Die berechnete durchschnittliche Geschwindigkeit von langfristiger Auffüllung (53 000 Ml/a) des Kreidegrundwasserleiters in East Yorkshire südlich von der Breite von Hempholme Lock war grösser als der 1972 wirkliche Abstraktion (37 000 Ml/a) aber war weniger als die gestattete 1972 Abstraktion. Die Hauptfehlerquelle im Schatzen von der totalen Auffüllung ist die Einsickerung, hauptsächlich diejenige durch die Hochblocklehme. Etwa 75% von der ganzen Abstraktion ist für das Volkswasserleitungs system und ist in 2.8 km vom Humber konzentriert.

In Jahren von schwerer Trockenheit gibt es einen Zug von über 19 000 Ml von der Grundwasserleiterslagerung. Ungünstige Nebenwirkungen sind fallende Grundwasserhöhen, Verminderungen in Brunnenabfluss spenden, Rivalität zwischen denjenigen, die für das Abziehen verantwörtlich sind, und auch, im Süden, Gefahr von erhöhter Salzintrusion. Der Hauptsalz-

intrusionsregion ist in Kingston-upon-Hull mit einer kleineren Front, die sich in Hessle abwechselnd entwickelt. Die Qualität von der Dunswell Quelle anderseits scheint abwechselnd von Salzpaläogrundwasser von unter Holderness gedroht zu sein.

Wenn man die Grösse und die Verbreitung der Abstraktion überlegt, ist es merkwürdig, dass die Salzintrusion nicht bedeutend grösser ist. Scheinbar ist diese eine Nachfolge der schnellen natürlichen Reduktionen in Grundwasserleiterübertragung nach dem Humber und Holderness. Die gegenwärtige Situation berechtigt nicht ein sofortiges Einschränken in Abstraktion oder besondere technische Anlagen, um die Salzintrusion einzuschränken. Drigend aber empfehlt man eine fortschrittliche Neuverteilung von grösserer Grundwasser-abstraktion als die ergiebigste Einrichtung von Grundwassermittel.

Groundwater resource development and saline water intrusion in the Chalk aquifer of North Humberside

S. S. D. FOSTER, E. L. PARRY AND P. J. CHILTON

Introduction

BACKGROUND

The groundwater resources of the Chalk aquifer have long been heavily developed on North Humberside for Kingston-upon-Hull water supply (Fig. 1). The principal public groundwater supply sources are located immediately to the west and north of the city (Fig. 2) and currently have an estimated combined drought yield of about 70 Ml/d. These sources, together with a river intake works on the Hull at Hempholme Lock (Fig. 2), supply all of North Humberside and much of Holderness, an area with a total population approaching 500 000.

Humberside has by British standards something of a history of water deficiency and shortage, particularly since the late 1940s (Fig. 1); the effects have been at best inconvenient, at worst insanitary and disruptive (Jones, 1955). Industrial water requirements have always been a large item in the total demand of the Humberside area and while significant quantities have been abstracted by individual companies from the Chalk, both in Kingston-upon-Hull and in Beverley, over the past 25 years this burden has increasingly fallen on the statutory water undertaking.

Under the stimulus of the Humberside food processing and preserving industries, recent years have seen major increases in large scale market gardening. Spray irrigation demands can be high and fluctuate enormously on both a daily and seasonal basis and are thus difficult and costly to accommodate from a public-supply distribution network. In the absence of reliable surface sources they are most economically met by direct groundwater abstraction from individual private boreholes. Over 70 boreholes are licenced to abstract for agricultural purposes in the principal market gardening area between Kingston-upon-Hull and Beverley. In extreme drought there is unfortunate competition for the available groundwater storage between public and private abstractors.

The source of most of the groundwater abstracted in the Humberside area is infiltrating rainfall on the Chalk outcrop or intake area to the west and north-west (Fig. 2). In the North Humberside area the Chalk aquifer is bounded in most other directions by bodies of saline water; poor quality water is also present at the surface in the tidal reaches of the Hull and its associated drainage systems. When the rate of abstraction exceeds that of freshwater replenishment there is considerable risk of saline water intrusion. In the old industrial areas of Kingston-upon-Hull local over-pumping led to this condition between 20 and 50 years ago (Gray, 1952); such conditions have also been reported in the Grimsby area of South Humberside (Gray, 1964).

Several previous workers (Lapworth, 1933; Hainsworth, 1950; Gray, 1952) have recognised the principal problem of water management to be the determination of the maximum reliable yield and groundwater flow-frontage of the main area of North Humberside groundwater abstraction, and in particular the major public supply sources in that area, and thus the evaluation of the risk of further encroachment of saline water into the Chalk aquifer.

PURPOSE AND SCOPE OF THE REPORT

This report re-examines the state of groundwater resources on North Humberside. Its primary purpose is to establish as accurately as possible the state of balance between groundwater replenishment and abstraction in the area, to provide a comprehensive basis for the future management of these valuable resources and to consider possible modifications in their mode of deployment. In this connection it is necessary to consider the entire hydrological system of

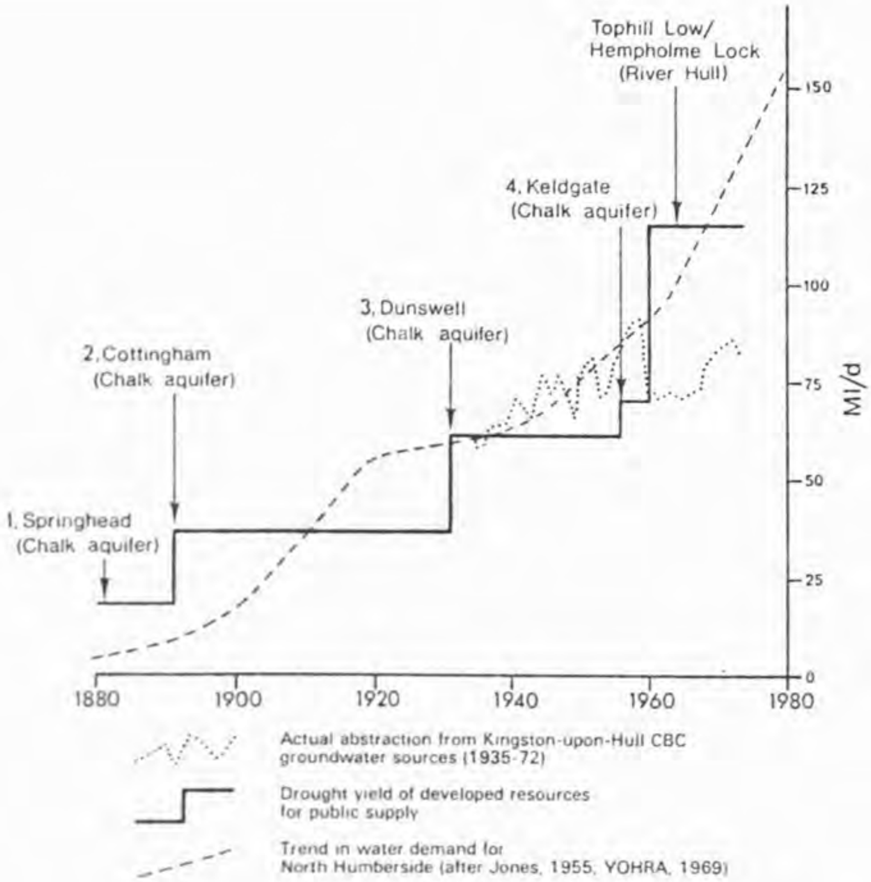


Fig. 1. Growth of demand and development of water-supplies on north Humberside

the Chalk as far north as the latitude of Hempholme Lock (Fig. 2). It is complementary to another (Foster and Milton, in press), which deals with the hydrology and potential development of groundwater storage capacity in the unexploited part of the East Yorkshire Chalk to the north of the latitude of Hempholme Lock.

Since the last report on the area (Gray, 1952), more accurate and continuous records of groundwater abstraction from the Chalk have accumulated through systems of statutory returns. Other new data presented or used in this report includes comprehensive groundwater level surveys in 1970 and 1971, a hydrogeochemical survey in 1967 and 1973 and the detailed investigations at Etton (Fig. 2) of the hydraulic behaviour of the Chalk aquifer (Foster and Milton, 1974). It has been possible to describe the extent of saline water intrusion in some detail on three occasions in the period 1951-1973 and compare it to variations in the amount and distribution of groundwater abstraction, using the operating records of the Kingston-upon-Hull CBC sources.

The present investigation is restricted by three deficiencies in data.

1. There is a lack of detailed study on infiltration to the Chalk, either by direct or indirect methods. Thus, the errors in estimating the total recharge may be considerable, limiting the accuracy of the groundwater balance overall.

2. There are no critically sited observation boreholes for electrical conductivity logging and depth sampling. It is therefore currently not possible to determine precisely either the location or the movement of the saline water interface or mixing front through a time sequence of hydrological conditions.

3. There have been no satisfactory hydrological pumping tests conducted in the Kingston-upon-Hull area, nor in the southernmost part of the Wolds, and information on aquifer properties and hydraulic boundaries has had to be extra-

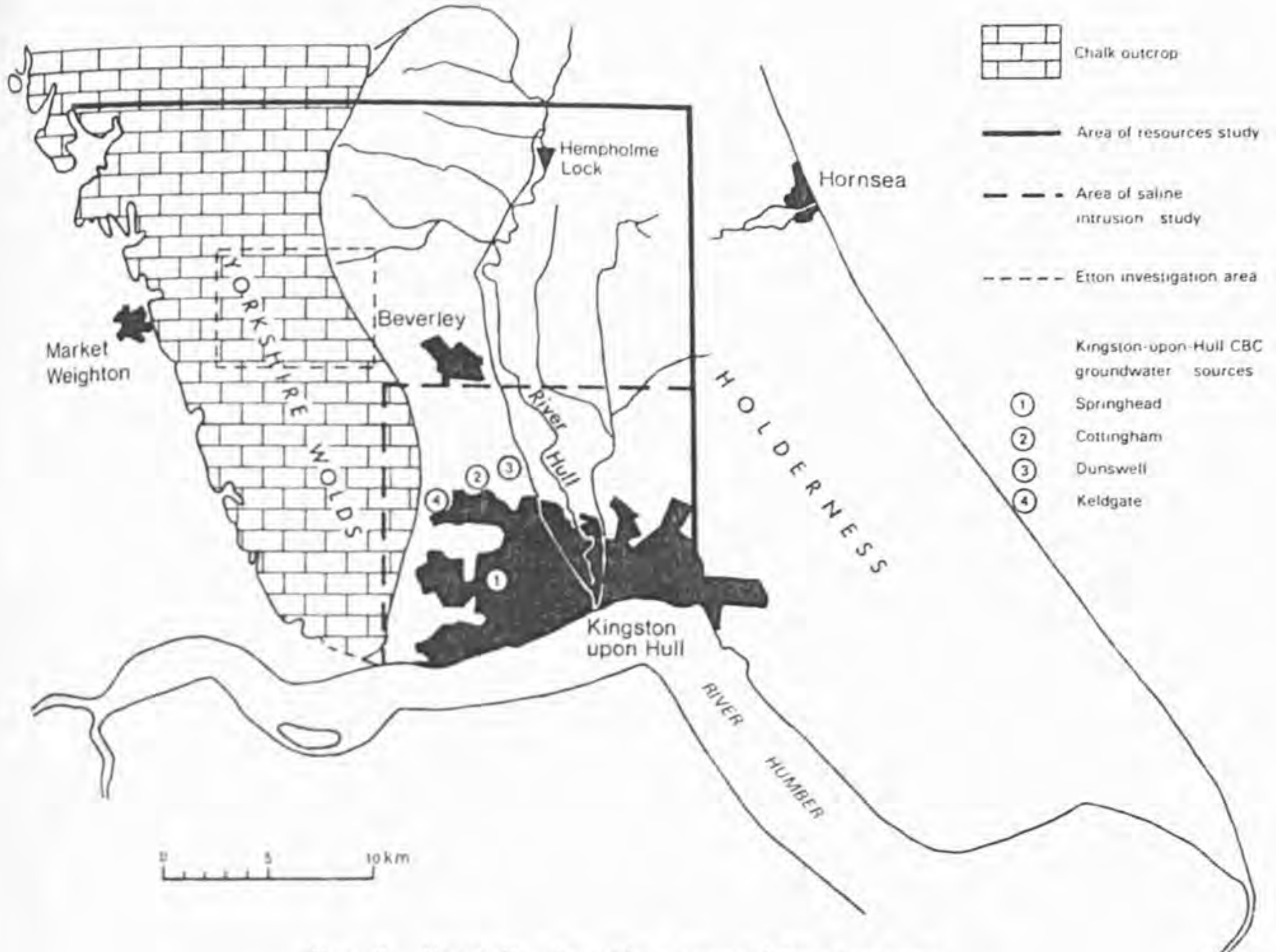


Fig. 2. North Humberside - general location map

polated from investigations at Etton and elsewhere.

These data deficiencies, particularly 2 and 3, would have to be satisfied before any major changes in the groundwater abstraction regime or measures to control saline water intrusion could be designed.

The Geological and Hydraulic Character of the Aquifer

CHALK STRATIGRAPHY AND STRUCTURE

The Chalk of East Yorkshire comprises a uniform sequence of pure white limestones with a maximum thickness in excess of 420 m. Microscopically these limestones are composed primarily of a matrix of plates of minute spheroidal organic bodies (coccoliths) less than 3 µm in diameter, in which occasional larger particles are embedded (Black, 1953; Hancock and Kennedy, 1967). While there are some variations in physical properties in the vertical sequence, and both weathering and the presence of secondary structures may have induced modifications, the rock material normally possesses only moderate porosity (0.13 to 0.21), less than its stratigraphic equivalents in southern England, and very low intergranular permeability (Foster and Milton, in press). The implication is of exceedingly small pore diameters and this is borne out by the very low specific yields (mainly less than 0.003) obtained from core samples in laboratory centrifuge tests. Both flow and storage of groundwater, in the saturated zone, must be essentially confined to physical discontinuities in the rock mass, joints and less regular fissures, enlarged locally by solution.

The sequence of limestones is broken by occasional but persistent primary marls, rarely more than 50 mm in thickness, and more frequently by secondary features, notably nodular and tabular flint bands up to 300 mm in thickness and stylolitic solution features with associated marl seams.

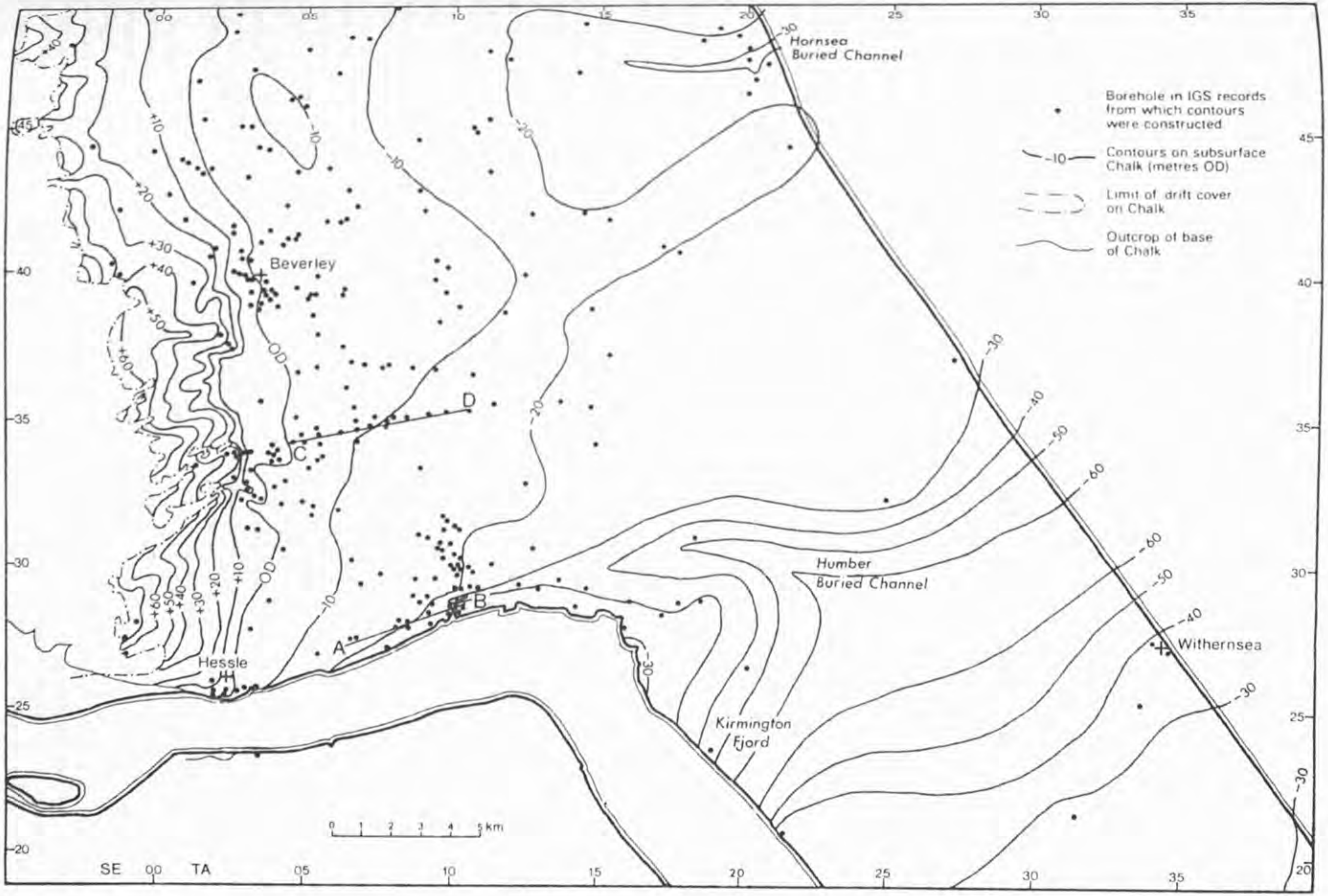


Fig. 3. Contours on the sub-drift Chalk erosion surface

The subdivision of the East Yorkshire Chalk and the stratigraphic validity of existing subdivisions remain under study (Wood, C.J., personal communication). At present it is probably only practical for hydrological purposes to recognise two subdivisions of the Chalk, namely, the Lower Chalk, bounded above and below by the Black Band and the Red Chalk respectively, and the overlying undivided Middle/Upper Chalk. The latter is hydrologically the more important. It is a uniform sequence but flints are thought to be frequent only in the basal 140 to 180 m; the total thickness may exceed 300 m in places, but the actual thickness present at a given locality will be largely dependent on erosion.

The available data on the geological structure and occurrence of joints and discontinuities in the East Yorkshire Chalk have already been summarised (Foster and Milton, in press). The southern Yorkshire Wolds represent the western part of the outcrop of an open south-easterly plunging syncline; the dip of the Chalk is to the east and generally less than 2°, except where tectonic and superficial disturbances are present. The minor structures within the main syncline are not fully established; there appear to be one or two minor very open folds with west-east axes in the southern part of the region, and the possibility of minor faults cannot be precluded.

The sedimentation and structure of the underlying Jurassic strata were dominated by persistent but intermittent uplift centred on a belt running west-east across the area immediately north of the latitude of Market Weighton (Kent, 1955); only relatively mild influences, however, appear to be present in the Cretaceous sedimentation. When traced northwards from the Humber, the base of the Chalk oversteps each member of the Jurassic sequence and rests on a variety of rock types down to the Lower Lias. The majority of these strata are virtually aquicludes but there are some relatively permeable formations in the Jurassic sequence which, over limited areas close to the escarpment, are probably in hydraulic continuity with the Chalk (Foster, 1968); this factor may influence the position of the Chalk groundwater divide locally.

In East Yorkshire there are no strata representing the Tertiary, during which the deformation of the Chalk strata, including the folding of the main syncline, occurred. This was an extended period of uplift and denudation; the escarpment and other essential features of the present topography were developed and considerable thicknesses of the uppermost divisions of the Chalk eroded from the higher ground and the crest of the existing escarpment. The Tertiary topography was then modified by Quaternary processes which affected the Chalk groundwater reservoir in two ways, firstly by the erosion and weathering of its surficial layers at levels now below hydrological base level, and secondly by the deposition in the lower lying areas of a cover of mainly low permeability materials. This had the effect of confining the chalk groundwater and allowing only localised discharge or reducing rates of infiltration and generating surface run-off.

The buried erosion surface of the Chalk (the rock-head) has been contoured from the evidence of about 250 boreholes contained in the Institute's records (Fig. 3); this map is an extension of that previously prepared for the northern part of the region (Foster and Milton, in press). Two distinct types of erosional feature, a buried coastline and some major buried channels, are revealed. The buried coastline is a continuation of the feature that runs in the subsurface from north-east of Bridlington along the eastern flank of the Wolds, continuing (Fig. 3) to meet the Humber Gap near Hessle. Locally it reaches the dimension of a buried cliff. In its vicinity the buried surface of the Chalk has experienced marine erosion and exceptionally high permeability is likely to be associated with deep fissuring and beach deposits; the feature as a whole is potentially of major significance to regional hydrology and groundwater development (Foster and Milton, in press).

Within the area illustrated in Fig. 3, there are three major buried channels; that beneath Hornsea, the Humber Buried Channel and the so-called Kirmington Fjord, which continues into north Lincolnshire. Of most significance here is the buried channel system of the Humber. East of Hessle it departs from the course of the existing river and is located to the north of the northern bank in the Kingston-upon-Hull city centre, thereafter continuing approximately due east beneath southern Holderness.

Throughout East Yorkshire the surface layers of the Chalk, whether or not drift covered, have been affected by Pleistocene cryoturbation (freeze-thaw) processes. In many places a layer up to 10 m thick of in-situ broken up chalk (called 'chalk bearings' by water well drillers) or a redistributed chalk-flint gravel are present and can be responsible for gross permeability variations. Local differences in ice action appear to be responsible for development of impermeable 'putty-chalk' up to 3 m thick, replacing the bearings at a few scattered

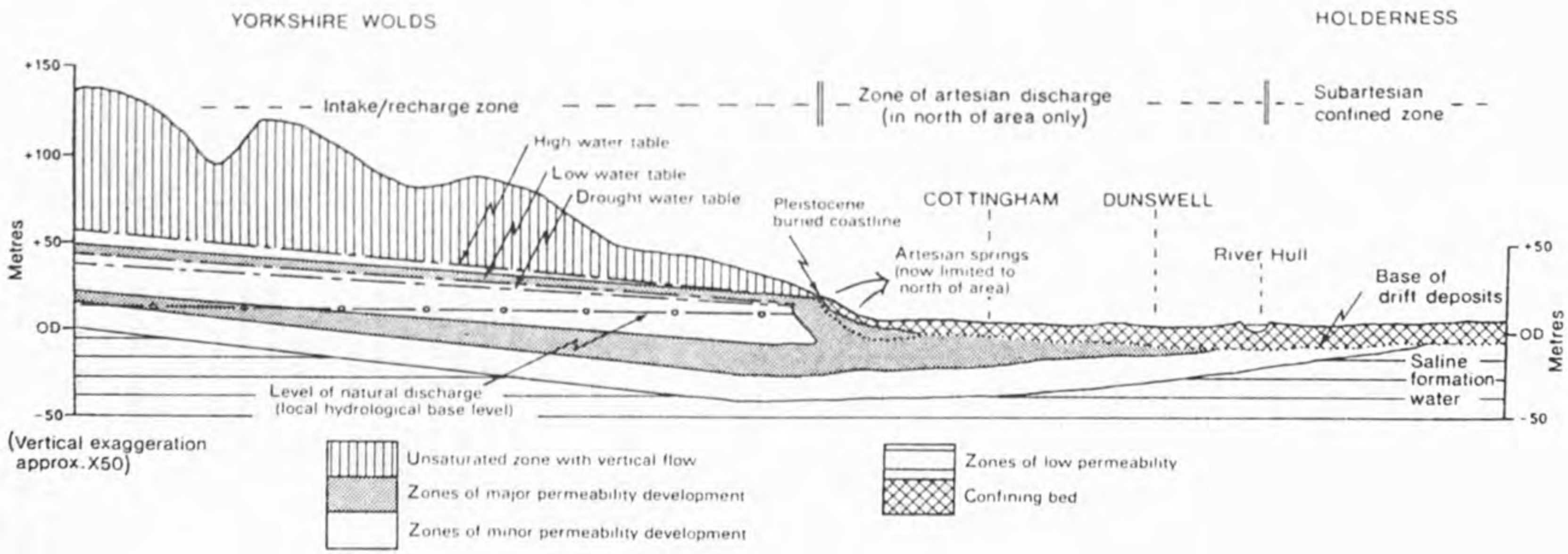


Fig. 4. Generalised interpretation of the groundwater flow regime and hydraulic boundaries of Chalk aquifer

locations.

The landscape of the Chalk outcrop in the southern Yorkshire Wolds is dominated by the dry valley network which dates back to the Tertiary/Quaternary periods. Most of this network does not, it would seem, bear directly on the present day hydrogeology of the Chalk because of the considerable depth to the water table.

ETTON INVESTIGATIONS: THE WATER TABLE AQUIFER

The boundary between the zones of aeration and saturation in the outcrop area of the East Yorkshire Chalk appears generally to be that of a simple water table. Investigations of the water table aquifer in the Etton area (Fig. 2) have been documented independently (Foster and Milton, 1974). They centred around a series of hydrological pumping tests during which the level of control over experimental conditions was in most respects exceptional. Supporting data were obtained by geophysical borehole flow investigations and by monitoring the natural recession of groundwater levels.

The Etton investigations led to a number of important conclusions on the hydraulics of the water table aquifer. The existence of a laminar (Darcy) flow regime was confirmed even for high pumping rates at distances down to 122 m from the point of abstraction. The unsteady state observation borehole responses to test pumping showed neither major lateral hydraulic boundaries nor strong lateral anisotropy in the cone of pumping depression. At near minimum groundwater levels in October 1970, T (transmissivity) and S (storage coefficient) values of 1000 m^2/d and 0.005 were indicated. It is likely that the latter represents the effective specific yield (S_y) but it is possible that other minor sources of longer delayed yield contributions could be present. Subsequent test pumping in April 1971, with a higher (although not maximum) level of saturation, gave similar results but with a much greater T value (2200 m^2/d), demonstrating the extremely high horizontal permeability of the zone of seasonal water table fluctuation.

The geophysical flow investigations showed the levels of entry of groundwater into the Etton pumping boreholes to be restricted; at depth the bulk of the water pumped was derived from a zone of about 7 m thickness, whose base was located 17 to 22 m below OD at the site. The presence of marked chloride residuals (the products of previous acid treatment of the boreholes) suggested minimal regional groundwater movement below about -29 m OD.

The Chalk aquifer in the outcrop area thus appears to approximate to an areally-uniform, layered, high T/low Sy, laminar-flow, carbonate aquifer characterised by fast hydraulic responses and moderately high actual flow rates. Its layered hydraulic character (Fig. 4) has been corroborated by the analysis of riverflow and groundwater data in the Hull-Hempholme catchment to the north; the similarity in form of groundwater recessions throughout the Yorkshire Wolds, including the Etton area, suggests that such layering is a widespread feature (Foster, 1974). The extremely high permeability of part of the zone of seasonal water table fluctuation can be attributed to preferential solution increasing the aperture of discontinuities in this part of the rock mass; its areal uniformity probably indicates that solution has been concentrated on horizontal discontinuities.

CHANGES DOWN-DIP

Permeability development in the East Yorkshire Chalk, as in other limestone terrains, appears to be due to solution during the long term circulation of fresh groundwater to a given base level; it is thus to be expected that T values will increase down the dip-slope towards the discharge areas on the flanks of the Hull valley, where the total volumetric flow must have been greatest. At those times in the post-Cretaceous history when a much lower hydrological base level existed, the development of significant solution permeability at depth in the Chalk aquifer might have been expected. The occurrence of a major flow zone at around -10 to -20 m OD at Etton may be associated with the Pleistocene buried channels and drainage system.

Under increasing drift cover radical changes in the storage coefficient (S) of the Chalk aquifer are to be expected. The limited evidence from data on specific capacity of, now mainly disused, water supply boreholes in Holderness suggests a rapid decrease in T also and an apparent absence of solution permeability (Foster and Milton, in press).

Despite its transitional position, the area between the water table aquifer of the Wolds outcrop and the subartesian aquifer in Holderness has hydraulic properties which are far from transitional; geological factors exercise the overriding control. The presence of the buried Pleistocene coastline, together with the surficial layer of cryoturbated chalk, results in the likelihood of extremely high permeability over limited areas and saturated depth intervals (Fig. 4). A T value in excess of 6000 m^2/d has been suggested for the most permeable zone in the Haisthorpe area to the north (Foster and

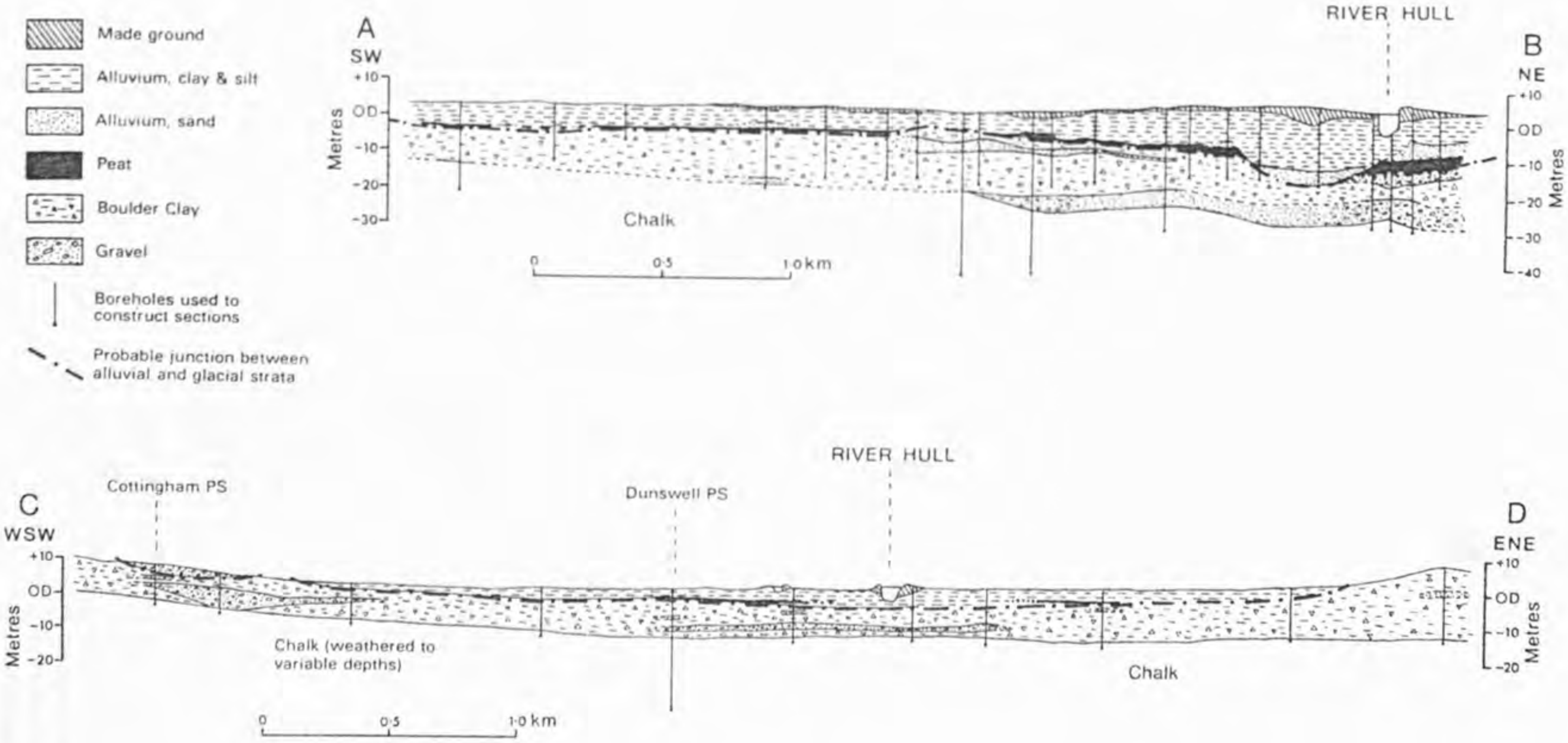


Fig. 5. Geological sections of drift deposits of the lower Hull valley (lines of section indicated on Fig. 3.)

Milton, in press). Wherever present, such a feature could exert major influence on the spread of interference effects from a centre of pumping.

The account by Green (1950) of the hydrogeological conditions encountered during the driving of new headings in attempts to increase production of the Cottingham and Dunswell public supply sources are further indicative of the lateral and vertical heterogeneity that can be expected in the transitional down-dip zone of the aquifer. At Dunswell a horizontal north-south adit about 1.5 km long was driven at a depth of about -29 m OD, the southern end being significantly nearer to the Chalk erosion surface. At that end large quantities of groundwater were encountered while the northern end was absolutely dry. At Cottingham a second north-south adit about 1.2 km long, in line with and 15 m below the original adit (at about -30 m OD) was constructed; it was dry in the new lower adit despite the fact that about 32 Ml/d were being pumped from the overlying Chalk. Green (1950) concluded that almost the entire groundwater flow was concentrated in the top 10 to 15 m of cryoturbated chalk immediately below the confining bed and that no permeability development at depth had occurred.

Similar conditions appear to have been encountered by well-sinkers at numerous sites in the Kingston-upon-Hull area. The yield-drawdown characteristics of pumping boreholes frequently show strong breakaway from the Theson (1959) type behaviour, as soon as the pumping water level is drawn below the principal flow horizons.

CHARACTER OF THE CONFINING BEDS

Drift deposits form the confining bed of the Chalk aquifer and reach a maximum thickness of 75 m in parts of Holderness. They comprise a series of glacial sediments, overlain in the Hull Valley by alluvial deposits. Most important are the boulder clays, considered to be glacial tills or ground moraines of ice sheets. A detailed study of these deposits is available (Catt and Penny, 1966) but problems occur in their use for hydrogeological purposes because they relate almost exclusively to the coastal exposures.

The Boulder Clay forms a continuous blanket over the Chalk, being more than 10 m thick throughout the lower lying land (Fig. 5); it continues for considerable distances eastwards beneath the bed of the North Sea and westwards it encroaches onto the flanks of the Wolds. In general the over-consolidated silty clays might be expected to possess low, but possibly significant permeability, although very little field data is available. Bonnell (1972) suggests values of less than 0.01 m/d below the weathered soil horizon. The presence locally of sandy or gravelly lenses, pipes and stringers and old blow-well features will increase the overall permeability.

The post-glacial drainage system in the Hull Valley has cut a broad, open channel into the glacial deposits and subsequently deposited a series of alluvial deposits (Fig. 5), predominantly organic clays and silts, with minor bodies of sand and gravel. The overall vertical permeability of the alluvial deposits is likely to be an order of magnitude or more higher than that of the Boulder Clays but no laboratory or in-situ test results are known to be available.

In the lowest reaches of the Hull Valley, the alluvial deposits reach their greatest thickness and maximum depth. Contours drawn on their base from data in the Institute's records (Fig. 6) reveal a shallow buried channel following approximately the course of the present River Hull, with a second buried channel entering from a north-westerly direction. Comparison with contours on the Chalk rockhead shows however that a minimum of 6 m of glacial deposits still remain and examination of the individual borehole logs suggest that nowhere is the Boulder Clay itself reduced to less than 4 m; typically it is more than double this thickness.

It is of relevance to consider the order of overall vertical leakage capacity (Qv) of the Boulder Clay cover. Assuming a permeability of the order quoted above and considering a fully saturated thickness of 10 m, values of Qv of 1.0 Ml/d per km^2 of area per metre of vertical head are obtained. Under heavy pumping during low saturation conditions, it is likely that the vertical head available for downward leakage could average 2 m over an area of 15 km^2 of the lower Hull Valley and thus it is possible that such leakage could be a significant factor in increasing the fresh or brackish water recharge from the land surface. Lower values of permeability would reduce the Qv correspondingly. It is possible that the storage of the drift deposits is too limited to sustain such a leakage rate throughout a long drought.

HUMBER BED RELATIONSHIPS

Of greater importance in the context of saline intrusion into the Chalk aquifer is the geology of the present Humber bed. At the only two sections recently investigated by offshore boreholes (the Hessle/Barton and Thorngumbald/Skitter sections) the detail proved extremely

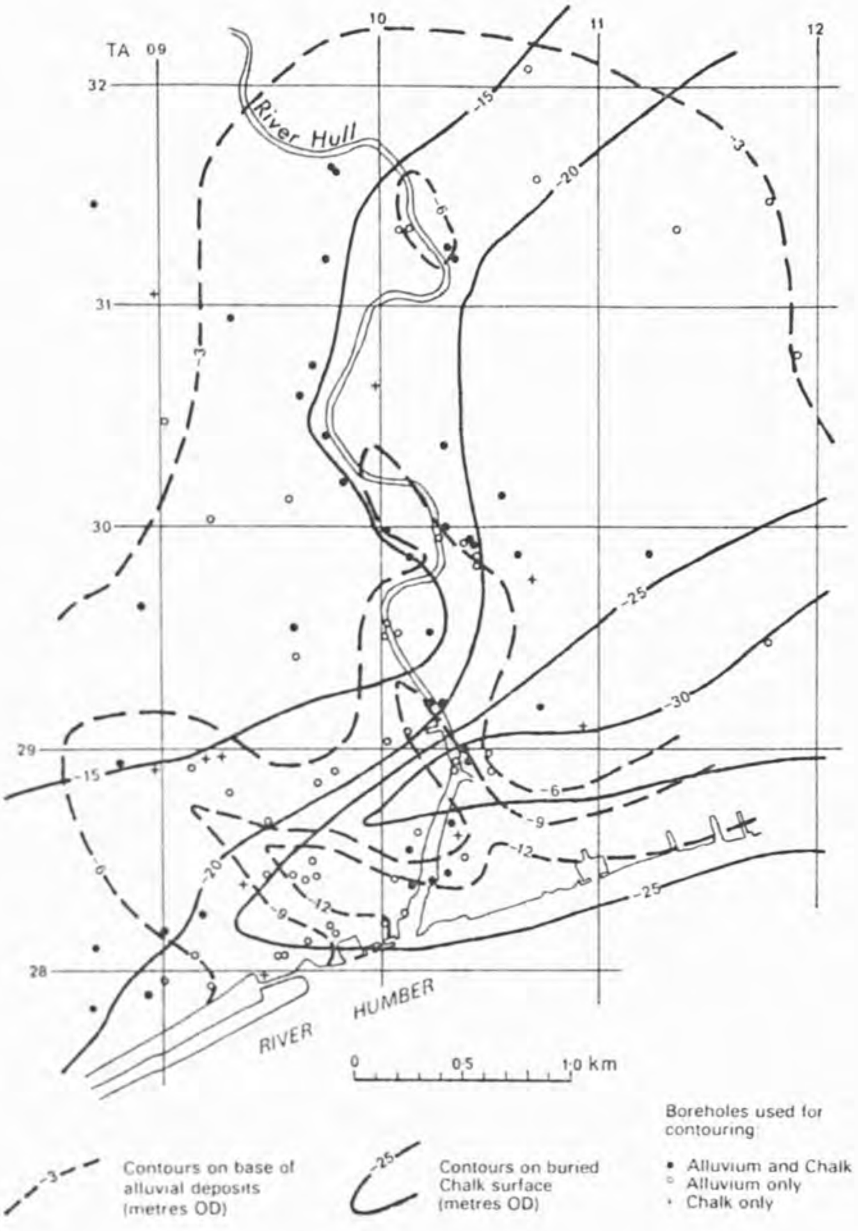


Fig. 6. Structure contours on the drift deposits of the central Hull area

complex. Numbers of major cycles of erosion and deposition have occurred. There has been deep re-working of earlier sediments along restricted channels which do not of necessity conform in trend with earlier buried channels. Thus the sediments as a whole exhibit extremely rapid lateral variation. Beneath the Humber, the Chalk erosion surface is probably composite being in part Recent and in part Pleistocene and possibly older; many local variations are believed to be present and for this reason the contours were omitted from Fig. 3.

The predominance of sand in the post-glacial riverbed sediments has been proved by seismic sparker and grab sampling surveys (McQuillin and others, 1969), but geophysical work continues and its full interpretation is not yet possible. The boulder clays of the land area appear to be generally discontinuous across the Humber; this is in part due to erosion but they also seem to lense out when traced towards the Humber. In places physically comparable consolidated laminated silty clays have been proved but these also are known to be absent from extensive areas. Thus, over significant areas sandy post-glacial riverbed deposits probably rest directly on the Chalk.

The Regional Hydrological System

THE OVERALL GROUNDWATER FLOW PATTERN

In East Yorkshire, as in most carbonate rock terrains, the overall hydrological regime is determined by the regional geological structure since it controls the position of the permeable rock outcrop, its confining beds and thus the location of the recharge and discharge areas of the groundwater system. The Yorkshire Wolds are the topographic expression of the Chalk outcrop and form an undulating thin soil-covered upland area (40 to 180 m OD) virtually devoid of surface water. This is the intake area of the Chalk aquifer, drainage being entirely subsurface and directed primarily towards the Hull Valley.

Under natural conditions the Chalk aquifer appears to have discharged in numerous sizeable springs all along the western side of the Hull Valley and from small springs at the foot of the escarpment overlooking the Vale of York. Hearsay evidence also suggests former perennial chalk springs in the bed of the Humber at Hessle, probably in an area of submarine Chalk outcrop or at least one from which Boulder Clay has been eroded. The former springs generated minor tributaries of the River Hull which were tidal over their lower sections, the Hull being tidal throughout the area as far north as Hempholme Lock. (It should be noted that the tidal limit may possibly be moved downstream in the future by engineering measures). The Hull itself is essentially a Chalk watercourse, over 85 per cent of its flow at Hempholme Lock being derived from spring discharges to the north of the area under present consideration. A complex system of artificial cuts (dykes) with pumping stations to generate flows has been developed throughout the Hull Valley and Holderness to augment the poorly developed natural drainage.

Throughout the southern part of East Yorkshire, however, the natural discharge regime of the Chalk aquifer has been substantially modified by the heavy development of its groundwater resources and the creation of pumping centres in the Kingston-upon-Hull area. One side effect has been the virtual drying-up of all dip-slope chalk springs and their associated watercourses northwards to beyond Beverley. The lowering of groundwater levels and diminution of springflow over large areas was probably initiated before 1930 and perhaps before 1900 with steady expansion in the development of public water supplies (Fig. 1). The supplies obtained directly from the Chalk, utilising its storage capacity to sustain abstraction rates, have provided a much more reliable supply both in quantity and quality than had the chalk watercourses, such as that at Springhead which formed the original supply for the city.

DELINEATION OF SUB-CATCHMENTS

In order to improve the delineation of groundwater flow directions and sub-catchments, comprehensive water level surveys using all accessible and reliable deep wells and boreholes in the area were undertaken in early April and late October 1970. The data were used to construct maps of groundwater level contours (Figs. 7A and 7B); these are extensions of the maps previously presented for the north of the region by Foster and Milton (in press); the collection and reliability of the data have been discussed in detail by these authors. The intention was to obtain data representative of the configuration of the water table at moderately high and fairly low saturation within a typical annual hydrological cycle. It should be noted that the patterns presented are not steady state but instantaneous pictures of constantly varying conditions of groundwater potential and flow. Some caution must therefore be exercised in their use to compute mass flow quantitites. Simultaneous surveys of the distribution of natural discharge from the Chalk aquifer were undertaken and the data are also summarised in Figs. 7A and 7B.

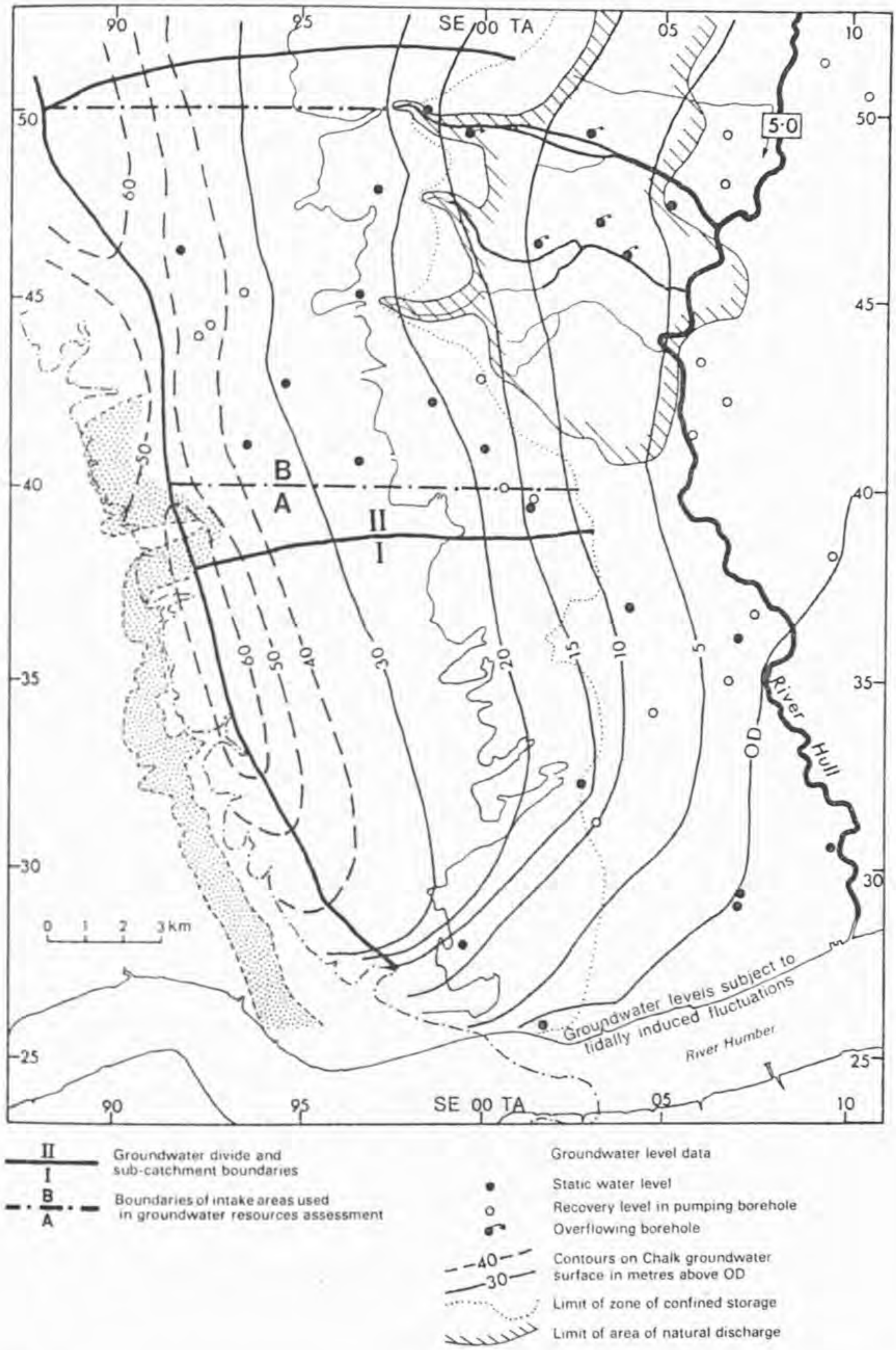


Fig. 7a. Groundwater level contours and discharge regime of Chalk aquifer: March 1970

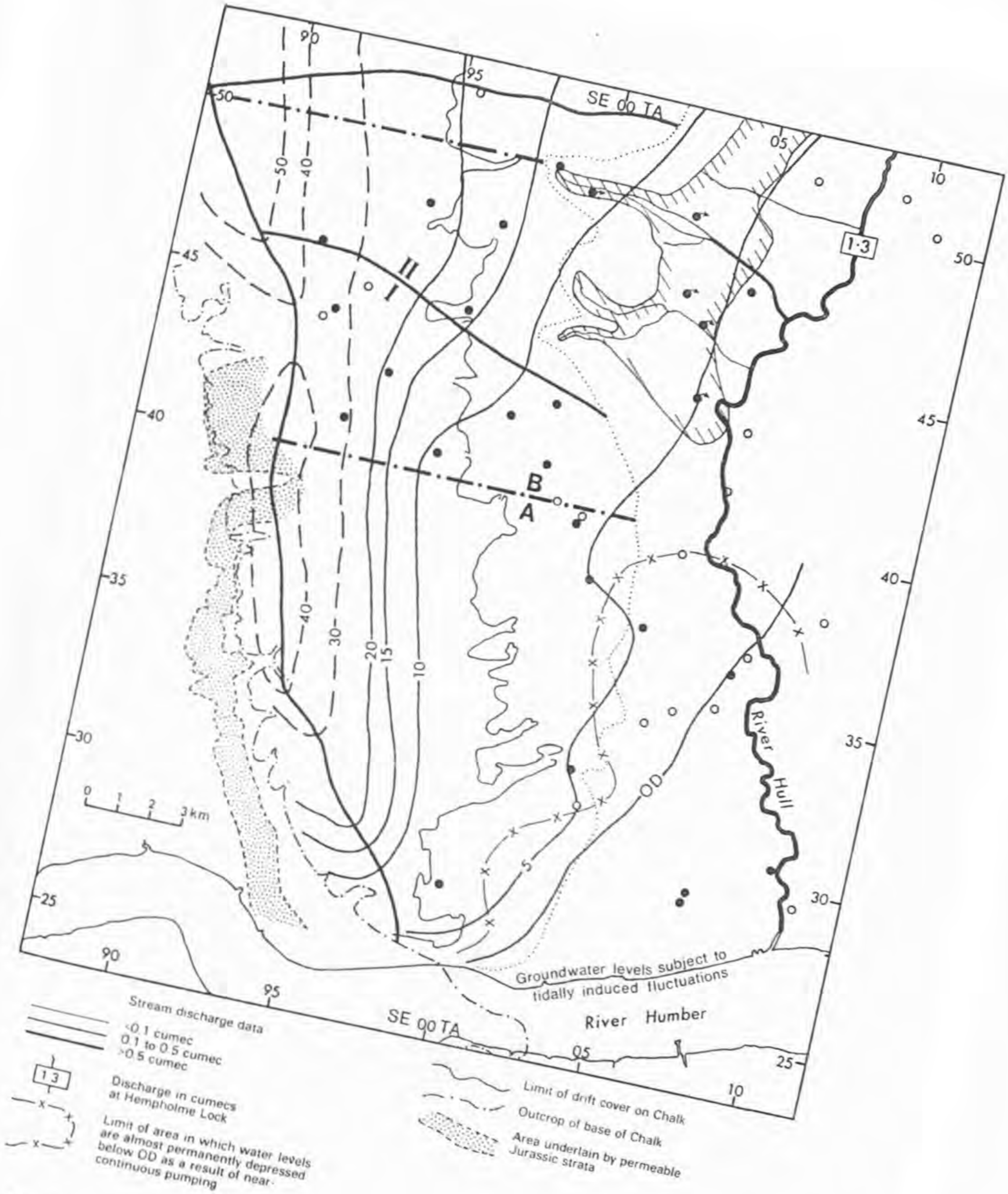


Fig. 7b. Groundwater level contours and discharge regime of Chalk aquifer: October 1970

Over very limited areas the Chalk formation is shown (Figs. 7A and 7B) to drain towards its escarpment giving rise to numerous small contact springs. The localisation of springs is probably partly dependent upon superficial disturbances in the Chalk strata associated with the formation of the escarpment itself. The definition of the water divide between this drainage direction and that towards the Hull Valley can be reasonably accurately established and is relatively stable, principally as a result of the regional geological structure and the level of the outcrop of the base of the Chalk. A minor complication occurs where the immediately underlying Jurassic strata are permeable.

The bulk of the subsurface flow in the Chalk is directed towards the Hull Valley. Any attempt to make a logical subdivision of this fairly extensive catchment area must consider the groundwater flow lines. It must be recognised, however, that groundwater catchments can undergo major seasonal variations in shape and area both naturally and due to pumping, in contrast to surface water catchments which are essentially of fixed area and boundaries.

Of fundamental importance is the subsurface flow-line separating groundwater currently draining to the tidal and non-tidal Hull, that is, to the south and north of Hempholme Lock respectively. This line does not appear to vary its position much seasonally (Figs. 7A and 7B), although it could be altered should groundwater development occur in its vicinity.

The groundwater level and streamflow surveys led to a much closer definition of the zone of artesian discharge in the Hull Valley than had previously been possible. The southernmost chalk watercourse believed to be flowing perennially is Scorborough Beck, some 5 km north of Beverley, and this is one of three significant chalk streams draining to the tidal Hull (Figs. 7A and 7B). A detailed survey of the groundwater increment along the entire length of Scorborough Beck under high water table conditions showed that some 60 to 80 per cent of the total discharge originated in five discrete springs all located on the 'upstream side' of the artesian discharge zone.

The subsurface divide between groundwater flowing towards the natural discharge area and that flowing towards the pumping centres south of Beverley can be established approximately from groundwater contours at any particular instant in time. The divide, however, shows major variation in its position seasonally (Table 1) and considerable variation from wet to dry years. Under maximum conditions in 1970 (Fig. 7A) the hydraulic gradient was east or east-north-east throughout most of the area under consideration and the flow frontage from the Chalk outcrop as far north as the latitude of Beverley appeared sufficient to satisfy the heavy extraction in the Kingston-upon-Hull area. Detailed observations in the Etton area have shown that at some time during the annual recession of groundwater levels (normally in July or August) the hydraulic gradient swings round to the south-east (Fig. 7B). This occurs as a result of the expansion of the cone of pumping depression associated with increasing abstraction from groundwater storage in the area of heaviest development. Moreover, even when the 'flow-frontage' to the Kingston-upon-Hull area has expanded to 15 km (as in Fig. 7B), it is unlikely that the total flow to the pumping centre is much more than 50 Ml/d, taking as typical the appropriate T value from the Etton investigations.

It is most important to recognise that subsurface flow-lines determined largely as a result of existing groundwater development, (and possibly existing over-development) are not a suitable basis for the discussion of resources. It is therefore proposed for this purpose to divide the Chalk intake area draining to the Hull Valley into two blocks; that between the Humber and the latitude of Beverley (A in Fig. 7A) and that between Beverley and the latitude of Hempholme Lock (B in Fig. 7A). The aquifer intake areas within these two blocks are summarised in Table 2.

ASSESSMENT OF GROUNDWATER RECHARGE

Clearly in an area of heavy development of groundwater resources the assessment of the rate of groundwater recharge is of critical importance. Nevertheless its determination as a long term average or for individual years presents formidable problems.

The bulk of the total groundwater recharge originates as infiltrating rainfall in the Chalk outcrop area. The average annual precipitation (1916-1950) in the southern part of the Yorkshire Wolds is just under 700 mm, with only minor differences between the totals for any given month or season (Yorkshire Ouse and Hull River Authority, 1969). Unlike rainfall, temperature and other climatic parameters do show moderate seasonal differences and lead typically to a considerable excess of evaporation over precipitation in the months of May, June, July and August and near balance in March, April and September. An overall picture of summer and autumn soil moisture deficits thus

Table 1. Variation of sub-catchment areas based on groundwater contours.

Hydrological conditions	Sub-catchments (km^2)			
	High saturation (Fig. 7A)		Low saturation (Fig. 7B)	
	Chalk outcrop only	Chalk and upland Boulder Clay	Chalk outcrop only	Chalk and upland Boulder Clay
I Hull-Beverley abstraction area	62	106	101	175
II Natural discharge area	81	126	41	72
I and II	143	232	142	247

Table 2. Details of Chalk aquifer intake areas.

	Intake area (km^2)	
	Chalk outcrop only	Chalk and upland Boulder Clay
A Humber to Beverley	72	123
B Beverley to Hempholme	62	95
A and B	134	218

emerges.

The difficulties of measuring actual evaporation have led to the development of methods for its calculation from meteorological data; the method in most widespread use in Britain is that of Penman (1948) and its many subsequent refinements. It is probable that at the present time such a method gives estimates of evaporation which are superior for water resources purposes to any which could be generated from one or two direct measuring installations.

The Penman method estimates the potential evaporation (Ep) defined as the maximum evaporation that would take place in a given climate from a continuous cover of vegetation with constantly saturated soil. There is only one station in the part of Chalk outcrop under consideration where sufficient meteorological parameters are measured for Ep to be computed (Leconfield, TA 026 438) and even here the available record is short. However county average estimates are available for the southern part of East Yorkshire (Ministry of Agriculture, Fisheries and Food, 1967) for a longer period; a semi-empirical correction for sunshine record and altitude having been applied. The average annual figure is 490 mm, of which over 85 per cent occurs in the months of April to September inclusive. The long term average infiltration is unlikely to be less than the difference between the long term averages for precipitation and potential evaporation, that is, about 200 mm. This assumes that the potential evaporation has not been underestimated, that there is no overall change in soil moisture conditions and that an overall change in climatic conditions is not at present occurring.

Actual, as opposed to potential, evaporation is limited by availability of soil moisture and is in turn a function of type of vegetation and soil conditions; in extended dry periods actual evaporation may be considerably less than potential. Adopting the method of Grindley (1968), but using a simplified relationship with a limiting soil moisture deficit of 75 mm, Foster and Milton (in press) have evaluated the actual evaporation and effective infiltration on a monthly basis during 1962-1970 for the Chalk of the Hull-Hempholme catchment to the north. In that period the total precipitation and potential evaporation were near the long term averages, which for that area are some 40 mm more and 20 mm less than the corresponding respective averages for the southern part of the Yorkshire Wolds. Thus the average annual value of effective infiltration obtained for the Hull-Hempholme catchment (310 mm), would probably correspond to a value closer to 250 mm in the present area. It is also of interest to note the contrast between the infiltration in the driest and wettest winters of that period, 1964-1965 and 1965-1966 respectively, for which values of 130 mm and 335 mm were obtained from meteorological parameters by the above method.

For the Hull-Hempholme catchment also, estimates of effective infiltration have been made indirectly by analysis of the riverflow data for the principal tributaries of the Hull. In the catchment of the West Beck to Wansford Bridge, the total baseflow component during the period 1962-1970 was equivalent to an infiltration of about 360 mm/a over the entire Chalk outcrop (Foster and Milton, in press). Assuming as before that the infiltration in the southern part of the Wolds is likely to be some 60 mm or so less, this would be equivalent to an effective annual infiltration of 300 mm in the latter area. The values derived from baseflow separation exceed those from meteorological parameters by more than 15 per cent, and indeed the same was found to be true for most of the individual years analysed, except the driest. Although the baseflow could have been systematically over-estimated an appraisal of the possible sources of error suggests that probably the reverse is the case. The values derived from meteorological parameters are more likely to be in error because of inaccurate potential evaporation data, use of an inappropriate root constant or unreliable averages for monthly precipitation. It should, however, be recognised that the process of infiltration and recharge to the Chalk aquifer's saturated zone is complex; the available tritium age determinations posing fundamental questions on the mechanism and rates of groundwater movement in the unsaturated zone (Foster and Crease, 1974). It is possible that changes in storage in the unsaturated zone could invalidate comparison between values of effective infiltration obtained by the above two methods, although they appear to be closely related.

A summary of the first order estimates of long term average infiltration made by previous workers has been given by Gray (1952), who adopted an average value of 305 mm for the entire region. The Yorkshire Ouse and Hull River Authority (1969) adopted a value of 255 mm for the southern part of the Yorkshire Wolds. In view of the uncertainties of estimating the average infiltration reliably, it is proposed here to evaluate the volumes of recharge equivalent to given rates of annual infiltration (Table 3) and use this as the basis for the discussion on the state of groundwater resources. The significance of an error of 25 mm in an estimate is also evaluated.

One further problem arises, namely the question of recharge to the Chalk through the Boulder Clay cover. This will depend greatly on the latter's lithology, thickness and equally on the vertical hydraulic gradients. Gray (1952) allowed an arbitrary 50 mm/a for all areas with less than 9 m of Boulder Clay cover and in studies of East Anglian catchments Ineson and Downing (1965) derived values varying from about 40 to 130 mm/a. In the area under present consideration it is most likely that some rainfall infiltrates the Boulder Clay and recharges the Chalk all along the flanks of the Wolds above the main buried coastline feature, where the Chalk is still unconfined. There appears to be little surface runoff in this zone and it is possible that the entire excess rainfall infiltrates the Boulder Clay and thus an allowance for this possibility has been made in Table 3. In the Hull Valley and Holderness, where the Boulder Clay is significantly thicker and downward hydraulic gradients less or even non-existent, significant recharge to the Chalk is only likely to be induced as a result of heavy pumping. It is more likely in summer and autumn than in spring, when natural groundwater levels are higher, but could only take place if there was sufficient volume of groundwater stored in the overlying drift deposits at that time of year; such water could be brackish in some areas.

Groundwater Abstraction

AVAILABILITY AND RELIABILITY OF DATA

In order to make the best possible assess-

Table 3. Summary of potential replenishment of the Chalk aquifer.

Total annual precipitation recharge	Corresponding recharge for given intake area (Ml/a)					
	Chalk outcrop alone			Chalk and upland Boulder Clay		
	A	B	A + B	A	B	A + B
200 mm/a	14 400	12 400	26 800	24 600	19 000	43 600
300 mm/a	21 600	18 600	40 200	36 900	28 500	65 400
25 mm/a	1 800	1 550	3 350	3 075	2 375	5 450
100 mm/a severe drought	7 200	6 200	13 400	12 300	9 500	21 800
225 mm severe 2-year drought	16 200	13 900	30 100	27 700	21 400	49 100

Table 4. Actual annual groundwater abstraction (Ml/a).

Area	A	B	A+B	Percentage of A+B pumped by K-u-H CBC	Overall total, A+B and escarpment
1972	33 500	3000	36 500	77	38 200
1965	28 900	500	29 400	75	31 300
1951	35 200	500	35 700	79	36 600

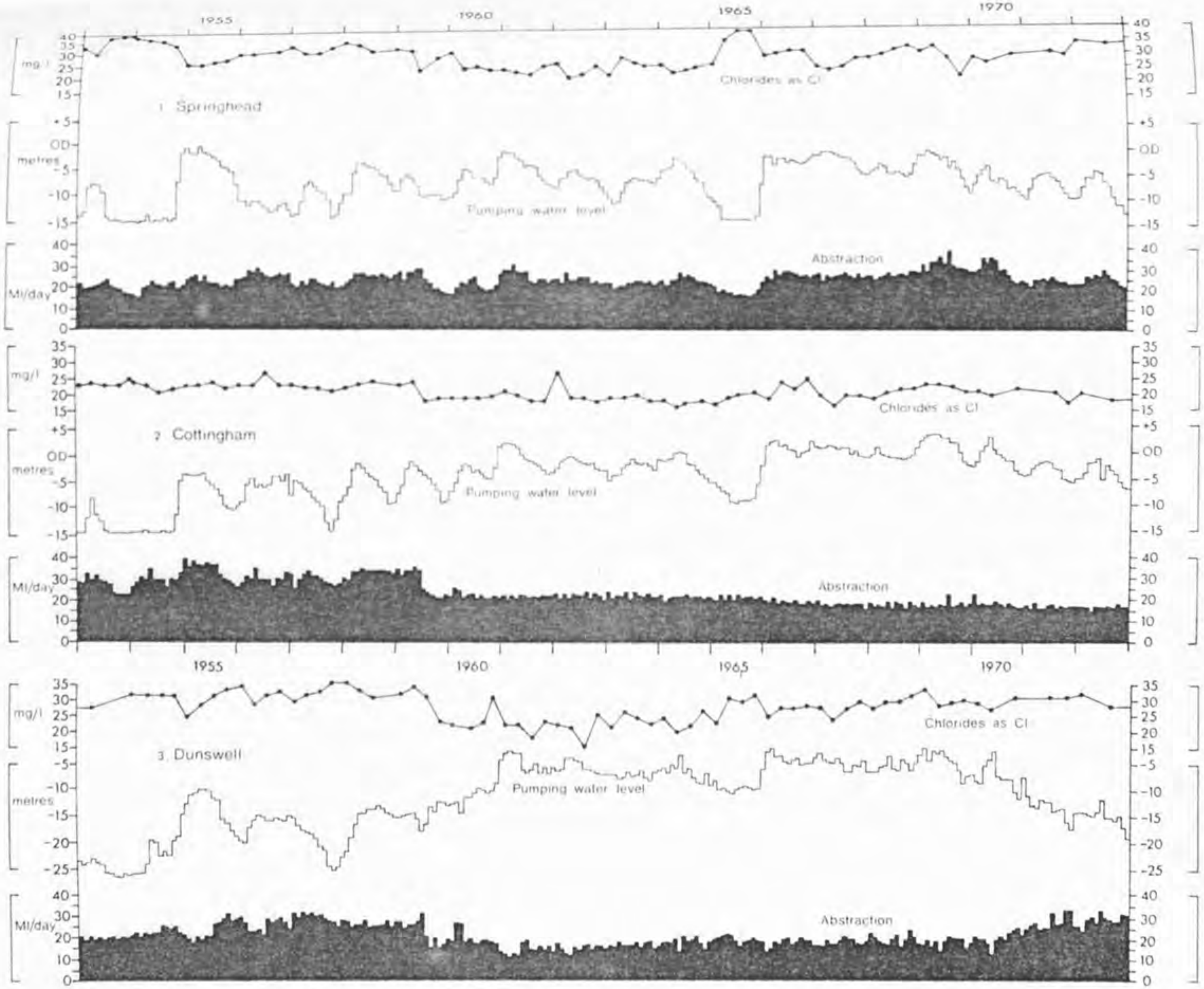


Fig. 8. Long-term abstraction, pumping water-levels and chloride concentrations for major Kingston-upon-Hull groundwater sources

ment of the state of development of groundwater resources it is essential to have accurate data on groundwater abstraction.

Prior to the Water Act 1945, groundwater users were not required by law to measure their abstractions. Section 6 of that Act however, required abstractors in this area to keep records if their pumping rate exceeded 0.23 Ml/d (50 000 gpd); the first returns became available in 1948.

On the implementation of the Water Resources Act 1963, abstractors had to make annual returns of groundwater abstraction in accordance with Section 114. Whilst almost all groundwater abstraction was subject to licence by the River Authority, returns were only called for if the abstraction exceeded 9 Ml/a (2 mga) if the water was used for domestic, agricultural and spray irrigation purposes and 136 Ml/a (30 mga) if it was used for public supply, manufacturing or cooling. The first adequate returns under this system became available in 1969.

For the present report and for the specific purpose of an assessment of the variation in the extent of saline intrusion, an accurate picture is required of the changes in the magnitude and distribution of actual abstraction during the period 1951-1973. For 1951, the Water Act (1945) returns have been used with additional information from the Institute's records in the case of abstractions of less than 0.23 Ml/d, since a comprehensive survey of pumping wells and boreholes was undertaken in that year. In 1972 a fairly reliable estimate of the actual abstraction can be made from the returns under the Water Resources Act (1963). An allowance amounting to 50 per cent of the licence abstraction has been made in those cases where no return was required by law.

The Kingston-upon-Hull County Borough Council was by far the largest abstractor; their abstraction represented something like 75 per cent of the total in the area under present study and in excess of 90 per cent of the total abstraction in the immediate North Humberside area. Since detailed and reliable records (for example, Fig. 8) are available for these sources to at least as far back as 1935, correspondingly accurate estimates of the growth of groundwater abstraction in the North Humberside area can be made with relative reliability.

LONG TERM VARIATION IN ACTUAL ABSTRACTION

The regional distribution of actual abstraction in 1951 and 1972 is summarised in Fig. 9, in which the actual abstractions have been totalled for each square of a 2 km grid. The total annual abstractions in these years and for 1965 also have been computed separately for the balance areas A and B (Table 4).

In 1951 the only significant abstraction outside the Kingston-upon-Hull/Beverley area was that at North Newbald on the escarpment where 641 Ml/a was drawn for public water supply (Fig. 9). The total 1951 abstraction in area A+B is estimated at 36 500 Ml; 77 per cent of the total represents the abstraction at Springhead, Cottingham and Dunswell alone. Numerous industrial premises in the Kingston-upon-Hull area and along the Humber waterfront had private boreholes and these collectively accounted for 4100 Ml in 1951. The only other significant industrial abstraction was in Beverley.

Between 1951 and 1965 there were no marked changes either in the quantity or distribution of groundwater abstracted. The overall total decreased by 5300 Ml/a, nearly all of this being due to a reduction in the abstraction from the Kingston-upon-Hull CBC groundwater sources (Fig. 8). Abstraction in the Hull industrial area totalled 4400 Ml/a, an increase of only about 300 Ml/a since 1951.

The data for annual abstractions in 1972 (Fig. 9) is more comprehensive. The total groundwater abstraction in 1972 was 38 200 Ml, representing an increase of 6900 Ml over that in 1965 but only 1600 Ml above that in 1951. The 1965 abstraction was atypically low, partly as a result of the reduction in groundwater abstraction by the Kingston-upon-Hull CBC with the new development of their river-intake supply at Hempholme Lock, and partly as a result of the extreme drought in that year limiting the actual capacity of many wells and boreholes to produce groundwater. Industrial abstraction in the Hessle-Hull area stood at 3500 Ml in 1972; a reduction of 15 to 20 per cent from the 1965 and 1951 figures. Elsewhere the development of a major source by the East Yorkshire (Wolds Area) Water Board at Etton, from which about 2600 Ml was abstracted in 1972 with further expansion planned, represented a major increase in abstraction from balance area B. Its other sources in the south of East Yorkshire located at Hutton Cranswick, Market Weighton and North Newbald (Fig. 10) do not enter into the groundwater balances considered in this report.

Between 1965 and 1972 there was an apparent increase in the total number of groundwater abstractors; in part real as a result of the rapid expansion of intensified agricultural and horticultural enterprises in the area and partly imaginary, the result of the improved system of licensing and returns introduced under the terms

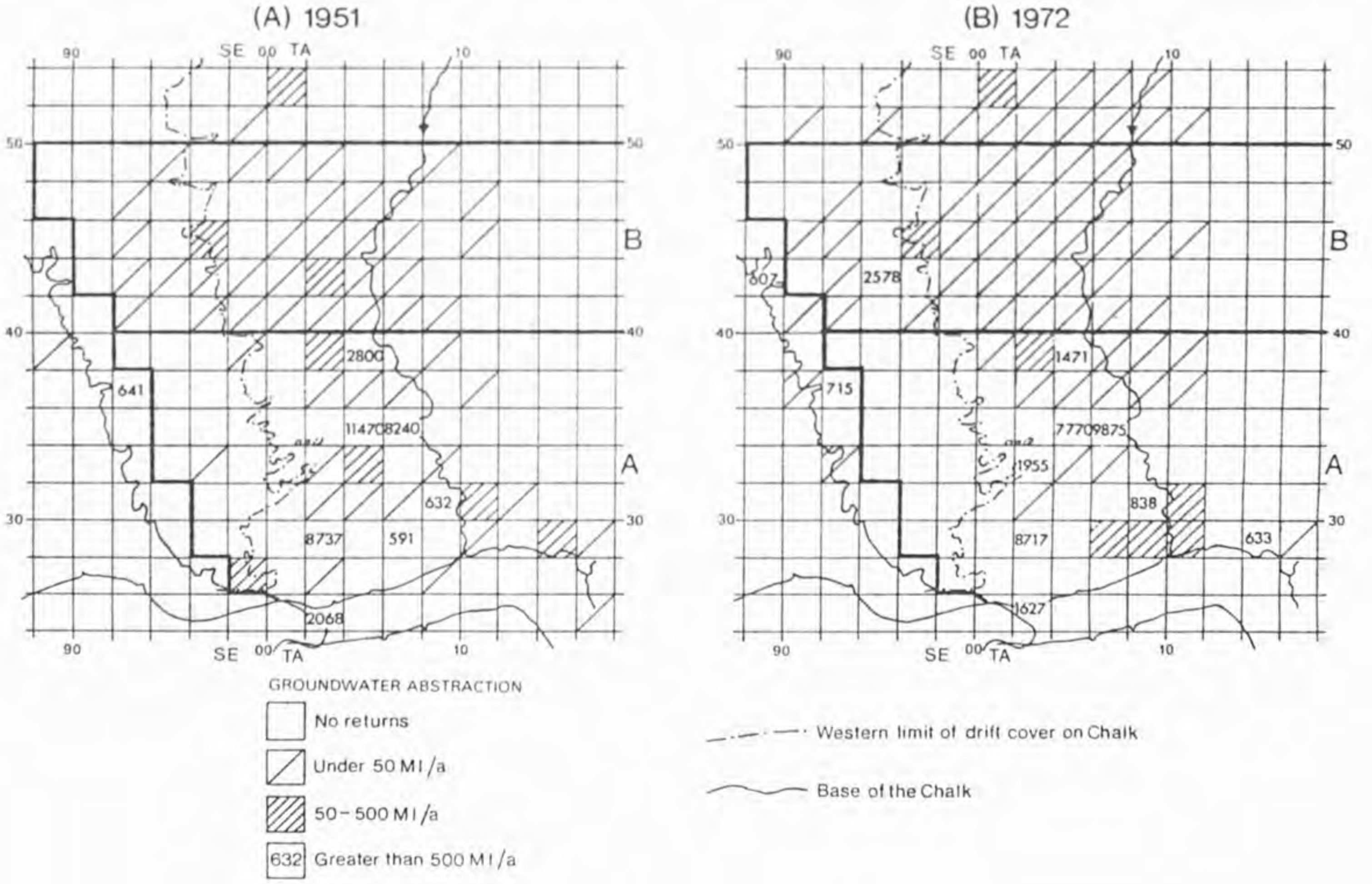


Fig. 9. Distribution of actual groundwater abstraction from Chalk aquifer

of the Water Resources Act 1963.

Since the changes in groundwater abstraction in the North Humberside area as a whole are dominated by those at the Kingston-upon-Hull CBC sources, it is worthwhile studying their pumping records in further detail. Total abstraction from the three main sources (Springhead, Cottingham and Dunswell) grew steadily from 20 900 Ml/a in 1936 to a maximum of 29 900 Ml/a in 1958; only in those years of extended drought did the total abstraction fall, this as a result of the limitations on well yields. The development of the Tophill Low river-intake works on the Hull at Hempholme Lock led to a reduction in the amount of water pumped at the three sources to around 21 000 to 23 000 Ml/a during 1960-1963 (Fig. 8). In the late 1960s with demand steadily rising, abstraction from the groundwater sources had to be increased once again, reaching a total of 25 100 Ml/a in 1972.

DISTRIBUTION AND USE OF LICENSED BOREHOLES IN 1972

Under the Water Resources Act 1963 each licence to abstract water is classified according to the purpose for which the water is required. This information was used to construct a map of the distribution of licensed wells and boreholes of the various classes for the area under consideration (Fig. 10).

A number of points arise:

1. There is no groundwater abstraction for human consumption in the highly populated area within a radius of 5 km of the confluence of the River Hull with the Humber, a result of extremely poor chemical quality of groundwater.
2. Spray irrigation users are concentrated in the area immediately south of Beverley.
3. There are large numbers of domestic boreholes around Beverley, a reflection of total dependence in these rural areas on direct groundwater abstractions.

EXCESS OF LICENSED OVER ACTUAL ABSTRACTION IN 1972

A comparison of the licensed abstractions in 1972 with the actual abstractions, as measured by the statutory returns, has been undertaken for all those 2 km squares of the grid (Fig. 9) where the actual abstractions exceed 500 Ml/a (Table 5).

This comparison shows everywhere a considerable excess of licensed over actual abstraction, ranging from 34 per cent to 94 per cent. The overall totals show that only 54 per cent of the licensed quantities were in fact used in 1972 with the result that some 33 000 Ml/a were reserved, unused, within the licensing system. Much of this excess was held by the Springhead, Cottingham, Dunswell and Keldgate sources of the Kingston-upon-Hull CBC.

Saline Water Intrusion

EXTENT OF SALINE INTRUSION

Where an aquifer is in contact with the sea, salinity layering will occur with the more dense saline water generally occupying the lower levels of the formation. Under static conditions there will be a relatively sharply defined interface with the overlying fresh water which, according to the classical Ghyben-Herzberg equation, will occur at a depth below mean sea level of some 40 times the height of fresh water above sea level, a result of the hydrostatic equilibrium between the two fluids of different densities. Where large scale abstraction occurs from a coastal aquifer, water levels will be lowered and the interface becomes shallower; prolonged heavy abstraction may eventually create an overall landward hydraulic gradient causing lateral encroachment of the saline water interface into the aquifer. Under dynamic conditions the usefulness of the Ghyben-Herzberg relationship is limited and an adaptation of the classical Hubbert formulae is more appropriate (Perlmutter and Geraghty, 1963), moreover a thick zone of mixing will normally develop through intermingling of different waters as a result of both density and hydraulic gradients in vertical and horizontal directions (Cooper, 1959).

In the North Humberside area the situation is further complicated by the localisation of the freer points of hydraulic communication between aquifer and saline water, the variable salinity of the Humber water, the large semi-diurnal tide, and, perhaps most important of all, marked permeability layering in the Chalk aquifer.

Detailed groundwater sampling surveys have been carried out and the general distribution of chloride ion in pumped samples determined on three occasions: in May 1951 32 samples from pumped boreholes were taken for analysis of chloride: in November 1967 31 boreholes were sampled for chemical analysis, and conductivity logging carried out where access permitted; in May 1973 36 boreholes were sampled, 25 for full analysis and the remainder for partial analysis (trace element and tritium samples were also taken, and conductivity logging of boreholes carried out where access permitted).

This sampling and chemical analysis gives an indication of the areal extent of saline water

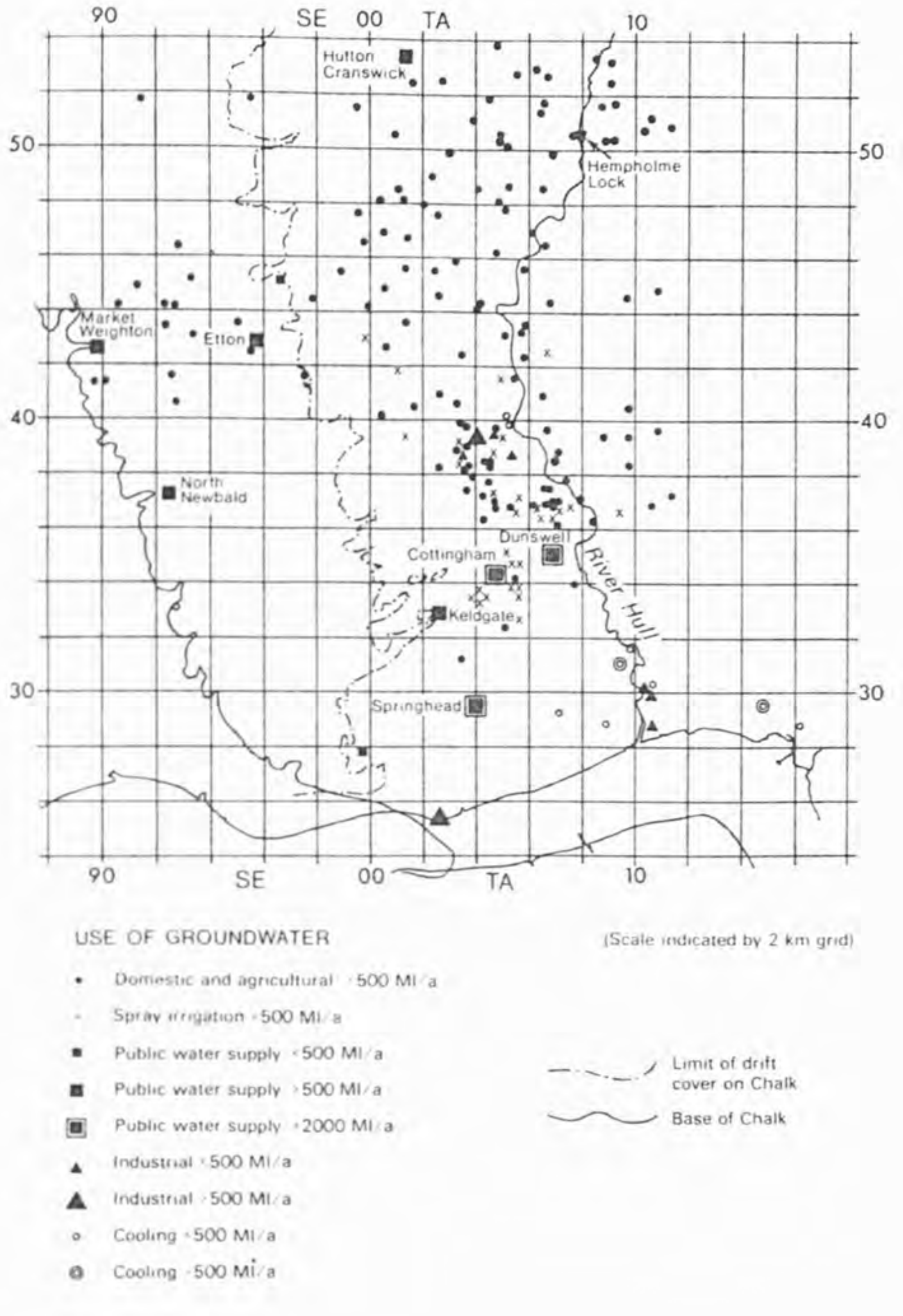


Fig. 10. Classification of licensed Chalk abstraction boreholes (1972)

Table 5. Comparison between actual and licensed abstraction in 1972 [for grid squares in which abstraction was greater than 500 Ml/a; see Fig. 9].

	1972 Abstraction		
Grid square	Actual Ml/a	Licensed Ml/a	Actual/Licensed %
SE 8842	607	908	67
9236	715	1135	63
9442	2578	5091	50
TA 0052	381	798	48
0224	1627	2724	60
0228	8717	13620	64
0232	1955	2088	94
0434	7770	18232	43
0438	1471	4325	34
0634	9875	16571	59
0830	838	898	93
1428	633	1194	53
Overall Total	38 200	71 300	54

intrusion; it is, however, essential to recognise that the problem is dynamic and three-dimensional and that there are major limitations to a two-dimensional approach. Conductivity logging can help to complete the picture by measuring the variation of salinity with depth, but few existing boreholes provide suitable access, particularly in the critical areas. The investigation was also limited by the distribution of existing boreholes. In the central Hull area many boreholes have been abandoned, sealed or filled in due to the high salinity of the groundwater, decreasing the already limited number of sampling points in the most saline area.

The data obtained at the above three dates is summarised in three maps (Fig. 11A-C). By 1951 an area of saline intrusion in central Hull was already established with a wide zone of mixing between the fresh (50 mg/1 Cl) and saline (5000 mg/1 Cl) water. In 1967 and 1973 the high salinity front had advanced only very slightly if at all, but significant changes appear to have occurred in the position of the fresh water front. The 50 mg/1 and 100 mg/1 isochlors have advanced towards Springhead and the zone of mixing has widened. The steep rise in chlorides across boreholes 6 and 17 in 1973 (Fig. 11C) shows this must be a critical area close to the interface.

VARIATION OF CHLORIDE WITH TIME IN CHALK GROUNDWATER

Although the spatial distribution of chlorides was not determined at any date prior to 1951, the major groundwater sources have had regular chemical analyses carried out for many years. Chloride determinations for Springhead, Cottingham and Dunswell from 1953 to 1972 are included in Fig. 8 and data going back at least to 1936 are available. Both seasonal and long term variations in chloride can be identified.

The seasonal variation in salinity is characterised by rising chlorides in summer and autumn, and lower chlorides after winter recharge. The correlation of high chlorides with periods of drought is best seen at Springhead, particularly in 1965 for example, when a rise in chlorides to 40 mg/1 coincided with a marked decline in pumping water level. Dunswell also shows similar chloride variation, but at Cottingham, closer to the recharge area, the chloride content of the water is always lower and the variations less marked.

The 1953-1972 data for the Kingston-upon-Hull

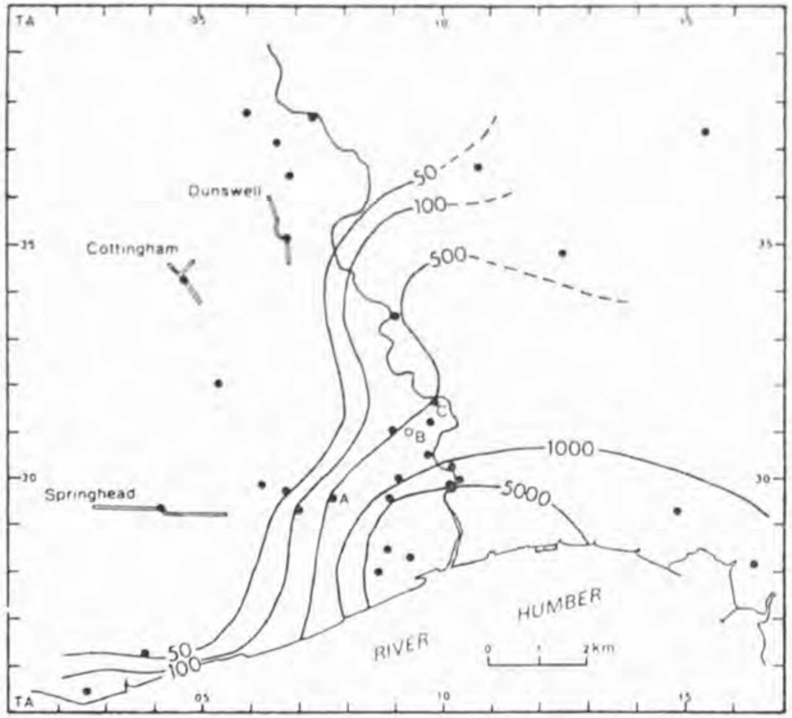


Fig. 11A. Distribution of chloride in Chalk groundwater: May 1951

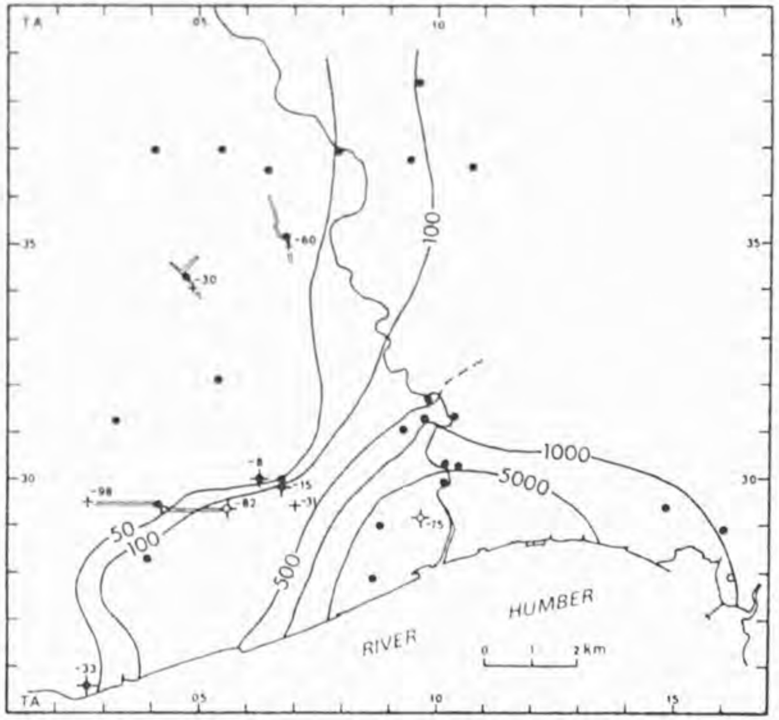


Fig. 11B. Distribution of chloride in Chalk groundwater: November 1967

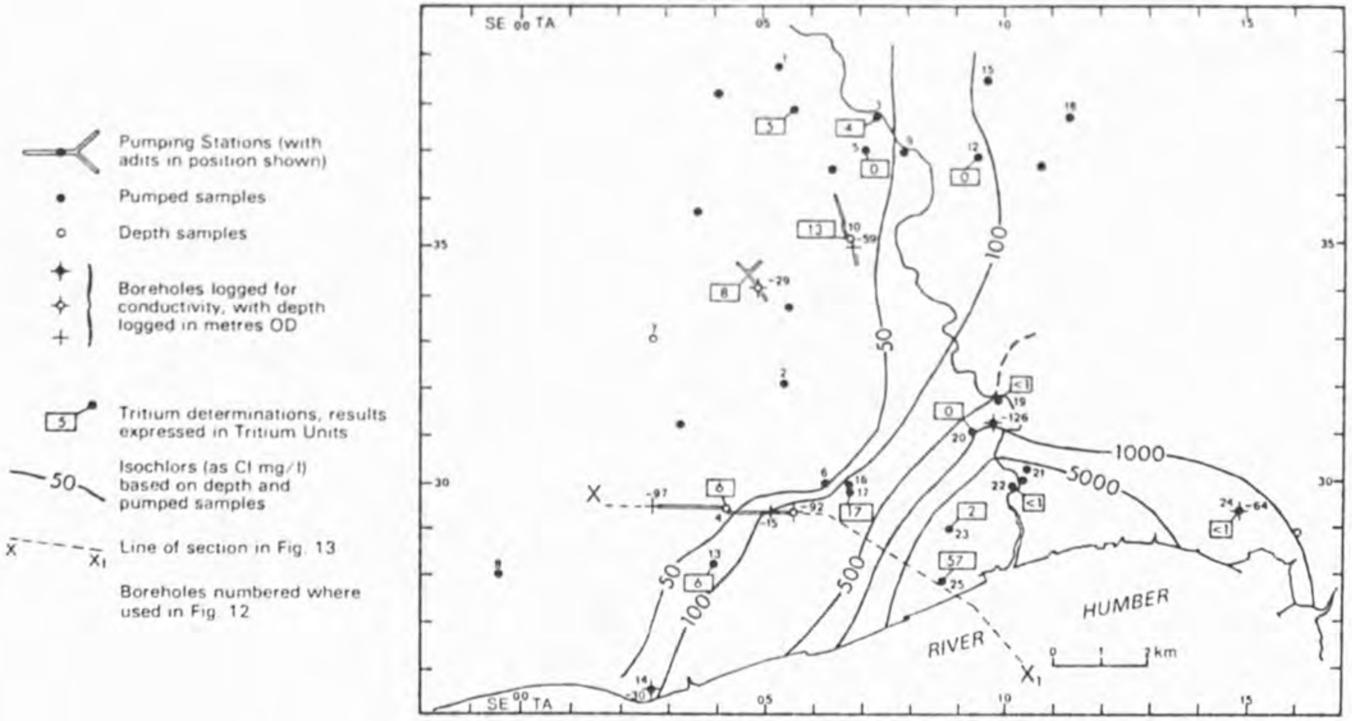


Fig. 11C. Distribution of chloride in Chalk groundwater: May 1973 groundwater sources do not reveal overall increases in chloride (Fig. 8). However in the earlier data there is evidence of a clear long term rise in chloride at Dunswell, from 20 mg/l to about 28 mg/l. There is also evidence of a worsening of water quality at Springhead; groundwater in the eastern adit has high salinity and the adit was sealed-off many years ago. During the 1967 fieldwork, depth samples from that adit contained 293 mg/l chloride at the eastern end, and 30 mg/l at the western.

The seasonal variation in chloride of water pumped at Hessle (site 14 in Fig. 11C) is very strong but the boreholes are only about 300 m from the Humber. Increasing salinity first became a problem in 1914; there is however no evidence of overall long term increases.

There are no boreholes with regular analyses in the area of greatest saline encroachment, but occasional analyses from three boreholes before 1951 are quoted in Table 6; these boreholes are located by A, B and C on Fig. 11A. A shows a clear increase in chlorides before the first detailed survey in 1951, the salinity at B and C has been moderately high for the whole period for which analyses are available, but with indications of post-war increases in the case of the former.

ORIGINS OF SALINE WATER

Important natural changes in groundwater chemistry occur down-dip in limestone aquifers as they pass under argillaceous cover. These have been studied in some detail by Ineson and Downing (1963) and Edmunds (1973) for the Chalk and Lincolnshire Limestone respectively, and reported by Foster and Milton (in press) for the Chalk of the northern part of East Yorkshire. The main changes that occur are the disappearance of dissolved oxygen and a sharp fall in redox potential (Eh) with the reduction of SO_4^{2-}, NO_3^- and generation of N_2 and H_2S, followed by base exchange with the minerals of the argillaceous confining strata. Beyond this zone there is a pH rise and mixing with older formation or connate water, which produces major increases in Na^+ and Cl^-. In the area of study all of these changes probably occur over a relatively short distance, within 8 to 15 km of the outcrop.

Other chemical changes down-dip include the increase in iron content of the groundwater with the onset of reducing conditions, caused by the replacement of Fe^{3+} by the more soluble Fe^{2+}. High iron was commented on by the owners of several of the boreholes visited, particularly in the area north-east of Dunswell, and was revealed by a brown residue on aeration of the groundwater samples.

On North Humberside there appear to be three possible sources for the saline groundwater:

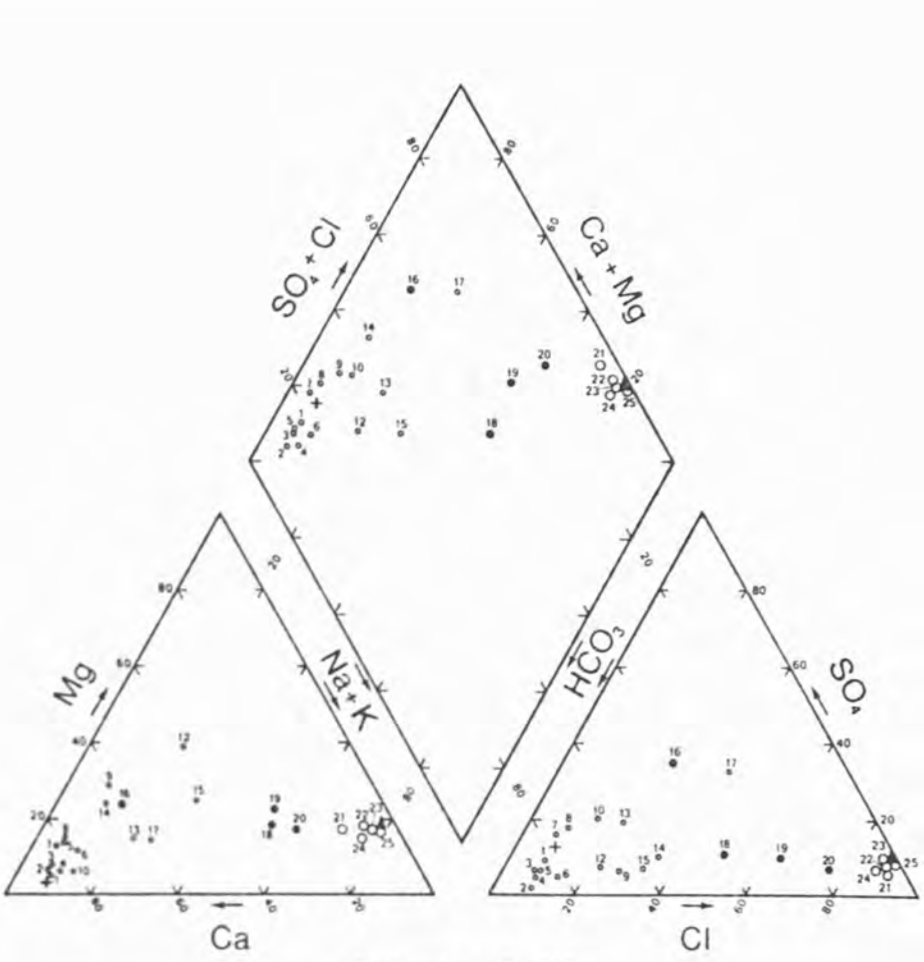
1. Connate or old formation water in the Chalk of the Holderness area, where groundwater circulation is absent or very sluggish.
2. Recent or old saline water from the Humber.
3. Recent or old saline water from the lower reaches of the River Hull.

A common approach to the investigation of mixing of groundwaters is to consider the ratios of the chemical constituents. A standard method of data presentation is a trilinear plot of chemical equivalents. Such a plot (Fig. 12) shows mixing between fresh Chalk water and saline water in the North Humberside area. No typical Humber analyses are available for any of the major ions except chloride, so a standard sea water analysis has been included. The most saline samples from central Hull have equivalent proportions very close to sea water. Further north it appears more likely that the saline component has been drawn from the Holderness Chalk as a result of long-term abstraction at Dunswell, but it is difficult to demonstrate this chemically. The current average chloride content in the River Hull near Beverley is only about 50 mg/l at high water (Yorkshire River Authority, 1973), and it cannot be the source of relatively high salinity in the area to the east of Dunswell.

Of the trace elements, strontium is particularly useful in distinguishing recent sea water from older saline groundwater. If the Holderness groundwater was either connate or old sea water, a higher strontium to other cations ratio than in present sea water might be expected. A log-log plot of Cl^- against Sr^{2+} however, does not show any abnormally high strontium values neither does a triangular plot of $Mg^{2+} : Ca^{2+} : Sr^{2+} \times 100$.

Various hydrochemical methods thus show no positive evidence of chemical differences between the encroaching Humber water and the Holderness Chalk water. The latter may in fact be comparatively recently intruded sea water rather than connate water but there are very few boreholes far enough east to provide representative samples. A further problem is the lack of a sequence of full chemical analyses of the Humber and Hull river waters as hydrochemical controls.

Of the pumped groundwater samples collected in May 1973, 15 were subjected to tritium (HTO) determinations; their distribution and the results are given in Fig. 11C. The current controversy over the interpretation of



Numbering as on Fig 11C

▲ Sea water

\+ Fresh Wolds water (Etton No. 1, 8 May 1973)

Total determined constituents

· <1000 mg/l

● 1000 to 5000 mg/l

○ >5000 mg/l

Fig. 12. Trilinear plot of hydrochemical data for May 1973

Table 6. Chloride analyses in the central Hull area (boreholes identified on Fig. 11A).

								Detailed regional surveys		
Borehole A (IGS ref. no. 80/63)	Date	1/29		5/37		5/48		5/51	11/67	5/73
	Chloride (mg/l)	50		65		223		510	Borehole no longer in use	
Borehole B (IGS ref. no. 80/66)	Date	5/28	12/28	5/38	5/61	7/61	10/61		11/67	5/73
	Chloride (mg/l)	426 387	471	340	598	626	613	-	645	930
Borehole C (IGS ref. no. 72/122)	Date	3/22	3/23	8/29	8/47		12/48	5/51	11/67	5/73
	Chloride (mg/l)	474	561	560	420		385	375	481	520

HTO levels in Chalk groundwater (Foster and Crease, 1974) makes it difficult to draw firm conclusions from these data, but the low HTO levels (less than 10 TU) of the fresh groundwater is currently typical of many intake areas. The more saline groundwater, particularly from east of the River Hull, mostly have very low HTO levels (less than 1 TU) but there is a very high value (57 TU) for a site on the Humber bank, which might be interpreted as evidence of intrusion of relatively recent saline water from the Humber.

In summary the hydrochemical investigations provide strong evidence of saline intrusion, apparently from localised points in the Humber bed opposite Kingston-upon-Hull and intermittently, at Hessle, but little evidence of the entry of poor quality water from the River Hull or from its alluvial deposits. More detailed local sampling around the major groundwater sources is needed to investigate the latter possibility, including samples from the perched groundwater body in the alluvial deposits. There is some evidence of 'drawing-back' of relatively saline Chalk water from Holderness towards the Dunswell area. The investigations as a whole were in no sense adequate to establish the distributions of saline water, and its chemical variation with depth in the aquifer; it is probable that 'coning-up' of saline water occurs beneath the major pumping centres and may even contribute to the observed salinities of the pumped samples.

Discussion and Implications

THE STATE OF GROUNDWATER RESOURCES

Using the definition of aquifer intake areas (Fig. 7A) and the estimates of groundwater recharge (Table 3), together with the data on actual abstraction (Table 4), the current state of development of groundwater resources can be assessed (Table 7). It is important to appreciate fully the underlying assumptions employed. The intake areas are arbitrary but nevertheless consistent with the hydrogeological regime. The main source of inaccuracy is thus the selection of the annual infiltration rate to the Chalk directly and through the upland Boulder Clay, both in average and drought conditions. An error of 25 mm in the infiltration at the Chalk outcrop represents more than 3000 Ml/a in the overall water balance of intake areas A + B (Table 3). Potentially much larger errors could be involved in the estimation of the infiltration to the Chalk through the cover of upland Boulder Clay along the flanks of the Yorkshire Wolds; a figure of 50 per cent of that at the Chalk outcrop has been selected but a variation from 0 to 100 per cent would represent ± 12 600 Ml/a over intake areas A + B in an average year and ± 4200 Ml/a in severe drought (Table 3).

Considering the probable long term average condition (Table 7), it is evident that the southern of the two intake areas (A) appears to be marginally in deficit but when areas A + B are considered there is a surplus of some 16 000 Ml/a; these latter areas combined would still be in surplus even if there were no infiltration through the upland Boulder Clay. This actual surplus, however, is transformed into a significant potential deficit (16 000 Ml/a), as a result of the large volume of groundwater reserved within the licensing system (Table 5).

In practice also, non-uniformity in the distribution of abstraction with its heavy concentration in the south of intake area A means that the resources of area B are only tapped after the abstraction from storage in area A is sufficiently large to intercept a correspondingly large flow frontage. Thus the volume of groundwater discharged to the Chalk watercourses in the north of area B (Fig. 7A, B), is somewhat larger than the overall surplus of areas A + B combined. Apart from some very limited direct abstraction, its value as an amenity and a small contribution towards dilution of effluents in the tidal Hull, this high quality groundwater flows to waste.

The position in severe drought is a most important consideration. A theoretical draught on aquifer storage of the order of 19 000 Ml and 33 000 Ml in a one and two year drought situation respectively is indicated (Table 7), and in practice the abstraction from storage would be considerably greater as a result of the non-uniform distribution of pumping. This abstraction from storage is inevitably associated with some undesirable side-effects — falling groundwater levels and well yields, competition for available groundwater supplies and advance of the fronts of saline water intrusion. Induced leakage from the drift deposits of the Hull Valley may partially counteract these effects. While there is no evidence to suggest that such a recharge component would be of poor quality, its volume may be restricted.

It is interesting to note that the groundwater abstraction has exceeded the drought-year replenishment of intake area A ever since 1900-1910 (Fig. 1, Table 3) and the groundwater resources could be regarded as having been overdeveloped since that time. That this would be taking an excessively restricted view on development however, is more than proved by the many subsequent years of inexpensive water-

Table 7. State of development of groundwater resources.

		A	B	A+B	Notes
A.	Probable long term average conditions				
Estimated replenishment	Ml/a	29 000	24 000	53 000	Taking 300 mm/a precipitation recharge, and assuming 100 % infiltration at Chalk outcrop and 50 % over upland Boulder Clay.
Current actual abstraction	Ml/a	34 000	3000	37 000	1972 data.
Surplus or deficiency	Ml/a	-5000	+21 000	+16 000	
	%	-17	+87	+30	
B.	Severe drought in a single year				
Estimated replenishment	Ml/a	10 000	8000	18 000	Taking 100 mm/a precipitation recharge and infiltration assumptions as above.
Current actual abstraction	Ml/a	34 000	3000	37 000	1972 data. In practice yields could probably not be maintained and demand would not be achieved.
Surplus or deficiency	Ml/a	-24 000	+5000	-19 000	
	%	-240	+62	-105	
C.	Severe drought in two consecutive years				
Estimated replenishment	Ml	22 000	18 000	40 000	Taking 225 mm precipitation recharge in 2-year drought and infiltration assumptions as above.
Current actual abstraction	Ml	67 000	6000	73 000	1972 data. Yields could probably not be maintained in drought, as above.
Surplus or deficiency	Ml	-45 000	+12 000	-33 000	
	%	-205	+67	-82	

supplies that have been derived from the Chalk with only limited undesirable side-effects.

IMPLICATIONS FOR EXISTING AND FUTURE WATER SUPPLIES

The balance of the evidence presented does not of necessity warrant a cut back in the abstraction from the major public groundwater sources. Both the Springhead and Dunswell sources are threatened by saline intrusion particularly during severe drought (the former by saline water originating from the Humber and the latter from that in the Chalk beneath Holderness). There may have been a marginal worsening of the situation since 1951 (cf. Figs. 11A and C), but it still appears unlikely that the chloride level during drought in these sources will reach 50 mg/l, if abstraction is maintained at the present level.

In view of the very large groundwater abstractions concentrated at distances of only 2 to 8 km from the Humber, it is pertinent to consider why there has not been more extensive intrusion of saline water from the estuary. Interference effects generated by this pumping can be measured at distances in excess of 10 km to the north during extreme drought. While restricted hydraulic communication through the bed of the Humber and falling yields in drought may both be contributory factors, it is more likely that a rapid down-dip decrease in aquifer transmissivity (probably to below 200 m^2/d) towards the Humber and beneath Holderness has prevented a worse situation by limiting saline water movement, even when high landward heads have prevailed.

It is clear, however, that there is no further room for conventional large scale groundwater development in area A, even if the licensing anomaly is resolved; though existing or future smaller developments for horticultural or industrial purposes may be permitted. One reservation in this connection might be development in or immediately adjacent to the zone of highly saline water in the centre of Kingston-upon-Hull, since new abstractions here might affect the total dissolved solids and chloride concentrations of existing groundwater sources used for sensitive industrial processes.

As a result of the favourable hydrogeological conditions, engineering measures specifically designed to stop or control the intrusion of saline water from the Humber do not appear to be justified. However, the situation is not one for complacency, particularly in the case of the Springhead source which is separated by only small lateral and vertical distances from water of 5000 mg/l Cl^- (Fig. 13), and an improved understanding of Chalk aquifer hydraulics and monitoring of the front of saline intrusion are required.

There is scope for a beneficial re-distribution of groundwater abstraction for major public supplies. Cutting back or phasing out production from one or more of the existing sources and their replacement by groups of large diameter boreholes in area B would reduce the draught on storage in intake area A during extreme drought and thus relieve both the threat of saline intrusion and the competition between private and public abstractors in this area. Some care would be required in the planning of this operation so that at no stage was there risk of re-establishing natural groundwater discharge at the surface from the Chalk aquifer in area A, since this might cause troublesome problems to urban structures and agricultural drainage. The former are likely to be the more serious since numerous suburbs to the north and west of Kingston-upon-Hull (Anlaby, Willerby and Cottingham) have been constructed since the initial fall in groundwater levels and the cessation of spring discharge earlier in the century.

While re-distribution of major public abstraction would probably be the most effective management policy for water resources, others could also be considered. For example, the existing sources could be operated conjunctively with other new sources, less vulnerable to side-effects in drought and outside the area under present consideration. The former could then be pumped at maximum rates at times of higher water table with the abstraction rates reduced progressively during the recession, when the other sources could be brought into heavier production. Another possibility might be the artificial recharge of the Chalk in area A using excess flows on the River Hull and the Holderness land drainage system, or other sources such as the River Derwent. Such a scheme, however, would require complex technical and economic studies to assess feasibility.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

An urgent requirement, for the improved management of the groundwater resources of North Humberside, is the drilling of 6 to 8 small diameter boreholes principally for the monitoring of the seasonal and long term movement of the saline water fronts and their associated zones of mixing.

Some investigation of the infiltration through the upland Boulder Clay on the flanks of the Yorkshire Wolds and of induced recharge from

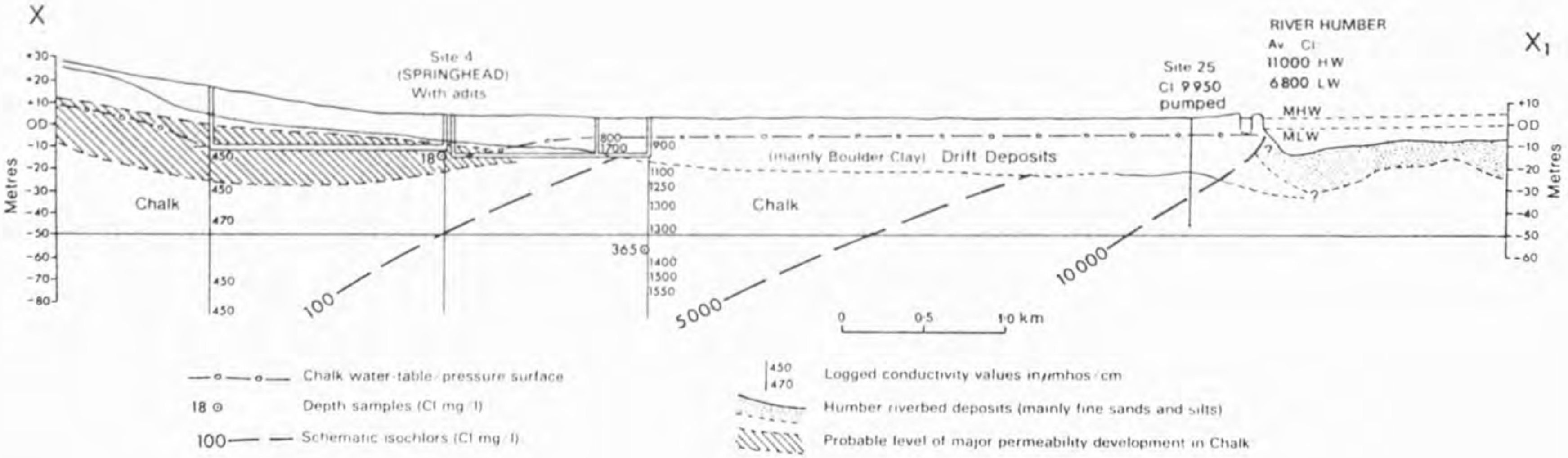


Fig. 13. Schematic section of Chalk aquifer on north Humberside to show extent of saline water intrusion

the drift deposits of the Hull Valley would serve to refine the water balance presented in this report. The former would probably have to be approached by monitoring the saturation profiles of the Boulder Clay and relating them to fluctuations in the groundwater levels in the underlying Chalk aquifer and the latter by a pumping test on a Chalk borehole with suitable observation borehole control.

Before any major re-distribution or change in the mode of development of groundwater resources is attempted, further data on the hydraulic properties of the Chalk aquifer are required. These could be generated by conducting three controlled pumping tests, one in the outcrop area, a second close to the buried coastline and the third in Kingston-upon-Hull itself.

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Dd. 196304 K8

Printed in England for Her Majesty's Stationery Office
by Unwin Brothers Limited, The Gresham Press, Old Woking, Surrey

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MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

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Proceedings of a Conference
organized by the Agricultural Development
and Advisory Service and the Agricultural
Research Council
17–19 December 1974

LONDON
HER MAJESTY'S STATIONERY OFFICE
1976

The Vulnerability of British Groundwater Resources to Pollution by Agricultural Leachates

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Summary

The outcrops of the major British aquifers, the Chalk and the Permo-Triassic Sandstones, form extensive tracts of valuable agricultural land in central, southern and eastern England. Their groundwater resources in the main originate as rainfall which infiltrates farming land in these areas. As such they are, and always have been, directly vulnerable to diffuse pollution by agricultural practices.

Evidence of widespread pollution at significant or serious levels is mainly limited to nitrate, but the monitoring of many sources is rather scanty. Rapid rises of NO_3-N in groundwater supplies from various parts of eastern England since 1968–70 are the greatest cause of current concern; for the most part these rises are in regions of intensive cereal growing.

The interpretation of the chemistry of water supplies pumped from an aquifer requires considerable caution, since their origin is liable to be complex. Many misconceptions result from a lack of understanding of the groundwater flow regime both above and below the water-table. A major part of the paper is thus devoted to a review of the physical properties, chemical characters and hydrological regimes of the two major aquifers. The effect of stratification of recharge below the water-table in the deep Permo-Triassic basins and of slow intergranular seepage in the thick unsaturated zone of many Chalk aquifers *could mean* that only a small proportion of water supplies at present abstracted will be recent (post-1970) infiltration. Both effects require further study; the Chalk unsaturated zone, in particular, being a highly controversial topic. *But,* if small components of recent infiltration do prove responsible for the recent increases, then these rises might be only 'the tip of the iceberg' as far as NO_3-N levels in groundwater supplies are concerned.

The nature of groundwater systems, and the British aquifers in particular, is such that monitoring of the chemistry of water supplies alone is an inadequate basis, albeit the only one currently employed, for the management of groundwater quality.

Significance of groundwater in British water supply

Some 25–30 per cent of all authorized water supply development in England and Wales is from groundwater resources. Coal mine drainage and cooling water for electricity generation are excluded from this estimate. If potable supplies only are considered then the proportion approaches 40 per cent.

Total groundwater development is in the order of 7,000 Ml/d; of this more than 50 per cent is derived from the Chalk and about 30 per cent from the Permo-Triassic Sandstones.

Although direct groundwater abstraction has in many places reached, and in some places surpassed, reliable yield calculated from the replenishment (Ineson, 1970), it is thought that by more effective deployment groundwater can satisfy about 25 per cent of the demand for new supplies anticipated to the end of this century (Water Resources Board, 1974). Fuller exploitation of the vast volumes of subsurface storage is the objective, in conjunctive use with surface water supplies, for river regulation by groundwater abstraction and by artificial groundwater recharge with surplus surface run-off.

The increasingly complex effluent load in many lowland rivers may threaten the potability of water supplies obtained from them, particularly through a wide variety of trace pollutants. It further strengthens the case for protection of the high quality of most groundwater supplies and the prevention of levels of pollution incompatible with potability.

In view of the importance of the Chalk and Permo-Triassic Sandstone formations in water supply at the national level, it is the intention to concentrate exclusively upon them in this paper. It should be noted in passing, however, that groundwater from other formations (Jurassic and Carboniferous Limestones, Cretaceous Greensands and Alluvial/Glacial Gravels) is significant in the local water supply of some areas.

The distribution of the Chalk Aquifer is shown in Fig. 1; in considering the risk of agricultural pollution the primary concern is with the groundwater intake areas, which are also volumetrically more important in water supply. They are essentially contiguous with the outcrop and comprise extensive wolds and downs in the counties of East Yorkshire, Lincolnshire, Norfolk, Cambridgeshire, Kent, Buckinghamshire, Berkshire, Wiltshire, Hampshire and Dorset. The Permo-Triassic Sandstones generally occupy lower-lying land, often have a thick cover of drift or superficial deposits (Fig. 1) and a more complex recharge regime.

Physical and chemical characteristics of the major aquifers

CHALK

The Chalk is a uniform, highly-pure and exceedingly fine-grained sequence of white limestones. The bulk of the rock is normally composed of fragments of calcareous microfossils (known as coccoliths) of 0·5–5·0 μm diameter (Plate I) together with scattered larger particles (mainly broken mollusc shells and foraminifera) of 20–100 μm diameter (Black, 1953). The overall lithology of the rock depends on the relative proportions of the above constituents and on diagenetic factors (Bathurst, 1971). Soft porous white chalks are composed principally of coccoliths and have fairly scant cementation (Hancock and Kennedy, 1967); they dominate the sequence in the 'southern depositional province' (as far north as Norfolk). Allowing for intragranular in addition to intergranular pore space, the total porosity on deposition probably exceeded 0·50 and in the case of the Upper Chalk of Berkshire for example, 0·45 is still preserved at some points in the sequence (Edmunds *et al.*, 1973). At occasional horizons (e.g., the Chalk Rock), hardgrounds formed with a porosity reduction to less than 0·15 by calcite

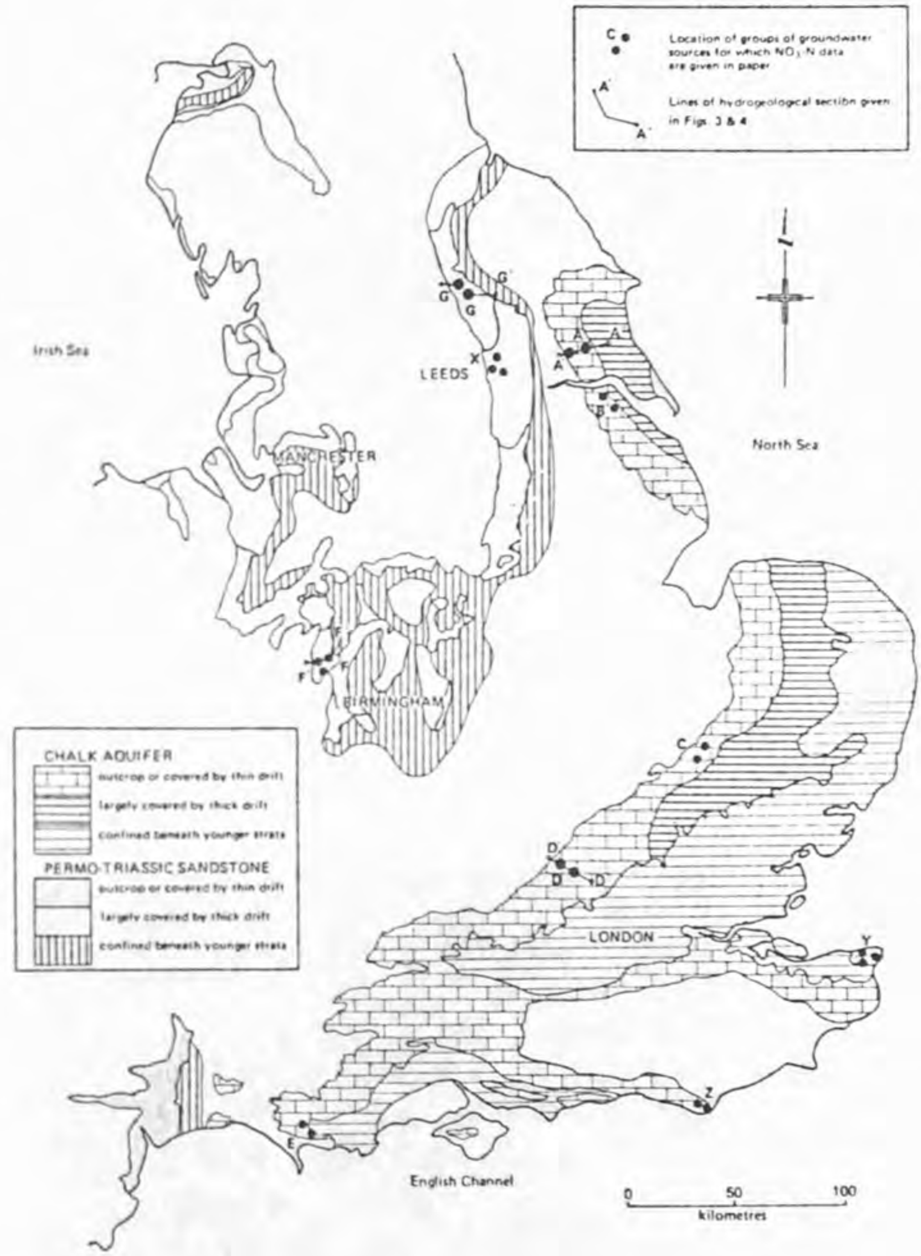


Fig. 1. Location map showing distribution of Chalk and Permo-Triassic Sandstone Aquifers.

PLATE I

Electronmicrograph of a sample of Middle Chalk from a Berkshire borehole (overall width of field of view about 30μm)

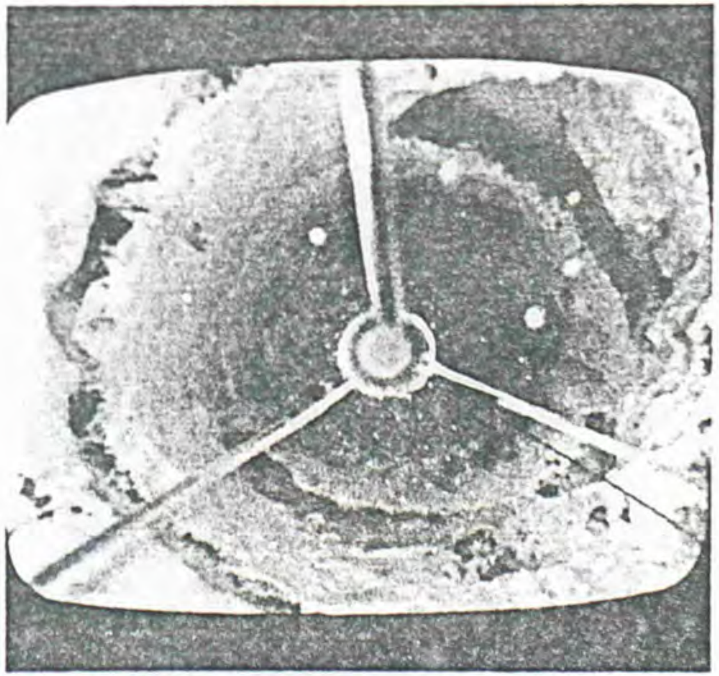


PLATE II

Axial cc tv view down a 900 mm diameter borehole in the Upper Chalk of Norfolk, showing fissure development on horizontal discontinuities

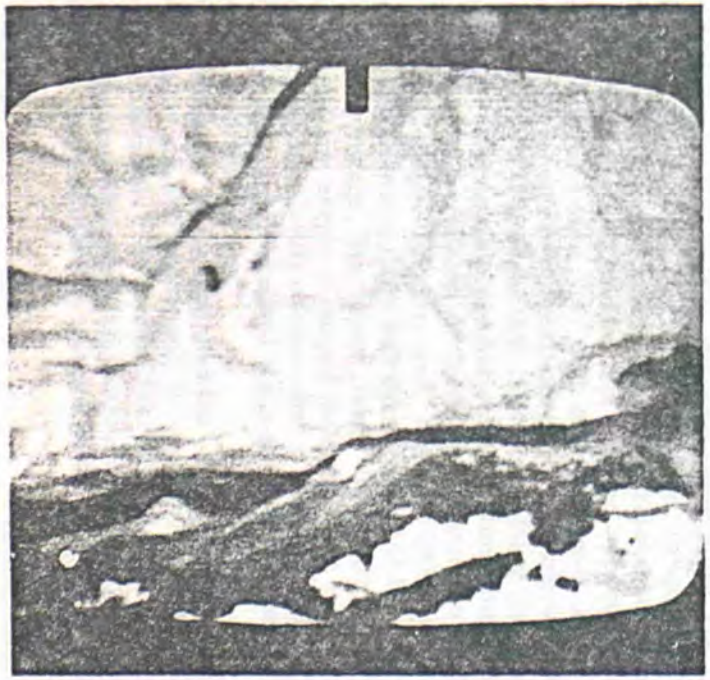


PLATE III

Radial cc tv view of part of a single fissure from Plate II with marl seam below (overall width of field of view about 150 mm)

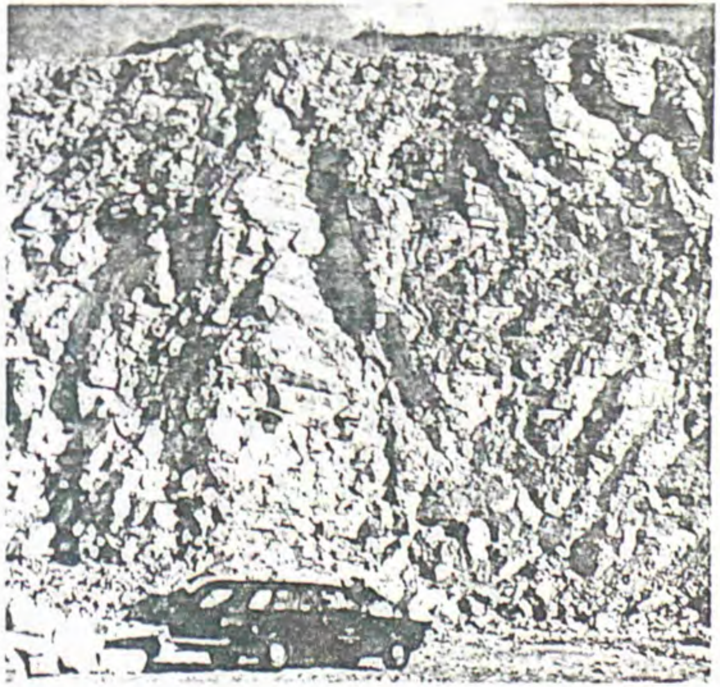


PLATE IV

Typical quarry exposure showing jointing and horizontal discontinuities in the Upper Chalk of East Yorkshire cementation, with the development of glauconite and apatite and other distinctive features.

In the Chalk of the 'northern depositional province', including Lincolnshire and East Yorkshire, cementation and hardening are more common features and dominate the sequence. Porosities are typically in the range 0·13–0·21 (Foster and Crease, 1974).

The Upper and Middle Chalk sequence is broken only occasionally by primary marl bands (0·01–0·20 m thick) and more often by secondary flints and stylolites with their associated marl seams.

The chalk of this sequence is itself an exceptionally pure limestone, the acid insoluble fraction being only 0–5 per cent, with montmorillonite and clay mica as the most frequent clay minerals (Weir and Catt, 1965; Young in Gray, 1965; Jeans, 1968). The Lower Chalk is distinctive by its more marly character, by the presence of other impurities imparting colour to certain horizons and by the general absence of flints. Acid insoluble residues of 5–30 per cent are common and kaolinite is often present as an additional clay mineral. Other frequent trace impurities in the Chalk are quartz, apatite and disseminated pyrite, the latter being commonly oxidized to calcium sulphate.

Despite high porosity, laboratory samples of Chalk exhibit very low permeability, rarely exceeding 10^{-3} m/d (Table 1). This combination of physical properties is a reflection of the exceedingly small particle sizes and pore diameters (Plate I). PSD determinations by the mercury-injection method (Fig. 2) show the bulk of the pores to have equivalent capillary diameters of 0·3–1·5 μm. Drainage will occur only under tensions of the order of 2–5 atmospheres, explaining the very low specific yields and very high specific retentions obtained in centrifuge tests on core samples (Table 1). The values of less than 0·01 and frequently less than 0·005 for the former, probably represent drainage from an occasional pore of larger diameter.

In its saturated zone the Chalk Aquifer is thus an entirely fissure-flow and largely fissure-storage aquifer, the pore-water being for the most part physically immobile. The flow of groundwater through the rock mass is controlled by the geometry of discontinuities (inclined joints, bedding planes, less regular fissures and cavities and solution openings) with respect to natural or applied heads. Very high transmissivities (more than 100,000 times the intergranular component) are frequently reported from the outcrop area (Table 1). It is thought that high permeability has developed due to limited calcite solution mainly on horizontal discontinuities (Plates II and III) during long-term circulation of fresh groundwater to existing and pre-existing base levels (Foster and Milton, 1974). Such horizontal discontinuities are particularly well developed in the Chalk of the 'northern depositional province' but occur fairly frequently in the south also. Permeability is not evenly developed throughout the entire thickness of the formation and is frequently concentrated at shallow depths below the water-table and in the zone of seasonal water-table fluctuation. At depth there is often little groundwater flow.

The significance of inclined jointing in the development of secondary permeability is not well understood; it is believed that the *in situ* horizontal permeability normally exceeds that in the vertical direction by more than one order of magnitude. In quarry exposures the rock mass is normally traversed by relatively large numbers of inclined joints (Plate IV). These may appear

Table 1

Comparison between laboratory and field values for hydraulic properties of Chalk and Permo-Triassic Sandstones at selected sites

Formation	Location	Laboratory samples							Field tests		Type of flow regime	Reference
		Mean k_H (m/d)	k_H range (m/d)	Mean k_V (m/d)	Mean Ø	Ø Range	T_i (m²/d)	Mean cSy	T_t (m²/d)	S_t		
Upper and Middle Chalk	Berkshire Downs	10^{-3}	$3 \cdot 10^{-4}$ to $5 \cdot 10^{-3}$	10^{-3}	0·35	0·25–0·45	10^{-2}	0·01	2,800	?0·02	F	Edmunds *et al.* (1973)
Upper/Middle Chalk	Yorkshire Wolds	$2 \cdot 10^{-4}$	$5 \cdot 10^{-5}$ to $6 \cdot 10^{-4}$	10^{-4}	0·17	0·13–0·21	10^{-2}	0·005	1,000	0·005	F	Foster and Milton (1974)
Bunter Sandstone	Sherwood Forest, Notts.	4	$2 \cdot 10^{-2}$ to 10	3	0·29	0·14–0·34	300	0·22	1,500	—	F + I	Williams *et al.* (1972)
Penrith Sandstone	Eden Valley, Cumbria	3	10^{-1} to 20	1	0·26	0·20–0·32	155	0·14	2,500	0·001	F	Price (personal communication)
Bunter Pebble Beds	Cannock Chase, Staffs.	9	—	—	—	0·26–0·33	270	—	2,800	0·0005	F + i	Lovelock (1972)
Bunter Sandstone	Fylde, Lancs.	0·5	10^{-1} to 10	0·2	—	—	65	—	1,100	0·002	F	Brereton and Skinner (1974)

k_H horizontal intergranular permeability
k_V vertical intergranular permeability
T_i computed intergranular transmissivity
Ø porosity
cSy centrifuge specific yield
T_t total *in situ* transmissivity
S_t *in situ* storage coefficient
F fissure component dominant
I major intergranular component
i minor intergranular component.

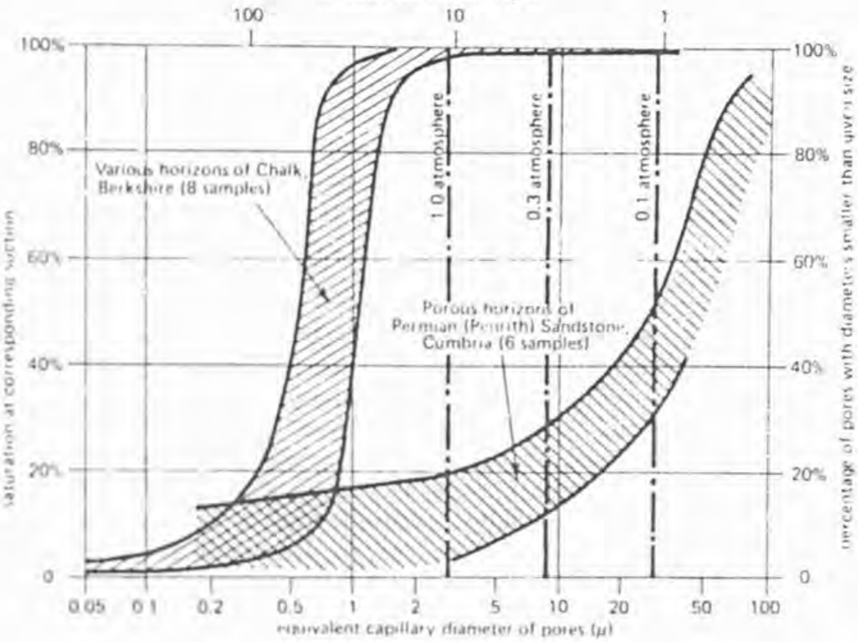


Fig. 2. Pore size distribution (PSD) envelopes.

closed 'tight' at relatively shallow depths of burial but it should be borne in mind that small openings can impart high permeability to a rock mass (Foster and Milton, 1974). For example, if each joint of a parallel set with 1 metre spacing had an effective opening of only 0·2 mm, a permeability of 400-4,000 times the vertical intergranular value would be developed.

In summary the Chalk is a most unusual aquifer containing two contrasting physical components – a small volume /high permeability fissure porosity and a large volume/very low permeability intergranular porosity. By virtue of the minute pore diameters, the latter will be almost always fully saturated, even in the unsaturated zone. In addition to the small volume of minerals of high cation exchange capacity, there thus must be a large capacity for straightforward dilution of new constituents in the fissure-water by aqueous diffusion with the pore-water system (Foster, 1975). Major pollution of the aquifer will probably have occurred before it is recognized by the associated pollution of groundwater supplies and will remain long after the source of pollution has been eradicated.

PERMO-TRIASSIC SANDSTONES

In contrast to the Chalk, the Permo-Triassic Sandstones are more normal aquifers, with significant intergranular permeability accompanying moderate porosity at most horizons.

They are, however, also essentially consolidated formations and in recent years (Lovelock, 1972; Williams *et al.*, 1972; Brereton and Skinner, 1974) it has become increasingly apparent that fissure-flow normally plays a significant or dominant role in their hydraulics (Table 1).

The Permo-Triassic Sandstones show wide vertical and lateral lithological variation on all scales. In each area where they are present a number of lithological sub-divisions are usually recognized. A comprehensive work on the lithological and hydraulic characteristics of the sub-divisions in the various regions is available (Lovelock, 1972) and indicates that the physical parameters also vary widely within a given sub-division in any given area. This is a reflection of their largely fluvial environment of deposition. A typical sedimentary feature is the fining-upward cycle from basal pebbly sandstones through laminated fine-to-medium grain sandstones and siltstones, the topmost member of the cycle being a thin impersistent mudstone or marl. The thickness of individual cycles and the relative thickness of each part of the cycle varies widely from formation to formation. Aeolian sandstones are also well developed at some horizons in certain areas.

For the present purpose it is practical to give only a general idea of the range of physical properties likely to be encountered, by reference to specific examples. At a site in Nottinghamshire, Williams *et al.* (1972) recognized four distinct lithologies within the Lower Mottled Sandstone and the Bunter Pebble Beds (known collectively as the Bunter Sandstone). The commonest rock type was a fine-to-medium grained sandstone characterized by a permeability of 4–6 m/d but exceptionally reaching 16 m/d, a high porosity (0·30) and a centrifuge specific yield of over 0·20. Other rock types present included highly-laminated sandstones with permeability ranging from less than 1 m/d to 8 m/d with lower porosity and centrifuge specific yield, well-cemented sandstones with a porosity of about 0·20 and permeabilities of only about 0·3 m/d and mudstones with permeabilities of less than 10^{-2} m/d. Average overall horizontal permeability determined from field pumping tests proved to be about 5 times the value calculated for intergranular permeability from tests on laboratory samples and the lithological log. The range of physical properties of the Bunter Sandstone in Nottinghamshire is fairly representative of the characteristics of the Permo-Triassic Sandstones in other areas (Table 1) although fine-grained, well-cemented sandstones of less than 1 m/d permeability dominate in some areas, notably North Yorkshire and the Cumbrian coast (Lovelock, 1972).

The bulk of the sandstones are formed of quartz and feldspar, which are relatively unreactive. Clay minerals (kaolinite, montmorillonite and clay mica) and various species of hydrated ferric oxides are normally abundant in the matrix (Taylor in Sylvester-Bradley and Ford, 1968; Morgan-Jones, personal communication). The sandstones are predominantly red, the abundance of haematite being directly related to the colour; green or white mottling is fairly common and resulted from syndepositional or diagenetic reduction of the primary red iron oxides.

Typical hydrological regimes and hydrochemical environments

CHALK

The Chalk Aquifer tends to develop similar hydrological regimes wherever it occurs; cross-sections of two areas are given (Fig. 3). In the present paper the main concern is with the intake area of the aquifer, since here exists the greatest risk of pollution from the surface. The following discussion is accordingly biased.

Over much of the intake area the Chalk itself is at outcrop with only a thin

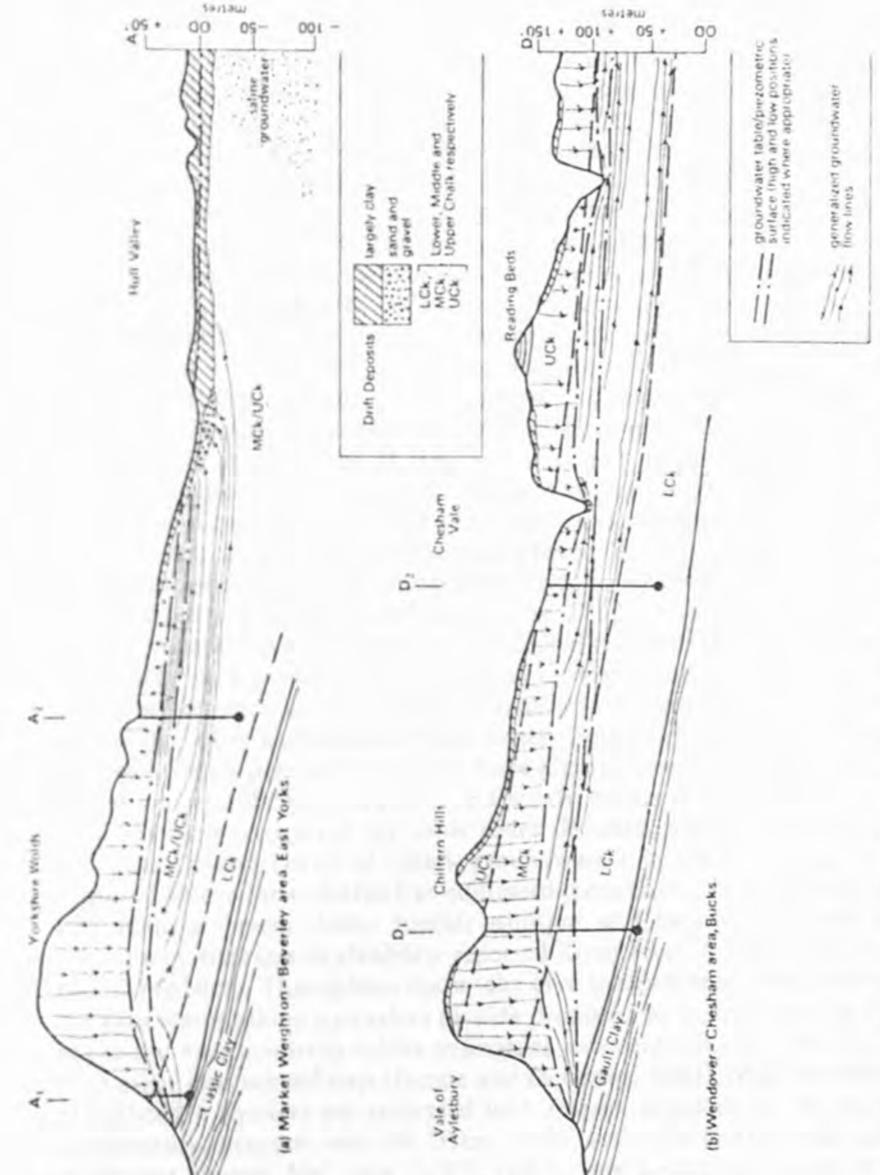


Fig. 3. Hydrogeological sections of the Chalk Aquifer (vertical exaggeration × 20 approx.).

soil cover; elsewhere 0·5–3 m of superficial deposits (upland Boulder Clay, residual clay-with-flints) may also be present. In these areas most, if not all, the excess rainfall infiltrates and aquifer recharge rates in the range 100–500 mm/a result, depending on the meteorological variables. Long-term average annual infiltration is usually 200–300 mm. In contrast recharge through a Boulder Clay cover of 10 m or more thickness, in the sub-artesian confined areas of East Anglia for example, is less than 100 mm/a, and may only be induced by groundwater abstraction. Infiltration in any year is mainly limited to a few weeks during September–March but minor infiltration is sometimes observed following high intensity rainfall outside these months.

The unsaturated zone is normally 10–100 m thick. For many years it was thought that fissure-flow at rapid rates dominated downward groundwater movement through the zone after infiltration, in the same way as horizontal flow in the saturated zone is localized in fissures. However, the low-level of thermonuclear tritium in the saturated zone throughout most of the intake areas and the form of the unsaturated zone tritium profiles at two sites (Smith *et al.*, 1970; Smith, 1973), have been interpreted to indicate a largely intergranular flow regime in the unsaturated zone with average seepage rates of less than 1 m/a. Such a flow regime is not easy to reconcile with the hydraulic properties of the Chalk (Foster and Crease, 1974); it is particularly difficult to explain the higher of the short-term infiltration rates (over, say, 20 mm/d) during periods of zero soil moisture deficit, without evoking a major component of fissure-flow. Surface run-off might be expected from non-jointed Chalk. The case for a dominantly slow regime of downward flow in the unsaturated zone is still far from proven. Resolution of the controversy is of major relevance to the understanding of pollution from the land surface in Chalk outcrop areas (Foster and Crease, 1974). Attention has been drawn to the unusual physical properties of the Chalk; it appears possible that these might lead to a manifold dilution of new constituents in circulation in the fissure-water (such as thermonuclear tritium), by aqueous diffusion into the apparently older and immobile pore-water (Foster, 1975). It is interesting to note that Chalk pore-waters can be more highly mineralized than the present fissure-water at the same horizons (Edmunds, personal communication).

It has been recognized for some years (Buchan, 1958) that many of the chemical characteristics of Chalk groundwaters in the saturated zone are acquired before the recharge has infiltrated more than 1–2 m through the soil and surficial layers. Some further solution of Chalk is indicated by the subsequent increases in alkalinity reported (from 80–170 mg/litre to in excess of 210 mg/litre). Throughout the intake area solution reactions predominate; the rain water taking up carbon dioxide produced by microbiological activity in the soil and dissolving calcite to produce an essentially Ca^{++}, HCO_3^- water with other ions subordinate (Ineson and Downing, 1963). Most groundwaters of carbonate aquifers are saturated with respect to calcite at the given field temperature, pressure and pH (Hem, 1963) and precipitation may occur if conditions change. Na^+, Mg^{++}, SO_4^{--} and Cl^- are commonly higher in Chalk groundwater in those intake areas where a thin clay cover is present.

Not enough is known about the capacity of the Chalk and chalk soils for self-purification of polluted recharge. Any heavy metals may be co-precipitated and ion exchange processes may immobilize the exchangeable cations, though no quantitative data are available. Although the bacteriological quality of Chalk groundwaters is usually high, incidents of contamination are known for most sources sited on the outcrop, even in areas without water-table quarries or other direct pollution threats; natural mechanical filtration is thus not as effective as in unconsolidated formations.

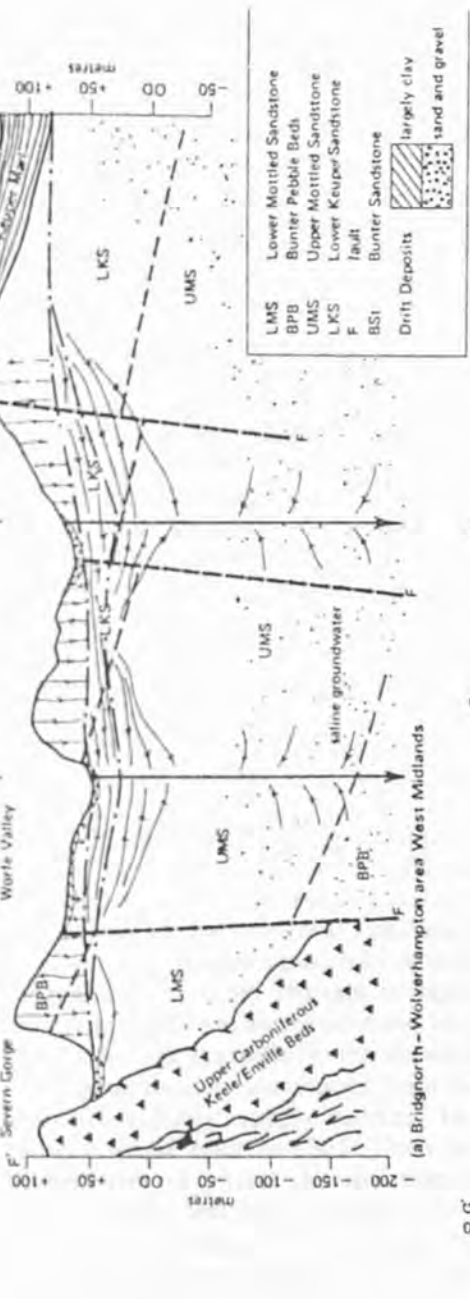
The permeability heterogeneity in the saturated zone has already been described, the major development of fissure permeability frequently being localized at restricted levels. At these levels natural groundwater flowrates will frequently exceed 100 m/d and perhaps reach 500 m/d locally. (Karstic solution features, however, are uncommon even on a small scale, except where rather exceptional local conditions occur.) At depth there is often minor or insignificant development of fissure permeability, and in the absence of a significant intergranular component, water supply boreholes derive no measurable inflows (e.g., Foster and Milton, 1974).

There is little evidence to suggest that even marginally anaerobic conditions are likely to be established anywhere beneath the aquifer intake area, except at times in the soil horizon and possibly also at greater depth beneath some intensive animal feeding areas. A plentiful supply of air is presumably present during the infiltration process and will probably be maintained by diffusion through the unsaturated zone, though *in situ* measurement of Eh in groundwater is subject to difficulties (Hem, 1963). Groundwater chemistry may be affected by slow changes in the input of oxygen to aquifers due to groundwater development or to differing agricultural practices. Down-dip in the confined zones, beyond the areas of major groundwater circulation, flowrates are reduced by more than two orders of magnitude and a complex chain of hydrochemical changes occurs (Ineson and Downing, 1963; Edmunds, 1973), including cation exchange reactions with the clay minerals of the confining bed, development of reducing conditions and mixing with connate water.

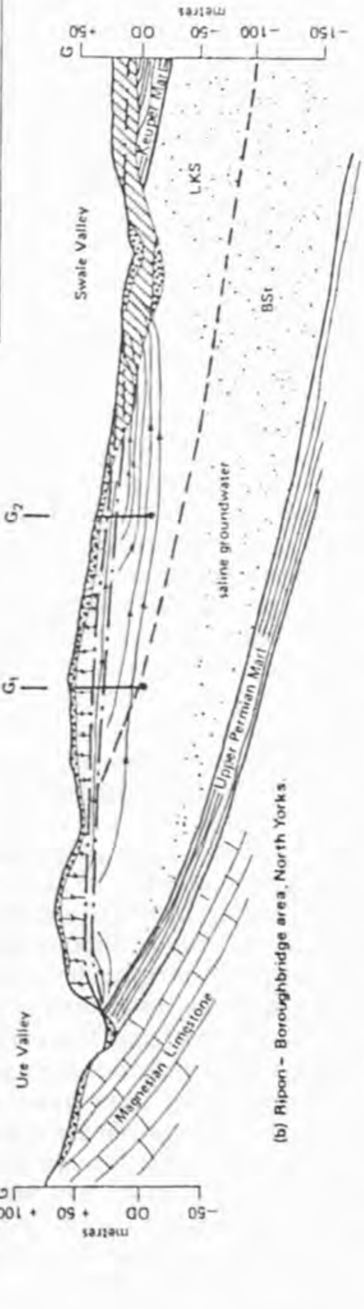
PERMO-TRIASSIC SANDSTONES

The hydrological regimes and hydrochemical environments associated with the intake areas of the Permo-Triassic Sandstones differ in a number of significant ways from those associated with the Chalk.

In general, the formation has a greater thickness than the Chalk, most of this thickness being located below local hydrological base-level (Fig. 4) and possessing moderate intergranular permeability. The ratio of the available aquifer storage in the intake area to average annual throughput is probably more than 50 for many Permo-Triassic Sandstones compared with less than 5 for the Chalk. In the absence of heavy pumping, localized shallow flow regimes tend to develop around the natural discharge areas with stratification of the recharge. The most recent recharge is likely to be found in a thin layer immediately below the water-table with older fresh water below and invariably giving way to connate, increasingly-saline water in depth. Deep pumping boreholes frequently tap a mixture of groundwaters of various origins and recharge histories and the chemistry of their discharge may vary widely depending on the details of production regime and construction (Fig. 5). Supplies from neighbouring boreholes of different depth may have widely different concentrations of any pollutants derived from the surface and present only in recent recharge. Groundwater quality monitoring can



(a) Bridgnorth – Wolverhampton area West Midlands



(b) Ripon – Boroughbridge area, North Yorks.

Fig. 4. Hydrogeological sections of Permo-Triassic Sandstone areas (vertical exaggeration × 20 approx.).

only be effectively undertaken at a three-dimensional level with accurately located depth samples being regularly obtained from purpose-drilled boreholes. Such data are rarely available even locally.

The outcrop of the Permo-Triassic Sandstones tends to form lower-lying land than that of the Chalk and is frequently transected by naturally effluent rivers, which may become influent with heavy groundwater development. The outcrop is frequently drift covered and in general develops thicker soils than the Chalk.

Groundwater flowrates will still be relatively high when a fissure-flow component is present but at many horizons where fissure permeability development is minimal natural flowrates are unlikely to exceed 5 m/d.

Precise data on the hydrochemical environments are very limited. In the West Midlands aerobic conditions generally appear to exist to at least 100 m bgl and carbonate saturation is only encountered in the lithological units with calcareous cement (Edmunds, personal communication).

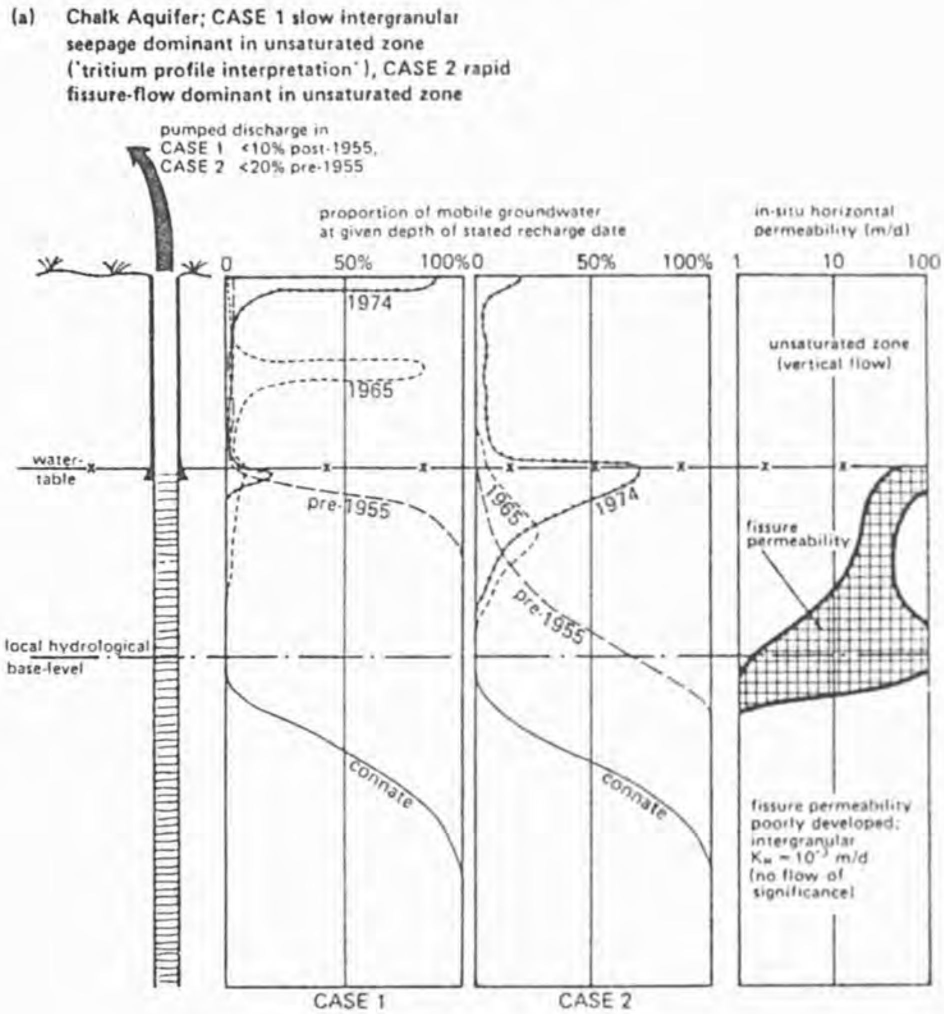
Evidence for regional groundwater pollution by agriculture

It is now of interest to examine any evidence for regional pollution of our major aquifers by agriculture. In this connection it is important to distinguish diffuse pollution at a regional level, resulting from efficient farming practices, from localized incidents originating at point sources.

Many facets of soil and crop management clearly have the potential to cause deterioration in groundwater quality, particularly bearing in mind that the hydrochemical characteristics are largely acquired during initial infiltration through the soil layers (Buchan, 1958). Included are manuring and slurrying, fertilizer application and the use of pesticides and herbicides. Numerous compounds are applied for soil fertilization and management: NH_4OH, NH_4NO_3, $(NH_2)_2CO$, $(NH_4)_2SO_4$, $NH_4H_2PO_4$, $Ca\ (H_2PO_4)_2$, KCl, $CaSO_4$, $CaCO_3$. Among the fertilizer constituents K, NH_4 and P have strong affinity for soil minerals and do not usually migrate far from the point of application but the anions NO_3, Cl and SO_4 are highly mobile in soil water (Kurtz, 1970). Since nitrate is unique, being the most soluble and being added in the largest amount to soils and representing a health hazard at relatively low concentrations in water supplies (World Health Organization, 1970), it is of primary interest. Leaching by drainage waters, though difficult to quantify, is always potentially a major process in the fate of fertilizer nitrogen. Among other changes in agricultural practice the application of fertilizer nitrogen has increased many fold in Britain during the past decade.

The only data available for the identification of long-term NO_3-N trends in British groundwaters are derived from the routine quality monitoring of raw waters from public supply sources. In many cases even these data are relatively sparse prior to 1965. There are other obstacles to interpretation. The problems of nitrate determination in natural waters are well known (Waters, 1964) and pose questions on the reliability of routine analyses (Foster and Crease, 1974). Pumped groundwater samples are invariably mixtures of different origins (Fig. 5) and long-term trends in the aquifer recharge chemistry may be damped or masked by dilution with older water in storage or by intermittent local pollution. The source of nitrate pollution may be in part other than agricultural (e.g., from an influent polluted river or

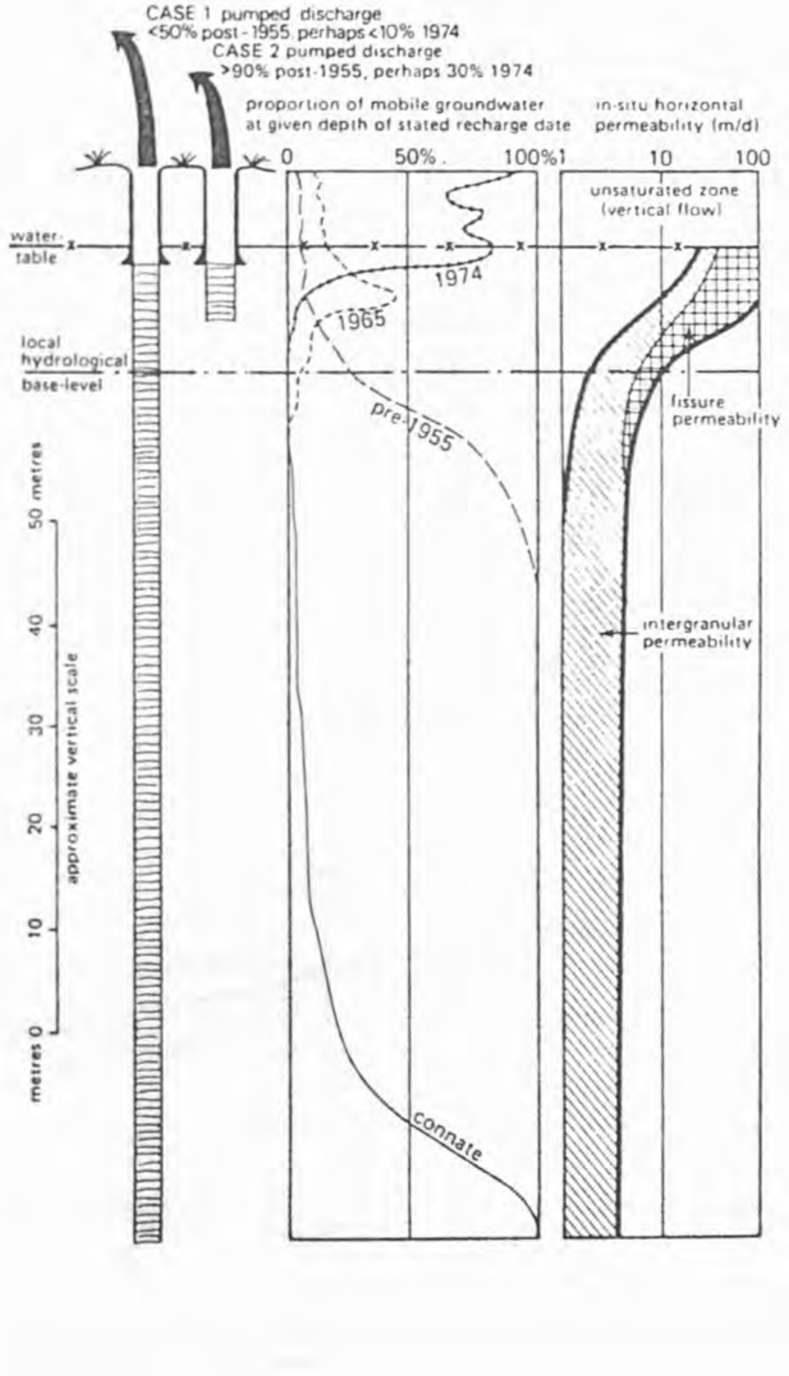
[continued on page 82]



(a) Chalk Aquifer; CASE 1 slow intergranular seepage dominant in unsaturated zone ('tritium profile interpretation'), CASE 2 rapid fissure-flow dominant in unsaturated zone

Fig. 5. Hypothetical aquifer profiles to illustrate potentially complex origin of pumped groundwater supplies/samples.

(b) Triassic Sandstone (thick sequence, in-situ vertical permeability ≪ horizontal permeability); CASE 1 deep borehole, CASE 2 shallow borehole



from direct seepage of sewage effluent). Such factors should be remembered when viewing the data presented in Figs. 6 and 7; they have, however, been minimized by considering annual mean NO_3-N levels and by selecting pairs or groups of adjacent sources with comparable trends, which are free from persistent organic or bacteriological pollution and in most respects of high quality. The data from East Yorkshire, North Lincolnshire and the Eastbourne area of Sussex are after the published work of Foster and Crease (1974), Davey (1970) and Sumner (1973), and Greene and Walker (1970) respectively.

In Fig. 6 the NO_3-N trends for five pairs of Chalk groundwater sources in different regions are compared. All the sources concerned have comparable

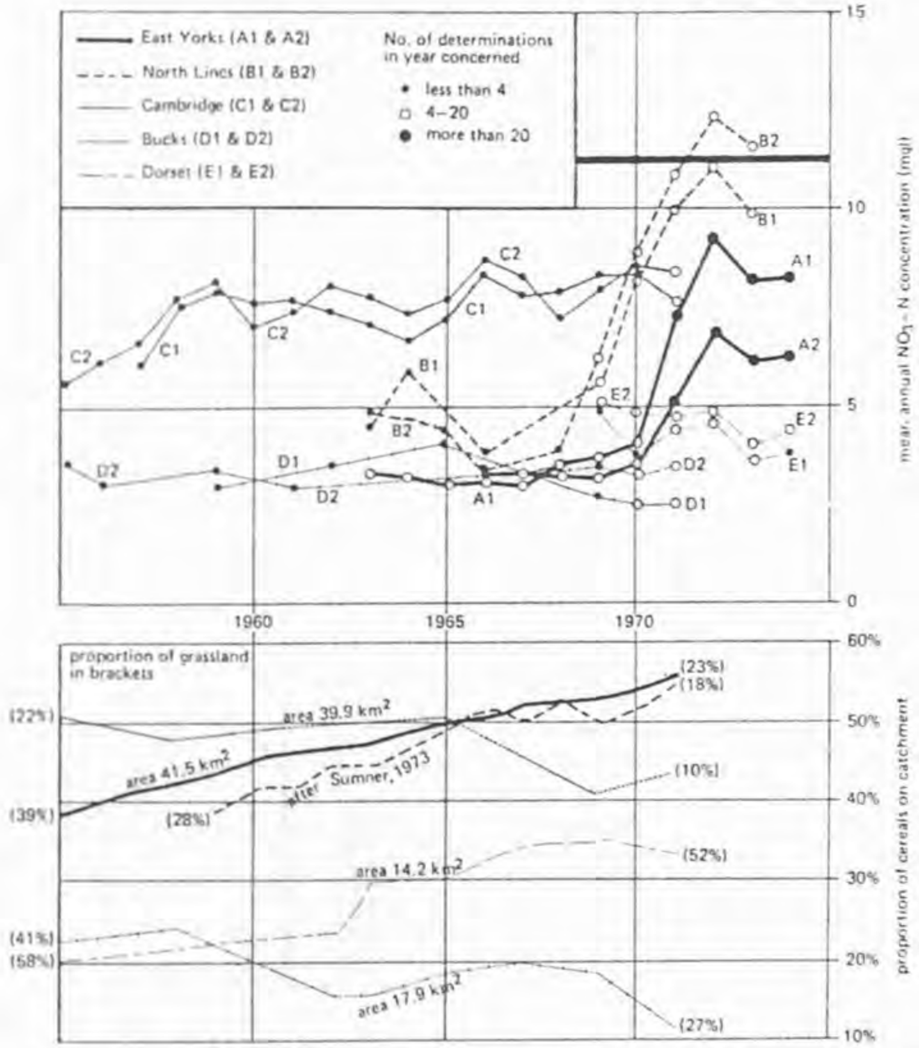


Fig. 6. Trends in NO_3-N levels for selected pairs of Chalk groundwater sources with land use data for corresponding catchments.

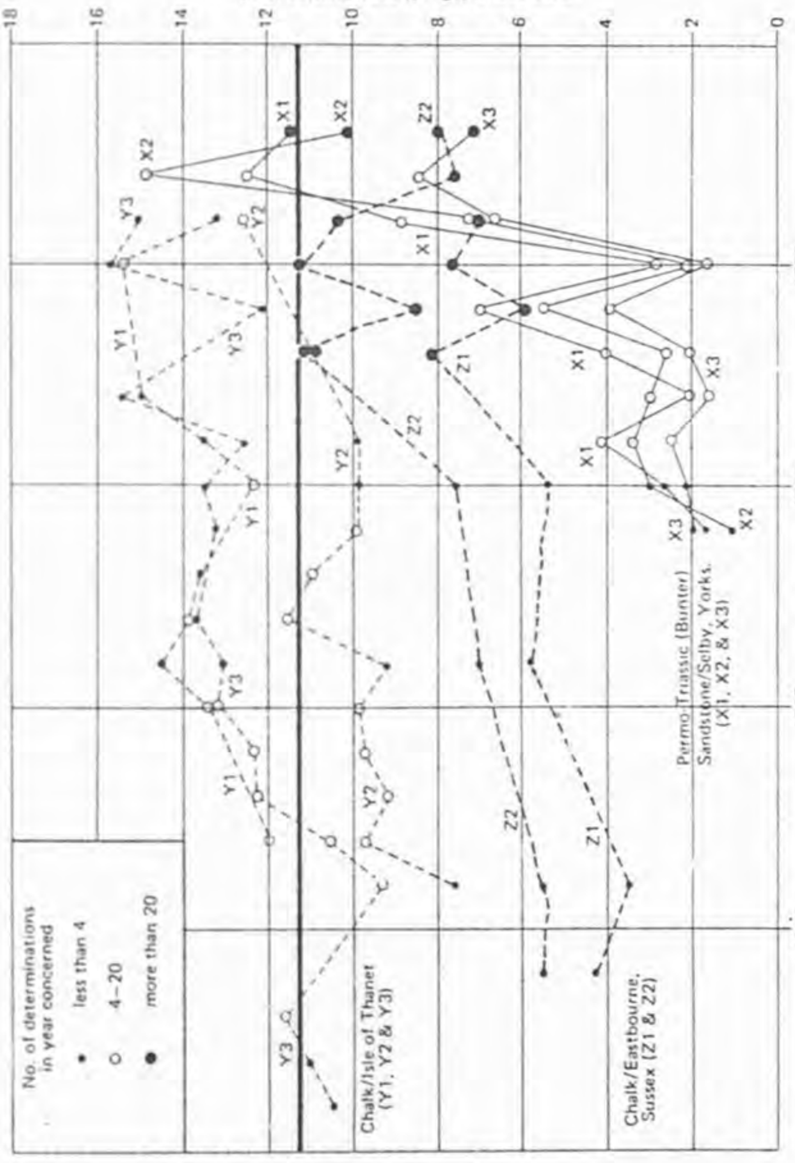


Fig. 7. Trends in NO$_3$-N levels for groups of groundwater sources with marked nitrate pollution.

hydrogeological environments, though there are differences in Chalk stratigraphy and the character of the Drift cover. The proportion of cereals in the land use of the parishes forming the groundwater catchment of the sources is also given; a broad correlation is apparent and has perhaps been accentuated by the major increase in fertilizer nitrogen application to cereals in the last decade. Some seasonal fluctuation in NO_3-N levels is normally present (Fig. 8) and leads to significantly higher maxima (Table 2) than are apparent in Fig. 6, where annual means only are considered. In North Lincolnshire in particular a substantial increase in mean NO_3-N levels has occurred and the lower W.H.O. limit (11·3 mg NO_3-N/l) is now frequently

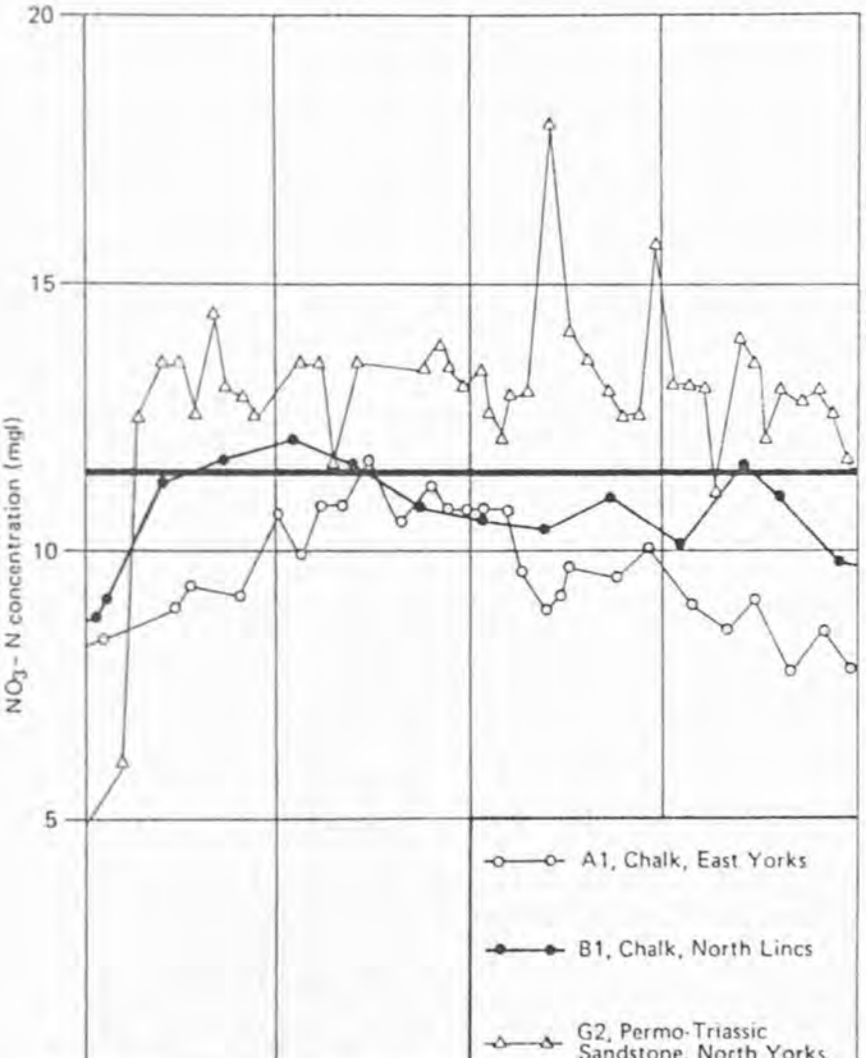


Fig. 8. Fluctuation of NO_3-N levels in selected groundwater sources during 1972.

Table 2

Summary of NO_3-N determinations in selected groundwater sources for 1970, 1971 or 1972

Area	Source no.	Aquifer	Drift cover	Yield Ml/d	Year	No. of analysis	Mean NO_3-N mgl	Peak NO_3-N mgl	Min. NO_3-N mgl	Max variation of NO_3-N in 10 (mgl)	Percentage of year with NO_3-N	Proportion of cereals in catchment
East Yorks.	A1 A2	LCk MCk/UCk	none	2 14	1972 1972	27 28	9 7	12* 9*	7 6	2 2	< 10 0	36%
North Lincs.	B1 B2	MCk/UCk MCk/UCk	none	15 4	1972 1972	14 12	11 12	12* 14*	8 11	n.d. n.d.	30 90	55%
Cambridge	C1 C2	MCk, LCk MCk, LCk	isolated Boulder Clay and Glacial Gravel	5 12	1971 1971	5 5	8 9	8 10*	7 7	n.d. n.d.	0 ? 0	43%
Bucks.	D1 D2	LCk MCk, LCk	extensive thin clay-with-flints	1 5	1971 1971	6 8	3 4	3 4	2 3	n.d. n.d.	0 0	12%
Dorset	E1 E2	UCk UCk	none	2 3	1972 1972	5 4	4 5	5 5	4 4	n.d. n.d.	0 0	33%
West Midlands	F1 F2 F3	UMS, BPB LKS, UMS UMS, BPB	some Boulder Clay and Glacial Gravel	8 4 14	1972 1972 1970	2 2 2	4 5 7	n.k. n.k. n.k.	n.k. n.k. n.k.	n.d. n.d. n.d.	0 0 ? 0	30%
North Yorks.	G1 G2	LKS LKS	extensive Glacial Gravel some Boulder Clay	< 1 < 1	1972 1972	48 41	17 14	22* 18*	4 6	11† 6†	90 90	59%
Selby, Yorks.	X1 X2 X3	BSt BSt BSt	thick alluvium except on 'bedrock islands'	5 4 5	1972 1972 1972	6 6 6	13 15 9	16 27* 14*	11 10 5	n.d. n.d. n.d.	90 80 10	
Isle of Thanet	Y1 Y2 Y3	UCk, MCk UCk, MCk UCk, MCk	some thin head/ brickearth	3 1 2	1970 1971 1971	5 5 2	15 13 15	17 15 n.k.	13 11 n.k.	n.d. n.d. n.d.	?100 ? 80 ?100	25—35%
Eastbourne, Sussex	Z1 Z2	UCk, MCk UCk, MCk	isolated thin clay-with-flints	3 4	1970 1970	278 143	11 7	23* 14*	5 3	6† 5†	? 50 ? 30	30—40%

Chalk Aquifer
UCk Upper Chalk
MCk Middle Chalk
LCk Lower Chalk

Permo-Triassic Sandstones
LKS Lower Keuper Sandstone
UMS Upper Mottled Sandstone
BPB Bunter Pebble Beds
BSt Bunter Sandstone

* distinct seasonal fluctuation in NO_3-N levels

†flashy fluctuation in NO_3-N levels also

n.d. – not determined.

n.k. – not known.

exceeded. Concomitant increases in SO_4 from 65 to 90 mg/l and Cl from 30 to 40 mg/l are reported (Sumner, 1973). Significantly lower NO_3-N levels are characteristic of the selected sources in Buckinghamshire and Dorset, where the corresponding land use data indicate less than 35 per cent dedicated to cereal growing.

Few data were available to the author on Permo-Triassic Sandstone groundwater sources (Table 2). Values for the two areas illustrated in Fig. 4, West Midlands and North Yorkshire, are given, the latter having high NO_3-N levels and being an area of intensive cereal growing. It should be noted, however, that fairly wide variations in NO_3-N concentrations have been observed between adjacent boreholes throughout both these regions (Edmunds and Edwards, personal communications) and probably reflect stratification of groundwater recharge and complex origin of pumped samples. Some high NO_3-N levels (above 15 mg/l) are frequently reported from farm boreholes. These may be due to adjacent point sources of pollution or to the shallow depth of the boreholes concerned, or to both.

In Fig. 7 the annual mean NO_3-N trends are presented for three further sets of important groundwater sources, all of which are experiencing very marked nitrate pollution. While the leaching of fertilizers applied to cereals could also be a major factor in these areas, the more restricted acreages suggest that either another source of pollution may be present or that, for some reason, the soils are more vulnerable to leaching. Similar trends to that of source Y2 (Fig. 7) have also been reported for Chalk groundwater supplies in the Sutton area of Surrey (McCanlis in Greene and Walker, 1970).

As statistical study of groundwater chemistry, employing over 400 samples in an area of 1,000 km^2, of an outcrop glacial sand-and-gravel aquifer in the North German Lowlands has been reported by Groba and Hahn (1972). Strong evidence of the influence of land use and of the pollution potential of extensive areas of intensive cereal growing was revealed. In such areas groundwater nitrate levels normally exceeded 10 mg NO_3-N/l and reached 40 mg NO_3-N/l. There was some evidence of an increasing trend. In contrast samples from below extensive tracts of meadow and forest were less than 1 and 4 mg NO_3-N/l respectively. In areas of mixed land use intermediate levels were recorded.

Malpractice in the handling, storage or disposal of agricultural feedstuffs, chemicals and wastes clearly also threatens groundwater quality locally. Normally incidents have to be assessed on an individual basis. In a detailed study, Gilham and Webber (1969) report nitrate levels of 15 mg NO_3-N/l up to 30 m from a manure storage area on a shallow unconsolidated aquifer, whose background levels were about 2 mg NO_3-N/l. The polluted recharge was of very small volume and was rapidly dispersed by dilution. It was estimated that the rate of leaching did not exceed 0·03 kg N/d (and was probably less than 5 kg N/a). By taking core samples Stewart *et al.* (1967) found low Eh values beneath similar sources of pollution and that lack of oxygen was apparently inhibiting NO_3^- formation from the relatively immobile NH_4^+ ions in the leachate. Richards (1972) has discussed the pollution potential of silage clamps sited on the Chalk outcrop, which are likely to generate a small volume (less than 0·1 Ml/a) of liquor with very high NH_4^+, B.O.D. and phenols.

Most pesticides and herbicides are believed to be rapidly immobilized by absorption in soils (Eye, 1968; Scalf *et al.*, 1969) and Croll (1972) was unable to detect any pollution in an area of the Chalk of Kent with shallow water-table and the highest rates of pesticide application in Britain. Comprehensive investigations, however, have not been undertaken.

Discussion of the problem of groundwater quality management

It is now well established that groundwater supplies abstracted from numerous areas of the major British aquifers are significantly polluted by nitrate. The evidence suggests a rising trend in these areas but problems in the routine chemical analysis for nitrate together with the general sparseness of pre-1965 data, make it difficult to establish with certainty the precise rate of rise. It appears likely that changes in land use and agricultural practice, in particular the increased acreages devoted to cereals and the increased use of nitrate fertilizers to sustain them, are either directly or indirectly the cause of the rising levels. In some cases there may also be other sources of pollution present.

The predominance of rapid fissure-flow in the saturated zone of the Chalk and, to a degree, in the Permo-Triassic Sandstones, limits the effectiveness of 'protected areas' around major water supply sources, although such areas do afford a degree of protection against heavy bacteriological pollution. The self-same process of fissure-flow, however, should ensure relatively thorough mixing between groundwater recharge from immediately adjacent areas and down streamlines. This factor probably accounts for the fairly even distribution of nitrate revealed in detailed surveys of Chalk groundwater chemistry in parts of East Yorkshire (Foster and Crease, 1974) and North Lincolnshire (Sumner, 1973). It is suspected that only immediately after groundwater recharge will differences be observed in the groundwater chemistry between directly adjacent areas of differing land use.

Where diffuse groundwater pollution by agriculture is concerned, the management of the pollution at tolerable levels appears on numerous grounds to be a more practical approach than measures for its prevention or elimination, except where trace toxic compounds are concerned. The most important process in groundwater quality management will probably in many instances be dilution.

There is a pressing need to predict the maximum likely NO_3-N levels that may be encountered in the future and it is thus of interest to discuss the sources of dilution in this context. Since there is, as yet, no evidence for the widespread presence of anaerobic conditions beneath the intake areas of the major aquifers, denitrification cannot be assumed to reduce the NO_3-N levels of the groundwater recharge. Now Cooke and Williams (1970) reported that the maximum NO_3-N concentrations in drainage water from plots of winter wheat receiving 95 kg N/ha on the Chalk at Rothamsted did not exceed 30 mg NO_3-N/l. If the drainage waters from adjacent grassland and other fields contained 4 mg NO_3-N/l then the groundwater recharge would rapidly be diluted to 20 mg NO_3-N/l, in an area with 60 per cent of the land employed in cereal growing. Leaching at similar or higher levels would presumably result only for short periods under unfavourable conditions with heavy spring rainfall. Groundwater already in storage and largely originating from winter recharge would be likely to have lower NO_3-N levels and to provide further dilution in the case of supplies pumped from aquifers. Nevertheless such conditions will always be liable to produce troublesome levels intermittently.

Long-term average nitrate levels in the drainage water from the Rothamsted fertilized winter wheat plots were about 7 mg NO_3-N/l (Cooke and Williams, 1970), representing a loss of some 18 kg N/ha for 250 mm of infiltration. It should be noted that larger leaching losses are to be expected from spring sown cereals and from less-controlled fertilizer application, and that the Chalk at Rothamsted has a cover of residual clay-with-flints and may not be typical of the thin light sandy soils associated with most Chalk wold and downland.

A serious situation would develop if losses of, say, 50 kg N/ha were more representative of intensive (60 per cent) cereal growing areas. For 250 mm of infiltration the *average* NO_3-N in the groundwater system would eventually rise to 14 mg/l; for less infiltration (200 mm) the corresponding level would be 17 mg NO_3-N/l. It is of interest to note that the annual average NO_3-N level of the selected sources in North Lincolnshire, the Selby area and the Isle of Thanet are currently in the range 11–15 mg/l (Table 2). Any increase above 4 mg NO_3-N/l in the amount of NO_3-N 'leaking' from grassland would further aggravate the position. Since it is on grassland that the greatest scope for increased fertilization probably exists, this situation requires careful observation.

Moreover it is most important to bear in mind that all the reported cases of rising NO_3-N levels refer to the levels in supplies pumped from an aquifer, the origin of which is liable to be complex (Fig. 5). While the case for a dominantly slow regime of downward flow in the unsaturated zone of the Chalk, for example, is still far from proven, its existence would imply that only a small proportion of present Chalk water supplies will be post-1970 infiltration. A similar effect produced by an entirely different process could occur for some Permo-Triassic Sandstone boreholes (Fig. 5).

Since, in theory at least, these small components of recent infiltration could alone be responsible for the rises in NO_3-N levels, the aquifers concerned could already be more extensively polluted than the current NO_3-N levels in the pumped supplies might suggest. There can be no grounds for complacency until active surveys have been undertaken in various areas to establish the spatial distribution of NO_3-N (and other constituents) throughout the aquifers both above and below the water-table and to determine the rates of physical movement and chemical modification in the component parts of the groundwater system. Monitoring of the chemistry of groundwater supplies alone will not safeguard against the cumulative effects of diffuse pollution and is an inadequate basis for the management of groundwater quality.

Acknowledgments

The paper is published by permission of the Director of the Institute of Geological Sciences. It is essentially a review and the author is indebted to many colleagues for data and discussion, particularly M.J.Bird, Dr.W.M.Edmunds, M.Morgan-Jones, M.Price and T.K.Tate. A.C.Cripps gave energetic and able assistance throughout compilation.

A.H.Goodman (Department of the Environment/Directorate General of Water Engineering) is thanked for drawing the author's attention to sources of additional data. K.Guiver and H.G.Headworth (Southern Water Authority), D.P.Black (Cambridge Water Company), Mrs. Sheila Bloxham (Severn-Trent Water Authority/Wolverhampton Water Supply Division), Dr. A.M.C.Edwards (Yorkshire Water Authority) and J.L.Fisher (Wessex Water Authority/Avon and Dorset Supply Division) are thanked for their generous provision of unpublished data and the corresponding organizations for permission to publish. The land use data quoted were derived from the records of the M.A.F.F. Statistics Branch.

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October 1976
Volume 80 Number 968
Regd. ISSN 0043-1168

Water SERVICES

RESOURCES, SUPPLY, SEWAGE & EFFLUENT

(23)

Water SERVICES

RESOURCES, SUPPLY, SEWAGE & EFFLUENT

OCTOBER 1976 Vol 80 No 968

AN INDUSTRIAL NEWSPAPERS PUBLICATION

ISSN 0043-1168

Published and © 1976 by

Fuel & Metallurgical Journals Ltd.,
Queensway House,
2 Queensway, Redhill,
Surrey RH1 1QS

Telephone: Redhill 68611
Telex: 948669

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Annual Subscription: United Kingdom £15.00, Overseas £20.00, single copy £1.42 (including postage).

Technical articles of full page length, or over, appearing in *Water Services* are indexed in *British Technology Index*

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Chalk pore-size measurements and their significance

by M Price, M J Bird and S S D Foster*

In the current discussion of problems related to Chalk water resources, two issues figure prominently:

1) What are the flow mechanisms and flow rates of water and of pollutants through the unsaturated zone of the aquifer? Studies using thermonuclear tritium have introduced the possibility of a predominantly slow, intergranular flow regime in the unsaturated zone (Smith and others, 1970; Smith, 1973). Such a regime could imply a serious deterioration of groundwater quality in the future, because pollutants which have entered the ground in increasing quantities during recent years would still be in transit to the water table (Foster and Crease, 1974; Foster, 1976).
2) Can gravity drainage of Chalk pore water be expected to contribute to the aquifer's specific yield? A number of major schemes, currently under development, aim to use the natural storage of the Chalk aquifer to augment riverflow during drought. At present there is uncertainty about the volume of this exploitable storage and, in particular, whether the Chalk pore space is likely to contribute significantly to it (Foster and Milton, 1974; Foster 1975a).

While the degree of open fissure development in the Chalk exercises the major control over its behaviour as an aquifer, the physical properties of the rock mass itself and, in particular, the pore dimensions, are of direct relevance to consideration of the above questions. Furthermore, they are such as to make it a more unusual aquifer than is generally recognised. During recent years a number of pore-size measurements have been made by the Institute of Geological Sciences in the course of various research programmes. In this paper all the Institute's pore-size measurements on the Chalk have been combined both to illustrate some of the above aspects and for the general information of engineers and scientists concerned with the development and management of Chalk groundwater. They may also be of interest to agricultural scientists and earth scientists working in other fields.

Background

The Chalk is the most important aquifer in Britain, supplying about 15 per cent of all potable water supplies in the country. The precise origin of this fine-grained limestone is still the subject of debate, but it was probably deposited in a relatively shallow sea—within the range of 100 to 600m deep. Electron microscopy shows it to be composed predominantly of calcareous plates from the skeletons of planktonic organisms (coccoliths), with little cementation (Plates 1-4). Together with a small percentage of non-calcareous material, these plates make up the fine matrix of the rock, in which whole coccoliths and fragments of larger shells may be embedded. An

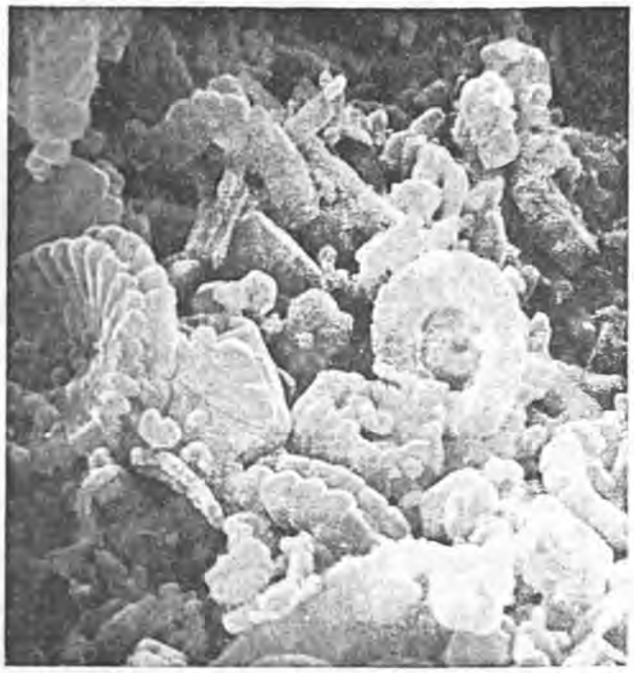

Plate 1 Upper Chalk from Berkshire (sample No 899-3V; depth 98.3m; effective porosity (a) 42.1 per cent; permeability (k) 4.6 md; median pore diameter (d_{50}) 0.50μm). Note the abundance of well preserved coccoliths. The field of view is about 15μm.

Plate 2 Upper Chalk from Yorkshire (721V; quarry face; a = 29.9 per cent; k = 1.2 md; d_{50} = 0.40μm). The field of view is about 15μm.

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* Hydrogeological Department, Institute of Geological Sciences, London.

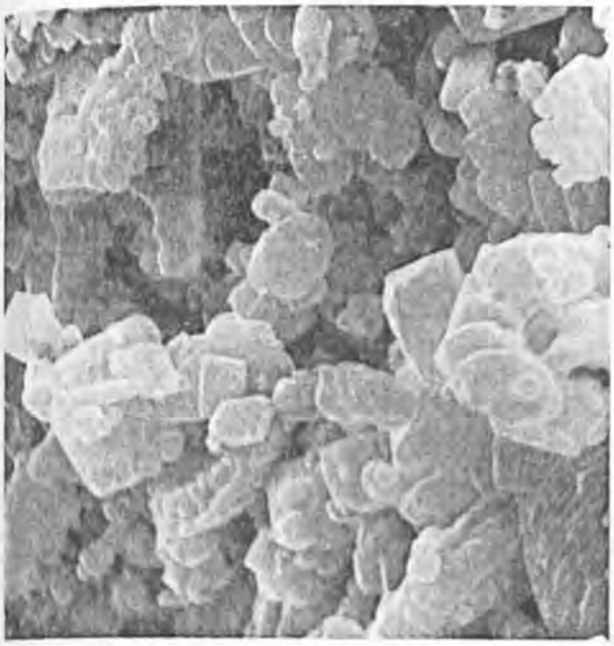

Plate 3 Middle Chalk from Norfolk (991-6; 472.3m; a and k not available; d_{50} = 0.62μm). The field of view is about 15μm.

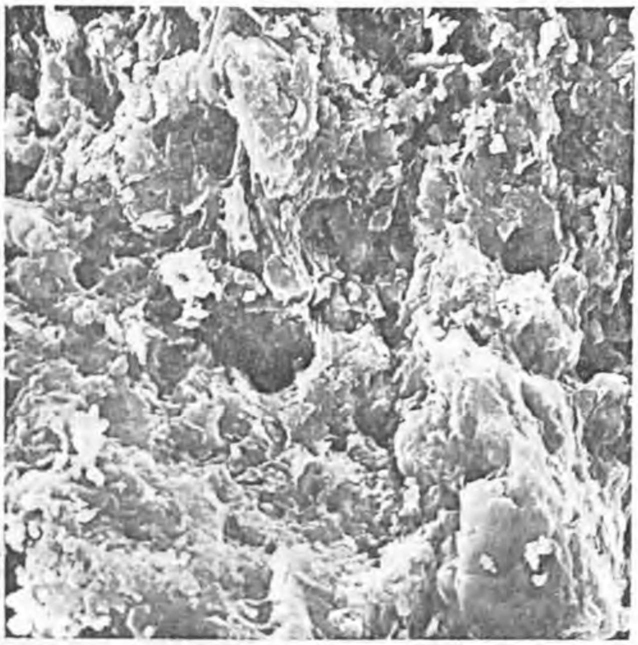

Plate 4 Lower Chalk from Surrey (233-15V1; 254.7m; a = 16.5 per cent; k not available; d_{50} = 0.08μm). This surface is composed almost entirely of clay minerals : calcite crystals are rare. The field of view is about 70μm.

excellent review of the petrology of the formation has been given by Hancock (1975).

The maximum thickness of the formation in Britain is about 500m. It is capable of division into a series of stages and zones on fossil evidence, but a simpler three-fold division exists, largely on the basis of lithology, into Lower, Middle and Upper Chalk. These divisions will be used in this paper. The Chalk of northern England differs from that of the south, being extensively cemented and recrystallised. For the British land area it is common to speak of a northern and a southern 'province'; the division between the two is believed to occur in Norfolk, but for the purpose of this paper samples from Norfolk have been assigned to the southern province.

Pore-size distribution (PSD) determinations, supported where possible by porosity and permeability measurements, have been made on 52 samples from 28 localities ranging from Dorset to Yorkshire. In this context 'locality' means a surface exposure, quarry or borehole. The samples were selected to be representative both geographically and stratigraphically; normally one sample was taken from each locality, but in the case of boreholes a succession of samples was taken from different depths. No samples were taken from more than 500m below ground surface.

Experimental methods

To measure the pore sizes, the mercury injection technique (Ritter and Drake, 1945) was employed, using an Aminco motor driven 15 000lb/in² Porosimeter (Plate 5). In this machine a small sample (usually less than 2g) contained in a penetrometer (a glass tube with a graduated capillary stem) is placed in a filling device (the large glass vessel to the left of the machine). The filling device and penetrometer are evacuated and the penetrometer is filled with mercury. The pressure in the filling device is increased in steps up to atmospheric pressure and the amount of mercury leaving the penetrometer stem and invading the sample is observed visually. The penetrometer is then transferred to a pressure vessel where more mercury is forced from the stem into the sample by pressurised alcohol. A probe automatically follows the mercury-alcohol interface and permits measurement of the mercury invasion at each pressure step.

The pressure required to force a liquid into a spherical cavity of diameter d† is:—

$$p = \frac{-4\sigma \cos \theta}{d} \qquad (1)$$

Writing $p = \rho gh$ (2)

equation (1) becomes

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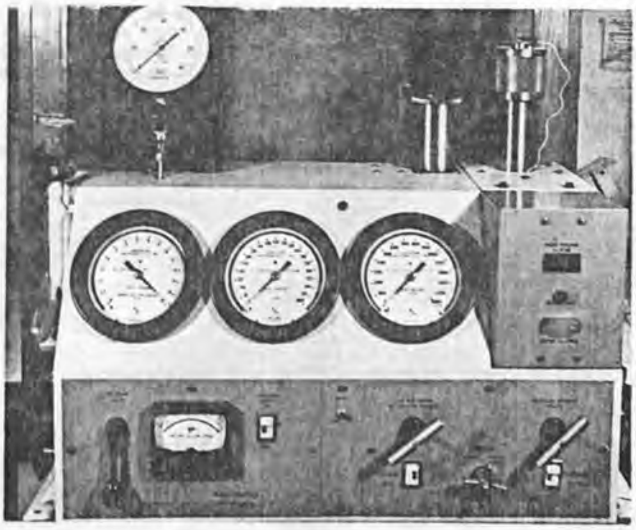
† *An explanation of symbols is given at the end of the paper.*

Plate 5 Aminco 15 000 lb/in² mercury injection porosimeter.



$$h = \frac{-4\sigma \cos \theta}{d\, g\, \rho} \qquad (3)$$

For water at 10°C (a typical UK groundwater temperature) $\sigma = 0.074$ N/m and θ for most materials is effectively zero so that

$$h_w = \frac{-3.0 \times 10^{-5}}{d} \qquad (4)$$

with h_w and d measured in metres.

(The negative sign implies that water is drawn into the cavity and that a suction or tension is needed to remove it. This is the pore-water tension referred to by soil scientists).

For mercury against a vacuum at 20°C, a value for σ of 0.480 N/m may be taken as an average of published values; θ lies between 130 degrees and 140 degrees. Assuming $\sigma = 0.480$ N/m and $\theta = 130$ degrees then

$$h_m = \frac{9.2 \times 10^{-6} \text{ m head of mercury}}{d} \qquad (5)$$

or

$$h_m = \frac{1.24 \times 10^{-4} \text{ m head of water}}{d} \qquad (6)$$

Mercury is a non-wetting fluid and displaces the wetting fluid (residual air and mercury vapour) from a sample in the same way that air displaces water during drainage. Thus the mercury invasion curves can be converted to equivalent water drainage curves.

It will be seen from a comparison of equations (4) and (6) that the pressure required to force mercury into a pore of given diameter has a magnitude which is approximately four times that of the pore-water tension exerted by that pore, depending upon the precise values of σ and θ which are assumed.

The above discussion implicitly assumes that the cavities are spherical, while the electron photomicrographs (Plates 1-4) clearly show that natural Chalk pores depart from this ideal shape. The work of Brown (1951) and Purcell (1951) suggested that the effect of this departure would be to alter the effective values of σ and θ for mercury and thus the ratio h_m/h_w. If another method of measuring pore sizes is available, the ratio h_m/h_w can be determined empirically. In this study, the very small pore size common in Chalk effectively precluded the use of an alternative method, and equation (5) has been used to calculate the pore sizes. On this basis the porosimeter measures volumes of pores with diameters between 100 and 0.012μm, although in practice it is likely to be the pore-neck diameters which are the controlling influence on both mercury invasion and water drainage.

Effective (interconnected) porosity was measured using a liquid saturation method (API, 1960) in which the sample was oven dried at 60°C, evacuated and saturated with de-ionised water. Porosity was determined by comparison of the dry, saturated and submerged weights.

Intergranular permeability was measured using a gas permeameter (API, 1956) with air or nitrogen as the test fluid. The measured permeability was then corrected for the effects of gas slippage to an equivalent liquid value. This intrinsic permeability (expressed in millidarcys) can be converted to a hydraulic conductivity (expressed in, say, metres/day) by assuming a typical groundwater density and viscosity.

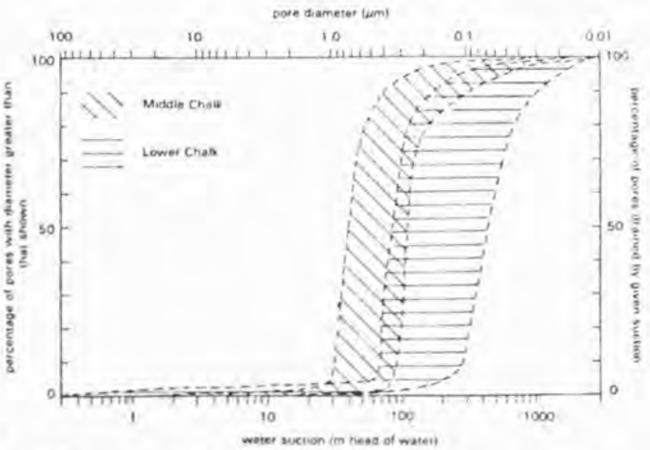


Fig 1 Envelopes of available bore — size distribution curves for the Lower and Middle Chalk of England (Lower Chalk — 8 determinations from 4 localities; Middle Chalk — 16 determinations from 11 localities).

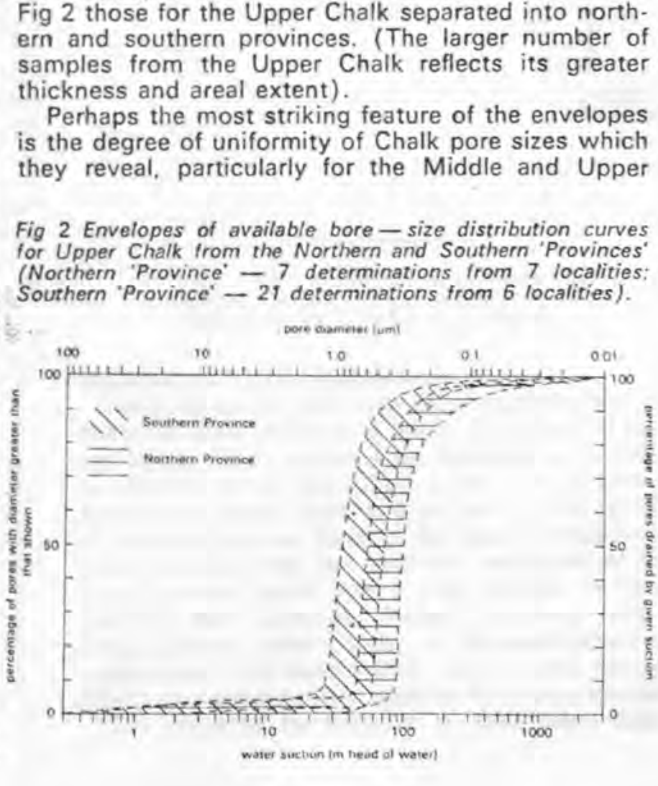
The normal procedure was to measure the porosity and permeability of a 25mm diameter core which was then broken up to provide a chip for PSD measurement. In some cases only sample chips were available and in these cases porosity was usually measured but permeability could not be determined.

Discussion of results

For each sample a graph was constructed of total pore volume invaded against applied mercury pressure. Application of equation (5) permits this graph to be interpreted as a graph of pore volume against pore size, *ie* a PSD curve. For ease of presentation the curves have been generalised into envelopes, each containing all the curves corresponding to a major stratigraphical or geographical division. Fig 1 shows the envelopes for the Lower and Middle Chalk and Fig 2 those for the Upper Chalk separated into northern and southern provinces. (The larger number of samples from the Upper Chalk reflects its greater thickness and areal extent).

Perhaps the most striking feature of the envelopes is the degree of uniformity of Chalk pore sizes which they reveal, particularly for the Middle and Upper

Fig 2 Envelopes of available bore — size distribution curves for Upper Chalk from the Northern and Southern 'Provinces' (Northern 'Province' — 7 determinations from 7 localities; Southern 'Province' — 21 determinations from 6 localities).



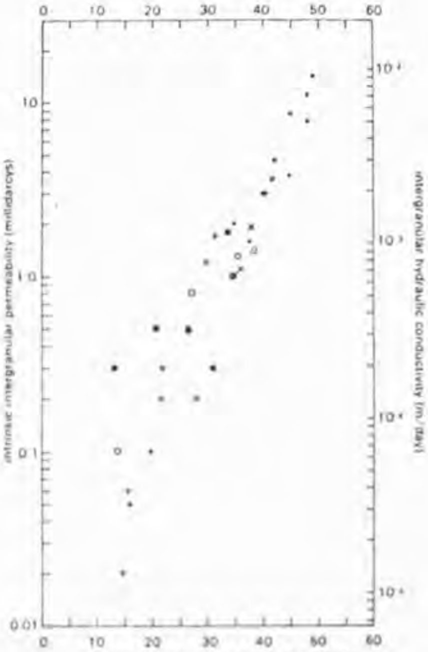


Fig 3 Plot of intergranular permeability against porosity for 34 Chalk samples for which pore-size measurements are available (symbols as in Fig 4).

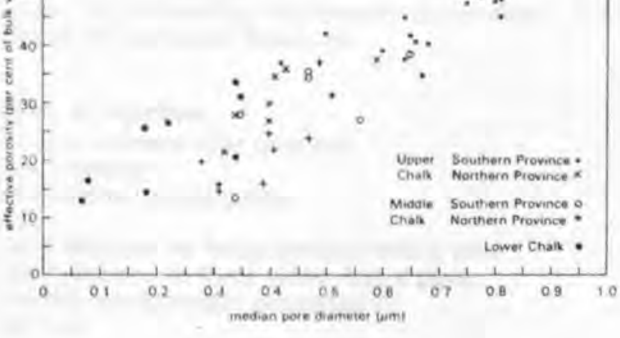
Chalk. The Upper Chalk from the north has slightly smaller pores than that from the south, which is to be expected in view of its more extensive cementation. The greater range of pore sizes, and the generally smaller pores, of the Lower Chalk are probably due in part to its much higher marl content (Plate 4).

For ease of comparison the median (d_{50}) pore sizes of all the measured samples have been summarised in the Table, which emphasises in quantitative terms the points outlined above.

Further information is summarised in Figs 3, 4 and 5 (which are intended primarily for data presentation rather than for the derivation of relationships). Fig 3 shows the expected, though not inevitable, positive correlation between intergranular permeability and porosity. The positive correlation between porosity and median pore diameter displayed in Fig 4 shows that higher porosity is a result, at least in part, of larger pores and not simply greater numbers of them.

The correlation between permeability and median pore diameter (Fig 5) is perhaps poorer than might be expected; in part this may be due to the influence of occasional larger pores. The low intergranular permeabilities and generally high porosities are in agreement with similar measurements reported elsewhere (Edmunds and others, 1973; Bird, 1976).

Fig 4 Plot of effective porosity against median pore diameter for 45 Chalk samples.



Median pore sizes of English Chalk

Formation and area	No of samples tested	Median pore sizes (μm)	
		mean	standard deviation
Chalk	52	0.49	0.20
Upper Chalk (Southern province)	21	0.65	0.14
Upper Chalk (Northern province)	7	0.41	0.08
Middle Chalk (Southern province)	8	0.53	0.14
Middle Chalk (Northern province)	8	0.39	0.08
Lower Chalk	8	0.22	0.11

The variation in reported measurements of σ and θ for mercury, and the lack of perfect sphericity of Chalk pores, must imply some margin of error in the quoted pore sizes. In this context it is worth mentioning that, where porosity was determined from the actual chip used subsequently for the PSD measurements, the difference between pore volumes measured by the two methods was less than one per cent.

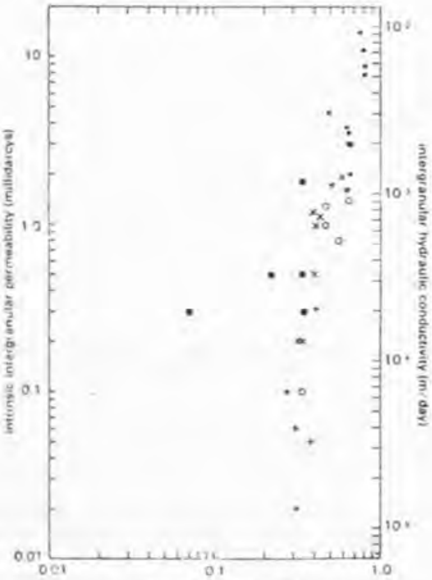


Fig 5 Plot of intergranular permeability against median pore diameter for 34 Chalk samples (symbols as in Fig 4).

Significance of the measurements

Because of its high interstitial porosity the Chalk contains large volumes of water. Each km³ of saturated Upper Chalk contains on average some 300 000 to 400 000 Ml of interstitial water, and, assuming a maximum specific yield of 2 per cent, up to 20 000Ml of water in fissures. Most of the fissure space must be freely draining, but because the pores are so small, nearly all the water which they contain is held by capillary and molecular forces, and very little can drain or move under gravity. In the unsaturated zone, evaporation and transpiration are the only processes which can substantially deplete the water content.

The potential for diffusion to take place between the pore water and any fissure water, and the possible implications, have been discussed by Foster (1975b). The bulk of the pore water will constitute a relatively immobile or 'stationary' phase with respect to mobile groundwater in any fissures or interconnected larger pores. Such a system can be expected to behave like a chromatogram, with diffusion occurring between the stationary and mobile phases. The initial effect will be to dilute the concentration of any solutes, including pollutants, in solution in the mobile phase and the end effect to greatly retard the average apparent downward movement of the solutes with respect to that of the water.

It is generally accepted that gravity drainage ceases at pore-water suctions between 1 and 5 metres of water: that is to say, pores with diameters less than about 10μm will not drain under gravity and so do not contribute directly to specific yield. On this basis (Figs 1 and 2) not more than three per cent of Chalk pores represents potentially useful storage. This is less than one per cent of bulk volume and is of the same order as laboratory values of Chalk specific yield measured by centrifuging (Bird, 1976). The extent to which pore drainage occurs under field conditions will depend on the relationship between the larger and smaller pores and between the larger pores and the fissures, but it is worth noting that interstitial specific yield is more likely to be evenly distributed throughout the aquifer (and therefore available at all groundwater stages) than fissure storage which is frequently concentrated at particular levels (Foster, 1975a).

An important question to agriculturists is how much of the pore water is potentially available to plants, which can draw water against suctions of up to 15 atmospheres or about 150m (Marshall, 1959), corresponding to a pore diameter of 0.2μm. The plant available moisture capacity, *ie* the pores in the range 0.2 to 10μm, includes over 80 per cent of the pores of the tested Upper and Middle Chalk samples but less than five per cent of those of some Lower Chalk (Figs 1 and 2).

Finally, the results emphasise the uniform nature of the Chalk as a formation. Even allowing relatively small number of samples studied, it is remarkable that between Dorset and Yorkshire the median pore size of the Upper Chalk should vary only by a factor of less than four (Fig 2) — further evidence, if it were needed, of the unusual nature of this formation.

Acknowledgements

The work was carried out under the general direction of Mr J B W Day, chief hydrogeologist. We are grateful to several colleagues at IGS for helpful discussion, in particular John Black, Michael Edmunds and Christopher Wood and to Brenda Coleman who took the photomicrographs.

The paper is published by permission of the director, Institute of Geological Sciences.

Explanation of symbols

a	effective intergranular porosity
d	pore diameter
g	gravitational acceleration
h	head
h_m	head required to force mercury into a pore
h_w	head required to force water into a pore
k	intrinsic intergranular permeability
p	pressure
θ	angle of contact
ρ	density
σ	surface tension

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THE INSTITUTION OF
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Symposium on Maintenance of Water Quality

Proceedings of Symposium held at the
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1975

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4. **Control of effluents, by R. G. Toms,** BSc, FRIC, Chief Scientific Officer, Wessex Water Authority

short-term economic difficulties it could lead to long-term problems of water quality deterioration.

Written Discussion

Mr. S. S. D. Foster (Institute of Geological Sciences) wrote that in his introduction the author had acknowledged that the paper did not consider in depth hydrogeological factors. Whilst congratulating him on the readily implementable and practical nature of his check list for pollution protection, he himself did not believe that the subject of maintenance of groundwater quality could be effectively discussed without detailed consideration of such factors. It was only through appreciation of the hydrogeology that the implications for water quality management of the important differences between surface water and groundwater systems would themselves be fully appreciated.

Dr. Wilkinson (p.37) had already dealt with certain hydrogeological considerations. He himself would like to add two further topics to the discussion—the rôle of the unsaturated zone and the problem of groundwater sampling.

In the case of almost all aquifers except karstic limestones, it was unquestionable that the unsaturated zone played a major rôle in intercepting, diluting, or delaying the penetration of pollution originating at the land surface. At the same time, it was potentially capable of storing-up water quality problems for the future. Yet comparatively little was known about the various physical, chemical, and biological processes involved[*]. It was likely that very high concentrations of certain water pollutants occurred in many parts of the unsaturated zone of the important British aquifers—nitrate was a particular case in point.[**] Yet in no area had there been a detailed survey of the distribution of pollutants in the unsaturated zone nor did we know if they were, in fact, moving down to the water-table. Investigation was expensive, involving of necessity a large amount of drilling, but it was hoped that the current IGS and WRC research programmes, relating primarily to groundwater nitrates, would answer some of the most pressing questions.

It was important to realize that, as a result of such factors as frequent gross heterogeneity in permeability distribution in aquifers (especially fissure-flow formations) and their variable hydraulic boundary conditions, pumped samples of groundwater frequently had complex origins.[*] Studies to detect and evaluate pollution incidents needed a more controlled basis for sampling. Depth samples would be preferable in many cases and purpose-drilled investigation boreholes would often be required. Use of temperature and conductivity logging techniques and borehole flow measurements[‡] could elucidate the levels of groundwater flow and the origins of the borehole column, thus providing a rational basis for depth sampling.

It was worth noting that in the field of groundwater quality studies, a detailed understanding of the hydraulics of the groundwater system was an essential prerequisite to any chemical work. This was quite distinct from the situation in studies of river pollution.

Author's Reply to Discussion

Mr. R. J. Slater, in reply to the discussion, wrote concerning Mr. Jeffery's contribution, that he understood that very few (possibly four or five) sets of byelaws, made under Section 18 of the Water Act 1945, remained in existence and that these could not be extended when they ceased to have effect at the end of the ten-year period commencing

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(25)

Journal of Hydrology

Elsevier Scientific Publishing Company
Amsterdam – Oxford – New York

Journal of Hydrology, 25 (1975) 159–165
© North-Holland Publishing Company, Amsterdam – Printed in The Netherlands

THE CHALK GROUNDWATER TRITIUM ANOMALY – A POSSIBLE EXPLANATION

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(Received August 30, 1974; accepted September 3, 1974)

ABSTRACT

Foster, S.S.D., 1975. The Chalk groundwater tritium anomaly – a possible explanation. J. Hydrol., 25: 159–165.

Attention is drawn to a mechanism which could profoundly complicate the interpretation of tritium determinations in investigations of the rate of groundwater movement in the British Chalk and other physically-comparable formations. It could explain the anomalously low levels of thermonuclear tritium currently observed in the saturated zone of the Chalk aquifer, with important implications for pollution control.

BACKGROUND

The low level of thermonuclear tritium in groundwater from the *saturated zone* of the Chalk aquifer throughout much of its intake area has been recognised as a major anomaly in British hydrogeology in recent years. The tritium profile of pore-water from the *unsaturated zone* at a Berkshire site in October 1968 led Smith et al. (1970) to suggest that about 85% of the total flow of vadose groundwater was by intergranular seepage at a mean rate of less than 0.9 m/year, contradicting the widely-held concept that fissure-flow dominated downward movement. A similar profile was determined in September 1970 for a site in Dorset (Smith, 1973).

This work had serious implications for resources management and pollution protection in this important aquifer, from which about 15% of all national water-supplies are derived. In the case of nitrate pollution resulting from arable farming for example, a critical question was the potentially high nitrate concentration of vadose pore-waters, by implication, in slow transit through a thick unsaturated zone to the water-table (Foster and Crease, 1974).

The unquestionable advantages of tritium (HTO) as a tracer in studies of groundwater movement (e.g. Libby, 1961; Smith, 1973) give considerable strength to the interpretation, but there are significant hydraulic objections. While the physical properties of Chalk are not such as to preclude significant intergranular seepage in the unsaturated zone, in the absence of a major fissure-flow component, it is difficult to see why surface run-off does not develop particularly after prolonged or high-intensity rainfall.

The purpose of the present note is to draw attention to a possible process which could explain the present low levels of HTO in the *saturated zone* and at the same time would be compatible with relatively-rapid flow down joints and fissures in the *unsaturated zone.*

HYDRAULIC CHARACTERISTICS OF CHALK

The physical characteristics of the Chalk are such as to make it a most unusual porous medium. The rock matrix has very low permeability ($10^{-3}-10^{-4}$ m/d) but moderate to high porosity (0.15—0.40), very high specific retention (specific yield less than 0.01), exceedingly small pore diameters (mostly less than 1 μm) and an exceptional specific interstitial surface area (Edmunds et al., 1973; Foster and Crease, 1974). It is generally a very-pure fine-grained carbonate (Hancock and Kennedy, 1967) but at some horizons there are significant proportions of clay minerals and at others occasional thin marl bands.

The jointing of the rock-mass varies with depositional province, stratigraphical zone, tectonic and morphological setting, but the Chalk is normally traversed by frequent high-angle joints and numerous horizontal discontinuities associated with bedding and secondary structures (Fig.1), the latter group being most commonly associated with major permeability development in the saturated zone. In the unsaturated zone the opening on some joints may be relatively large (> 5 mm), particularly where the rock-mass is in overall tension as on escarpments and where they have been enlarged by solution, but more typically is small or even microscopic. Nevertheless it is likely that *in situ* every metre of Chalk is traversed by at least one high-angle joint with an effective opening of 0.1 mm. Such a system alone would impart an overall permeability to the rock-mass 50—500 times greater than the intergranular value. It is thus evident that the Chalk aquifer possesses two distinct physical components each with highly-contrasting permeability and porosity; one of these components, the intergranular pore-space, will be almost always fully saturated, even in the *unsaturated* zone, except perhaps very close to the land surface.

EVALUATION OF HTO DIFFUSION PROCESS

Self-diffusion of HTO in Chalk pore-water was considered by Smith et al. (1970) as one process which would "necessarily lower and broaden" the main peak of the tritium profile (in a vertical sense), causing significant changes in concentration over distances of perhaps 0.3—0.5 m after periods of numbers of years. Implicit are the assumptions that the profile was not varying laterally on any scale, that the input was areally uniform and that no lateral diffusion was occurring, despite the probability of the Chalk being traversed by frequent high-angle joints.

It seems more probable that the input to the unsaturated zone (after infil-

Fig.1. Examples of jointing in a Chalk rock-mass; (above) Turonian of Lincolnshire, "northern province" and (below) Turonian of Buckinghamshire, "southern province". (Photos by C.J. Wood.)

tration through the very thin soil cover) will be localised on joints. In the late 1950's when the first groundwater containing thermonuclear tritium entered the system, there would have been large HTO concentration gradients between the joint-water and the existing pore-water. In response to these gradients some diffusion of HTO into the pore-water would have occurred. Diffusion in the water-phase of a non-homogeneous porous medium is a complex subject; some idea of the resultant reduction in HTO levels of water passing through joints can be gained from application of the theoretical equations of non-steady state diffusion to simplified situations. The coefficient of self-diffusion (D) for HTO in water at 10° C is $1.6 \cdot 10^{-9}$ m^2/sec (Wang et al., 1953) but in water-saturated porous media will be lower and depend on the porosity (ϕ) and saturation of the media and the tortuosity of the pore-space. In the case of saturated Chalk it is unlikely to be less than 10^{-10} m^2/sec (Smith et al., 1970).

One appropriate solution of Fick's diffusion laws would appear to be that for diffusion from an infinitesimally thin layer for which boundary condition the following applies (Crank, 1956; Golubev and Garibyants, 1971):

$$\frac{(C_{xt}-C_{xo})}{(C_{bo}-C_{xo})}=\frac{b}{\sqrt{\pi Dt}}\cdot\exp(-x^2/4Dt)$$

where C_{xt} is the concentration at a distance x from the joint after time t, C_{bo} and C_{xo} the initial concentrations in the joint-water and pore-water respectively and $2b$ the joint opening; the decreasing HTO concentration with time in the joint-water itself (C_{bt}) being given by $(C_{bt}-C_{xo})/(C_{bo}-C_{xo})=b/\sqrt{\pi Dt}$. The theoretical picture of diffusion from a joint of small opening, 0.2 mm for example, can thus be estimated (Fig.2); empirical corrections to allow for the effect of the matrix porosity (ϕ taken as 0.30) have been attempted by balancing the distributions so that they always hold the same amount of HTO as the initial input. It can be seen that, while the theoretical increases in HTO concentration in the matrix pore-water are very localised, the process appears capable of producing major reductions in the HTO level of the water in this size of joint by about 10,000 sec (3 h). The case of more open joints ($2b$ = 1.0 mm for example) has been evaluated (Fig.2), using a solution for diffusion from a confined finite region (Crank, 1956):

$$\frac{(C_{xt}-C_{xo})}{(C_{bo}-C_{xo})}=\frac{1}{2}\left[\operatorname{erf}\frac{(b-x)}{(2\sqrt{DT})}+\operatorname{erf}\frac{(b+x)}{(2\sqrt{DT})}\right]$$

Even here the rate of reduction in the HTO level of the joint-water is still significant but overall the effect becomes less rapid with increasing joint-opening and also with reduction in porosity and with decreasing saturation.

Such a process would continue to occur with each successive incident of infiltration as long as a favourable concentration gradient existed; between infiltration incidents and particularly during extended periods of soil moisture

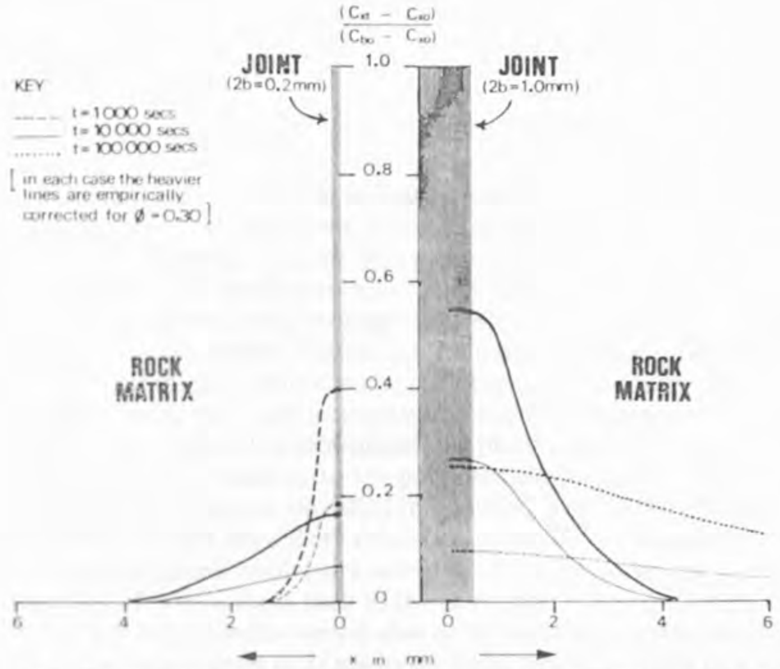

Fig.2. Theoretical non-steady self-diffusion of HTO in water from idealised joints into the saturated pore-space of a rock matrix.

deficit, the HTO concentrations throughout the pore-water itself would tend to equilibrate. As the concentration in the unsaturated zone pore-waters built-up, HTO would tend to pass downwards to the water-table more readily. A consequence of the high porosity and specific retention of the Chalk, together with its frequently thick unsaturated zone, is that the volume of pore-water available to take part in a diffusion process will in general be a number of times greater than the total infiltration to date containing thermonuclear tritium.

It is important to establish how much time is available for diffusion to occur during downward groundwater movement in high-angle joints under field conditions. The *main* response to infiltration (as identified by rising water-table in observation boreholes) traverses the unsaturated zone of the Chalk at *average* rates of 2—10 m/day (Headworth, 1972; Foster and Crease, 1974). This response is most likely to be *directly* due to a fissure-flow infiltration front but it could alternatively be transmitted via a discontinuous air phase with slower actual rates of flow. Maximum diffusion of HTO into the Chalk pore-water would occur at any level where the passage of the infiltration front was retarded by tighter jointing and lower vertical permeability, such as immediately above marl bands, and the HTO profile might be expected to vary widely between neighbouring sites with an overall tendency for the highest concentrations to occur at shallow depth. An exception would be where highly-preferred routes of flow have developed, for example in the occasional major solution feature.

CONCLUDING REMARKS

In summary, the diffusion process appears to have considerable capacity for reducing HTO concentrations in Chalk groundwater recharge. The same process would continue to occur below the water-table with further reduction in the HTO levels of the fissure-water, which represents only 1—5% of the total volume in saturated zone storage. The role of diffusion thus needs to be further investigated before tritium determinations can be interpreted with confidence in studies of groundwater movement in the Chalk and any similar formation with two contrasting hydraulic components and thick unsaturated zones. In particular, the interpretations placed upon previous tritium "age" determinations in relation to the possible delay between the times of infiltrations and sampling, can be called in question. Carefully-controlled and appropriately-scaled laboratory experiments would be required together with field investigations involving a network of boreholes at any one site and a sequence of boreholes in time at the same site.

The diffusion process would also occur with any ions in solution, though the appropriate values of D are likely to be lower. In most cases the ion concerned would have been present in the infiltration for much longer periods and equilibrium conditions would be approached. Where concentrations of a given ion have increased or new pollutants are present, the process would influence their rate of penetration from the land surface.

ACKNOWLEDGEMENTS

This work is published by permission of the Director of the Institute of Geological Sciences. Dr. G.B. Allison is thanked for a helpful discussion and Mr. Harold Ackroyd, Dr. W.M. Edmunds, Mr. D.A. Gray and Dr. R. Kitching for their comments.

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The Institution of Civil Engineers

PROCEEDINGS

PART 2

March 1975
Volume 59

Research and Theory

Foster

Proc. Instn Civ. Engrs, Part 2, 1975, **59**, Mar., 181–188

TN 110

Hydraulic behaviour of the Chalk Aquifer in the Yorkshire Wolds

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Introduction

The groundwater hydraulics of the Chalk Aquifer in the Yorkshire Wolds have been investigated in detail through a major hydrogeological pumping test and associated techniques in the Etton area[1] and by the analysis of groundwater level and river flow data from the West Beck catchment.[2] The aim of this Paper is to draw attention to the more important results of these investigations and their implications for the engineering of Chalk groundwater resources.

2. Since the work of Ineson[3,4] there have been few publications on the hydraulic behaviour of the Chalk in its saturated zone. Nationally this aquifer accounts for about 15% of all water supplies and in Chalk catchments interest now focuses on the potential for augmentation of low river flows by pumping from groundwater storage. The design of such river regulation schemes is necessitating a detailed knowledge of the nature of Chalk permeability and storage; such information is also relevant in the prediction of the movement of pollutants and in the estimation of dewatering requirements for excavations.

3. The Middle/Upper Chalk, which forms the Yorkshire Wolds, is a highly uniform and exceedingly fine-grained limestone sequence, broken occasionally by thin primary marls and more frequently by secondary flint bands and stylolites with associated marl seams. Laboratory tests on core samples show very low intergranular permeability (less than 10^{-3} m/day) and thus, despite moderate porosity (0·14–0·20), the formation must constitute an essentially fissure flow aquifer, permeability in the saturated zone being a function of the configuration of physical discontinuities in the rock mass. In East Yorkshire quarry exposures there is usually a high density of inclined joints of multidirectional aspect together with frequent horizontal discontinuities, but the persistence of both in depth is rather uncertain. Hydraulic heterogeneity was a particular question, because local hearsay evidence suggested that groundwater flow might be largely restricted within a few random fissures.

Written discussion closes 15 May, 1975, for publication in *Proceedings*, Part 2.

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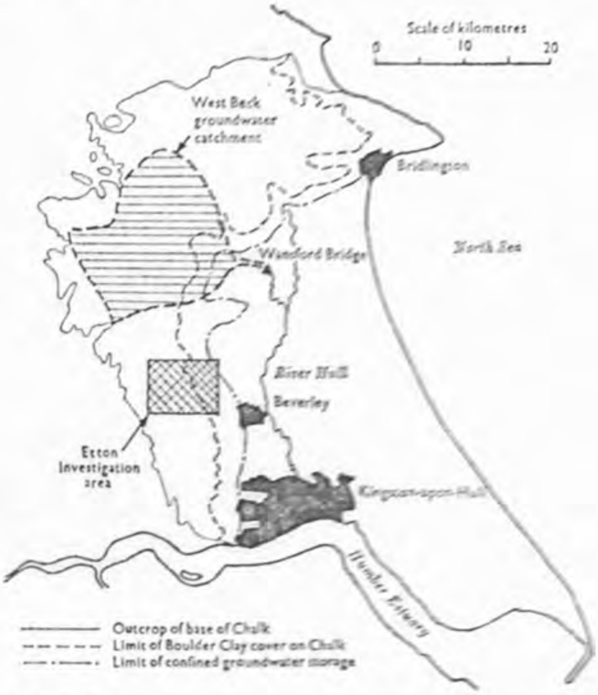

Fig. 1. East Yorkshire

Etton pumping test investigations

4. The pumping test is a powerful hydrogeological tool and can provide evidence on the hydraulic parameters of an aquifer, its confinement and boundary conditions. However, full and reliable interpretation requires detailed knowledge of local geological conditions, adequate data control through the drilling of observation boreholes and supporting data from other independent lines of investigation.

5. The Etton area (Fig. 1) is fairly typical of outcrop Chalk dip slopes, which form the major intake areas of the aquifer. It appears to have an uncomplicated geological structure and a straightforward hydrogeological regime with a simple water-table, the pumping boreholes being located in a minor shallow dry valley. Within 4 km radius, 15 boreholes were available for water-level observation and a further three were purpose-drilled at short distances from the production boreholes and to similar depths. The control over experimental conditions during test pumping was thus, in many respects, exceptional.

6. In autumn 1970 at low water-table (site rest water level of + 11 m OD), the non-equilibrium drawdowns and recoveries in the observation boreholes, associated with steady pumping at rates up to 90 l/s in the test borehole,

showed a basic consistency in form, after correction for various interfering factors (e.g. Fig. 2). No major lateral hydraulic boundaries appeared to be present in the cone of pumping depression and the general similarity in the magnitude and rate of drawdown in boreholes E4 and E5, almost equidistant from the test borehole in perpendicular directions, suggests a high degree of isotropy in hydraulic properties, although the difference in the early time responses (Fig. 2) is not fully understood. Interference effects in the more distant observation boreholes, resulting from the various regimes of test pumping, confirmed the considerable overall radial uniformity of the aquifer.

7. The relationship between pumping rate and observation borehole drawdown in all the inner observation boreholes (the nearest of which was 120 m from the pumping borehole) was strictly linear, signifying a laminar flow regime[1]—an important point as it confirmed the character of the aquifer's secondary porosity to be such that conventional groundwater hydraulics can be applied.

8. The early time, non-steady state drawdown data for all the inner observation boreholes (Fig. 2) show to a degree those characteristics often attributed to instantaneous relief from pressure storage followed by delayed yield of gravity drainage.[5,6] Application of standard methods of analysis on the late time data give consistent transmissivity T values of around 1000 m^2/day. The analysis for storage coefficient S is rather more subjective, but a value of the

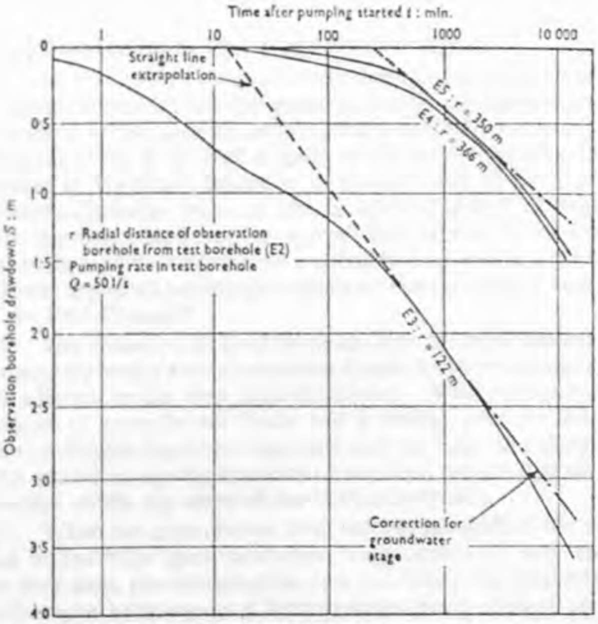

Fig. 2. Selected observation borehole data from the autumn 1970 pumping test at Etton

order of 0·005 appears to be indicated and probably represents the specific yield S_y of the Etton Chalk at low water-table. However, it is possible that a longer delayed contribution to specific yield, from microjoints or pores, might occur.

9. Subsequent test pumping in spring 1971 with a higher, although not maximum, water-table (site rest water level of +18 m OD) also gave results capable of consistent interpretation[1] with T values of about 2200 m^2/day, the saturation of the basal 7 m of the zone of seasonal fluctuation more than doubling the transmissivity.

10. Geophysical investigations of borehole flow[7] showed the entry of groundwater into the Etton pumping boreholes to be at a number of restricted levels.[1] The order of contribution from various levels was estimated by impeller flowmeter and tracer injection–detection techniques. In autumn 1970 the bulk of the water pumped from borehole E2 was derived from a zone 7 m thick, the base of which was located at about −22 m OD. In July 1970 with a site rest water level of +14 m OD, the adjacent borehole E1 (400 m up dip) had given similar results but with the base of the corresponding zone of major permeability development being at about −17 m OD and more than 30% of the total pumping rate being derived near or above the pumping water level. The existence of marked chloride residuals in both boreholes (the products of previous acid treatment) suggests minimal regional groundwater movement from about −29 m OD to the base of the boreholes (at −40 m OD) and probably below this level.

Groundwater level and river flow analysis

11. In permeable catchments groundwater level and river flow recessions are useful indicators of the gross hydraulic characteristics of an aquifer, particularly of the zone of seasonal water-table fluctuation. The West Beck catchment of the River Hull is north of the Etton area (Fig. 1) and its gauging structure at Wansford Bridge is so situated that 85–95% of the entire flow represents discharge from an area of about 235 km^2 of largely undeveloped Chalk Aquifer. However, its annual flow recessions cannot be represented by a single log/linear relationship although they can be split into a number of log/linear segments recurring in relatively closely defined flow ranges throughout the 1962–72 data.[2]

12. The groundwater level recession data are more limited, but by 1972 six continuously monitored observation boreholes were available in and immediately adjacent to the West Beck catchment. With only minor exceptions, the recession of groundwater levels had a similar form to those of river flow, with two definite log/linear segments and the trace of a third towards the end of the recession; similar recessions have been recorded in the Etton area and elsewhere on the dip slope of the Yorkshire Wolds.

13. When the groundwater level records for each of the observation boreholes in the West Beck catchment were correlated with the corresponding river flow data, the relationships were not linear—as would be expected if the aquifer were behaving as a homogeneous linear storage reservoir.[2] It was apparent that each of the correlation lines could be split, at about the same value of river flow, into two linear sections corresponding to linear aquifer

storage elements, with the suggestion of a third where sufficient data were available for the consideration of extreme drought conditions.

14. Each storage element in the zone of seasonal water-table fluctuation must have a distinct combination of T and S_y values; those for S_y correspond solely to the particular element undergoing drainage. The analysis can be extended to compute catchment average values of S_y for each storage element; results of 0·010–0·015, 0·015–0·020 and 0·005–0·010 were obtained for the three elements, the last value being that appropriate for extreme drought.[2] Furthermore, if the existence of a single linear element of aquifer storage between extreme drought groundwater level and hydrological base level (the level of zero discharge) is assumed, it is possible to estimate its average S_y. A value of about 0·002 is obtained—significantly less than that of all the overlying elements.

Nature of Chalk permeability and storage

15. It is concluded that the Chalk Aquifer of the Yorkshire Wolds forms a layered, high transmissivity, low specific yield, laminar fissure flow, unconfined system. In depth the main permeability development is localized in two layers of limited thickness and not distributed evenly throughout the thickness of the formation. The upper of these two layers constitutes the lower part of the zone of seasonal water-table fluctuation; the other is located significantly below hydrological base level. It is tempting to attribute the former to solution during long-term circulation of fresh groundwater to the existing base level; the T values would then be expected to increase down dip towards the major spring heads. The latter could well be due to a similar process operating to a much lower base level, perhaps in Pleistocene time, although it is possible that in this case there may be an element of stratigraphic control.[1]

16. In order to extend this interpretation it is relevent to consider the hydraulics of idealized fissure systems. The theory develops[2] from classical Navier–Stokes and Hele–Shaw laminar flow, parallel plate, hydraulics from whence the discharge Q over a width W_y of an idealized fissure of opening b perpendicular to the direction of flow x is given by

$$Q = \frac{b^3}{12}\frac{g}{\nu} I_x W_y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where ν is the kinematic viscosity of the fluid and I_x is the component of hydraulic gradient in the plane of the opening. For a parallel series of such idealized fissures, the equivalent transmissivity T_x is $54\sum b^3$ m^2/day, taking ν as $1{\cdot}3 \times 10^{-6}$ m^2/s for groundwater at 10°C, g as 9·8 m^2/s and expressing b in mm.[2] The importance assumed by relatively minor changes in b, due to solution for example, should be noted; just one fissure of 5 mm effective opening in the plane of the hydraulic gradient will contribute over 6000 m^2/day to the T value and introduce major heterogeneity or anisotropy to most aquifers. In this context the radially isotropic response of the Etton Chalk and its high value of T probably indicate that the solution permeability development is concentrated along horizontal discontinuities, although this explanation is not unique. Implicit in the development of equation (1) is the assumption of laminar flow, which is likely to prevail in idealized fissures of up to 5 mm opening under the hydraulic gradients associated with most horizontal flow processes.[2] The idealized fissure will be departed from in practice both in respect of planarity and wall roughness, producing tortuosity of flow path and affecting the critical Reynolds' number. However, the departures may not be so marked for bedding plane discontinuities in Chalk as in some other formations.

17. If within a limited thickness a rock mass can be considered to have a single parallel series of fissures of uniform separation $1/n$, then the equivalent permeability K_x of the system is 54 b^3n m/day, i.e. 0·063 b^3n cm/s.[1] The theoretical storage S_s of such a system is simply bn. It can thus be shown that the combination of hydraulic properties seen in the lower part of the zone of seasonal fluctuation at Etton ($K_x = 150$–200 m/day and $S_y = 0{\cdot}005$–$0{\cdot}010$) could be generated by a single set of fissures of high density (about 10/m) with effective openings of 0·5–1·0 mm. However, it is more probable that a much smaller number of horizontal master conduits (perhaps four or five) of greater opening (say 2 mm) contribute the bulk of the permeability development, although these could not contribute all of the storage. Most of the intergranular pores have diameters of less than 1 μm and are unlikely to drain under suctions of less than 3 atm. Centrifuge specific yield tests on core samples suggest that pore water drainage under gravity is of minor significance, the greatest part of the saturated porosity (0·14–0·20) constituting physically inert storage. It must be suspected, therefore, that additional gravity storage is perhaps present in a high density system of inclined microjoints.

18. It is not the intention to suggest that the Yorkshire Wolds are necessarily typical of the unconfined Chalk Aquifer in all the extensive tracts of wold and down which form its outcrop. Nevertheless there will be numerous features in common and river flow and groundwater level recession data comparable to those of the West Beck catchment have been reported from the East Anglian and Hampshire Chalk.[9,10]

Implications for water resources engineering and management

19. It is clearly inadequate to assume a uniform distribution of permeability and storage with depth in a carbonate aquifer such as the Chalk; in particular, the storage at depth could be relatively limited. A layered hydraulic structure is likely to be present and it must be expected that borehole yields, borehole yield–drawdown characteristics and the spread of pumping interference effects will show marked variations with groundwater level. Considerable caution is thus required in interpretation of preliminary investigation and extrapolation from pilot operation for river augmentation schemes which—ultimately at full-scale—will involve the manipulation of aquifer storage located well below drought groundwater levels. Problems in digital modelling of regional water resources schemes could arise. The magnitude and propagation of interference effects from remote pumping centres to distant spring heads and surface water features will be especially sensitive to potential variation in operating S_y. Assuming abstraction from groundwater storage alone, consider for example the differences in drawdown resulting after 100 days' pumping at 20 Ml/day when T and S_y are 800 m^2/day and 0·002 respectively as opposed to 1400 m^2/day and 0·012 (Fig. 3).

20. The large seasonal variation in T has other implications: natural aquifer throughflow will vary in much greater proportion than the associated hydraulic gradient and there will be profound seasonal differences in the yield–drawdown

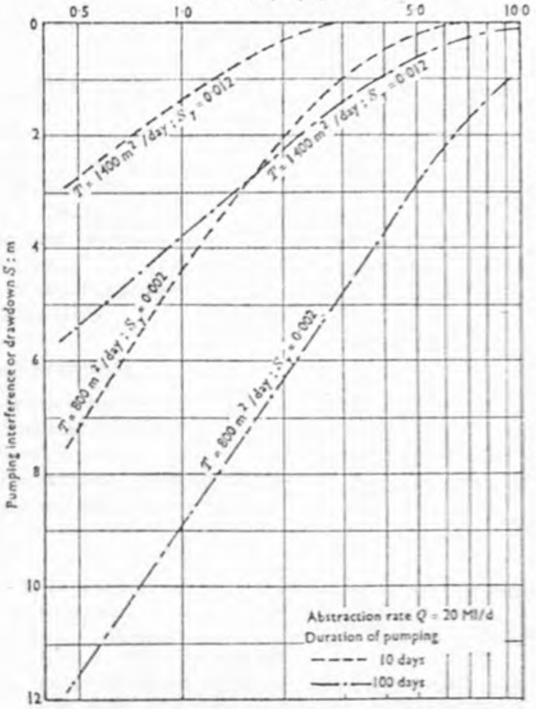

Fig. 3. Variation in distant pumping interference effects with aquifer properties

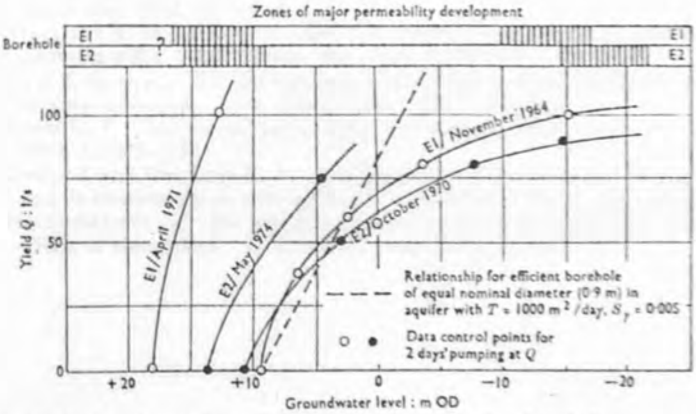

Fig. 4. Yield–drawdown characteristics of Etton production boreholes

characteristics of pumping boreholes. At Etton the yield for 5 m drawdown in borehole E1 varied between 56 l/s in November 1970 and 98 l/s in March 1971 (Fig. 4). At low water-table the characteristics are also strongly influenced by the level of the lower zone of major permeability development, the boreholes tending to approach a limiting yield at drawdowns of about 20–25 m. The level of that zone is thus far more important than overall saturated aquifer thickness because it more directly affects the heads that can be utilized in groundwater abstraction.

21. A high transmissivity, low specific yield, water-table aquifer will have a more rapid hydraulic response than most unconfined systems. Actual groundwater flow rates will also be relatively fast—although less so than for karst systems—and even under natural hydraulic gradients they could exceed 200 m/day: a significant factor in the spread of pollution should pollutants reach the water-table.

Acknowledgements

22. The work is published by permission of the Director of the Institute of Geological Sciences and the East Yorkshire (Wolds Area) Water Board. The Yorkshire River Authority provided the river flow data for West Beck. The support of the Authors' colleagues Mr R. S. Hudson, Miss A. S. Robertson, Mr T. K. Tate and particularly Mrs V. A. Milton is gratefully acknowledged.

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The Quarterly Journal of Engineering Geology

Q. Jl Engng Geol. 1975 Vol 7 pp. **III–III**

Printed in Northern Ireland

LETTER TO THE EDITOR

Dear Sir

Q. Jl Engng Geol. 1974 Vol 7 pp. 197–205
Rapid Groundwater Flow in Fissures in the Chalk: an Example from South Hampshire
T. C. Atkinson and D. I. Smith

I read the work on the Chalk groundwater of the Horndean-Havant area with interest. I entirely agree with the authors' claim that their tracer investigations provide unequivocal evidence of the existence of highly-localised, very rapid, probably turbulent, conduit flow of Chalk groundwater, at least at that location.

Part of their discussion and conclusions however, namely the suggestion that similar near-karstic features are generally responsible for the widespread existence of zones of high transmissivity, is distorted and likely to lead to the results being quoted out-of-context by non-groundwater specialists. Comparable conditions are only likely to be found at occasional locations mainly along the margin of the Tertiary outcrop where Chalk solution has been accelerated by concentrated run-off or recharge of low pH; certain examples are known from the London Basin (Water Resources Board 1972). Subaerial weathering on the Tertiary erosion surface will also have contributed to the development of secondary permeability. Indeed, is it not possible that the main conduits of the flow system described in the paper are developed along the Cretaceous-Tertiary unconformity?

Now high fissure transmissivity is one thing but near-karstic conduits (in which transmissivity is a meaningless concept and for which the basic laws of porous media hydraulics do not even approximately apply) are another. It is fair to say that high fissure transmissivities (over 500 m^2/d and often over 1000 m^2/d) are developed over wide areas of the Chalk outcrop intake area. It is such areas that are of greatest volumetric importance and most topical interest in the field of water resources development and for which *in situ* horizontal permeabilities of the order of 80 m/d (a figure quoted totally out-of-context in the paper) are frequently present over limited depth intervals below the water-table. It is likely that most of the transmissivity development is due to solution during the long-term circulation of fresh groundwater to existing and pre-existing base levels (Foster 1974). However the solution features are of a much smaller scale than those of the Bedhampton system and there is a growing body of evidence to suggest that quite limited enlargement of the openings on near-horizontal features such as bedding planes and stratiform secondary discontinuities is commonly responsible for the permeability development. Only limited enlargement is required to explain the observed transmissivity values (Foster & Milton 1974). Moreover an aquifer of this structure would be entirely consistent with the generally observed areal uniformity of groundwater level contours and pumping test responses in dip slope areas(e.g. Foster & Milton 1974). Actual groundwater flow velocities under natural hydraulic gradients would still be high; probably in the range 40-400 m/d.

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Engineering Hydrology Today

Conference organized by the Institution of Civil Engineers,
the International Hydrological Decade Committee
and the Institute of Hydrology

18–20 FEBRUARY 1975

THE INSTITUTION OF CIVIL ENGINEERS
LONDON, 1975

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Mr S. S. D. FOSTER, Institute of Geological Sciences

My primary aim in contributing is to ask the Authors of Paper 9 to what extent they think they are justified in at best grossly oversimplifying, and at worst practically ignoring, variation in aquifer properties with depth.

16. Most of the models currently in existence in UK are designed to guide important regional groundwater developments involving abstraction of large volumes of water from aquifers during drought, thereby artificially depressing water tables substantially lower than ever before.

17. The Authors have gone to some length (§§ 37, 40 and 64) to stress that T and S 'may change significantly' with groundwater level, that a model is only as good as the quality of the input data, etc. But they know as well as I do, that in practice what often tends to occur is that one or two fairly rough pumping tests – whose timing may be dictated more by contractual considerations and staff availability than by hydrological conditions – are undertaken and the values obtained are assumed to be the result of uniform distribution of permeability and storage throughout the entire geological thickness of the formation concerned. Models based on this assumption will invariably show vast volumes of groundwater storage, at least on paper, and this 'paper water' then enters the hands of the resource planner, who may take little interest in anything as mundane as the physical nature of the potential resource concerned.

18. To illustrate my point I would like to discuss the groundwater storage of the UK's most important aquifer, the chalk. I was incidentally alarmed by the confusion between groundwater levels and groundwater storage in Paper 3 and the implication in its title that groundwater storage was something that can be measured in the same way as stream flow, for example.

19. There is not time to go into the methods employed in such work, but well-designed, carefully controlled and cautiously interpreted pumping tests, supplemented by borehole flow logging[E1] and laboratory tests on core samples[E2], are the essentials, coupled with sound understanding of local geological and hydrological conditions.

20. From laboratory work in the case of intergranular properties and near first principles in that of fissure properties, some values can be put on the two physical components of the chalk aquifer (Table E1). Despite high porosity the pores are so small that the intergranular permeability is insignificant in terms of flow to wells and the gravity drainage of pores is also relatively minor. The hydraulic properties of the aquifer are thus largely dependent on the fissure component; very high permeabilities accompanied by specific yields of perhaps up to 2% can be developed but only where some solution along joints has occurred[E3].

21. It is of interest now to consider the yield-drawdown behaviour of a chalk borehole at what I believe to be a reasonably representative unconfined site[E3], on the lower part of the aquifer's dip slope (Fig. E1). A striking difference between the behaviour at high and low water table is observed. The underlying reasons were revealed by geophysical logging for borehole inflow levels and volumes. Most of the inflow levels and permeability development are concentrated in two limited and relatively shallow depth intervals, the upper corresponding to the lower part of the zone of seasonal water-table fluctuation. There is no measurable flow at depth. Such information permits an estimation of the yield-drawdown behaviour of the borehole if it were operating as part

Table E1. Permeability and storage components of chalk

	Intergranular pores	Joints and fissures	
Porosity	15–40%	0–2%	*
Specific yield	0–1% (rarely > ½%)	0–2%	
Permeability	< 10^{-3} m/day (insignificant)	0–200 m/day (though over 1000 m/day is possible)	

* Maximum values developed only if significant solution has occurred.

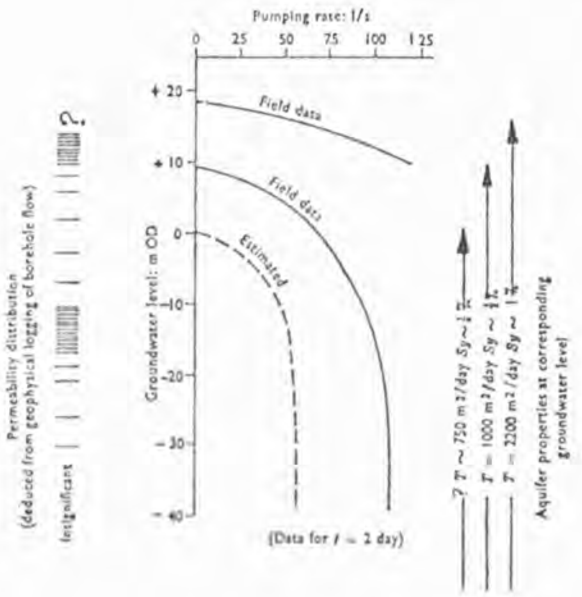

Fig. E1. Yield/drawdown characteristics of a chalk borehole in unconfined aquifer and related hydrogeological data

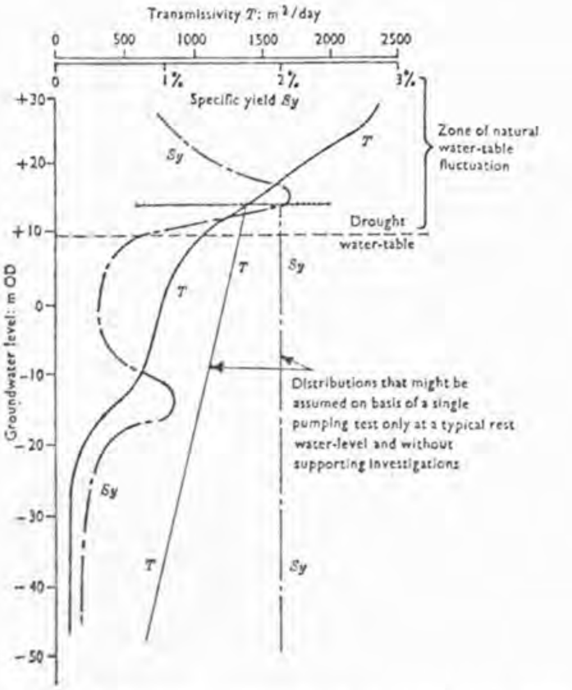

Fig. E2. Probability variation of T and Sy of chalk aquifer with falling water-table at same site

of a major drought storage development scheme with a regional drawdown of say 10 m. The limiting yield would be reduced by perhaps 50%.

22. Should anyone need convincing that the chalk at depth can be impermeable, I would refer them to a long-standing account of the driving of additional headings in Middle Chalk at Cottingham, East Yorkshire, in an attempt to increase groundwater production[E4]. It is said that it was possible to remain quite dry in a new lower adit despite the fact that some 32 ml/day could be pumped from the original adit 15 m above.

23. Returning to the previous site (Fig. E1), T and Sy values are available from pumping tests at two water-table levels. Using these values and various supplementary data[E3, E5], it is possible tentatively to predict the likely pattern of T and Sy variation with falling groundwater level (Fig. E2). I make no apology for the speculative nature of such a procedure – this is part of what a groundwater hydrologist is paid for. My claim is that this picture, and variations of it for other sites and other areas, are likely to be nearer the truth than the distribution commonly assumed, particularly by groundwater modellers, on the basis of a pumping test at an average rest water level.

24. Such reductions in T and Sy with depression of the water table must imply a substantial fall in gross borehole yield and/or in net gain of the resource system (as a result of increased interception and recirculation)[E6].

25. I do not wish to suggest that there is no storage available for development at drought in aquifers; simply that there may be significantly less than might at first sight appear, particularly in the case of the chalk. In terms of engineering the hydrological regimes of aquifers, it is helpful to postulate on the probable value of the ratio between the exploitable (mobile, fresh) groundwater storage at drought and the mean annual recharge from rainfall. Taking typical unconfined aquifers, I estimate a value of 1–3 for chalk and over 20 (and perhaps a lot greater) for the higher permeability faces of the Bunter sandstone. I would welcome the Authors' comment on these figures. It should be recognized that it will only be economic in practice to abstract a proportion of this storage.

26. Finally, I would make the plea that T and S values and boundary conditions used in groundwater models for major schemes need careful selection by experienced hydrogeologists who are capable of assessing all the relevant factors and who are given the time and the money to mount preliminary field investigations. Any tendency to substitute, rather than to supplement, the field hydrogeologist with the groundwater modeller or active field investigation with office computation in the long run may well prove retrogressive.

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JOURNAL OF THE INSTITUTION OF WATER ENGINEERS

VOL. 28
NO. 3

MAY
1974

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THE INSTITUTION OF WATER ENGINEERS
Secretary: J. P. BANBURY, *MBE*
6–8 SACKVILLE STREET, PICCADILLY,
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Telephone: 01-734 5422
PRICE £0·75 post free

*** also published in reduced form in

Groundwater Pollution in Europe
Cole J A (ed) 1974 : 269-274
Water Information Center (Port Washington)

Groundwater Pollution in Europe

Proceedings of a Conference
organized by
The Water Research Association
in Reading, England, September 1972

Edited by

John A. Cole
Chief Hydrologist
The Water Research Association
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WATER INFORMATION CENTER, Inc.
Port Washington, New York
1974

NITRATE POLLUTION OF CHALK GROUNDWATER IN EAST YORKSHIRE—A HYDROGEOLOGICAL APPRAISAL[*]

By S. S. D. FOSTER, BSC, CENG, MICE (*Member*)[**]
R. I. CREASE, BSC (*Tech*), CENG, MICE, AMBIM (*Fellow*)[***]

SYNOPSIS

During 1970–72 there have been marked increases of nitrate level in Chalk groundwaters from widely-distributed locations in East Yorkshire. The most likely cause appears to be some change in agricultural practice; indicating an urgent need for collaborative studies by water-supply and farming interests.

Hydrogeological investigations show the situation to be complex. Tritium determinations suggest that, even below intake or recharge areas, the polluted groundwater could be more than 10 years old. The hydraulics of the implied slow-transit system above the water-table, in what had always assumed to be predominantly a fissure-flow formation, are not readily understood. The dilemma is defined in detail.

If such a system is controlling subsurface flow, the steady increase in applications of nitrogenous fertiliser since 1959 gives rise to a most pressing question. How much nitrate is contained in the groundwater of the unsaturated zone, already in transit to the water-table? Preliminary investigations have revealed levels of 10–35 mgl NO_3-N in Chalk pore-water from shallow depths below fertilised arable land.

BACKGROUND TO NITRATE POLLUTION PROBLEM

Introduction

Prior to 1970, routine monitoring had shown Chalk groundwaters from East Yorkshire (Wolds Area) Water Board (EYWB) sources to contain 2·5–4·5 mgl NO_3-N. Since 1970 levels ranging up to 7·5–11·5 mgl NO_3-N have been recorded for these widely-distributed supplies. Somewhat similar rises have been reported from comparable areas in Sussex and Lincolnshire by Green & Walker[3] and Davey[4], who attempted to correlate the pollution with coincident changes in local agricultural practice or regional land-use.

In East Yorkshire the apparently sharp rises in nitrate level are alarming but the maximum concentrations experienced are not yet critical. This paper, based on the synthesis of largely pre-existing data amplified by limited field investigation, defines and discusses the state of knowledge of the problem, especially its hydrogeological aspects.

Limitation on Nitrate in Water Supplies

The effect of increasing nitrate on the potability of water continues to be a subject of debate among medical research workers. A health hazard results from nitrate reduction on ingestion; the build-up of stable nitrate compounds in the bloodstream reducing its

---

[*] The authors presented this topic in outline at the WRA Conference on "Groundwater Pollution" at the University of Reading on 25–27th September 1972.

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Note. Details of numerical references are given on p. 194.

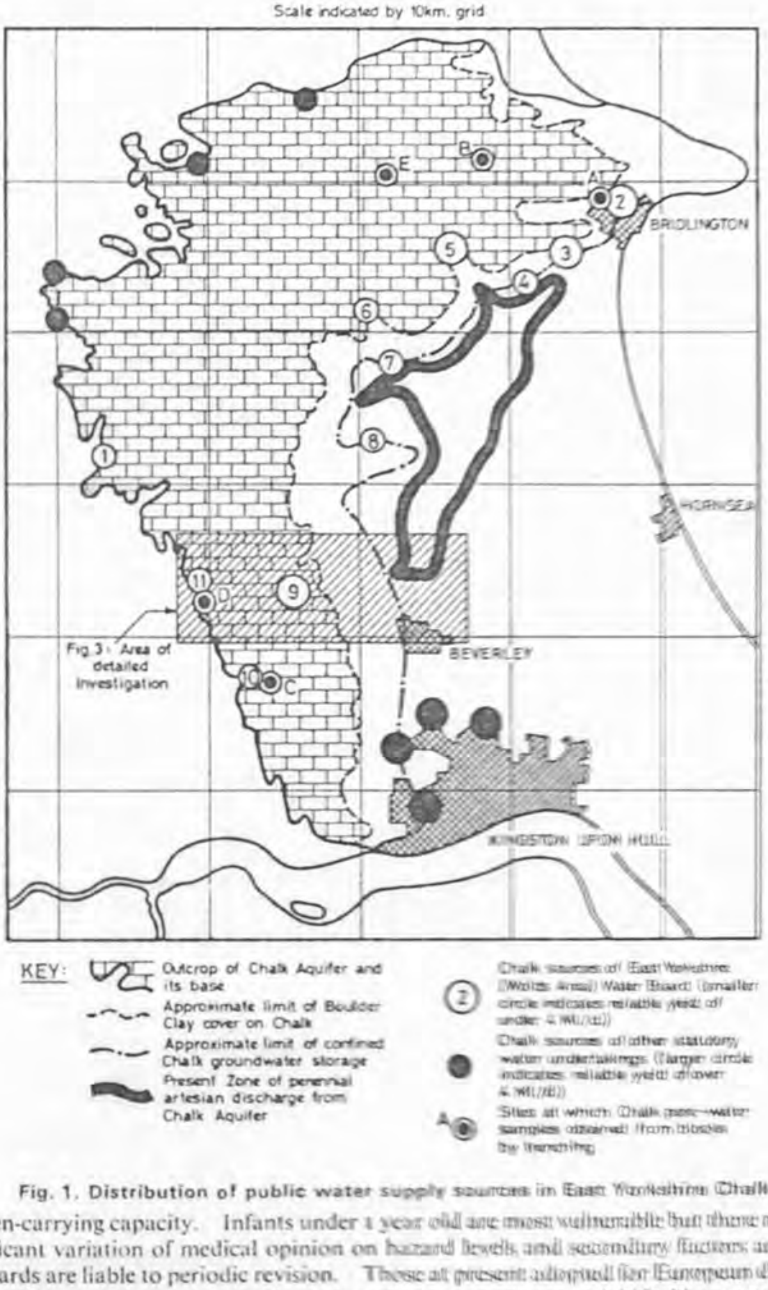

Fig. 1. Distribution of public water supply sources in East Yorkshire Chalk

oxygen-carrying capacity. Infants under 1 year old are most vulnerable but there remains significant variation of medical opinion on hazard levels and secondary factors and thus standards are liable to periodic revision. Those at present adopted for European drinking waters[22] suggest that concentrations should not exceed 11·3 mg/l NO_3-N (50 mg/l NO_3).

but occasional levels of up to 22·6 mgl NO_3-N (100 mgl NO_3) might be acceptable*. In the latter case closer observation by the medical authorities or special arrangements for the supply of drinking water for infants would be required.[15]

The total relaxation of the lower recommended limit has been called for but a recent study in North America[21] concludes that there is insufficient medical evidence to safely justify such action and recent work[14] points to other reasons for minimising the total volumes of ingested nitrate. Nitrate poisoning can also occur in livestock, and high nitrate levels in process waters can be troublesome in certain industries.

Role of Chalk Aquifer in Regional Water Supply

The East Yorkshire Chalk provides the bulk of all water-supplies in a region with a population of over 500 000; the licensed abstraction of all Chalk sources totalling in excess of 200 Ml/d. In particular the EYWB have 11 Chalk sources (Fig. 1), mainly large-diameter boreholes, with a combined drought yield of some 53 Ml/d. The protection of the Chalk Aquifer from a level of pollution incompatible with its water-supply function is thus of regional significance. Moreover its large unexploited storage capacity in the northern part of East Yorkshire would appear to have a role in meeting the future demands of the North Humberside conurbation.[8]

Some 80–90 per cent of the flow of the River Hull is derived from Chalk springs. Nitrate enrichment could lead to fertilization of weeds in the river itself and to algal problems in the water-supply reservoirs at the intake works.

INTERPRETATION OF HYDROCHEMICAL DATA

Trends of NO_3-N in Chalk Water Supplies

The long-term trends in NO_3-N concentration for selected sources are shown in Fig. 2. During 1962–69 all had relatively constant nitrate levels of around 3·0 to 4·0 mgl NO_3-N. In 1970 more variable results with some increases were recorded. An apparently sharp rise followed in 1971 and 1972; the worst-affected source reaching a peak of 11·5 mgl NO_3-N in May 1972. Other sources had comparable, though less steeply rising trends (Fig. 2 and Table 1). There are seasonal variations with late spring/early summer maxima and autumn minima but daily and weekly samples have not revealed any flashy fluctuation. Elsewhere in the Chalk, a change from 7·2 to 16·0 mgl NO_3-N over only 10 days in a borehole water supply has been reported.[9]

TABLE 1. SUMMARY OF INCREASES IN NITRATE LEVELS IN EYWB SOURCES (*not presented in Fig. 2*)

Source No. (Fig. 1.)		1	2	3	4	6	7	8	10
pre-1970 background	NO_3-N mgl	2·9	3·2	3·4	2·9	3·2	3·4	3·2	3·2
1972 peak		6·8	9·3	6·1	7·2	7·9	7·0	6·3	9·5

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* Throughout the remainder of this paper nitrate concentrations are expressed in mgl NO_3-N units only (multiply NO_3-N by 4·4 for NO_3 units).

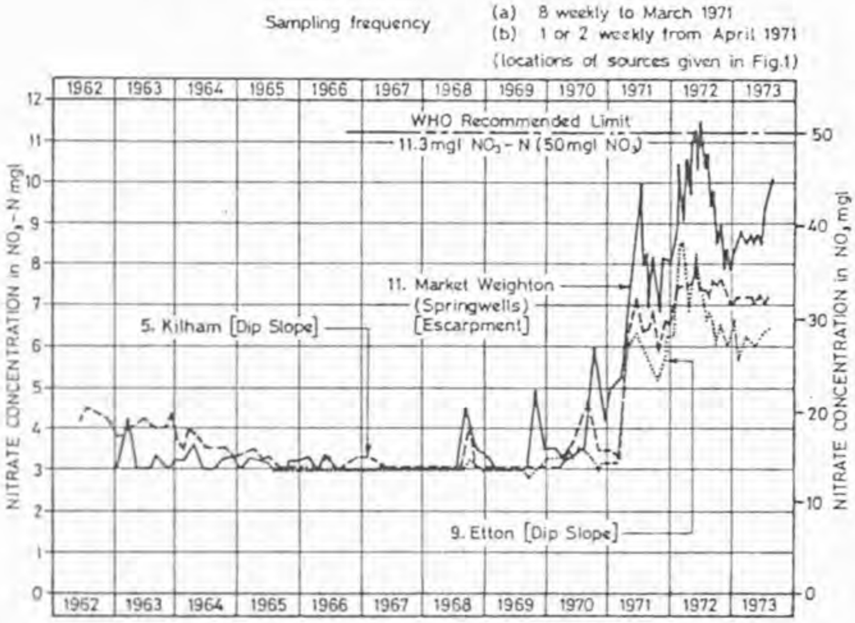


Fig. 2. Trends of nitrate concentration in selected sources

The sources have always had low levels of nitrite and organically-bound nitrogen (ammoniacal and albuminoid N not exceeding 0·04 and 0·05 mgl respectively) and no increases have accompanied the rises in NO_3-N. Neither have there been clear simultaneous changes in other inorganic ions such as chloride, sulphate or potassium, although there are only restricted data in respect of the latter. Chloride levels in Chalk groundwaters of the Yorkshire Wolds are typically close to 20 mgl; the Market Weighton (Springwells) source however records somewhat higher values, which have increased since 1967 from 23–26 mgl to 24–34 mgl. The bacteriological standard of the raw waters from all sources is consistently high, with only very occasional low coliform counts.

Reliability of Analytical Techniques

The interpretation of long-term trend data as evidence for pollution depends to a considerable extent on the accuracy and reliability of nitrate analyses. Numerous analytical techniques are available for the determination of nitrate in waters. Waters[20] reviewed those methods involving colorimetric measurement, both directly and indirectly after reduction. Significant problems arise because of changes in concentration during transport and storage, varying effects of interfering ions and natural colours of water and incomplete conversion of the nitrate ion to the distinct molecular species to be colorimetrically determined. Moreover since the percentage conversion depends considerably on experimental conditions, failure to adhere to standardized procedures leads to irreproducibility of results by the same method.

A study of differences between 10 different laboratories employing various methods, gave a mean result of 4·43 mgl NO_3-N for a standard solution of 4·60 mgl NO_3-N, with a lowest value 0·89 mgl NO_3-N below standard.[3] Interlaboratory work was introduced in the present investigation mainly to aid the interpretation of past data, though rapid analytical methods involving direct observation of the ultra-violet absorption and a specific ion electrode were also included. The results for some split samples (Table II) revealed an absolute variation of more than ±1·0 mgl NO_3-N, both between methods and in repeated determinations with the specific ion electrode. It is thus clear that the analytical problem will, in many cases, restrict the interpretation of historical or sequential nitrate data. A similar problem may also be posed when attempting to implement any recommended limit for water-supply.

TABLE II. INTER-LABORATORY COMPARISON OF NITRATE ANALYSES ON CHALK GROUNDWATERS FROM EAST YORKSHIRE

Split samples taken on 15 February 1972. All results in mgl NO_3-N

Source No. (Fig. 1)	Lab A		Lab B	Lab C		Lab D		Lab E*	Mean	Absolute Variation from Mean	
	Method		Method	Method		Method		Method			
	DCpda	DCxyl	DCpda	SIonEl	DCbr	UVSp	DCpda	SIonEl		+	−
9	8·4	8·5	8·5	9·0M	7·8	7·8	8·0	7·7m	8·2	0·8	0·5
8	6·3	7·0M	5·9	6·7	5·7	5·4	5·2m	5·5	6·0	1·0	0·8
5	7·1	7·5	7·4	8·2M	7·0	7·0	7·2	6·9m	7·3	0·9	0·4
11	10·5	10·0	9·1	10·9M	8·6	8·3m	8·8	8·4	9·3	1·6	1·0
10	11·0M	10·5	8·7	9·0	8·9	8·2	8·6	8·1m	9·2	1·8	1·1
3	6·7	7·0M	5·5	6·5	4·9	5·0	4·8m	4·9	5·7	1·3	0·9
	+0·7	+0·8	−0·1	+0·6	−0·5	−0·7	−0·5	−0·7	Average Variation from Mean		

M: maxima. m: minima

KEY TO METHODS:

DC: Direct Colorimetric Methods with phenol −2·4 disulphonic acid (pda) or brucine reagent (br) or 2·4 xylenol (xyl)[20]

SIonEl: Specific Ion Electrode[4]

UVSp: Ultra-violet Spectroscopy[12]

* Mean of five determinations in 5 days with variation of about ±1·0 mgl.

This applies in some degree to, but does not invalidate, the trend data for the Chalk groundwaters of East Yorkshire (Fig. 2). All analyses were carried out by the same technique, the direct colorimetric method with phenol-disulphonic acid, although there have been changes of analyst and analytical laboratory including a change (from Lab. A to Lab. B of Table II) in 1971. There must therefore be some doubt as to the absolute magnitude of pre-1971 levels, but the sharp rise in recent years has been confirmed through the detailed and careful work of Lab. B alone. Earlier background values are, to an extent, substantiated by the relationship between the results of Lab. B and Lab. A in the inter-laboratory determinations (Table II).

Distribution of NO_3-N in Chalk Groundwater

The network of sources with long-term trend data (Table I) are scattered throughout the rural parts of the region (Fig. 1). The detailed spatial distribution of nitrate in groundwater of the saturated zone has been investigated within a cross-section 6 km wide

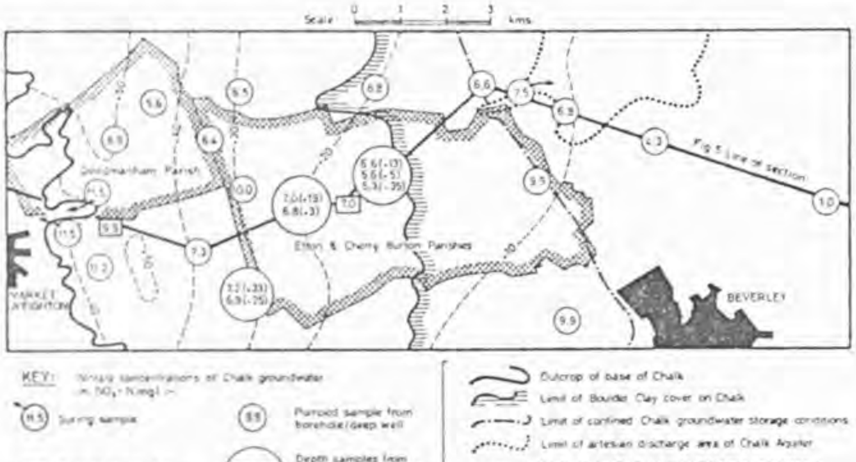


Fig. 3. Nitrate concentrations of Chalk groundwater in the Market Weighton-Beverley area in August 1972

and 16 km long. A sampling programme was carried out during August 1972 and 16 pumped-samples, 3 spring-samples and 7 depth-samples were collected for analyses. The results (Fig. 3) show nearly all groundwaters below the outcrop or intake area to have NO_3-N concentrations in excess of 6·0 mgl, with values exceeding 10·0 mgl NO_3-N near the escarpment. These values are probably some 20–25 per cent below the all-time maxima reached a few months earlier.

An electro-magnetically operated depth-sampler was used to skim the water-table and for sampling at greater depths in three observation boreholes. Little nitrate stratification or submerged zone of nitrate reduction was revealed (Fig. 3). Natural Eh changes, causing reduction of nitrate, appear to occur in the confined zone however, since levels fall to 1·0 mgl NO_3-N some 6 km down-dip (Fig. 3). Conditions down-dip are of somewhat academic interest however, since they cannot be used to significant advantage in water-supply because of the coincident fall-off in permeability and well yields in this direction.[8]

The distribution of NO_3-N in Chalk groundwater above the water-table was also of considerable interest. A few results in respect of pore-water have been produced for 5 sites (Fig. 1) at which Chalk blocks were carefully removed from trenches dug rapidly by mechanical-excavator to depths of 4 metres. Pore-water samples were extracted from the blocks after crushing to a paste; this method may not be ideal and might lead to underestimates if nitrate is not fully-recovered from the smallest pores. The results (Fig. 4) are nevertheless of interest and show Chalk pore-water frequently to contain more than 15 mgl NO_3-N (and sometimes in excess of 30 mgl NO_3-N) at shallow depths beneath fertilized arable land. The corresponding values for unfertilized grasslands were mostly below 2·0 mgl NO_3-N. Differences between the exterior and centre of blocks were observed and it is possible that accumulation of soluble salts might be occurring after evaporation without any net groundwater movement, or through other processes.

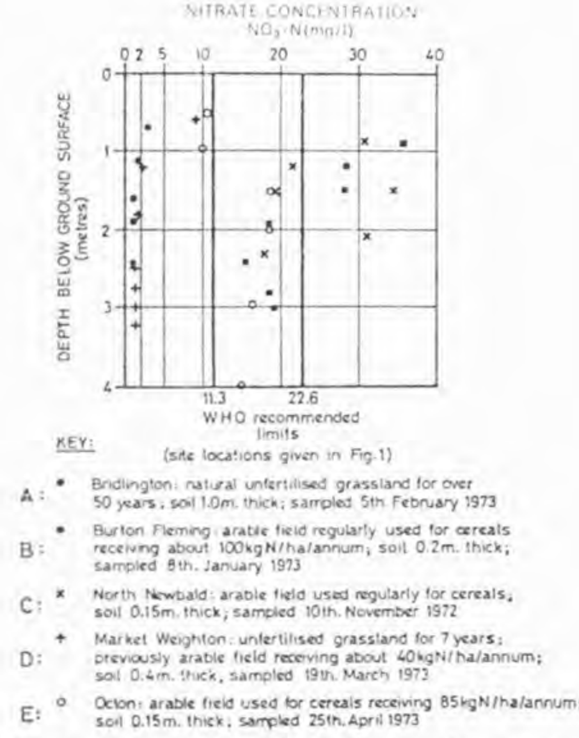


Fig. 4. Nitrate concentrations of Chalk porewater in unsaturated zone

GROUNDWATER FLOW REGIME IN CHALK AQUIFER

Overall Pattern of Recharge, Storage and Throughflow

In the Market Weighton-Beverley area of the Yorkshire Wolds the hydraulic behaviour of the Chalk in its saturated zone has been studied in detail, using hydrological pumping tests, geophysical borehole flow investigations and other methods. The Chalk is a fissure-flow and largely fissure-storage formation with horizontal permeability (k_h) in the range 20–200 metres/day in the active flow zones. Corresponding velocities of throughflow to the discharge areas under natural hydraulic gradients must be in the range 10–50 metres/day (Fig. 5).

Throughout the Chalk outcrop the recharge regime was believed to be relatively simple, with infiltrating precipitation and corresponding recharge at the water-table, at times of zero soil moisture deficit. The unsaturated zone is typically in the range 20–100 metres thick and rapid fissure-flow was thought to dominate downward groundwater movement through this zone to the water-table. However, as will be discussed below, the results of isotope work suggest that a totally different unsaturated flow regime may in fact prevail.

The long term average infiltration in the Yorkshire Wolds is estimated to be about 300 mm/annum. Foster & Milton[8] have computed the maximum monthly infiltration for the northern part of the region during 1962–70 to be in excess of 130 mm with a total of 480 mm during the period September 1965–February 1966. Infiltration is usually concentrated in the months October-March, but there is frequently some post-March and in certain years this can be a significant proportion of the total (e.g. April 1966, May 1967).

The response of the water-table to infiltration as recorded in observation boreholes, appears reasonably predictable, both in magnitude and time-lag. There is generally a small very rapid response (probably in fact partly barometric) with the main recharge to the water-table commencing a few days after the corresponding rainfall and spread over a number of days. The response times in respect of the latter are normally of the order of 0·1–0·3 days/metre of unsaturated zone. On the evidence of groundwater levels in observation boreholes, minor "flash" infiltration during periods of large soil moisutre deficit also appears to occur occasionally after short heavy rainfall.

Determinations of Environmental Tritium

Tritium is a radioactive isotope of hydrogen with a half-life of 12·3 years. Tritiated water occurs both naturally and artifically in the atmosphere from where it enters the groundwater cycle as infiltrating precipitation. The tritium level in precipitation increased from below 10 TU (tritium units or tritium atoms per 10^{18} protium atoms) to a peak in excess of 2000 TU in summer 1963, as a result of thermo-nuclear testing in the preceding 10 years. Observed or correlated tritium levels in British rainfall have been given by Smith *et al*[16] and it is important to note that they did not fall below 50 TU during 1962–70; the annual means, adjusted for decay, have exceeded 100 TU in every year since 1958.

Some 30 tritium determinations were carried out during 1970–72 on Chalk groundwaters from East Yorkshire, by the method of Allen[2]. Most of the samples were pumped from water-supply boreholes but some depth samples and spring samples were also included. The groundwater conditions on the sampling dates were those of moderate drought in October 1970, high water-table in March 1971 and fairly low water-table in August 1972. All of the tritium counts are low (less than 50 TU) and no less than 21 of the samples had counts below 10 TU with a further 5 below 20 TU.

Ten of the sampling stations were located in the area of detailed investigation (Figs. 1 and 3) and the results for this area are illustrated in Fig. 5. It is of note that:

(*a*) Despite major recharge of the Chalk water-table between October 1970 and April 1971, no significant increase in tritium levels was observed at the 3 stations sampled on both dates.

(*b*) Depth samples skimmed from the surface of the water-table in August 1972 had low tritium levels and it appears that tritium layering cannot explain the low values obtained for the pumped samples.

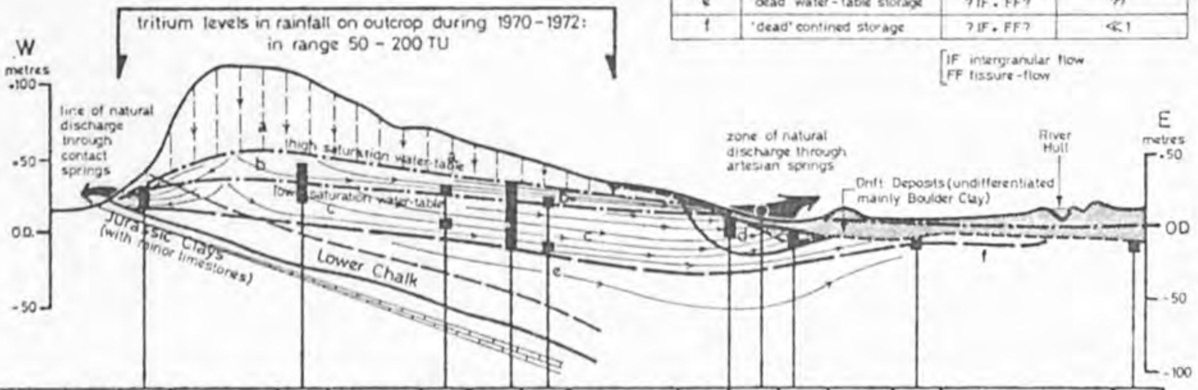
Environmental tritium is considered a particularly suitable tracer for water since it is part of the water molecule. Sample contamination would in most circumstances lead only to increased counts. While limited isotopic concentration in the liquid phase during evaporation has been recorded and in low velocity groundwater flow systems isotopic diffusion may produce significant dispersion, the possibility of any selective delay or retention of tritium by soil or chalk is believed to be remote.

The most satisfactory explanation of the low tritium levels in the Chalk groundwater of East Yorkshire, when compared to recent rainfall, is that the bulk of the recharge to the water-table must reside more than 10 years, and probably more than 18 years, in the unsaturated zone during downward percolation. Low tritium levels are being recorded from the saturated zone of the Chalk over much of the country, including North Lincolnshire where nitrate pollution is also reported. Direct investigation of the unsaturated

KEY TO GROUNDWATER FLOW REGIME

SYMBOL	ZONE OF	TYPE OF GROUNDWATER FLOW REGIME	ACTUAL NATURAL GROUNDWATER FLOW RATES metres/day
a	unsaturation	?IF + FF?	??
b	water-table fluctuation	FF	25 - 50
c	'active' water-table storage	FF	10 - 30
d	natural discharge	FF	
e	'dead' water-table storage	?IF + FF?	??
f	'dead' confined storage	?IF + FF?	≪1

IF intergranular flow
FF fissure-flow



TRITIUM DETERMINATION IN T.U. ON GROUNDWATER SAMPLES																
	AUG. 1972	25		—		4/4	1	3/2		—	—	—		—		—
	APRIL 1971 (high saturation)	—		1		—	4	—		—	—	4		—		—
	OCT. 1970 (low saturation)	32		2		—	2	—		3	7	0		0		3

Fig. 5. Hydrogeological cross-section of the Yorkshire Wolds in the Market Weighton-Beverley area to show groundwater flow regime and tritium age determination

zone however has been relatively limited. Smith *et al*[18] determined the total tritium of unsaturated zone pore-water from a cored Chalk borehole on the Berkshire Downs in 1968 It was concluded that 85 per cent of the total downward movement was intergranular seepage at a net flow rate of only 0·88 metres/annum; the 1963 tritium peak being clearly in evidence at just below 4 metres depth.

In East Yorkshire, only at sampling sites on the escarpment and near some dip-slope springheads, were somewhat higher tritium levels recorded and components of more recent water implied. These included the source at Market Weighton (Fig. 5) the worst affected by nitrate pollution. On the available evidence, it is not possible to say whether such levels result from the limited thickness of the unsaturated zone in parts of these areas, from the existence here of a significant rapid-transit fissure-flow component or from other factors.

Dilemma of the Unsaturated Zone

The existence of a dominantly slow-transit intergranular flow regime in the unsaturated zone is not easy to reconcile with the known hydraulic properties of the Chalk.

The physical and hydraulic properties of 28 selected samples of East Yorkshire Chalk have been determined[8] and more comprehensive laboratory core analysis of an individual Chalk borehole in Berkshire has been reported.[7] It should be noted however that cementation is more extensive in the East Yorkshire Chalk and that there are significant differences between its properties and those of the southern Chalk. Although weathering, the presence of stylolites and minor changes in lithology have a measurable effect on physical properties at the intergranular level, and there may be a tendency for porosity to reduce with depth, it is possible to quote order-of-magnitude values for the purpose of the present discussion. In the Yorkshire Wolds, inter-connected porosity (ϕ) is only moderately high and unlikely on average to exceed 0·20 in the unweathered state; in strong contrast the inter-granular permeability is extraordinarily low, with k_V (saturated vertical permeability) in the order of 10^{-4} metres/day. This combination clearly implies exceedingly small particle sizes and pore-channel diameters and such have been demonstrated by scanning electron microscopy.[11] The bulk of the particles in the fabric are coccolith plates, believed to be in the order of 1 μm diameter, with even smaller pore-sizes. The Chalk must be amongst the finest of naturally-occurring granular materials and if an unbroken intergranular column existed, it could be expected to support a capillary fringe of unusual height. Pores of such diameter would drain only under suctions in the order of 3 atmospheres and explain the very high specific retentions. Centrifuge specific yield tests on core samples from East Yorkshire gave values up to 0·009 with an average of about 0·003 and the drainage probably derives entirely from occasional pores of larger diameter.[8]

In quarry exposures the rock mass is traversed by frequent major joints of multi-directional steeply-inclined aspect and even larger numbers of minor joints; the typical density of the major inclined jointing is reported to be 0·7–1·3 per metre.[8] There is evidence from the Chalk of Norfolk that many of these inclined joints may be closed 'tight' at relatively shallow depths of burial, but it should be borne in mind that very small openings can impart high permeability to a rock mass. If, for example, each joint of a set of 1 metre spacing had an effective opening of 0·1 mm, they would develop a permeability of 0·05 metres/day (about 500 times the intergranular k_v). Horizontal discontinuities must also be present in the unsaturated zone. In the East Yorkshire quarries their density of occurrence ranges from 0·6–3·6 per metre and solution on them is believed to be responsible for the very high permeability (about 120 metres/day) of the zone of water-table fluctuation at Etton.

Given this framework of hydraulic properties, specific questions concerning the dilemma of unsaturated groundwater flow in the Chalk originating in the tritium results should be discussed.

(A) Does the unsaturated zone have sufficient storage capacity, in absolute terms, to hold 10 or 20 years infiltration?

Taking $\phi = 0{\cdot}20$ and an average annual infiltration of 300 mm, 10 and 20 years recharge could be stored in thicknesses of 15 and 30 metres, which are present over most of the intake area except in escarpment dry valleys and near some dip-slope springheads. The potential fissure-storage of the unsaturated zone is almost certainly an order-of-magnitude smaller.

(B) What order of vertical intergranular flow rates are physically possible?

Any downward movement at the intergranular level for partial saturation will be under the complex interaction of capillarity and gravity; both the unsaturated k_v and the suction head being a function of moisture content and pore diameter. Saturated downward movement under unity gradient is the limiting case and, taking $k_v = 10^{-4}$ m/day and $\phi = 0{\cdot}20$, actual flow rates would not exceed 0·2 m/annum. Higher k_v and ϕ (5×10^{-4} m/day and 0·25), due to weathering could increase the upper limiting flow rate to about 0·7 m/annum at shallow depths.

(C) Do mechanisms exist for the pore-space to accept an annual infiltration of up to 480 mm in 6 months at maximum rates probably exceeding 130 mm/month and 30 mm/day?

In view of the Chalk's extremely high specific retention it is assumed that high saturations, probably in excess of 98 per cent, must exist throughout most of the unsaturated profile; though this has not been confirmed. Evapotranspiration and possibly direct evaporation from the walls of fissures seem the only possible processes available to further reduce saturation. Such processes would be significant probably only to limited depth below the thin soil zone and their existence could imply significant departures from the classical evaporation model or would require re-appraisal of the root constant. Assuming an average $\phi = 0{\cdot}25$ at shallow depths, the mean saturation down to 3 m would have to be reduced to about 36 per cent (i.e. a water content (θ) of 0·09) to accommodate the above annual infiltration in that depth range. The corresponding saturation for a 300 mm infiltration would be 60 per cent ($\theta = 0{\cdot}15$). Comprehensive field saturation profiles are not available but in the limited investigations to date such low water contents have not been encountered; the saturation of the blocks obtained for pore-water sampling (including pit C (Fig. 1) excavated during moderate drought) being consistently in the range 80–90 per cent. At these saturations the top 3 m of Chalk could not accommodate much more than the first 150 mm of infiltration. Further infiltration could only be accepted into the pore-space through downward displacement, that is by some mode of piston-flow. At full saturation any excess external head at the top of the intergranular column would generate a downward-moving pressure front with rapid displacement of water at the base.

The velocity of the downward-moving pressure front will clearly vary considerably, for a given porous medium, with such factors as saturation and the distribution and state of confinement of the air phase. In the laboratory response rates in excess of 1 m/day have been demonstrated for small increases in external head at nearly full saturation and could explain in part the observed recharge response of the water-table to infiltration. However, without substantial prolonged ponding in the thin soil zone and superficial fissures, whose available storage above field capacity is in any case quite limited, the actual rate of acceptance of infiltrating rainfall by this mechanism would be more-or-less limited to that Darcy flow rate corresponding to the saturated k_v and a hydraulic gradient only marginally above unity, that is about 0·5 mm/day. This does not approach the higher infiltration rates or rainfall intensities.

(D) Why are the inclined discontinuities not more significant in the unsaturated groundwater flow regime?

It is perhaps possible that individual inclined joints are not continuous in depth and the overall flow process might be controlled by intergranular seepage between discontinuities at various levels. High suctions will certainly prevail at shallow depths if saturations are significantly reduced and the initial part of the annual infiltration would be drawn into the pores. However, if continuous joints, even of microscopic aperture, are present in depth and any near surface pore-water deficiencies have been satisfied, it remains difficult to understand why preferred-route (fissure) flow would not become rapidly established, particularly when rainfall intensities and infiltration rates are high. Overland flow or shallow lateral groundwater movement (interflow) might also be expected to develop locally over short distances in any non-fissured locations.

To summarize, no adequate explanation of the inferred slow-transit system is available and the overall regime of infiltration, evaporation and unsaturated flow in the Chalk must remain uncertain. Flow rates could be more than 5 m/hour through some fissures, less than 1 m/year through the pores or variable components of both systems.

TABLE III. OUTLINE OF CURRENT FERTILISER PRACTICE IN THE YORKSHIRE WOLDS

Month / Crop-Type	J	F	M	A	M	J	J	A	S	O	N	D
Winter Cereals				top dressing 50–100 kgN/ha (S)						seed bed approx. 20 kgN/ha (C)		
Spring Cereals			seed bed 75–100 kgN/ha (C)									
Grassland				intermittent dressings of up to 90 kgN/ha total 0–375 kgN/ha (S or C) mean 150 kgN/ha								
Potatoes				seed bed 125–190 kgN/ha(C)								
Root Crops					seed bed 75–125 kgN/ha (C)							
Peas			seed bed up to 20 kgN/ha (C)				after harvest 'haulms' are ploughed-in					

125 kgN/ha = 100 N units/acre = 1 cwtN/acre

(S) straight nitrogenous fertiliser

(C) combined N/P/K fertiliser

AGRICULTURAL PRACTICE IN THE YORKSHIRE WOLDS

Present Land-Use and Cropping Pattern

The widespread and relatively even distribution of the rising nitrate levels, together with the high organic and bacteriological quality of the affected groundwaters, appear to eliminate many possible sources of pollution and it is concluded that it must be due to some change in the land and the way that it is farmed. The uncertainty about the age of the polluted waters questions the relevance of discussion on the present land-use and cropping pattern. Nevertheless, this is a convenient starting point for looking at the overall changes in agricultural practice which have occurred over the last 30 years.

The Yorkshire Wolds are a rich agricultural region with light-textured freely-drained soils resting directly on shattered Chalk. Over wide areas the soil zone is less than 0·2 m in thickness and only in the bottom of the dry valleys does it reach 1 m and have a more clayey character.

Arable farming dominates the region and as much as 60 per cent of the land area is dedicated to cereal growing. There is very little woodland or rough pasture; only locally does such land-use exceed 10 per cent of the total and overall it may less than 5 per cent.

Barley is by far the most important crop. It is sown in March and April, with a fertiliser application of 75–100 kgN/ha as shown in Table III. This is by no means a high application rate. Many unfertilised agricultural soils contain in excess of 1000 kgN/ha in the top 0·15 m, the bulk of which is organically-combined and derives from the decay of plant residues and direct fixation from the atmosphere. In Britain mineralization of these soil reserves typically generates some 50 kgN/ha/annum and is largely associated with intense microbial activity in late spring and to a lesser extent in autumn.[5] In excess of 150 kgN/ha/annum is required for high yields of most non-leguminous crops, the greatest deficiency occurring in the lighter soils farmed with continuous or frequent cereals.

Typical fertiliser practices for other crops are also illustrated in Table III; that for grassland varies widely, even within restricted areas.

Long-term Changes in Land-Use and Fertiliser Application

A detailed consideration of three typical parishes, in the area of detailed investigation marked in Fig. 3, has been undertaken. The greatest change is the doubling of the area devoted to barley between 1955 and 1966. This increase has been achieved more by the gradual replacement of traditional crop rotations with repeated cereal growing, than by expansion of the arable acreage. Grassland has remained stable at 25–35% of the total land use. The increased barley production has been possible only through the use of fertilisers and is reflected by the increase in the application rate from 20 kgN/ha/annum in 1957 to 93 kgN/ha/annum in 1971 (Fig. 6). Unfortunately data on fertiliser application cannot readily be related to parish or crop type and application rates may vary widely. Local investigations suggest that, in the three selected parishes, the county picture is probably representative. In recent years $(NH_4)_2SO_4$-based fertilisers have been progressively replaced by NH_4NO_3-types.

The cultivation of peas and beans for processing has increased in certain areas recently, though only locally to exceed 5 per cent of the total land-use. Peas are leguminous and the crop residues (haulms) are rich in nitrogen. They are ploughed in after harvest (Table III) and have been suggested as a possible source of nitrate pollution in other areas.[6] The cultivation of the processing pea is however fairly localised in East Yorkshire and it appears unlikely to be a significant regional factor.

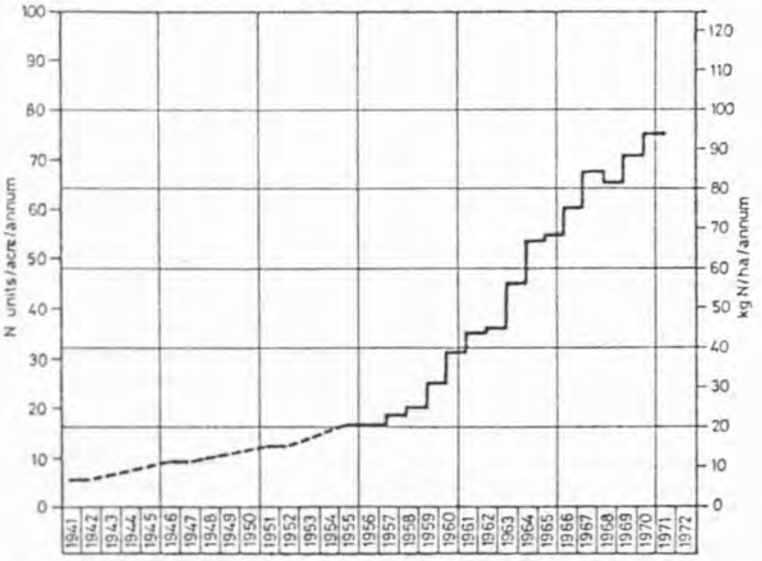

n.b. Based on data supplied by M.A.F.F. & I.C.I.

Fig. 6. Regional trend in application rates of fertiliser nitrogen to all cropped land

Overall the numbers of livestock in the Yorkshire Wolds have not shown marked consistent increases during the period 1941–72, but the character of some livestock feeding operations has changed radically. There are uncertainties about estimating the nitrogen content of animal excreta but it appears that in many parishes at least 50 kgN/ha/annum are being generated. This traditionally was returned to the land; although evaporative losses must have been high, the manure being heaped in mounds on fields to dry before autumn and then ploughed-in. The recent concentration of the animal population, particularly pigs, as a result of the development of intensive rearing units, presents a waste disposal problem especially where little land is available.

Vulnerability of Nitrogenous Fertilisers to Leaching

Among all elements nitrogen is the most commonly deficient in agricultural soils. Whatever the form in which fertiliser nitrogen is applied, in aerobic soils it is fairly rapidly transformed to the nitrate ion by biological activity.[13] The process is normally complete within a few weeks and $(NO_3)^-$ (unlike $(NH_4)^+$) is neither absorbed or precipitated in soil and thus highly mobile and readily leached. Shaw showed that 200 mm of infiltrating rainfall completely removed a fertiliser application of 134 kgN/ha from the top 0·15 m of a sandy soil; the leachate must have contained 67 mgl NO_3-N.[17]

The nitrogen cycle in fertilised soils has been a research subject in agricultural chemistry for many years. Leaching, together with other mechanisms of loss of fertiliser nitrogen have received less attention than utilisation by crops and immobilization or fixation in the soil. It is difficult to relate much of the published work on leaching losses to actual agricultural practices in given field conditions of other areas, due principally to differences in soil properties, variation and variability of weather conditions and diversity of soil management and cropping procedures. Nevertheless many important results are presented in some of the works.

Cooke & Williams[5] have summarized the many decades of lysimeter and field drainage experiments on the Chalk at Rothampsted, Herts. Significant nitrate leaching has been observed from unfertilized fallowed soils particularly when rainfall intensity exceeded 20 mm/day in the spring. Peak nitrate levels in the drainage water from plots of fertilised or manured winter-wheat (receiving 95 kgN/ha) approached 30 mgl NO_3-N, but the long-term average was 7·2 mgl NO_3-N; for 250 mm of drainage the latter would represent a loss of 18 kgN/ha. Unfertilized plots had drainage waters with an average of about 4·0 mgl NO_3-N and a three-fold reduction in crop yields. They point out that losses of nitrate from spring-sown cereals could be expected to be greater than for winter-wheat, which both reduces drainage due to spring transpiration and takes-up nitrate significantly earlier, in March or April. In contrast to arable land, drainage from Rothampsted grassland contains very little $(NO_3)^-$, even when fertilised or manured at typical rates.

Stewart *et al*[19] and Olsen *et al*[16] have used destructive core-sampling methods to study losses of nitrate from agricultural land in Colorado and Wisconsin, U.S.A. respectively. Both works illustrate the pollution potential of arable farming using fertiliser applications of 150–170 kgN/ha/annum and the latter suggests that, as a result of the slow average rate of downward movement of NO_3-N through the soil profile (0·4 m/annum), this might not be apparent in groundwater supplies for some years. A comprehensive survey of a shallow unconsolidated aquifer in the North German lowlands has shown nitrate levels consistently in excess of 20 mgl NO_3-N in the groundwater below extensive intensively-cropped tracts of arable land, contrasting to 1·0 mgl NO_3-N below areas of forest and meadow with intermediate values in areas of mixed land-use.[1]

In the Yorkshire Wolds the 75–100 kgN/ha applied on sowing spring cereals will be particularly vulnerable to leaching for perhaps 6–8 weeks until it begins to be taken-up by the growing crop in May. The long-term average infiltration is around 300 mm/annum and about 60 per cent of the total land area is now devoted to cereals; overall rates of leaching of 46 and 102 kgN/ha/annum would thus be required to raise the mean nitrate levels in groundwater to 10 and 20 mgl NO_3-N respectively. This assumes the drainage from the remaining 40 per cent of the land area, not utilized for cereal farming, to contain only 2·0 mgl NO_3-N. Any tendency for this value to be exceeded, as a result of uncontrolled slurrying on grassland for example, would further aggravate this situation.

SUMMATION AND APPRAISAL

Current Situation in East Yorkshire

It is now well-established that the Chalk groundwaters of the saturated zone in the aquifer's intake area currently have nitrate levels approaching the lower recommended WHO limit for potable supplies. At the same time most of these groundwaters appear to contain very little, if any, thermonuclear tritium and would appear by implication to be 10 years or perhaps even 20 years old; though significant hydraulic objections to this interpretation can be raised.

The Yorkshire Wolds have become an area of increasingly intensive cereal growing, with barley as the dominant crop, and it appears likely that changes in agricultural practice, in particular the increased use of nitrogenous fertiliser, are either directly or indirectly the cause of the rising nitrate levels in groundwater. It is tempting to link the steady rise in fertiliser application rates, which commenced in about 1959, with the rise in NO_3-N of the groundwater supplies in 1971. If the available evidence is interpreted to imply that the bulk of the nitrate pollution currently being experienced is of such age, it could be inferred that further increases will occur because the rate of application of nitrogenous fertilizers has more than quadrupled. Thus a most pressing question is "How much nitrate is in the water of the unsaturated zone already in passage to the water-table?" This could be answered by direct investigation, though the work may be expensive, time-consuming and be confronted with practical difficulties.

Examination of Chalk pore-water at shallow depths below fertilized arable land has already revealed nitrate concentrations in excess of 15 mgl NO_3-N and locally in excess of 30 mgl NO_3-N; in strong contrast to those below unfertilized grassland. While it has not been demonstrated that such pore-water is in motion downwards towards the water-table, the concentrations show the pollution potential of nitrogenous fertilizers as currently used in cereal growing in East Yorkshire. It arises because of the rapid conversion of fertilizer nitrogen to nitrate in the soil, the time which elapses between application and uptake by the growing crop and the fairly high probability of infiltration during this period. Other sources of pollution also could be present locally.

Implications for Water-Supply Engineering and Agriculture

While the maximum nitrate concentrations experienced to date are not critical, they give grounds for concern inasmuch as the increase might be sustained. Since most of the Chalk groundwater sources of the region could be affected, the scope for alleviating the impact of pollution by mixing is currently limited.

Rising NO_3-N levels in groundwater supplies may well prove to be a national problem; though in all cases regional trends throughout an extensive aquifer must be distinguished from local ones, which may be related to totally different origins. The mechanism of pollution will generally be difficult to determine but a fuller understanding than at present is essential if a realistic policy for future water-supply and land-use is to be formulated. Knowledge of the process of leaching of the nitrogenous fertilizer is required to suggest optimum application rates and times for the local conditions. Control over leaching might be exercised by limiting and splitting applications or by introduction of new fertilizer types, though climatic variation and unpredictability would always constitute a problem.[1]

It might be argued that nitrate pollution of groundwater is an inevitable by-product of efficient high-yield arable farming, the problem not being how to eliminate nitrates but how to live with them; eventually weighing the cost of water treatment against the value of the increased crop yield. However, there is no well proven economical method of removing nitrate from drinking water.[21] The present distribution of nitrate in the unsaturated zone and its rate of movement to the water-table could be critical in putting a time-scale on the urgency for development of techniques.

Groundwater pollution frequently can be insidious, not being recognized until aquifers are irrevocably affected; quality monitoring alone, without sound understanding of the groundwater flow regime, is often ineffective as a safeguard to water-supplies. There is also danger in linking deteriorations in water-quality somewhat casually with likely-looking sources of pollution without consideration of the hydrogeological processes operating in the vast volumes of intervening rock.

ACKNOWLEDGEMENTS

The paper is published by permission of the Director of the Institute of Geological Sciences and of the East Yorkshire (Wolds Area) Water Board. The authors were encouraged by the active interest of Mr. D. A. Gray and Mr. Harold Ackroyd, the Chief Hydrogeologist and the Engineer of the respective organizations.

People from various organisations provided important data, performed essential work or contributed valuable discussion and the following especially are acknowledged: P. W. Izzard (Chemist, Kingston-upon-Hull CBC); D. B. Smith (UKAEA, Harwell Laboratories); J. Webber (MAFF, Leeds); S. C. Wyatt (MAFF, Beverley); P. E. R. Lovelock (Institute of Geological Sciences); N. G. Bunton (DTI Laboratory of the Government Chemist); A. E. M. Hood (ICI, Jearott Hill Research Station); M. J. R. Holmes (Fisons, Levington Research Station); C. Renn (University of Hull); R. Williamson (East Yorkshire (Wolds Area) Water Board).

Local well owners/operators and farmers are thanked for their interest and co-operation.

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Journal
of
Hydrology

Elsevier Scientific Publishing Company
Amsterdam – Oxford – New York

Journal of Hydrology, 23(1974)299—311

GROUNDWATER STORAGE—RIVERFLOW RELATIONS IN A CHALK CATCHMENT

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(Received December 31, 1973; accepted January 22, 1974)

ABSTRACT

Foster, S.S.D., 1974. Groundwater storage—riverflow relations in a chalk catchment. J. Hydrol., 23: 299—311.

Data from continuously monitored observation boreholes and the permanent river gauging station in the West Beck catchment of the East Yorkshire Chalk are presented and analysed. Layered hydraulic structure in the chalk aquifer is reflected in the form of and correlation between recession characteristics. A series of fairly well defined linear storage elements, each with differing coefficients of permeability and storage, appear to be present. The distribution and variation of storage and permeability with depth may be critical factors in catchments such as this, where schemes for augmentation of drought riverflows from groundwater storage are under consideration or in pilot development.

INTRODUCTORY REMARKS

The chalk formation underlies a large area of lowland Britain and is the nation's most important aquifer. In those catchments with chalk bedrock the groundwater component of total river discharge frequently exceeds 50% and may reach 95%.

In numerous chalk catchments, current interest centres on the exploitation of sub-surface storage for augmentation of low riverflows and in artificial recharge schemes (Ineson, 1970). The former involves a degree of regulation of natural aquifer discharge through the manipulation of groundwater levels with pumping boreholes.

Precise understanding of the natural groundwater storage—riverflow relationships in chalk catchments is thus of considerable practical relevance to water resources development, particularly in relation to operating conditions in drought. Moreover, the analysis of riverflow and groundwater level data can give valuable indications of the gross hydraulic characteristics of a permeable catchment, against which the results of localised pumping test investigations can be viewed.

BASIC CONSIDERATIONS

Horton (1933) and Barnes (1939) found that the components forming a discharge hydrograph, including those derived from a groundwater system, frequently each had a recession that could be approximated by simple exponential relationships of the form:

$$Q_t = Q_0 e^{-kt} = Q_0 K^t \tag{1}$$

where Q_0 and Q_t are the discharge at the beginning of the measurement period and after time t respectively and k and K are known as recession constants. When $\log_{10}Q$ was plotted against t, a straight-line relationship thus resulted for each component, in which for one log cycle of Q:

$$k = 1/\Delta t.\log_{10}e = 1/0.43\Delta t \tag{2}$$

Clearly, in the case of the groundwater component, k will be a function of the aquifer transmissivity (T), storage coefficient (S) or specific yield (S_y), and the catchment geometry. Moreover, the total amount of groundwater storage above outlet or hydrological base-level (S_t) corresponding to a river baseflow (Q_t) will equal the total potential drainage:

$$S_t = \int_t^{\infty} Q_t \mathrm{d}t = Q_0 e^{-kt}/k \tag{3}$$

from which it follows that:

$$S_t = Q_t/k \tag{4}$$

Such a groundwater system can be termed a "linear reservoir" because its rate of natural discharge is directly proportional to its storage and storage levels. It is implicit in the Horton (1933) equation.

Using a mathematical model of simplified systems, Singh and Stall (1971) have shown that the boundary conditions to which log-linear recessions strictly relate are horizontal flow to a partially-penetrating river from a hydraulically connected large homogeneous and isotropic water-table aquifer, when variations in stream-stage are negligible in comparison to those in saturated aquifer thickness; departures occur in the case of a fully penetrating river. In practice the relationship probably holds providing hydrogeological conditions are relatively simple with one extensive, fairly uniform aquifer, negligible direct evapotranspiration of groundwater in riparian areas, absence of major groundwater development, river regulation and significant effluent discharges.

Under more heterogeneous conditions but without artificial interferences, a non-linear reservoir relationship of the form:

$$Q_t = Q_0 e^{-kt^n} \tag{5}$$

is probably appropriate, with n a variable exponent.

DATA FROM EAST YORKSHIRE CATCHMENTS

Riverflow—groundwater level recession characteristics

In the course of an analysis of riverflow data for regional hydrological study of the East Yorkshire Chalk (Foster and Milton, 1974), it became apparent that each of the recessions of the two main tributaries of the Hull river system could not be represented by any single log-linear relationship. The gauging structures on these tributaries, at Wansford Bridge (W) on West Beck and Foston Mill (F) on Foston Beck (Fig.1), are situated such that almost their entire flow (85—95%) is discharge from the undeveloped chalk aquifer. The approximate sub-surface boundaries of the respective groundwater catchments are also indicated in Fig.1.

It was also evident that the riverflow recessions could be split into a number of log-linear segments (a, b and c in Fig.2). The examination of data for other years with uninterrupted recessions corroborated this analysis. For both gauges three segments appeared to be present and in the 1962—72 data recurred in relatively closely-defined flow ranges (Table I).

The recession of groundwater levels, in the only observation borehole in the area continuously-monitored with an autographic water-level recorder (N in Fig.1), had a similar form to the riverflow recessions but included only two definite log-linear segments (x and y in Fig.2) with the trace of a third towards the end of the recession. When the riverflow data for W and F were correlated with the groundwater level data for N (Fig.3) their relationship was certainly not linear, as would be expected if the aquifer behaved as a simple linear storage reservoir. This was particularly apparent when extreme drought conditions (1964) were considered. No part of the departure from linearity could be attributed to differences between spring, summer and autumn groundwater evapotranspiration from riparian areas because their extent was far too restricted, nor to artificial interferences which were negligible.

It was apparent that a split into two linear sections, or possibly three in the case of the W—N correlation (Fig.3), was possible, the data tending to a base-level of about +15 m OD in the case of W and nearer to +16 m OD for F. Although this was perhaps stretching the interpretation, representation of a complex groundwater system by a series of linear storage elements is preferable, if at all practical. It should be noted that for the lower flow-ranges in the respective cases, the total riverflow is virtually all baseflow (i.e. chalk aquifer discharge) but at higher flows other minor components, such as surface run-off and bank storage, are also present. The position at higher flows is also complicated by minor incidents of recharge, although most of these were deliberately avoided in the choice of data analysed.

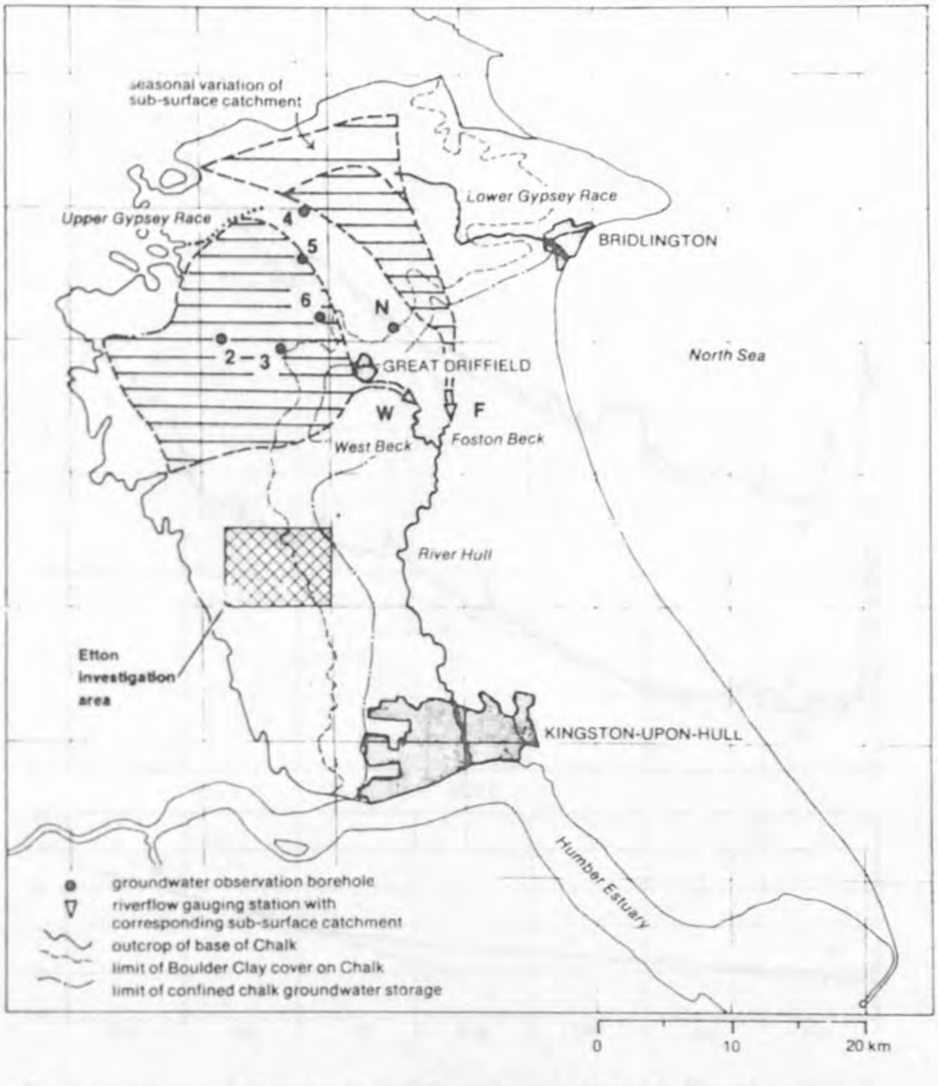

Fig.1. Location map of East Yorkshire. For explanation of symbols see text.

The Foston Beck catchment is not ideally suited to hydrological analysis because of the seasonal variability in its groundwater catchment resulting from a complex relationship with an intermittent water-table river, the Lower Gypsey Race, to the north and east (Foster and Milton, 1974). The variation in catchment area (as indicated in Fig.1) is substantial; increasing from about 50 km^2 to almost double that area, fairly early in the recession. This factor may exert some influence on the data from this gauging station for values of F in excess of about 0.7 cumecs and certainly affects those for F much above 1.0 cumecs. Hence analysis of data from this station is not pursued further.

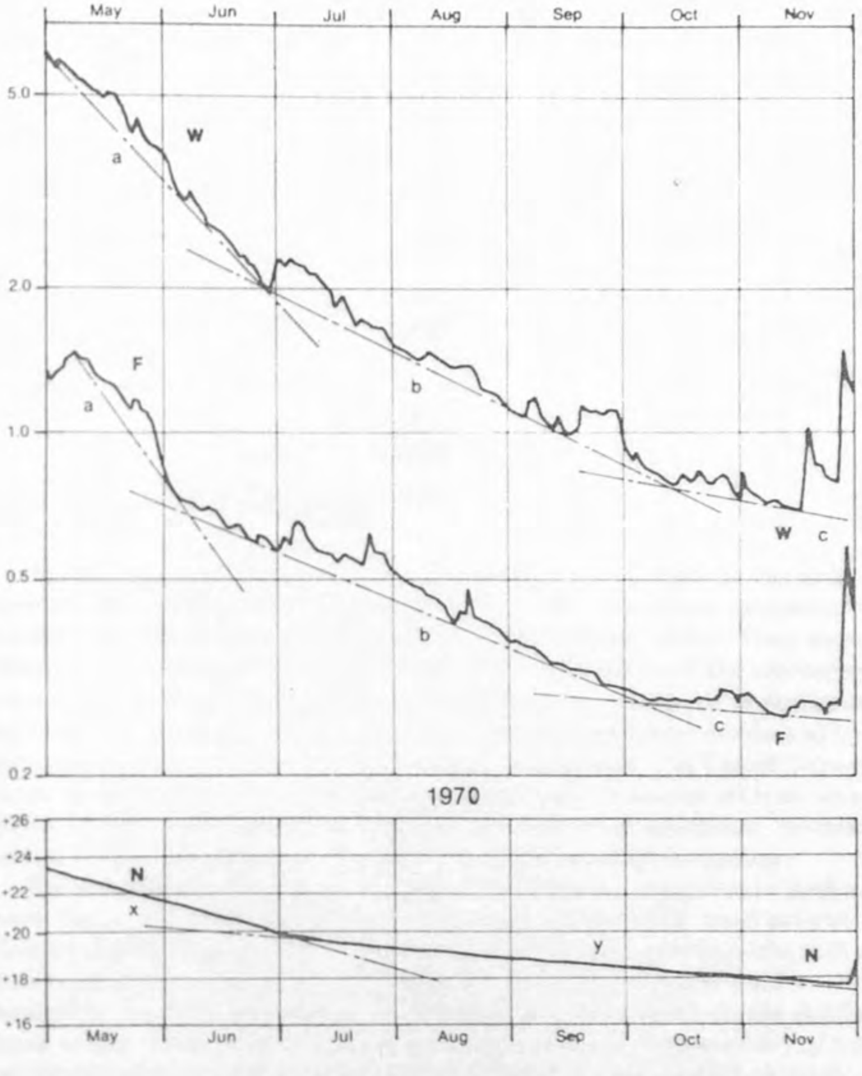

Fig. 2. Riverflow and groundwater level recession characteristics. For explanation of symbols see text.

Hydrogeology of the West Beck catchment

The bulk of the flow in West Beck originates from a group of major artesian springheads to the immediate southwest of Great Driffield; although in conditions of highest water-table the increase in groundwater pressure is not fully dissipated by increased flow at the perennial springheads, and new springs and seepage areas are initiated at higher levels.

TABLE I

Summary of riverflow recession characteristics*

Segment	Recession constant *k* (days^{-1})	
	W	*F*
a	0.020	? 0.018–0.022
Inflexion (cumecs)	1.8–2.4	? 0.5–1.0
b	0.010	0.008
Inflexion (cumecs)	0.6–0.8	0.3–0.4
c	0.004	0.003

*For explanation of symbols see text.

On the basis of groundwater level contours, the flow lines to the main springheads and thus the lateral boundaries of the subsurface catchment can be defined with tolerable accuracy (Foster and Milton, 1974). They were shown to be relatively stable seasonally. The outer limits of the catchment can also be defined fairly closely although they are somewhat complicated by complex geological structure on the northwestern water-divide and by recharge from a minor semi-perched chalk watercourse, the Upper Gypsey Race, in the north. The net result is a sub-surface catchment with an area of 235 ± 15 km^2 and a small inflow (about 0.1 cumecs at maximum, decreasing to less than 0.02 cumecs at drought) across the northern boundary.

The gauging structure itself at Wansford Bridge is a compound standing-wave flume, the rating of which is occasionally affected by weed growth. Certain minor irregularities in flow are caused by the operation of a mill and non-consumptive abstraction at a trout farm, but the effluent load is negligible. There is, however, a by-pass flow in a relief drain on the southern bank which could perhaps lead to an underestimate in excess of 5% of total catchment discharge (Foster and Milton, 1974). A small buried channel underlies the gauge but the shallow underflow can be shown from first principles to be insignificant; the deep underflow in the chalk is greater but will rarely exceed 0.05 cumecs. The export and consumptive use of chalk groundwater in the catchment is also virtually negligible at present; the equivalent of less than 0.02 cumecs.

The topography of the West Beck catchment is typical of chalk outcrop country, undulating with many dry valleys; the elevation exceeding +30 m OD throughout and reaching in excess of +150 m OD in the northwestern extremities. The outcrop is freely draining and virtually devoid of surface water except for the occasional pond.

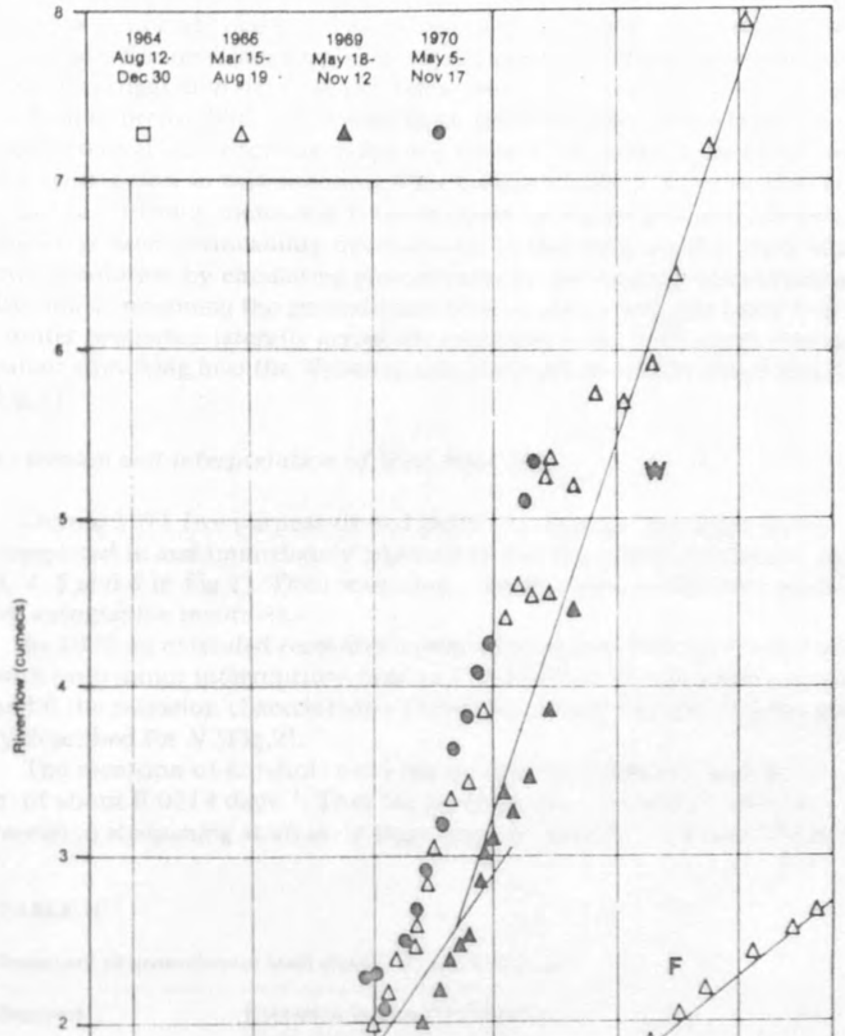

Fig.3. Chalk groundwater level—discharge rate correlation. For explanation of symbols see text.

In its saturated zone the chalk formation is a dominantly fissure-flow and essentially fissure-storage high T—low S_y aquifer. Its hydraulic behaviour has been investigated in detail in the Etton area to the south (Fig.1) (Foster and Milton, in prep.). Within the West Bank catchment the groundwater contours or equipotential lines decrease in spacing towards the major springheads despite the converging flow in this direction. This inverse situation is interpreted as indicating steadily increasing T values down hydraulic gradient towards the discharge area, permeability development in the chalk aquifer being largely due to solution by circulating groundwater on pre-existing discontinuities. By similar reasoning the groundwater level contours indicate fairly uniform aquifer properties laterally across the catchment, but with above average T values stretching into the Wetwang area (towards boreholes nos.*2* and *3* in Fig.1).

Extension and interpretation of West Beck data

During 1971 five purpose-drilled chalk observation boreholes were completed in and immediately adjacent to the West Beck catchment (nos.*2*, *3*, *4*, *5* and *6* in Fig.1). Their water-levels have subsequently been monitored by autographic recorders.

In 1972 an extended recession commenced in late-February and continued with only minor interruptions until mid-December. For boreholes nos.*2*, *3* and *6* the recession characteristics (Table II) closely resembled those previously described for N (Fig.2).

The recession of borehole no.*5* has no distinct inflexions and has an overall k of about 0.0014 days^{-1}. That for borehole no.*4* is distinct with the recession steepening at an early stage from an initially slow rate (Table II);

TABLE II

Summary of groundwater level recession characteristics*

Segment	Recession constant k (days^{-1})					
	N (1964–70)	2	3	6	5	4
		(1972 data only)				
x	0.0030	0.0020	0.0020	0.0020	approx. 0.0014	0.0007
Inflexion (m OD)	+20	+21	+20	+22		+52
y	0.0008 –0.0006	0.0004	0.0004	0.0006		0.0012

*For explanation of symbols see text.

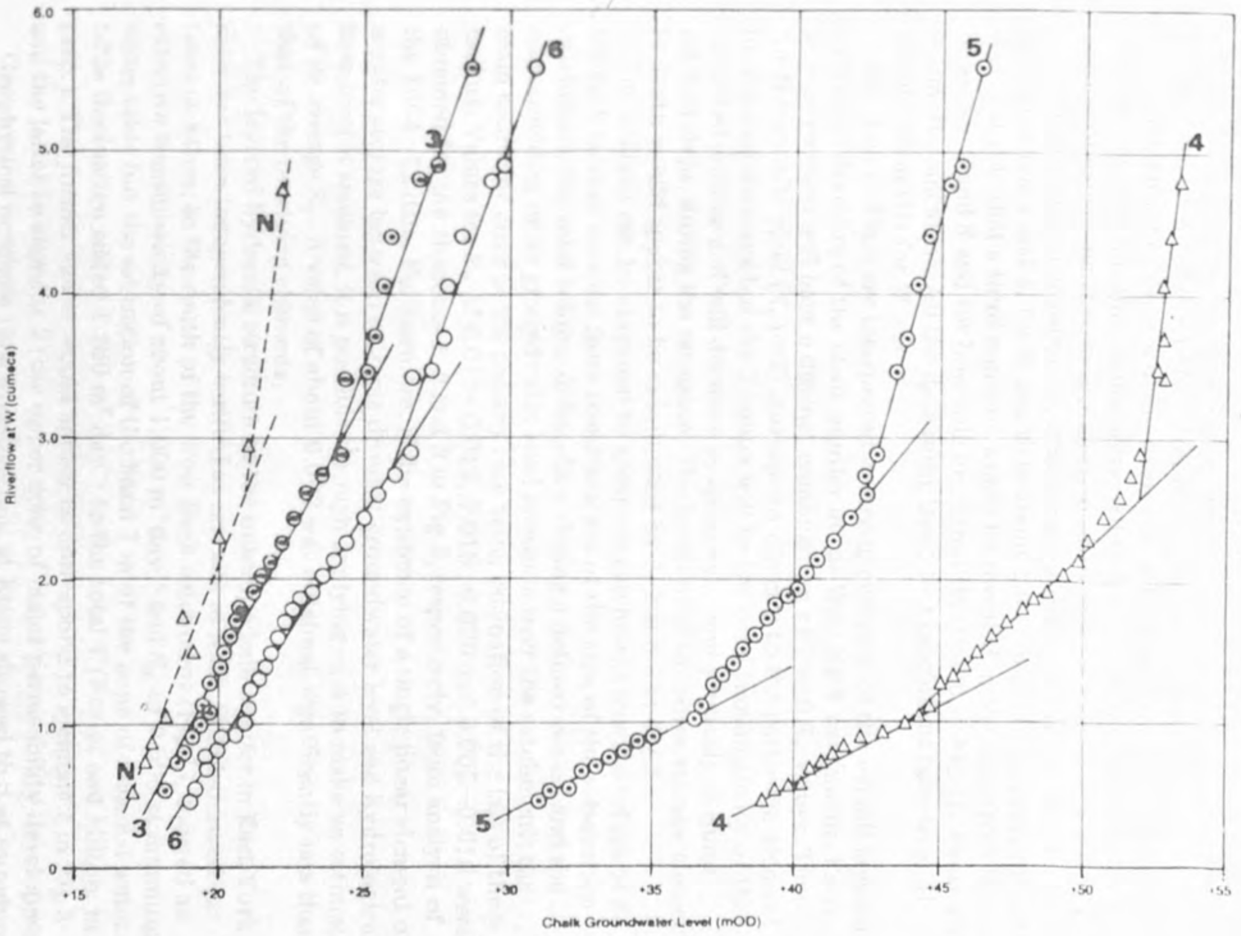

Fig.4. Groundwater level—riverflow relations for West Beck catchment during 1972 recession. For explanation of symbols see text.

this could be due to the influence of recharge from the Upper Gypsey Race or to local differences in aquifer properties.

The correlation of the 1972 water-level data from the new observation boreholes with the corresponding riverflow at *W* (Fig.4) corroborates and considerably extends the results presented in Fig.3. The separation into two linear storage elements corresponding to flows at *W* of greater and less than 2.5—3.0 cumecs is consistent. A third element is present in the data from boreholes nos.*4* and *5*, for *W* less than about 1.0 cumecs. In extreme drought it is probable that a third segment would be revealed in the data from boreholes nos.*3* and *6* and for borehole no.*2* (not illustrated in Fig.4), whose plot is almost coincident. All the data must trend to a catchment base-level of about +15 m OD for $W = 0$.

The data in Fig.4 are interpreted as strong evidence of the overall layered hydraulic structure of the chalk aquifer in the West Beck catchment. Each storage element will have a distinct combination of T and S_y values. Those for the specific yield (S_y) will correspond directly to the particular element undergoing drainage but the T values will be the total transmissivity of the saturated aquifer and will decrease progressively, and probably in quite marked steps, during the recession. The location of the three storage elements in depth would appear to be as indicated by *1*, *2* and *3* in Fig.5.

The analysis can be extended to compute catchment average values of S_y for each storage element from consideration of the area of the sub-surface catchment, the total volume of baseflow during a defined period and the corresponding mean groundwater level recession over the catchment; the main source of error in the present case being estimation of the last of these factors. Values for S_y of 0.010—0.015, 0.015—0.020 and 0.005—0.010 were obtained for the elements *1*, *2* and *3* in Fig.5, respectively, from analysis of the 1964—72 data. Furthermore, if the existence of a single linear element of aquifer storage between extreme drought groundwater level and hydrological base-level is assumed, it is possible through applying eq.4 to make an estimate of its average S_y. A value of about 0.002 was obtained, significantly less than that of the overlying elements.

The layered hydraulic structure of the outcrop chalk aquifer in East Yorkshire has been independently verified at one site at least. Detailed investigations at Etton, to the south of the West Beck catchment (Fig.1), showed an effective transmissivity of about 1,000 $m^2\,day^{-1}$ and S_y of 0.005 at minimum water-table but the saturation of the basal 7 m of the zone of seasonal water-table fluctuation added 1,200 $m^2\,day^{-1}$ to the total T (Foster and Milton, in prep.). The former values would appear to correspond to element *1* in Fig.5 and the latter to element *2* (the upper zone of major permeability development).

Geophysical borehole flow investigations at Etton showed that at minimum water-table the bulk of the flow and the total T was contributed by an 8 m thick layer with its base at around −20 m OD; there appeared to be negligible groundwater flow (and presumably restricted storage) below about −30 m OD. This factor together with the exceptionally high permeability of the chalk in

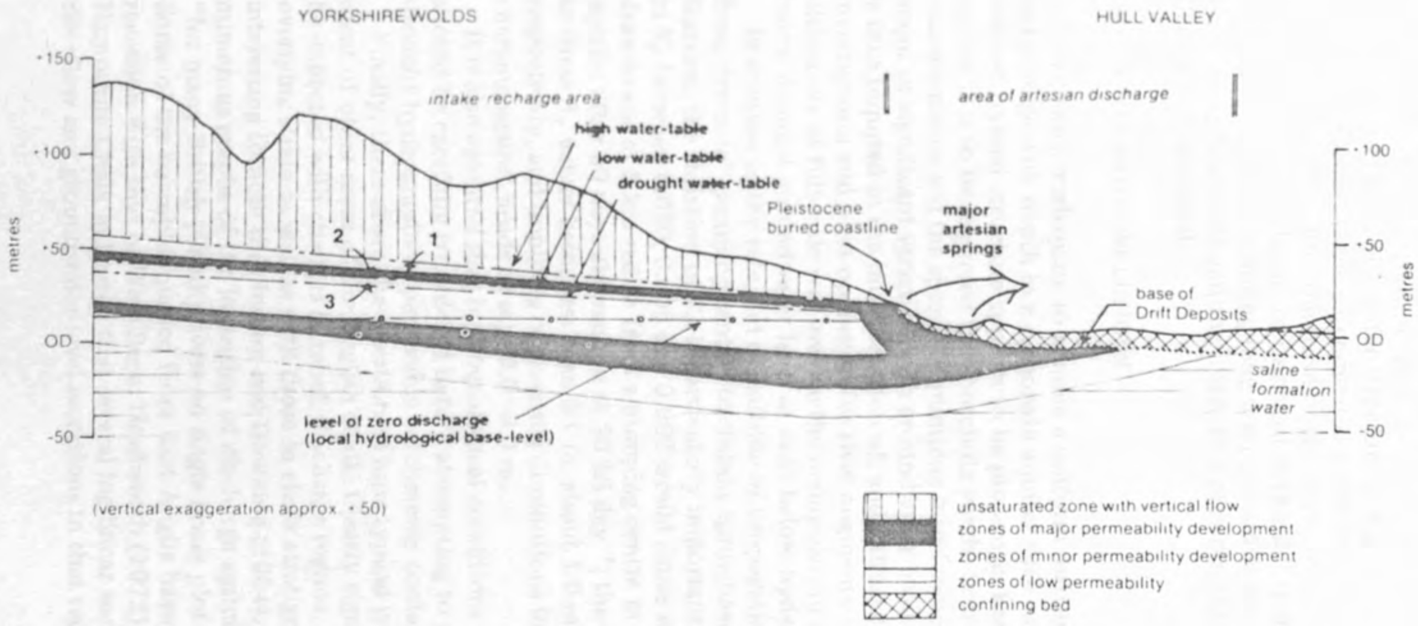

Fig.5. Schematic interpretation of the hydraulic structure of the chalk aquifer in East Yorkshire. For explanation of symbols see text.

the vicinity of the Pleistocene buried coastline along the perimeter of the Hull valley, proven at Haisthorpe (Foster and Milton, 1974), have been used in the interpretation of aquifer structure in Fig.5; uniformity perpendicular to this section across the catchment and throughout the East Yorkshire dip slope being reflected by the form of groundwater level recessions throughout the region. The two layers of principal permeability development may be attributed to solution during long-term groundwater circulation, the upper to the existing base-level and the lower to a previous much lower and probably Pleistocene base-level.

DISCUSSION AND CONCLUSIONS

It is clearly inadequate to assume a uniform distribution of permeability and storage with depth in a carbonate aquifer such as the chalk. A fairly well-defined layered structure appears to be present in East Yorkshire. In such an aquifer it is to be *expected* that borehole yields, borehole yield-drawdown characteristics and the spread of pumping interference effects will show major or significant variation with groundwater level. Considerable caution is thus required in the interpretation of, and extrapolation from preliminary investigation and pilot operation for river augmentation schemes, which ultimately at full-scale will involve the manipulation of aquifer storage located below drought groundwater level or even below hydrological base-level.

In relation to the rate and magnitude of propagation of interference effects from "remote" pumping centres to distant springheads and surface-water features, the variation of S_y is particularly important. For example, variation in S_y between 0.020, 0.005 and 0.002 would cause marked differences in the drawdowns at 5 km radius from a pumping centre in a $T = 1{,}000\ \mathrm{m^2\ day^{-1}}$ aquifer after 50 days abstraction at 20 Ml day^{-1}; the drawdowns corresponding to these S_y values being less than 0.1 m, about 1.0 m and in excess of 2.0 m, respectively, and implying contrasting diminutions in flow of springs discharging against heads of say, 0.5—3.0 m.

It is also *essential* that hydrogeological conditions and aquifer properties should be carefully considered before attempting to synthesise or extrapolate drought hydrographs in permeable catchments containing this class of aquifer.

Finally, there arises the question of how typical is the West Beck catchment of other areas of the English chalk. Clearly significant variations are to be expected with changes in relief, discharge regime, geological structure and overlying strata as well as with those in chalk stratigraphy. It is, however, interesting to note that Ineson and Downing (1964), after examining numerous graphs of the logarithm of discharge against time, suggested that "for many British (Chalk) rivers no single linear plot can be constructed". Some of the examples quoted from East Anglia have a comparable form of recession with that of West Beck. Headworth (1972) in a study of the Hampshire Chalk indicated that several log-linear sections are present in some riverflow and groundwater-level recessions in that region also.

ACKNOWLEDGEMENTS

The Yorkshire River Authority and the East Yorkshire (Wolds Area) Water Board initiated or collaborated with the Institute of Geological Sciences in the collection of the basic data presented.

The work is published by permission of the Director of the Institute of Geological Sciences and with the support of its Chief Hydrogeologist, Mr. D.A. Gray. Mr. K.H. Tattersall of the Yorkshire River Authority is thanked for his comments and Mrs. V.A. Milton for her assistance.

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INTERNATIONAL ASSOCIATION OF HYDROLOGICAL SCIENCES
ASSOCIATION INTERNATIONALE DES SCIENCES HYDROLOGIQUES

HYDROLOGICAL SCIENCES BULLETIN

DES SCIENCES HYDROLOGIQUES

No. 4
Volume 19
December 1974

Editor: JOHN C. RODDA, Water Data Unit, Reading RG1 8PS, UK

Hydrological Sciences — Bulletin — des Sciences Hydrologiques, XIX, 4 12/1974

THE PERMEABILITY AND STORAGE OF AN UNCONFINED CHALK AQUIFER

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MS. received 12 March 1974

ABSTRACT

In its saturated zone the Chalk, the most important British aquifer, is a dominantly fissure-flow and essentially fissure-storage formation. This paper evaluates the results of a comprehensive investigation into its hydraulic behaviour in an area of some 40 km^2 of the East Yorkshire outcrop. The hydraulics of idealized fissures are used to extend the interpretation. No strong lateral anisotropy of hydraulic properties is apparent in this area but vertical heterogeneity is very marked, with the main permeability development probably being along horizontal discontinuities in two layers of restricted thickness.

RÉSUMÉ

Dans la zone saturée de la Craie, la plus importante nappe du Royaume-Uni, l'écoulement souterraine se rencontre surtout dans les fissures, et les ressources en eau s'y contiennent aussi. Dans ce rapport on évalue les résultats d'une investigation étendue du régime hydrodynamique de la Craie dans une région de 40 km^2 de l'affleurement de l'est de Yorkshire. Pour étendre l'interprétation on fait usage de l'hydrodynamique théorique de fissures idéalisées. Dans cette zone il n'y a pas de grande anisotropie latérale des caractéristiques hydrauliques, mais une hétérogénéité verticale est bien évidente, et selon toute apparence le principal développement de perméabilité se trouve le long de discontinuités horizontales dans deux couches d'épaisseur limitée.

INTRODUCTION

Background

Since the work of Ineson (1959, 1962) there have been few publications on the hydraulic behaviour of the saturated zone in the Chalk. The Chalk Aquifer underlies a large area of lowland Britain and accounts for some 15 per cent of the national water supply. In those catchments of southern and eastern England with Chalk bedrock, the groundwater component of total river discharge frequently exceeds 50 per cent, and may reach 90 per cent. Current interest centres on the possibility of augmenting low river flows by pumping from groundwater storage; the design of such river regulation schemes requires a more precise knowledge of aquifer hydraulics than has been needed previously. This knowledge is also of relevance in predicting the movement of pollutants and in the design of deep excavations.

Ineson's work on Chalk permeability was based essentially on a statistical approach to record data for pumping boreholes. Such data may be of indifferent quality and inadequate for interpretation of aquifer confinement parameters, hydraulic boundaries and distribution of permeability and storage with depth. Of the subsequent research, that of most practical value has been the use of geophysical investigations of pumping boreholes (Tate *et al.*, 1970) to determine the levels of groundwater inflow. A disadvantage of this technique, when used in isolation, is that it is often difficult to distinguish essentially borehole conditions or processes from those in the aquifer itself.

The most direct method for investigation of groundwater hydraulics is the pumping test but reliable interpretation in a formation like the Chalk requires sound knowledge of local hydrogeological conditions, adequate observation borehole control and supporting data from other investigations. An opportunity to conduct comprehensive testing came in 1970 with the proposal to develop further groundwater production from the Etton area of the East Yorkshire Chalk (Fig. 1).

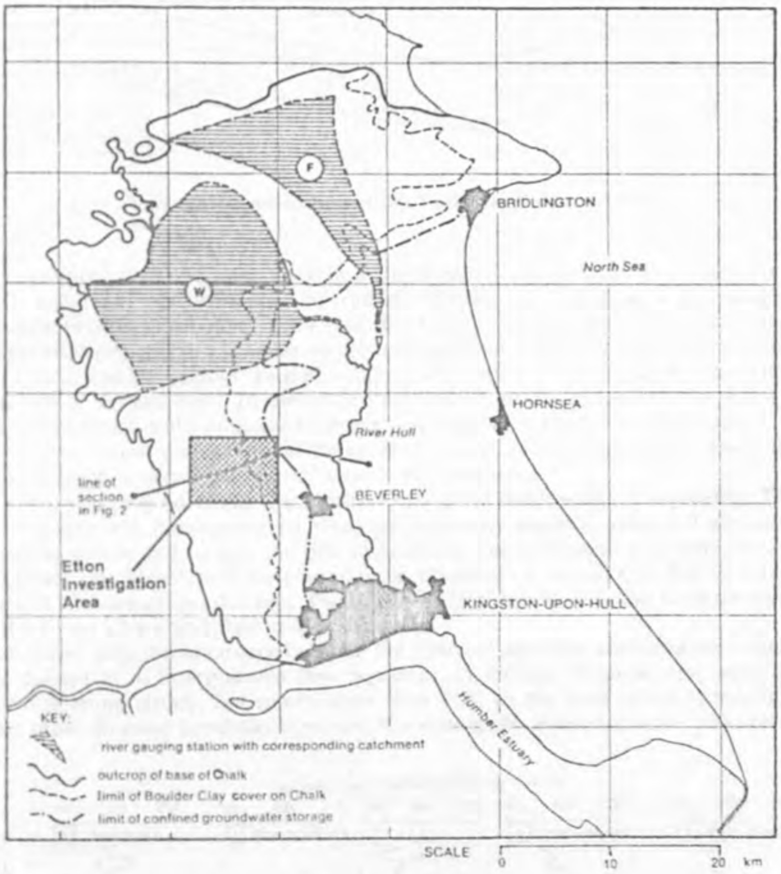


Fig. 1 — Location map of east Yorkshire.

Geohydrological Setting of the Etton Area

The Etton area is fairly typical of Chalk dip slopes and has a simple geological structure; the dip rarely approaches 5° and no tectonic disturbances are known (Fig. 2). During the deposition of the underlying Jurassic strata, structural controls dominated but only some mild influences appear to have persisted into the Chalk.

The Middle/Upper Chalk, which is the primary concern, comprises a highly-uniform, exceedingly fine-grained sequence of pure white limestones broken only occasionally by primary marls, which rarely exceed 50 mm in thickness. More frequent breaks in the sequence are associated with secondary features, particularly the ubiquitous stylolites with their associated marl seams and the flint bands. Laboratory tests on core samples of the Chalk show extremely low intergranular permeability ($<10^{-3}$ m/day), despite moderate porosity (0·14–0·20).

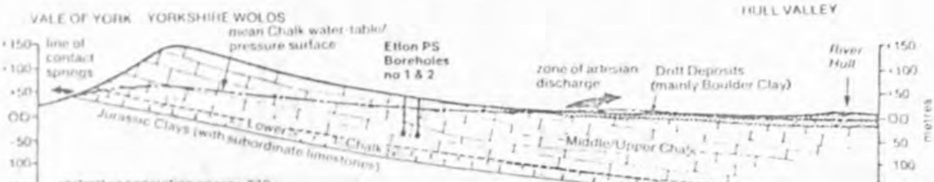


Fig. 2 — Generalized cross-section of the Yorkshire Wolds in the Etton area.

In its saturated zone the East Yorkshire Chalk must constitute an essentially fissure-flow aquifer; the same may not necessarily be true of infiltration and vertical flow through the unsaturated zone (Foster and Crease, 1974) but this topic is outside the scope of this paper. The saturated permeability will be a function of the configuration of the physical discontinuities of the rock mass (joints and less regular fissures, solution openings, fractures and cavities) with respect to the external or applied head. In the limited number of quarry exposures, the major inclined joints are normally of multi-directional aspect and high density (0·7–1·3 per metre), with the frequency of horizontal discontinuities being in the range 0·6–3·6 per metre. Their degree of persistence in depth however cannot be stated with confidence.

The Etton pumping boreholes are located in a typical shallow minor dry-valley. The stratigraphy of the site was investigated by electrical resistivity logging, using a 3 electrode 1·5 m inverse spacing considered to give the best measure of true formation resistivity (Gray, 1965). Certain features capable of local correlation were identified (*A*, *B* and *C* in Fig. 3) and indicate a dip of about 2° more-or-less due east. The resistivity logs are also a useful basis for comparison between the Etton Chalk and that in other areas.

In the Etton area the boundary between the zones of aeration and saturation seems to be as clearly defined as in intergranular-flow aquifers; on drilling boreholes the water generally rises after first being struck, but rarely more than 1 m, to the level of an apparently simple local water table. In most boreholes however, barometrically-generated water level fluctuations

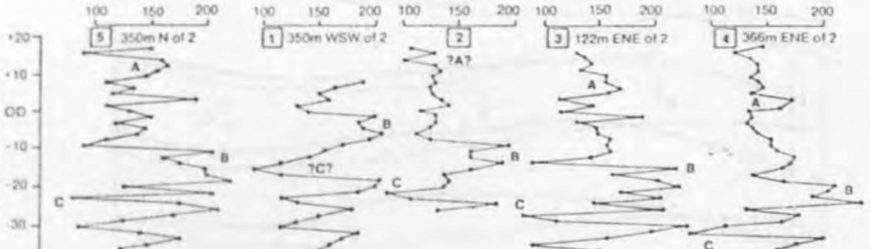


Fig. 3 — Electrical resistivity logs of the Etton boreholes.

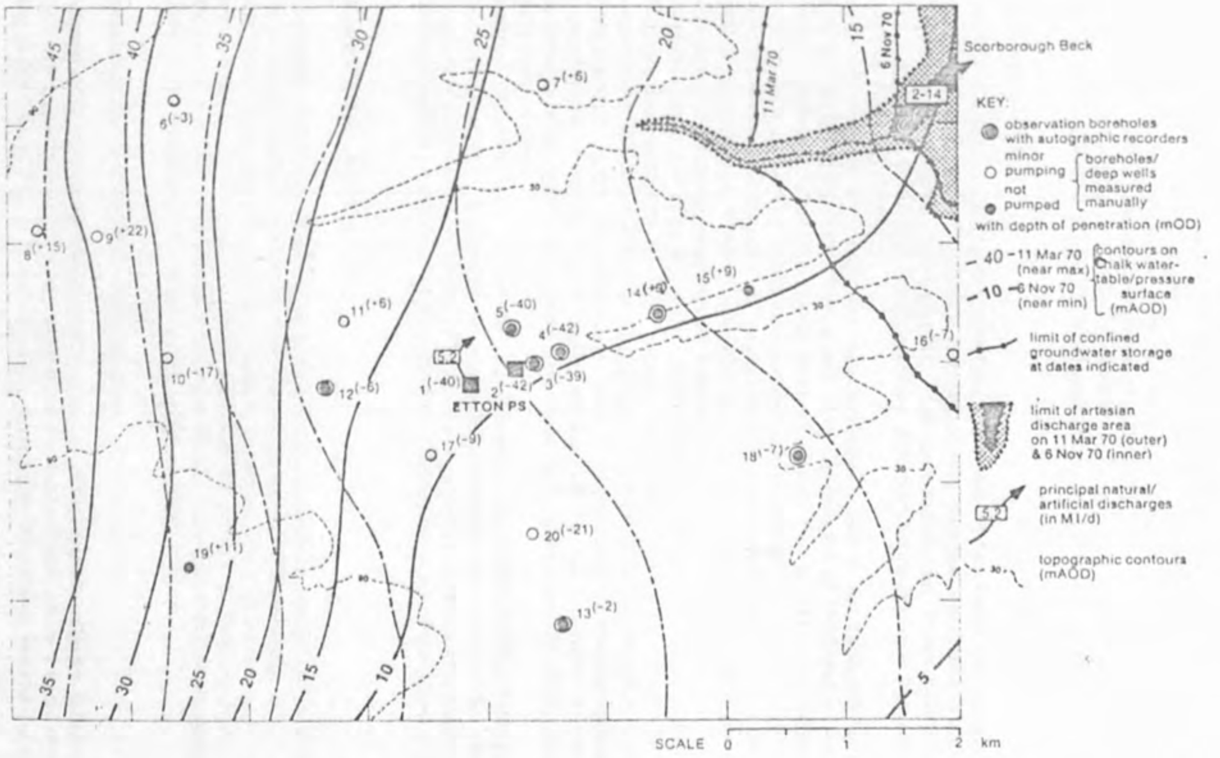


Fig. 4 — The Etton area borehole locations and groundwater level contours.

appear to occur, particularly during the rising limb of the groundwater hydrograph when the barometric efficiency may exceed 0·05.

The regional hydrological regime is determined by the geological structure (Fig. 2) and involves rainfall recharge to the water table throughout an outcrop area devoid of surface drainage with sub-surface flow towards the lower lying areas, primarily the Hull Valley. In the groundwater level contour data for 1970 (Fig. 4), and those of all available previous years, the hydraulic gradient at peak levels was eastnortheast towards the natural discharge area. During the annual recession (normally in July or August) the gradient swings around to the southeast as a result of heavy groundwater abstraction in the Beverley–Hull area. The most extreme hydrological conditions experienced in the last decade correspond to water table levels of +9 and +32 m OD at the Etton site, in March 1965 and February 1966 respectively.

The Scope of the Investigations

Within a radius of 4 km of the Etton production boreholes, 15 boreholes were available for water level measurement (Fig. 4) and these had been monitored monthly since 1962. To promote research into the hydraulic response of the aquifer, three narrow-diameter observation boreholes were drilled and completed to similar depth at short distances from the new large-diameter production borehole (No. 2 in Fig. 4).

This exceptional network was used for data collection during the comprehensive test pumping of both production boreholes (Nos. 1 and 2) in the autumn of 1970 under near minimum hydrological conditions (site rest water level of about +11 m OD). The observation borehole response to four periods of carefully-regulated abstraction or recovery in one or other of the production boreholes was determined, using steady pumping rates in the range 50–90 l./s for time intervals of up to 9 days. A combined yield test at a rate of 155 l./s was then carried out over 12 days. During test pumping, geophysical flow investigations were simultaneously undertaken using boreholes Nos. 1–5 (Fig. 4); some preparatory work had been done in July 1970.

It was necessary for continuity of water supply to continue abstraction from the No. 1 borehole throughout the test programme in the autumn of 1970. This complication was overcome by adopting a steady, moderate pumping rate (60 l./s) 14 days prior to commencement and sustaining it through most of the period of aquifer testing. All the water pumped was put into supply and the considerable expense of piping this water to a hydrologically-satisfactory discharge point was thus avoided.

A second phase of testing was carried out with a higher water table (+18 m OD) in April 1971; this was more limited in scope due to operating considerations and rapidly changing groundwater stage. It was based on the recovery from steady pumping at 90 l./s and recommencement at 120 l./s from the No. 1 borehole, using the No. 2 borehole as an observation well.

ANALYSIS OF PUMPING TEST RESULTS

Perhaps the more important function of a good hydrogeological pumping test is that of providing evidence on the general hydraulic response of the aquifer, its confinement and boundary parameters rather than that of obtaining accurate transmissivity (T) values. Certainly the former is more critical in predicting long-term response to pumping. Heterogeneity was a particular question in the case of the East Yorkshire Chalk, hearsay evidence suggested that groundwater flow might be largely restricted within a few random fissures.

Hydraulic Responses in the Autumn 1970 Pumping Test

The non-steady state drawdown and recovery (s) in the observation boreholes, following the onset or shut down of a constant rate (Q) of pumping in the test borehole, show a basic regularity and consistency in form (e.g. Fig. 5 A and B), after correction for various interfering factors.

These include the continuously-receding groundwater stage (falling at a rate of about 0·03 m/day) and the effects of previous pumping regimes but both are only significant for $t > 2500$ min or so (Fig. 5 A and B). In Fig. 6, comparable data for s and t have been plotted in a unified form to

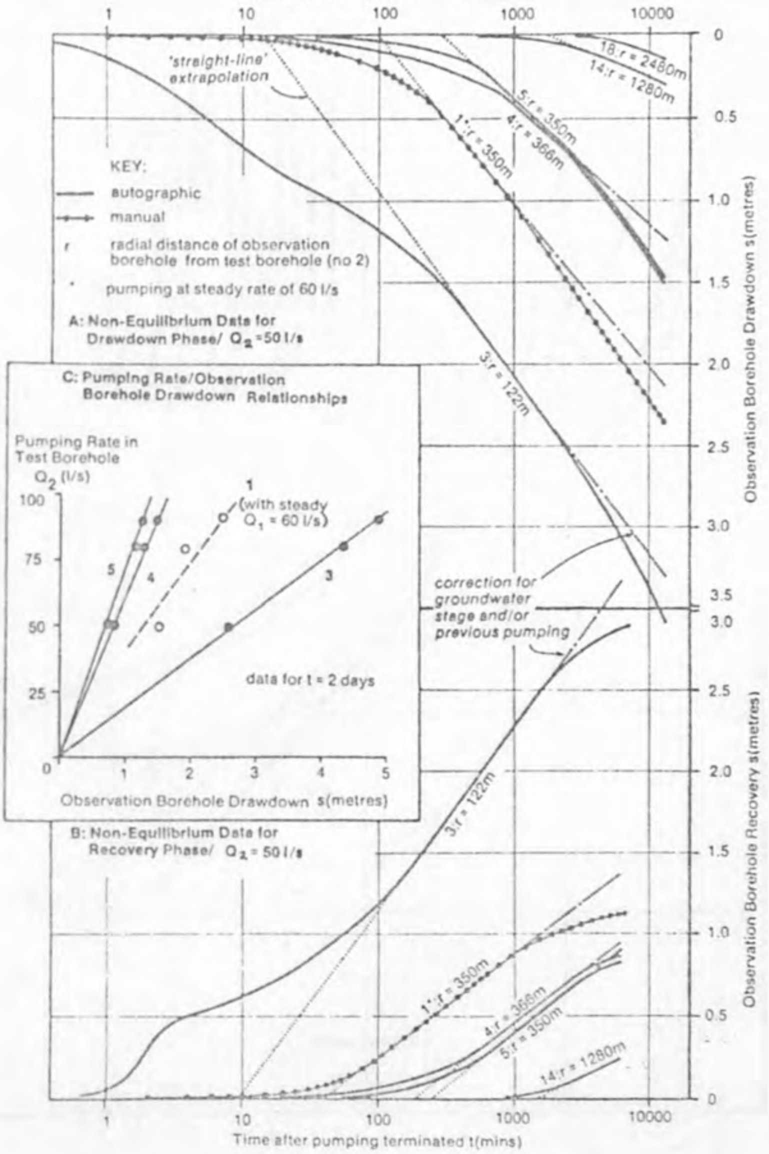


Fig. 5 — Observation borehole data from the autumn 1970 pumping test.

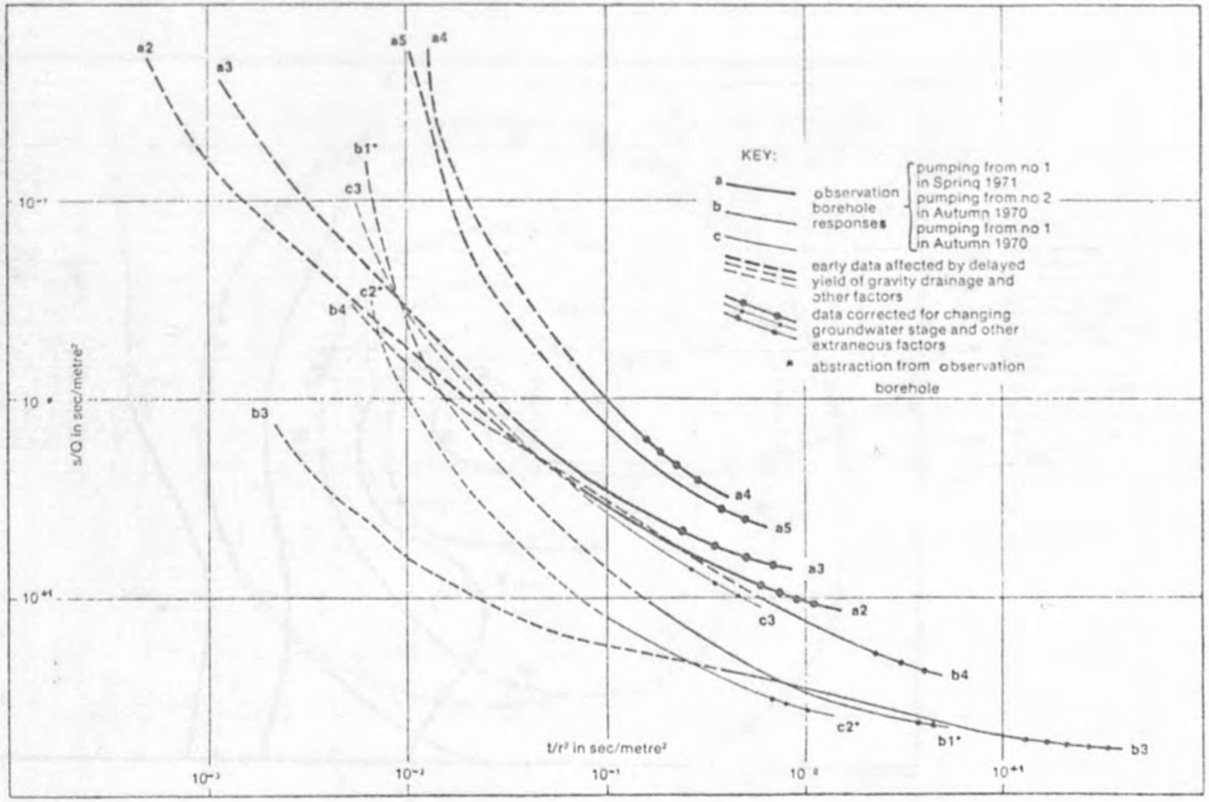


Fig. 6 — Comparative plot of time–drawdown data from autumn 1970 and spring 1971 pumping tests.

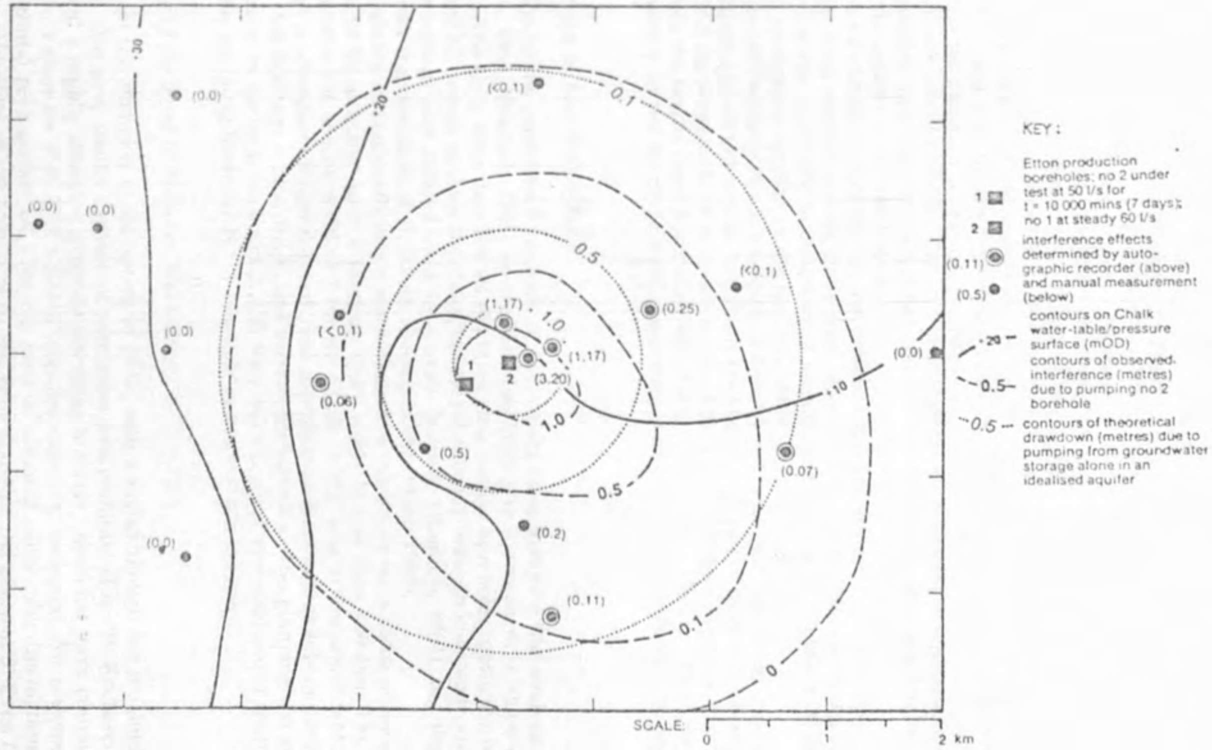


Fig. 7 — Pumping interference effects during the autumn 1970 test.

allow direct comparison of the differing aquifer responses at individual observation boreholes in the same test, and for the entire group of observation boreholes in tests at different times.

Before proceeding with any analysis it is necessary to consider the relationship between Q and s for the inner observation boreholes. This is strictly linear in all cases (Fig. 5C), confirming laminar flow at the corresponding distances from the point of abstraction under the hydraulic gradients associated with pumping rates of up to 90 l./s; an important point since it establishes that conventional groundwater hydraulics and pumping test analysis may be applied. This is not always the case in the Chalk; non-laminar flow conditions have been reported up to 260 m from a well in Hertfordshire when pumping was at 120 l./s (Ineson, 1957).

No major lateral hydraulic boundaries appear to be present in the cone of pumping depression. The general similarity in the magnitude and rate of drawdown in boreholes Nos. 4 and 5 (Fig. 5 A and B) is such as to suggest no strong lateral anisotropy in hydraulic properties, related to jointing and/or the direction of dry valleys; the reason for the differing initial response in these boreholes is not understood however. The interference effects in the distant observation boreholes (e.g. Fig. 7), resulting from the various regimes of test pumping, confirm the considerable overall uniformity of the aquifer in a lateral sense.

No observation borehole equilibrium was achieved during testing, even at a pumping rate of 50 l./s, but after long periods of time there were signs of a fall off in the rate of depletion of storage, reflecting the increasing interception of aquifer throughflow. Such effects tend to be masked by the corrections applied to the late time data.

The response of borehole No. 1, pumping at a steady rate with near equilibrium water level, to the test pumping regime in borehole No. 2 was anomalous; the rate of drawdown being somewhat greater and the magnitude of drawdown considerably greater than would be expected by comparison with the results from boreholes Nos. 4 and 5 (Fig. 5A). This can be explained by decreased efficiency in the borehole itself, associated with the further reduction in saturated thickness.

Aquifer Properties at Low Water-Table

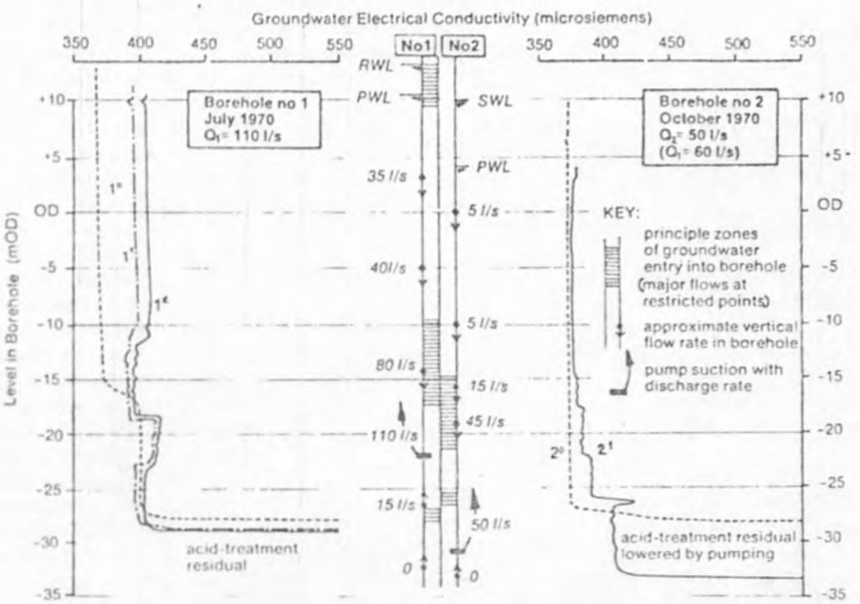
Application of the established methods of non-steady state pumping test analysis (Theis, 1935; Boulton, 1963; Prickett, 1965) on the late time data give a consistent T value of 1000 ± 300 m^2/day. The early time data for all the inner observation boreholes, particularly No. 3 (Figs. 5 A, B and 6), appear to show the characteristic relationship between instantaneous release from pressure storage and delayed yield by gravity drainage (Boulton, 1963), but this could result from other combinations of hydraulic properties (Stallman, 1965).

The analysis for storage coefficient is somewhat more subjective but a value of the order of 0·005 appears to be indicated with a Boulton delay index of less than 100 min. The former probably represents the specific yield (S_y) for the Chalk in this area at low water table, but it is possible that a subsequent longer delayed yield contribution from microjoints or pores might be present or that drainage is retarded by low vertical permeability. The pumping test values of S_y relate to levels in the rock mass which will have been drained and resaturated many times during previous pumping from the No. 1 borehole in its production regime.

Transmissivity of the Zone of Seasonal Fluctuation

Subsequent test pumping in the spring of 1971, with a higher though not maximum level of saturation, also gave results capable of consistent interpretation (Fig. 6). Recharge of the water table and a rapidly changing groundwater stage however, presented some complications in the analysis. Values for T of 2200 ± 500 m^2/day are definitely indicated. An extremely high value of horizontal permeability (K_x) for the zone of seasonal water table fluctuation is thus suggested; the saturation of the basal 7 m of this zone doubling the effective T. Even higher T values are to be expected for a higher water table, but the increases would probably not be of similar proportion.

A: Groundwater Flow Regime in the Etton Production Boreholes



B: Changes in Groundwater Temperature Profiles during Autumn 1970 Pumping Test

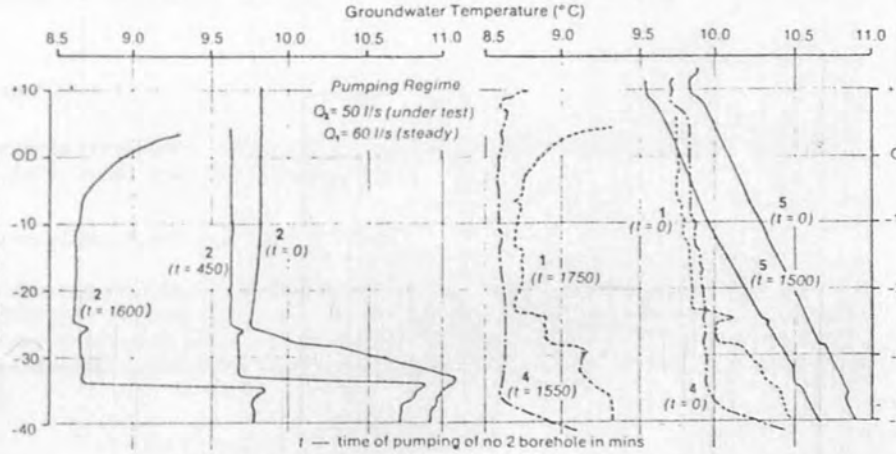


Fig. 8 — Selected results of geophysical borehole flow investigations.

Geophysical Investigation of Borehole Flow

In fissure-flow aquifers it is not sufficient to know only the magnitude of fissure T; the three-dimensional distribution of permeability which it represents is also required. The level and thickness of main permeability development is more important than the overall saturated thickness, since it directly relates to the heads that can be utilized in groundwater abstraction and therefore the behaviour of individual boreholes. Geophysical flow investigations (Tate *et al.*, 1970) aimed at determining this distribution were carried out in July 1970 and during the main pumping test in the autumn of 1970.

Differential electrical conductivity (Fig. 8A) and temperature logging showed the levels of groundwater entry into the Etton pumping boreholes to be restricted. Approximate vertical flow rates in the boreholes were estimated from impeller flowmeter and tracer injection detection techniques (Fig. 8A). These results must be treated with some reservation in respect of absolute accuracy because of the variable cross-sectional area of the boreholes together with the existence of eddies around certain plant and opposite some levels of entry.

In October 1970 at near minimum water levels, the bulk of the water pumped from the No. 2 borehole was derived from a 7-m-thick zone whose base was located at about −22 m OD (Fig. 8A). Investigations in the No. 1 borehole in July 1970 with a somewhat higher water table, had given similar results but with the base of the corresponding zone of permeability development at about −17 m OD and more than 30 per cent of the total discharge being derived near or above the pumping water-level (Fig. 8A). The existence of marked chloride residuals in both boreholes (the products of earlier acid treatment) suggest minimal groundwater movement from about −29 m OD to the base of the boreholes and probably below this level.

Sequences of temperature logs at the start of test pumping from No. 2 borehole showed a systematic response with cooling of the groundwater in all of the other boreholes at the Etton site (Fig. 8B); compelling evidence of their hydraulic intercommunication. One significant anomaly arises however. The temperature logs for borehole No. 5, sited on the interfluve of the minor dry valley at the site, show more positive temperature gradient and smaller response than the other boreholes. The most reasonable interpretation is that less groundwater movement occurs in this direction, though this is not compatible with the observation borehole drawdown data. Some anomalies may also be ascribed to the fact that the observation boreholes (Nos. 3, 4 and 5) were constructed only shortly before the autumn 1970 pumping test.

NATURE OF CHALK PERMEABILITY AND STORAGE

In order to extend the interpretation of Chalk permeability and storage it is of relevance to consider the hydraulic properties of idealized fissure systems.

Permeability of Idealized Fissured Media

The theoretical hydraulics of fluid flow in fractured media (Serafim and del Campo, 1965; Snow, 1969) develop from classical Navier-Stokes and Hele-Shaw parallel-plate hydraulics, in which the velocity distribution (v), for laminar steady-state flow of a viscous incompressible fluid in an idealized semi-infinite smooth parallel-walled opening of aperture b, is shown to be parabolic:

$$v = -\frac{1}{2\mu} \cdot \frac{\mathrm{d}p}{\mathrm{d}x} \cdot (bz - z^2) \qquad (1)$$

where $\mathrm{d}p/\mathrm{d}x$ is the pressure gradient in the plane of the opening and μ is the dynamic viscosity of the fluid. Now $v_{\max}$ occurs when $z = b/2$ and the mean velocity (V) is $2v_{\max}/3$ thus

$$V = -\frac{b^2}{12\mu} \cdot \frac{dp}{dx} \qquad (2$$

From whence the discharge (Q) from a parallel series of such fissures over a width W_y in the direction of the plane of opening and perpendicular to that of the flow (x) is given by

$$Q = \frac{\gamma}{12\mu} \cdot I_x W_y \cdot \Sigma b^3 = \frac{g}{12\upsilon} \cdot I_x W_y \cdot \Sigma b^3 \qquad (3$$

where γ and υ are the specific weight and kinematic viscosity of the fluid respectively and I the hydraulic gradient or component of the hydraulic gradient in the plane of the opening. Fron (3) it can be seen that the equivalent transmissivity (T_x) of such a system is

$$T_x = \frac{g}{12\upsilon} \cdot \Sigma b^3 = 54\, \Sigma b^3 \text{ m}^2/\text{day} \qquad (4)$$

taking $\upsilon = 1{\cdot}3 \times 10^{-6}$ m^2/s for groundwater at 10°C and with b in millimetres.

The importance assumed by relatively minor changes in b, due to solution or variations i fluid pressure for example, should be noted. Just one fissure of 5 mm effective opening in the plane of the hydraulic gradient would contribute over 6000 m^2/day to the T of an aquifer: giving an idea of the order of heterogeneity and anisotropy that its presence would introduce. In this context the relatively isotropic radial response of the Chalk at Etton accompanied b its high T, probably indicate that development of solution permeability is concentrated alon horizontal discontinuities. In the presence of a high density of multi-directional inclined jointing, this explanation is not unique.

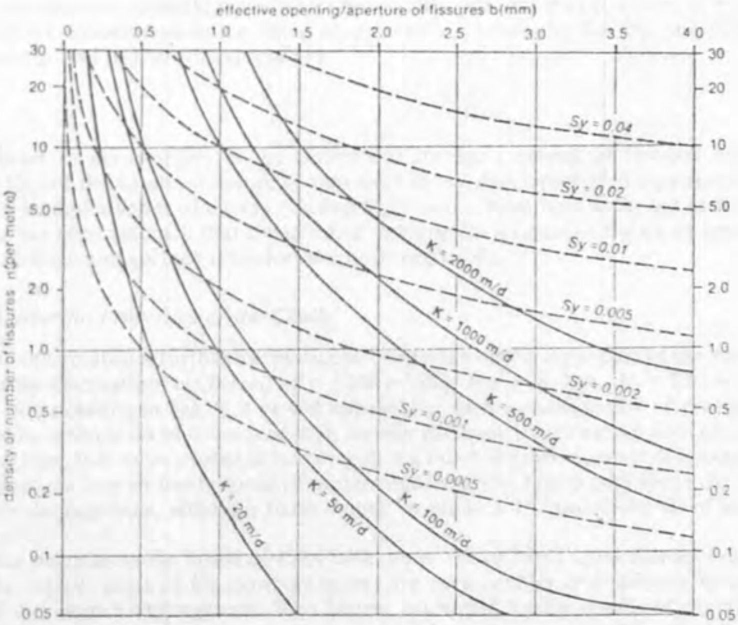


Fig. 9 — Permeability and storage of a rock mass with a single parallel system of idealized fissures.

If within a limited thickness (m_z), a rock mass has a series of equal, parallel fissures with uniform separation ($1/n$) then (3) can be written

$$Q = \frac{b^3 n}{12} \cdot \frac{g}{\upsilon} \cdot I_x W_y m_z$$

The equivalent permeability (K_x) of the system is given by

$$K_x = \frac{b^3 n}{12} \cdot \frac{g}{\upsilon} = 54\, b^3 n \text{ m/day} = 0{\cdot}063\, b^3 n \text{ cm/s} \qquad (5)$$

expressing b in millimetres and $1/n$ in metres. For such idealized media, a family of curves relating K_x, b and n can be constructed (Fig. 9).

The idealized fissure will, in almost all cases, be departed from in practice in respect of planarity (because of briding and constriction) and wall roughness, producing tortuosity in the flow path. The departures may not be so gross in the case of bedding-plane discontinuities in Chalk as in some other formations. It has been shown in laboratory tests on irregular rough-faced tension joints in an igneous rock with openings of 0·2–1·5 mm, that the exponent of b in equation (3) was reduced to 2 or less, even for laminar flow (Sharp and Maini, 1972).

Implicit in the development of the above equations is the assumption of laminar flow. The theoretical validity of this assumption can be examined by consideration of Reynolds number criteria. For the idealized parallel-plate model $R_b = Vb/\upsilon$; substituting from (2) and taking the lower critical value as 1000, it can be shown that the critical hydraulic gradient below which laminar flow is inherently stable is about $2/b^3$ (b in millimetres). Non-planarity, face roughness and tortuosity of flow path have a major effect on the onset of turbulence however (Sharp and Maini, 1972), and may reduce the lower critical R_b and hydraulic gradient by even two orders or more. It would still be unlikely for non-laminar flow to develop in fissures with an effective b of less than 2–3 mm under most natural groundwater flow conditions, but the possibility of turbulence deserves careful consideration in the siting of observation boreholes for test pumping in fissure-flow formations and in their interpretation.

Fissure Storage

Of equal interest to permeability is the theoretical storage capacity of fissured media. The specific yield (S_y) of the idealized fissure system used in the development of equation (5) is simply the product bn and a series of curves relating S_y, b and n have been included in Fig. 9. For this purpose it has been assumed that the effective opening (b) is equal to the mean opening and that pressure storage and surface retention are both negligible.

Interpretation of Hydraulic Properties of the Chalk

It is now possible to consider further the hydraulic properties of the lower part of the zone of seasonal water table fluctuation at Etton; $T = 1200$ m²/day for $m = 7$ m, $K_x = 170$ m/day, $S_y = 0{\cdot}005$–$0{\cdot}010$. Interpolating in Fig. 9, it would appear that such a combination of properties could be generated by a single set of fissures of high density (n about 10 per metre) with effective openings of 0·5–1·0 mm. It is more probable however that a much smaller number of horizontal master conduits (perhaps four or five in total) of greater opening (say 2 mm) contribute the bulk of the permeability development, although these would be unlikely to contribute all of the S_y also.

The bulk of the particles in the fabric of the Chalk are of the order of 1 μm diameter (Hancock and Kennedy, 1967); most of the pore diameters are even smaller and unlikely to drain under suctions of less than 3 atmospheres. This factor, confirmed by the results of centrifuge specific yield tests on core samples from the East Yorkshire Chalk (mean $CS_y = 0{\cdot}002$ with maximum values of around 0·005), suggests that pore-water drainage under gravity will be of only minor significance, the greatest part of the saturated porosity (0·14–0·20) constituting physically inert storage. It must be suspected therefore that additional gravity storage is present in a high density system of inclined microjoints.

There are few descriptions of the state of the discontinuities in the Chalk at depth. At a site in Norfolk (Ward *et al.*, 1968), horizontal 'separation planes' open in places to as much as 10 mm were described just above the water table during the direct inspection of the walls of large-diameter boreholes. At the same site it was observed (R.W. Gallois, personal communication) that deeper than a maximum of about 14 m bgl most of the discernible inclined joints were closed tight; the far greater density of inclined joints in the core from an adjacent borehole suggests that *in situ* many must be microscopic, perhaps less than 0·2 mm aperture.

Implications

It is not a primary aim of this paper to draw implications from the hydraulic behaviour of the Chalk. In the context of groundwater storage development and management they have been fully discussed elsewhere (Foster and Milton, in press). Some of the more important points are worthy of mention here.

A high-T/low-S_y water table aquifer such as this, will have a much more rapid hydraulic response than that of most unconfined systems. Actual groundwater flow rates will be relatively fast, though less fast than for karst systems. Even under natural hydraulic gradients they could reach 200 m/day; a significant factor in the spread of pollution, should pollutants reach the water table. High flow rates were confirmed by the movement of the products of acid treatment from the No. 2 to the No. 1 borehole at Etton, a distance of 350 m. The first arrival, peak and mean travel times were measured at about 6, 15 and 27 h respectively for a pumping rate of 30 l./s and overall hydraulic gradient of about 1/150.

The large seasonal variation in T has a number of implications; pumping interference effects will show major seasonal variation and the natural aquifer throughflow will vary in much greater proportion than the associated hydraulic gradient. There will be profound seasonal differences in the yield–drawdown characteristics of pumping boreholes. At Etton, the yield for a 5-m drawdown in the No.1 borehole varied between 56 l./s in November 1970 and 98 l./s in March 1971, and the limiting yield at low saturation was strongly influenced by the level of the main lower zone of permeability development. It should thus be evident that considerable care is needed in the planning of groundwater investigations, if reliable evaluations of drought behaviour are required for major schemes.

CONCLUDING REMARKS

The Chalk Aquifer in the outcrop area around Etton forms a layered, high-T/low-S_y, laminar fissure-flow, unconfined system. Although some anomalies exist, laterally its properties are relatively isotropic; in depth however permeability development is localized in two main layers of limited thickness, not distributed through the entire thickness of the formation. It is probably associated with a small number of horizontal discontinuities which have experienced a degree of preferential solution.

The uppermost of the two layers of permeability development constitutes the lower part of the zone of seasonal water table fluctuation; the other is located significantly below local hydrological base level. It is tempting to attribute the former to solution during long-term circulation of fresh groundwater to the existing base level (with the T values increasing down the dip slope towards the natural discharge areas). A similar conclusion has been drawn in the studies of a number of carbonate systems (le Grand and Stringfield, 1971) and appears to be due to the fact that the gross long-term circulation is often volumetrically greatest at this level. The lower zone of permeability development could well be attributable to a similar process operating to a much lower base level, perhaps in Pleistocene times, although there is also a suggestion of stratigraphic control, since it may be associated with feature *C* of the resistivity logs (Fig. 3).

The layered hydraulic structure of the East Yorkshire Chalk has been corroborated in part, and the properties of the zone of seasonal water table fluctuation elucidated, through analysis of groundwater level recession and river flow data in the West Beck and Foston Beck catchments (*W* and *F* in Fig. 1) to the north of the Etton area (Foster, 1974). Moreover the hydraulic uniformity of the dip slope of the aquifer appears to be confirmed by the similarity of groundwater level recessions throughout the region.

It is not the intention to suggest that the Etton area is necessarily typical of the unconfined Chalk Aquifer in all the extensive tracts of wold and down which form its outcrop. Similar conditions probably persist southwards from East Yorkshire into Lincolnshire but variations probably occur further south, associated with changing relief and hydrological discharge regime, geological structure, stratigraphy and lithology. Only the harder 'chalk rock' beds of south-eastern England have a comparable porosity to that of the bulk of the East Yorkshire Chalk; perhaps introducing a greater likelihood of stratigraphic control over joint and permeability development. Nevertheless there will be many features in common.

The simple theoretical permeability and storage relationships for idealized fissured systems presented, are probably not of direct practical application in the prediction of formation properties because of the formidable difficulties in field measurement of the parameters involved, particularly the effective fissure opening. They have however considerable relevance in the physical interpretation of results of *in situ* testing, which is essential if such results are to be meaningfully employed in the evaluation and management of water resources stored in fissure-flow formations.

ACKNOWLEDGEMENTS

This work is published by permission of the Director of the Institute of Geological Sciences and with the support of its Chief Hydrogeologist, Mr. D.A. Gray. The collaboration of the East Yorkshire (Wolds Area) Water Board and the extensive assistance of Mr. R.I. Crease (Deputy Engineer) is especially acknowledged. Mr. K.H. Tattersall of the Yorkshire River Authority is thanked for his interest. Two colleagues, Mr. T. K. Tate and Miss A.S. Robertson, undertook and interpreted the geophysical work from which Fig. 8 was compiled.

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The Institution of Civil Engineers

PROCEEDINGS

PART 2

September 1974
Volume 57

Research and Theory

Proc. Instn Civ. Engrs, Part 2, 1974, 57, Sept., 451–466

7715

Water supplies from Ulster valley gravels

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Using four examples from Ulster, this Paper discusses the extent to which techniques of geological exploration and hydrological analysis can be used in the practical evaluation of valley gravels as a water resource. Limitations arise from the geological heterogeneity of these strata and from financial constraints relating to their overall potential, but it is usually possible to make reliable semi-quantitative evaluations of the recharge and storage elements, so permitting logical water-supply development.

Notation

A_r	area of river-bed over which river-bed recharge occurs
D_x	size of mesh opening which will retain $x\%$ of a representative sample of unconsolidated material
I_r	rate of induced or river-bed recharge per unit area (Q_r/A_r)
K_h	permeability measured in a horizontal direction
K_v	permeability measured in a vertical direction
K_r	vertical permeability of river-bed
m	saturated aquifer thickness
Q	well discharge or pumping rate
Q_r	rate at which river-bed recharge occurs
r	distance between pumping well and observation well
s	well drawdown
S_y	specific yield
t	time since pumping began
T	transmissivity ($K_h m$)

Introduction

The ground water resources of Ulster are restricted by the limited occurrence of geological formations of sufficient permeability, thickness and areal extent to form aquifers. However, where favourable conditions exist, as in the superficial deposits of many valleys, useful well yields (10–40 l/s) are obtainable. Development by groups of relatively shallow (6–25 m), large diameter (300–600 mm) wells can be an economical proposition to meet localized demands for industrial and public water-supplies of up to 10–15 Ml/day (10 000–15 000 m^3/day), particularly where such demands can be met on site or very close to the consumer.

Written discussion closes 15 November, 1974, for publication in *Proceedings*, Part 2.

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2. Traditional methods of ground water development in Ulster valleys paid little attention to hydrogeological factors and wells were frequently brought into production without any real knowledge of their source. In the case of modern industrial and public supplies reliable evaluation is becoming increasingly important and this necessitates an understanding of the resource being used.

3. In practice, the prime concern is with the gravels of alluvial and/or glacial valley fill, whose volume, in common with that of most British gravel deposits, is relatively small. Such aquifers cannot be considered as conventional ground water reservoirs and must usually be treated as parts of water resource systems intimately related to associated rivers. River water can be abstracted via the gravels, which act as a natural filter; the limited storage and through flow in the gravels augment the supply during periods of low stream flow. These principles are well known in the USA[1-3] and are achieving recognition in the UK.[4-6]

4. The two essential elements in investigation are exploratory drilling and pumping tests with observation boreholes.[7] Both elements need careful planning and controlled execution. Many methods of pumping test analysis have been developed to evaluate this type of hydrological environment[3,8-11] but there are frequently severe practical limitations to their application. These stem from natural heterogeneity in field conditions, the generally narrow and thin nature of UK valley fill and the imposed restraints of project finance. In many cases evaluation and development are demanded urgently and there is rarely an opportunity to install a hydrometric network and collect long-term data.

5. In this Paper these problems are discussed and the investigation and development of water supplies from valley gravels are illustrated by short case histories from sites in four Ulster valleys (Figs 1 and 2). Factors complicating the evaluation phase of a project are listed separately from those affecting the

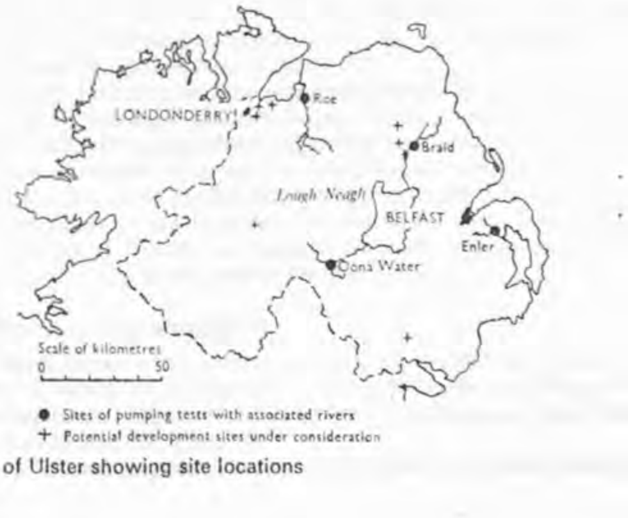

Fig. 1. Map of Ulster showing site locations

development phase, although the two are closely related and the division is to some extent arbitrary. On the basis of experience, recommendations are made on the form of contractual organization most compatible with systematic investigation and logical development.

Factors complicating evaluation

6. Rapid lateral variations and complex boundaries are characteristic of most valley fill deposits and affect in varying ways all the sites investigated. They add to the cost of, or prohibit, full geological exploration and they complicate well siting. In the Enler and Braid Valleys electrical resistivity and seismic refraction surveys, respectively, proved useful in mapping the depth to bedrock, but they were unable to define the main gravel strata and variations in their saturated thickness.

7. These rapid variations in thickness and facies result in corresponding changes in aquifer permeability and saturated thickness, and therefore also in transmissivity. Ground water bodies are often locally confined by overlying alluvial silts, causing variation in storage coefficient from less than 10^{-3} up to the specific yield, which itself may vary from 0·05 to 0·25 in gravel formations. Great care must therefore be taken in the design and execution of pumping tests and considerable caution in their analysis and interpretation, if misleading results are to be avoided. Inadequate observation borehole siting could mean that hydraulic boundaries are overlooked and false values derived for transmissivity and the coefficient of storage.

8. Associated with the lateral variations, the frequent presence of vertical variations in lithology of valley fill deposits requires care in identification of the aquifer under test and in selection of corresponding strata for the screened intervals in observation boreholes. Where vertical hydraulic continuity between distinct gravel strata is greatly restricted it may be necessary to consider them as semi-independent aquifers.

9. River-bed recharge (also termed river-bed or induced infiltration), induced by ground water abstraction, is frequently the major component of a supply obtained from a valley fill aquifer. The full evaluation of its potential requires complex hydrogeological investigation; the practical aspects are discussed in the Enler Valley case history (§§ 16–24).

10. The general lack of river flow and ground water level records in many of the Ulster valleys normally makes it impossible to estimate the rainfall infiltration to the valley fill or the lateral subsurface contribution from the valley sides. While the valley sides in general are much less permeable than the valley fill, their contribution could be significant under drought conditions in some areas. The sparseness of low flow data for the Ulster rivers means that the amount of river flow at drought available for induced recharge cannot always be estimated, particularly in the case of smaller rivers.

Factors affecting development

11. In general, because the valley gravel aquifers are shallow, there is only limited depth in which to accommodate the well screen and the available drawdown is restricted. Efficient well design and completion are thus of major importance to minimize well losses.[12]

12. The vertical heterogeneity in valley fill deposits can cause difficulty in

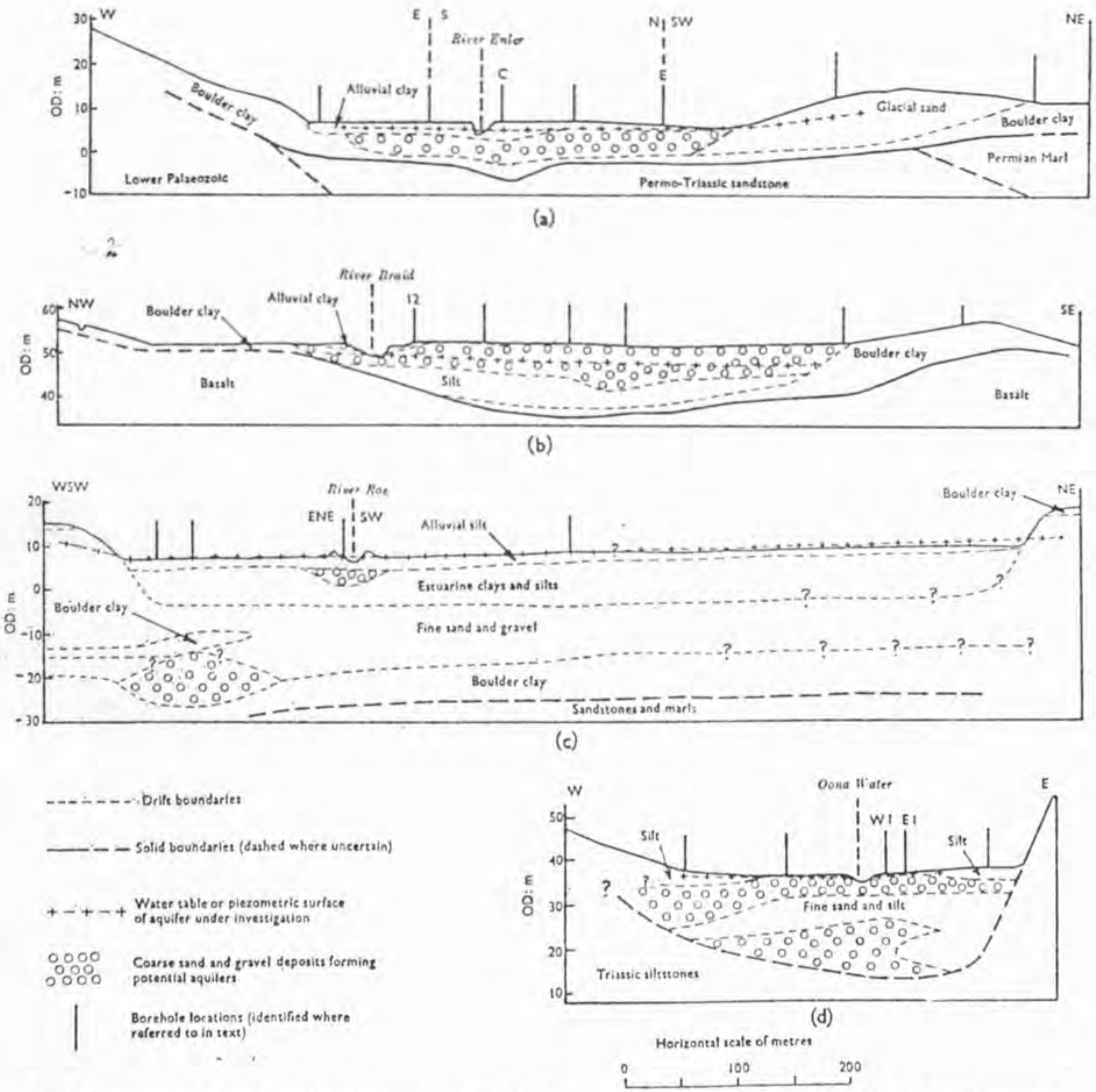

Fig. 2. Representative hydrogeological cross-sections of (a) Enler Valley at Comber, (b) Braid Valley near Ballymena (c) Roe Valley near Limavady, (d) Oona Water at Shanmoy

Table 1. Summary of well yields, pumping tests and aquifer properties

Location	Well	Distance from river, *m*	Yield characteristics			Pumping test analysis						Comments
			Discharge, *l/s*	Draw-down, *m*	Limiting factor*	Number of observation boreholes	Transmissivity, *m²/day*	Saturated aquifer thickness, *m*	Horizontal permeability, *m/day*	Storage coefficient or specific yield	Dominant boundary†	
Enler Valley, Comber	D 10	10 10	7 11	5·9 2·4	T P	2+3	315	7	45	0·001§	R, B	Unicarval site
	C	18	11	5·8	F	1+4	570	6	95	0·002§	R	Upper Kennel Bridge site (see Fig. 4)
	E‡	160	27	22·9	P	1	105	70	1·5	0·0002	V	
	A1	14	20	4·3	F	3	650?	5	130?	?	R?	Lower Kennel Bridge site
Braid Valley, Ballymena	13	350	19	1·4	P	1	2300	5	460	0·110	B	(See Fig. 6)
	9	230	45	5·6	F	2	2200	6	365	0·050	B	
	14	177	18	1·4	P	1	1800	4	450	0·080	B	
	5	335	14	2·4	P	2	1400	4	350	0·070	B	
	12	23	3	1·5	T	2	300	3	100	?	R	
Roe Valley, Limavady	6	160	15	13·2	P	1	65	11	6	0·0002	B, V	—
Oona Water, Shanmoy	W1	20	35	6·1	P	1	4700	10	470	—	B	Lower gravel
	E1	30	12	2·4	T, P	0	—	15	—	—	—	Upper and lower gravel

* P pump capacity, T temporary or inefficient well, F formation.
† R recharge, V vertical leakage, B barrier.
‡ Deep Permian Sandstone borehole.
§ Conditions became unconfined following heavy pumping.

borehole construction; considerable care is required in the identification of the most permeable horizons and in the selection of appropriate screen size to allow unimpeded entry of water from these horizons, while excluding entry of fines from interbedded and associated silts and fine sands.[12, 13] Although conventional large (300–900 mm) diameter production boreholes with various types of well screen and gravel pack have been used at all the sites discussed in this Paper, where conditions and water requirements are appropriate consideration should be given to the use of collector or well-point installations, since the many-fold increase in effective well radius leads to significant improvement in specific capacity.

13. The small cross-sectional area and volume of most UK valley gravel deposits mean that even when such formations are of high permeability and specific yield the underflow (the natural flow of ground water through them) is also small and the ground water storage is strictly limited.

14. The contribution from river-bed recharge to ground water supplies at a given site will vary with river water temperature, ground water level, river stage and river-bed permeability. Of these, variation in the river-bed permeability is by far the most difficult to treat as it is associated with such factors as siltation and with physical clogging and organic growth due to the recharge process itself.

15. A major advantage of abstracting river water by induced recharge is the benefit of natural filtration; at all the sites investigated in Ulster the ground water quality was far superior and more consistent in relation to suspended solids and organic and bacteriological content than was the quality of the neighbouring river water. However, filtration will not have any effect on most ions in solution and supplies remain liable to pollution by organic and inorganic solutes should river water quality deteriorate in these respects. The intermittent presence of soluble toxic elements in the river would seriously threaten the continuity of supplies. Shallow aquifers may also be directly vulnerable to pollution by agricultural and horticultural processes.

Case histories of investigation and development

Enler Valley, Comber, Co. Down

16. Intermittently during 1963–69 the Drift deposits of the Enler Valley have been explored as a source of additional municipal supplies for the town of Newtownards. Three sites in the vicinity of Comber, about 5 km south-west of Newtownards, have been investigated in detail. A cross-section of the valley at one (Upper Kennel Bridge) is shown in Fig. 2(a); those of the other two sites (Unicarval, 1000 m upstream, and Lower Kennel Bridge, 400 m downstream) are similar.

17. The principal drift aquifer is a gravel up to 6 m thick occupying a channel cut through glacial sands and into boulder clay. At all three sites the transmissivity was sufficient to permit moderate short-term well yields (Table 1) but these could not be expected to be sustained by ground water underflow, which was estimated to be less than 0·5 Ml/day, as a result of the restricted width of the buried channel (Fig. 2(a)).

18. In detail the gravel formation showed areal anisotropy and marked vertical heterogeneity, the D_{50} size of disturbed samples ranging from 7 mm to 40 mm and the uniformity coefficient D_{40}/D_{90} from 4 to 30. These factors

were reflected in the limited tracer experiments conducted at the Unicarval site, where actual flow rates of up to 140 m/day were observed towards the pumping well, indicating that the preferred flow paths probably had a horizontal permeability of 10–15 times the average pumping test value of 45 m/day.

19. For those observation boreholes located closer to the test production well than its distance from the Enler River, the time–drawdown data showed signs of early recharge (Fig. 3), although these were much stronger at the Unicarval site. Type-curve methods[14] were used in the initial analysis but s versus log t plots[10, 15] are particularly useful in revealing hydraulic boundaries, which can also be analysed by time-departure curve methods.[16] The method used in Fig. 3 of plotting s/Q against log (t/r^2) allows direct inter-site comparison of the response of the aquifer in the vicinity of the pumping well.

20. For the given test rates (Table 1), equilibrium was established within a few hours of starting pumping at the Unicarval site and within 24 hours at Upper Kennel Bridge. At the former site, the equilibrium was clearly due to the effects of river-bed recharge induced by pumping; such recharge was also present at the latter site, although masked by marked aquifer anisotropy and interception of lateral flow (Fig. 4).

21. Where recharge induced by pumping is likely to be a major component of a ground water supply, it is important to determine its rate of flow Q_r, the area of river-bed A_r involved and the river-bed vertical permeability K_r. During recession most rivers are effluent (Fig. 5(a)) and interception of natural discharge will precede the major development of induced recharge (Fig. 5(b)). With increasing pumping rate the water-table will at some stage be drawn below the river-bed (Fig. 5(c)), when the rate of induced recharge ($I_r = Q_r/A_r$) in this section will have reached its limiting value and further recharge can be achieved only if the cone of influence spreads upstream and downstream. At constant river stage, the limiting I_r will be a function of K_r alone. Under idealized conditions and while the water-table remains above the level of the

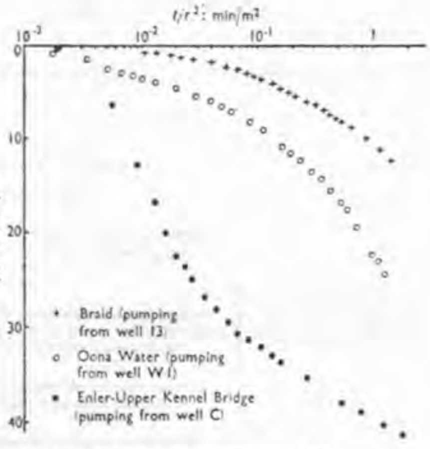

Fig. 3. Selected observation borehole pumping test data

river-bed, the system is theoretically capable of full solution by pumping test analysis alone. However, direct observation of the distribution of ground water head at equilibrium, including where feasible measurements in piezometers driven through the river-bed, will greatly aid interpretation of the pumping test data.[17] Confirmation of the presence, but rarely the magnitude, of river-bed recharge can in some circumstances be derived from geochemical techniques or from stream flow measurement, but the cost of gauging structures and the inaccuracy of current-meter work usually mean that the latter method is of little use at the investigation stage. In this investigation tolerable estimates of Q_r, A_r and the head used in river-bed recharge could be made for both the Upper Kennel Bridge and the Unicarval sites from the total observation borehole data. The importance of observation boreholes on the bank of the river opposite to the pumping well is noteworthy in this respect (Fig. 4) although for land access, cost and other reasons the observation borehole layout was not ideal in any of the investigations.

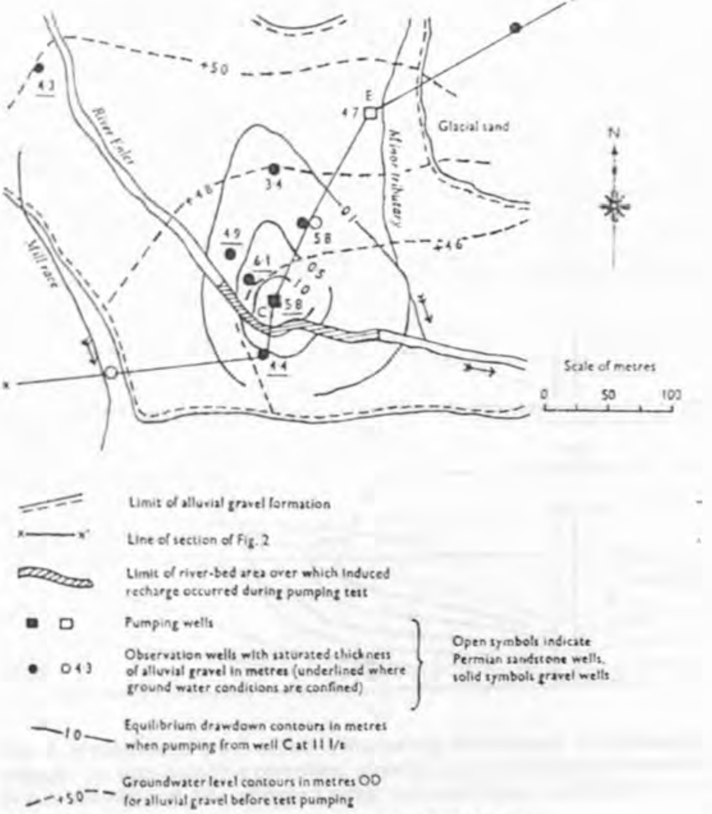

Fig. 4. Detailed plan of Upper Kennel Bridge site, Enler Valley

22. Values for K_r of 1·0 and 3·4 m/day were derived; these are average values and must be greatly exceeded in the centre of the channel, although even here they are probably less than the vertical permeability K_v of the gravel formation itself. Assuming comparable conditions, the maximum Q_r from the 1000 m length of river between the two sites would be greater than 10 Ml/day provided this does not exceed the total river flow in extreme drought or cause it to fall below an acceptable level. Development could be achieved by a line of wells parallel to the river at a spacing of about 100 m. The Enler is a small river with a highly variable flow regime. During test pumping after an extended dry period, flows did not fall below 9 Ml/day but, in the absence of reliable data on minimum flows, development was deliberately restricted pending the establishment of a gauging station. While interest in the flow data centres on the measurement of the minimum flow from the upper catchment

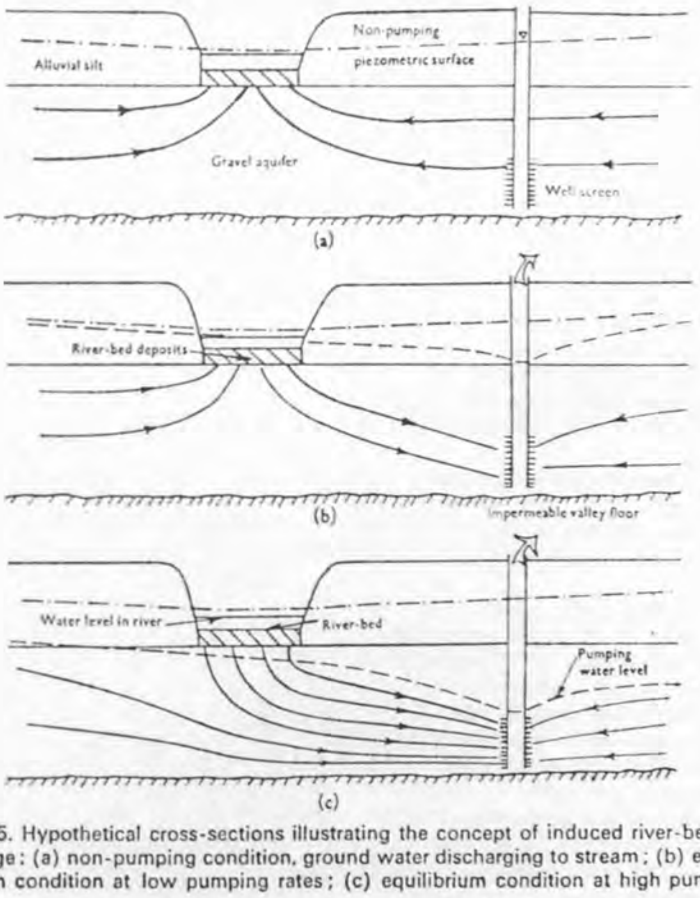

Fig. 5. Hypothetical cross-sections illustrating the concept of induced river-bed recharge: (a) non-pumping condition, ground water discharging to stream; (b) equilibrium condition at low pumping rates; (c) equilibrium condition at high pumping rates

which is available for induced abstraction in the lower reaches, consideration also has to be given to measurements which will permit evaluation of the infiltration into the valley deposits and any lateral ground water flow from the valley sides. The latter appear to sustain the effluent condition in dry weather (Fig. 4).

23. By virtue of the cover of alluvial silt (Fig. 2(a)) the storage coefficients in the pumping tests (Table 1) were in the confined range but the volume of water in confined storage is negligible. From the grain size distributions the specific yield of the gravel formation is estimated[16] to be about 0·15 and thus storage must be about 45 Ml per 1000 m length of the valley for each metre lowering of the water-table; this is comparatively limited and can be abstracted only at the total expense of river flow.

24. During exploratory drilling in 1968 it was discovered that the lower reaches of the valley, including both Kennel Bridge sites, are underlain by more than 50 m of permeable Permian Sandstone with no known outcrop. A pumping test (Table 1) showed that recharge to this sandstone can be induced by vertical leakage from overlying valley deposits and in turn from the Enler River. Abstraction from the bedrock was an attractive alternative because of the higher individual well yields, greater available storage and reduced risk of pollution, although well construction was much more expensive.

Braid Valley, Ballymena, Co. Antrim

25. During 1969 an investigation was undertaken into the availability of ground water as the perennial supply, or a make-up or stand-by supply, for a factory under construction in an industrial development area on the flood plain of the Braid Valley, about 2–3 km east of Ballymena.

26. As in the Enler Valley, the aquifer is an alluvial gravel (Fig. 2(b)) but the Braid site was atypical of those investigated because the aquifer distribution was known at the outset from the logs of many previous site investigation boreholes. The data (Fig. 6) show the saturated thickness variations characteristic of valley fill aquifers and these have a critical influence on well yields (cf. wells 9 and 5 in Table 1).

27. Pumping tests showed the gravel to be generally of high permeability ($K_h > 350$ m/day) and water-table storage (S_y up to 0·11) but hydraulic barriers, reflecting the impermeable boulder clay of residual mounds and the valley sides (Fig. 6), dominated the response to abstraction (Fig. 3) and equilibrium was not readily achieved.

28. While considerable restriction on land access and acquisition prevented the production wells from being sited close to the Braid River, a pumping test at well 12 (Fig. 6 and Table 1) subsequently showed a many-fold diminution in transmissivity (resulting from reductions in both K_h and m) in this direction and explained the limitation on induced river-bed recharge. Apparently as a consequence of its location at the extremity of the valley, the Braid was found to be naturally influent in the reaches investigated, even during periods of prolonged dry weather. The degree to which the hydraulic gradient away from the river could be steepened by pumping was limited by the relatively high base of the gravel formation with respect to the river, and the perennial yield of the site was thus thought to be limited to about 4 Ml/day.

29. The storage potential of the gravel formation was investigated empirically by a long-duration multiple-well test in May–June 1969. From the results

it was extrapolated that a pumping rate of more than 6 Ml/day could be sustained for at least 70 days from wells 9, 13 and 14 (Fig. 6); to draw on storage for longer periods or at higher rates more wells would be required, preferably sited in the deepest part of the gravel channel (Fig. 6).

30. Using a cooling tower to reduce the overall water requirement, the factory has been brought into production with a steady 2·3 Ml/day abstraction and 5·2 Ml/day have been abstracted intermittently for periods of up to 40 days. Moreover the prospects of obtaining further supplies within the development areas seem favourable, particularly 500 m or more downstream where the Braid occupies a more central position in the valley close to the centre of the buried channel.

31. Land drainage, downstream river engineering and dewatering operations during factory construction are believed to have recently lowered the

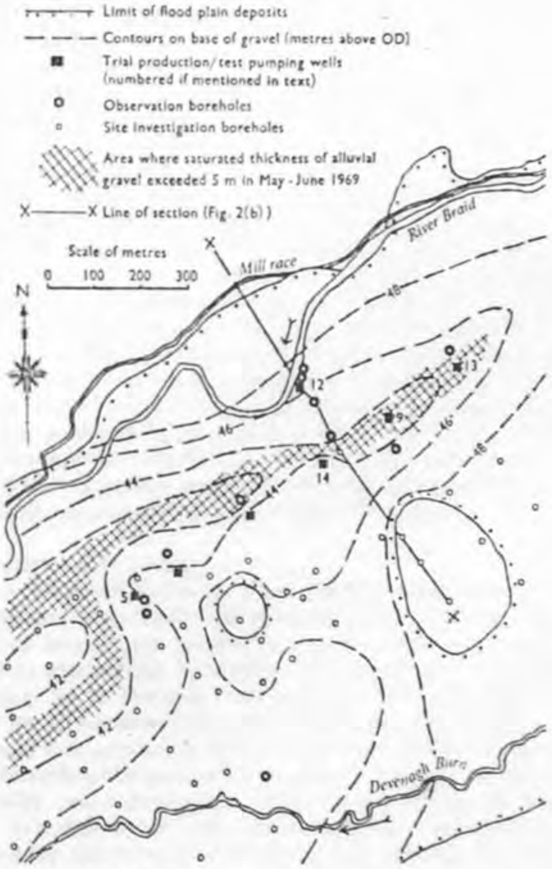

Fig. 6. Detailed plan of Braid site

water-table throughout most of the valley gravels by 1–2 m, although it was not possible to establish what proportion of this was permanent. This has certainly had an adverse influence on ground water potential, reducing both saturated thickness and available drawdown.

Roe Valley, Limavady, Co. Londonderry

32. Investigation into the possibility of augmenting the water supply of Limavady from local ground water sources began in 1968 and attention was focused on the superficial deposits of the Roe Valley, 1 km to the north.

33. Some knowledge of the geology had been gained from a nearby highway site investigation and exploratory boreholes confirmed the presence of a thick glacial outwash, coarse on the western side of the valley, overlain by estuarine deposits (Fig. 2(c)). The general sequence of the valley fill made a direct induced recharge scheme impossible, but it was thought that induced vertical leakage and interception of lateral ground water drainage from the sandy interfluves (Fig. 2(c)) might sustain worthwhile well yields.

34. Initially it was believed that the coarser sand and gravel at depth was fairly widespread and it was decided to test pump this formation first and to investigate the overlying finer granular sequence subsequently. A dual-completion production well, abstracting water from both levels, was considered but was rejected on grounds of the cost and difficulty of construction.

35. The production borehole was successfully completed in the coarser sand and gravel using bridge-slotted screen with a gravel pack, but some of the observation boreholes failed to encounter the same horizon and it became apparent that the coarser material was restricted to a limited channel (Fig. 2(c)) of probable NW–SE trend. In the observation boreholes considerable difficulty was experienced in excluding fine material, but one was eventually completed successfully in the coarse sand and gravel with wire-wrapped screen.

36. A pumping test was carried out and showed a low transmissivity value (Table 1) with a barrier boundary but, despite this, equilibrium was achieved for an abstraction rate of 0·7 Ml/day through leakage from the overlying sands. A higher yield was achieved for greater drawdown and could perhaps have been sustained although overall the area proved of relatively poor potential and extremely difficult to exploit because of the large quantities of silt and fine sand interbedded at numerous levels in the valley fill sequence.

Oona Water, Shanmoy, Co. Tyrone

37. The Oona Water at Shanmoy, 6 km south of Dungannon, is a small river but its valley contains considerable thicknesses of gravel (Fig. 2(d)) which have recently been investigated for public supply. Three exploratory boreholes, to double as observation boreholes, were drilled and given short performance tests (e.g. E1 in Table 1). At that stage it was apparent that the upper and lower gravel horizons (Fig. 2(d)) were considerably more permeable than the sands and silts separating them, but it was anticipated that the finer materials might be sufficiently permeable to allow recharge to be induced to the lower gravel aquifer, and a production well (W1) was drilled and screened in this formation. Whether or not such leakage occurred could not be deduced from the pumping test results or from chemical analysis, because the site controls during testing were not adequate. The pumping test data (Table 1 and Fig. 3) show that, although the materials have a very high permeability, barrier

boundaries are dominant and there is no trend towards equilibrium at high discharge rates. The successive barrier boundary effects are caused by the cone of depression reaching the edge of the gravel channel or the valley sides, which are composed of relatively impermeable Triassic siltstones and fine sandstones.

38. It was concluded that, although well W1 is capable of abstracting water from the lower gravel at a high rate, it draws on restricted underflow and storage since recharge from the river is limited by the slow rate of vertical leakage, and the well is therefore unlikely to provide the 4–5 Ml/day required perennially.

39. The grain size distribution curves for the upper gravel suggest that its permeability will be of the same order as that of the lower gravel. The upper gravel is in hydraulic continuity with the river and suitable conditions therefore exist for an induced recharge scheme. Two difficulties exist: first, because the upper gravel is relatively thin, a conventional well would not be deep enough to provide for an adequate screen length and sufficient drawdown for a useful abstraction rate and second, there is no information on the drought flows of the Oona Water.

40. The former difficulty could perhaps be overcome by the installation of a well point system or by use of a simple collector, but the latter is more serious, especially as there is very limited water storage in the upper gravel. However, it is believed that the flow of the Oona Water plus the upper gravel throughflow would not fall below 9 Ml/day for a period of more than 30 days, although this needs confirmation.

41. Current recommendations are that the upper gravel should be explored for an induced recharge scheme throughout the year and that the existing lower gravel production well should be used as a stand-by in drought.

Contractual organization

42. To economize on drilling costs there is often pressure for exploratory boreholes to double as pumping test observation boreholes; this can be unsatisfactory because they will of necessity have to be completed before the geology of the site is adequately investigated and the precise objects of the pumping test are established. Another problem is that the cost of efficient well screen is usually considered too high for use in observation boreholes. In induced recharge schemes there is pressure to put trial production wells closer to the river than is desirable for investigation, in the interest of maximizing specific capacity Q/s.

43. Standard pumping test procedures tend to be cumbersome and there may be conflict between the need to investigate the aquifer and the need to establish the well characteristics. For the hydrological purpose a 24 hour test may in some circumstances suffice, whereas in others it may be desirable to continue steady pumping for 10–20 days. Above all flexibility is required with the scope to modify test procedure should circumstances demand.

44. The organizational limitations that may prejudice systematic investigation can be minimized by proceeding in distinct contractual stages. The first stage includes exploratory drilling and sampling, the exploratory boreholes generally being lined so as to permit collection of regional water-level data. The second stage—the most critical—includes the construction of trial production wells, pumping test observation boreholes and any other installations

such as driven piezometers or temporary river gauging structures required for aquifer testing. The interval between these two stages can be as little as a month but depends on such factors as negotiations for land acquisition or access, the delivery time on well screen, the amount of data to be processed, laboratory testing and the timing requirement for the pumping tests. Further development, as the final stage, can follow any time after the analysis of the results of the second stage; additional production wells or installations would normally be subjected to some pre-production testing.

Conclusions

45. Investigations in Ulster have shown that under suitable conditions UK valley gravels can be developed to provide low-cost water supplies, particularly where industrial demands of about 10 Ml/day exist. Induced recharge installations are frequently useful as alternatives to river intakes for small to moderate supplies. In addition to lower capital and running costs, such schemes have the advantage of utilizing natural storage, albeit limited.

46. The natural complexity of the valley fill environment frequently makes it economically or physically impossible to carry out a total hydrogeological evaluation, but with flexible contractual arrangements and modern hydrological techniques (especially controlled pumping tests) it is usually possible to obtain semi-quantitative estimates on the nature of the resource and its principal components (induced river-bed recharge, aquifer underflow and storage) and thus to plan for logical development.

47. In the UK as a whole, induced recharge schemes have received little attention and merit consideration where suitable geological environments exist.[19] In Ulster, other valleys worthy of further investigation include those of the Faughan, Co. Londonderry and Main, Co. Antrim, where preliminary studies have indicated the presence of extensive deposits of thick gravel. Suitable conditions are not confined to Ulster and it may be that valley gravels could be developed in regions which previously have not been considered as ground water provinces.

Acknowledgements

48. The investigations described in this Paper were initiated at the request of the Northern Ireland Ministries of Development and Commerce in relation to the requirements of various local water undertakings and industries.

49. The work was carried out in co-operation with Messrs R. Ferguson and S. McIlveen and Messrs W. D. R. & R. T. Taggart, who acted as consultants to the Ministry. Borehole construction, test pumping and other contractual aspects were variously undertaken by Cementation Co. Ltd, Glover Site Investigations Ltd and George Stow & Co. Ltd.

50. During all the investigations, close collaboration was maintained with the Geological Survey of Northern Ireland and in particular with Mr H. E. Wilson (District Geologist), Mr P. I. Manning, Dr R. A. Bazley and Dr W. I. Mitchell, who handled the geological exploration aspects of the investigations and some of the hydrological data collection.

51. The work was carried out under the general supervision of Mr D. A. Gray, Chief Hydrogeologist, and the Paper is published by permission of the Director, Institute of Geological Sciences.

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GROUND WATER

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DISCUSSION OF PAPERS

DISCUSSION OF "Hydraulics of Sheetlike solution Cavities," by Gerald K. Moore, July-August Issue, pp. 4-11

by S.S.D. Foster, B.Sc.-C.Eng., Mice Miwe, and Michael Price, M.Sc., Institute of Geological Sciences, Hydrogeological Department, Exhibition Road, London SW7 2DE United Kingdom

Gerald K. Moore discussed the hydraulic behaviour of the sheetlike solution cavities that conduct ground water and supply wells in the Tennessee limestones. It was most encouraging to see some quantitative work on fissure hydraulics—a much neglected topic in ground-water hydrology.

In the United Kingdom, fissure-flow dominates ground-water movement in the principal aquifers, and recently some attempts have been made to evaluate the hydraulics of the Chalk and Permo-Triassic Sandstones at research pumping test sites in East Yorkshire and Westmorland respectively. These will be published in due course (Foster, *et al.*; Lovelock, *et al.*, in preparation). Investigations have been based on pumping tests with purpose-drilled observation boreholes supplemented by geophysical borehole flow investigations (Tate, *et al.*, 1970), in-situ television inspection of geological features, laboratory core-analysis for intergranular properties, conventional formation logging, analysis of natural ground-water level fluctuations as well as consideration of the hydraulics of idealised fissures. In both the formations, small openings (0.1-10 mm) on near horizontal discontinuities related to bedding are believed frequently to make the principal contribution to hydraulic conductivity.

We agree that consideration of the hydraulics of idealised fissure systems can extend the physical understanding of the formation constants determined from pumping tests but would suggest that, particularly when a knowledge of the number of levels of flow (N) is available, expressions of the type

$$T = \frac{g}{12\nu} \cdot Nb^3 \quad \text{or} \quad T = \frac{g}{12\nu} \cdot \Sigma b^3$$

are more appropriate (symbols as used by Moore). Cautionary points to be noted are that such equations refer to parallel-sided smooth-walled openings. Sharp and Maini (1972) have shown that, in laboratory tests on irregular and rough-faced fissures of opening 0.2-1.5 mm, the exponent of b was reduced significantly below 3, even for laminar flow.

Similar caution must be exercised in applying Reynold's Number criteria, as the transition from laminar to turbulent flow may take place at widely-varying N_R values, depending on the irregularity of the fissures and roughness of the fissure walls. It may be impossible to select N_C when the relief of the surface roughness approaches the magnitude of the fissure opening.

We find it difficult to understand why Moore selects a non-circular conduit rather than a parallel-plate opening as the model for his Reynold's Number calculations, particularly as he then selects a value of N_C generally considered more appropriate for the latter than the former. Nevertheless this would only modify his formula for the critical discharge/radius relationship under conditions of radial flow to

$$Q_c = 2000\, \pi r_c \nu.$$

We also consider his subjective argument for the general presence of laminar, rather than turbulent, flow in the cavities he considered to be a weak one and would prefer to see this proved through study of the abstraction (Q)/observation borehole drawdown(s) relationship during a step-test. If this relation is strictly linear, an over-all laminar flow regime is conclusively demonstrated; if, in the absence of hydraulic boundaries, departures from linearity occur for large Q, a turbulent component of flow is implied. For example Ineson (1957) reported that, at a site in the Chalk of Hertfordshire, turbulence was present 260 metres from a pumping well abstracting 120 litres/sec. On the other hand in the same formation at a site in East Yorkshire, Foster, *et al.* (in preparation) showed strictly laminar Q-s responses in observation boreholes situated 120-370 metres from a pumping well abstracting up to 90 litres/sec.

Referring to Moore's Figure 6, it is obvious that the line drawn has the minimum possible slope and could almost have been drawn through the origin. Under the latter condition $s_W \simeq CQ^2$, implying the almost total absence of a laminar flow component! In practice the form of s_W/Q against Q plots is normally linear only for small Q in fissured formations. For larger Q the slope frequently increases towards the vertical as the pumping water level falls below successive ground-water entry levels, since increasing s_W then has no further effect on the contribution from these fissures.

It is however clear that an improved understanding of fissure hydraulics based on theoretical considerations and modified in the light of field evidence is required before values of formation constants can be confidently interpreted for use in the evaluation and management of the water resources stored in fissured aquifers.

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Groundwater Pollution in Europe

Proceedings of a Conference
organized by
The Water Research Association
in Reading, England, September 1972

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WATER INFORMATION CENTER, Inc.
Port Washington, New York
1974

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LEGAL AND ADMINISTRATIVE MEASURES TO PROTECT AQUIFERS

HYDROGEOLOGY AND HYDRAULICS OF POLLUTION MOVEMENT UNDERGROUND

by S.S.D. Foster and P.E.R. Lovelock
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It was pleasing to see the flag of hydrogeology waving in the field of groundwater pollution, which would be a fertile area of endeavour for the future. However, one should be critical of the context being restricted to unconsolidated formations with intergranular flow, as Hunter Blair's introductory remarks had seemed to suggest (p. 62-66).

Taking a general view of the major British aquifers, two of which are consolidated formations in which fissure flow predominates, Table 4 gives typical ranges of their hydraulic properties; it is these which quantitatively define 'the entry and movement of polluted water.... influenced by the interstices of the geological formation'. Note here the use of a 1/500 hydraulic gradient, purely to give realism in the comparison of aquifers. The fissure-flow in the Chalk and the Bunter Sandstone is an order of magnitude faster than that in the Alluvial Gravels, despite the high conductivity of the latter. These differing flow regimes also have a bearing on hydrodynamic dispersion and surface adsorption of pollutants.

Gaining knowledge of this sort is a slow process, partly because of the high cost of observation boreholes and of core-drilling. The locally great significance of heterogeneity in modifying the hydraulic properties was emphasized in the pollution context where one was more concerned to know the distribution of particulate travel times and distances rather than finding the average mass-movement through the formation as a whole. Heterogeneities were frequently responsible for the surprisingly early first-arrival times observed in many field tracer experiments.

The movement of polluted water in the unsaturated zone could sometimes be assessed from a knowledge of saturated vertical permeabilities found in laboratory tests, which allow for estimating maximum downward flow rates after making certain assumptions about the hydraulic conditions. Very little, however, is known, except by inference, about the influence of fissure-flow in the unsaturated zones of the Chalk and Bunter Sandstone, for example.

In summary, the significance of fissure-flow in the hydrogeology of the British aquifers and therefore in the pollution of their groundwaters should be recognized as fundamental, but has hardly been discussed.

TABLE 4

TYPICAL HYDRAULIC PROPERTIES AND INFERRED NATURAL FLOW RATES FOR SOME BRITISH AQUIFERS IN THE SATURATED ZONE OF THEIR INTAKE AREAS

FORMATION	HYDRAULIC PROPERTIES				REAL HORIZONTAL FLOW RATES FOR I = 1/500 V_H (km/year)	SOME SOURCES OF MAJOR HETEROGENEITY
	FLOW TYPE	HORIZONTAL PERMEABILITY K_H (metres/day)	POROSITY ∅	SPECIFIC YIELD S_y		
CHALK East Yorks North Lincs	INTERGRANULAR	<0.0005	0.15-0.30	0.002		
	FISSURE	40-80	0.005-	0.015	2-10	Zone of water table fluctuation K_H & V_H × 3
ALLUVIAL GRAVELS Thames Valley Ulster	INTERGRANULAR	50-150	0.15-0.25	0.10-0.15	0.2-1	inter-bedded clean coarse-grained horizons K_H & V_H × 10
	FISSURE					
BUNTER SANDSTONE Midlands Notts only	INTERGRANULAR	1-4	0.23-0.30	0.15-0.20	0.004-0.01	differential cementation
	FISSURE	10-20	<0.005		1.5-3	mining subsidence

(35)

PHILOSOPHICAL TRANSACTION
OF
THE ROYAL SOCIETY
OF LONDON

A. MATHEMATICAL AND PHYSICAL SCIENCES

VOLUME 272 PAGES 79–274 NUMBER 1221

PTRMAD 272 (1221) 79–274 (1972)

4 May 1972 Price £5.00 (U.S. $14.00)

A Discussion on problems associated with the subsidence of southeastern England

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PUBLISHED BY THE ROYAL SOCIETY
6 CARLTON HOUSE TERRACE LONDON SW1Y 5AG

Phil. Trans. R. Soc. Lond. A. **272**, 245–257 (1972)   [245]
Printed in Great Britain

Urban influences upon groundwater conditions in Thames Flood Plain deposits of Central London

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[Plates 1 to 3]

Study of the groundwater in the riverine deposits of the Flood Plain Terrace of the River Thames in Central London indicates that the current conditions are dominated by man-made influences, particularly the underground railway systems and the river walls. Operation of the proposed Thames barrier in a half-tide mode would modify these influences and could lead to additional drainage problems and affect basement structures.

INTRODUCTION

The principles governing the occurrence of groundwater in the flood plain deposits of rivers are well established, but the modifications induced by man's long-continued occupancy of a flood plain on the scale of that in London are not well known. Except where such deposits have been developed intensively for water-supply purposes, their groundwater has been considered only in relation to excavation and construction problems at individual sites rather than on an overall basis.

The Thames Barrier Project Groundwater Working Party, established by the Greater London Council, initiated studies to determine the probable effect of the construction of a tidal control barrier on groundwater conditions throughout the Flood Plain Terrace upstream of the proposed site in Woolwich Reach. There would be little object in preventing flooding from surface water only to bring about a somewhat similar though more gradual and less catastrophic effect by raising the groundwater levels in the Flood Plain! The area under examination is bounded on the north and south by the outer limits of the Flood Plain, and to the west by Teddington Weir (figure 1).

The study programme was divided into several phases. Initially, the distribution and lithology of the deposits themselves had to be defined and for this purpose existing data in the form of geological maps and drilling records held by the Institute of Geological Sciences were adequate. An analysis of this information has been published (Mather, Gray & Houston 1971). The second stage was to examine existing data on groundwater quantity and quality, but these were insufficient to define the occurrence of groundwater in detail and a drilling programme had to be mounted to meet this need; a total of 39 boreholes had been drilled up to April 1971. Co-ordinated facts were required on the construction and condition of the river walls to identify those reaches of the river where hydraulic communication between the groundwater body and the river was possible and mass transfer of water could take place. These several lines of approach had to be collated to provide an indication of the overall pattern of groundwater flow in the Flood Plain deposits (Foster 1971).

Information on the shallow foundation design and basement construction of the buildings on the Flood Plain was also required to ascertain the possible significance of changes in groundwater levels in terms of increased seepage to drainage installations, new or additional uplift pressures on basement floor slabs and changes in foundation stresses. Some of the many types of development presently occupying the Flood Plain are shown in figures 2*a*, *b*, *c* (plates 1, 2 and 3). Serious seepage and stability problems occurred in King's County, New York City, when water levels rose following cessation of groundwater abstraction after many decades (Perlmutter & Soren 1963). Similar problems resulting from rising groundwater levels on the flood plains of the Ohio, Mississippi and Missouri have been avoided by installation of new or additional permanent de-watering systems (Leggett 1962).

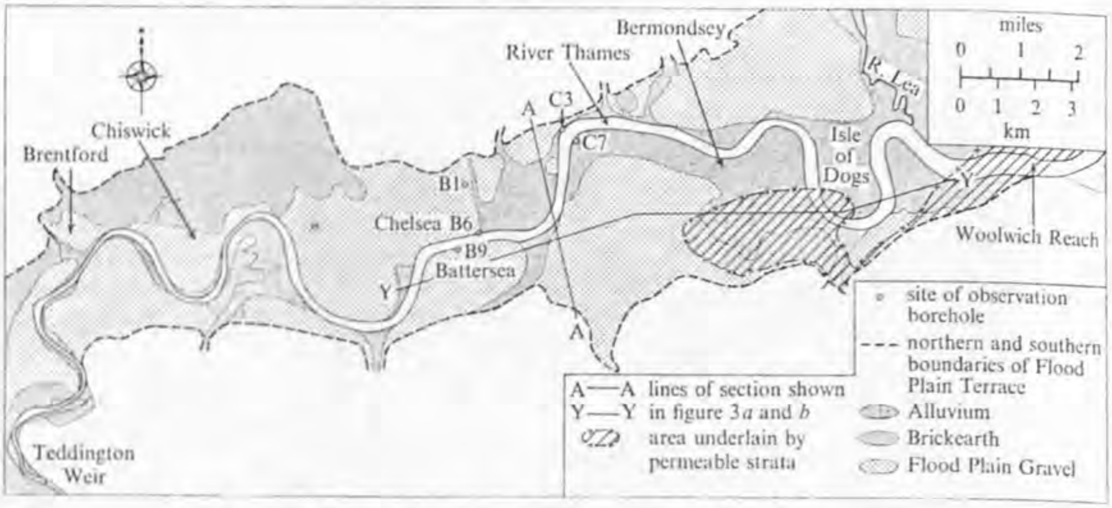


FIGURE 1. Location map and distribution of Flood Plain deposits.

Much of the detail of the groundwater study has been published elsewhere in a format appropriate to the Thames Barrier investigations (Gray 1969; Foster 1971). The present paper is concerned primarily with man's role in the recent past in modifying the natural groundwater conditions and the implications for future major civil engineering works on the Flood Plain Terrace.

DISTRIBUTION OF THE FLOOD PLAIN DEPOSITS

The terraces of the Thames have been the subject of much study and there is an extensive although scattered literature. The Flood Plain is of prime significance in the present paper and the higher terraces are not considered further. The Flood Plain Terrace is at the lowest elevation and comprises typically 6 to 18 m of sediment of three principal lithologies – alluvial silts and clays, brickearth (locally only, particularly in the west) and sands and gravels (figure 3*a* and *b*): it is these latter deposits through which the principal groundwater flow takes place. However, the requirement to consider the saturation conditions throughout the full thickness of the Flood Plain deposits necessitates consideration of the relationship of the groundwater in the low permeability, fine-grained materials to that in the highly permeable gravels. Over much of the Flood Plain, however, the deposits are overlain by made ground, exceptionally up to 6 m in thickness.

The geological history of the Flood Plain deposits was discussed by King & Oakley (1936). For present purposes, however, it is the character of the deposits themselves rather than their geological history which is of immediate relevance and as a first stage in the present study over

FIGURE 2. Oblique aerial photographs illustrating typical building and structures in the lower Thames Flood Plain. (Courtesy Aerofilms Ltd). (*a*) Kings Reach – Westminster – Waterloo (SV 10120). The narrow strip of Flood Plain on the north bank in the Central London area and the ground slope associated with its boundary is shown. The foreground includes the artificial lake in St James's Park and the complex of historic buildings in Westminster, whose original foundations and basements in general are probably shallow and thus potentially affected by changes in groundwater conditions. The modern developments on the south bank have pile foundations and extensive deep basements and subways which must interrupt the continuity of the Flood Plain strata. Much of the river wall in this area is relatively modern and has a deep foundation, nearly, or completely, cutting off the gravel stratum.

FIGURE 2 (*b*). Bermondsey and Isle of Dogs (SV 997). A high proportion of the total area has roof- and paved-cover and artificial surface drainage. Old buildings, probably with shallow foundations and small basements in Flood Plain gravel, predominate with some multi-storey blocks, probably with deep-piled foundations. The variable river-wall construction of the commercial waterfront and the large area occupied by the docks is well illustrated. The railway viaduct is a dominant feature, but probably has a shallow foundation and does not cut off the gravel stratum.

FIGURE 2 (*c*). Kensington area (SV 1009). A significantly higher proportion of open space than in (*b*). Dominantly terraced houses probably with shallow foundations and invariably with small basements in the Flood Plain gravel: increasing size of building is probably accompanied by increasing depth of basement, but shallow foundations were probably still employed.

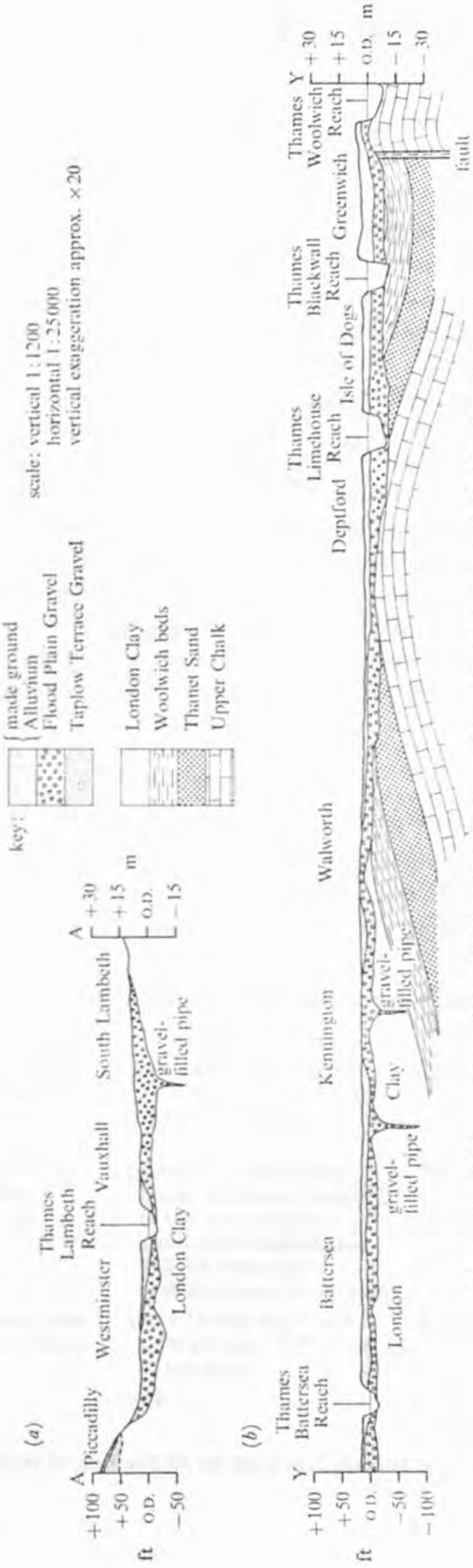


FIGURE 3. (*a*) Cross-section of the Flood Plain deposits. (*b*) Longitudinal section of the Flood Plain deposits.

1000 drilling records were analysed to compile a series of isopachyte and structure contour maps covering the area from Chiswick to Beckton (Mather *et al.* 1971). Five factors are illustrated.

(*a*) Thickness of the sand and gravel deposits.

(*b*) Thickness of the alluvium and brickearth.

(*c*) Contours on the surface of the sand and gravel.

(*d*) Contours on the surface of the solid strata.

(*e*) Percentage of sand and gravel in the Flood Plain deposits.

The deposits occupy a shallow, rather flat-bottomed channel cut in the underlying and impermeable London Clay, except in areas adjacent to the Isle of Dogs where a faulted anticline brings the Lower London Tertiaries (Woolwich Beds and Thanet Sand) and Upper Chalk to a subcrop beneath the Flood Plain deposits (figures 1 and 3*b*). The Thanet Sand and Chalk are permeable and can act as drainage sinks for water derived from the overlying riverine deposits and from the bed of the Thames. There is reference in much of the literature to the 'buried channel' of the Thames and Dewey & Bromehead (1921) indicate that such a channel can be traced downstream from Brentford. However, analysis of the drilling records indicates that a buried channel as a single feature of limited lateral extent does not exist. It is rather a broad, infilled channel with an irregular base in which subsidiary channels are present. At several locations abnormal thicknesses of gravel occur but these are considered by Mather, Gray & Houston (1970) to occupy local pipes such as those described by Edmunds (1931) at Battersea. These gravel-filled pipes are up to 23 m thick but they appear to be isolated from one another and do not form a continuous curvilinear feature. They may have a common periglacial origin (Higginbottom & Fookes 1971).

HYDRAULIC PROPERTIES OF THE FLOOD PLAIN GRAVELS

The hydraulic properties of the gravels are important from the present viewpoint and available data have been reviewed and analysed by Foster (1971). The principal relevant properties are summarized in table 1, but sampling and testing procedures are such that the values are

TABLE 1. PRINCIPAL HYDRAULIC PROPERTIES OF THE FLOOD PLAIN GRAVELS

hydraulic property	range of values	reference
permeability derived from *in situ* pumping tests without observation boreholes	0.56–0.81 $m^3\ day^{-1}\ m^{-2}$ 1150–1650 gal $day^{-1}\ ft^{-2}$ (0.055–0.080 cm/s)	Glossop & Collingridge (1948)
grain size distribution (g.s.d.) of borehole samples	typically bi-modal distribution with more than 50% of any given sample classified as medium sand (0.2–0.6 mm) and/or medium gravel (6—20 mm)	Foster (1971)
permeability estimated from mean g.s.d. by the Hazen formula†	$1.42 \times 10^{-3}\ m^3\ day^{-1}\ m^{-2}$ 2.900 gal $day^{-1}\ ft^{-2}$ (0.160 cm/s)	Foster (1971)
specific yield	0.14	Foster (1971) after Berry & Dean (1937)

† The Hazen formula relates to sand and its use for gravel material is strictly outside the range of valid application.

'order of magnitude' only. No satisfactorily controlled pumping tests with appropriate observation boreholes are known to the authors within the area under consideration.

THEORETICAL RIVER–GROUNDWATER RELATIONS

The typical relation between the water in a river and the groundwater of the deposits through which it is flowing is illustrated in figure 4. Fluctuation in the groundwater level is a complex function of several variables of which the principal are the level of the river, the hydraulic gradients prevailing in the riverine deposits and the porosity and permeability of those deposits. In non-tidal reaches and at low-flow stage (figure 4*a*), the river is effluent, i.e. it is gaining flow from the groundwater body. At high river stage the converse occurs and under this influent condition river water is recharged into the alluvial deposits. The high river stage (figure 4*b*) can be caused either by flood flows from upland sources, in which case the water quality will be fresh, or by tidal conditions in the estuarial reaches when saline water will be present. Under tidal régimes, influent and effluent conditions alternate in response to the diurnal tides and secondary groundwater tides are generated having amplitudes and frequencies related *inter alia* to the tidal régime of the river. Analysis of these two factors enables the hydraulic properties of homogeneous deposits to be determined where natural conditions obtain.

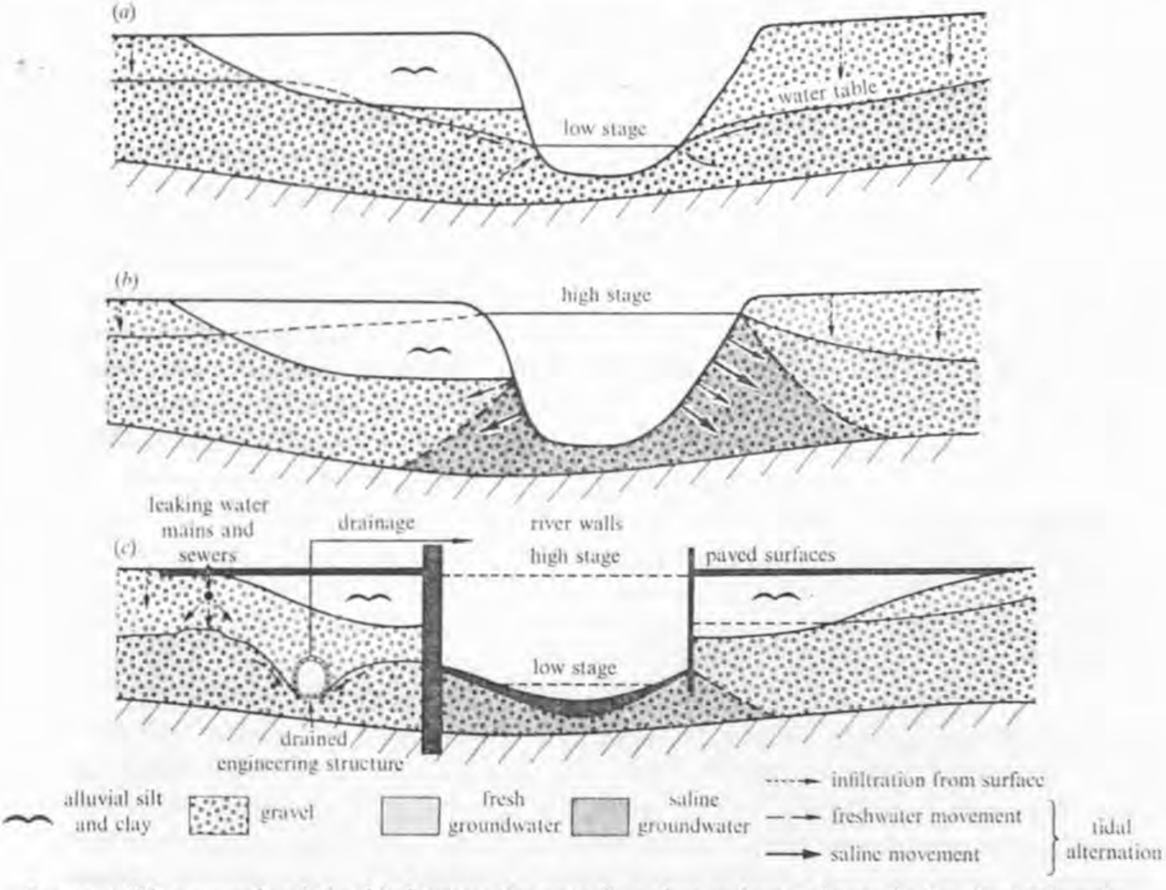


FIGURE 4. Diagrammatic relationship between the water in a river and groundwater in the alluvial deposits. (*a*) Natural conditions with low flow in the non-tidal reaches. (*b*) Natural conditions with high flow in the tidal reaches. (*c*) Man-modified conditions, including river walls and river-bed deposition.

In the tidal reaches, wedges of saline water can extend laterally from the river into the base of the alluvial deposits by virtue of greater density (figure 4*b*). The position of the interface between fresh and saline water will be defined by relative densities of the two fluids and the hydraulic properties of the deposits. This situation is further complicated by variations in the diurnal and monthly tidal heights and salinities and in the rate of tidal movements up and down the river. Superimposed on the effects of the diurnal and lunar tidal cycle there will be a seasonal effect whereby during periods of low upland flow, the saline content of the river at any given location may increase significantly. In the Thames this effect is highly significant (Anon. 1964).

This already complex flow and hydrogeochemical situation has been further modified by several of the man-made factors discussed below.

PRINCIPAL EFFECTS OF MAN'S OCCUPANCY

Although parts of the Flood Plain of the Thames have been occupied since pre-historic times, London developed from its original settlement on two low hills around St Paul's Cathedral and the City, and on a few lower islands, by a process of embankment and marsh reclamation on the south bank (Stamp 1947). Subsequent large growth in the low-lying marshlands became possible only after the creation of drainage systems on a sufficient scale to modify the natural conditions significantly. The process was gradual; the installation of the major low-level sewers and associated drainage works dating only from the 19th century. Prior to that some minor changes in groundwater level resulted from marsh reclamation and locally from bridge construction, and in the quality of the groundwater from the disposal of organic and inorganic pollutants derived from domestic and industrial sources.

The medieval London Bridge, for example, is likely to have caused a local modification to the hydraulic gradient. Its construction resulted in a fall in river level across the structure during some states of the tide and the higher water level upstream is likely to have led to a small rise in groundwater levels in the Flood Plain deposits under the adjoining banks. The detail of such local effects remains speculative, however, and there are few facts on early groundwater conditions which can be accurately identified as to precise location and elevation. The general outlines of the groundwater flow régime can be deduced from the geography of the tributary streams as these are likely to have acted as the drainage controls.

Since the early and middle 1800s, however, man has modified the original water balance of the Flood Plain deposits as well as the groundwater conditions in them in many ways; some pertain to groundwater levels and flow directions, and others to its chemical and bacterial quality. The principal factors are discussed below but few are mutually exclusive and their interactions have locally produced complex conditions, particularly as some operated at differing scales in different areas at different times and for differing periods.

(i) The creation of extensive impermeable surfaces associated with stormwater sewers for drainage of both roofs and paved areas. This has virtually eliminated natural infiltration over much of the Flood Plain, except in some parks, gardens and other open spaces. Conversely, uncontrolled recharge undoubtedly takes place locally through soakaways, leaking drains, high-level sewers and water mains, but on the present evidence quantification of this factor is not possible.

(ii) The construction of more or less continuous river walls which in some reaches reduce or eliminate hydraulic continuity between the Flood Plain deposits and the river.

(iii) Engineering construction employing various techniques which may alter the local flow net, including the use of blanket drains and the construction of water-tight tanked basements extending into or through the saturated gravel.

(iv) Artificial lowering of the water table by pumping, principally for drainage but occasionally for water-supply purposes. The gravels were a source of water, often grossly polluted, for medieval London, but have been little used in more recent times, either for domestic or industrial supplies.

(v) Raising the ground surface by the emplacement of appreciable thicknesses of made ground (Mather *et al.* 1971) and subsidence due to consolidation of the London Clay following abstraction of groundwater from the Chalk (Wilson & Grace 1942). Settlement of the Flood Plain deposits themselves must also have occurred.

(vi) The local modification of the climate in the Central London area resulting in changes in evaporation and transpiration rates following elimination of natural vegetation.

(vii) Culverting or diverting most of the streams which originally drained the area (Barton 1962). Relatively short lengths of these crossed the Flood Plain Terrace, but they were probably the base levels to which drainage originally took place and as such controlled the groundwater level. It is likely that the gravels beneath their courses may accept flow preferentially, where the more recently induced hydraulic gradients permit.

(viii) Since the middle of the 19th century the reduction, if not elimination, of the pollution which had entered the deposits before the introduction of main sewerage may have led to a reduced volume of recharge into the formations. This may, however, have been offset by leakages from water mains and sewers.

(ix) Variation of the chemical, bacterial and thermal pollution of the Thames has in turn varied the quality of the water infiltrating into the gravel during periods of high river stage.

(x) Alteration of the river régime will have modified the river–groundwater relation. For example, the constriction of the river by embankments will have changed the depositional–erosional balance and may have led to a rise in the height of tide levels (Bowen 1972, this volume p. 187).

Of most significance in the river–groundwater relationship is the construction of river walls which partially or completely eliminate hydraulic continuity between the two water bodies (figure 4*c*). Over sections of Kings and Lambeth Reaches, the walls act as total cut-offs with their footings set in the effectively impermeable London Clay beneath the gravels. Elsewhere, however, the walls are founded at shallower depths and hydraulic continuity is probably maintained. The structure of the walls in the old commercial-water fronts is not known in detail but is extremely variable. Throughout the Central London area, damaged and deteriorated sections of the wall are likely to exist but difficult to locate. An indication of the cut-off condition of the river walls throughout the present area is given in figure 6. Siltation of the river-bed also bears on the hydraulic continuity between the river and the groundwater body, but has not been studied in detail.

Another major man-made modification of the groundwater flow régime is the effect produced by pumping from the deposits in temporary or permanent dewatering systems used to protect civil engineering structures (figure 4*c*). Such abstraction can produce significant effects on groundwater levels and can modify the hydrochemical condition. For example, 6800 m^3/day have to be pumped continuously from the District and Circle Line underground railway to maintain effective track drainage between West Kensington and Temple Stations (Foster 1971). The result of this abstraction is that groundwater levels over much of the Flood Plain Terrace of the north bank drain to an artificial base below river level and fluctuations are largely damped out.

On the present limited evidence, artificial recharge into the gravels from leaking mains and sewers (figure 3*c*) is of lesser significance than de-watering. The current evidence for such recharge has not enabled the volume to be estimated even at an 'order of magnitude' level; this factor could be large and is undoubtedly one for which a significant allowance should be made in any urban water balance. The quality of the water which gains access to the gravels in this way would differ significantly from natural recharge in that it would not have infiltrated through a soil zone and undergone the alteration normally produced in that zone.

Groundwater levels

In civil engineering practice the level and possible fluctuations of the water table and the piezometric surface within the site boundaries control elements of foundation and basement design. Under natural conditions, groundwater levels in flood plain gravels can be expected to fluctuate in response to three principal causes – changes in river level including tides, seasonal variations in infiltration derived from precipitation and changes in barometric pressure. The rapidity of response of groundwater levels to changes in river levels is well illustrated by the tidal effect.

In the alluvial deposits of tidal rivers the propagation of groundwater tides is characterized by lateral movement of sinusoidal waves having a decreasing amplitude and increasing phase-lag with increasing distance from the river bank. The river wall cut-off in Central London has so modified the natural conditions that analysis for hydraulic properties has not yet proved possible.

The inverse relation between change in barometric pressure and change in groundwater level has already been widely observed in the present study. In the most sensitive boreholes, the effect recorded during periods of rapid barometric change has been up to 0.3 m per day. The rate of onset of the atmospheric change influences the response considerably and accurate correction of levels for this effect is not feasible. At times the changes may mask fluctuations resulting from other causes. Foster (1971) discusses groundwater fluctuations resulting from all causes in detail and the examples given below have been selected to illustrate the effects caused by man's activities.

The hydrographs (plots of water level against time) from five boreholes have been selected to illustrate artificial influences on fluctuations in water levels. The sites of the boreholes (B1, B6, B9, C3 and C7) are shown in figure 1, and relevant details in table 2. The water-level recorder charts for the period 10 to 30 July 1970 have been redrawn to a common scale and are shown in figure 5 related to Ordnance Survey Datum (O.D.).

Several features resulting from man's activities are illustrated. First, the hydrographs can be divided into those showing and not showing diurnal or monthly tidal effects. Secondly, a range of water levels which extends from 3.3 m below O.D. at borehole C3 to a mean level of 0.6 m above O.D. at B9. The highest tidal response (tidal ratio 0.30) also occurs in borehole B9, 24 m from the south bank of the Thames in Battersea Park and in which 2.7 m of gravel lies below the bottom of the revetment and the top of the London Clay. At a similar distance from the north bank in Chelsea, borehole B6 shows a greatly reduced tidal response (tidal ratio 0.01), as well as having a lower mean water level at 1.2 m below O.D. The lower tidal response is thought to be due partly to a lesser thickness of gravel available for hydraulic continuity and partly to artificial drainage. The level is held below O.D., and two metres or so below the mean level in the adjacent river, by pumping from underdrains beneath the tracks of the District and Circle Lines. A comparable low level is also seen in borehole B 1 to the north of the railway and too remote from the river to have a tidal response. Some 6800 m^3/day are abstracted from various drainage works between the West Kensington and Temple Station. Without these artificial effects the tidal response of borehole B6 would probably approximate to that of B9 and the water levels in gravels on the two banks would be comparable.

TABLE 2. BOREHOLE DETAILS AND TIDAL RATIOS

	(i) depth and (ii) ground surface elevation		distance from specified bank	thickness of gravel below wall foundation		river
borehole	m (i)	O.D. (ii)	m	m	tidal† ratio	wall construction
B1	10.9	7.4	1250 north	—	0.00	—
B6	10.7	5.6	24 north	1.2	0.01	mass concrete and sheet piling
B9	7.8	4.4	24 south	2.7	0.30	concrete revetment
C3	12.7	5.0	119 north	0.3	0.00	masonry-clad mass concrete
C7	10.4	4.0	49 south	0	0.01	mass concrete and sheet piling

† Ratio of the fluctuation of the groundwater level to that of the river in the same reach.

Similarly the water level in borehole C3 in the Victoria Embankment Gardens was held at 2.6 m below O.D. from June until October 1969 by pumping from permanent drainage works at Charing Cross Station. Since that date the level has fallen a further 0.6 m and is now held at 3.2 m below O.D., presumably due to additional, but at present unidentified, groundwater abstraction. The hydrograph from borehole C7, located on the promenade of the South Bank in front of the Festival Hall, was also well below O.D. in July 1970. This was a short-lived condition, however, related to the de-watering of the foundation excavations for the National Theatre and for St Thomas's Hospital. Until November 1969 the mean groundwater level was at or close to O.D. but during the de-watering, which lasted for almost 12 months, it was maintained at a lower level, down to 2.4.m below O.D. This example emphasizes the the necessity of maintaining water-level observations in studies of an urban environment for as long as possible and generally for not less than a year.

Under natural conditions, replenishment of the groundwater in the gravels takes place by infiltration derived from precipitation during the winter and early spring, with the subsequent recession of groundwater levels extending into late autumn or early winter. Such conditions apply in Battersea Park where artificial disturbances to the Flood Plain Terrace is minimal. The mean level of the boreholes in the Park declined from 0.85 m above O.D. in April to 0.46 m in October 1970. In boreholes elsewhere the natural recessions were modified to a greater or lesser extent by the reduction of the surface area of the Terrace deposits exposed by infiltration.

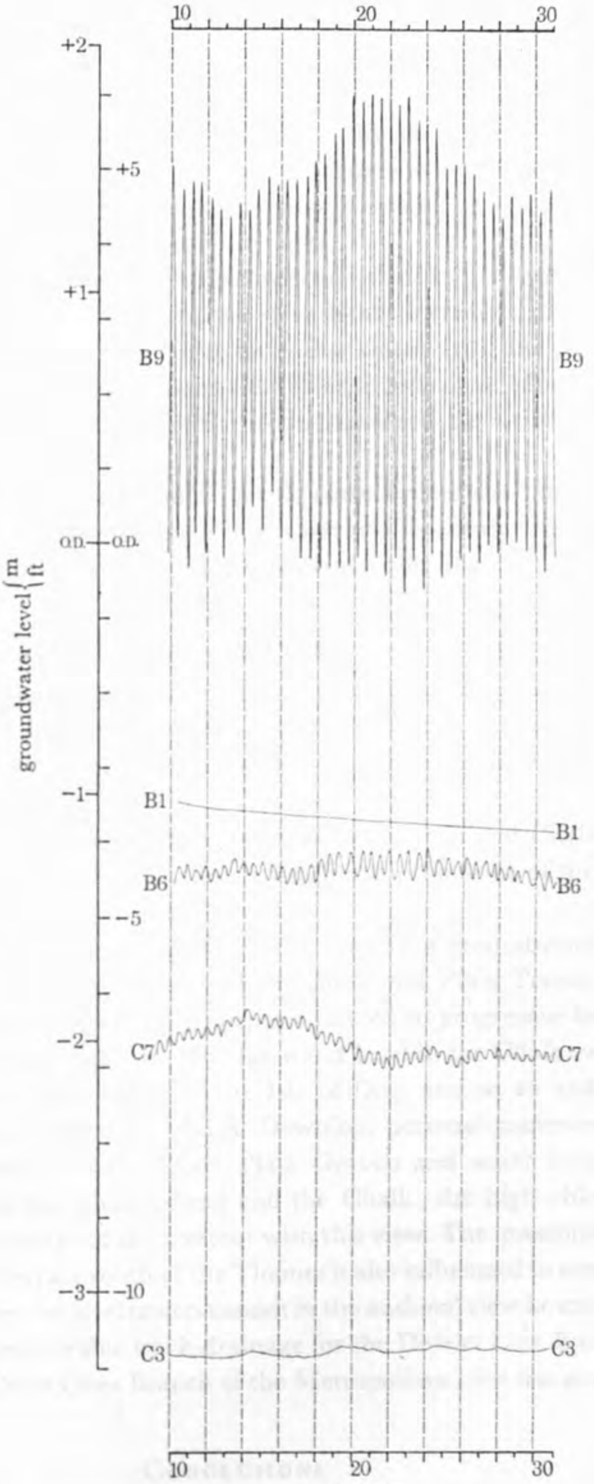


FIGURE 5. Selected well hydrographs from 10 to 30 July 1970.

HYDROGEOCHEMISTRY

Limited hydrogeochemical investigations were mounted to obtain a second and independent source of evidence on the river–groundwater relation and on the directions of groundwater movement. It was appreciated that the high cost and physical difficulties of arranging for temporary pumping from boreholes in an urban environment would preclude the routine sampling essential for the best results. Nevertheless, limited sampling was undertaken and the results have been described by Edmunds (in Foster 1971).

Analysis of the inorganic constituents in the groundwater samples generally showed decrease in all dissolved constituents as distance from the river banks increased, although there were some marked discrepancies. Additionally, in some embankment areas the possibility of small by-pass effects, due to damaged walls or leaking tidal flaps, is indicated. More obvious artificial effects relate to the locally heavy pollution of the groundwater samples as indicated by bacterial counts and nitrogen values.

In summary, the limited hydrogeochemical work corroborates the interchange of water between the river and the groundwater body but is not readily compatible with the concept of net mass transfer of water landward from some embankment areas.

GENERALIZED GROUNDWATER FLOW RÉGIME

A generalized flow régime, based on a summation of all available data, has been described by Foster (1971) and a simplified diagrammatic representation is shown in figure 6. Apart from the influence of the river walls, two principal man-made controls on the flow can be recognized – one on each bank.

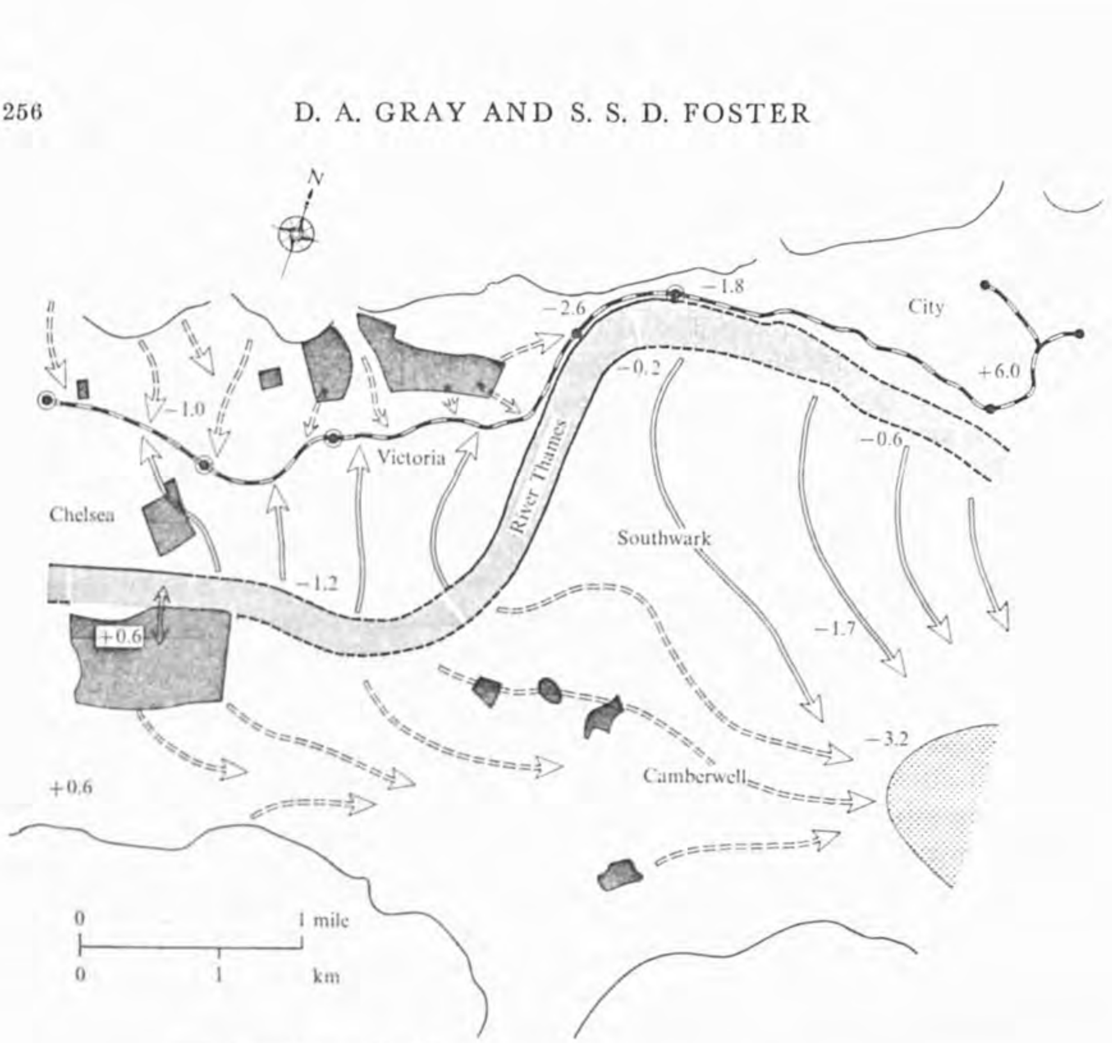
On the north bank, the protective drainage works of the District and Circle Line cause the railway to act as an asymmetric curvilinear sink. A significant proportion of the water draining to this sink appears to be derived from the Thames.

On the south, the principal drainage appears to be towards a groundwater sink where the permeable Thanet Sand and Upper Chalk underlie the Flood Plain Terrace. Groundwater abstraction from the Chalk for water-supply purposes has led to progressive lowering of water levels in that formation (Buchan 1938). In 1965 the water level in the Chalk varied from 7.5 m above O.D. at Greenwich to 7.5 m below in the Isle of Dogs and to 45 and 75 m below at Stratford and Charing Cross respectively (R. A. Downing, personal communication). Under those conditions groundwater from the Flood Plain Gravels and water from the bed of the Thames, could infiltrate into the Thanet Sand and the Chalk; the high chloride content in Chalk groundwater in the area is not inconsistent with this view. The possibility that the flow pattern in the Flood Plain Terrace south of the Thames is also influenced to some extent by flow into underdrains beneath the low-level sewers cannot in the authors' view be entirely discounted.

The significance of the considerable track-drainage for the District Line Railway in the East End of London and for the New Cross Branch of the Metropolitan Line has not been examined in detail.

CONCLUSIONS

The original concept of a flood-prevention structure across the Thames included consideration of a fixed barrage as well as of a removable barrier. Half-tide control of the removable barrier selected for construction has been advocated to improve the amenity in Central London by



— boundary of Flood Plain.

░ area where Flood Plain gravel is underlain by Thanet Sand and Chalk (probable groundwater sink)

▨ significant areas of open space on Flood Plain gravel outcrop (potential areas of precipitation recharge)

Probable degree of river wall cut-off

— full cut-off.

----- partial cut-off

‐ ‐ minimal cut-off.

═ sections of the L.T.E. underground railway where drainage of the Flood Plain gravel is undertaken

Pumping stations in track drainage network

◉ with average pumping rates > 455 m³/day

● with average pumping rates < 455 m³/day

−0.6 average ground water level in investigation boreholes in metres O.D.

⇒ groundwater flow direction substantiated by water level data

⇢ probable groundwater flow in other areas

FIGURE 6. Generalized groundwater flow régime in the Flood Plain deposits.

permanently submerging at least part of the inter-tidal flats. A fixed barrage would have led to a rise in groundwater levels throughout the Flood Plain Terrace, as well as in lower reaches of the Lea Valley. The effect of half-tide control of the removable barrier would be similar over much of the area. Prediction of the amount of the general rise in water level which would follow half-tide control formed an integral part of the study and has been undertaken.

The results of the study indicate that the groundwater conditions in the Flood Plain deposits have been and are greatly influenced by man. The Thames barrier to be erected in the Woolwich Reach could be operated in such a way that these influences would be modified appreciably. It follows that current drainage practices might require alteration, that major problems might arise due to increased uplift on basement floor-slabs and that minor interferences on shallow foundation stresses could occur.

The authors conclude that it is incumbent upon the promoters to determine the existing conditions and the probable effects on those conditions of the proposed method of operation of the barrier (Gray & Foster 1971). A fuller understanding of man's influence on the groundwater conditions and the interaction of individual influences would assist in the planning and implementation of many future civil engineering activities in the Thames Valley.

The extensive assistance in the field and the office provided to the staff of the Institute of Geological Sciences by the staff of the Director of the Greater London Council's Department of Public Health Engineering is gratefully acknowledged. Thanks are also due to the Chief Civil Engineer of the London Transport Executive for access to records and to the representatives of the several organizations serving on the Groundwater Working Party. The paper is published with the permission of the Director of the Institute of Geological Sciences.

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GROUND ENGINEERING

Proceedings of the Conference organized by the
Institution of Civil Engineers in London
16 June 1970

THE INSTITUTION OF CIVIL ENGINEERS, LONDON, 1970

CONTENTS

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On the question of interpretation of the data from field pumping tests the Authors of Paper 3 mentioned (§ 21) the use of transient condition analyses, but only in cases where the Dupuit equation is not justified. Has consideration been given in civil engineering site investigations to collecting full non-equilibrium data and applying such analyses as a matter of routine? This is the practice in hydrological work. For example, in the case of valley gravels it is accepted that such methods are useful not only in the evaluation of the permeability of the formation under investigation but also in the hydraulic behaviour of any nearby boundaries, such as rivers, which greatly modify its response to pumping whether for dewatering or for water supply purposes.

D325. Could some of the difficulties mentioned (§ 19) in making realistic assessments of the required size of dewatering installations result from an inadequate evaluation of the site conditions at the investigation stage, rather than an inadequate appraisal of their implications? Powerful as they unquestionably are, analogue models presumably are only as reliable as the information on which they are based.

D326. The importance of paying careful attention to the degree of penetration of the pumping wells and observation boreholes in relation to the problem to be solved is worth stressing. In cases where the full thickness of the water-transmitting formation was the concern, even 80% observation borehole penetration could lead to erroneous results should the formation consist of stratified sand and gravel deposits with a thin bed of clean cobbles at its base. Such formations were by no means exceptional.