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Overseas Geology Series

UNCONSOLIDATED SEDIMENTARY AQUIFERS : REVIEW NO 6 - GROUNDWATER MANAGEMENT IN UNCONSOLIDATED SEDIMENTARY AQUIFERS

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Sigatoka River flood plain, Fiji

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Unconsolidated Sedimentary Aquifers

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UNCONSOLIDATED SEDIMENTARY AQUIFERS (UNSAs)

PREFACE

This Review is one of a set of reports prepared as part of a project entitled 'Groundwater Development in Alluvial Aquifers', Project No R5561 (BGS 93/2), under the ODA/BGS Technology Development and Research (TDR) Programme of aid to the developing countries. The project addresses all unconsolidated sedimentary aquifers (UNSAs) not only alluviums.

This particular publication combines four Reviews by different authors. Each of these Reviews covers an important issue for management of the development of groundwater from UNSAs. Other management issues are covered in other companion Reviews. Those already published are listed overleaf. Also, the lead publication of the project entitled The Development of Groundwater, will be completed during 1995, which will give further guidance on the broader issues of management.

This publication is a compilation of existing knowledge. It is intended to be updated, as appropriate, following the results of research which will be carried out during the lifetime of the project, which is scheduled to run until 1996.

The project is funded by ODA as part of their research and development programme designed to improve living standards and conditions in the world's developing countries.

Project Manager: Dr R Herbert
Hydrogeological Adviser to ODA
British Geological Survey

A Guide to the sedimentology of unconsolidated sedimentary aquifers (UNSAs)

INTRODUCTION

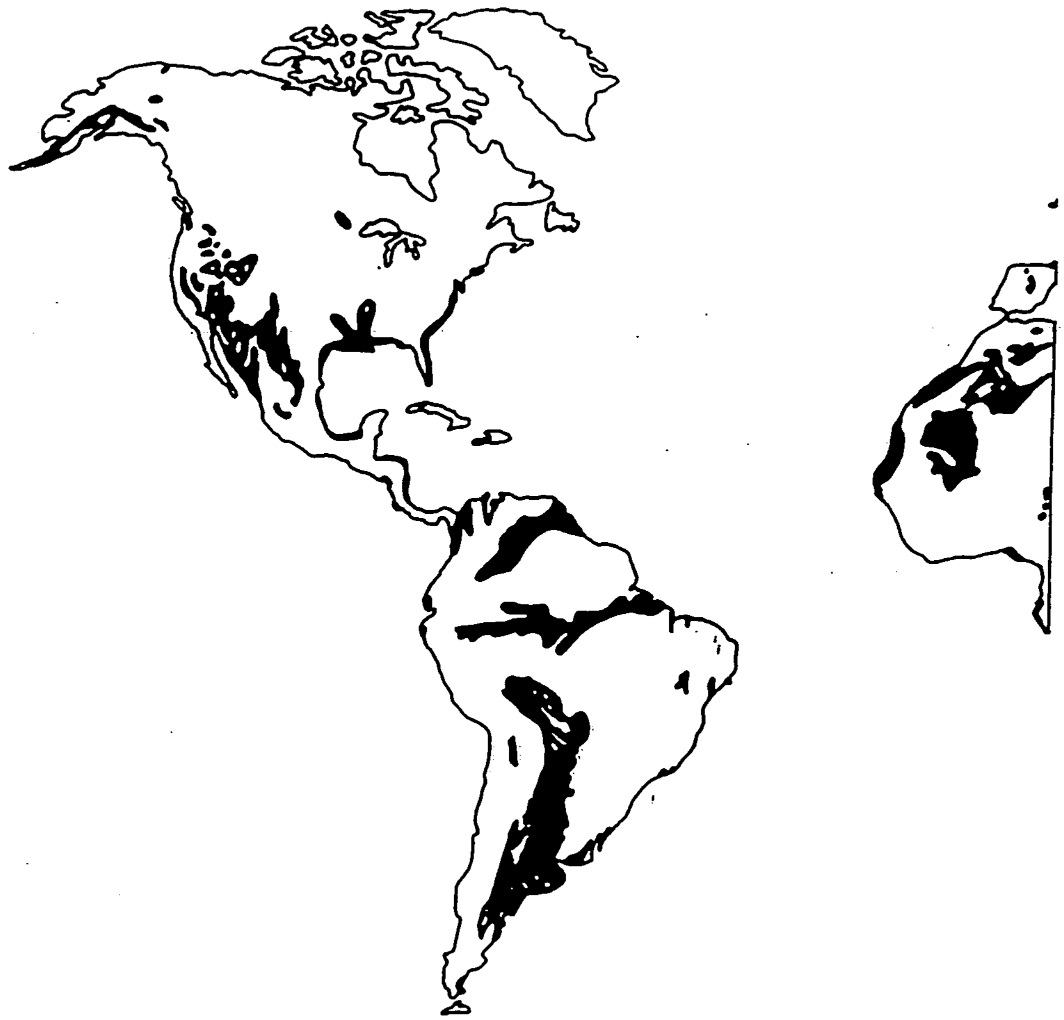
WHAT ARE UNSAs AND WHY IS IT IMPORTANT TO UNDERSTAND THEM?

UNSAs are unconsolidated sedimentary aquifers. These are the water-bearing strata within the swathes of unconsolidated sediment that mantle much of the earth's surface. There is no clear dividing line between UNSAs and aquifers in consolidated rocks, as lithification is a gradational process: deposits a hundred years old can be lithified, while some deposits 500 million years old are still essentially unlithified. However, for most purposes, UNSAs can be understood as deposits which have accumulated over the past few million years, that is during Quaternary and Neogene (late Tertiary) time. They are important sources of water in many parts of the world, and in particular constitute the only major sources of groundwater for vast areas throughout the developing world. In the influential text book ***Hydrogeology*** by Davies and De Weist it says:

> *"The search for ground water most commonly starts with an investigation of non-indurated sediments. There are sound reasons for this preference. First, the deposits are easy to drill or dig so that exploration is rapid and inexpensive. Second, the deposits are most likely to be found in valleys where ground water levels are close to the surface and where, as a consequence, pumping lifts are small. Third, the deposits are commonly in a favourable location with respect to recharge from lakes and rivers. Fourth, non-indurated sediments have generally higher specific yields than other material. Fifth, and perhaps most important, permeabilities are much higher than other natural materials with the exception of some recent volcanic rocks and carvernous limestones".*

To date, though, few attempts have been made to understand the detailed internal structure of unconsolidated aquifers even though such knowledge may be crucial to the long term success of any water development project. This shortcoming is probably the reason why the operational lives of many water boreholes are frequently much shorter than expected.

Understanding of the internal structure or 'architecture' of many types of sedimentary deposit has, however, advanced greatly over the past couple of decades. Part of this research has been academic, but much has been sponsored by the oil industry, so as to better predict the possible location of oil within sedimentary traps. Oil, like water, is most profitably located within bodies of relatively coarse-grained and porous sediment. Thus, there is obvious scope for applying this recently gained understanding to hydrogeological problems. Advances have also been made in the understanding of the geometry of complex 'soft-rock' deposits by the application of appropriate combinations of investigative techniques, including remote sensing, rapid geophysical methods and new drilling techniques. The combination of these bodies of knowledge can provide a framework for locating and assessing UNSAs.



MAJOR AREAS OF UNCONSOLIDATED SEDIMENTARY AQUIFERS WORLDWIDE

- The map shows the distribution of the thickest and most extensive Quaternary deposits in the world. The great majority of these are unconsolidated, and many include water-bearing deposits (UNSAs).

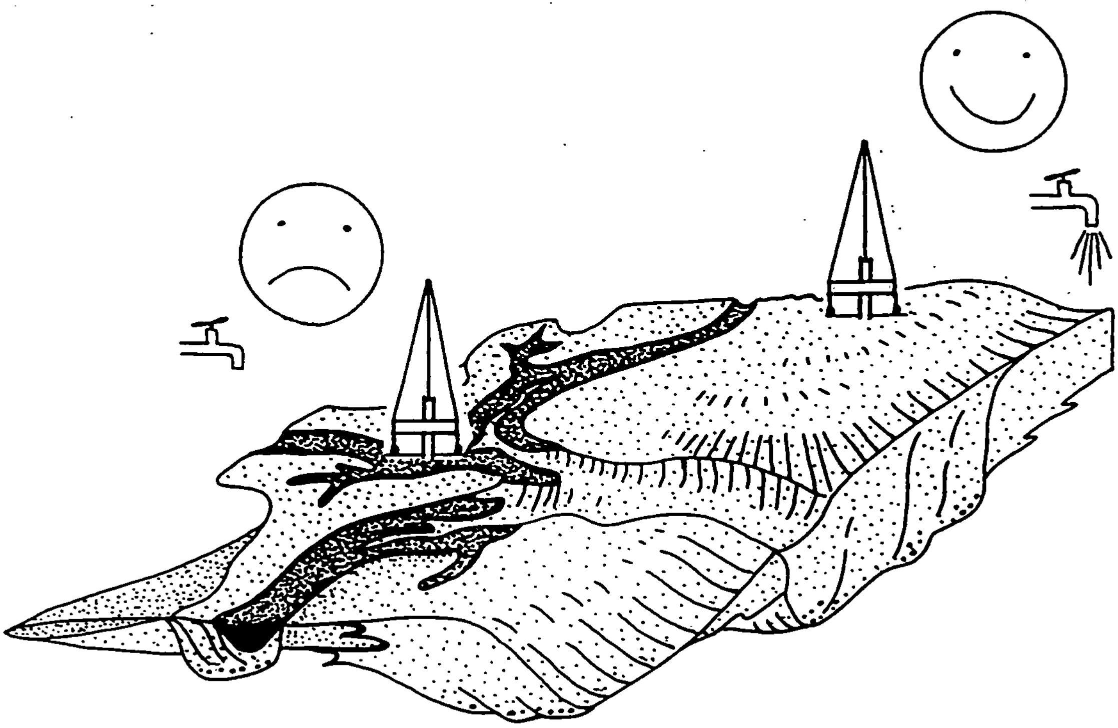
- A generalised world map such as this, though, severely under-estimates the true extent of UNSAs worldwide. This is because:

  - unconsolidated pre-Quaternary deposits are omitted; these too have a wide distribution, though are difficult to delineate (as they grade into consolidated deposits); they too can include significant UNSAs.

  - the simplification of linework necessary at this scale means that a large proportion of unconsolidated deposits have had to be omitted. The inset map shows the example of Uganda, which seems to have no unconsolidated sediments at the global scale, while significant and extensive deposits 'appear' once the country is looked at more closely. At a yet larger scale the unconsolidated sediments appear yet more widespread. The message is clear. *Unconsolidated sediments, and therefore UNSAs, are ubiquitous.*

Diagram data modified from various sources.


UGANDA
Lake Victoria
200 km
10 km



Sedimentary bodies are characterised by variably complex geometry and internal structure. These properties exert a strong internal control on the location, quantity and quality of groundwater. Diagram adapted from Galloway and Hobday (1983).

GROUNDWATER MANAGEMENT IN UNCONSOLIDATED SEDIMENTARY AQUIFERS

Compiler - N S Robins

Overexploitation
B Adams and A M MacDonald

Groundwater protection
B Adams

Groundwater drought
N S Robins and R C Calow

Subsidence caused by groundwater abstraction
T R Shearer

OVEREXPLOITATION OF UNCONSOLIDATED SEDIMENTARY AQUIFERS

by

Brian Adams & Alan MacDonald

CONTENTS - Part 1
OVEREXPLOITATION OF UNCONSOLIDATED SEDIMENTARY AQUIFERS

UNSAs OVEREXPLOITATION

1. AIMS

The purpose of this review is to discuss the concept of overexploitation of groundwater resources of UNSAs. The many possible impacts of overexploitation will evidently have implications for the socio-economic development of the region served by the aquifer in question; thus it is important that resources-management-strategies in UNSA environments take them into account.

The first noticeable effect of groundwater abstraction is that of lowering of the piezometric surface, initially on a local level (i.e. at the abstraction borehole itself) and subsequently at a regional level. If the total abstraction from the aquifer is less than the total recharge to it then, at some subsequent time, equilibrium conditions will once again pertain and water levels will stabilise. However, if the total abstraction continuously exceeds the recharge water levels will decline, in theory, until the aquifer has been dewatered. This latter condition is obviously one of overexploitation. However, even where recharge to the aquifer is greater than the total abstraction the decline in water levels can be sufficient to have undesirable impacts on the UNSA environment. Many of these impacts are discussed in detail in other reviews in this series, namely:

Saline Intrusion
Water Quality
Land Subsidence
Urbanisation
Agriculture and Rural Pollution

All such undesirable impacts can be considered as effects of overexploitation and reference should be made to the above mentioned reviews for a detailed consideration of the various processes involved. The objectives of this review are: to discuss the meaning of the term "overexploitation" (and related terms) as used in the literature and place it in the context of groundwater resource development strategies; to consider the duration of the transient stages in the development of any aquifer and to introduce implications for the socio-economic development of regions served by UNSAs.

This review is therefore essentially a discussion of a concept rather than a technique and as such will not strictly follow the format of the other reviews in this series.

2. AQUIFER OVEREXPLOITATION

2.1 Introduction

The concept of aquifer overexploitation is one that is poorly defined and is possibly incapable of definition. A number of terms have been used in the literature over the years to convey the concept but close examination shows that possibly there is really no one suitable generic term. Some of the terms which have widely been used are as follows.

Safe Yield: Meinzer (1920) defined safe yield of an aquifer as the water that can be abstracted permanently without producing undesirable results. This is a concept developed from the point of view of developers (i.e. managers and engineers).

Maximum Sustained Yield: (ASCE, 1961). The maximum rate at which water can be drawn perennially from a particular source.

Permissive Sustained Yield: (ASCE, 1961). The maximum rate at which water can economically and legally be withdrawn perennially from a particular source for beneficial purposes without bringing about some undesired results.

Perennial Yield: (Todd 1976) The flow of water that can be abstracted from a given aquifer without producing an undesired result - takes account of the influence of the exploitation pattern.

Overexploitation: This term is used from the point of view of administrators, environmentalists, sociologists and the public in general and puts more emphasis on the negative effects resulting - often used when total abstraction persistently exceeds total recharge.

Groundwater Mining: Generally used when groundwater is persistently withdrawn at a rate exceeding the recharge. As a consequence this yield must be limited in time until the aquifer storage is depleted.

Maximum Mining Yield: (ASCE, 1961). The total volume of water in storage that can be extracted and utilised.

Permissive Mining Yield: (ASCE, 1961). The maximum volume of water in storage that can economically and legally be extracted and used for beneficial purposes, without bringing about some undesired result.

Optimal Yield (Domenico, 1972). This is a dynamic concept which takes the form of an operating rule being a function of time (in the future) and the system's state (volume of water in store). It may also sometimes be considered to be a function of the water quality.

In general these terms depend on a concept of "undesirable results", a term which will be understood differently by the exploiter, an affected third party, the licensing authority, and an environmentalist. As such, "overexploitation" is a relative concept that depends upon the criteria used to define it: qualitative, economic, social, ecological etc.

Using general hydrogeological criteria, the concept of overexploitation has often been used to express a level of groundwater abstraction which exceeds the recharge over a given period of time and generates readily identifiable negative effects, some of which can be irreversible. However, as will be discussed in Section 2.2, even when recharge exceeds abstraction there will necessarily be a transition period, following the start of abstraction, before a state of so called dynamic-equilibrium is attained. During this transition period water levels will fall and, depending on local conditions, can initiate undesirable effects. Conversely, in terms of resource development in the context of development of the local and national socio-economies a purely hydro-geological definition of overexploitation will not be appropriate; in many situations there will be times when short-term abstraction at rates exceeding that of recharge will make sound long-term economic sense.

Sections 2.3 and 2.4 of this review consider the major undesirable impacts of groundwater development, the majority of which are due to declining water levels. Firstly the physical effects are considered and then the impacts on water quality. A brief consideration of the socio-economic implications is also given.

The discussion will show that it is generally more appropriate to consider "overexploitation" as a level of groundwater development rather than as a hydrogeological concept; in many cases the resultant undesirable effects not having been foreseen due to lack of knowledge of the groundwater resources and their behaviour under both natural conditions and when stressed.

Essentially adequate hydrogeological assessment of a groundwater resource is frequently difficult and a proper understanding, and indeed the formulation of proper management policies, can only realistically be established when an aquifer has been stressed (Lloyd, 1992). Thus, in general, overexploitation is not an easily bounded concept and depends upon the perception of both the short and long-term consequences of abstraction on the quantity and quality of the groundwater and on the related environment (Custodio, 1992).

A distinction between "aquifer overexploitation" and "groundwater exploitation" has been proposed (UNDTCD, 1991) and, as this is felt to be helpful to the debate, it is repeated here:

> Aquifer Overexploitation is chiefly concerned with the hydrogeological aspects.
>
> Groundwater Overexploitation is more management and economics oriented.

Thus this review is concerned with both aquifer and groundwater over-exploitation and indeed, as it is the managerial and developmental aspects which are of overriding interest, it is the groundwater overexploitation aspects which will be emphasized. Given this emphasis, a more useful definition of overexploitation is that given by Young(1992) as:

> a failure to achieve maximum economic return to the resource.

As mentioned above, definitions of overexploitation have generally depended upon the concept of "undesirable results", a term which will be interpreted differently by different groups of interested parties. Thus it is possible to classify the consequences of overexploitation into those which are considered to be undesirable by the exploiter, a third party or the environment. Inevitably there will be some overlap where some of the consequences will affect more than one of the groups. An example of such a classification for various of the effects of overexploitation is as follows:

Impacts on exploiters

- Decline of water levels: decreasing production, affects on permeability, increasing production costs.
- Decline in level causing conflict between neighbouring but differing interests.
- Local decrease in water level resulting in clogging of river bank sediments thus decreasing recharge from surface flow.
- Increase in the size of the unsaturated zone could reduce recharge rates.
- Loss of quality by induced pollution/saline intrusion.

Impacts on third parties

- Intensive exploitation in countries with temperate or humid tropical climates, can decrease outflows at the limits of the aquifer - a reduction in spring and base flows will affect any uses of these surface flows.
- Subsidence.
- Decrease in soil moisture - with undesirable effect on crops.

Impacts on the environment

- Decrease of springs and base flows affecting surface water courses and wetlands.
- Induced pollution.
- Subsidence.
- Decrease in soil moisture affecting natural flora and habitats.

Evidently prevention of the various consequences of overexploitation can be achieved by imposing controls on abstractions. Thus any form of exploitation which does not conform to those controls could be classified as overexploitation.

2.2 Transient stages during aquifer exploitation

2.2.1 Groundwater level decline

The first noticeable impact of abstraction on any groundwater system is a lowering of groundwater levels. It is therefore important to consider at what stage these falling water levels become serious and what level of drawdown is acceptable.

In an aquifer's natural state (i.e. prior to any development) all discharges usually balance the mean annual recharge, and groundwater levels will be constant around a given value, i.e. a state of dynamic equilibrium obtains. During the initial stages of development, piezometric levels decline, evaporation reduces as do horizontal and vertical outflows, recharge increases and a new dynamic equilibrium may be achieved. Under advanced development natural outflow continues to decrease (in some cases to zero), levels decline and recharge might decrease - particle movement may occur causing a reduction of the original porosity and permeability thus producing a lower infiltration capacity. Descending levels and increasing hydraulic gradients provoke drainage from the upper saturated zone and, in the extreme, fracture and subsidence can occur.

Thus at all stages of development there can be a state of hydraulic disequilibrium. However, this disequilibrium does not necessarily indicate excessive abstraction, and conversely "excessive" exploitation need not necessarily cause an indefinite state of hydraulic disequilibrium (see 2.2.2 on quality considerations). In those cases where total abstraction is maintained at a level less than the total recharge, a new state of dynamic equilibrium will eventually be attained. Thus, regional lowering of water levels over a significant period of time does not necessarily indicate that total abstraction is greater than recharge; however it might be that the associated effects of this lowering of levels are undesirable, e.g. increased pumping costs, dewatering of shallow boreholes/wells, saline intrusion, land subsidence.

Few studies have apparently dealt specifically with the duration of these transient stages between states of dynamic equilibrium but some general comments might be helpful.

As discussed in the hydrogeologic literature the time of dissipation of a perturbation is dependent upon the parameter

$$\alpha = L^2 S/T$$

where:

	L	=	a measure of the dimension of the aquifer
	T/S	=	aquifer hydraulic diffusivity
	T	=	transmissivity
	S	=	storage coefficient

Custodio (1992) reports that a perturbation essentially dissipates after a time $t = \beta.\alpha$ where β varies in the range 0.5 to 2.5. Figure 1 shows how aquifer size affects the duration of the transient stage for high and low transmissivity, unconfined and confined aquifers. Thus it can be seen that in medium to large,

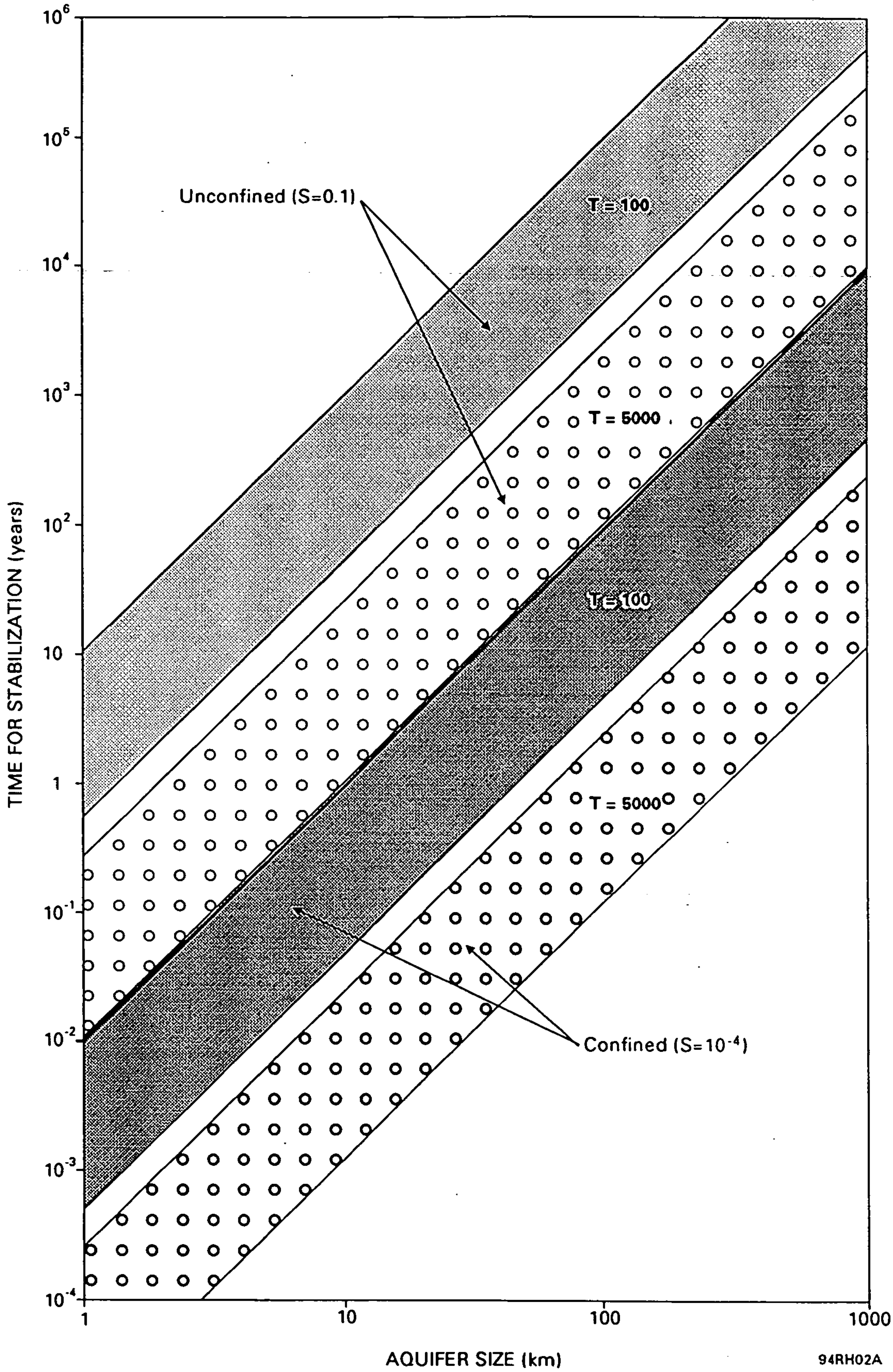


Fig 1. Time for stabilization of drawdowns (in years) in an aquifer after a sudden change in the water balance, according to size (L, in km) and as a function of transmissivity (T, in m^2/day) and the storage coefficient (S). The time is proportional to L^2S/T. (after Custodio 1992)

and especially low permeability aquifers, a continuous decline of water levels is not evidence enough to indicate that abstractions are necessarily greater than recharge - especially in the content of short-term (of the order of, say, 10 years) aquifer studies.

2.2.2 Groundwater quality

It is evident that, in general, derogation of groundwater quality would be deemed an undesirable effect and, whilst not necessarily caused by total abstraction exceeding recharge, could then be said to be indicative of over-exploitation. The falling water levels which occur during transition between stages of dynamic equilibrium can induce recharge of poor quality water from both surface water bodies and vertically adjacent saturated formations. Coastal saline intrusion can be induced or enhanced, and there has been a suggestion that inelastic compaction of clay layers (resulting from abstraction from layered aquifers) can induce undesirable quality changes in groundwater, e.g. increase in arsenic content (Welsh et al, 1988).

Again, a consideration of the duration of such transient states which might result in quality changes will be useful.

If a quality criterion is used to indicate overexploitation then other considerations arise, as shown for example in the case of the physical displacement of salinity fronts. If piston flow displacement is taken as a first approximation, then from Darcy's Law the velocity of displacement is given by,

$$V = k.i/m$$

in which:
- V = velocity of front displacement
- k = permeability in the direction of V
- i = hydraulic gradient
- m = kinematic porosity

Figure 2 uses the above relationship to show the time required for the horizontal displacement of a front, depending on permeability and various values of the kinematic porosity multiplied by hydraulic gradient.

A displacement time of a few years is a matter of concern and indicates a high probability of "overexploitation" but hundreds or thousands of years will probably be acceptable in the context of long-term development strategies.

In the case of a variable density fluid, for example in the case of seawater intrusion, the situation is complicated due to the influence of water density in the hydraulic head distribution (see the companion review on Saline Intrusion). In coastal aquifers a landward hydraulic gradient is a clear indication of overexploitation danger, but even maintaining a seaward gradient may produce salinisation problems due to the higher density of sea water (Custodio, 1992).

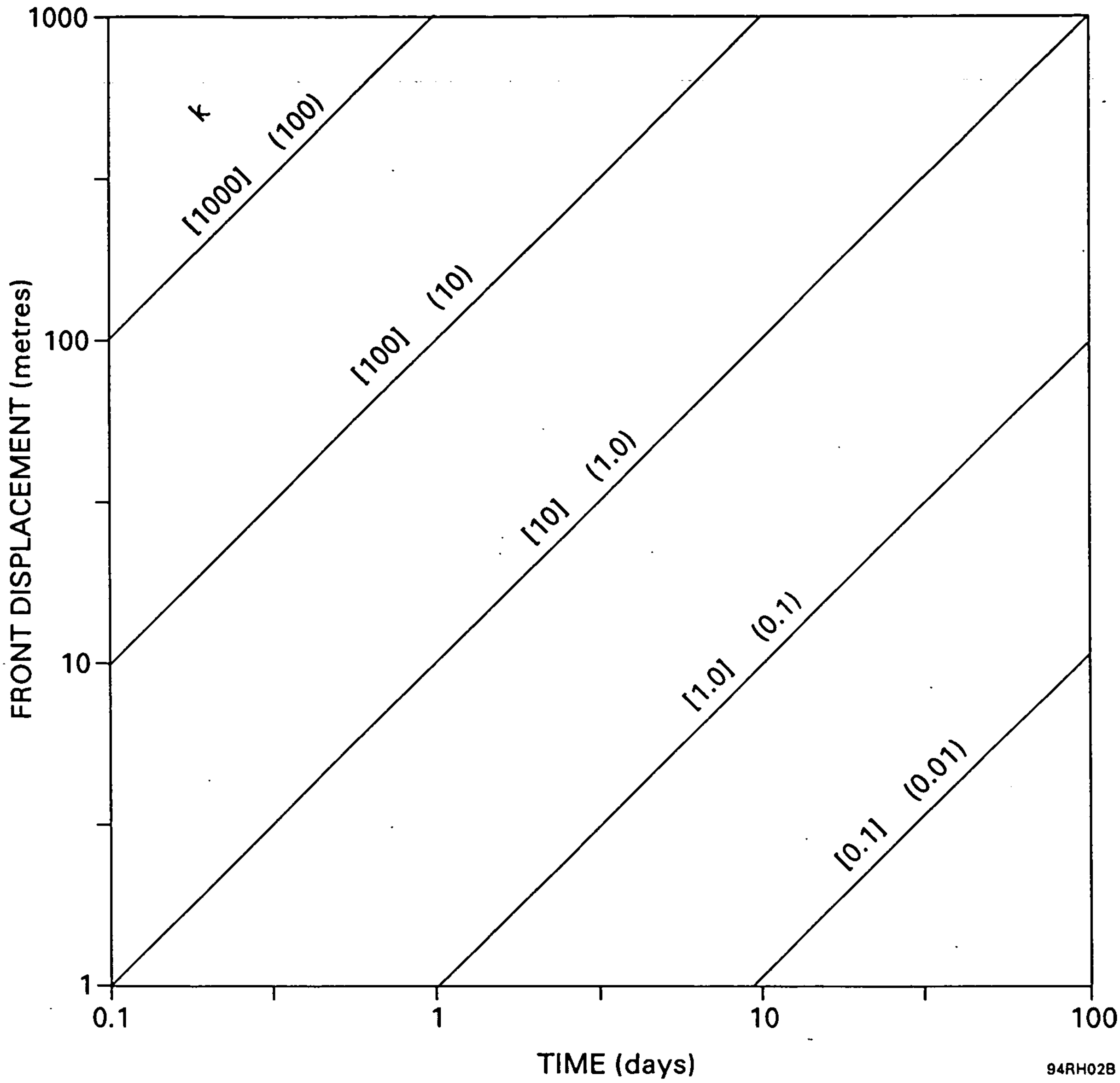


Fig 2. Time for horizontal displacement of a front or interface in an aquifer. k is permeability in m/day. [ ] is for m.i=3.10^{-4} (eg m=0.15 and i=0.002) and ( ) is for m.i=5.10^{-4} (eg m=0.25 and i=0.002). (after Custodio 1992)

2.3 The impacts of groundwater level decline

2.3.1 When do declining water levels become serious?

All aquifers, whether over-exploited or not, experience some degree of water-level decline as a response to pumping. It is important to consider, however, at what stage these falling water-levels become serious and what level of drawdown is acceptable. Ideally, this decision should only be made by people involved in managing the resource who can give careful consideration to both the physical and the socio-economic consequences of water-level decline. It is the purpose of this section, however, to consider only the physical aspects.

Water-level decline must be considered seriously when an aquifer is in disequilibrium, or in other words, when water-levels are unlikely to stabilize in the foreseeable future. The equilibrium state of an aquifer is governed by the following equation:

$$Q + D + \Delta D \Leftrightarrow R + \Delta R \qquad (1)$$

where Q is the abstraction from the aquifer; R is the recharge to the aquifer; D is the discharge from the aquifer; and ΔR and ΔD are respectively the change in recharge and discharge as a result of abstraction. If the abstraction is very high the recharge and discharge cannot sufficiently adjust to balance the equation, therefore, there is a deficit in the water balance and the aquifer is not in equilibrium. This deficit is met by adding another term to the water balance equation:

$$Q + D + \Delta D \Leftrightarrow R + \Delta R + \Delta S \qquad (2)$$

where ΔS is the change in groundwater storage. As groundwater is continually taken from storage, the resource will be depleted and groundwater levels will steadily decline. Some aquifers with a large component of groundwater storage can continue in this state for many years, no aquifer, however, can sustain this level of exploitation indefinitely. Unfortunately, gathering all the information required to undertake a large water balance calculation is not always feasible and as a result it can be difficult to ascertain whether an aquifer is in equilibrium. In many cases, however, the abstraction is so much larger than the recharge that the disequilibrium of the aquifer is obvious.

Any other classifications of the significance of groundwater-level decline are necessarily arbitrary and will vary according to local conditions. A pragmatic approach, however, can give very simple guidelines based on the relative fall in water-levels with respect to the thickness of the aquifer. An example of such an approach is shown in Table 1.

Relative fall in water-level	*Seriousness of decline*
< 20%	slight
20-60%	significant
> 60%	great

Table 1. A example of classifying the seriousness of water-level decline by the reduction of water-level with respect to the initial saturated thickness of the aquifer (after UNTCD 1991).

Some aquifers are more susceptible to water-level decline than others. The following sections outline the most important factors to consider when determining the susceptibility of an aquifer.

2.3.2 The significance of the geological environment

2.3.2.1 Introduction

Throughout the world, a great variety of rock types and sedimentary deposits are used to supply groundwater. These aquifers vary greatly in composition and structure, and each aquifer will respond slightly differently to pumping. Consequently, some geological environments are more susceptible than others to falling water-levels. To examine in detail how each particular aquifer geology can promote water-level decline would be a huge and somewhat unprofitable exercise, therefore a different approach has been taken. Three different aspects of geology are discussed: the hydraulic diffusivity; aquifer stratification; and lateral heterogeneity, each of which should be applicable to all geological environments. Consideration of these three parameters will show that UNSAs are particularly susceptible to over exploitation and will give some insight into why.

2.3.2.2 Hydraulic Diffusivity

When investigating the effectiveness and reliability of a rock strata or sedimentary deposit for providing a source of groundwater, the two most important aquifer parameters to determine are the transmissivity, T and storage coefficient, S. Numerous analyses have been developed over the years to help provide reliable estimates of these two parameters from pumping test data (Kruseman and de Ridder 1990). When considering how susceptible an aquifer is to over-exploitation it is useful to combine the two terms to give the *hydraulic diffusivity (Hd)*:

$$Hd = T/S \qquad (3)$$

Therefore, aquifers with a high transmissivity and low storativity will have a high hydraulic diffusivity and those with low transmissivity but high storage coefficients will have a low hydraulic diffusivity. In general, the higher the hydraulic diffusivity the more susceptible the aquifer is to water-level decline.

Aquifers with high hydraulic diffusivity allow groundwater to move rapidly throughout the aquifer, but have relatively little groundwater storage. Groundwater levels can therefore rapidly decline as the small amount of groundwater in storage is moved quickly to abstraction boreholes and pumped out. In aquifers with low hydraulic diffusivity, however, groundwater cannot move so quickly through the aquifer, and the amount of groundwater in storage is relatively high. As a result, drawdowns are more localised and the aquifer on a regional basis will be less susceptible to general water-level decline.

Variation in hydraulic parameters both laterally and with depth in some UNSA environments can result in some areas being more susceptible to groundwater level decline than others.

2.3.2.3 Stratification

It is very unlikely that an aquifer will be uniform throughout its entire thickness. In UNSA environments particularly, cyclic sedimentation often occurs, giving lenses of clay among silts, sands and gravels. The degree to which an aquifer is stratified can have a marked effect on how susceptible it is to groundwater-level decline. There are two main ways in which stratification can affect an aquifer - inhibiting vertical recharge and reducing transmissivity.

Inhibiting Recharge:

The presence of low permeability layers within an aquifer can reduce the vertical movement of water within that aquifer. As a result, a situation is created where there is not one large aquifer, but many smaller aquifers. The particular horizon from which water is being abstracted, therefore, might not receive any recharge from the surface, and water-levels could quickly decline. The true stratified nature of the aquifer might not be identified from short pumping tests, with the result that the resources available for exploitation would be over-estimated.

Reduction in transmissivity:

A number of aquifers have discrete horizons of enhanced permeability. The majority of flow is derived from these horizons with the rest of the aquifer remaining relatively unproductive. As water-levels decline, the most productive layers can progressively be dewatered, significantly reducing the transmissivity of the aquifer and thus enhancing groundwater decline.

An example of where this dewatering has occurred is in the Quaternary aquifer system of Lima, Peru. The aquifer comprises unconfined alluvial deposits with irregular sedimentation. Geophysical investigations have identified two layers with different permeabilities: the top layer comprises 50 m of sand and gravel, and the second layer clays and silts. Groundwater levels have declined to such a degree that the top layer has been totally dewatered and the water is now derived from the second less permeable layer (Uchuga 1991). The specific yield of the abstraction boreholes has dramatically reduced, resulting in greater drawdowns for less yield.

2.3.2.4 Lateral Heterogeneity

The majority of groundwater flow through an aquifer is horizontal in a direction imposed by the regional hydraulic gradients. If the vertical component of recharge reaching the aquifer is small, then lateral sources of recharge become more important. If the aquifer is laterally extensive and highly permeable, then recharge can travel long distances to replenish the depleted parts of the aquifer. Lateral heterogeneity, however, can impede the movement of this recharge, thus exacerbating water-level decline.

Lateral heterogeneity can take several forms: (1) lithological heterogeneity, with the result that persistent strata are not developed; (2) tectonic discontinuities, which can truncate or break up aquifers; and (3) buried channels - palaeo-geographic relief can be back filled with less permeable deposits (Marinos and Diamandis 1992). Whatever the nature of lateral heterogeneity, the results are similar - the impediment of the lateral movement of groundwater and the reduction of recharge to the aquifer. The groundwater barriers might only become apparent after several weeks pumping and therefore would not be detected by a short pumping test. This highlights the need for pumping test results to be treated with caution - they should always be interpreted in light of the local geology and structure.

2.3.3 Recharge

2.3.3.1 Introduction

The quantity and reliability of recharge is one of the most important factors in determining the susceptibility of an aquifer to over-exploitation. Unfortunately, it is also one of the most difficult parameters to accurately predict. Recharge to an aquifer can occur in several different ways which fall broadly into two categories - diffuse and point sources. These will now be considered in turn.

2.3.3.2 Diffuse sources of recharge

When considering the recharge to an aquifer the primary concern is often to estimate the amount of precipitation that falls onto the aquifer outcrop. A proportion of this rainfall will be used to supply the water requirements of vegetation, some more will constitute surface runoff or intermediate flow through the soil horizons discharging to first order tributaries or streams. A certain amount, however, will drain through the soil and unsaturated zone and be used to recharge the groundwater resources of the aquifer.

In arid or semi-arid regions, precipitation can be low and sporadic. As a result the annual replenishment of the groundwater resources cannot be relied upon and significant recharge may only occur once every 5 or 10 years. In other environments, the aquifer may not receive any significant modern recharge - the abstracted groundwater might originate from rainfall that fell tens of thousands of years ago during a pluvial period. Equation (2) illustrates that if recharge is low, the water balance is maintained by taking water from storage, which results in the lowering of groundwater-levels. On the other hand, if recharge to the aquifer is high, the aquifer has a renewable source of groundwater and water-level decline, if occurring, should be reversible at any stage by reducing abstraction.

From studies undertaken in Zimbabwe, Houston (1989) suggested that if the annual amount of rainfall was below 400 mm then it was unlikely that the aquifer would receive any significant recharge. Above this value, the proportion of rainfall that would reach the aquifer would be dependent on the soil type and vegetation cover. Aquifers with very low precipitation over the outcrop, can however, receive recharge depending on the nature of the recharge events. If the annual allocation of rainfall occurs in only one storm, it is possible for the soil moisture deficit in the soil to be overcome and for a significant proportion of the rainfall to infiltrate. If rainfall is too heavy, however, the pore spaces and cracks in the soil can become saturated and a lot of the rain can flow over the surface and lost to streams or rivers. This can sometimes benefit other parts of the aquifer, where the local flooding of a river can allow water to infiltrate into shallow aquifers (eg wadis or river valley flood plains).

It is a well documented fact that the exploitation of groundwater can result in an increase in the diffuse recharge to an aquifer (Martinez 1991). The lowering of the water-table creates space in the unsaturated zone for increased drainage, therefore reducing runoff, and can also reduce the evaporation losses from the aquifer. As groundwater-levels continue to fall, however, this beneficial state can be lost.

In heavily exploited aquifers which have not yet reached a state of dynamic equilibrium it is possible that recharge occurring at the outcrop of the aquifer might never reach the water-table. A simple calculation should demonstrate this: if the vertical movement of recharge through the unsaturated zone is 1 mmd^{-1} and water-levels within the aquifer are declining at a rate of 1 myr^{-1}, then the recharge front would be travelling at a slower rate than the water-table. This effect would be enhanced by the presence of low permeability layers within the unsaturated zone.

2.3.3.3 Point Sources of Recharge

Important replenishment to aquifers can be given by the surface hydrology. Aquifers which are particularly reliant on point sources of recharge should be managed carefully to ensure that this important connection is not lost.

Initially, as with diffuse recharge, the exploitation of groundwater resources can increase recharge by reversing flow directions within the aquifer. Streams and rivers for example, which originally were fed by groundwater, can end up recharging the aquifer, if the head in the aquifer is reduced to below the head in the river. For some aquifers in arid regions this is the primary source of recharge.

With decreasing water-levels, however, the water-table might decline so far beneath the surface hydrology that this direct connection is lost. However, in some instances, local reductions of water table in an aquifer may cause deposition of silt on the river bed leading to a reduction in permeability and hence diminished recharge (Margat 1992).

The quality of the recharging water is extremely important for the protection of the aquifer. If the river becomes polluted then the aquifer can become vulnerable to contamination and the water supply affected (this is dealt with in more detail in Section 4.4). It is therefore important to ensure not only that the quantity of recharge is kept high, but also that the quality of the water is good.

2.3.4 Geometry

2.3.4.1 The volume of the aquifer

UNSAs occur in a variety of shapes and sizes, ranging from small alluvial deposits on basement rocks to large sedimentary basins. The volume and thickness of an aquifer can be very important in determining how susceptible it is to significant water-level decline and therefore possible over-exploitation.

In general, an aquifer with a large volume will also have a large amount of groundwater stored within it. If this volume of groundwater in storage is substantially larger than the annual abstraction then it can act as a buffer against declining water-levels. Water can flow from other parts of the aquifer to replace the abstracted water - therefore abstraction can be sustained by distributing the effect over a much larger area. An aquifer with a small volume, however, does not provide this buffer. If the total groundwater storage is not much more than the annual abstraction, the failure of one recharge event could significantly reduce the groundwater resource with the result that wells and boreholes could become dry.

2.3.4.2 The thickness of the aquifer

The thickness of an aquifer can also determine how seriously an aquifer will be affected by water-level decline. In a thin aquifer, falling water-levels are much more important than in a thick aquifer, since relatively speaking more of the aquifer is lost: ie a 10 m drawdown would cause a 50% water-level decline in a 20 m aquifer, but only a 10% decline in an aquifer 100 m thick.

Groundwater decline in a thin aquifer significantly reduces the saturated thickness and therefore the transmissivity of that aquifer. As a result of this lowered transmissivity, or possibly if the regional hydraulic gradient is small, the lateral movement of water within the aquifer can be impeded, thus locally exacerbating water-level decline. The groundwater cannot move freely to the places where it is most required. This could be considered as a positive effect, acting as a natural regulator to stop the complete emptying of the aquifer, but in practice it renders the aquifer over-exploited locally, where the water is needed the most (Rushton 1986).

2.4 The impacts of abstraction on groundwater quality

2.4.1 Introduction

The abstraction of large amounts of groundwater can often lead to the deterioration of water quality within an aquifer. This deterioration can occur for various reasons, but in general, the new hydraulic head distribution, created by pumping, encourages bodies of low quality water to move into the aquifer, therefore, contaminating an originally fresh resource. The low quality water can have many different origins, seawater incursion, the upconing of deep connate waters, and also the downward leakage of contaminated surface waters. An aquifer which has been contaminated as a result of over-pumping can be considered over-exploited.

Once contaminated, it can be very difficult to restore the aquifer to its original condition (often, even if remediation is possible, it is financially prohibitive). Intrusion of poorer quality water should, therefore, be identified and prevented at the earliest opportunity.

Maximum recommended salinity (mgl^{-1})				
700	850	1300	1700	2100
French Beans	Beans	Onion	Artichoke	Spinach
Strawberries	Celery	Cauliflower	Tomato	Asparagus
Flowers	Lettuce	Cucumber		Beetroot
Peas	Potato	Sweet Corn		Cabbage
	Citrus	Grape Vine		

Animal	*Maximum Salinity (mgl^{-1})*
Sheep	6000
Beef Cattle	4000
Horses	4000
Dairy Cattle	3000

Table 2. **(a) The maximum recommended salinity of various garden plants under average conditions of soil type and drainage; and (b) The salinity tolerance of various animals for healthy growth, providing sufficient feed is available. (Department of Agriculture, UK 1982)**

Evidently contamination of fresh water can affect its potability and, for water used for domestic supply, any pollution which results in the standards for potable water not being met needs to be recognised. Equally, plant and animal life can suffer if they do not receive a good supply of fresh water. Different plants or animals have different tolerances to brackish water, some are extremely sensitive to small changes in the water salinity while others can tolerate quite large increases without much deterioration in health (Table 2). Three broad bands are suggested for gauging the seriousness of increasing salinity, based on the effect on plant and animal life (Table 3). Groundwater that falls into the category of slightly saline is still fit for human consumption and can be used to grow most garden crops. As the salinity increases to serious levels, the water can only be used to irrigate the hardiest crops, but can still be used to water most livestock. Extremely saline water, however, is not really of any agricultural use apart from providing drinking water for sheep.

Salinity of groundwater (mgl^{-1})	*Seriousness of increase*
< 1000	slight
1000 - 5000	serious
> 5000	extreme

Table 3. **A classification of the seriousness of increasing salinity levels in groundwater based on the deterioration in the health of plant and animal life.**

Another way in which the intrusion of water with dissimilar hydrochemistry can affect an aquifer is to alter the *physical* properties of the aquifer. These physical changes can manifest themselves in changes in porosity and permeability and result from diagenetic processes, brought about by water-rock interaction (Goldenburg et al 1986). Therefore, if the chemical properties of the pore water are altered, a new chemical environment is created in which various minerals and ions will react to achieve a new equilibrium. These changes will not only occur when saline water is drawn into an aquifer, but also when saline water is flushed out by fresh water. Consequently, the processes can be non-reversible and irrevocably damage the fabric and transmissivity of an aquifer. It is therefore important to know both the geochemistry of the aquifer and the hydrochemistry of the recharge water to accurately predict any diagenetic processes.

The factors which make an aquifer more susceptible to a deterioration in water quality are discussed in the following sections.

2.4.2 The existence of a saline front

When pumping from an aquifer, hydraulic gradients are set up which induce groundwater to move towards an abstraction source. As discussed previously in Section 2.3, this lateral movement of groundwater is necessary to stop water-levels declining too rapidly. There is no guarantee, however, that the water moving to replace the abstracted groundwater will be of as good quality as that abstracted. If a body of saline water exists in hydraulic continuity with the aquifer, then the new hydraulic head distribution will draw the saline water into the aquifer, thus reducing the quality of the water in the aquifer. Therefore the vulnerability of an aquifer to quality deterioration as a result of pumping, depends on the existence and proximity of a body of saline water.

The most obvious place to experience saline intrusion is beside the sea. Under normal circumstances the head in the aquifer will be higher than sea-level, therefore, water will flow from the aquifer to the sea. If, however, over-pumping reduces the head in the aquifer to below sea level then this scenario is reversed and saline water will flow from the sea to the aquifer. The situation is further complicated due to the density difference between saline and fresh water and the presence of a mixing zone between the two waters. As a result the saline front is unlikely to be a sharp vertical line separating the two types of water, but rather a curved, indistinct boundary with the saline water encroaching furthest at depth.

If there is negligible circulation of groundwater, some aquifers may contain large amounts of connate or ancient waters. These waters may originate from the time of deposition, which, if marine, may have been highly saline. Mineral dissolution can also produce saline groundwater. Again, if there is negligible throughflow of groundwater, water-rock interactions can take place over millions of years resulting in high levels of minerals in solution. Since these sources of saline water require little circulation of groundwater, they tend to be more common at depth. As a result of pumping, the hydraulic regime is disrupted and these waters can upcone into the exploited aquifer.

Shallow aquifers and the surface hydrology can also be sources of poor quality water. In Section 2.3.3 it was suggested how pumping could increase the downwards leakage of recharge into an aquifer, either through the soil horizon or from streams and rivers. These shallow sources of water are particularly vulnerable to contamination, therefore, increasing the downward movement of groundwater can correspondingly increase the vulnerability of the deeper aquifers. Contamination can happen directly, either, through urban or agricultural pollution. Increased application of pesticides and fertilizers can be leached into the groundwater; industrial waste can pollute rivers or shallow aquifers; urbanization without proper sanitation can introduce chemical and biological contaminants into the aquifer.

Contamination of shallow aquifers can also happen *indirectly* as a result of high rates of evaporation. Inappropriate use of irrigation can result in much of the water evaporating and the minerals being left in the soil. Salinity levels in shallow aquifers can, therefore, steadily increase, rendering deeper aquifers vulnerable to contamination.

In summary, when estimating how susceptible an aquifer is to saline intrusion and therefore over-exploitation, it is extremely important to identify any sources of poor quality water in the vicinity. For aquifers close to the sea the problem is easily identified, for inland aquifers, however, the threat may be less apparent although no less significant.

For more detailed discussions on saline intrusion and water quality considerations, the reader is directed to the appropriate companion reviews in this series.

2.5 Subsidence

The extraction of water from UNSAs can give rise to land subsidence depending upon the quantity of water involved and local geological conditions. Usually, much of the subsidence occurs within the fine-grained interbeds (aquitards) located within the coarser component of UNSA aquifer systems. When water is extracted all strata are subjected to an increase of stress which causes them to compact. However, compaction in the aquifer layers is small compared to that in the compressible interbeds.

In extreme cases the effects of such subsidence can be enormous; subsidence of the order of 9 m has occurred in the UNSA underlying Mexico City for example.

For a more detailed account of this phenomenon the reader is directed to the companion review in this series on subsidence.

2.6 Socio-economic considerations

2.6.1 Introduction

Groundwater exploitation produces economic benefits through water application in agricultural and industrial activities, and accomplishes a socio-economic role in supplying water for urban and rural areas. However, exploitation-related problems may have a direct or indirect influence upon economic costs as well as being the cause of social protest and economic changes; they represent a real cost although its evaluation is a difficult (and controversial) task.

Fear of encountering problems related to overexploitation frequently leads to the establishment of aquifer exploitation rules (e.g. water laws and regulations, exploitation permits and regional/national water plans). Such rules are obviously intended to avoid the negative effects of exploitation but they may also counteract some of the advantages inherent in groundwater (Custodio, 1989).

2.6.2 Controlled development versus unrestricted exploitation

Whilst recognising that neither Utopian government control nor a perfect groundwater market will ever be found in practice, economic comparison of controlled-development with unrestricted groundwater exploitation is useful for discussion (Foster, 1992; Custodio, 1989).

A typical evolutionary trend for unrestricted exploitation compared to the controlled development case is illustrated in Figure 3. Figure 3a includes the effects of aquifer deterioration and, in the case of unrestricted exploitation, shows a rapid increase with time in the total abstraction and number of wells until the point is reached where deterioration in quality causes a sharp decline in both the number of wells maintained in production and the total abstraction. The long term total abstraction is likely to be lower than would have been the case had controlled development taken place, indicating the need for increasing caution at the irreversibility margin. Such caution is likely to be ignored by unrestricted private exploiters anxious to squeeze maximum benefit from a resource which might soon be exhausted.

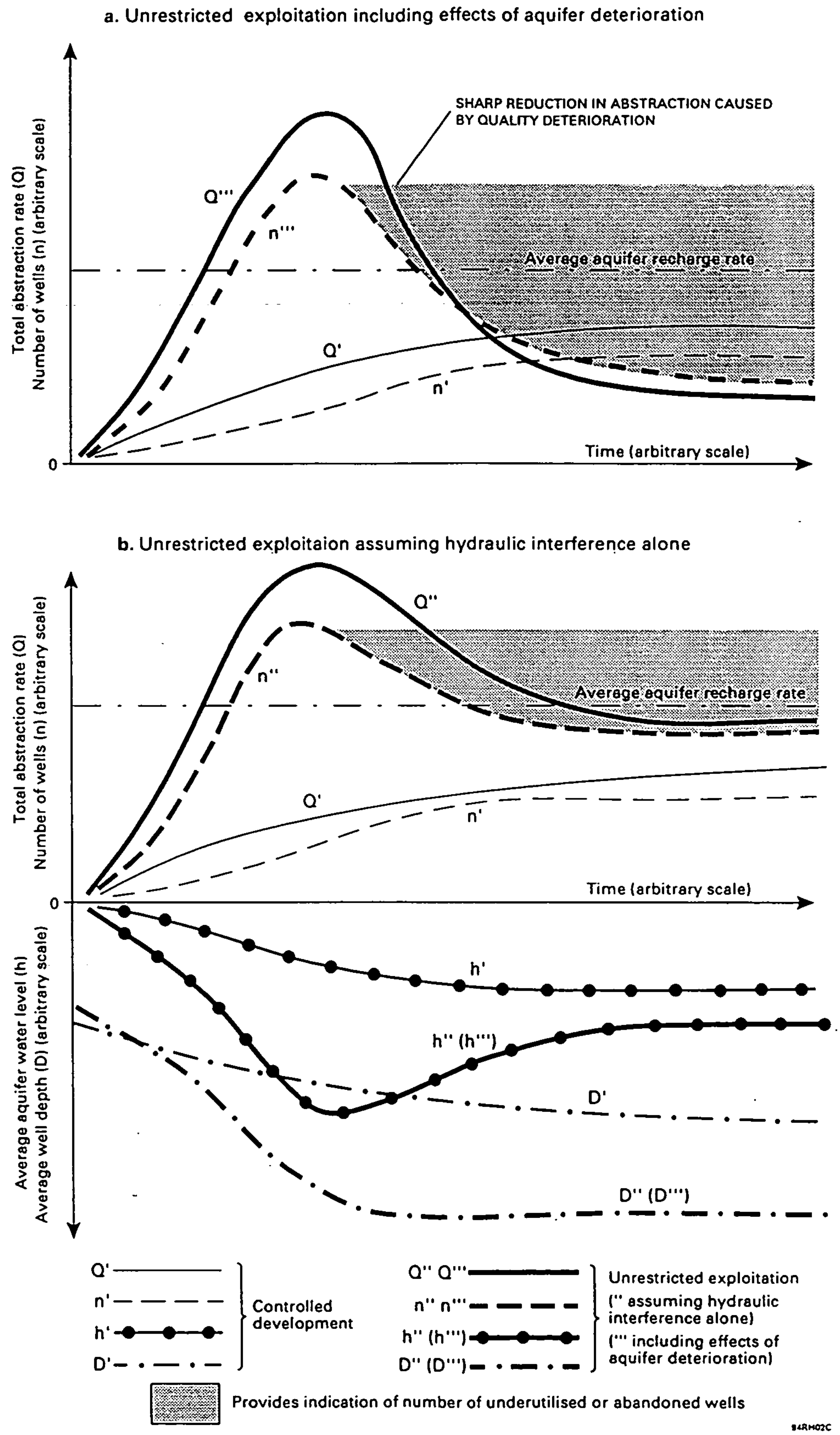


Fig 3. Evolutionary trends for unrestricted exploitation and controlled development of groundwater resources (after Foster 1992, developed from Custodio 1989)

In Figure 3b the only externality of groundwater exploitation taken into account is hydraulic interference with other water users (i.e. quality is not considered). In this case unrestricted exploitation is likely to achieve a higher level of resource exploitation more quickly although at the possible price of drilling a disproportionally larger number of wells (n″ max. as compared to n′ max) to greater than optimum depth (D″ long term as compared to D′ long term).

The potentially sharp reduction in abstraction, as a result of the ingress of poor quality water soon after peak levels of exploitation are reached (Figure 3) can result in major losses of capital investment in groundwater development and utilisation (Thomas and Martin, 1989). These trends are expressed in relative cost terms in Figure 4.

This is a typical example of a class of resource problems called "common pool" problems. When no one owns the resource, users have no incentive to conserve for the future, and the self-interest of individual users leads to over-rapid exploitation as shown in Figure 3.

Custodio (1989) suggests that unrestricted groundwater development apparently yields long-term efficient results if a breakdown at the stage of maximum withdrawal can be avoided; such breakdowns may result in serious economic and social repercussions which would prove unacceptable. However, such "breakdowns" might only affect those with least ability to defend their "rights" and thus might not be identified until significant impacts have resulted. This is the problem of external costs or externalities, i.e. unwanted and uncompensated costs imposed on third parties who do not themselves benefit from the exploitation activity. Where such costs are significant separate cost-benefit calculations by individual exploiters will not yield a collectively optimal rate of exploitation.

It has to be recognised that an optimally-controlled development which eventually achieves the maximum resource utility for minimum number of production wells and lowest level of recurrent costs while taking all externalities into account is effectively unachievable in practice. Some form of control over groundwater exploitation is often only introduced after substantial abstraction has already developed. This is normally achieved by prohibiting or limiting the construction of new boreholes and/or restricting abstraction rates from existing boreholes, with the aim of protecting existing users against subsequent developers.

Foster (1992) proposes a more logical approach whereby all groundwater development should be submitted to a compensation criterion such that it would only be permitted if those who benefit can afford to fully compensate those they derogate; however, he recognises that evaluation of appropriate compensation is problematical and thus the criterion cannot be very widely adopted.

Custodio (1989) proposes a flexible water development plan containing some restrictions to preserve and protect water quality and environmental values, but largely open to free development - however he does note that *"illconceived Water Plans may be worse than no Plan at all"*.

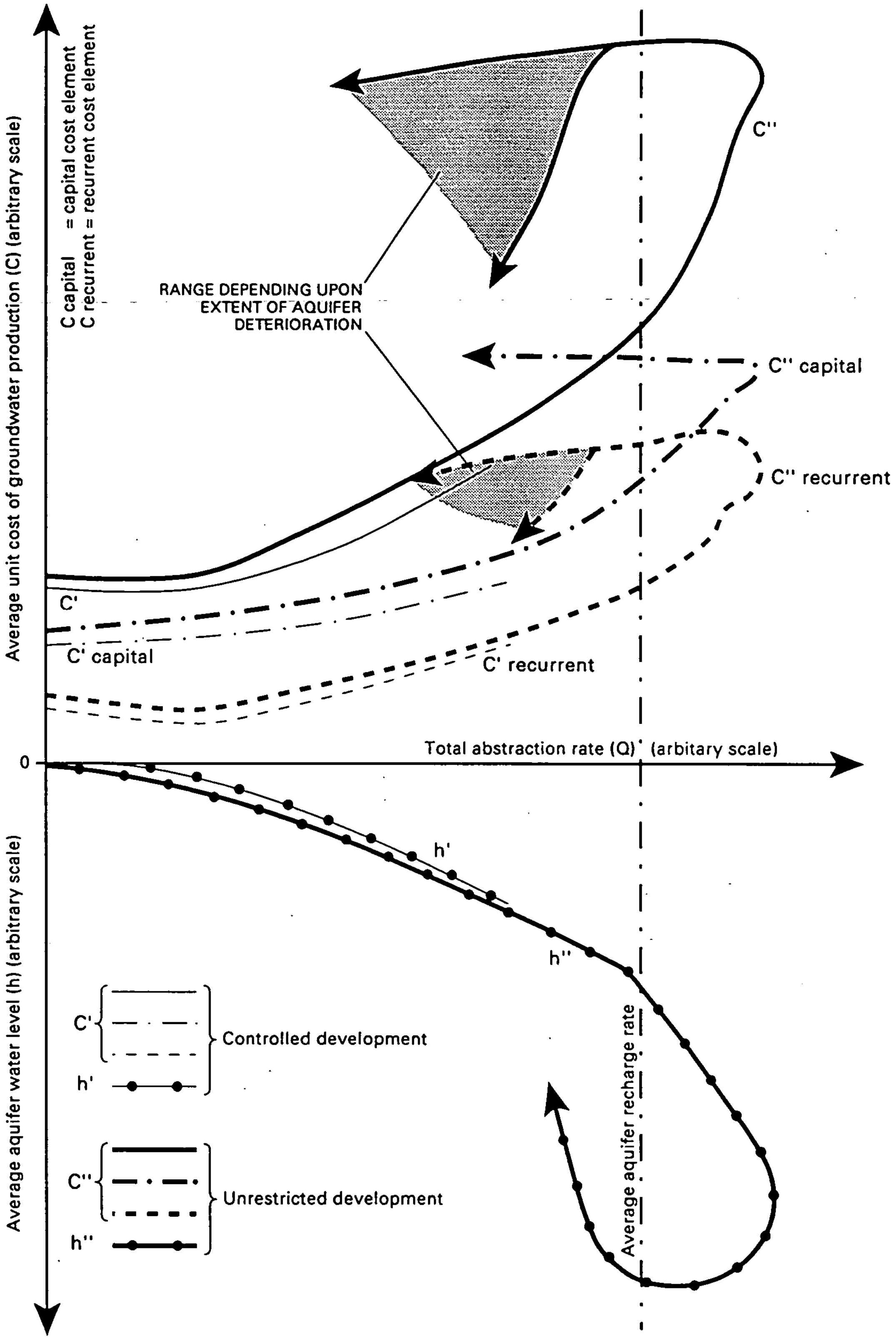


Fig 4. Trends in the cost of groundwater production with increasing abstraction rate for unrestricted exploitation and controlled development (after Foster 1992 developed from Thomas and Martin, 1989).

2.6.3 A study of aquifer overexploitation

A recent study (Adams et al 1994) investigated aquifer overexploitation in the Hangu area of the Municipality of Tianjin in the People's Republic of China. The study investigated the socio-economic impact of overexploitation of the UNSA, with a view to providing a framework for improved water resource management; this was achieved by socio-economic analysis of the impact of overexploitation and of alternative abstraction regimes, and development of a digital hydrogeological model to simulate land-subsidence resulting from the aquifer overexploitation.

The study established a methodology based on a spread-sheet to evaluate the various costs associated with the separate physical impacts of overexploitation. The cost categories identified were: (i) extra investment and pumping, (ii) land subsidence damage, (iii) changing to alternative and often more expensive water sources. Quantification of these costs was attempted from available data and a methodology for their estimation established. Within the limitations of the data used, the results suggested that the increased operational costs of abstraction were responsible for the major cost-increase resulting from overexploitation. Surprisingly, the costs of land subsidence did not figure prominently. It should be noted however that this was not a definitive conclusion and it could change if different assumptions were made and if a more sophisticated model, taking geographical area into account, could be developed.

This type of inter-disciplinary study is seen as necessary to develop optimum management of groundwater resources in UNSAs, either to avoid the onset of overexploitation as defined by Young (1992 - i.e. a failure to achieve maximum economic return to the resource), or to mitigate its impact.

3. GLOSSARY

Overexploitation:

> Aquifer overexploitation: a level of groundwater development having undesirable hydrogeological impacts.
>
> Groundwater overexploitation: a non-optional level of groundwater development having undesirable socio-economic impacts.

Hydraulic Diffusivity:

> The ratio of an aquifer transmissivity to storage coefficient:

$$Hd = T/S$$

4. THE FUTURE

At the time of preparation of this review, a 3 year study of Aquifer Overexploitation (BGS/ODA TDR project Ref No: R5544) is drawing towards completion. In this study consideration is given to development of a set of diagnostics to determine particular aquifers' susceptibility to overexploitation. Although this current review is concerned only with UNSAs it is expected that a subset of the diagnostics developed could be appropriate to discussion of UNSA environments. The same ongoing study is also developing a simple socio-economic model to enable comparison of the costs of alternative means of meeting a region's future groundwater supply requirements, taking into account the overexploitation impacts of the alternative schemes. It is likely that, in the future, such socio-economic models, linked with groundwater flow and quality models, will provide an important management tool for the exploitation of UNSAs.

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PROBLEM SUMMARY SHEET (01)

TITLE: Overexploitation of UNSAs

The Problem

The first noticeable effect of groundwater abstraction is that of lowering of the piezometric surface, initially on a local level (i.e. at the abstraction borehole itself) and subsequently at a regional level. If the total abstraction from the aquifer is less than the total recharge to it then, at some subsequent time, equilibrium conditions will once again pertain and water levels will stabilise. However, if the total abstraction continuously exceeds the recharge water levels will decline, in theory, until the aquifer has been dewatered. This latter condition is obviously one of overexploitation. However, even where recharge to the aquifer is greater than the total abstraction the decline in water levels can be sufficient to have undesirable impacts on the UNSA environment. Such impacts can include: Saline Intrusion, Derogation of Water Quality, and Land Subsidence - an abstraction regime resulting in such impacts is often termed as being overexploitation.

The concept of overexploitation is one that is poorly defined and is possibly incapable of definition. In general, definitions used in the literature depend upon a concept of "undesirable results", a term which will be understood differently by the exploiter, an affected third party, the licensing authority, and an environmentalist. As such, "overexploitation" is a relative concept that depends upon the criteria used to define it: qualitative, economic, social, ecological etc.

A useful distinction can be drawn between "aquifer overexploitation" and "groundwater exploitation":

Aquifer Overexploitation is chiefly concerned with the hydrogeological aspects.

Groundwater Overexploitation is more management and economics oriented.

Given that the socio-economic emphasis is important to the development of a region, a consideration of "Groundwater Overexploitation" is probably more relevant in the context of the series of UNSA reviews of which this document is one. Hence a relevant definition of overexploitation is that given by Young(1992) as:

a failure to achieve maximum economic return to the resource.

The following Project Summary Sheet summarises a recent inter-disciplinary study which gives an insight into the methodology that can be required to develop optimum management strategies for UNSAs' groundwater resources; either to avoid the onset of overexploitation, or to mitigate its impact.

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PROJECT DESCRIPTION SHEET (02)

TITLE: **Aquifer Overexploitation in the Hanhu Region of Tianjin, People's Republic of China**

The Project

A collaborative project between the Hydrogeology Group of the British Geological Survey (BGS) and the Tianjin Bureau of Geology and Mineral Resources (TBGMR) was established in January 1992 to investigate aquifer overexploitation in the Hangu area of the Municipality of Tianjin in the People's Republic of China. Socio-economic aspects of the study were undertaken by the Natural Resources Institute (NRI) under a consultancy agreement with BGS and Nankai University, Tianjin, as consultants to TBGMR.

The purpose of the study was to study the socio-economic impact of overexploitation of the layered aquifer system with a view to providing a framework for improved water resource management. This was to be achieved by socio-economic analysis of the impact of overexploitation and of alternative abstraction regimes, and development of a digital hydrogeological model to simulate land-subsidence resulting from the aquifer overexploitation.

The socio-economic study established a framework of physical impacts and associated costs. The cost categories identified were: (i) extra investment and pumping, (ii) land subsidence damage, (iii) changing to alternative and often more expensive water sources; there were few data available on this final category for inclusion in the study.

From available data, quantification of these costs was attempted and a methodology for their estimation established. The principal items on this methodology being the costs of investment in replacement wells, operation and maintenance and land subsidence. Given the limitations of the data used, the results suggested that the increased operational costs of water abstraction were responsible for the major cost-increase resulting from overexploitation. Surprisingly, the costs of land subsidence did not figure prominently. It is emphasised, however, that this was not a definitive conclusion and could change if different assumptions are made and if a more sophisticated model which takes geographical area into account could be developed.

The relationship between the rate of depletion and its economic cost was studied, based on certain assumptions about abstraction and cost. This was achieved by construction of a model to study the increase in cost of water abstracted assuming overexploitation (and thus aquifer depletion) continued over a 20-year period. The model indicated how the unit cost of water could be expected to increase over time. Consideration of the benefits side of the analysis indicated that, while the chemical industry is the greatest industrial consumer of water in Hangu, the water used is low in value compared to other industrial uses. The value of water used for irrigation is lower still, being even lower than the cost of supply. This suggests that present water supply policies are not sustainable in the long-term.

Alternative management strategies for Hangu were then considered. Whilst options generally being considered in China are primarily concerned with supply augmentation, it was argued that a demand-side strategy should be considered alongside. The principal means of reducing the increase in demand would be the use of economic pricing with incentives also being offered for increased use of recycling and water-saving devices.

In order to better understand the relationship between abstraction and subsidence a computer model of the aquifer systems was developed. This was based on the US Geological Survey's groundwater model "MODFLOW" with an interbed drainage module developed specifically as part of this study. The model was calibrated against the best available estimates of subsidence over the past 35 years. The model was then used in predictive mode to estimate the subsidence likely to result from various pumping scenarios up to the year 2020.

It is hoped that future work will include further validation of both the socio-economic and land-subsidence models and also investigation of the means of linking the two models to assist with evaluation of management options for continued development of the groundwater resource.

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GROUNDWATER PROTECTION IN

UNCONSOLIDATED SEDIMENTARY AQUIFERS

by

Brian Adams

CONTENTS - Part 2

GROUNDWATER PROTECTION IN UNCONSOLIDATED SEDIMENTARY AQUIFERS

1. AIMS

The major objectives of any approach to groundwater protection should be to protect both the quantity and quality of the groundwater resources as a whole, and of existing and potential individual groundwater supply sources (boreholes, wells and springs). This review discusses both aspects (i.e. protection of quantity and quality) and, where necessary, makes reference to other reviews in this series where further relevant detail may be found.

The purpose of this review is therefore to consider the protection of existing groundwater availability and quality from anthropogenic impact. Whilst little can generally be done to protect groundwater availability in UNSAs from derogation due to natural causes (e.g. lack of recharge during prolonged drought) some consideration is given to this problem. However, it is worth noting that so-called natural derogation (such as saline intrusion) often only becomes significant when exacerbated by man's activities (such as groundwater abstraction).

Protection of groundwater availability by controlling exploitation is generally well understood although not necessarily widely practised, and, in the often relatively finely balanced hydrogeologic environment of UNSAs, it is important that both the rights of individual abstractors and the overall resource availability are adequately protected. Protection of groundwater quality is perhaps less well understood and less widely practised than "protection of quantity". This review report presents a pragmatic approach to both aspects and makes reference to some of the alternative methodologies available.

2. APPROACHES

2.1 Control of Exploitation

2.1.1 Introduction

A useful discussion of the control of groundwater exploitation was provided in a manual by Foster et al (1993) and this has been used as the basis of this section of the current report.

There are two aspects to the control of groundwater exploitation, namely the administrative/legal framework and public awareness. The first is important in order to provide a means by which the responsible agencies can enforce protective measures but the second is important so that "the abstractors" understand the reasons for such enforcement. Public awareness/education is especially important where the legislative framework is particularly weak or resources are not sufficient to fully implement or effect the legislative controls.

A recommended legal control on groundwater exploitation would be that any individual or company wishing to abstract groundwater (by means of borehole, well or spring capture) is required to obtain a permit to do so. The regulatory authority must be empowered to approve or decline such permits and also be able to authorise the design of the required structure. A final technical report on the structure, and any tests carried out on it, should be mandatory and a copy lodged with the appropriate agencies as a means of maintaining an up-to-date database on the aquifer system. Additionally the regulatory authority must have the power to licence for the abstraction of a controlled quantity of water (which may or may not be seasonally variable). An annual charge should be levied for such licences to raise revenue for the regulatory agency - the charge being related to the permitted abstraction rate.

For its part, the regulatory agency should provide the potential licensees and their agents (e.g. drilling contractors) with sound technical advice and information and be seen to apply their licensing procedures in an equitable manner. In order to achieve this latter objective, publicity on the current state of groundwater resource exploitation will be invaluable if properly handled. General education on the need for efficient resource management should also be seen as an important responsibility of the regulatory agency. The need for such regulation is to prevent overexploitation of the groundwater resource which can have both undesirable quantitative and/or qualitative implications for the groundwater and undesirable physical and chemical effects on the aquifer. Further reference to such effects are made in the companion reviews in this series on UNSAs on the topics of overexploitation, land subsidence and saline intrusion.

2.1.2 Existing Status of Groundwater Exploitation

In order to be able to protect an aquifer system from overexploitation (see the companion UNSAs review on overexploitation), it is evidently important that the existing status of groundwater development and the size of the total resource are known. Definition of the resource is obviously not easy and the high cost of hydrogeological investigation together with temporal and spatial variation in recharge and problems over definition of recharge areas and/or mechanisms means that resource estimates must have a degree of uncertainty. It is therefore not generally realistic to mount a strict abstraction policy based on the initial resource estimate; a degree of flexibility must be allowed for as this estimate is updated with further development. Equally, in previously unregulated areas, the existing abstraction will probably be unknown and steps must be taken to quantify and, if necessary, control this amount.

In order to be able to monitor the effect of existing and additional abstraction on the aquifer system, a network of observation boreholes to permit regular measurement of piezometric levels (and quality) will be necessary. Due to variability of pumping cycles and times of water-level recovery in production boreholes, the observation network should be established in non-pumping boreholes; inevitably this will generally require installation of a series of dedicated monitoring boreholes. Priority for such monitoring boreholes should of course be given to areas where demand for groundwater development is greatest.

The objectives of regular monitoring of UNSA piezometric levels should be:

i) determination of groundwater flow direction,

ii) determination of the response of the piezometric surface to groundwater abstraction and identification of areas in hydraulic disequilibrium (i.e. continuously falling levels),

(iii) estimation of recharge volumes during wet periods and depletion of aquifer storage during drought.

In coastal areas prone to saline intrusion under conditions of significant groundwater extraction, the monitoring network should provide the means of establishing the position of the freshwater-saline water interface (see the companion UNSA review on Saline Intrusion).

2.1.3 Water-well Drilling and Completion Control

In order to provide adequate control of groundwater exploitation, it is desirable that the regulatory agency has legislative authority to limit borehole drilling to recognised drilling companies only. Such recognised companies would then require separate permits for each borehole (or group of boreholes) to be constructed. The detailed procedure to be followed will vary according to the state-of-knowledge of the groundwater resource available but the type of information which will be required by the regulatory agency in order to issue a drilling permit is indicated in Table 1.

Where the regulatory agency has good field-control data it is advisable for them to undertake a feasibility study on behalf of the applicant and, if warranted, to provide a technical design for the installation based on data from existing wells. Where existing data is inadequate the applicant may be required to arrange for a hydrogeological study to be undertaken. The purpose of this study would be to estimate the probable recharge capture area and cone of influence of the proposed borehole, indicate the probable groundwater quality and to provide the basis of the technical design for completion of the borehole. The applicant should be legally bound to adopt the approved technical design and to maintain the works open to inspection by the regulatory agency. Upon completion, full details of the borehole (including location, design, proposed use, licensed abstraction etc) should be registered with the regulatory agency. Throughout the whole process, from application to completion, the regulatory agency must be in a position to offer technical advice on such aspects as maximum obtainable and maximum permissible yields from the UNSA, borehole design, spacing of boreholes and the design of sanitary protection. This latter point is of prime importance as direct contamination from the wellhead is probably the commonest mechanism of groundwater supply pollution.

Table 1. Summary of information required at various administrative stages in production well construction (after Foster et al, 1993).

ITEM	TYPE OF INFORMATION	TECHNICAL DESIGN SPECIFICATION	FINAL REPORT SUBMISSION	ABSTRACTION LICENCE APPLICATION
- location of borehole/well	map	*	*	*
- borehole/well design	depth/diameter	*	*	
• solid lining tubes/well screen/gravel pack/sanitary seal	depth/range/diameter/type	* (probable)	* (actual)[A]	
- drilling method	type of rig	*	*	
- abstraction rate	l/s, m^3/d	* (desired)	* (feasible)	* (requested)[B]
- water-supply use (effluent generation)	classify (propn of total)	*	*	*
- hydrogeological conditions	map/section	*	* A	
- groundwater quality	partial analysis	* (probable)	* (actual)	
- test pumping				
• step test/development (min 4 stages)	Q-s-t data	* (proposed)	* (actual)[A]	*
• steady rate (1-7 days)	table, map	*	*	*
- neighbouring boreholes/wells	1/2. m^3/d	*	*	*
• abstraction rate	m		* (estimated)	*
• potential interference				

* must be given at stages indicated

A includes lithological log in specified format and construction drawing at same scale

B additional information to be provided at this stage where appropriate includes: storage tank capacity, area and type of crops under irrigation

2.1.4 Control of Groundwater Abstraction

In order to adequately control groundwater abstraction legislation should exist to require would-be abstractors to apply to the regulatory agency for an abstraction licence. Such application would normally be made upon completion of a new borehole although the agency should of course expect to provide an indication as to whether a licence is likely to be granted prior to commencement of any major works. In support of the application the applicant should be expected to provide a technical report on the borehole or spring capture with full data on pumping-tests of adequate duration. The agency should provide details to applicants and/or their contractors as to the nature of the tests required. The decision on the permissible yield granted by the licence will be based upon the overall state of groundwater exploitation in the area (in relation to the resource as a whole), the results of the pumping test(s), the proposed use for the water and the quality requirements for that use (Foster et al, 1993).As part of the licensing process it is important to establish the way in which the yield is controlled. Possible approaches include restriction on:

a) The penetration of the borehole in the saturated zone of the aquifer (at the pre-design stage).

b) The diameter of the borehole (at pre-design stage).

c) The type of pump installed.

d) The hours of pumping per day and annual or monthly abstraction rates.

It is evident that in order to monitor compliance with the licence requirements, a monitoring programme will need to be followed by the regulatory agency; this could involve periodic inspection of major abstraction and occasional spot-checks in the case of smaller ones.

In order to enforce an effective resource protection policy, some form of legal sanctions or penalties against non-licensed abstractors or those who exceed licensed limits are necessary. The most appropriate form of sanction will generally be temporary or permanent prohibition on use of the well, depending on the effect of the unauthorised abstraction; monetary fines have generally been found to be ineffective.

In situations where UNSAs have already reached a state of overexploitation (see the companion review on overexploitation) measures will generally be required to reduce abstraction. Initially much might be achievable through investigation of borehole and pump efficiencies. The importance of operational monitoring of production well performance to diagnose well and pump maintenance requirements is often overlooked but should be an integral part of any groundwater protection policy; being to the benefit of both the regulatory authorities, in efficient use of the resource as a whole, and to the individual abstractors, as a means of increasing the useful life of their assets and controlling pumping costs. Other means of reduction of abstraction, such as reducing pumping periods or selective closure of wells, but will be difficult to implement unless alternative sources of water are available.

Special protection measures will be necessary in regions susceptible to saline intrusion (see companion review on Saline Intrusion). Foster et al (1993) recommend the following as a normal strategy:

(a) Ensure that dynamic groundwater levels remain above sea-level.

(b) Control the depth of wells and capacity of pumping plant installed in susceptible areas - reducing depths in already affected wells.

(c) Where feasible, redistribute abstraction away from the susceptible areas especially at times of drought.

(d) Develop a borehole network for regular monitoring of groundwater levels and salinity/conductivity depth logs, to provide a more reliable basis for aquifer management.

2.1.5 Abandoned Wells

Serious groundwater pollution incidents have widely been reported due to illegal use of abandoned wells for effluent disposal - the pollutants concerned being, in effect, injected into the most permeable parts of the aquifer, bypassing the unsaturated zone where the most opportunity for attenuation exists (see Section 2.2.2.2). It is therefore recommended that the regulatory agency should maintain a comprehensive well inventory for the UNSA and identify those that are disused. Disused wells should have sealed caps with a 20 mm diameter access hole (with cover) to permit monitoring - if pollutant discharge continues then the borehole should be backfilled. An essential part of any groundwater protection programme is that of public education and, in relation to abandoned boreholes, well owners and operators should be made aware of the risks associated with the discharge effluents.

2.2 Protection of Groundwater Quality

2.2.1 Introduction

There are at least three essential elements to any effective approach to groundwater protection.

(a) It should strike a realistic balance between protection of the resource (the aquifer as a whole) and sources (individual boreholes, wells and springs) used for public potable water-supply;

(b) It must address the control of both point and diffuse sources of pollution;

(c) It must achieve a practical balance between water quality concerns and development interests (although the two have a circular interrelationship).

It is notable that some approaches to groundwater protection have neglected both resource protection and consideration of diffuse pollution.

Resource protection depends on a consideration of the vulnerability of UNSAs to pollution while protection of individual sources within UNSAs depends on the definition of areas related to the catchment of, and saturated flow times to, those individual sources.

Even though the procedure presented is relatively uncomplicated, and therefore highly practical, it is founded on sound hydrogeological concepts and does permit the use of scientific evaluation and judgement in individual cases.

2.2.2 Resource Protection

2.2.2.1 Concept of Aquifer Vulnerability

The vulnerability of an aquifer is dependent upon a set of intrinsic characteristics of the strata separating the saturated aquifer from the land surface (Foster, 1987). These will determine the sensitivity of the aquifer to quality deterioration as a result of an imposed contaminant load. Aquifer vulnerability is then a function of:

(a) The inaccessibility of the saturated zone in a hydraulic sense, to the penetration of pollution, and

(b) The attenuation capacity of the strata overlying the saturated zone as a result of physicochemical retention or reaction of pollutants.

Some authors (e.g. Aller et al, 1987) include a consideration of the nature of the saturated zone, associating a high hydraulic conductivity with higher pollution potential as the pollutant has greater potential for moving quickly away from the point in the aquifer where it is introduced thus resulting in a larger volume of aquifer being polluted.

The alternative view is that once a contaminant has reached the saturated zone the groundwater has been contaminated and hence the aquifer vulnerability has been realised.

Land use planning might require the establishment of relative vulnerabilities (generally by production of an aquifer vulnerability map) in areas where there are either potential alternative groundwater sources to UNSAs or where UNSAs are of large aerial extent, in order to identify the areas of highest vulnerability which should be avoided for the siting of potentially polluting activities.

The literature contains several methods by which aquifer vulnerability can be determined. However, there is necessarily an element of subjectivity in all of these methods and they essentially give relative values of vulnerability in any one region. The methods enable determination of relative vulnerability for a wide range of aquifer types from highly fissured aquifers through granular flow media to formation with high clay content which are essentially non-aquifers. Evidently, with regard to UNSAs, a subset only of these overall vulnerability methodologies is required.

It should be realised that the general vulnerability concept has serious limitations as, in rigorous scientific terms, the general vulnerability to a universal contaminant in a typical pollution scenario has little meaning. Thus, Anderson and Gosk (1987) proposed that vulnerability mapping should be carried out for specific individual contaminants and pollution scenarios. This approach would be scientifically ideal, but (even if it were possible, and with our current state of knowledge, it is not) it would generate an atlas of maps that would be complex for general land-use planning purposes, and a simpler basis will normally be required (Foster, 1987).

2.2.2.2 *Role of Unsaturated Zone*

Due to both its strategic position between the land surface and the saturated zone, and its potential for pollutant attenuation and elimination, the unsaturated zone represents the first line of natural defence for UNSAs. Water movement in the unsaturated zone is normally slow and restricted to the smaller pores with larger specific surface, the chemical condition is normally aerobic and frequently alkaline, hence (Adams & Foster, 1992) there is considerable potential for:

- i) Interaction, sorption and elimination of pathogenic bacteria and viruses.
- ii) Attenuation of heavy metals, and other inorganic chemicals, through precipitation (as carbonates, sulphides and hydroxides), sorption or cation exchange; and
- iii) Sorption of many, and biodegradation of some, natural and synthetic organic compounds.

It should be noted however that due to the complexity of groundwater flow and pollutant transport in the unsaturated zone, its ability to attenuate pollutants can be difficult to predict (Foster, 1987). In general, the degree of attenuation will depend upon:

- i) the hydraulic loading of the pollution event;
- ii) the chemical nature of the pollutant;
- iii) the chemical environment of the unsaturated zone.

In practice, for persistent, mobile pollutants the unsaturated zone will merely introduce a time-lag before arrival at the water-table without significant attenuation (Adams & Foster, 1992). In most other cases the degree of attenuation will be highly dependent upon unsaturated zone flow regime and residence time.

In considering transit times in the unsaturated zone for the purposes of general aquifer vulnerability it is obviously important to be conservative. Thus, as the worst pollution scenarios will involve heavier hydraulic loading than that resulting from average rainfall infiltration, it is important to consider the effect of hydraulic load on unsaturated zone flow and residence time. Under conditions of gross hydraulic surcharge saturated flow conditions will be approached and therefore transit times will be dependent upon lithology and, essentially, will be a function of effective porosity and saturated vertical hydraulic conductivity (Adams & Foster, 1992). Hence, in general application, lithological character, especially the grade of consolidation and degree of fissuring of the unsaturated zone will be the key factors in the general assessment of aquifer vulnerability to pollution. However in the specific case of UNSAs fissuring will generally be absent and consolidation, by definition is not present, and so relative vulnerabilities will depend upon grain size and sorting of the sediments and comparative depths to water-table.

2.2.2.3 Significance of Soil Zone

Most of the processes causing attenuation of pollutants in the unsaturated zone occur at much higher rates in the biologically-active soil zone due to its higher clay mineral and organic matter contents and very much larger bacterial populations. However, it is often the case for point sources of contamination that the pollutant load is applied below the base of the soil zone in excavations such as pits, trenches, lagoons and soakaways or from leaking subsurface pipes and tanks; the soil zone thus has no impact on groundwater protection in these cases. However, the soil zone is important in the case of diffuse agricultural pollution, since it exercises a major control over the leaching of nutrients and pesticides.

2.2.2.4 Determination of Vulnerability

As noted earlier, there are several published alternative methods for determining the relative vulnerability of differing formations across a region. Some authors recommend systems of ranking geological characteristics comprising vulnerability to generate overall vulnerability indices. Others (Adams & Foster, 1992) recommend the retention of hydrogeological variables in vulnerability mapping and this is the approach adopted here. Thus, for regional evaluation of the relative vulnerability of UNSAs as compared to adjacent formations three main classes can be recognised (Table 2), with a subdivision of the "variably permeable" class dependent upon the nature of the porosity/permeability. Within this classification Class A is the most vulnerable to pollution and Class C the least. Subclasses in the two permeable groups are based on the unsaturated zone thickness; thus recognising the protective capacity of the unsaturated zone (section 2.2.2.2), the greater its thickness the more effective the protection. If the non aquifer or Class C formations are less than 5 m thick then the vulnerability is classed according to the formation which underlies it (A or B); this thickness of 5 m was taken as the depth to which surface disturbance activities (such as excavation or foundation work) can have an impact, thus negating the protective capacity of the low permeability formation. Evidently UNSAs will generally fall into class B2. Mapping of relative vulnerability within UNSAs will essentially depend upon a knowledge of regional variations in both depth to water and facies; thus, whether this can be achieved or not will depend upon appropriate data availability.

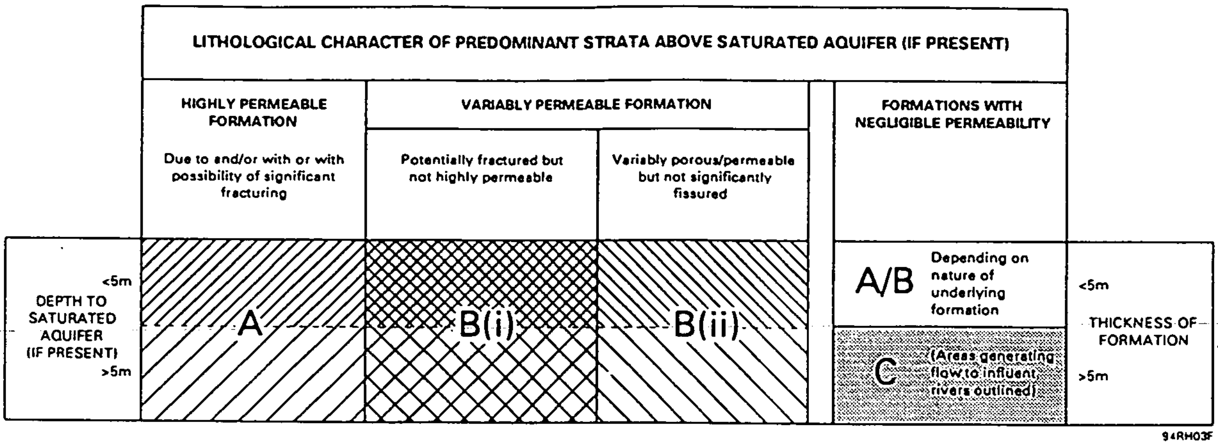

Table 2. Aquifer vulnerability classification.

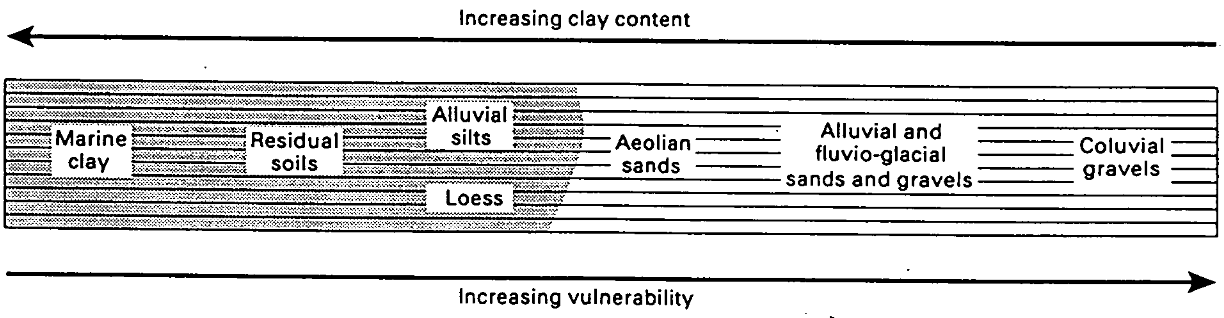

Fig 1. Relative vulnerability of unconsolidated sediments.

It is normal in the case of multilayered aquifers (as will generally be the case with UNSAs) to determine the vulnerability of the uppermost aquifer only - although consideration should be given to hydraulic connection between layers within UNSAs. Figure 1 gives an indication of the relative vulnerability of a range of unconsolidated sediments.

2.2.3 Hydrogeochemical environment of the saturated zone

Mention has already been made (2.2.2.2) of the relevance of the chemical environment of the unsaturated zone to the attenuation of pollutants. However, whilst some authors include a consideration of the hydraulic nature of the saturated zone in the determination of aquifer vulnerability (2.2.2.1), the complexity and variety of hydrogeochemical environments within the saturated zone will normally preclude this factor being incorporated into a generally applicable concept of aquifer vulnerability. It should be noted however, that the process of abstracting groundwater from boreholes can alter the hydrogeochemical environment in such a way as to have negative effects on both the quantity and quality of groundwater produced. Such effects are noted in the companion UNSA review report on Overexploitation.

2.2.4 Source Protection

2.2.4.1 Introduction

The objective of source protection is to provide a framework for protection of selected individual groundwater sources (boreholes, wells and springs). The criteria for selection of which sources should be protected will normally depend on their use and/or their importance. For example, while it is obviously desirable to protect all sources used for potable supply (regardless of the size of population served - a measure of their importance), such an approach might not be logistically possible. Thus, in practical terms only those sources which have a supply greater than some nominated value or serve a particular minimum size of population might be chosen. The means of achieving source protection is by placing tighter controls on activities within all, or part, of the sources recharge capture areas.

2.2.4.2 Recharge Capture Area

The recharge capture area to an individual source is the area within which all aquifer recharge, whether derived from precipitation or surface water, will be captured at that source. The area of recharge-capture area is directly proportional to the source production rate and inversely proportional to the recharge. It is considered pragmatic to define the recharge capture area according to the long-term average recharge - it has to be recognised that in an extreme drought the actual capture area may be larger than the protected. Similarly a decision must be made as to which value of source production rate is used, i.e. maximum licensed, actual average or maximum possible - the choice will often depend upon data availability.

To completely eliminate the risk of source contamination would require prohibition of all potentially polluting activities within the capture zone - a course of action which will normally be impractical due to socio-economic pressure for development. Therefore some division of the recharge capture zone is required so that strictest control will be applied in areas closest to the source. Such subdivision could be based upon a variety of criteria, depending on the perceived pollution threat, including: horizontal distance, horizontal flow time, proportion of the recharge area, saturated zone dilution, and/or attenuation capacity. For general application Adams and Foster (1992) concluded that horizontal flow time and distance criteria are the most appropriate factors.

No more than 2 or 3 sub-divisions of the total capture zone will generally be practical and their implementation will depend upon the scale of development of the UNSA concerned and the resources available to the agency(ies) responsible for the protection. The sub-division could include the following: an operational courtyard area, an inner protection zone related to the control of pathogenic contamination and, in cases where socio-economic pressure for development has resulted in land scarcity, an outer protection zone to allow differential control of point-source or diffuse-source pollution in the remaining area.

2.2.4.3 Operational Courtyard

Ideally this area of land, which forms the innermost protection area, should be under the ownership and control of the groundwater abstractor. In this area no activities should be permitted which are not related to water abstraction itself, and even these activities need to be carefully controlled to avoid the possibility of pollutants reaching the source, either at the wellhead directly or via adjacent disturbed ground. Specification of the dimension of the area is necessarily somewhat arbitrary but, for major urban supply boreholes, a radius of 30 m is probably sufficient whilst, for rural supplies from handpumps or springs, smaller areas will be satisfactory.

2.2.4.4 Inner Protection Zone

The purpose of the inner protection zone is to prevent pathogenic contamination of groundwater sources, and is based on the distance equivalent to a specific horizontal flow time. The flow times used by different authorities have varied from 10 days to 400 days (Adams and Foster, 1992). However, a review of all published case histories of groundwater contamination (Lewis et al 1982) concluded that the horizontal travel distance between the borehole or spring and the proven source of pollution was equivalent to no more than the distance travelled by groundwater in 20 days. Whilst it is recognised that pathogens can survive in the sub-surface for up to 400 days it was concluded that the horizontal travel distance is governed principally by groundwater flow velocity which is of course enhanced at boreholes and springs.

A value of 50 days is therefore recommended as a reasonable basis to define the inner protection zone in UNSAs as it conforms to existing practices in many countries and provides a certain factor of safety, over the 20 days noted above, to allow for data deficiencies.

2.2.4.5 *Outer Protection Zone*

An outer protection zone may be necessary to permit differential control of point-source and/or diffuse source pollution in the remaining area. However, the current scientific uncertainty about the rates of sub-surface degradation of contaminants (other than pathogens), together with the complexity of sub-surface dispersion and dilution processes, mean that its definition will inevitably be somewhat arbitrary. Adams and Foster (1992) proposed that, for consistency, the area of the outer protection zone should be defined on the same basis for all groundwater sources. A practical approach, which is suitable for both point-source and diffuse-source pollutants, is to use a horizontal flow time one order of magnitude greater than that used for the inner protection zone (say, 365-500 days) but to set a minimum limit of, say, 25% on the proportion of the overall recharge zone so protected.

2.2.4.6 *Delineation of Source Protection Area*

The requirement is to produce a set of closed curves on a map either representing the whole recharge capture zone of individual sources or specific times of travel to each source (these latter curves which represent the inner and outer protection zones are referred to as isochrons). These curves cannot generally be directly constructed and the method invariably used is to track the movement of water away from a source (in an upstream direction) in small steps, using the flow-velocity distribution to determine the time to pass from one point to the next and hence the total travel time to the source. One such sequence of points leading away from a source is termed a pathline. By constructing a number of pathlines of equal travel time but emanating from the source in different directions, an outline of an isochron can be established (Figure 2). For a capture zone the pathlines must continue to a point of zero velocity or to the edge of the region under study.

The velocity distribution required in the tracking process will normally itself have been determined from a head distribution, and that head distribution will, in most cases, be determined with the aid of a groundwater flow model. Figure 3 summarises the tasks that will normally be required to construct a set of protection zones. This is necessarily an over-simplification of the problem which is complicated by a number of factors such as parameter uncertainty and transient aquifer behaviour.

Figure 4 gives an indication of the variation in size and shape of source-protection areas under differing hydrogeological conditions. It should be noted that, whilst the definition of the recharge capture area is mainly dependent upon the recharge regime, any protection zone based on horizontal flow time can also be highly sensitive to errors in the estimation of aquifer parameters.

2.2.4.7 *Control of activities within the Recharge Capture Area*

Having established a system of land surface zoning for resource and source protection, based on the concepts of aquifer vulnerability and source protection zones respectively it is necessary to define which potentially polluting activities need to be prohibited or controlled in which areas.

Table 3 gives a possible scheme for variable pollution controls within both source protection areas and areas of differing aquifer vulnerability.

2.2.5 Implementation

Figure 5 shows the conceptual framework for groundwater protection which includes both resource and source protection as described above; the approach is ideally suited to management by a Geographical Information System (GIS) as there are several "layers" of information which need to be utilised in different combinations (Adams & Foster, 1992). However, introduction of a groundwater protection policy is by no means dependent upon a GIS.

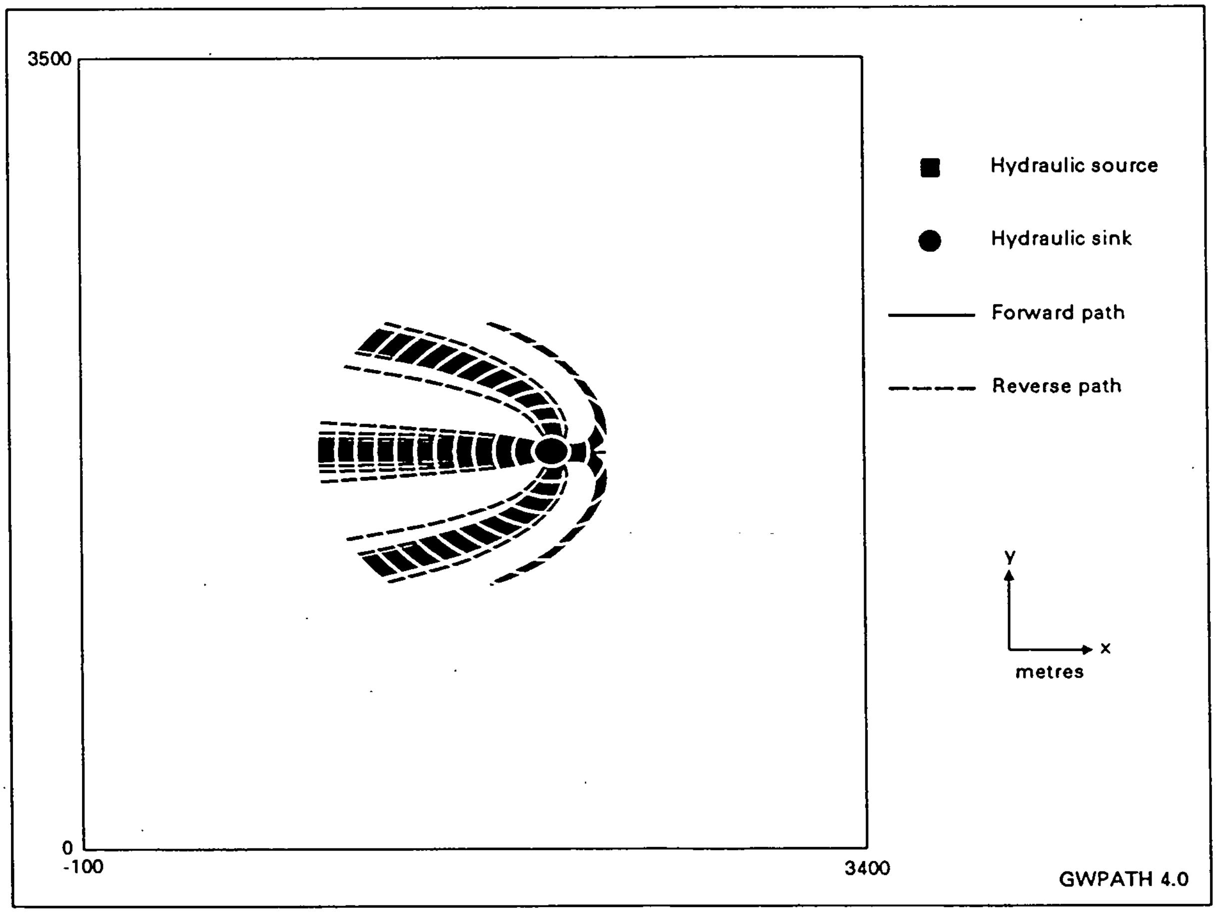

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Fig 2. An example of reverse tracking using the GWPATH software package to develop an isochron

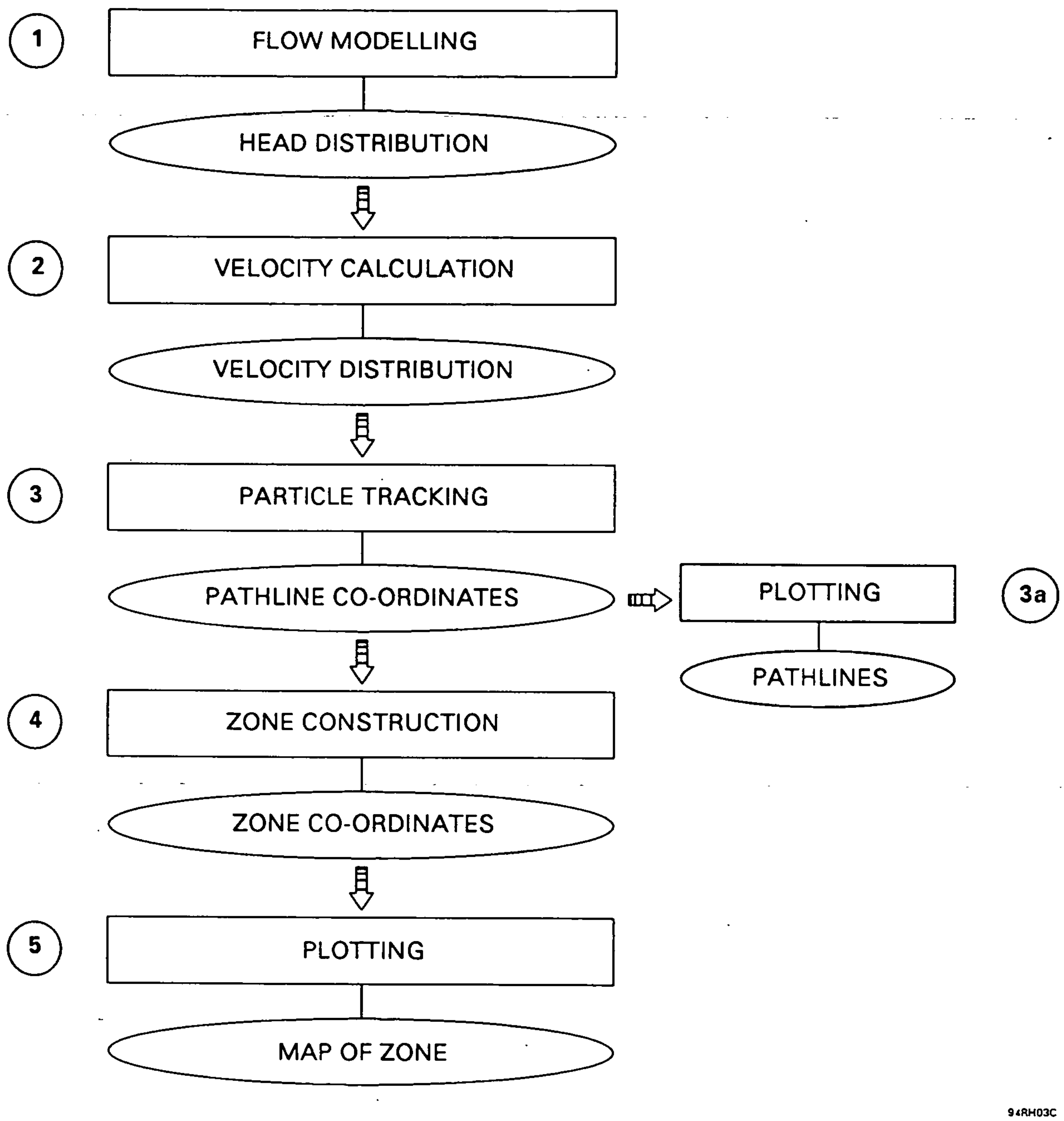
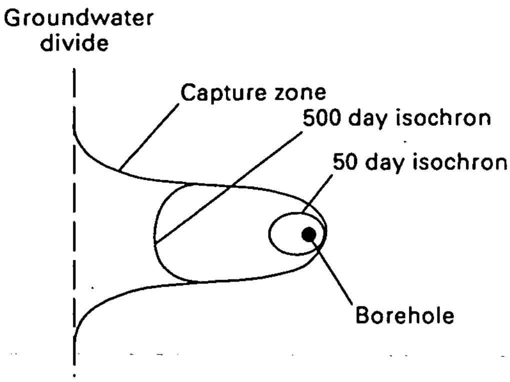
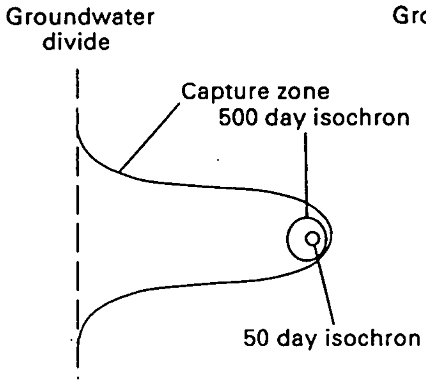


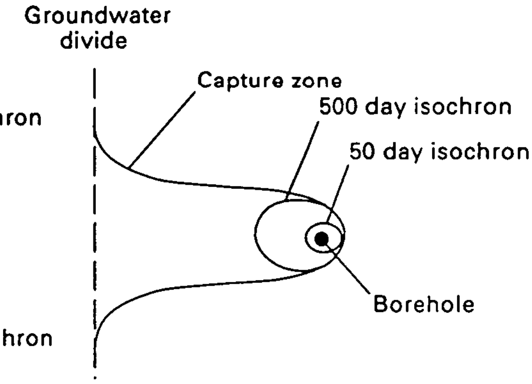
Fig 3. The 5-stage process of zone construction when the head distribution is determined using a flow model.



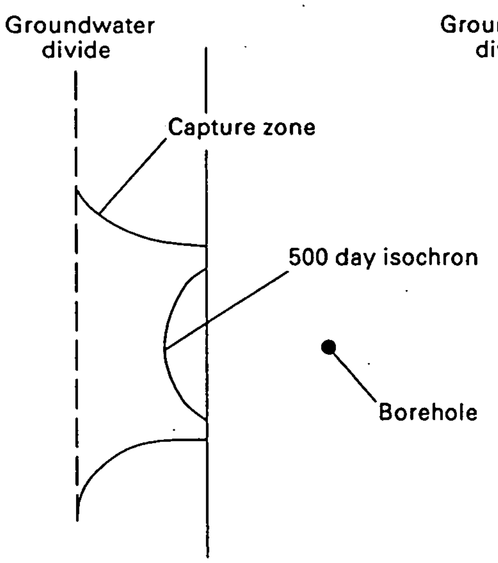
a) Transmissivity = 100 m²/d, porosity = 0.01, aquifer thickness = 50 m, average recharge = 400 mm/a, abstraction rate = 2000 m³/d



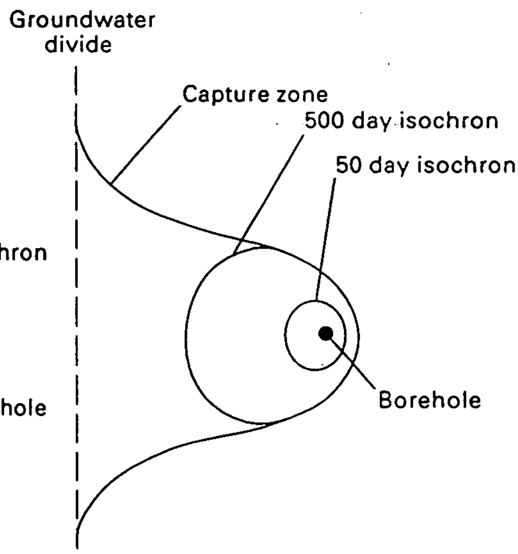
b) As a) except transmissivity = 200 m²/d porosity = 0.20



c) As a) except transmissivity = 200 m²/d porosity = 0.20, aquifer thickness = 10 m



d) As a) except aquifer partially confined



e) As a) except average annual recharge = 200 mm

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Fig 4. Comparison of source protection areas for different aquifer types and recharge conditions

Table 3. **Acceptability matrix of common potentially-polluting activities and installations within land surfaces zones for groundwater protection (after Foster et al, 1993).**

POTENTIALLY-POLLUTING ACTIVITY REQUIRING CONTROL MEASURES	LEVEL OF CONTROL REQUIRED				
	SOURCE PROTECTION AREAS		REST OF LAND SURFACE		
	inner zone	catchment area	vulnerability		
			high	moderate	low
Infiltration Lagoons					
- industrial effluent	U	U	PU	PA	PA
- cooling water	PA	A	A	A	A
- municipal effluent	U	PU	PA	A	A
Solid Waste Disposal by Landfill					
- industrial hazardous	U	U	U	U	PA
- industrial other	U	PU	PU	PA	A
- municipal domestic	U	PU	PA	PA	A
- construction/inert	U	PA	A	A	A
- cemeteries	U	PU	PA	A	A
Land Disturbance					
- mining	U	U	PU	PA	A
- quarrying, open-cast mining	U	PU	PA	PA	A
- construction	PA	PA	A	A	A
Septic Tank Soakaways, Cesspits & Latrines*					
- individual properties	U	PA	A	A	A
- communal properties, public buildings etc	U	U	PA	A	A
Soakaway Drainage					
- building roofs	A	A	A	A	A
- minor roads, amenity areas	PA	A	A	A	A
- major roads	U	PU	PA	A	A
- industrial sites	U	PU	PA	A	A
	U	PU	PU	PA	A
Effluent Land Application					
- food industry	U	PA	PA	A	A
- all other industrial	U	U	PU	PA	A
- sewage effluent	U	PU	PA	A	A
- sewage sludge	U	PA	PA	A	A
- farmyard slurry	U	A	A	A	A
Industrial Sites					
- liquid chemical storage	U	U	PU	PA	PA
- hydrocarbon fuel storage	U	PU	PA	PA	A
- solid chemical storage	U	PU	PA	A	A
Intensive Livestock Rearing					
- effluent lagoons	U	PU	PA	A	A
- farmyard and feedlot drainage	U	PA	PA	A	A

U unacceptable in virtually all cases
PU probably unacceptable, except in some cases subject to detailed investigation and special design
PA probably acceptable subject to specific investigation and design
A acceptable subject to standard design
* connection of industrial effluent or stormwater drainage is not acceptable

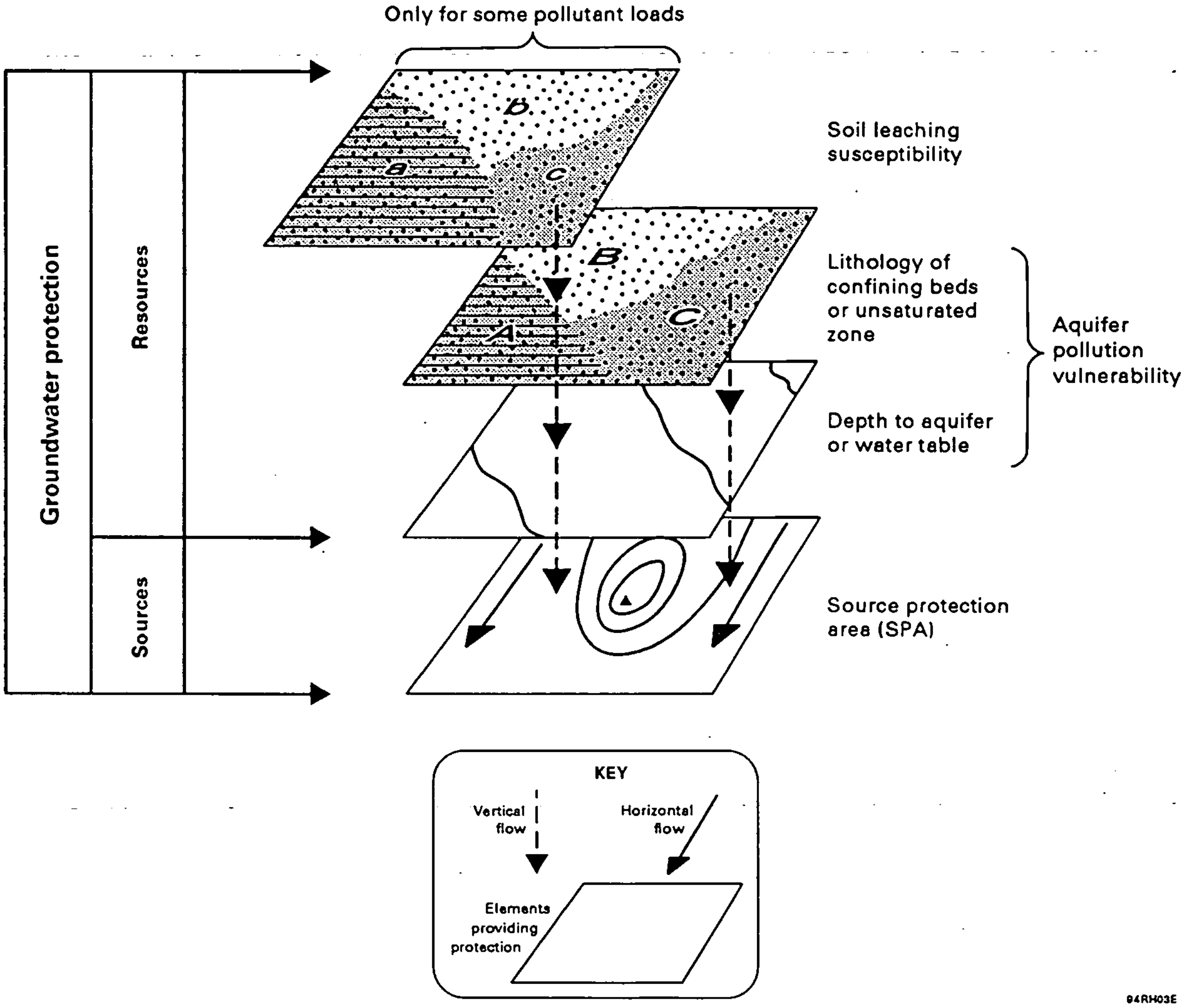

Fig 5. Conceptual framework for groundwater protection. This indicates the principal elements used for zoning the land surface in relation to the implementation of groundwater pollution control measures.

Any form of groundwater protection initiative will be ineffective without an adequate groundwater quality monitoring system. This is necessary both to evaluate the effectiveness of the protection measures and to detect incipient pollution of previously uncontaminated aquifers and worsening situations of previously polluted aquifers in order to allow aquifer pollution-control measures to be implemented. Division of the land surface on the basis of aquifer vulnerability and source protection zones will immediately indicate priority areas where monitoring should be instigated. In order to keep analytical costs at a minimum, potential pollution threats within source recharge capture areas can be listed and the production water need only be analysed for those pollutants. These pollutant inventories should be established on a catchment or a borehole-recharge-capture area basis (Chilton et al, 1990) and would ideally include all potential groundwater pollutants used or stored in (and even transported through) the area concerned.

When groundwater protection procedures are first initiated in a region there will often be activities present which, under those new procedures, would not have been permitted in their present location. Once again effective monitoring will be required to investigate existing and potential problems. In many cases engineering solutions may be available to overcome existing problems but in some instances relocation of the activity may be necessary if the resource or source in question is to be adequately protected.

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METHOD SUMMARY SHEET (01)

TITLE: Determination of Aquifer Vulnerability

Scope and Use of Method

The determination of aquifer vulnerability is important for the protection of groundwater resources from pollution. The source, Groundwater Protection Review should be read in conjunction with this summary sheet.

Method

Table 2, extracted from the source Review, gives a broad classification of aquifer vulnerability for all formations. Within this classification Class A is the most vulnerable to pollution and Class C the least. Subclasses in the two permeable groups are based on the unsaturated zone thickness; thus recognising the protective capacity of the unsaturated zone, the greater its thickness the more effective the protection. If the non aquifer or Class C formations are less than 5 m thick then the vulnerability is classified according to the formation which underlies it (A or B); this thickness of 5 m was taken as the depth to which surface disturbance activities (such as excavation or foundation work) can have an impact, thus negating the protective capacity of the low permeability formation. Evidently UNSAs will generally fall into class B2, but knowledge of the full table is important in order to be able to consider relative vulnerabilities of formations adjacent to the UNSAs under consideration. Relative vulnerabilities within an UNSA can be obtained by a consideration of depth to water and facies. Figure 1 shows the relative vulnerability of unconsolidated sediments based on clay content, whilst increasing depth to the saturated layer is indicative of decreasing vulnerability.

Some methods of determination of vulnerability rank the geological characteristics comprising vulnerability and combine them to generate an overall vulnerability index. Such methods (e.g. Aller et al, 1987, Foster and Hirata, 1988) might be of assistance where relative vulnerabilities of UNSAs are required in areas of complex heterogeneity.

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	LITHOLOGICAL CHARACTER OF PREDOMINANT STRATA ABOVE SATURATED AQUIFER (IF PRESENT)				
	HIGHLY PERMEABLE FORMATION	VARIABLY PERMEABLE FORMATION		FORMATIONS WITH NEGLIGIBLE PERMEABILITY	
	Due to and/or with or with possibility of significant fracturing	Potentially fractured but not highly permeable	Variably porous/permeable but not significantly fissured		
DEPTH TO SATURATED AQUIFER (IF PRESENT) <5m	A	B(i)	B(ii)	A/B Depending on nature of underlying formation	<5m THICKNESS OF FORMATION
>5m				C (Areas generating flow to influent rivers outlined)	>5m

94RH03F

Table 2. Aquifer vulnerability classification.

METHOD SUMMARY SHEET (02)

TITLE: Determination of Source Protection Areas

Scope and Use of Method

In order to protect individual supply boreholes, wells and springs from pollution it is necessary to define their catchment areas. By subdivision of the catchment area into a series of source protection zones, potentially polluting activities can be prevented or controlled within the catchment area to prevent pollution of the supply source. Where potentially polluting activities already exist within catchment areas priority can be given to monitoring of groundwater quality both at the source and adjacent to the suspect activities to provide warning of potential problems and, where necessary/practical, initiate preventative action. The source, Groundwater Protection Review should be read in conjunction with this Summary Sheet.

Method

Figure 3, extracted from the source Review, shows the stages to be followed in order to delineate source protection areas. A digital model is established to simulate the groundwater flow of the region under consideration, and, as part of the model calibration process, develops a groundwater head distribution. This head distribution is used as the basis for calculation of the velocities of groundwater flow to and from adjacent nodes in the model. A particle tracking routine is then used to track the movement of water away from a source (in an upstream direction) in small steps, using the flow-velocity distribution to determine the time to pass from one point to the next and hence the total travel time to the source. One such sequence of points leading away from a source is a *pathline*. By constructing a number of pathlines of equal travel time but emanating from the source in different directions, an outline of an isochron can be built up - Figure 2 also extracted from source Review. For a capture zone the pathlines must continue to a point of zero velocity or to the edge of the region under study.

A software package such as FLOWPATH or MODFLOW would generally be used to achieve this process.

Key References

Adams B & Foster S D, (1992). Land-surface zoning for groundwater protection. Journal I.W.E.M. No. 6, June pp 312-320.

Foster S D, Adams B, Morales M & Tenjo S, (1993). Groundwater protection strategies, a guide towards implementation. CEPIS Technical Report, Lima.

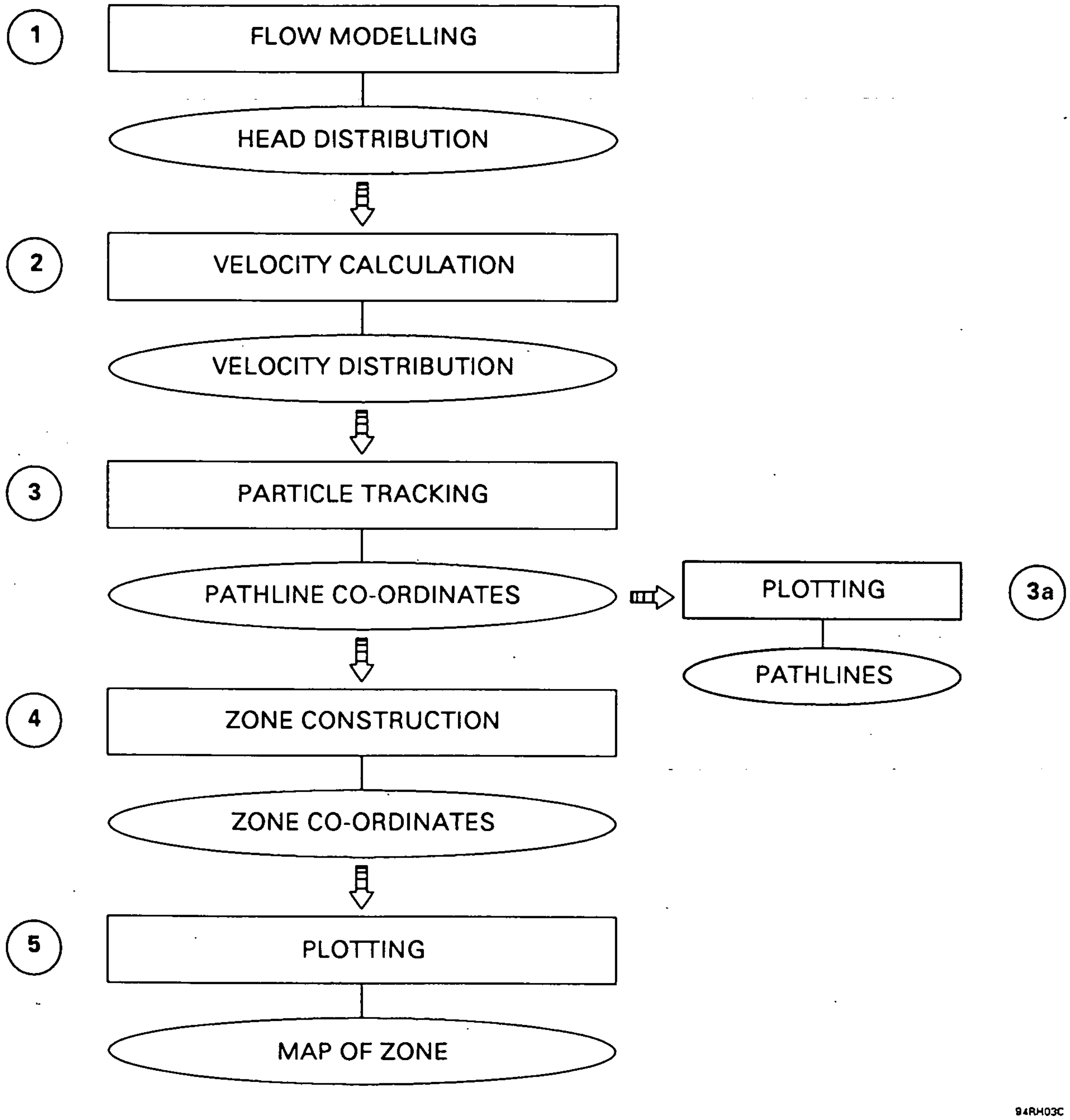

Fig 3. The 5-stage process of zone construction when the head distribution is determined using a flow model.

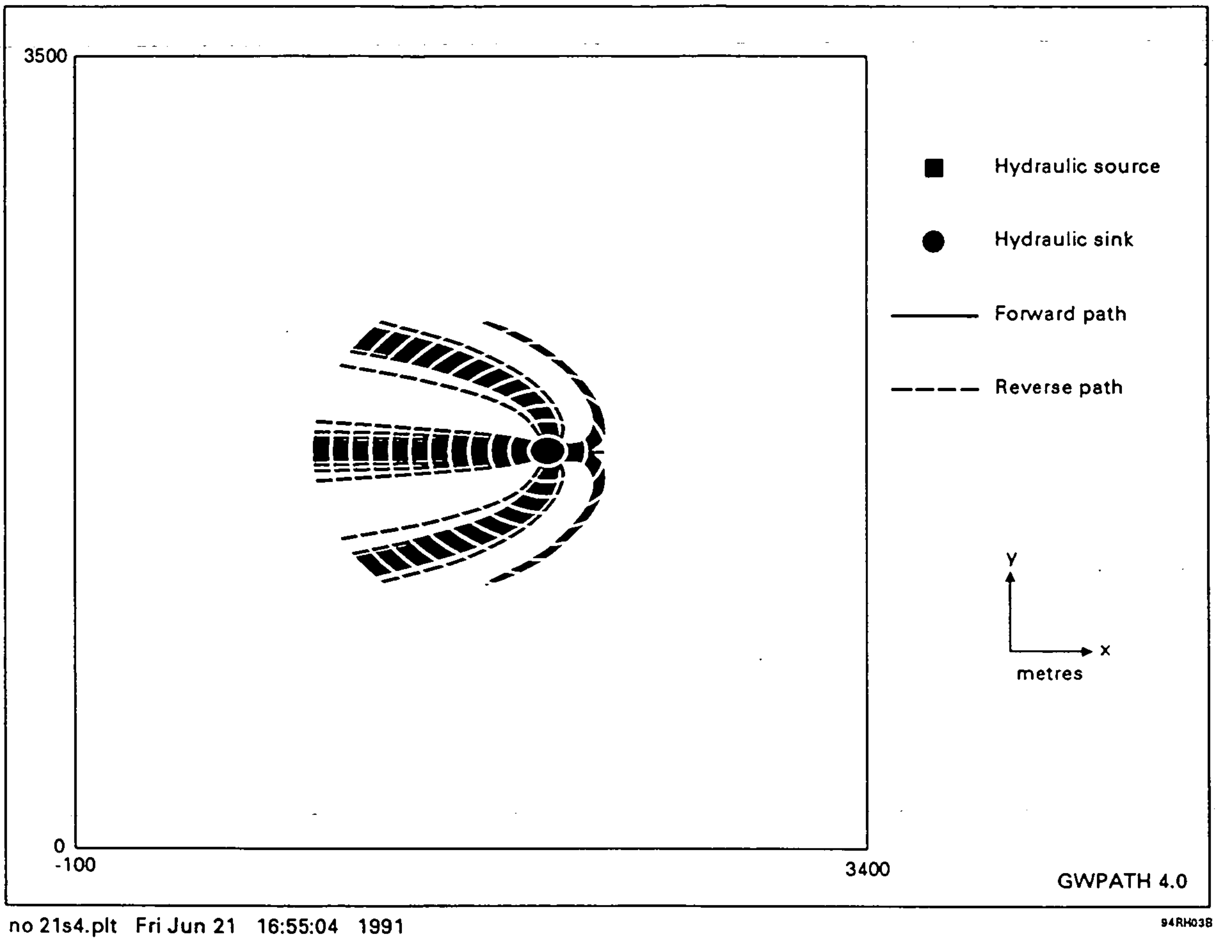

Fig 2. An example of reverse tracking using the GWPATH software package to develop an isochron

GROUNDWATER DROUGHT

WITH PARTICULAR REGARD TO

UNCONSOLIDATED SEDIMENTARY AQUIFERS

by

N S Robins & R C Calow

CONTENTS - Part 3

GROUNDWATER DROUGHT WITH PARTICULAR REGARD TO UNCONSOLIDATED SEDIMENTARY AQUIFERS

1. AIMS

1.1 Introduction

Groundwater drought is severe. It is the final stage of drought which follows surface water drought when people rather than food have to be moved. It is becoming an increasing problem due to reducing recharge and increasing demand. Many boreholes and wells, and some areas or geological terrains, are more vulnerable to groundwater drought than others; unconsolidated sedimentary aquifers, which have limited storage and relatively high hydraulic conductivity are at risk. Assistance for groundwater drought is provided as crisis input on the assumption that groundwater drought is a short term shock rather than a recurring event. However, prediction and planning can enable better targeting of limited resources to vulnerable areas, and ensure timely and effective assistance at the onset of groundwater drought.

A great deal of international effort has been put into the investigation of drought conditions and the prediction of drought occurrence (eg Yevjevich et al, 1983; Frederiksen, 1992). This effort has concentrated on the preliminaries to groundwater drought, the failure of the rains, the failure of the crops, drying up of surface waters, the death of animals . . . but it has not gone on to consider the onset of groundwater drought. The reasons for this are unclear, but they relate to the complexity of the issue due to the interaction of prevailing climatic conditions, groundwater demand and geological conditions, as well as to the resources available on the ground with which to carry out the necessary investigations. The consequences of groundwater drought are horrendous, often economically devastating to whole nations.

1.2 Aims of the review

The ultimate aim has to be the alleviation of the impact of groundwater drought on vulnerable communities. The aim of this review is merely to identify the issues pertaining to groundwater drought, particularly in unconsolidated sedimentary aquifers, and to flag the approaches that can sensibly be made (given the resources) in order to offset the worst human and economic ravages of groundwater drought.

2. BACKGROUND

2.1 Drought and groundwater drought

Although drought may occur anywhere in the world it is most severe in the African continent. The ratio of runoff to precipitation for the whole of Africa is 0.20, which is only just over half the global mean of 0.35. Regional variation within the continent is considerable (Table 1), but nowhere compares with the runoff: precipitation ratio for Asia which is as high as 0.4.

Table 1. **Regional variations in rainfall and precipitation in Africa (after Wright, 1985)**

	Precipitation (mm)	Runoff (mm)	Runoff precipitation ratio	Runoff (m^3 km^{-2})
Atlantic Ocean slope				
External runoff area	1020	241	0.24	242 000
Internal runoff area	196	11	0.06	-
Indian Ocean slope				
External runoff area	730	84	0.10	84 000
Internal runoff area	648	46	0.07	-
Mean	725	141	0.18	142 000

The word drought means different things to different people. In England drought such as that experienced between 1988 and 1992 meant nothing worse than a ban on washing cars and watering gardens, whereas the groundwater drought in Zimbabwe in 1991/92, in which rainfall levels were between 40 and 60% of normal, caused death, widespread hardship, and economic ruin.

The economic aspect of drought is important. If a country is rich enough it can purchase and import food as well as sufficient spare parts to maintain its boreholes and pumping equipment. However, economic failure, as was the case in Zimbabwe, enhances drought, as food and spares can no longer be imported.

Although groundwater drought is "endemic" in Africa the dominant hydrogeological province is shallow weathered basement and a relatively small area of the continent is served by unconsolidated sedimentary aquifers (see Foreward in yellow pages). The major areas of water bearing unconsolidated sedimentary strata occur in Northern and Central Africa, throughout Eastern Africa and along the eastern coast of the continent. Nevertheless, all of Africa utilises the riverine alluvial deposits that line most surface water-courses, and much of Africa can draw water from sand river beds long after the surface water has ceased to flow. Under normal conditions groundwater is relatively easy to develop from these sedimentary aquifers and population density on them is generally high.

In dryland areas, groundwater may be the only reliable source of supply for many people. Local populations are well aware of this, and have an understanding of the importance of groundwater deeply imbued in their cultural psyche, characterised by the care commonly accorded to the village well or spring. In past times, limited settlement and nomadic existence were appropriate to sustainable water use. In more recent years settlement patterns and ways of life have changed with the movement of people into drylands and the disappearance of nomadic ways. Some settlements have grown rapidly, increasing pressure on scarce water resources and, therefore, vulnerability to drought. The net result for many is that groundwater, which could at one time be relied upon in even the most severe droughts, may disappear under the combined pressures of reduced recharge and increased demand.

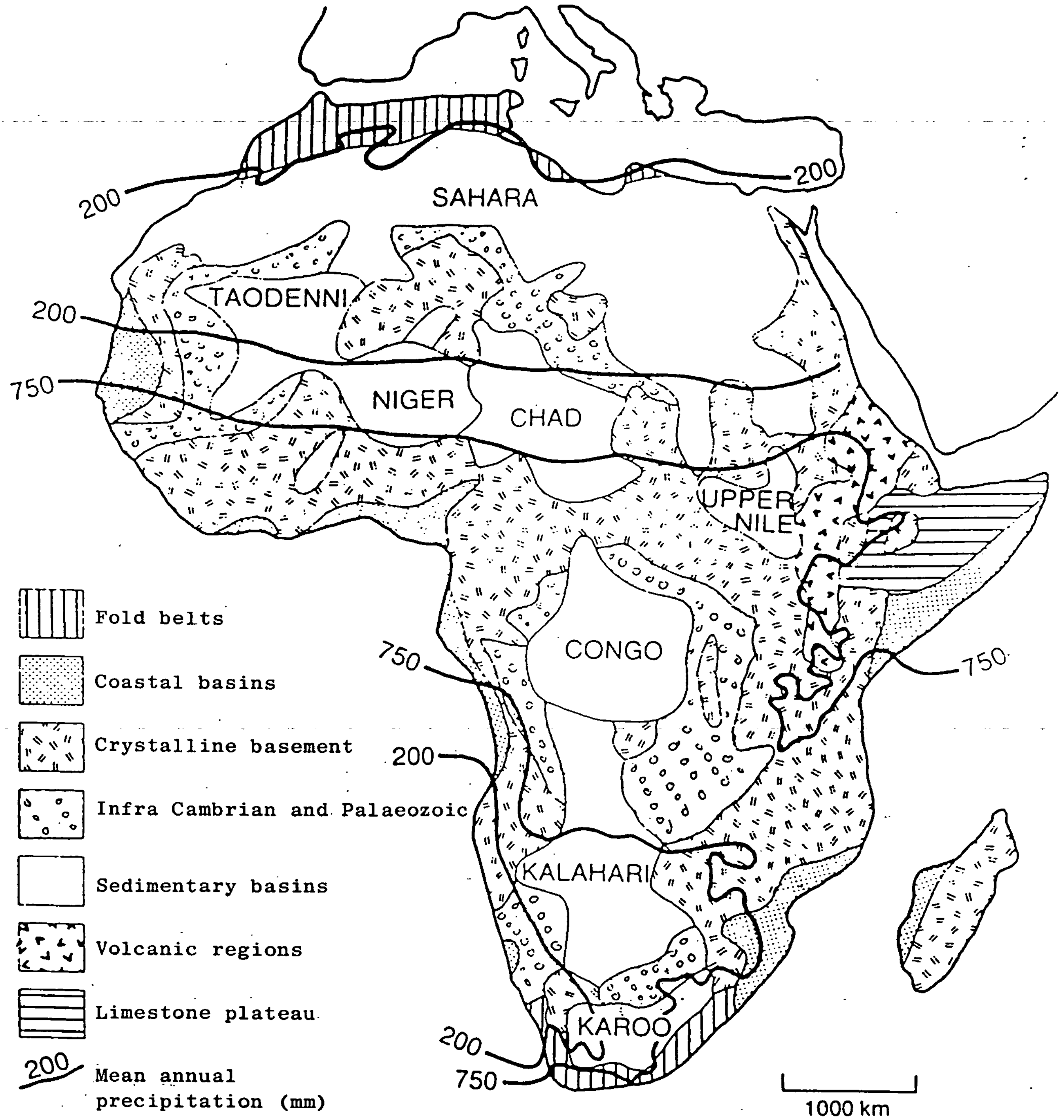

Figure 1. The sedimentary basins of Africa (after Wright, 1985)

2.2 Unconsolidated sedimentary aquifers of Africa

The sedimentary basins of Africa are shown in Figure 1. Not all the sediments are unconsolidated, the main regional occurrences of unconsolidated sediments are in the Sahara, Sahel and Congo basins. However, all the sedimentary basins contain very large amounts of groundwater and the aquifers are commonly high yielding with good quality. Active recharge may not be occurring, certainly on a regular basis, to large areas of the deeper aquifers and much of the groundwater exploitation is in reality groundwater mining. By contrast, the unconsolidated sedimentary aquifers are shallow, and active recharge is essential in order to replenish their comparatively small storage capacity.

Typical unconsolidated deposits include clay-bound sands with gypsum or calacareous patches. They are characterised by high porosity and high permeability. Recharge to these deposits may locally be restricted by the presence of red-brown and yellow-brown soils and other dessicated surfaces which are relatively impermeable and restrict the penetration of rainwater. Other deposits include riverine alluvium which may vary in lithology from fine-grained clayey deposits to coarse-grained material and even cobble beds.

2.3 Drought prediction

The development of drought follows a clear and well defined pattern. Phase 1 is the failure of just one years rain and the consequent loss of the harvest; phase 2 is the failure of a second years rain and the decline of surface waters and probable loss of animals as well as crops. Throughout this period of drought food is moved into the relief areas in order to sustain the communities. Water is still available from the deeper wells and boreholes, although some sources may dry up seasonally or will, in any case, dry up after one or at most two dry years. The effect of this sort of drought is not devastating; although the subsistence element of the population is lost, provision can readily be made to sustain the people, albeit with considerable and widespread hardship. This level of drought is quite easy to predict from historical observations on drought prone areas and the effect of diminished rainfall over one, two or more years.

What cannot be so readily predicted is the onset of groundwater drought, the time when the wells and boreholes and even the traditional coping methods such as dug-outs in dry river beds begin to fail. This is the critical stage of drought when people have to be moved away from their land until such time as renewed rain will allow them to return. Identification of areas prone to groundwater drought and predicting when groundwater sources will fail is, therefore, very important. Even more important is the identification and the implementation of a strategy, which must at least be on a national basis, of alleviating the stress of groundwater drought, and targeted at the recognised drought prone areas.

Long-term rainfall records are available for many parts of the world. Investigation of these records on a local, regional or global scale demonstrates that there are no obvious patterns that precede the onset of serious drought. Fredericksen (1992) states:

> "Serious droughts of five to eight years duration will occur with certainty. Prolonged periods of much lower precipitation are also likely. Their occurrence, severity and duration are quite impossible to predict - even when examining the preceding precipitation records with hindsight. And these precipitation patterns hold true for most regions of the world."

Nevertheless, scrutiny of meteorological records is an essential component of temporal drought prediction, although it is apparent that the rainfall record will only indicate that drought is likely after the first effects of drought have already occurred. Some little credence can be given to seasonal forecasting (perhaps six months ahead) based on statistical analysis of rainfall data; the long term effects of climate change also need to be identified for any given region. For example, the 1950s were the wettest and, therefore, the most prosperous years for most of tropical Africa since the 1870s. During this period rainfall was up to 19% above the long term average in some places (Iliffe, 1990).

Other indicators, the spacial indicators, must be looked at, and these are principally demographic. Changing land use is an important cause of disturbance to prevailing and long established hydrological regimes. Destruction of the vast areas of forest in, for example Ghana, induces rivers to dry up seasonally, which once flowed regardless of season or amount of annual rain. Changed land use may influence the climate; general circulation models are a useful means of assessing the effect of desertification, deforestation and atmospheric pollution.

Increased demand for water caused by population increase and the constant need to move into marginal land areas also causes stress to delicate resources in what can clearly be described, by definition, as drought prone areas. Groundwater availability in some hydrogeological units (eg shallow weathered basement) may be more prone to stress in times of drought than others. Identification of this enables a groundwater drought vulnerability map to be prepared (again at national level). Although such documents do not generally exist formally, there are few government agencies in Africa which are responsible for water that are not aware of areal variations in groundwater availability and vulnerability. This may be reflected in the unwillingness of drilling superintendents to allow drilling rigs into certain areas where they know that their success rates are likely to be low, it may also be reflected in the reluctance of some NGOs to move into certain areas for fear of little useful return against their investment.

3. DROUGHT MANAGEMENT STRATEGY

3.1 Data Collection

In order for drought management to be effective, certain basic data need to be gathered and assimilated. For example, it is essential to know where the village water supply springs, boreholes and wells are actually located. It is also useful to know something of the construction of the wells and boreholes and something about their pumping equipment, at least whether a motor or a hand pump is installed. In addition some intimation of the reliable yield of the source would be useful. Anecdotal reports regarding temporary failure, or changes in water quality are also useful; all water-points need maintenance, pumps fail, boreholes dry-up, and spares are needed. At any one time there may be a number of water points that are out of use. Increase in numbers can indicate economic failure and also highlight the best means of response (perhaps cash rather than technical assistance) to a drought situation in support of the maintenance programme.

Measured water level hydrographs for some representative local boreholes, which should be distributed evenly and as densely as resources permit, provide the best means of monitoring the onset and progression of drought. These data are not easy to collect because the responsible agency may be preoccupied with operational problems (eg drilling and pump maintenance) to the extent that resources are not available for routine monitoring work.

Change in water level due to excessively dry, or for that matter excessively wet conditions may often be accompanied by changes in groundwater quality. Records of total dissolved solids, and any other chemical parameters that can readily be determined are valuable. Monitoring of maintenance work is essential; ideally each water-point should be monitored and any down-time identified along with the cause.

The recommended data holdings comprise both fixed measurements of borehole and well locations and dimensions as well as time-series data. Data accessibility is important and paper records and Cardex systems are very much inferior to any of the modern off-the-shelf databasing packages that are available for PC use. Typical packages include MICROSOFT ACCESS, DBASE, etc, all of which are capable of importing data from spreadsheets such as EXCEL or LOTUS 123. The database packages greatly facilitate the handling, accessibility and interpretation of data, and can be used in conjunction with packages such as UN GROUNDWATER FOR WINDOWS for graphics presentation and reporting.

3.2 Demand Management

While demand management may not be feasible when only basic water needs are being met with existing supplies, it warrants serious consideration when water uses proliferate and basic needs have been satisfied.

Managing demand in urban areas, where water supply is often the responsibility of a utility or government agency, may involve long term moves towards the greater use of economic incentives and disincentives (eg prices and taxes), and mandatory controls such as licenses and quotas. Projects to install water saving technologies, such as recycling, low flush toilets etc, may also be effective. These measures may coincide with the adoption of a public education programme designed to make consumers aware of the scarcity and real value of water.

Reallocation of water between and within uses may also warrant consideration, both as a short term emergency measure, and as a longer term policy to improve drought resistance and economic efficiency. During the 1991/92 drought in Zimbabwe, tobacco farmers with their own wells continued to irrigate, while drought ravaged the homelands. In other areas, competition for water occurred between rural and urban areas. In all cases, however, and whether a short or long term measure, reallocation requires both institutional and physical plumbing for water transfers to take place.

Other methods of managing or controlling demand over time and space may also be important. For example, in critical recharge areas it may be necessary to restrict settlement and certain types of land use. In India, such restrictions have been debated for some time. Bhatia (1992) has suggested that the drought in Gujarat which occurred between 1985 and 1988 might have been exacerbated had the preferred crop of sugar cane, a profitable but water intensive crop, spread to the area. In cases such as this where economic policy may have an indirect effect on the water outlook, it is necessary for government to carefully consider the costs and benefits of policies, including environmental effects, and to consider the interests of present and future water users.

3.3 Traditional Coping Methods

Many communities are able to turn to relief supplies of water at times of hardship. The alternative source may be of poorer quality, or possibly distant from the village, so that neither source are used when the village well or borehole can satisfy demand. Local knowledge of past and fruitful dug-outs may be put to good use, care may be needed to exclude animals from such sources for fear of guinea worm and other risks of disease. Routine technical help in developing and safeguarding such alternative sources could greatly assist alleviation effort during groundwater drought.

3.4 Borehole Drilling and Siting

Borehole design appropriate for the geological conditions is essential for all new drilling. The principals of borehole design and rehabilitation in unconsolidated sedimentary aquifers are described in Howsam (1994). Borehole siting is commonly assisted by surface geophysical surveys in order to locate optimum sites for best sustainable results. Clearly a combination of aquifer thickness, hydraulic conductivity and available storage are component factors in obtaining best results; the deeper the base of the unconsolidated sedimentary aquifer the longer the borehole will remain in supply in drought conditions. Drilling of relief boreholes at geologically optimum sites, but away from villages may provide a fallback should village supplies fail. The village sources are quite probably located at hydrogeologically less favourable locations.

3.5 Institutional

Resources need to be targeted towards the more vulnerable areas within national and regional drought mitigation strategies. These mitigation strategies should include the strengthening and building-up of drought resistance ("drought proofing") outside drought periods, ie. not just crisis management during droughts.

Groundwater drought is often accompanied by economic hardship. In good times spare parts should be stored to meet the needs of routine maintenance in the infrequent drought periods. This longer term perspective involves consultation and participation with local communities to ensure sustainability of water supply developments, and integration rather than replacement of new supply schemes with existing, traditional sources.

The strategies should be devised from the available data and should depend heavily on the identification of vulnerable areas (defined on maps) and on the ability to predict the progression of a drought (drying up of the surface waters, death of animals) towards a full scale groundwater drought. The strategy may encompass many facets of groundwater management for drought alleviation or it may adopt, piecemeal, those components most likely to be effective in that particular area. For example, in an area or region in which most of the boreholes are 150 mm in diameter and equipped with, say, the Afridev hand pump, there is no room in the borehole for a water level dipper and little opportunity for collecting water level data. This is the case in Malawi over large areas, and a network of dedicated monitoring boreholes is having to be introduced.

3.6 The Unconsolidated Sedimentary Aquifer

The unconsolidated sedimentary aquifer typically possesses a relatively high hydraulic conductivity and storativity but a correspondingly low hydraulic gradient. Failure of surface waters may have an immediate adverse affect on groundwater levels as the two may be in hydraulic contact. Areal reduction of the water table in times of drought will, therefore, occur uniformly throughout the aquifer, provided that the are no significant barriers to horizontal groundwater flow. That being so, a borehole drawing from the deepest part of the aquifer will remain productive the longest, but barriers to vertical flow such as low permeability silt and clay horizons may impair the performance of deeper horizons within the aquifer.

For the most part, boreholes in unconsolidated aquifers tend to be drilled into bedrock in order to bottom the aquifer, and that there is little to be gained by deepening such boreholes as the water table falls in the unconsolidated sedimentary aquifer. Furthermore, deposits in the upper parts of catchment areas will tend to react to recharge or absence of recharge more quickly than similar deposits at lower elevations. This is due to the rate of drainage from the upper part of the catchment which has the least storage capacity.

Generic models can be prepared to enhance the understanding of the ability of an aquifer to withstand drought conditions. Estimates of normal recharge can be derived from water level monitoring and knowledge of the formation constants can be derived from test pumping, and then can be used to provide an overall figure for normal sustainable yield. Abstraction is from storage only during drought so that the product of specific yield and saturated volume to any elevation beneath the water table (including the bottom of the aquifer) provides the approximate drought yield of the aquifer. Data are commonly insufficient to undertake such estimates with any degree of accuracy, but it is desirable to move towards this level of understanding in order to implement a suitable drought management strategy.

3.7 Crisis Management of Drought

The normal institutional response to drought, particularly by the NGOs, is crisis drilling. Foreign teams of surveyors and drilling rigs are sent into an affected area and often large numbers of new boreholes are drilled and equipped over short time periods. Much of the data describing this work is mislaid or inaccurate, and even borehole locations may not be recorded accurately if at all. Worst of all the yield of the new boreholes may be ephemeral and short term relief may quickly turn to frustration as the new water source becomes dry. The crisis response is expensive and its long term payback is disappointing. Drought alleviation strategy is beneficial for the long term return to investors (the NGOs), service to the population, and sensible resource management. The NGOs themselves prefer steady expenditure into drought alleviation programmes rather than intermittent, but intensive spending on crisis drought relief programmes.

Acknowledgement

Much of the philosophy described in this review derives from discussion with Kabuka Banda of the Malawi Ministry of Irrigation and Water Development and Samuel Oppiah, who is with the Ghana Water & Sewerage Corporation.

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METHOD SUMMARY SHEET

TITLE: **Drought Management and Mitigation**

Drought Issues

- Groundwater drought is severe. It is the final stage of drought which follows surface water drought when people rather than food have to be moved.

- The economic aspects of drought are important. If a country is rich enough it can purchase and import food as well as supply sufficient spare parts and salaries to maintain its groundwater extraction programme.

- Drought is different in urban and rural areas. In urban areas demand can be reduced by a number of measures and water transferred from industry to supply. In most rural areas, depending on aquifer type and other issues, there is a permanent need for more water. The effects of drought are felt earlier.

- In arid and semi arid areas groundwater is the only source of supply for many people.

- In severe drought (long periods of low rainfall) yields reduce or dry up for increasing numbers of dug wells and boreholes. People utilise traditional coping methods from river beds or migrate. Little is known about this practice.

Method

There is much published on coping with famine resulting from drought and agencies and procedures exist to do so.

There is little published about coping with groundwater drought. A project is underway (ODA No. R6233) with the objective of developing an understanding of the socio-economic aspects of groundwater drought, and translating this into guidelines for short-term and long-term strategies for groundwater management in drought-prone areas.

The results of this project will be published by BGS in 1997. The strategy being developed is:

- Evaluation of regional experience of groundwater drought.

- Drought sensitivity analysis.

- Systems for predicting the occurrence and impact of groundwater drought.

- Groundwater management plans.

Preparation of the strategy should involve a full evaluation of the socio-economic impact of groundwater drought in different sectors and at different levels. The management strategy should include the following topics:

- Conjunctive use.

- Building on traditional methods of coping with groundwater drought.

- Borehole type, borehole siting and drilling.

- Most importantly experience of groundwater drought suggests that a simple database should be maintained of all groundwater extraction points. The location, construction details, yield with time and diagnosis of reason for failure should all be recorded regularly. This information is essential for normal maintenance and rehabilitation purposes but becomes even more relevant in drought when it is important to know where to direct relief measures, which might include increased rate of activity of rehabilitation and maintenance rather than increased provision of supply points.

- Targeting resources towards vulnerable areas with the aid of drought vulnerability mapping.

REVIEW OF SUBSIDENCE CAUSED BY GROUNDWATER ABSTRACTION

by

T R Shearer

CONTENTS - Part 4

REVIEW OF SUBSIDENCE CAUSED BY GROUNDWATER SUBSIDENCE

1. AIMS

To review the problem of land subsidence caused by groundwater abstraction. The geological mechanisms and processes that cause subsidence are described together with an outline of techniques used to study the phenomenon and a summary of management options. This is followed by a number of case histories.

1.1 An Earlier Review

In 1984, UNESCO convened a working group on "Land Subsidence due to Groundwater Withdrawal" under the chairmanship of JF Poland. The admirable and comprehensive work of that group is summarised in this review.

2. BACKGROUND

Land subsidence can occur for a number of reasons, both natural and man-made. Subsidence resulting from the abstraction of geofluids such as groundwater is one of the most widespread. It is of particular importance because it is often associated with areas of industrial development or other human activities where the ground level changes can have serious economic impact. It is, however, one of the few types of subsidence which is amenable to some degree of control.

Subsidence can be dramatic. Ground level changes of the order of 7.5 metres have been reported in the sedimentary formations underlying Mexico City and as much as 9 metres in the San Joaquin Valley of California, both due to groundwater extraction. Oil field subsidence in California has also reached 9 metres whilst extraction of hot water for geothermal power in New Zealand has caused subsidence of the order of 7 metres. In many coastal areas, for example Venice, even minor ground level changes can be critical.

2.1 Mechanisms of Subsidence

Land subsidence is the visible effect of compaction within the underlying geological formations. There are a number of processes, physical and chemical, that can be involved but the abstraction of groundwater is the most common. The susceptibility of aquifers to compaction depends on the basic characteristics of the geological strata and its hydrogeological history.

Non-indurated sedimentary formations are frequently affected by subsidence, particularly where there exists a sequence of alternating beds of coarse and fine-grained materials. The fine-grained interbeds form aquitards within the coarser component of the aquifer system. Major aquifers may contain up to one hundred interbeds and usually most of the subsidence occurs within these fine-grained interbeds: compaction of the coaser strata is comparatively small.

Terzaghi (1925) proposed the basic concept. Generally, sedimentary formations are laid down at comparatively low grain densities. As the thickness of the formation builds up and subsequent layers are deposited, the increasing weight of the overburden compresses the underlying strata. At each stage, the intergranular stress in the skeleton of the porous medium balances the weight of the overburden.

Sedimentary aquifers are often saturated at or shortly after formation. At that time, the buoyancy effects of the water content helps support the structure of the aquifer matrix. Subsequently as overlying, possibly confining, strata are laid down, the hydraulic head builds-up and this combines with the intergranular forces to resist the weight of the overburden: the compaction that the overburden would otherwise cause is reduced. When water is extracted from the aquifer, the hydraulic pressure decreases and all strata are subjected to an increase of compaction stress. The coarse-grained, sandy aquifer strata form a rigid matrix skeleton which resists compaction whereas the finer-grained, clayey aquitards are more plastic and hence, more prone to compact.

The actual response of a system to a particular reduction in piezometric head depends on the previous history of pressure changes. Variations of pressure within the limit of previous changes result in little if any extra compaction and what compaction there is, is usually elastic, when the pressure returns the formation rebounds. However once the previous maximum stress is exceeded, compaction does occur. This compaction is mainly inelastic, the strata does not fully recover if the piezometric head is subsequently restored.

The low permeability of an aquitard layer introduces a delay to the rate at which the piezometric head in the aquitard equilibriates with changes of head in the aquifer layers. This delay is reflected in the rate of subsidence.

An alternative, less common, mode of compaction involves the movement of fine-grained sediment into the void space of adjacent carbonate strata. The movement is again precipitated by changes in piezometric head. The areas affected by this type of subsidence are usually very limited in horizontal extent but the vertical movement can be significant.

On the other hand, it is possible for the addition of water to cause subsidence. In very arid areas, fine-grained sediments can be laid down with low density due to chemical bonding between clay particles. Wetting breaks the bonds and the sediment compacts under its own weight.

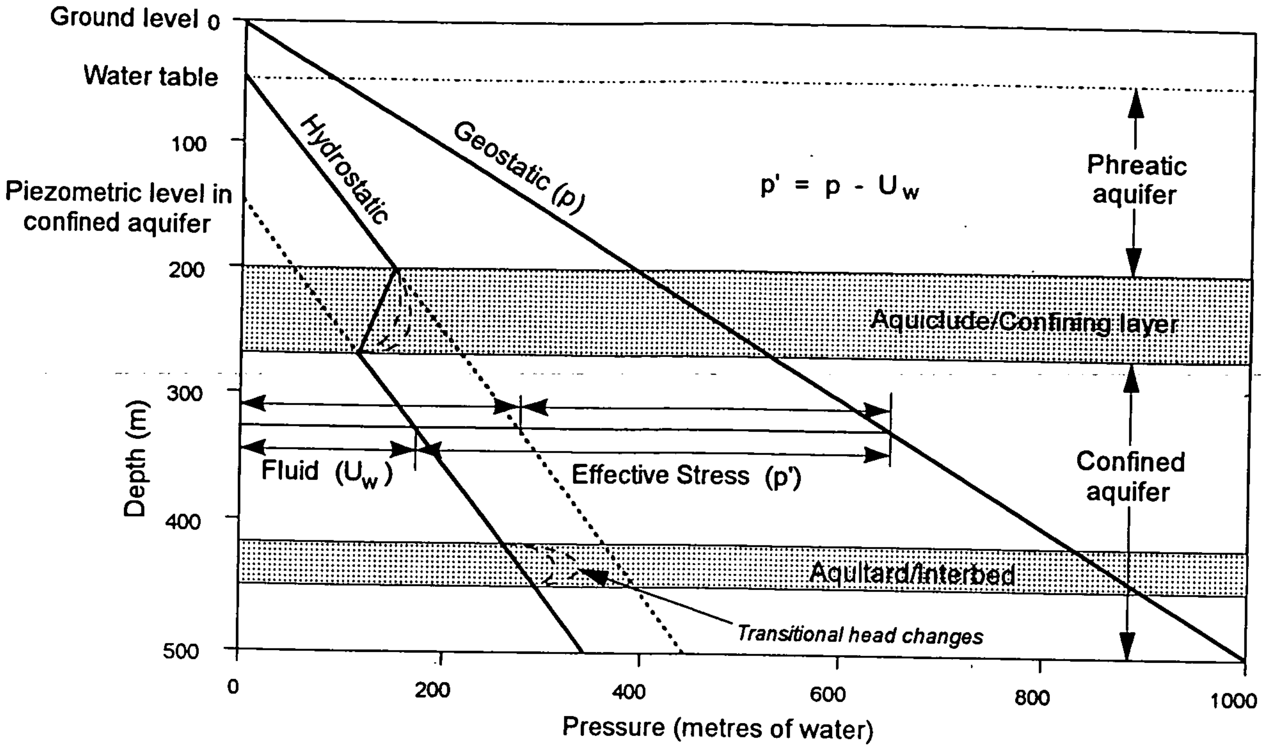

Figure 1. Stress relationships within an aquifer system. (After Poland, 1984)

2.2 Theory of Aquifer Compaction

Meinzer (1925) observed that artesian aquifers compress when the piezometric head decreases. In 1928 he concluded that water extracted from storage was released both by compression of the aquifer and by the expansion of the water and that the reduction of storage following compression of the aquifer may be permanent (inelastic) as well as recoverable (elastic).

Terzaghi (1925) developed the theory of one dimensional consolidation of clays which is now used to estimate the compaction in fine-grained clayey deposits when the stress changes. Compaction results from the slow escape of pore water from the fine-grained material, accompanied by a gradual transfer of stress to the granular structures of the material

$$p' = p - u_w \qquad (2.1)$$

where p' is the effective intergranular stress, p is the total geostatic stress and u_w is the pore fluid pressure.

Jacob (1940) recognised that in addition, water could be released from compressible clay interbeds within and adjacent to an aquifer. He suggested this could be the major source of water and that there might be a time lag in this process.

In 1969, Riley succinctly summarised the earlier work highlighting the time-dependency of the compaction on the rate of equalisation of the pore pressures within the aquitards to those within the aquifer.

"For a single homogeneous aquitard, bounded above and below by aquifers in which the head is instantaneously and equally lowered, the time, t, required to attain any specified dissipation of average excess pore pressure is a direct function of: (1) the volume of water that must be squeezed out of the aquitard in order to establish the denser structure required to withstand the increased stress, and (2) the impedance to the escape of this water. The product of these two parameters constitutes the aquitard time constant. For a specified stress increase, the volume of water is determined by the volume compressibility, m_v, of the aquitard, the compressibility, β_w, of the water, and the thickness, b', of the aquitard. The impedance is determined by the vertical permeability, K', and thickness of the aquitard. Thus, the required time, t, is a function of the time constant, τ, where

$$\tau = \frac{S'_s \, (b' \,/\, 2)^2}{K'} \tag{2.2}$$

and where S'_s is the specific storage of the aquitard, defined as

$$S'_s = S'_{sk} + S_{sw} \tag{2.3}$$

in which

$$S'_{sk} = m_v \, \gamma_w = \frac{\Delta b'}{b' \, \Delta h_a} \tag{2.4}$$

and

$$S_{sw} = n \, \beta_w \, \gamma_w \tag{2.5}$$

S'_{sk} is the component of specific storage due to compressibility of the aquitard, S_{sw} is the component due to the compressibility of water, h_a is the average head in the aquitard, n is the porosity, and γ_w is the unit weight of water. For consolidating aquitards $S'_{sk} >> S_{sw}$.

The inelastic compression of the aquifer/aquitard system represents a reduction in void space within the formation. This translates to a permanent loss of groundwater storage potential in the system.

3. METHODS

Before any attempt can be made to predict or control subsidence, a thorough knowledge of the physical and hydraulic properties of the formation is required. Generally, all the traditional laboratory and field techniques for determining these properties can be useful to the study of subsidence. However those methods that define the characteristics of the clayey interbeds are especially important.

General hydrogeological techniques are dealt with elsewhere in these reviews. Those methods that are largely specific to land subsidence are explained below.

3.1 Measuring and Monitoring Subsidence

Although the techniques are described separately, clearly they are most informative when used in combination, for example borehole geophysical logging with laboratory core analysis.

3.1.1 In the Field

The first requirement when addressing a situation of land subsidence is to determine the extent of the problem, both the amount and rate of subsidence and the land area affected. There are two basic techniques for measuring the ground-level change; surface surveying and extensometer wells.

Surface surveying traditionally relies on the precision levelling of fixed benchmarks using engineers spirit levels. The elevation of benchmarks in the subsiding area are measured relative to either a datum benchmark in a geologically stable area or to sea level. The requirement of a stable reference point frequently leads to very long (several kilometre) surveying lines which are time-consuming, and hence costly, to survey to the required degree of accuracy.

A recently introduced alternative is to use the high-precision functions of the NASA Global Positioning System (GPS) satellite navigation system. The GPS refers the elevation of the benchmark to a standardised global datum. This equipment can give similar accuracy (~5 mm) in a fraction of the time allowing a denser network of benchmarks to be routinely monitored.

Extensometer wells measure the surface subsidence relative to stable geological formations under the compacting strata. There are a number of different designs such as anchored-cable and standing-pipe but in principal the extensometer well passes through the compressible aquifer into the stable bedrock below. A fixed length measuring system is cemented in at the bottom and protrudes from the ground at the top allowing changes in the ground level to be recorded. This can be an expensive technique as formations liable to subsidence can be several thousand metres deep. A useful variation is to have several extensometers grouted-in at intermediate depths so that the differential measurements of ground-level change indicate the compaction of individual layers within the aquifer.

3.1.2 Laboratory Testing

The compressibility characteristics of fine-grained compressible aquitard layers may be obtained by making one-dimensional consolidation tests of "undisturbed" cores in the laboratory. These tests are described in detail in soil mechanics textbooks. A cylindrical core is compressed longitudinally and the compaction measured at various pressures.

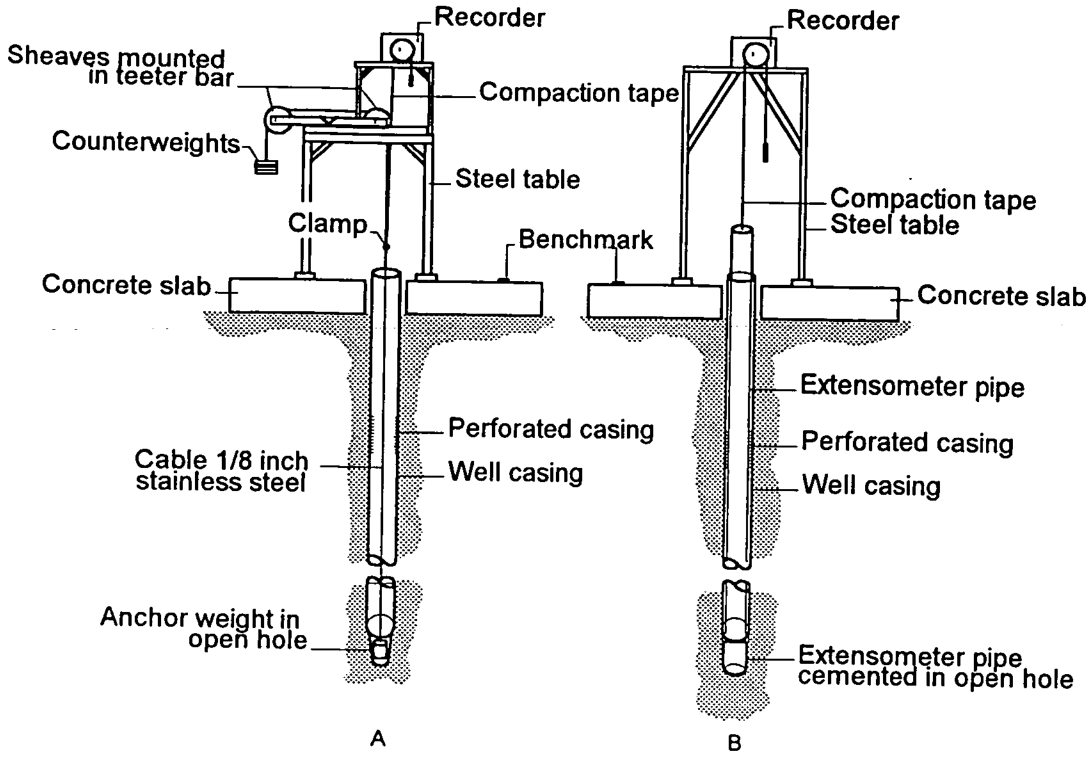

Figure 2. Recording extensometer wells.
(A, anchored cable. B, standing pipe). (After Poland, 1984)

The plot of void ratio against the logarithm of load (effective stress) is known as the e-log p plot. Three parameters that can be obtained from this plot are (1) the compression index, C_c, a measure of the nonlinear compressibility of the sample, (2) the coefficient of consolidation, C_v, a measure of the time rate of consolidation, and (3) the approximate value of the preconsolidation load, determined graphically. The preconsolidation load or stress is the maximum effective stress to which a deposit has previously been subjected and which it can subsequently withstand without undergoing additional permanent deformation.

For effective stress changes in the stress range less than preconsolidation stress, the compaction or expansion of both aquitards and aquifers is small and elastic - that is, approximately proportional to change in effective stress over a moderate range in stress, and fully recoverable if the stress reverts to the initial condition.

Within aquitards, for increases in effective stress that exceed the preconsolidation stress, "virgin" compaction occurs. This is chiefly inelastic - that is, not recoverable upon decrease in stress. However, there may be a recoverable elastic component though it is small compared to the nonrecoverable component. The virgin compaction usually is roughly proportional to the logarithm of effective stress.

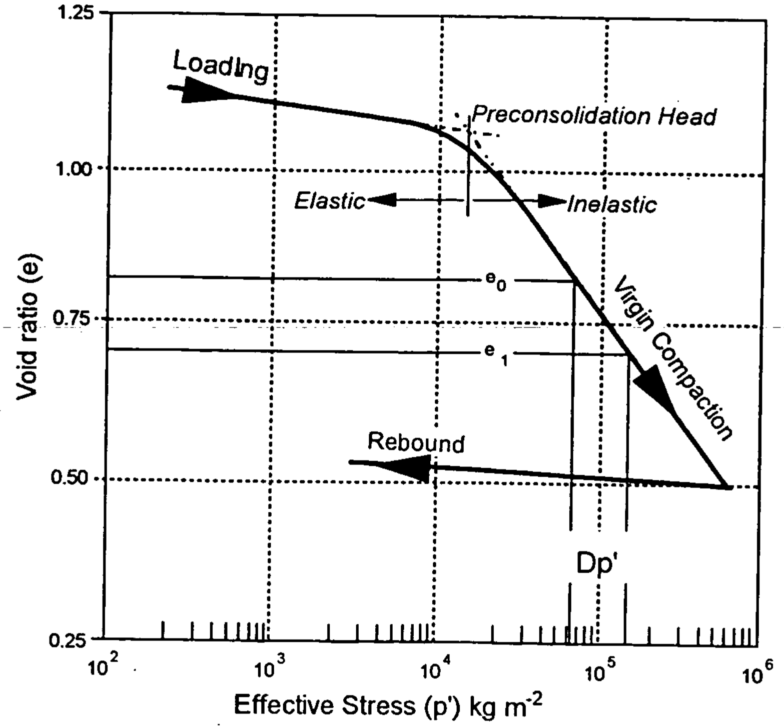

Figure 3. Stress - compaction relationship. (After Jorgensen, 1980)

The compaction of aquifers, in contrast to that of aquitards, is chiefly elastic (recoverable) but conversely it may include an inelastic component. In poorly sorted and angular sands and especially in micaceous sands, the inelastic component may dominate.

A semilogarithmic plot of void ratio, e, versus the logarithm of load (effective stress), p´, shown in Figure 3 illustrates a graphic method of computing compressibility. The coefficient of volume compressibility, m_v in soil-mechanics terminology, (Terzaghi and Peck, 1967).

$$m_v = \frac{e_0 - e_1}{(1 + e_0)\ \Delta p'} \qquad (3.1)$$

m_v represents the compression of the clay, per unit of initial thickness, per unit increase in load (for effective stress change in the range exceeding pre consolidation stress).

3.2 Predicting Subsidence

In order to plan effectively and minimize adverse effects it is very necessary to be able to predict future subsidence. Many methods have been used to predict rates of land subsidence due to pumping of groundwater from aquifers. The methods range from simple empirical methods to complex theoretical and modelling approaches.

3.2.1 Empirical and Semi-theoretical Methods

The simplest methods are usually based upon extrapolating existing data to derive a future trend. A smooth curve, quadratic, logarithmic or exponential, is fitted to the available data. Least squares fitting techniques may be used.

These empirical methods are useful where only limited data exist or where rough estimates only of future subsidence are required. The method is less valuable where rapid changes in water extraction have occurred or are proposed. For example, where it is desired to investigate radical control measures for serious subsidence occurrences.

A more sophisticated approach is to use the relationship between subsidence and other physical phenomena to estimate future trends. Early work by Wadachi (1939) showed that the rate of subsidence, not the actual subsidence, was proportional to the water level change.

Subsequent studies have used the relationship between the groundwater production or head decline and subsidence (Figure 4). Many observers have noted a strong correlation between the total volume of subsidence and the total volume of abstraction. The ratio of proportionality frequently being between 0.25 and 0.33. The value of this ratio depends on the percentage of clay in the formation.

The subsidence/head-decline ratio is the ratio between land subsidence and the head decline in the coarse-grained permeable beds of the compacting aquifer system, for a common time interval. It represents the change in thickness per unit change in effective stress ($\Delta b/\Delta p'$). This ratio is useful for predicting a lower limit for the magnitude of subsidence in response to a step increase in virgin stress (stress exceeding past maximum). If pore pressures in the compacting aquitards reach equilibrium with those in adjacent aquifers, then compaction stops and the subsidence/head-decline ratio is a true measure of the virgin compressibility of the system. However, until or unless equilibrium of pore pressures is attained, the ratio of subsidence to head decline is a transient value.

Another technique uses the depth porosity profile to estimate future compaction. It has been widely observed that the porosity of sedimentary formations decreases with depth in a roughly exponential manner. Schatz et al (1978) suggested this distribution was due to increased compaction at depth because of the greater stress of the overburden. They used the depth porosity curve to estimate the effect of increased stress due to a reduction in hydraulic pressure.

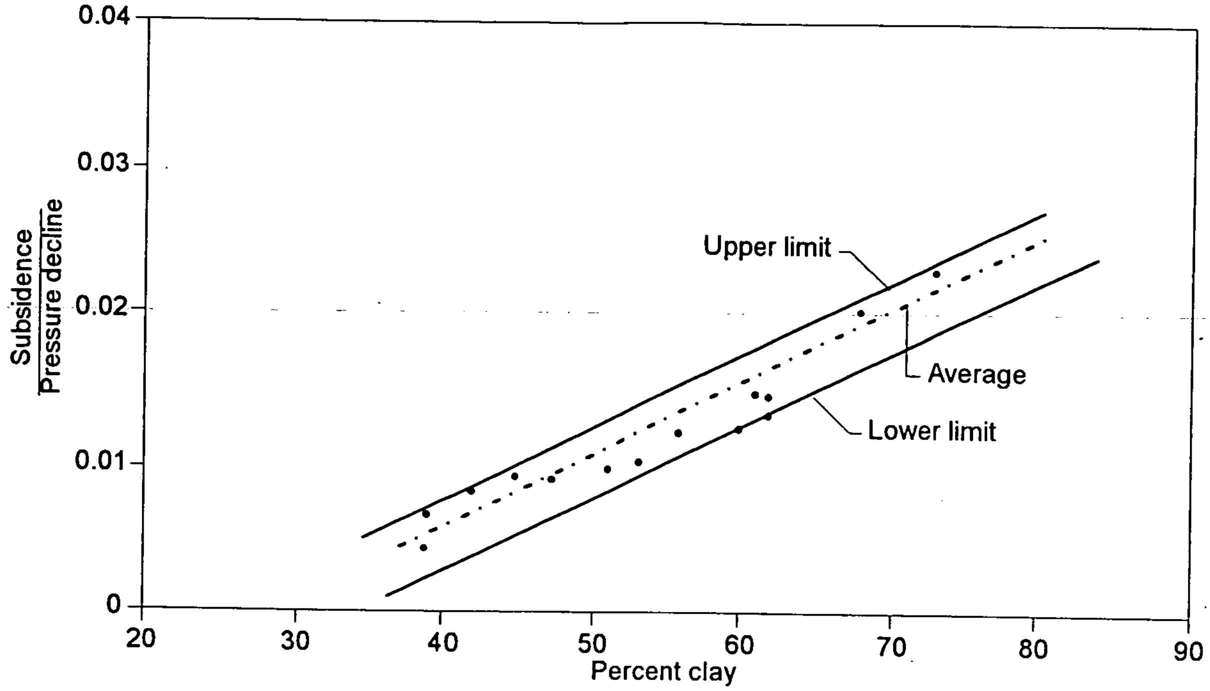

Figure 4. **The relationship between clay content and subsidence. (After Gabrysch, 1969)**

3.2.2 Theoretical and Modelling Approaches

Regional subsidence due to groundwater extraction is a complex phenomenon because soils incorporate into their mechanical properties all the behavioural aspects of their components, i.e. elasticity and plasticity of solids, viscosity of liquid, compressibility of gases, decay properties of organic matter, attraction and repulsion of ionic charges, etc.

Numerical models to handle all of these interacting, multi-phase phenomena would be extremely complex so there has been a tendency to make simplifications. The suitability of which may vary from one case or area to another.

Common assumptions used in the formulation of conceptual models are:

- Only one-dimensional vertical compaction (ie. horizontal, isotropic geological structure).
- Only linear elastic properties, no viscosity or plasticity.
- Only liquid and solid phases, no gases or chemical reactions.
- Only two modes - elastic and virgin compaction - with constant parameters for each.
- Only horizontal flow in aquifers, only vertical in aquitards.

As there is as yet no truly comprehensive theoretical model available, it is advisable to make several estimates of the subsidence using alternative methods.

3.2.2.1 *Compressibility coefficient and potential total subsidence*

In soil mechanics the coefficient of volume compressibility m_v is defined.

$$m_v = \frac{a_v}{1 + e_0} \tag{3.2}$$

where a_v is the coefficient of compressibility and e_o is the initial void ratio

$$a_v = \frac{e}{dp'} \tag{3.3}$$

is the change in void ratio with pressure.

Assuming compaction occurs only along the vertical axis, the compaction of a layer of thickness H_o when subjected to a change in effective intergranular pressure $\Delta p'$ is

$$\Delta H = m_v \, \Delta p' \, H_0 \tag{3.4}$$

So the total potential compaction for a soil column may be calculated as:

$$\overline{\Delta H} \approx \sum_{1}^{i} m_{vi} \, \Delta p_i \, H_{oi} \tag{3.5}$$

However the underlying linear relationship of the e log p´ plot assumes saturation so this method becomes inaccurate at extreme stress.

3.2.2.2 *Compressibility and the equations of groundwater flow*

Groundwater flow is governed by Darcy's Law

$$\overline{v} = - K \nabla h \tag{3.6}$$

and the principle of conservation of mass which for transient saturated flow can be expressed

$$- \nabla \bullet (\rho \, \overline{v}) = \frac{\partial (\rho \, n)}{\partial t} \tag{3.7}$$

where $\bar{v}$ is the intergranular fluid velocity vector, K the hydraulic conductivity, ρ the fluid density and n the porosity.

The righthand term represents the mass of water produced from storage. Eq (3.7) can be expanded

$$- \frac{\partial(\rho v_x)}{\partial x} - \frac{\partial(\rho v_y)}{\partial y} - \frac{\partial(\rho v_z)}{\partial z} = n \frac{\partial \rho}{\partial t} + \rho \frac{\partial n}{\partial t} \tag{3.8}$$

The first term on the right represents the rate of mass produced by the expansion of the water and the second tern is the rate of mass production due to changes in porosity following compaction of the porous medium.

However the specific storage S_s is defined as the volume of water produced by a unit head decline.

$$S_s = \rho g (\alpha + n \beta) \tag{3.9}$$

where α is the compressibility of the aquifer and β that of the groundwater.

Considering the rate of mass production

$$n \frac{\partial \rho}{\partial t} + \rho \frac{\partial n}{\partial t} = \rho S_s \frac{\partial h}{\partial t} \tag{3.10}$$

Substituting Eq (3.6) and Eq (3.9), Eq (3.10) simplifies

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{k} \frac{\partial h}{\partial h} \tag{3.11}$$

$$= \frac{S}{T} \frac{\partial h}{\partial t} \tag{3.12}$$

$$= \frac{1}{D} \frac{\partial h}{\partial t} \tag{3.13}$$

where S is the storativity (S_s b), T the transmissivity (Kb), D the diffusivity and b is the thickness of the aquifer.

Eq (3.13) is the diffusion equation. Considering the case of vertical flow in the aquitard,

$$\frac{\partial^2 h}{\partial z^2} = \frac{1}{D} \frac{\partial h}{\partial t} \tag{3.14}$$

as described by Terzaghi (1925).

The diffusion equation was developed by Jacob in 1940. In 1950 he produced a more rigorous deviation which highlighted the restrictions implicitly assumed in Eq (3.13): that the stress is one-dimensional and vertical and that the size of compaction is very small compared to the rate of pressure change.

3.3 Managing Subsidence

Subsidence causes damage with economic impact at both local and regional levels. On a small scale, the foundations of individual structures can be tilted resulting in the collapse of buildings, underground services can be disrupted, well casings crushed. At a larger scale the drainage patterns of rivers and canals can be modified followed by flooding or water shortage, areas can become liable to catastrophic inundation from the sea. Less dramatically there is a permanent loss in groundwater storage capacity. These risks must be managed in an appropriate manner.

Where subsidence can be largely attributed to the abstraction of groundwater there is the possibility of controlling it. The only long-term prospect for arresting the ground level fall is to prevent the further decline of piezometric heads. The following case histories illustrate that this can be a successful strategy but that there is likely to be a time delay between stabilising the groundwater levels and the complete cessation of subsidence. Allowing the piezometric heads to recover to their original level may bring some rebound of groundlevel but this is certain to be only a small proportion of the observed subsidence. Clearly in critical areas, such as where seawater inundation could occur, it is essential to act early before irreparable damage is done.

In aquifers with natural recharge simply stopping or reducing abstraction may be adequate to halt the subsidence. Elsewhere, when an immediate reduction in subsidence is required, artificial recharge may be appropriate. In either case an alternative supply of water is required. This will certainly be more expensive than the local groundwater. The most appropriate management technique depends on the balance of economic advantage between the subsidence and the water supply.

When attempting to assess the benefit of implementing remedial measures, however, it must be remembered that any formation that is liable to subsidence due to groundwater abstraction is also likely to be susceptible to other causes of subsidence such as tectonic movements. Unless the components from the separate contributing causes can be identified, the remedial measures may prove less effective than predicted.

4. CASE HISTORIES

4.1 Venice, Italy

Based on Carbognin et al., 1977

The ancient city of Venice is one of the most notorious instances of land subsidence. The rate of subsidence is not particularly high but the low elevation of the city and the proximity of the sea means even a modest decline in groundlevel could prove disastrous. Several processes are known to be involved in the subsidence at this location but the withdrawal of groundwater has been identified as the most important.

The city stands on a group of islands in a coastal lagoon at the northern end of the Adriatic Sea. Beneath it, multilayered Quaternary deposits form a confined aquifer system almost 1000 m deep. Directly under the city, the aquifer is composed of numerous sand layers interspersed with silt and clay aquitards. Further inland the sediments become increasingly coarse while the aquitards thin and eventually disappear. Towards the foothills of the Alps, these unconsolidated formations are unconfined and become more homogeneous sand and gravels. This forms the catchment that supplies the confined aquifer under the city.

The threat that subsidence poses for the city has been recognised for a number of years and several studies have been carried out including numerical modelling. There has been extensive monitoring of ground level changes and piezometric heads and two deep research boreholes were cored through the exploited section of the aquifer.

Before the middle of this century, groundwater exploitation was not intensive and the piezometric head remained above groundlevel throughout most of the area. A background rate of subsidence of 1 mm/y was identified.

Subsequently, industrial development at Marghera on the adjacent mainland coast caused a marked increase in groundwater abstraction. In the industrial areas the piezometric head fell on average 12 m. During the period 1952 - 1968 the average amount of subsidence was 11 cm in the Marghera and 9 cm in the city of Venice. In 1969 the rates of subsidence were 17 mm/y and 14 mm/y respectively. At this time the abstraction in the industrial zone was 460 l/s but only 10 l/s in the city. Most of the abstraction is taken from the upper 300 m of the aquifer.

The studies showed that the abstraction from the industrial areas had greatly altered the natural groundwater flow pattern of the area and that the resulting subsidence was not evenly distributed. For every one metre decline in the piezometric head, there was one centimetre of subsidence in the industrial area but two centimetres under the old city. This is explained by the greater proportion of clayey layers under the city. The rapid response of the subsidence to pumping is attributed to the thin and discontinuous nature of the aquitards; this facilitates their drainage into the adjacent sands and gravels.

The alarming situation of 1969 with increasingly rapid rates of subsidence provided the impetus for remedial measures to be implemented. Aqueducts were constructed to import water from beyond the coastal fringe and abstraction rates were cut. A more intensive monitoring system was established with 112 piezometric stations and annual geodetic surveys.

By 1975, 70% of the wells in the city had been closed down and the abstraction rate in the industrial area was reduced to 40% of the previous maximum rate. The piezometric head began to recover. A rise of 8 m in the industrial area and 3 m in the city was recorded in 1975. In addition there has been a ground level rebound of approximately two centimetres relative to sea level. This clearly demonstrates the role of groundwater abstraction in causing the subsidence.

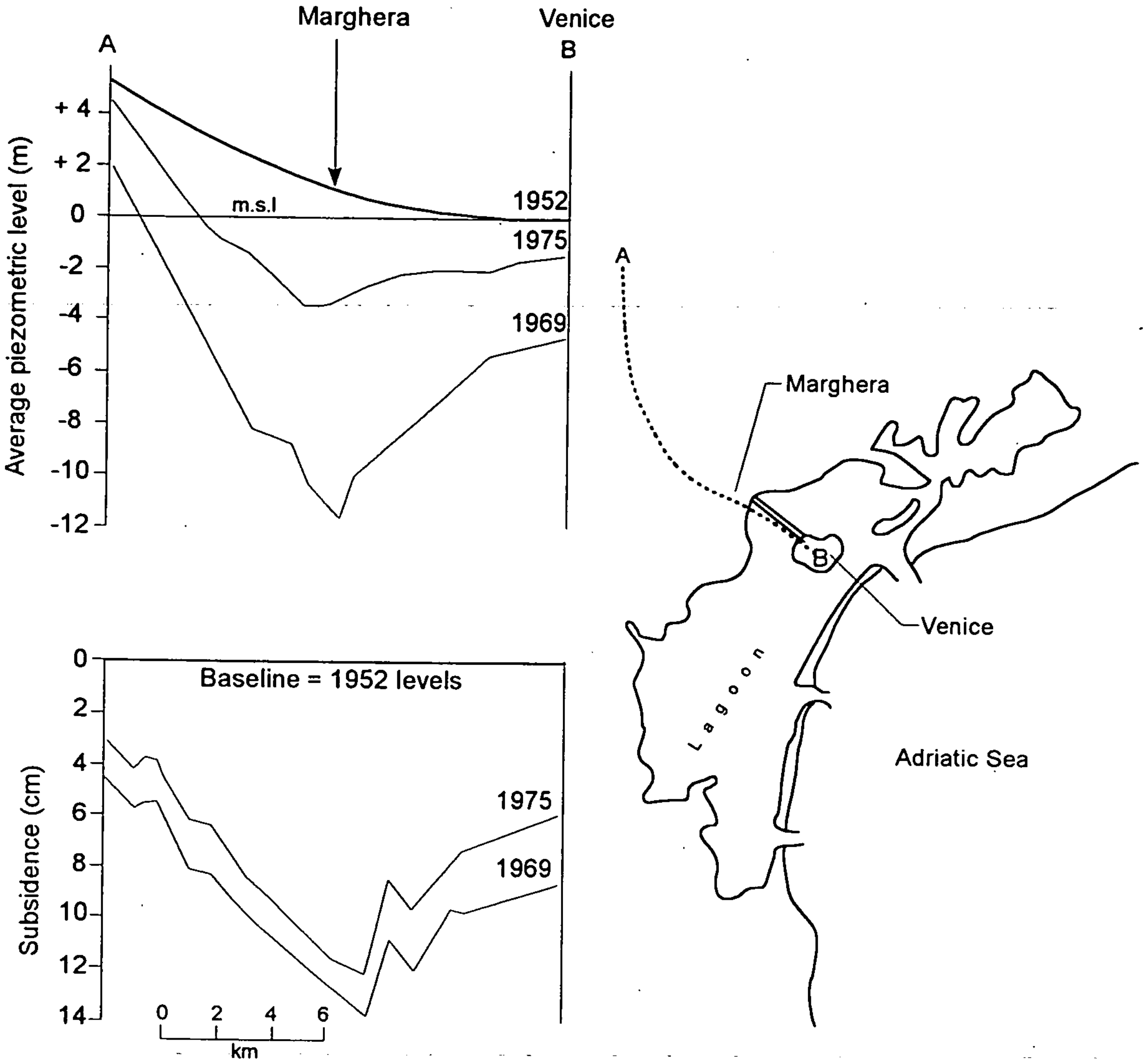

Figure 5. **Piezometric levels and subsidence at Venice. (After Carbognin et al, 1977)**

The piezometric head continues to recover and it is hoped that it will eventually be restored to the 1950 level despite the residual abstraction. It is anticipated that the ground level rebound will eventually reach 3 cm, about 20% of the subsidence. This indicates the ratio of elastic and inelastic compaction.

This case history demonstrates that appropriate remedial measures can arrest land subsidence caused by groundwater abstraction.

4.2 San Joaquin Valley, USA

Based on Poland & Lofgren, 1984

The San Joaquin Valley is the southern arm of the Central Valley, California. It lies just inland of San Francisco and is an important agricultural district, highly dependant on irrigation.

The valley is a broad structural downwarp. To the east is the mountainous Sierra Nevada. This granite basement dips gently beneath the valley. To the west is the complexly folded and faulted Coastal Ranges. The valley floor is covered with Late Cenozoic deposits up to 5000 m thick. The structure of these continental deposits is complex: chiefly fluvial with extensive lacustrine interbeds. There is a mixture of lenticular bodies of sand and gravels and sheet-like deposits of silt and clay. Around the margin are extensive coalescing alluvial fans of permeable gravel.

The deposits are divided into three units. At the top is a heterogeneous mixture of clay, silt, sand and gravel: these are mainly alluvial fans and flood-plain deposits. In the middle, a relatively impermeable diatomaceous lacustrine clay. At the bottom, more mixed clay, silt, sand and gravel: this time of lacustrine origin. This creates two principal hydrologic units. An upper semi-confined, water-table aquifer 275 m deep and below the clay layer a confined aquifer 60 to 600 m thick. At the bottom of the lower layer, the groundwater is saline.

Groundwater abstraction in the valley increased gradually from 2.5 km^3 in 1920 to 3.7 km^3 in 1940 and then at an accelerating rate to 12 km^3 in 1966 to meet the expanding agricultural demand for irrigation water. This abstraction from an area of 26,000 km^2 is estimated to be at least 5 km^3/y more than the sustainable yield. Piezometric heads fell by 60 to 180 m in the worst affected areas. The history of subsidence in the area closely matches the pattern of abstraction. By 1970, 13,500 km^2 were affected by subsidence exceeding 0.3 m. Groundlevel changes of 1.5 m to 3 m are common. The worst affected area is the western side of the valley where the sediments are deepest.

The maximum observed groundlevel fall is 9 m at a point 16 km west of Mendota. This is recorded in an apocryphal photograph showing a plaque marking the 1925 ground level two-thirds of the way up an electricity pole. A man (Dr J F Poland) standing at the base barely reaches one-third of the way up to the plaque marking the 1955 level. The cumulative volume of subsidence exceeded 19 km^3 in 1970: equivalent to 1.5 years of water consumption.

The area has been the focus of intensive study into the extent of the subsidence and of the controlling mechanisms. The studies concluded that the subsidence resulted almost wholly from the compaction of the fine-grained interbeds following the fall in piezometric potential.

The correlation between the cumulative subsidence and the cumulative abstraction is remarkably consistent. It indicates that there has been a permanent reduction in pore space within the clayey interbeds equivalent to almost one-third of the volume of water pumped or between one and four percent of the total pore space.

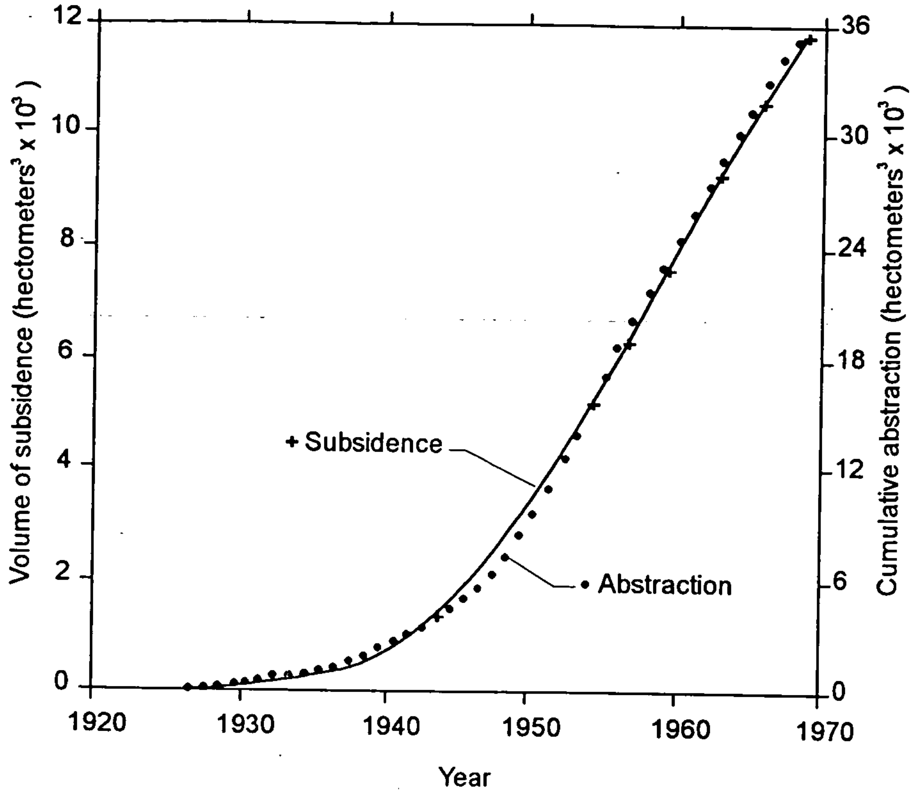

Figure 6. Cumulative volumes of subsidence and abstraction, Los Banos - Kettleman City area. (After Poland et al., 1984)

This rate of over-exploitation was clearly unsustainable, so the California Aqueduct was constructed to import water to the worst affected areas from the north. As a result, groundwater abstraction decreased sharply and the fall in artesian head was reversed throughout most of the area. By 1974 surface water imports to the west side of the valley reached 1.4 km^3/y while local abstraction fell to 0.25 km^3/y. Hundreds of irrigation wells were unused, the piezometric levels were recovering rapidly and the rate of subsidence decreased significantly.

At the worst affected location, west of Mendota, the water level which had fallen 125 m by 1969, recovered 73 m by 1977. The maximum rate of subsidence of 0.54 m/y between 1953 and 1955 reduced to 0.04 m/y between 1972 and 1975 (however the ground level is still falling).

The principal impact of the subsidence was the disruption of surface water features. Irrigation channels have required frequent realignment and river gradients have changed altering their erosion and depositional behaviour and requiring extra levee maintenance. In addition well failure due to compressive rupture of the casing has been common.

Perhaps ironically, the construction of the California Aqueduct, built to alleviate the subsidence problem, was beset by hydrocompaction. The route of the aqueduct had to be wetted for two years prior to laying the concrete linings of the canal to pre-compact the very dry, clayey surface sediments.

At the present time, the recovery of the piezometric head has almost eliminated land subsidence in the valley. The recovered aquifer saturation represents storage capacity that is available to make up temporary deficiencies in the supply of imported water. Such usage is unlikely to cause further subsidence as the present preconsolidation stress would not be exceeded. However there remains an increasing threat of long-term shortages of water available for importation. If supplies fail, there is likely to be renewed pumping of groundwater and the subsidence would reoccur.

4.3 Mexico City, Mexico

Based on Figueroa Vera, 1984 and Ortega-Guerrero et al, 1993

Mexico City, population 20 million, is located in the south-western section of the Valley of Mexico. It stands on a broad, flat Lacustrine plain at an altitude of 2235 m asl. The plain is surrounded by volcanic mountain ranges.

The valley is an inland drainage basin. There are no natural outlets and historically the floor of the valley was occupied by a number of inter-connecting lakes. Numerous large springs around the edge of the valley provided potable water from the Aztec through to the colonial period.

In 1789 a drainage canal, the Nochistango Trench, was cut through the mountains to drain some of the lakes. This led to the start of rapid population growth in the valley.

The bedrock beneath the city is the Tertiary volcanic formation that outcrops in the surrounding mountains. Over this, Upper Tertiary and Quaternary volcanic deposits form an alluvium and pyroclastics aquifer unit. Most of this is in turn overlain by an aquitard of clayey, Lacustrine sediments.

The aquifer contains thick strata of sand and gravel which are highly permeable. Wells yields are generally high, 180 to 360 m^2/hr.

Within the city area, the thickness of the clayey aquitard is 50 to 80 m. It is composed of 80% Montmorillonite and 15% Kaolinite. There are some intercalations of fine sands and silts but the porosity is very high, reaching 80-90% in places. Consequently its shear strength is very low and it is highly compressible. This creates general construction difficulties. Low buildings require continuous slab foundations and buildings exceeding 4 or 5 stories must be underpinned by piling through to the firmer sandy layers within the clay.

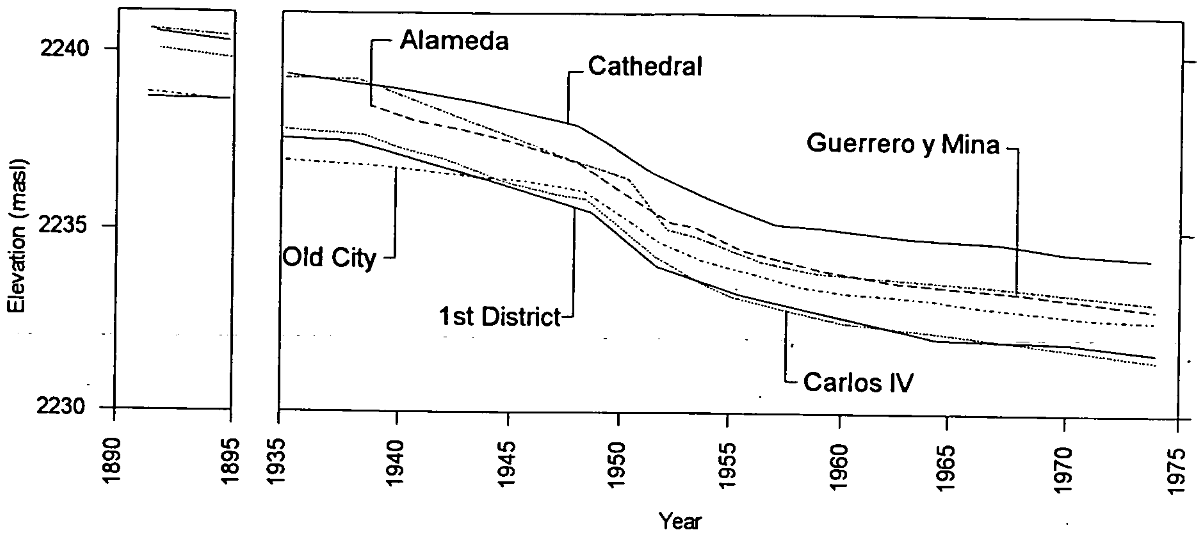

Figure 7. **Subsidence at benchmarks in Mexico City. (After Comisión de Aguas del Valle de México)**

Most of the recharge occurs on the permeable slopes of the mountains. The average annual rainfall is 890 mm, ranging from 60 mm in the lower areas to 1300 mm on the high slopes. Potential evaporation averages 1300 mm being 1900 mm in the lower zone and 900 mm in the higher.

Groundwater abstraction began around 1850 and intensified during the 1930s. There are no comprehensive records of total abstraction but it was estimated at 12 m^3/s in the early 1980s. Records show there were still flowing wells at the beginning of this century but since the middle of the century the water table has remained nearly constant 1 to 2 m below ground level.

Land subsidence was first noted by Gayal in 1929, it now ranks as one of the most remarkable examples in the world. Carrillo (1948) used a simple linear model to correlate the subsidence with neutral pore pressures within the aquitard and concluded that abstraction of groundwater was the main cause of the ground level decline.

Following this, a network of bench-marks and piezometric stations was established to monitor the phenomenon. Marsal and other investigators developed the conceptual model and made predictions of the magnitude of the eventual total subsidence. This led to a stratigraphic zoning of the city (Marsal & Mazoni, 1959):

i) Hills Zone - located over tuffs of low compressibility.

ii) Transition Zone.

iii) Lake Zone - located over clays of high compressibilities.

In the worst affected area, subsidence has reached almost 7.5 m. Correlation studies indicate that during the period 1970-1973, approximately 75% of the total subsidence was due to consolidation of the clayey aquitard, the remaining 25% occurring in the deeper aquifer.

There are no overall estimates of the cost of the subsidence but there are numerous examples of damage to buildings, roads and bridges. The disruption of the original gravity sewage system has necessitated the installation of a much more expensive pumping system.

Following disastrous flooding in 1951, the city authorities acted to reduce the subsidence by importing water from outside the Valley of Mexico. In this way the total abstraction of groundwater was kept constant for several years and the rate of subsidence began to decrease. However the continued population growth has now resulted in renewed pumping. The new wellfields are situated outside the city so that the worst problems are minimised but the new area has a much greater thickness of clay (100-300 m) so that there is a correspondingly greater potential for subsidence.

In the Chalco Plain, an agricultural district south-east of the city, new pumping caused 3 m of subsidence between 1960 and 1984. It is now 6 m and progressing at 0.4 m/y. Extrapolating the ratio of total subsidence to drawdown from Mexico City to this area where there is a potential for 60 m of drawdown, indicates the total subsidence could eventually reach 14 m.

Aerial photographs have indicated that the subsidence has caused the expansion of a shallow lake. Despite additional drainage schemes the lake is growing at 2 km^2/yr with consequent loss of agricultural production.

4.4 Shanghai, China

Based on Shi Luxiong and Bao Manfang, 1984

Shanghai, the largest industrial city in China, stands on the Yangtze Delta facing the East China Sea. The site is very low lying, just 3 to 4 m above sea level, and is bisected by several tidal waterways, principally the Whangpoo River and the Soochow Creek.

The bedrock is Quaternary and over this there is 300 m of unconsolidated sediment consisting of an alternating series of marine and continental facies. The upper 150 m is clayey soil and sand of littoral and fluvial-deltaic origin. The lower 150 m consists of alternating layers of fluvial sands and lacustrine clays.

Five confined aquifer units have been identified plus a phreatic layer. The aquifers are characterised as flat-lying, thick and fine-grained. They have low hydraulic gradients and low groundwater flow velocities. The aquifers share a distinct pattern of lithological changes. They become thicker and finer grained from north-east to south-west.

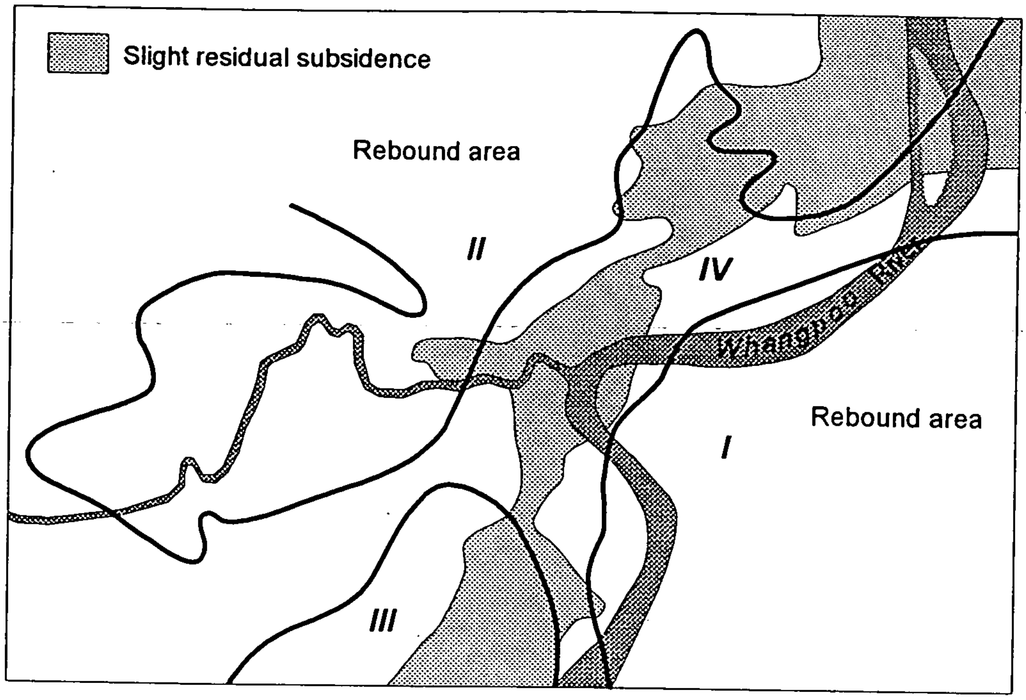

Figure 8. Relationship between geological areas and subsidence in Shanghai. (After Shi and Bao, 1984)

Aquitards are widely distributed but their absence in the east of the city and locally along the Whangpoo River allows direct interconnection between the first, second and third aquifer units.

The sediments have been divided into 13 layers according to their engineering-geological characteristics. There are three clay layers with low compressive strength, other clay layers have low void ratios and are correspondingly stiffer. The three soft-clay layers are associated with a non-compressible dark-green stiff clay layer. The relationship of these clays to each other and the adjacent first and second aquifer units allows the urban area of Shanghai to be divided into four zones based on geological structure (see Figure 8).

Area I — Consisting of the first and third compressible layers, the stiff clay and Aquifers 1 and 2.

Area II — Consisting of the first and second compressible layers, the stiff clay and Aquifers 1 and 2.

Area III — Consisting of this first and second compressible clay and Aquifers 1 and 2. The absence of the stiff clay allow interconnection between the aquifers.

Area IV — Consisting of all three compressible clays and Aquifer 2.

Land subsidence was first noted in 1921. The compaction continued steadily until 1950 when rapid industrial development caused greater groundwater extraction which led to an increase in the rate of subsidence. A maximum annual rate of

98 mm was recorded between 1956 and 1959 and the cumulative total subsidence amounted to 2.63 m in 1965. 121 km^2 were affected by subsidence exceeding 0.5 m.

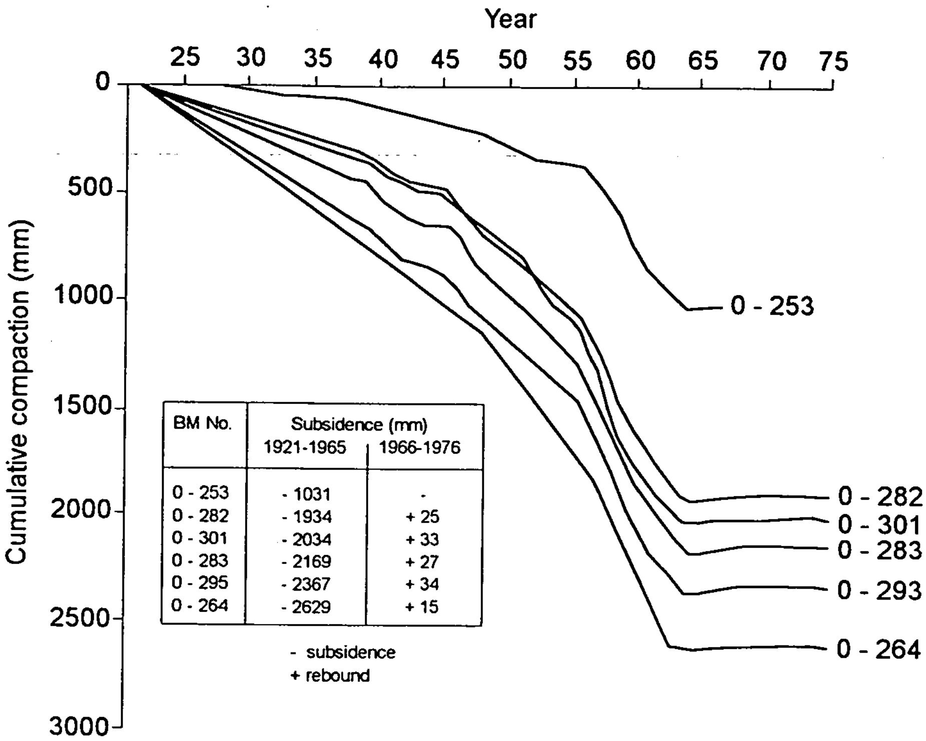

Figure 9. Cumulative subsidence at benchmarks in Shanghai. (After Shi and Bao, 1984)

Countermeasures were introduced in 1963. The industrial use of water was strictly controlled so by 1965 the rate of subsidence had reduced to 23 mm/y and by 1966 there had been a rebound of up to 6 mm in some areas.

As one would expect, it was observed that the greatest amount of subsidence occurred where the compressible clay layers were thickest. However it would also be seen that the presence of the stiff clay layer in areas I and II restricted the compaction of soft clay layer 1 compared to areas III and IV where the stiff clay is absent. Also the interconnection of aquifers 1 and 2 in area III causes greater compaction than in area II where there is no direct interconnection.

Since the introduction of the control measures there had been rebound of ground level in areas I and II and a reduction in the rate of subsidence in areas III and IV.

The design of the control procedures was initially based on a one-dimensional conceptual model. In 1972 this was translated into a numerical model and, following several years of calibration, this can naturally reliably predict piezometric heads and subsidence to high accuracy. The success of the method clearly stems from the wealth of data to calibrate the model and the extent of control that can be exercised over the use of water. The model is used each year to determine quotas for the subsequent years' abstraction.

Where possible consumptive use of water by industry has been transferred to surface water supplies. Elsewhere, the abstraction has been changed from aquifer units 2 and 3 to units 4 and 5. The clay layers associated with these deeper aquifers are much stiffer (possibly due to earlier compaction?) and it is inferred that little, if any, extra compaction will occur.

A significant proportion of the groundwater production is used for air-conditioning and industrial cooling. Some of this usage has been off-loaded to refrigeration but of the remaining groundwater used for this purpose, most is now artificially recharged into the aquifer to maintain water pressure and diminish subsidence. This has an additional benefit in that the recharged waters are used for seasonal heat storage. Cold surface water injected during the winter has lowered the groundwater temperature by up to 10°C making summer cooling much more effective.

It seems clear that the city authorities have at their disposal a system that can hold the subsidence in check.

4.5 Hangu, China

Shearer and Kitching (1994), describe how they used MODFLOW to simulate the subsidence associated with heavy groundwater pumping in Hangu, China, ODA TDR project reference no. 5500. There the slow draining nature of fine grained interbeds within the aquifer system had to be simulated and a special subroutine was written for MODFLOW to allow this. This occurrence is common geologically and it is thought this procedure will offer improvements to existing models of subsidence in many cases. This new procedure requires further validification but the good results at Hangu are promising. Practitioners in this field should read Shearer and Kithching (1994) and test its suitability for themselves.

5. SUMMARY

The abstraction of groundwater from aquifers is fundamentally linked to compaction effects within the geological strata. However, in the case of unconsolidated sedimentary formations, this compaction is frequently permanent and results in land subsidence. Many factors have be identified as being involved in the process. Whilst individually these are well recognised, their combined effect is complex and, as yet, poorly understood. To effectively manage a land subsidence situation requires detailed hydrogeological study preferably aided by the use of a numerical groundwater model.

The threshold effect of the preconsolidation stress means that simple extrapolation of current trends is not a reliable predictor of future subsidence. However simplified theoretical concepts have proved adequate to indicate the potential seriousness of the situation. As the damage to the aquifer is largely irreparable, prompt action is essential.

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METHOD SUMMARY SHEET (sub 1)

TITLE: Predicting Subsidence due to Groundwater Abstraction

Scope and use of Method

- the storage of groundwater within an aquifer depends on the compressibility of the fluid and the elasticity of the formation. Consequently the extraction of groundwater from UNSAs can result in compaction of the aquifer formation.

- the compaction has been shown to occur mainly within fine-grained, clayey layers (interbeds or aquitards) because of their plasticity. These are common in UNSAs.

- the low permeability of these layers can cause significant delays between the change of piezometric head in the aquifer and the resulting compaction. It can sometimes take a few years to achieve equilibrium when the interbeds are thick.

- computer modelling is often used to predict the consequences of aquifer exploitation however the calculation of compaction is not usually included.

Method

The source report (reference 1) describes an extension of the widely used groundwater flow model MODFLOW to incorporate the calculation of compaction due to abstraction. The new module addresses the delay effect mentioned above.

The code is a compromise between the complexities of the physical mechanisms known to be involved in compaction and the rather limited amount of observation data that can reasonably be expected for calibration.

Calibrating subsidence models requires extensive time-series data sets in addition to measurements of the usual hydrogeologic parameters. It is particularly useful if the transition from elastic to inelastic compression can be observed. Consequently where subsidence is a possibility, monitoring should be initiated as soon as exploitation begins.

Including the calculation of subsidence compounds the difficulties of creating a representative model. It is recommended that only experienced MODFLOW users attempt to implement the new code.

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METHOD SUMMARY SHEET (sub 2)

TITLE: **Determining the Consolidation Coefficient In-Situ by Aquifer Pumping Test Analysis**

Scope and use of Method

Because of natural heterogeneity, the laboratory measurement of the consolidation coefficient (c_v) of a deep aquifer system might require the testing of a very large number of samples. In addition to the expense of obtaining the core, there is the risk that the samples will be disturbed before testing. For confined or low permeability aquifers the coefficient can be determined in-situ from conventional aquifer pumping test data.

Method

In soil mechanics, the consolidation coefficient is defined as a function of the rate of dissipation of pore water pressure (u):

$$c_v \nabla^2 u = \frac{\delta u}{\delta t} \qquad (1)$$

The general equation governing groundwater flow depends on the potential head distribution (h):

$$\frac{T}{S} \nabla^2 h = \frac{\delta h}{\delta t} \qquad (2)$$

where T and S are the transmissibility and storage coefficient of the aquifer. These are routinely determined by aquifer pumping tests.

However, the pore water pressure at each point is related to piezometric head as follows:

$$u = \rho g (h - z) \qquad (3)$$

where z is the height of the point of interest above the datum level and ρ is the density of water. In the normal scope of aquifer used for groundwater production, the density of water is constant in relation to changes in head. Thus substituting for u from equation (3) reduces equation (1) to equation (2). Therefore the consolidation coefficient is related to the hydraulic parameters as follows:

$$c_v = \frac{T}{S} \qquad (4)$$

Large scale pumping tests are required to determine c_v values for more permeable rocks such as chalk or sandstone; small scale tests are adequate for low permeability strata.

Equation (4) provides a simple cross-check on c_v values obtained by alternative techniques. An additional advantage of this approach is that the value obtained is the average for a comparatively large volume of aquifer, generally a cylinder up to one hundred metres in diameter and the sample is undisturbed.

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