Institute of Hydrology

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D R A F T

RECHARGE IN LINCOLNSHIRE :
Estimates from soil water measurements

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Summary

1. Estimates of aquifer recharge have been derived from soil physical measurements made at sites located on the Lincolnshire Limestone, the Lincolnshire Chalk and the Spilsby Sandstone. Some 115 site-years of of neutron probe soil water content data, from 19 sites have been analysed. Most of the data were for the period 1983 to 1987 inclusive but at five sites measurements commenced between 1973 and 1976. Tensiometer and gypsum block measurements of soil water potential had been collected at four sites but only the data for 1983 and 1984 were useable in this analysis.

2. The combined Zero Flux Plane Water Balance Method was used to calculate soil drainage for all but one of the sites. Where drainage is vertical, soil drainage fluxes are a measure of recharge to the aquifer. Because few soil water potential data were available, zero flux plane depths were mainly derived from the soil water content data.

3. Mean annual recharge to the Central Limestone was estimated as 134 mm under grass and 154 mm under arable crops over 11 years. For the period 1983 to 1987 inclusive, the corresponding figures were 97 and 105 mm.

   Mean annual recharge to the Southern Limestone (1983-1987) was estimated as 107 mm for a site where rainfall was similar to that at the Central Limestone sites, and 157 mm at another where rainfall was greater by an average 55 mm.

   It was not possible to estimate recharge to the Northern Limestone aquifer because the soil water data suggested that lateral movement of water occurred into and out of the soils at the sites there.

   A mean annual recharge estimate of 165 mm to the Northern Chalk was calculated over four years, 1983 to 1987 excluding 1985.

   Mean recharge amounts over 13 years at a drift covered site on the Southern Chalk, and another where there was no drift, were similar, 209 and 216 mm respectively.

4. Evidence of lateral water movement at a site on the Spilsby Sandstone meant that an estimate of recharge could not be obtained with certainty.

5. Recommendations regarding future soil water monitoring at these sites to obtain recharge estimates have been made as follows:
   - intervals between neutron probe measurements should be not more than fortnightly;
   - soil water potential measurement should only be attempted if equipment can be serviced frequently, i.e. at least weekly;
   - it should be established how representative the sites on the Northern Limestone and Spilsby Sandstone are of these aquifers before continuing monitoring there;
   - measurements at the Ropsley arable plots should be continued throughout the year over several years if the data are to be used for determining soil water balances.

Contents

1. Introduction

This report describes the analysis of soil water measurements from sites located on the aquifer outcrops of Lincolnshire: the Lincolnshire Limestone, the Chalk and the Spilsby Sandstone. The work was conducted by the Institute of Hydrology under contract to the former Anglian Water Authority, now NRA Anglian Division. The aim was to use soil physical methods to estimate recharge to the aquifers for which suitable soil water measurements were available, and establish where possible, the temporal and spatial variability of recharge. Table 1 gives details of the soil water measurement sites, 19 in total, and Figure 1 shows their location. The records from these sites form the greater part of a soil water data archive initiated by the former Lincolnshire Division of the Anglian Water Authority. (It includes data from a further six sites, the positions of which are also shown in Figure 1). The oldest site is at Ulceby Cross on the Southern Chalk outcrop; it was established in November 1973. Four more sites were set up in 1975 and 1976 and the remainder were installed in 1982 or thereafter. The analysis has included all records up until the end of 1987; more than 115 site-years of data.

The records largely comprise neutron probe measurements of soil water content. These are supplemented by tensiometer and gypsum block measurements of soil water potential at four sites since spring 1983. The measurements have generally been made fortnightly but the frequency is variable.

The combined Zero Flux Plane - Water Balance method (Cooper *et al.*, 1990) has been used to estimate soil drainage from each site and hence aquifer recharge. Usually soil water potential data are used to obtain information about zero flux planes. In the absence of soil water potential data from all but four of the sites, and because of the poor quality of the potential data that were available, an alternative approach was necessary. A method involving interpretation of the soil water content data was used to determine zero flux plane depths. Its use has permitted drainage estimates to be calculated for almost all of the sites. The implications of those estimates for recharge are discussed for each aquifer. The data are presented in this report as annual totals and mean annual amounts for each site. However, the full data set is available in computer files and listings.

Table 1 Site Details

AQUIFER	SITE NO.	SITE NAME	NGR	AWA REF.	DURATION	CROP	INSTRUMENTS	NO. READINGS
CENTRAL	2	NAVENBY	TF030578	CD 3009	MAY '76 - DEC '87	ARABLE	NP	385
LIMESTONE	10	DUNSTON HEATH	TF037624	D1 3009	MAR '76 - DEC '87	GRASS	NP	393
	11	DUNSTON HEATH	TF037624	D2 3009	MAR '76 DEC '87	ARABLE	NP	391
	15	RAUCEBY GRANGE	TF014473	RG 3011	FEB '83 - DEC '87	GRASS	NP, T & GB	110
	17	ROPSLEY	SK978358	RG 112	NOV '82 - DEC '87	GRASS	NP	121
	18	ROPSLEY	SK977361	R1 3112	JAN '85 - AUG '87	ARABLE	NP	93
	19	ROPSLEY	SK977361	R2 3112	NOV '82 - JUL '84	ARABLE	NP	46
	20	ROPSLEY	SK977361	R3 3112	APR '84 - AUG '85	ARABLE	NP	21
	21	ROPSLEY	SK977361	R4 3112	JUL '86 - JUL '87	ARABLE	NP	18
NORTHERN	16	REDBOURNE	SK970998	903	MAR '83 - DEC '87	GRASS	NP, T & GB	106
LIMESTONE	23	SCAWBY	SE969057	SH 2903	JAN '84 - DEC '86	GRASS	NP	59
SOUTHERN	6	CORBY GLEN	SK993247	CG 3111	NOV '82 - DEC '87	GRASS	NP, T & GB	111
LIMESTONE	22	SALTBY	SK874362	SA 3001	NOV '82 - NOV '87	GRASS	NP	121
NORTHERN	8	CROXBY	TF193981	CX 2911	NOV '82 DEC '87	GRASS	NP, T & GB	122
CHALK	14	NORMANDY LE WOLD	TF113968	NW 2904	MAR '83 - DEC '87	GRASS	NP	105
SOUTHERN	5	CLAXBY	TF442716	CL 2916	APR '84 - AUG '89	ARABLE	NP	107
CHALK	25	ULCEBY CROSS	TF407730	UC 2914	NOV '73 - DEC '87	GRASS	NP, T & GB	416
	9	DRIBY	TF387745	DR 2914	JAN '75 - DEC '87	GRASS	NP	390
SPILSBY SANDSTONE	24	TETFORD	TF328748	TF 3014	JAN '83 - DEC '87	GRASS	NP	106

NP = 3 NEUTRON PROBE ACCESS TUBES, T = ARRAY OF TENSIOMETERS, GB - ARRAY OF GYPSUM BLOCKS.

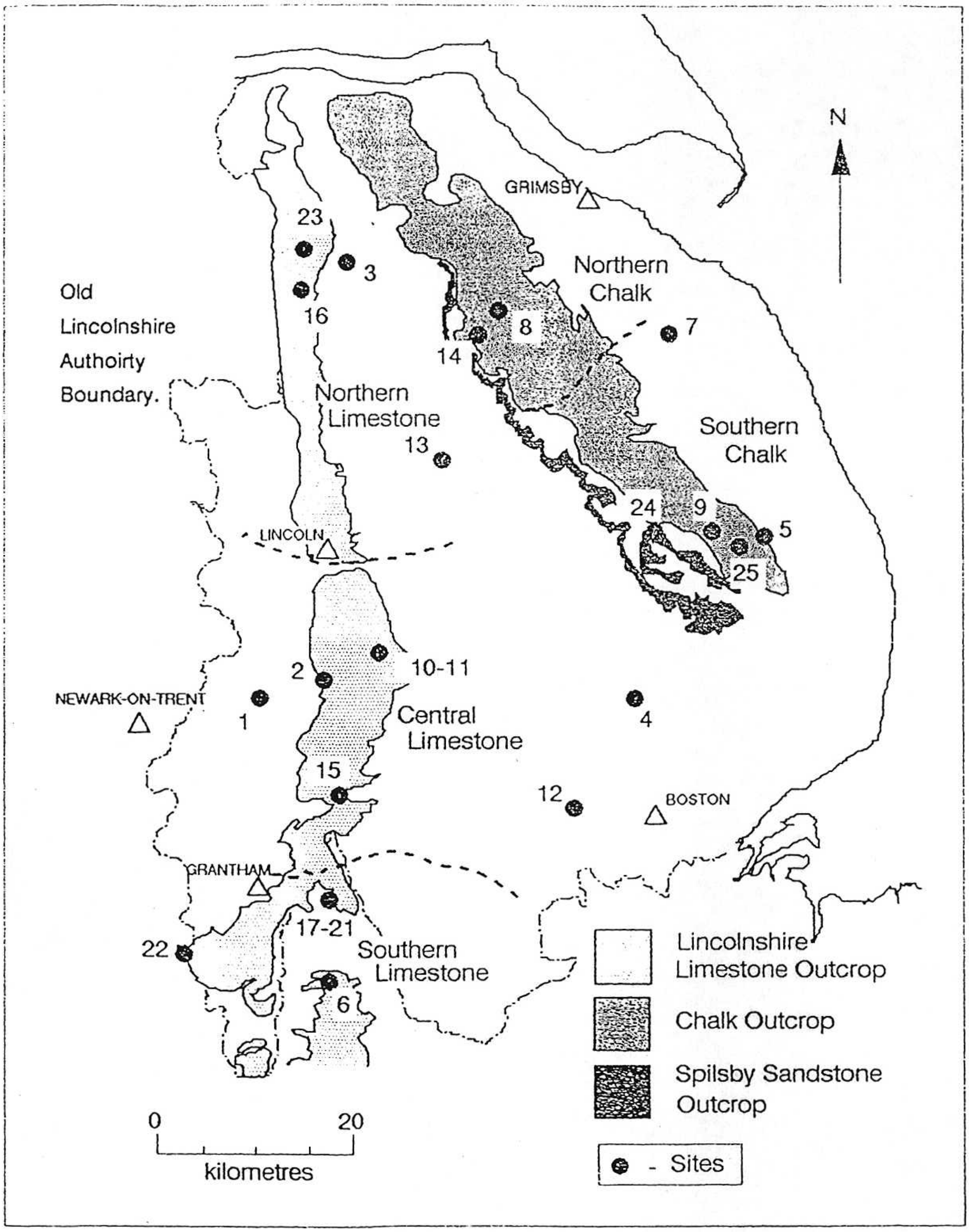

Fig. 1 Location of the soil water measurement sites relative to the aquifer outcrops

2. The Data Supplied

2.1 RAINFALL DATA

Rainfall data were supplied in the form of total quantity falling between neutron probe monitoring occasions at each site. These data had been recorded with on-site Meteorological Office standard gauges at most sites. It was necessary to check all the rainfall data, as in some instances it was found that the time intervals did not correspond with the intervals between neutron probe reading dates. In the main this was readily sorted out. However discrepancies in the rainfall data provided for some adjacent sites (the two at Dunston Heath and the five at Ropsley) were identified. This was most serious at Ropsley. It had been proposed to substitute data from the IH British Rainfall archive but no data from a suitably close site was available. As a result the analysis of data for the first few months of 1983 was abandoned.

It was also apparent that the annual rainfall totals recorded for the Ulceby Cross site changed by about 100 mm pre- and post-1983. The pre-1983 data were considered suspect and it was decided to substitute data from the archive at IH. In fact the nearest rain gauge for which there was a long enough record was at Driby Pumping Station, where the Driby soil water measurement site is located. Comparison of the pre -1983 data for the Driby site with daily data from the archive showed that there were also discrepancies in the data provided for that site and so the daily data were substituted for both Ulceby and Driby.

2.2 MEASUREMENTS OF SOIL WATER CONTENT: NEUTRON PROBE DATA

Three Wallingford type neutron probes had been used to make measurements at the sites. At each site, three access tubes had been installed. The data supplied were the mean for each measurement depth of the count rate recorded in the three access tubes at each site on each measuring occasion, the probe water count for the reading occasion and the soil calibration information for each site. Prior to any analysis the data were subject to a quality control procedure. This entailed:

Plotting the data as time series and visual inspection for inconsistencies. Because each data point represents the mean of three measurements, the effect of errors by the field observer in recording the data at an individual tube or the computer operator entering it, will have been mitigated to some extent. Less than 0.005% of the neutron probe readings were corrected; when necessary, an interpolated value was substituted.

Checking for inconsistencies in the water count history of the three probes used. Errors, due to the use of an inappropriate water count, affect all the data recorded at a site on a given occasion. The water count history of each probe had to be built up from the data supplied for each site. A number of discrepancies between the water count used for measurements from one site on a given day, and that used for another at which the same probe apparently had been used, were identified. Details of the discrepancies were given to AWA for checking against the original field sheets; the water counts were modified as recommended by AWA. Approximately 0.03% of the data were corrected.

The early neutron probe data (i.e. pre-1983) had been measured at the following depths below ground level: 0.04, 0.19, 0.34, 0.49, 0.64, 0.79, 0.94, 1.24, and 1.54 m. In the spring of 1983, the below ground measurement depths at all sites were changed to: 0.10, 0.25, 0.40, 0.55, 0.70, 0.85, 1.00, 1.30, and 1.60 m. It soon become apparent that it would not be possible to ignore this change in measurement depth. In particular it was very evident that neutron counts at 0.04 m were affected by proximity to the soil/air interface despite use of surface extension trays. Measurements at this depth were excluded from the analysis.

For several weeks prior to the changeover date, sets of measurements using both the old and new depths had been recorded at each site. Both datasets were supplied to IH but only the measurements at the new depths were used.

The calibrations used to calculate volumetric water contents from the recorded neutron counts are those supplied for each site by AWA. The usual equation:

$$\theta = \frac{mR}{R_w} + c$$

where θ = volumetric water count

R = neutron count

R_w = standard neutron count or water count

and m and c are calibration constants, was applied

The calibrations had been derived from the typical calibration equations published by Bell (1976), for the Wallingford neutron probe (and subsequently Didcot Instrument Probes) for three soil types:

Silts, sand and gravel (also used for chalk)	$\theta = 0.79 \ R/R_w - 0.024$
Loams	$\theta = 0.867 \ R/R_w - 0.016$
Clay (and also peat)	$\theta = 0.959 \ R/R_w - 0.012$

For each measurement depth in each access tube, the soil texture was determined, in many, if not all cases from laboratory determinations of particle size. On the basis of the textural description, either one of the three equation above was assigned as the calibration for that depth, or another was derived from them according to the percentage of silt, sand, loam and clay in the soil. A total of 34 new calibration equations were so obtained. The same calibration equations were used for the pre- and post-1983 data although the measurements had been made at different depths.

Where neutron probe measurements are made close to the soil surface, i.e. within 0.2 m of the surface, it is necessary to allow for the fact that some neutrons will escape through the soil surface and so neutron counts will be reduced. One method of preventing this is to use a surface extension tray i.e. a round tray about 0.15 m deep containing the same soil and growing the same vegetation as around the access tube (Bell, 1976). The tray is fitted over the access tube when making measurements to prevent the loss of neutrons through the surface. This method was apparently used at all the sites in place of the alternative, a specific calibration for the surface layer.

2.3 SOIL WATER POTENTIAL MEASUREMENTS: TENSIOMETER AND GYPSUM RESISTANCE BLOCK DATA

Tensiometer and gypsum resistance block measurements were provided for the following 4 sites for the period spring 1983 until December 1987:

6 Corby Glen
8 Croxby
15 Rauceby Grange
25 Ulceby Cross

2.3.1 Tensiometer Data

The tensiometers used were of the vacuum gauge type. They had been installed in arrays of 10 at the following depths: 0.15, 0.4, 0.55, 0.7, 0.85, 1.0, 1.5, 2.0, 2.5 and 3.0 m. These instruments measure soil hydraulic potential in centibars relative to the height of the vacuum gauge. To obtain hydraulic potential measurements relative to ground level, it is necessary to adjust the readings to allow for the weight of the column of water above ground. When the data were first supplied, it was believed that the tensiometers had been installed according to the manufacturers instructions so the vacuum gauges were all at the same height above ground level. The data were processed assuming a common gauge height of 200 mm. Subsequently it transpired that this was not the case and actual above ground heights were supplied for each tensiometer at Corby Glen, Croxby and Rauceby Grange. The data were reprocessed using this information. No above ground heights were available for the Ulceby Cross tensiometers and so the common height of 200 mm has been retained in data processing.

The tensiometer data collected in 1983 and 1984 were of mediocre quality; thereafter the data are very poor as a consequence of the malfunctioning of several tensiometers in each profile. Tensiometers only operate in the potential range 0 to -80 kPa and so those near to the surface might be expected to fail as potentials decreased in summer. However this does not account for the poor quality of the data at other times of the year. That is more probably due to infrequent or unsuccessful servicing of the tensiometers and frost damage to the vacuum gauge. They were read, and presumably attended to, on a weekly or, more usually, a fortnightly basis. Experience at IH suggests that for satisfactory results, tensiometers should be attended to at least weekly, and in winter they require purging of air after any frost.

2.3.1 Gypsum Resistance Block Data

The gypsum resistance blocks, and the meter (Soilmoisture Meter Model #5910-A) used to read, them were supplied by Soil Moisture Equipment Corporation. They had been installed in arrays of 8 at the following depths: 0.15, 0.40, 0.70, 1.0, 1.5, 2.0, 2.5 and 3.0 m.

The data provided were meter readings and needed to be converted to potential values. Using the information supplied by the manufacturer, the following calibration equation was derived using a log-log regression:

$$\psi = 10^{5.7} R^{-1.57}$$

where ψ = matric potential kPa

R = meter reading

The regression coefficient r = -0.998.

To obtain this good linear relationship, the highest potential/meter reading point (0.2 bar/92) in the manufacturer's literature was not included. This is justifiable as gypsum resistance blocks are unreliable at potentials above -40 kPa i.e. 0.4 bar (Wellings *et al.*, 1985).

Wellings *et al.*, (1985) recommend individual calibration of blocks and use of a temperature correction when calculating potential from measurements but no temperature data were available. In examining the gypsum resistance block data, the emphasis was on its use to supplement the information on ZFP depths derived from the tensiometer data. The data obtained is of variable quality. In 1983 and 1984, useable measurements were collected, except from Rauceby Grange. Thereafter the number of blocks giving sensible data declined and after a brief review no further effort was made to analyse the results. Three possible causes for this decline in the data quality are:

Subsequent summers, and even summer 1984, were wetter and pressure potentials probably remained higher and more often within the range where gypsum resistance blocks are unreliable;

2. Corrosion of the leads;

3. Change in the pore size distribution of the blocks, and hence their calibration, as a consequence of calcium carbonate deposition or

dissolution.

Once several blocks in an array start to produce dubious data, it is very difficult to distinguish which ones are suspect and which are functioning normally. When potential gradients are of interest (as here), the usefulness of the entire array is rapidly reduced as the number of faulty blocks increases.

3. Recharge Estimation by Soil Physical Methods

Soil drainage is the downward water flux at any point in a soil profile below both the maximum rooting depth and the maximum Zero Flux Plane (ZFP) depth (see below). Vertical drainage eventually recharges the aquifer. Storage changes within the unsaturated zone can modify the timing of the recharge. However, over a long period, the total quantity of soil drainage equates with recharge at the water table. A combination of the Zero Flux Plane method and a simple water balance approach has been used here to obtain estimates of soil drainage and hence aquifer recharge.

3.1 ZERO FLUX PLANES

When evaporation (i.e. plant transpiration plus evaporation directly from the soil) exceeds rainfall inputs to the soil profile, the water content of the upper part of the soil decreases with a resulting fall in hydraulic potential. Thus an upward hydraulic potential gradient is usually created inducing upward movement of water towards crop roots and the soil surface.

Meanwhile, the lower part of the soil will continue to drain as water moves downward due to gravity. The hydraulic potential profile will look as in Fig. 2a. Between the zone of upward and downward moving water is a plane where the flux is zero, the Zero Flux Plane (ZFP). This is called a divergent ZFP, for water is moving away from it on both sides. A convergent ZFP occurs when water moves towards a ZFP (converges) from both above and below. An example of this is infiltrating water meeting upward moving water, after rainfall.

McGowan (1974) and McGowan and Williams (1980) found that the position of the ZFP represented the extent of root abstraction of soil water in arable and grassland situations. Dolman *et al.* (1988) found very good agreement between evaporation measured by the ZFP method and calculations based on meteorological data at a forest site where it was known that roots penetrated below the ZFP, supporting the view that root abstraction of water from below the ZFP is very small. Cooper (1979) has discussed this in more detail.

With time, the ZFP moves progressively deeper in the profile. The maximum depth attained depends on the soil and the season. Usually the pattern of behaviour is similar from year to year. When a ZFP is present, rainfall will result in a convergent ZFP (equivalent to a wetting front) moving downward from the surface (Fig. 3). Depending on the rate of evaporation from the upper part of the soil, this may be an ephemeral feature or may reach the depth of the divergent ZFP, so neutralising it. The latter event occurs at some stage in the autumn, and depending on the soil type and the season,, may occur on several occasions during the spring and summer. Soil water content, potential changes and ZFPs have been discussed by Wellings and Bell (1982).

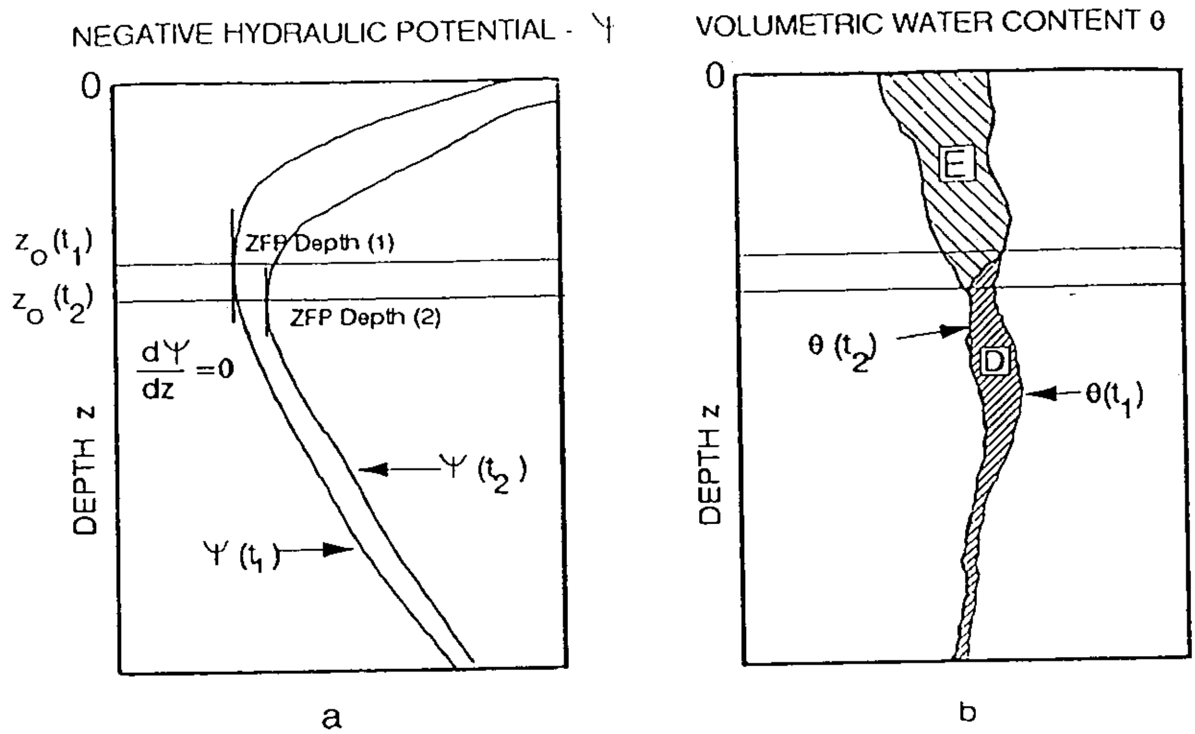

Fig. 2 The principle of the Zero Flux Plane Method.
a. Hypothetical pressure potential profiles
b. The corresponding water content profiles. The shading represents water which has evaporated or drained between t_1 and t_2. (After Cooper et al. 1990).

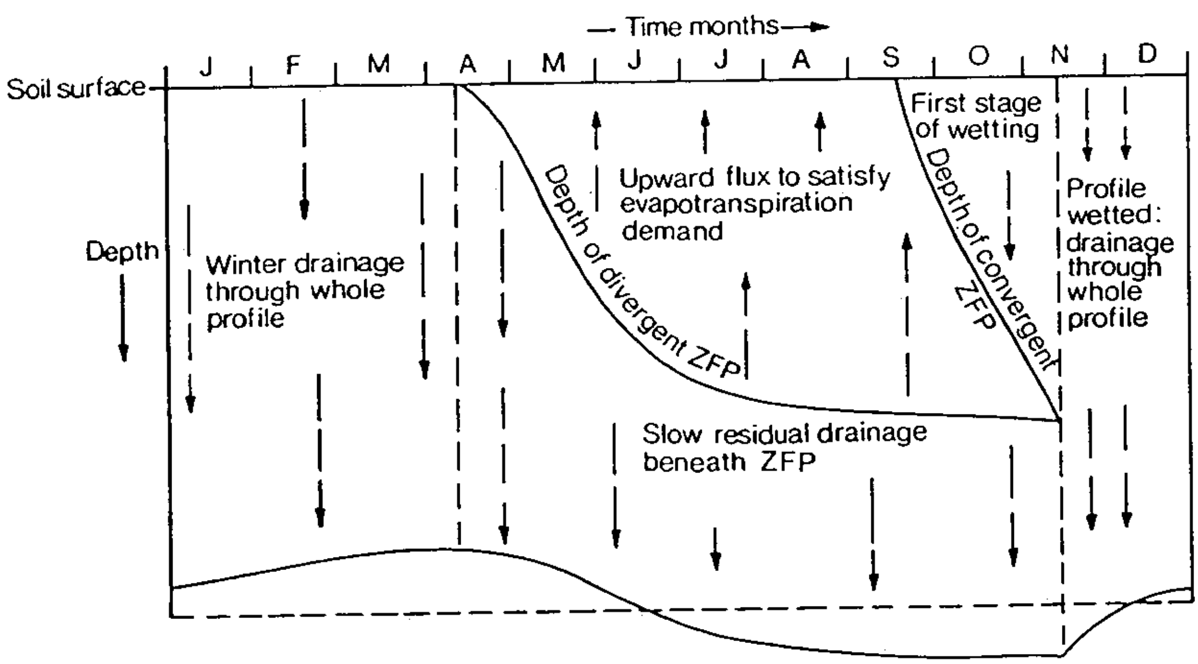

Fig. 3 The annual cycle of movement of the ZFP in a soil profile in a temperate climate (After Wellings and Bell 1982).

3.2 THE ZERO FLUX PLANE METHOD

When a ZFP is present, any change in water content above it must be due to water flow through the soil surface i.e. the balance between rainfall and direct evaporation and transpiration. Below the ZFP, water content change must be due to drainage (Fig. 2b). This is the basis of the ZFP method. Thus, if the changing depth of the ZFP, as it moves downward through the profile, is known, measurements of soil water content change above and below it are made and rainfall is monitored, a soil water balance can be calculated which is independent of meteorological estimates of evaporation. The method has been used in a variety of situations (e.g. Giesel *et al.* 1970; Cooper, 1979; McGowan and Williams, 1980; Wellings, 1984 and Gardner *et al.* 1990). Stammers *et al.* (1973) presented expressions for calculation of evaporation and drainage above and below a moving ZFP respectively.

The ZFP method is based upon a relatively simple concept. However, it involves certain assumptions. Firstly, that the depth of the ZFP represents the deepest limit of plant abstraction of soil water. Any water loss due to plant uptake from beneath the ZFP would be incorrectly ascribed to drainage. As discussed in section 3.1 above, the evidence is that any root abstraction from below it will be small and will not introduce a major error when using the method.

Under some circumstances, water may pass "through" the ZFP, to wet up the soil below it, via macropores or fissures. Flow via these routes is not determined by the direction of hydraulic potential gradients as measured in the soil matrix. Where this occurs, use of the ZFP method will underestimate drainage and overestimate evaporation by a corresponding amount. Another inherent assumption is that all rainfall at a site is either intercepted by the vegetation and evaporated, and/or infiltrates into the soil. If there is any net surface or subsurface run-on or run-off at the site, the approach is invalid unless the quantities can be recorded so that actual infiltration is known.

At the Lincolnshire sites, ZFPs developed every year at each site and usually persisted for several months. Hence the ZFP method could be used for part of each year to calculate soil drainage. At other times a simple water balance, as described in the next section, was used.

3.3 WATER BALANCE METHOD

If no ZFP is present in a soil profile, it is most often because the soil is wet and it is then reasonable to assume that evaporation losses are close to the potential evaporation rate determined by the prevailing atmospheric conditions (Penman, 1948). Drainage at any depth can be calculated from a simple water balance if rainfall, potential evaporation and soil water content change are known:

$$D = R - E + \int_0^z \theta(t_1)\,dz - \int_0^z \theta(t_2)\,dz$$

where D = drainage measured at depth Z,

R = rainfall over the period t_1 to t_2,

E = evaporation in the same period,

time,

θ = volumetric water content.

During the winter months, when atmospheric evaporative demand is low (<1 mm d^{-1}) and soils are wet, any difference between the calculated potential evaporation rate and actual evaporation will be small in absolute terms. Thus use of this simple water balance approach is unlikely to introduce large errors into the drainage estimate. Also, it is usually after the development of the ZFP in spring that the actual evaporation rate falls much below the potential rate, for it is the development of low soil water potentials in the rooting zone that causes the ZFP to develop and constrains plant water use. The same applies in summer if the ZFP is neutralised temporarily by rainfall. The re-wetting of the soil will usually enable the vegetation to resume transpiration at the rate determined by the atmospheric demand but the actual evaporation rate will fall below the potential estimate as the soil dries and soil water potentials fall, leading to the development of a ZFP again before evaporation rates fall significantly.

Although use of a direct measurement of actual evaporation, as in the ZFP method, is always preferable for calculating soil water balances, this simple water balance approach is usually satisfactory during wet periods since the errors involved are likely to be small. The possible errors may become unacceptable, however, where infrequent soil water measurements have been made through the summer, such that there are few ZFP depth measurements and the water balance method has to be used over long periods at this time of year.

4. Data input to recharge calculations

To use the ZFP method, rainfall, soil water content change and ZFP position are required. The rainfall and soil water data provided were used for each site and ZFP depths were determined from measurements of soil water potential or water content as described below. For use of the water balance method, estimates of potential evaporation are also necessary; estimates prepared by MORECS (Meteorological Office Rainfall and Evaporation Calculation System; Thompson *et al.* 1981) were used in the water balance calculations when the ZFP method could not be used. Weekly total potential evaporation estimates were abstracted from the weekly MORECS bulletins for the period 1983 to 1987 inclusive and entered into a database. Mean daily potential evaporation estimates were calculated from these. Weekly MORECS data were not available prior to 1983. Therefore, for calculations with data collected prior to 1983, monthly total potential evaporation estimates from the retrospective MORECS Climatological Data Set, were used. These data were available in a database at IH. Mean daily values were computed from the monthly totals.

Water balances were prepared for 1983 using both types of potential evaporation estimated (i.e. weekly and monthly) for the five sites from which both pre- and post-1983 data were available. This enabled the effect of use of the different MORECS estimates to be ascertained. Fig. 4 shows the location of all the sites relative to the MORECS grid squares.

4.1 USE OF NEUTRON PROBE MEASUREMENTS OF WATER CONTENT CHANGE TO DETERMINE ZERO FLUX PLANE DEPTHS

In the absence of any measurements of hydraulic potential profiles from most of the sites, an alternative method for determining ZFP depth was sought. McGowan and Williams (1980) described a method which uses neutron probe data alone and relies on the recognition of the depth of the drying front caused by crop extraction of soil water. McGowan and Williams demonstrated close correspondence between the depth of the drying front and that of the ZFP at any one time. An approach based on that described by McGowan and Williams was utilised here.

The data for the individual measurement depths deeper than 0.15 m, were plotted as time series of water content change relative to a standard winter water content determined for each depth. The standard water content was defined as the 9th decile of all the measurements made at a given depth in the months of January, February and March, of those years for which data were available. Thus, it can be assumed that for 90% of the time in those months, the volumetric water content was greater than the standard value. This definition is the same as that for field capacity which was used and discussed by Gardner and Field (1983).

Two sets of standard values were derived for those sites where, pre-1983,

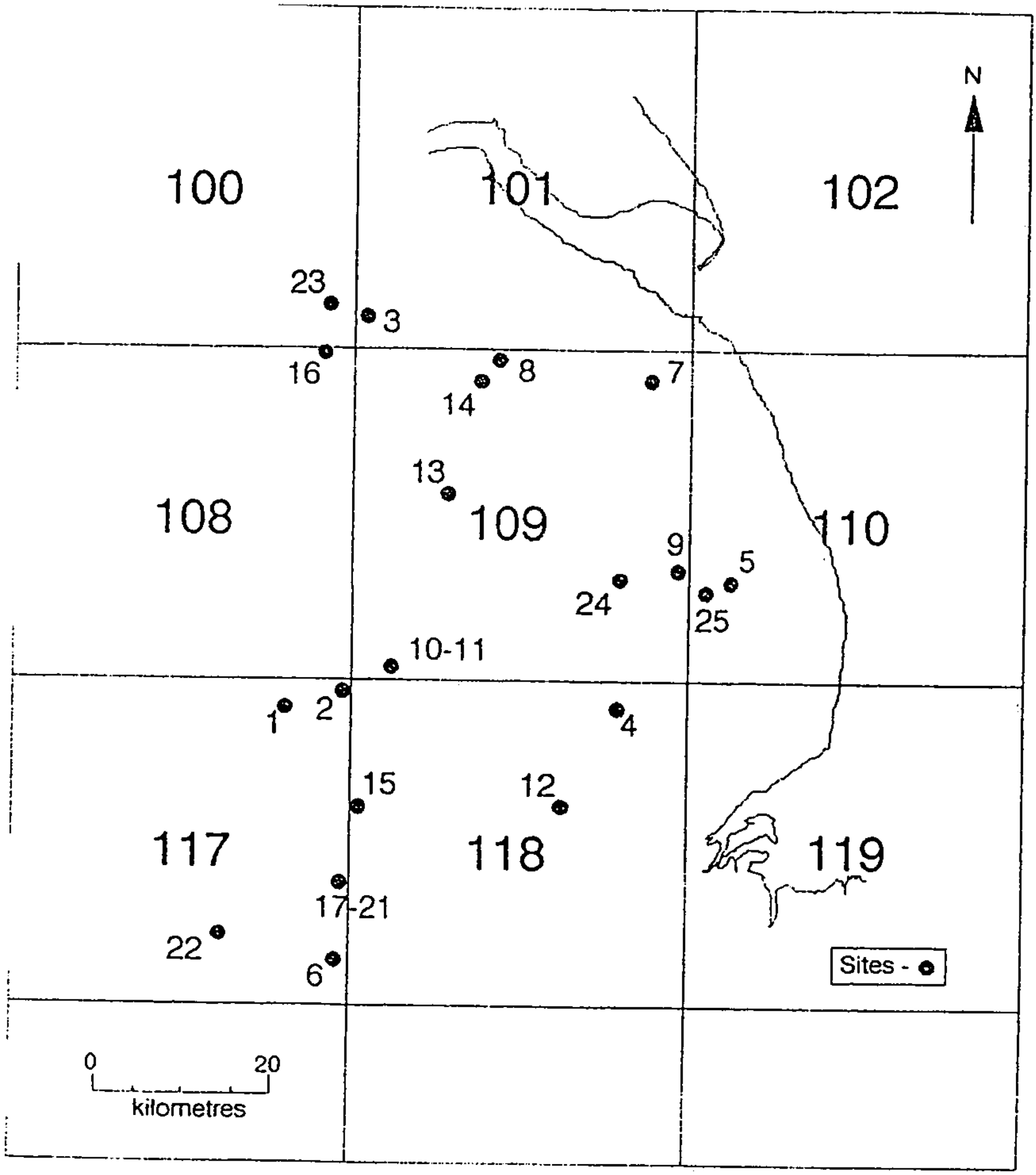

Fig. 4 Location of the soil water measurement sites relative to the MORECS grid.

different measurement depths had been used. The dry winter 1975/76 was excluded from the standard value determinations for this earlier period. Many soils did not wet up to their usual conditions in that winter (Gardner and Field, 1983).

ZFP depths were determined by careful examination of time series plots of the difference between the measured and standard volumetric water content for each measurement depth. The occasion when the water content at a specific depth first fell below the corresponding standard value was noted. Thereafter, a slow rate of water loss was still regarded as drainage. However, any subsequent discontinuity in the water content/time plot, indicating a sudden increase in the rate of water loss, was taken as evidence that the drying front had reached that depth (McGowan and Williams, 1980). Identification of the ZFP depth by this method is, however, complicated by the development of wetting fronts near the surface above a ZFP, and sometimes moving downwards sufficiently to cancel the ZFP. An example is illustrated in Fig. 5 which shows the time series for Normanby le Wold on the Northern Chalk, in 1983.

A ZFP was first observed at Normanby at 0.25 m depth on 14th June 1983. This was identified due to the rapid decrease in water content at this depth (Fig. 5). It remained there until the 21st June but by the 29th had fallen to 0.4 m. It then fell to 0.55 m in the following week, and had reached 0.7 m on 12th July where it remained for three weeks. Meanwhile small decreases of water content which were regarded as slow drainage, persisted from below the ZFP. 44.9 mm of rain fell in the period 26th July to 2nd August. This resulted in an increase in soil water content at all depths down to 0.7 m causing the ZFP to be neutralised. Thirteen days later (15th August) the ZFP was re-established at 0.4 m depth. A period of 22 days passed before the next readings were made on 9th September at which time the ZFP had apparently fallen to 0.7 m once more. Rainfall between 19th September and 17th October totalling 57.9 mm wetted the profile above the ZFP once more. The wetting front had reached 0.7 m by 31st October, neutralising the ZFP. However the dry period at the end of October resulted in another ZFP being established briefly at 0.25 m. After this the whole profile wetted up.

Below 0.7 m, volumetric water content changes of less than 0.02 occurred between 14th June, when a ZFP was first observed, and 6th September. There was then no drainage from the profile until the beginning of December.

In most years it was, with experience, not too difficult to discern the downward progress of the ZFP in spring through successive measurement depths. Another example, from the site at Tetford on the Spilsby Sandstone, is shown in Fig. 6. At Tetford in 1984 (Fig. 6), it was uncertain whether the loss of water at 1.0 m depth from mid-July onwards was due to plant abstraction or drainage (see section 5.7). The ZFP clearly reached 0.85 m but may have fallen to 1.0 m depth. The time-series also shows that at shallower depths in late August and then in late September, a wetting front moved down through the profile to 0.55 m, not far enough to neutralise the ZFP which persisted until 12th November.

For the Corby Glen, Croxby, Rauceby Grange and Ulceby Cross sites, ZFP depths were derived from the neutron probe data without reference to the measurements of hydraulic potential, and vice versa, for 1983 and 1984. The

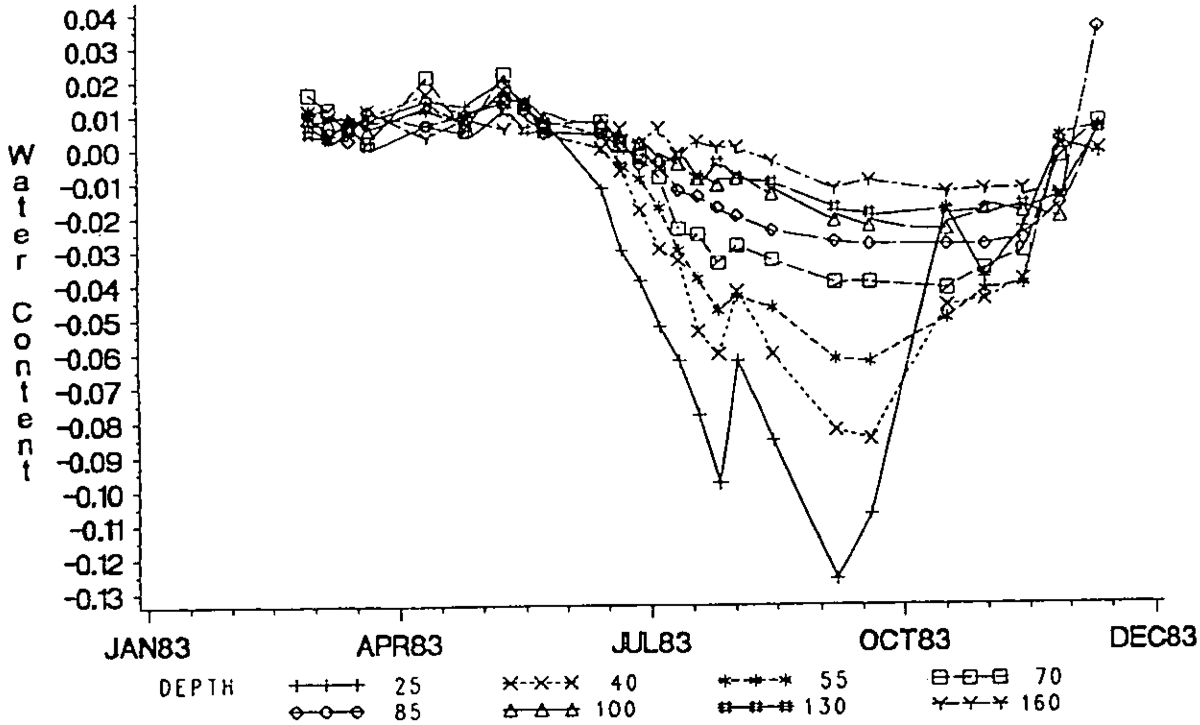

Fig. 5 Time series of soil water content change relative to the standard values for each measurement depth at Normanby le Wold in 1983.

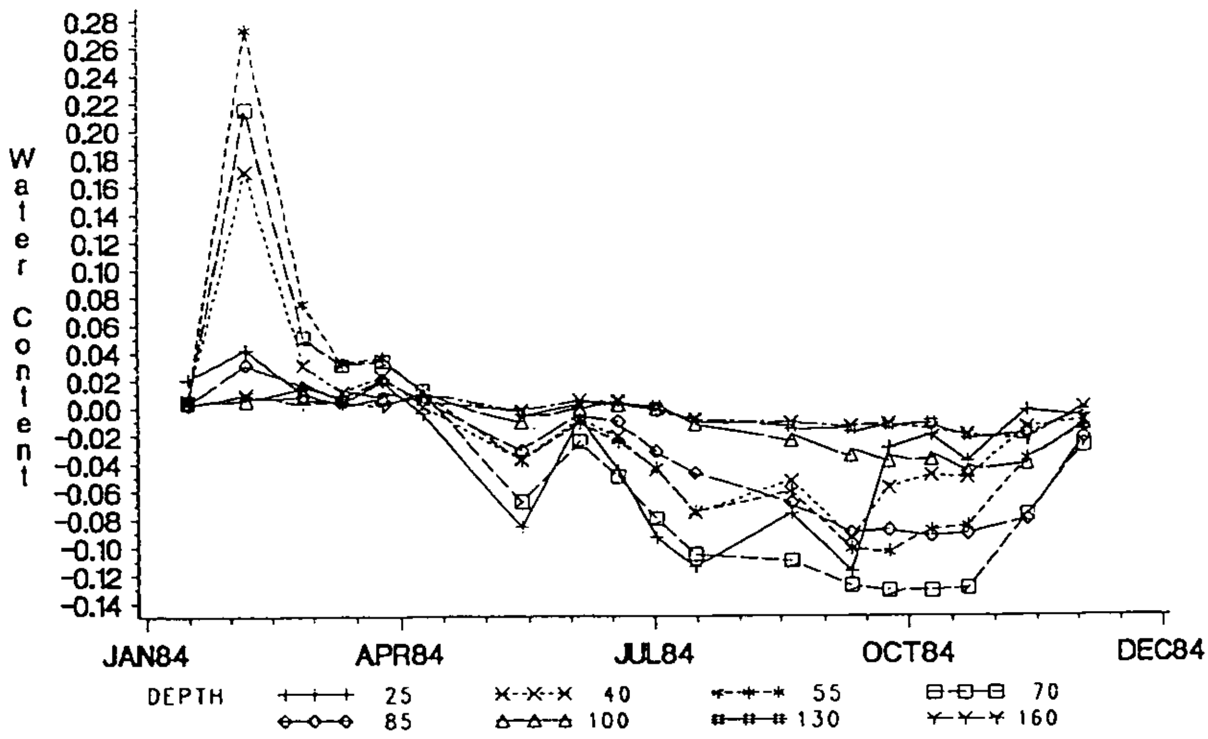

Fig. 6 Time series of soil water content change relative to the standard values for each measurement depth at Tetford in 1984.

results are illustrated in Fig. 7. With the tensiometer and gypsum block data, the depth of the ZFP was taken as that of the instrument which recorded the lowest hydraulic potential.

Figure 7 shows that, except in spring 1983 at Ulceby Cross, the timing of the commencement of the ZFP period determined by the two methods coincided well. Generally, interpretation of the late summer tensiometer data was abandoned due to instrument failure and thus only the gypsum block data were available to compare with those derived from the neutron probe measurements in late summer. These show that the timing of the end of the ZFP period determined by the two methods usually occurred on the same day or on adjacent reading occasions (these might be 2 or 3 weeks apart).

In autumn, the neutron probe data occasionally indicated the subsequent development of a shallow ZFP after the summer one had been annihilated by rainfall which was not apparent from the tensiometer or gypsum block data. One reason for this could be that the tensiometers were often not working.

The actual depths of ZFP determined from the probe data are in the main similar, if not the same as, those derived by the other methods. It should be noted that the tensiometer- and gypsum-block derived ZFPs are not always the same as one another. There are several reasons why the depths derived by different methods may not be identical:

Replicate sets of instruments of the same type do not always agree due to soil variability.

2. The maximum depth of water content measurement was 1.6 m compared with 3.0 m for hydraulic potential.

3. The depths and depth intervals used for the gypsum blocks differ from those for the other types of measurement. In the top metre, the neutron probe and tensiometer measurements are much closer together and so a more detailed history of the behaviour of the ZFP can be determined.

4. As indicated in Figure 7, some of the tensiometer and gypsum block derived data are qualified as tentative to indicate that malfunction of the other equipment in the profile may have led to incorrect assignation of ZFP depth.

In view of the above, ZFP depth determination from neutron probe measurements was regarded as satisfactory for these four sites, and was extended to the other sites.

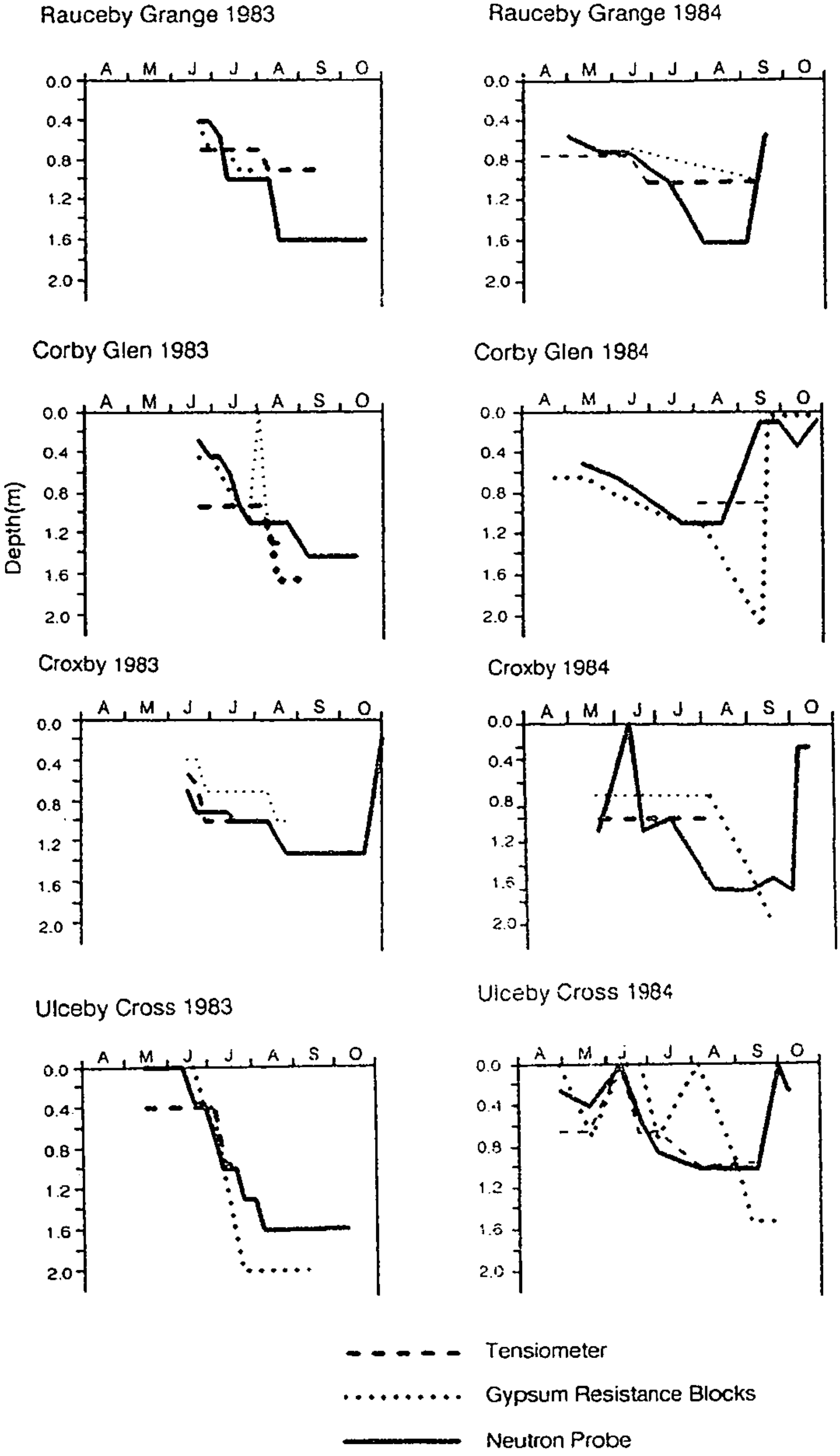

Fig. 7 Zero flux plane depth determined from tensiometer and gypsum block measurements of soil water potential, and from neutron probe soil water content change data, for 1983 and 1984 for Rauceby Grange, Corby Glen, Croxby and Ulceby Cross. Thin lines indicate depth determined is tentative.

5. Results of Data Analysis and Discussion

5.1 INTRODUCTION

In this section, after brief comments on the results as a whole, the data from the sites upon each aquifer are treated in turn. The short descriptions of the soil profiles at each site were obtained from records made as the sites were installed by staff from the former Anglian Water Authority. Those features of the soil water regime at each site relevant to the water balance analysis have been emphasised. The behaviour of the ZFP is discussed since that is particularly important to the derivation of the water balance.

5.1.1 Monthly v weekly MORECS Potential Evaporation

The effect on the water balance calculations of using monthly MORECS potential evaporation estimates rather than weekly, to obtain daily values of potential evaporation, was small. In fact the two sets of MORECS estimates gave slightly different annual totals for potential evaporation for the same year and square. For the three squares where the Navenby, 118, Dunston Heath, and Driby, 109, and Ulceby Cross, 110, sites are located (i.e. the sites established pre-1983), the weekly potential evaporation estimates gave annual totals which were 15 mm, 23 mm and 26 mm respectively less than those obtained using the monthly data. This led to larger estimates of annual drainage when the weekly MORECS data were used in the water balance calculations; the increases over the 1983 measurement period, 336 days, were:

Navenby	19 mm
Dunston Heath Grass	16 mm
Dunston Heath Arable	20 mm
Driby	23 mm
Ulceby Cross	29 mm

These increases are of the order expected given the difference in the potential evaporation estimates.

5.1.2 Negative drainage estimates

In the course of the water balance calculations, negative estimates for drainage over a few days resulted occasionally. This implies that water moved upwards into the soil profile. This could occur in summer if the ZFP were to fall to a depth below that of the measured profile, and induce an upward flux of water. However, the quantity of water involved in such fluxes would be small and probably only measurable as a loss of water from greater depth. Upward movement of water into a soil might also occur due to a watertable rising into the profile.

In fact, most of the negative drainage estimates are an artefact of the calculation procedure. They arose mainly because of the use of an estimate of potential evaporation at times in the spring and summer months, and to a lesser extent in autumn, when no ZFP was observed and hence an independent estimate of actual evaporation could not be obtained. Where the interval between soil water measurements is large, evaporation is assumed to have continued at the potential rate for much longer than was probably the case. As a consequence evaporation from the soil is overestimated and if there is little rainfall, a negative drainage figure is calculated to compensate. The process is exacerbated because the ZFP method may only be used when a ZFP is observed on two or more successive measurement occasions. Where infrequent soil water monitoring is combined with a wet summer (when the presence of a ZFP is intermittent) ZFPs may not be present on consecutive occasions. Hence it may be rarely possible to use the ZFP method in calculating the water balance and therefore potential evaporation rates have to be assumed over very long periods in summer although they are inappropriate.

It should be noted that there is evidence from other studies (Cooper, 1979; Gardner and Field, 1983) that vegetation does not necessarily resume transpiration at the potential rate when the soil has been rewetted by heavy summer rainfall. This implies that use of the potential evaporation estimate for periods of even two or three days in summer could lead to overestimation of soil evaporation, and hence underestimation of drainage at the same sites.

For certain sites, underestimation of drainage due to inappropriate use of the potential evaporation estimate in summer was a particular problem in 1985 when the summer was wet and readings were infrequent. Where this occurred,it has been noted in the discussion of the water balance for the site concerned. The size of the cumulative total negative drainage estimate provides a very rough guide as to by how much the drainage may have been underestimated.

Negative drainage values are also calculated if water moves laterally into the soil profile. The data for the two sites on the Northern Limestone, Redbourne and Scawby, and for Tetford on the Spilsby Sandstone, strongly suggested that this occurred at those sites, as discussed in the relevant sections following.

5.2 THE CENTRAL LIMESTONE

5.2.1 Sites, soil water behaviour and ZFPs

Data were supplied from four sites on the Central Limestone: Dunston Heath, where there was a grass and an arable plot (Fig. 1), Navenby, some 7 km to the southwest, where the site was under arable cultivation, and a grassed site at Rauceby Grange, 11 km south of Navenby. Recording began in 1976 at all the sites except Rauceby Grange where measurements commenced in February 1983; gypsum blocks and tensiometers were also installed there.

The soil profile descriptions provided indicate that although developed upon the same parent material, the soils differed in character. At Dunston Heath, the soil at the two sites (which are presumed to be about 100 m apart) is quite similar. Stony, silty textured soil, 0.6 to 0.7 m in depth occurs over weathered limestone with a clayey infill between blocks. The degree of weathering decreases with depth, such that at 1.6 m the limestone is little altered. At the grassed site a band of clay and oolitic sand was identified between 1.3 and 1.45 m depth. At Navenby, a 0.3 m deep sandy loam topsoil overlies a medium to coarse oolitic sand subsoil containing bands of less weathered limestone. Partially weathered limestone occurs at 1.3 m and below. The Rauceby Grange soil is also described as silty with weathered limestone, which includes 'marly' bands, below 0.85 m. Given the variability of these soils, it was not appropriate to make assumptions regarding soil water hydraulic potential changes at all sites on the basis of the potential measurements at Rauceby Grange, which was the only one equipped with tensiometers and gypsum blocks.

The sandiness of the Navenby soil is reflected in the particularly low standard winter water content values derived for that site (Table 2). However, at the other sites, the standard values are also relatively low, always less than 0.3 except at 1.6 m depth at the grassed Dunston Heath, site where the neutron probe calibration used reflects an increased clay content.

Rauceby Grange

At Rauceby Grange, at 1 m depth and below, volumetric water content changed by less than 0.05 throughout the monitoring period, behaviour similar to that at Navenby (see below) The upper part of the profile was usually wetter, even in summer. However, a dry summer such as 1976 was not monitored.

Table 2 Standard volumetric water content values determined for sites on the Central Limestone outcrop

DEPTH	DUNSTON HEATH		NAVENBY	RAUCEBY GRANGE
m	Grass	Arable	Arable	Grass
0.10	.261	.263	.134	.284
0.25	.276	.276	.148	.269
0.40	.234	.210	.124	.240
0.55	.229	.239	.128	.238
0.70	.223	.254	.136	.226
0.85	.222	.261	.149	.210
1.0	.229	.248	.149	.193
1.3	.237	.284	.176	.155
1.6	.357	.257	.175	.179

Tensiometer data were available for 1983 and 1984 for this site and indicated that the maximum ZFP depth achieved was 0.85 and 1.0 m in each year respectively (Fig. 7). The gypsum block data corresponded with the tensiometer information up until the end of July 1983, and on two occasions when good sets of readings were obtained, in 1984. Analysis of the neutron probe data suggested that the ZFP fell later to 1.6 m in both years. The water content changes below 1.3 and 1.6 m depth were small and so interpretation of the probe data should be treated with caution. However, these small water content changes mean that the likely error in water balance estimates is small (see next section).

For the following years, difficulties were also encountered in deciding whether the ZFP, having reached 1 m, remained there or fell to 1.6 m. The water balance has been calculated twice assuming that the ZFP did not exceed 1 m depth, and using the depths derived from the probe data. It is noteworthy that the tensiometers indicated that potentials were high between June and early August 1983, and that below the ZFP at 0.7 m, the profile was close to saturation (Fig. 8). The little reliable tensiometer data available for 1984 suggested that the same was true that year.

Navenby

There are two characteristic features of the soil water regime at the Navenby site:

absolute water contents at all depths in this limestone soil is always small, less than 0.2;

2. the partially weathered limestone at 1.3 m and below, remains wetter than the soil above every summer. Volumetric water content at this depth fluctuates by less than 0.02 in most years.

The water content time series (Fig. 9) shows the effect of the dry summer of 1983 on the water content profile. However, it is also noteworthy that in this soil the summers of 1976 and 1977 produced similar patterns of water content change.

The maximum ZFP depth achieved was 1.24 m in 1976 and again in 1979. In 1983 a maximum ZFP depth of 1.0 m was determined. In other years the ZFP remained much shallower and there was clear evidence of slow, continuous drainage from below it throughout the summer. In three years, 1985, 1986 and 1987, the maximum ZFP depth was only 0.55 m. That this was so is a reflection of the wet summers of those years and the fact that relatively little rainfall is required to re-wet the profile above the ZFP because of the low water holding capacity of the soil.

Dunston Heath

At Dunston Heath, except in 1976, maximum volumetric water content changes each year at and below 0.55 m were 0.07 or less, often only 0.03 at the grassed site. The data from the arable site were little different, despite the cropping regime. The soil water content data were quite difficult to understand in terms of ZFP movement due to the subtlety of the changes below 0.55 m. However, a fairly clear pattern was apparent, whereby the ZFP usually

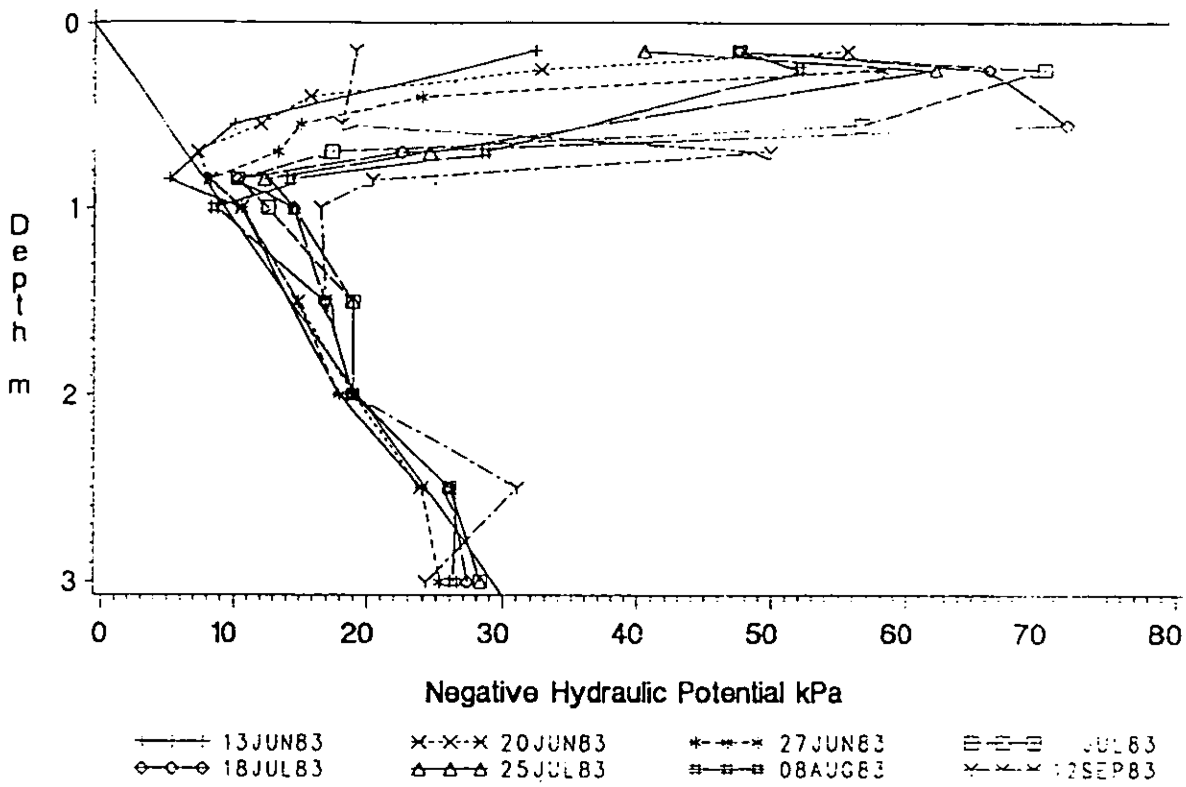

Fig. 8 Tensiometer data recorded at Rauceby Grange between 13th June and 12th September 1983. The ZFP reached 1 m depth on 8th August.

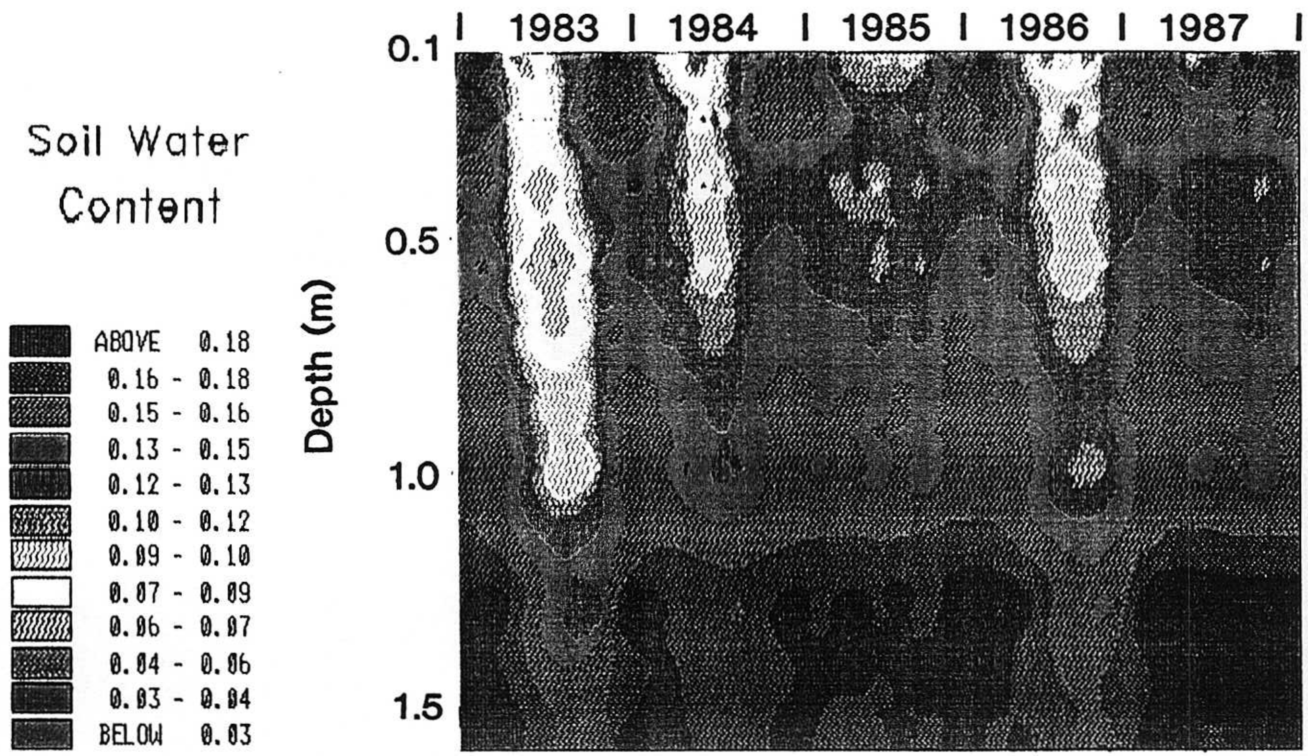

Fig. 9 *Time series of soil water content change relative to the standard values for each measurement depth at Navenby, 1983 to 1987 inclusive.*

descended to between 0.5 and 0.9 m, but in most years fell later to the base of the measured profile (1.6 m) and may have fallen below this. The ZFP did not reach the bottom of the profile in 1980, 1985 and 1987.

5.2.2 Water Balances

The results of the water balance computations for the Rauceby Grange site and the implications for them of the position of the ZFP, will be discussed initially. The Navenby site will be considered next and then the contrasts between the grass and arable sites at Dunston Heath. Finally all the results will be discussed in terms of recharge to the aquifer as a whole.

Rauceby Grange

Table 3 lists the water balance results as annual totals for the two sets of water balance calculations that were conducted. The ZFP depths were different in 1983, 1984 and 1985. However, the effect of altering the ZFP depths from 1 m maximum as implied by the tensiometers and gypsum blocks, to 1.6 m maximum depth as indicated by the soil water content measurements, is slight. The difference in terms of drainage was negligible in 1984, and 8 mm and 11 mm in 1983 and 1985 respectively, drainage being reduced when the ZFP was assumed to fall lower. However, as a percentage of annual drainage this represented only an 8% decrease in 1983, but a 29% decrease in 1985 when summer drainage was an important component of the drainage total for the year. In view of the small difference in these figures, the analysis using the 1 m maximum depth ZFP has been adopted for this site.

Table 3 Water balance results for Rauceby Grange (Central Limestone)

YEAR	NO OF READINGS	RAINFALL mm a^{-1}	EVAPORATION POTENTIAL mm a^{-1}	ACTUAL mm a^{-1}	DRAINAGE mm a^{-1}	DRAINAGE/ RAINFALL %
1983a	30	497	575	435	93	19
1984	22	609	606	463	139	23
1985	20	523	583	487	37	7
1986	20	549	627	486	74	13
1987	22	645	557	489	145	14
MEAN (1984-1987)		581	593	481	99	17

a From 21st February 1983

The cumulative values of the water balance components for this site are illustrated in Fig. 10 for 1984. It is apparent that as soon as a ZFP developed in May, actual evaporation fell below the potential rate. In late September rainfall neutralised the ZFP but actual evaporation was evidently less than the potential rate assumed as some negative drainage was calculated in October.

Year to year there are large fluctuations about the mean annual soil drainage of 102 mm a^{-1}. The low drainage total calculated for 1985 arose because the rainfall total was smaller than in other years (though not exceptionally so) but evenly distributed. Thus there was much summer rainfall, repeatedly wetting up the soil but not usually sufficiently to cause drainage. A large part of the year's rainfall was therefore evaporated. A similar pattern of events was recorded in 1985 at many of the other sites included in this study, as will be referred to later. Drainage as a percentage of rainfall, ranged from 7% in 1985 to 23% in 1984. Drainage when a ZFP was present in the summer months was important in some years, though not 1984 (Fig. 10), accounting for more than 18% of the total over the 5 year measurement period.

Navenby

The 11 year mean annual drainage at this site was 161 mm, 25% of the annual rainfall, (Table 4). However the variation is considerable; only 4 mm of drainage was calculated for 1985, less than 1% of the rainfall total for that year. The shallow depth of the ZFP in 1985 has already been referred to. In addition, the ZFP was not persistent, which meant that the

Table 4 Water balance results for Navenby (Central Limestone)

YEAR	NO OF READINGS	RAINFALL mm a^{-1}	EVAPORATION POTENTIAL mm a^{-1}	EVAPORATION ACTUAL mm a^{-1}	DRAINAGE mm a^{-1}	DRAINAGE/ RAINFALL %
NAVENBY						
1976a	21	329	478	174	63	19
1977	42	587	585	401	234	40
1978	36	595	553	473	94	16
1979	41	671	585	464	201	30
1980	44	730	585	440	320	43
1981	44	629	583	436	157	25
1982	42	613	604	445	176	29
1983	33	577	590	425	179	31
1984	21	619	606	473	134	22
1985	19	506	583	489	4	1
1986	19	568	627	491	83	15
1987	22	674	557	550	127	19
MEAN (1977-1987)		615	587	463	155	25

a From 26th May 1976

potential evaporation estimate had to be used in the water balance calculations for much of the summer resulting in a total of 140 mm negative drainage during the summer. As a consequence, drainage from this site in that year

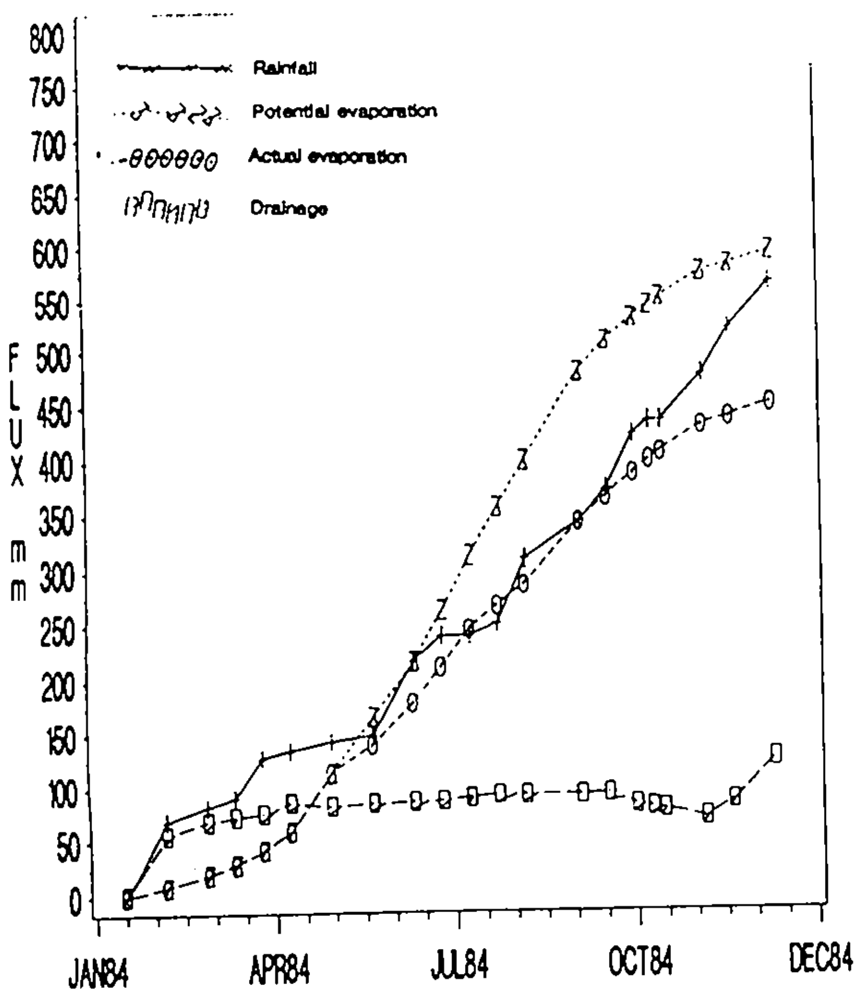

Fig. 10 *The cumulative values of the 1984 water balance components for Rauceby Grange.*

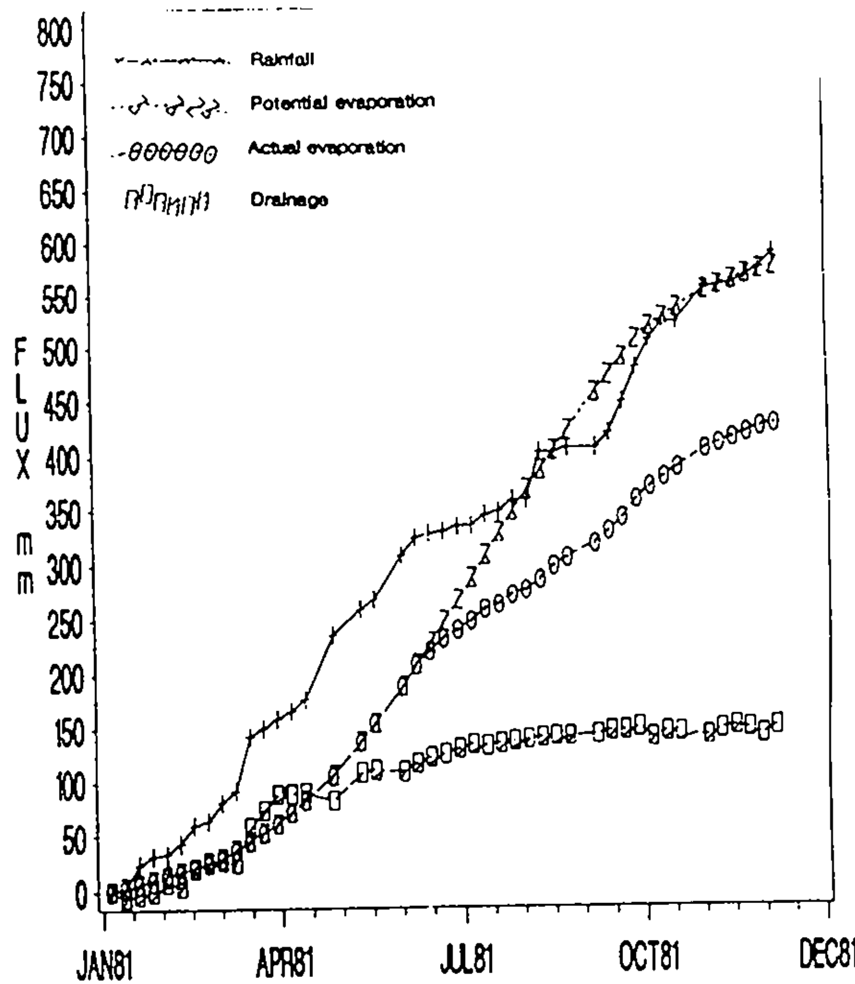

Fig. 11 *The cumulative values of the 1984 water balance components for Navenby.*

may have been underestimated (see section 5.1.2). However, excluding 1985 only increases the annual drainage figure to 177 mm, 27% of mean annual rainfall.

In 1987, the behaviour of the ZFP at Navenby was apparently similar to that in 1985. The much greater drainage figure calculated for 1987 arose because firstly there was 120 mm more rainfall that year and secondly only 63.5 mm of negative drainage was calculated in the summer months.

Table 5 details the cropping regime of the arable Navenby and Dunston Heath sites and the number of days in each year that each site was reported to be 'bare fallow'. The periods during which crop cover at the site was absent or very small was probably longer than these figures imply. There is no obvious correlation between crop type and drainage for this site.

A significant proportion, 22%, of the mean drainage total occurred whilst a ZFP was present at Navenby. This is not unexpected given that the ZFP remained well above 1.0 m depth in most summers and persistent drainage was observed from depths below it. Fig. 11 illustrates the cumulatve drainage estimated for 1981 when the ZFP developed in June.

Table 5 Cropping Regime at Navenby and Dunston Heath arable sites

YEAR	NAVENBY	DAYS NO CROP COVER	DUNSTON HEATH	DAYS NO CROP COVER
1976	PERMANENT GRASS-MOWN	0	BARLEY THEN MUSTARD	0
1977	PERMANENT GRASS-MOWN	0	PEAS	258
1978	SUGARBEET	14	S WHEAT	106
1979	S BARLEY	102	BARLEY	231
1980	W BARLEY	49	SUGARBEET	121
1981	W BARLEY	49	BARLEY	201
1982	W BARLEY	165	BEANS/PEAS THEN W WHEAT	112
1983	SUGARBEET	136	W WHEAT THEN RAPE/COLE	0
1984	BEANS/PEAS THEN OATS(?)	58	RAPE/COLE THEN W WHEAT	42
1985	POTATOES	114	W WHEAT	30
1986	S BARLEY	135	W WHEAT THEN GRASS	90
1987	SUGARBEET	139	BEANS/PEAS THEN WHEAT	79

W = WINTER S = SPRING

Dunston Heath

The 1976 data from the arable plot at Dunston Heath was excluded from the water balance computations because, for some inexplicable reason, the soil profile water content *increased* by 114 mm between 19th July and 10th August, during which period only 6.1 mm of rainfall was measured and the potential evaporation rate averaged 3.5 mm d^{-1}. The neutron probe data thereafter were consistent with an addition of water. A possible explanation is that the site was irrigated, although there is no record of this. According to the crop record for the site, barley was being cultivated at the time and was followed by a mustard crop.

It is possible that drainage from the grass plot in 1976 may have been underestimated. Inspection of Fig. 12 indicates that in May and June, when the ZFP was present intermittently, the independently calculated evaporation rate was much lower than the potential rate. For example, for the 14 day period 28th April to 12th May, the potential evaporation estimate was 37 mm compared with measured actual evaporation of 11 mm. However, because of the timing of the readings and the ephemeral ZFP it has been necessary to use the potential evaporation rate frequently in preparing the water balance. Consequently, negative drainage quantities totalling more than 65 mm, were calculated on several occasions up until the beginning of July (not shown in Fig. 12). It is therefore quite likely that actual drainage from the site was greater than the 6 mm calculated by up to 65 mm (see section 5.1).

In succeeding years the water balances were, in the main, straightforward and direct comparison of the data from the two plots is possible. Table 6 summarises the data from each and Figs 13 and 14 show the water balances results for 1981. Year to year the difference between the drainage totals for the two plots varied; in 1983 drainage was greater by 46 mm from the arable plot but in 1978 there was 22 mm more drainage from the grass plot. Fig. 14 shows that in autumn 1981, drainage from the arable plot was probably slightly underestimated as negative values were calculated at the end of the ZFP period when there was little crop cover. But for this, the drainage total would have been almost the same as for the grass plot in that year.

In most years, however, there was more drainage from the arable plot. The difference was greater than the errors expected due to possible misrepresentation of the ZFP depth (estimated to be about ± 10 mm a^{-1}). No correlation is apparent between the size of the drainage difference and the time that the plot remained bare in any year, or the crop type. Indeed, in 1983 when, according to the site crop record there was an almost continuous crop cover at the arable plot, the increase in drainage was greatest in both absolute and percentage terms, with the exception of 1985.

Drainage amounts in 1985 were small from both plots. In fact negative drainage quantities were calculated during of the summer because a persistent ZFP did not develop. The drainage totals are therefore probably underestimates.

Table 6 Water balance results for Dunston Heath Grass and Arable Sites (Central Limestone)

YEAR	NO OF READINGS	RAINFALL mm a^{-1}	EVAPORATION ACTUAL mm a^{-1}	POTENTIAL mm a^{-1}	DRAINAGE mm a^{-1}	DRAINAGE/ RAINFALL %
DUNSTON HEATH GRASS						
1976a	28	394	616	335	6	2
1977	49	587	579	470	141	24
1978	40	595	536	471	102	17
1979	34	671	570	471	204	30
1980	45	730	564	470	272	37
1981	45	629	596	470	149	24
1982	44	591	596	490	114	19
1983	34	611	560	508	116	19
1984	22	617	585	511	111	18
1985	20	546	571	516	26	5
1986	20	605	610	495	112	19
1987	22	662	551	531	131	20
MEAN (1977-1987)		623	574	491	134	22
DUNSTON HEATH ARABLE						
1977	48	587	579	448	155	26
1978	41	595	536	520	80	13
1979	32	671	570	459	209	31
1980	44	730	564	455	291	40
1981	44	629	596	477	126	20
1982	42	613	596	459	160	26
1983	33	611	560	451	161	26
1984	21	617	585	472	151	24
1985	19	546	571	475	67	12
1986	19	605	610	502	109	18
1987	22	662	551	500	162	25
MEAN (1977-1987		624	574	474	152	24

a From 26th May 1976

5.2.3. Recharge to the Central Limestone Aquifer

The results of the water balance calculations for the four sites on the Central Limestone outcrop are summarised in Table 7. Considering first the period 1983 to 1987 inclusive, when all the sites were operational, three points are notable.

> The slightly greater drainage from the arable site at Dunston Heath relative to the adjacent grass site; the increase averaged 27 mm a^{-1} (22%).

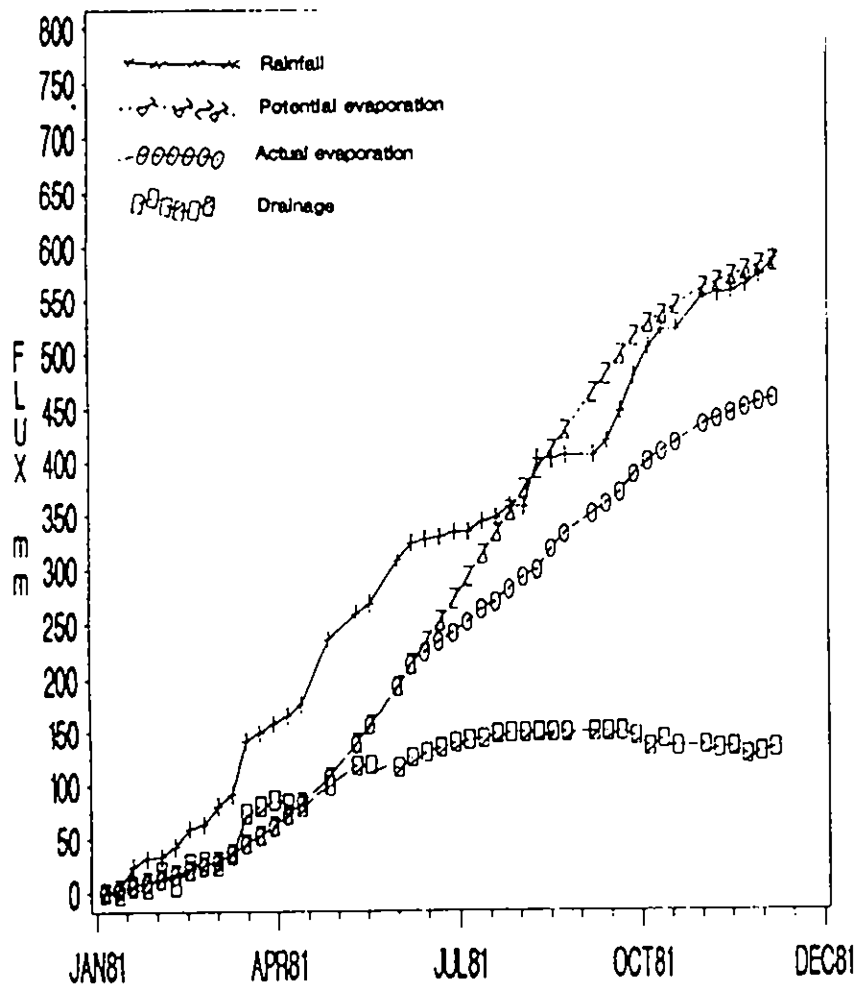

Fig. 13 The cumulative values of the 1981 water balance components for Dunston Heath grass plot.

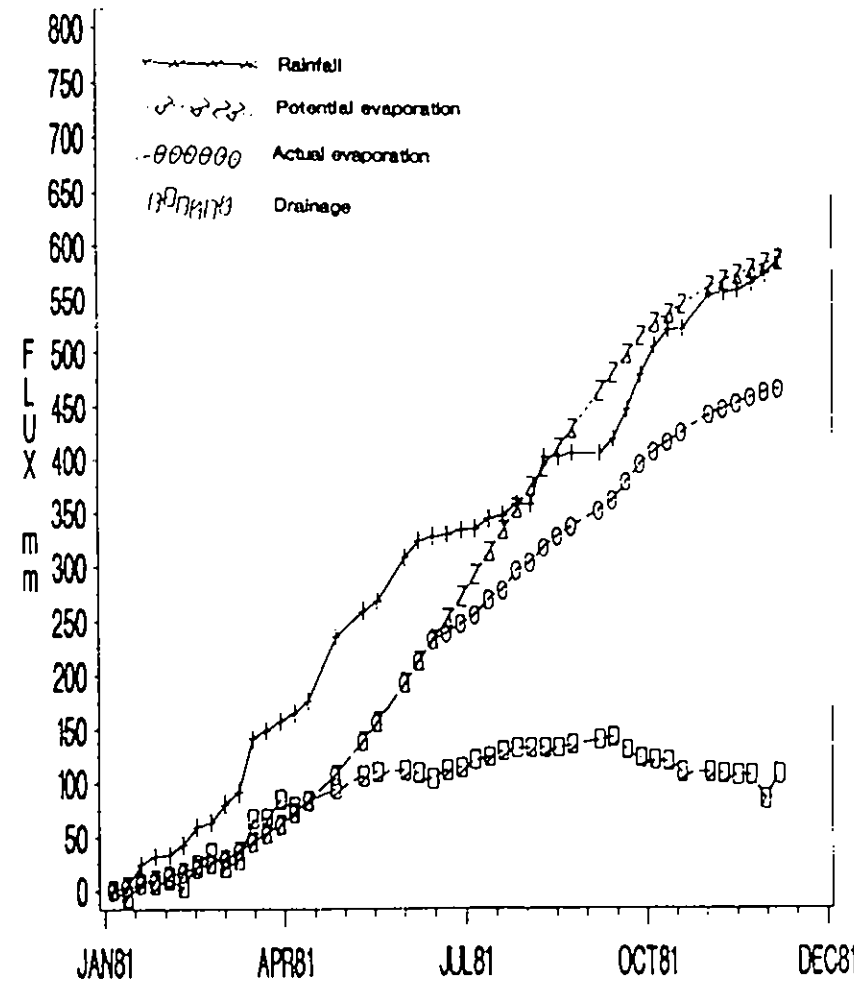

Fig. 14 The cumulative values of the 1981 water balance components for Dunston Heath arable plot.

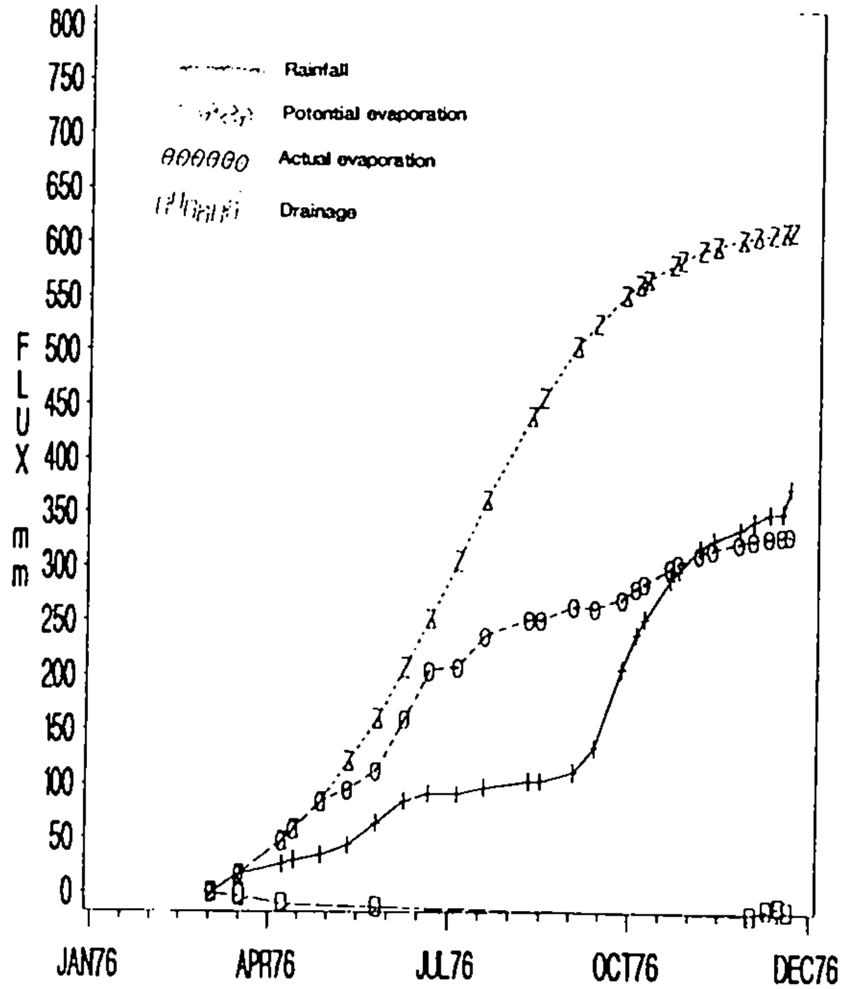

Fig. 12 Cumulative rainfall, potential and actual evaporation for the Dunston Heath grass plot in 1976. The negative drainage estimates are not shown.

The similarity in the mean drainage figures for the grass sites at Rauceby Grange and Dunston Heath, despite differences in rainfall and potential evaporation at the sites, the annual means differ by only 3 mm.

Although mean drainage from the arable Navenby and Dunston Heath sites differs by 35 mm, the actual evaporation figures only differ by 14 mm. The greater drainage occurs at Dunston Heath where 16 mm more rainfall was recorded.

Table 7 Summary of mean water balance results from the Central Limestone

SITE	RAINFALL mm a^{-1}	EVAPORATION POTENTIAL mm a^{-1}	EVAPORATION ACTUAL mm a^{-1}	DRAINAGE mm a^{-1}
1983 to 1987				
Rauceby Grange Grass	581	593	481	99
Dunston Heath Grass	608	579	513	95
Dunston Heath Arable	608	579	487	122
Navenby Arable	592	593	501	87
1977 to 1987				
Dunston Heath Grass	623	574	491	134
Dunston Heath Arable	623	574	474	152
Navenby Arable	615	587	463	155

Over the longer period, 1977 to 1987, the results again show a small (18 mm a^{-1}, 14%) increase in drainage due to arable cultivation at Dunston Heath but also a close similarity in the mean annual drainage figures for the two arable sites. (Dunston Heath and Navenby).

The implications of these results for recharge to the aquifer are that arable cultivation slightly increases recharge amounts relative to grassland areas by about 18 mm a^{-1} on average. Annual recharge amounts from arable areas are similar over the long term, averaging 153 mm a^{-1}. Recharge amounts from grassland areas probably also vary little spatially; the mean recharge from the one long term site was 134 mm a^{-1}.

5.3 SOUTHERN LIMESTONE

5.3.1 Sites, soil water behaviour and ZFPs

Two of the sites on this aquifer are about 15 km apart, Corby Glen being east of Saltby. Both were established in the autumn of 1982 in grassed areas. The soil descriptions from both sites are very similar with about 0.6 m depth of silt loam/silt marl over weathered limestone. The latter extends to 1.0 m at Saltby and 1.3 m at Corby Glen where a "marl residue" was noted. At both sites undisturbed limestone was observed below.

Between 1983 and 1987, a further six sites were installed at Ropsley where the limestone is covered by shallow boulder clay drift. Ropsley is about 10 km to the north of Corby Glen. Two sites were under grass; the first was established in early 1983, but abandoned in April 1985 in favour of the second, which was installed some 0.5 km away, close to the other sites. These sites were trial plots mainly under wheat cultivation (Table 8). They were monitored over differing time periods within the five years 1983 to 1987. It is not possible to establish from the crop records when the plots were harvested and ploughed.

Table 8 Cropping Regime at Ropsley Arable Plots

	SITE (IH NO)			
	I (18)	II (19)	III (20)	IV (21)
YEAR				
1983		Wheat		
1984		Wheat		
1985	Rape or Cole/Wheat		Wheat	
1986	Wheat		Wheat	Wheat
1987	Wheat			Wheat

The soil profile description for the original Ropsley grass site describes a clay top soil, a slightly sandy loam subsoil with "hard packed boulder clay" extending from about 0.45 m to 1.1 m. Below is very weathered limestone with a high "marly" clay content. At the four arable sites, clay loam top soils are described over what is generally a pebbly subsoil. Below 0.55 to 0.7 m is boulder clay which is stony. At the Ropsley III, sites sandy clay was recorded at the base of the profile i.e. below 1.6 m. There was no description of the second grass site at Ropsley, but because of its proximity to the arable trial plots, the soil was assumed to be similar to that encountered there. Thus it was only at the original Ropsley grass plot that the neutron probe access tubes extended below the boulder clay drift. There is no indication of the depth of the drift at any of the other sites.

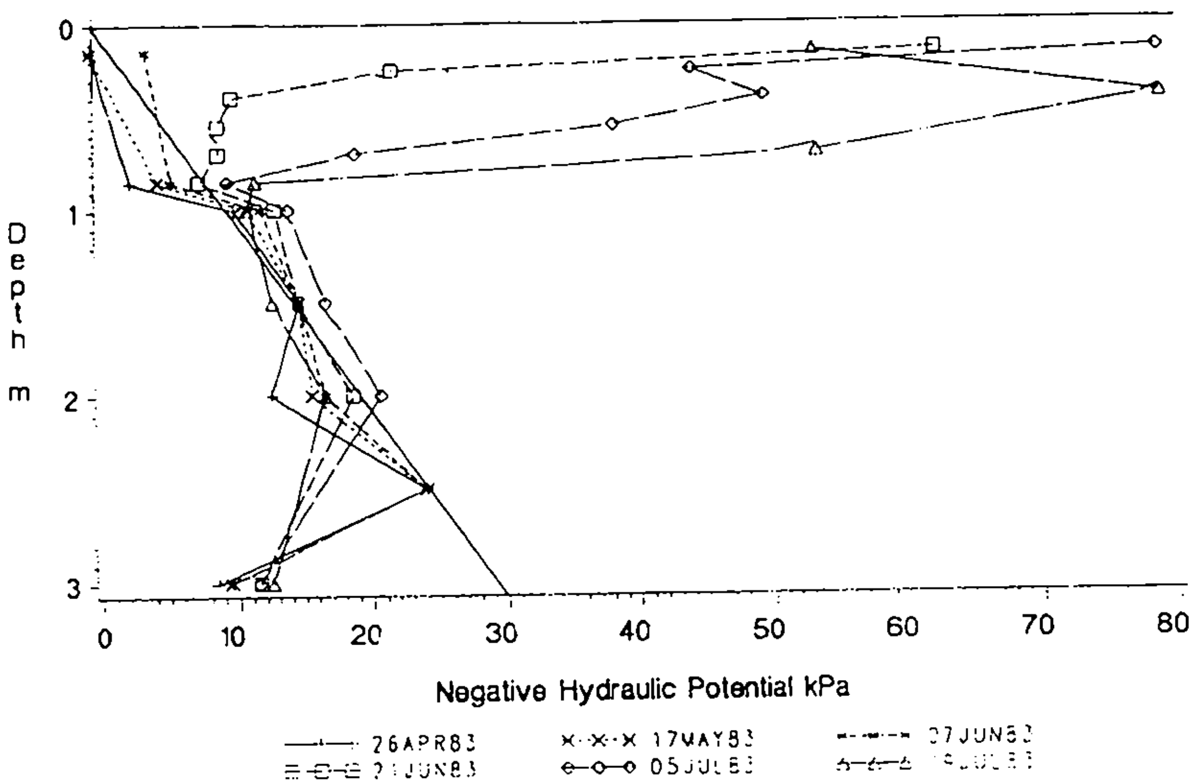

Fig 15 Tensiometer data from Corby Glen between 26th April and 19th July 1983. The data imply that the profile remained saturated until early June. The ZFP reached 1 m by 19th July.

The standard winter water contents for the Corby Glen and Saltby sites were fairly similar. Tensiometers and gypsum blocks provided soil water potential data in 1983 and 1984 at Corby Glen. The data indicate that, as at Rauceby Grange on the Central Limestone outcrop, much of the profile is close to saturation during the winter months and in spring until plant abstraction of water commences (Fig. 15). Some sensible data was also obtained from the tensiometers in 1985, up until the end of July. This suggested that although the surface dried out, potentials remained high at most depths.

The ZFPs derived from the tensiometer and gypsum block data (Fig. 7) suggest that the ZFP fell to 1.5 m in 1983 and 0.85 to 1.0 m in 1984. The neutron probe measurement-derived ZFPs correspond fairly well, and in later years a maximum ZFP depth of 1.0 m was recorded.

In contrast, the ZFP depths derived from the water content measurements at Saltby indicate that the ZFP usually fell rapidly to 1.6 m depth. A synchronous fall in water content was observed at all depths soon after the ZFP developed, as illustrated in Fig 16, which shows the data for 1984. Although the volumetric water content changes were not large in absolute terms, usually not exceeding 0.04, the pattern through the profile is clearly as expected as a consequence of root abstraction rather than drainage. The ZFP had fallen to 0.4 m on 21st May but was neutralised by 11th June. Thereafter, it fell rapidly from 0.55 m on 25th June, to 1.6 m by 23rd July where it remained until 1st October.

In summer 1983, at the original Ropsley grass site, a ZFP developed in late June and progressed down the profile to 1 m depth where it "stuck" in late July. It was neutralised by a wetting front caused by 43.6 mm of rain in the last few days of July. The ZFP was quickly re-established thereafter and again fell to 1 m in late August, where its progress halted for at least two weeks. It had disappeared by the following reading occasion five weeks later. It is probable that the drift/limestone interface at 1.1 m depth determined the maximum ZFP depth. This is because the weathered limestone may well be more conductive than the material above and so drains more readily, causing lower soil water potentials to develop within it. This phenomenon has been observed at two sites with clayey drift, of similar depth, over chalk (Gardner, *et al.*, 1990).

At the second grass site the maximum ZFP depth achieved was 0.85 m in summer 1986, and in other years it did not exceed 0.55 m depth. At the arable plots, the ZFP appeared to fall to greater depths in most years, reaching 1.6 m at the Ropsley II plot in 1985. However, for sites III and IV, from which only short soil water records were available, determining ZFP depths was not straightforward because the standard winter water content values were derived from a very small number of measurements and so were not necessarily representative. At Ropsley IV, measurements commenced in July 1986, and so the progress of the ZFP could not be followed. It was difficult to determine from the data whether the ZFP reached 0.55 or 1 m depth in July. Because of these uncertainties, the calculation of a water balance was abandoned for this site.

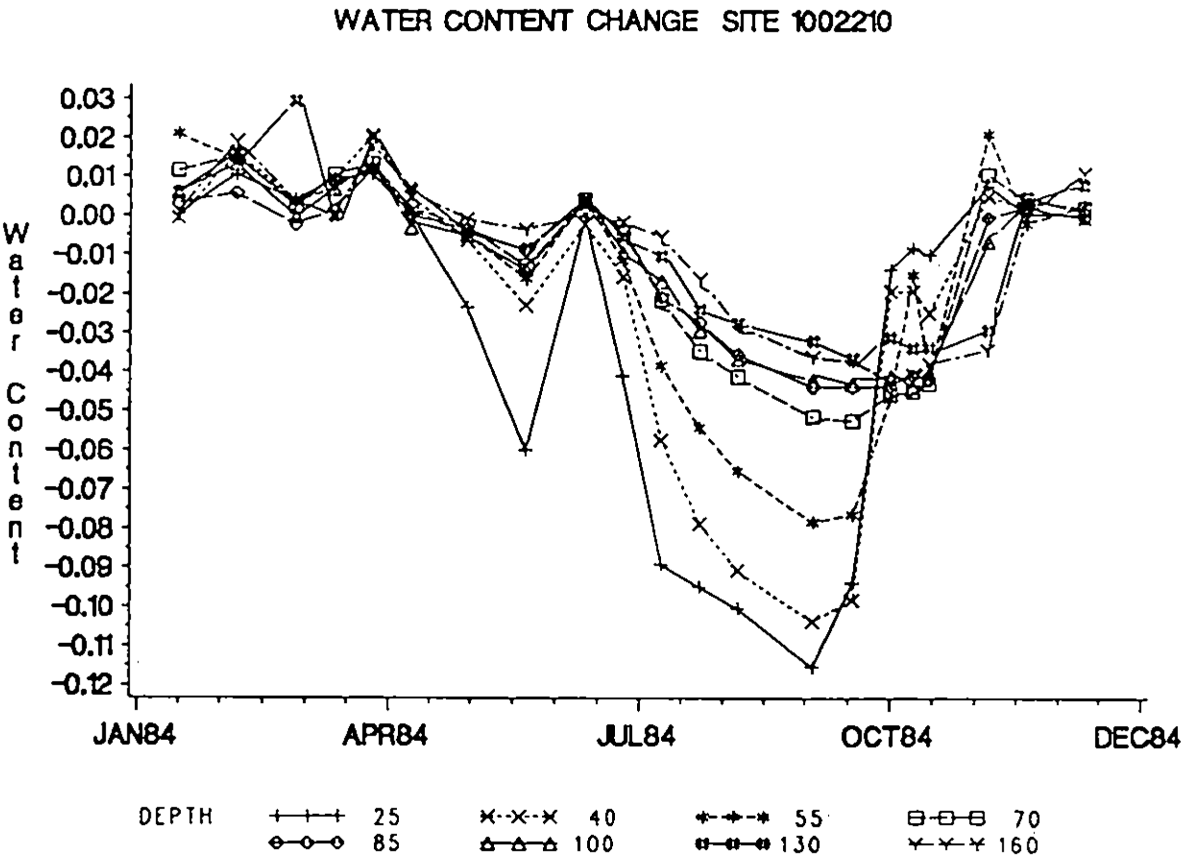

Fig. 16 Time series of soil water content change relative to the standard values for each measurement depth at Saltby in 1984.

5.3.2 Southern Limestone - Water Balances

Saltby and Corby Glen

The potential evaporation data used for all the sites on the Southern Limestone were the weekly MORECS estimates for grid square number 117. Over the five year monitoring period, on average 55 mm a^{-1} more rainfall was recorded at the Saltby site than at Corby Glen (Table 9). This resulted in more drainage from the Saltby site, on average 50 mm a^{-1} more over the measurement period. The difference between the water balances for the two sites in 1983 is illustrated in Figs. 17 and 18. It is possible that the data for 1987 from Corby Glen underestimate the annual drainage, see below. If the data are averaged over four years 1983 to 1986, the rainfall difference between the sites remains 55 mm a^{-1}, but the difference in drainage is reduced to 30 mm a^{-1}. Actual evaporation rates were greater at the Saltby site and so the difference in drainage amounts is smaller than the rainfall difference. The ZFP periods were almost the same at both sites. Although deeper ZFPs were characteristic of the Saltby site, over the five year period whilst a ZFP was present there was 58 mm and 107 mm drainage from Corby Glen and Saltby respectively.

Table 9 Water Balance results for the Southern Limestone

YEAR	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm	DRAINAGE/ RAINFALL %
CORBY GLEN						
1983a	25	571	571	475	134	23
1984	19	639	597	465	161	25
1985	18	586	570	512	74	13
1986	19	611	616	498	118	19
1987	21	605	545	552	48	8
MEAN (1983-1987)		602	580	495	107	18
SALTBY						
1983a	35	665	571	473	189	28
1984	21	641	597	472	182	28
1985	17	645	570	535	105	16
1986	19	675	616	540	126	19
1987b	21	658	540	472	184	28
MEAN (1983-1987)		657	579	498	157	24

a From 11th January 1983
b To 30th November 1987

The 1985 data are regarded as satisfactory for both sites since despite the wet summer, fairly persistent ZFPs apparently occurred at each site and so it was not necessary to use potential evaporation estimates in the summer water

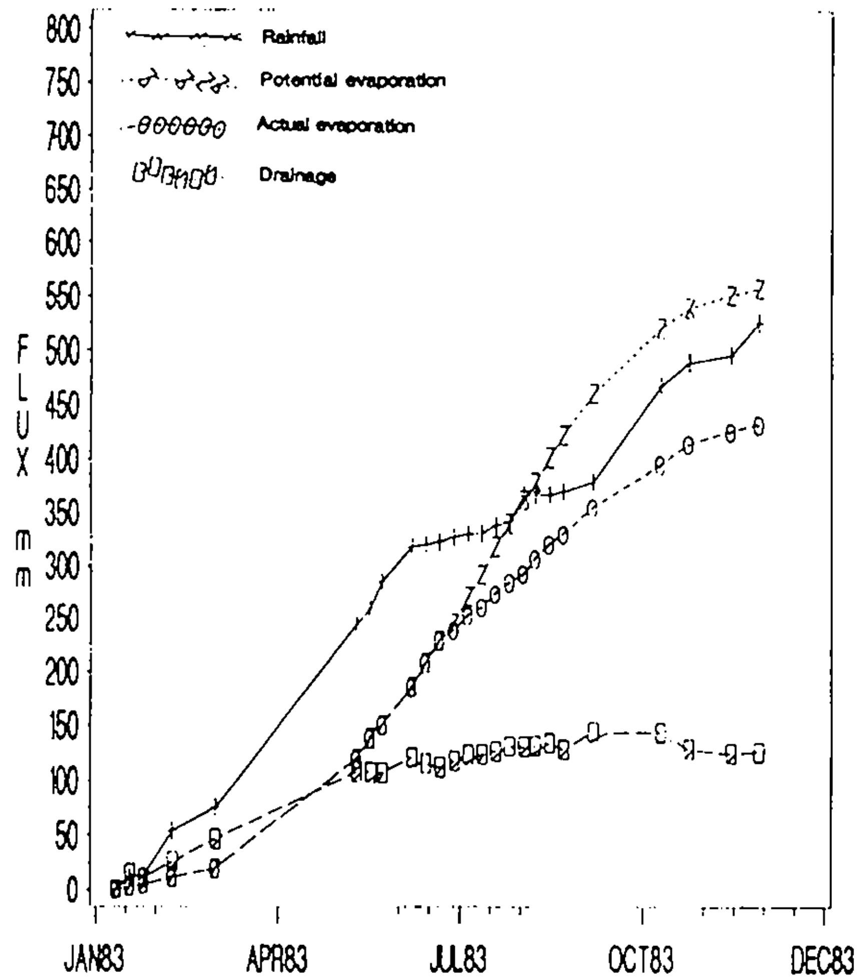

Fig. 17 The cumulative values of the 1983 water balance components for Corby Glen.

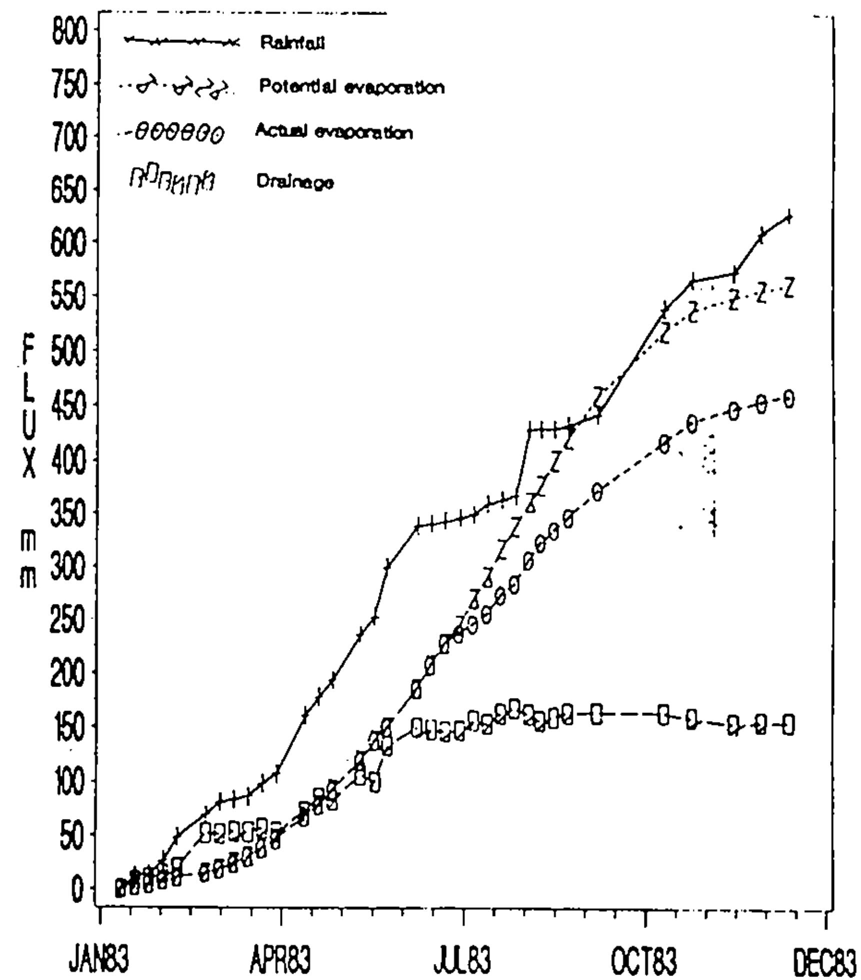

Fig. 18 The cumulative values of the 1983 water balance components for Saltby.

balance calculations to any great extent. However, for part of summer 1987, at Corby Glen the drainage estimates were persistently negative, largely due to the intermittent character of the ZFP. It therefore seems that the 1987 drainage estimates for Corby Glen may have been underestimated by up to 60 mm, i.e. the amount of negative drainage calculated over the summer.

Ropsley

Although data was available from some of the Ropsley sites from January 1983, ambiguities in the rainfall data prior to May of that year meant that water balance calculations had to commence from the 10th May 1983. The results are tabulated in Table 10.

Table 10 Water Balance results for the Ropsley sites

SITE	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm
ORIGINAL ROPSLEY GRASS					
1983 - 1984[a]		521	536	460	96
ROPSLEY GRASS					
1984[b]	12	367	513	424	-10
1985	19	595	570	505	88
1986	23	617	620	493	128
1987	19	648	540	487	164
ROPSLEY I					
1985	15	587	568	517	89
1986	19	612	621	481	131
1987	13	360	368	347	105
ROPSLEY II[c]					
1983	16	344	453	397	-12
1984	13	285	384	351	72
ROPSLEY III[d]					
1984	9	255	513	483	-239
1985	12	418	418	383	36

a From 10th May 1983 to 16th April 1984
b From 14th May 1984
c From 10th May 1983 to 30th July 1984
d From 16th April 1984 to 19th August 1985

The negative drainage figures for Ropsley II in 1983 and the second grass plot in 1984 arise because of gaps in the data after harvest, in the first instance, and in August and early September in the second. On these occasions, large negative drainage quantities were computed for both sites as there was no evidence of a ZFP in the soil water content data, although the rainfall amounts were small. Potential evaporation estimates were used in the calculations but were almost certainly inappropriate. The same occurred for the Ropsley III plot; in 1984 there were no readings between 30th July (harvest?) and 12th November and hence negative drainage of 239 mm was calculated as a consequence of potential evaporation being assumed despite probably dry soils and no crop cover for much of that period.

Because of the complexity of the different time periods over which the measurements were made at the various sites, it is difficult to compare the results. However, the data show that annual drainage fluxes from the grass and Ropsley I sites in 1985 and 1986 were very similar and very close to the results for the Corby Glen site in those years where rainfall amounts were nearly the same.

5.3.3 Recharge to the Southern Limestone aquifer

The data from Corby Glen and Saltby indicate the variation in both time and space of recharge to this aquifer where there is no drift cover. If the 1987 data for Corby Glen are excluded, the year to year range there still exceeds 80 mm, as at Saltby. This is more than the variation in annual rainfall. The 4 year mean annual recharge estimate was 151 mm a^{-1} at Saltby, representing 23% of annual rainfall. The corresponding figures for Corby Glen are 121 mm a^{-1} and 20%.

At both sites small water content charges occur at 1.6 m depth and probably small changes occur below. Indeed at Saltby it is possible that the ZFP falls to greater depth. Should the latter occur, aquifer recharge would be less than estimated here, but the difference is likely to be trivial. However, the occurrence of water content change below the measured profile will mean that the timing of recharge at the groundwater table is different from that calculated here, although the total quantities will be the same. The evidence available from the Ropsley sites, although tenuous, implies that where drift covers the limestone, arable cropping, rather than grass, has little impact upon drainage from these soils. Also, drainage quantities are similar from this site and Corby Glen, for which site the inputs to the water balance calculation were similar.

5.4 NORTHERN LIMESTONE

5.4.1 Sites, soil water behaviour and ZFPs

Two grassland sites were located on the Northern Limestone: Scawby, and Redbourne some 7 km to the south. Records were available from March 1983 to the end of 1987 for the Redbourne site, but only for three years, 1984, .1985 and 1986, from Scawby.

The profile descriptions for the two sites are fairly similar. Silty rendzina soils, 0.4 to 0.5 m deep, overlie limestone extending to 1.15 to 1.3 m depth, below which is a "silty clay marl" at Redbourne, and a "silty marl loam" at Scawby. At Redbourne, a grey-blue stiff clay was recorded below 1.8 m depth. The limestone aquifer is either very shallow at this point or includes bands of marl and clay. At both sites a zone of seasonal saturation was noted below 0.75 m.

The standard winter volumetric water contents of the limestone at both sites was 0.2 or smaller whilst larger standard water contents were determined for the rendzina soil above and the marl material below. It is presumed that the seasonal water logging is caused because the marl below the limestone is only slowly permeable, if at all.

The soil water content data from Scawby showed almost no change at 1.6 m depth, suggesting that the base of the profile is probably saturated all year. At 1.3 m, the pattern of water content change was consistent with slight drainage in summer. Seasonal saturation was observed to affect measurements at 1.0, 0.85 and 0.7 m depth, and occasionally at 0.55 m depth as illustrated in Fig. 19 for 1984. The increase in water content persists much longer at 1.0 m depth than above. At shallower depths, a water content increase was often recorded on a single reading occasion but these layers had drained by the following reading, two or three weeks later, causing wetting at 1.0 m but not below. It seems unlikely that the water could percolate through the underlying material in such a short time and the drainage out of the profile is assumed to be a consequence of lateral water movement.

The annual soil water regime at Redbourne was very similar to that at Scawby. There was very little change in water content at 1.6 m depth throughout the year. In winter, water content at 1.3 m was almost constant. It thus appears that the profile is saturated at 1.3 m and below during winter and at 1.6 m all year. Large water content changes were observed between 0.7 and 1 m depth in winter and spring (and in 1984, also at 0.55 m) (Fig. 20). The increases persisted only briefly above 1 m, but for longer periods at 1 m, a pattern consistent with a temporary rise in the water table. As at Scawby, it seems improbable that the water which moved fairly rapidly out of the profile after these events, did so by vertical drainage. Lateral movement to a stream, a springline, or a point where the water could percolate vertically seems probable. In the first two cases, drainage from the profile would not equate with recharge to the aquifer.

The soil water balance calculations provided further insight into the cause of the marked increases in water content. At both sites the rainfall in the period preceding these events was, almost always, insufficient to account for the increase in soil water content. For example, at Redbourne, 43.5 mm of rainfall was recorded between the 12th and the 26th of March 1984. In the same period there was 11.4 mm of potential evaporation, leaving 32.1 mm to wet the soil profile. Yet, the soil profile water content increased by 70 mm. Some 38 mm of additional water is required to account for the disparity. It seems possible that it was supplied by lateral movement to the soil water measurement site, either over, or through the soil. In the following two weeks 48.5 mm of drainage was calculated.

At Scawby, over the same period in March 1984, the disparity between the measured rainfall and soil water content increase, after allowing for

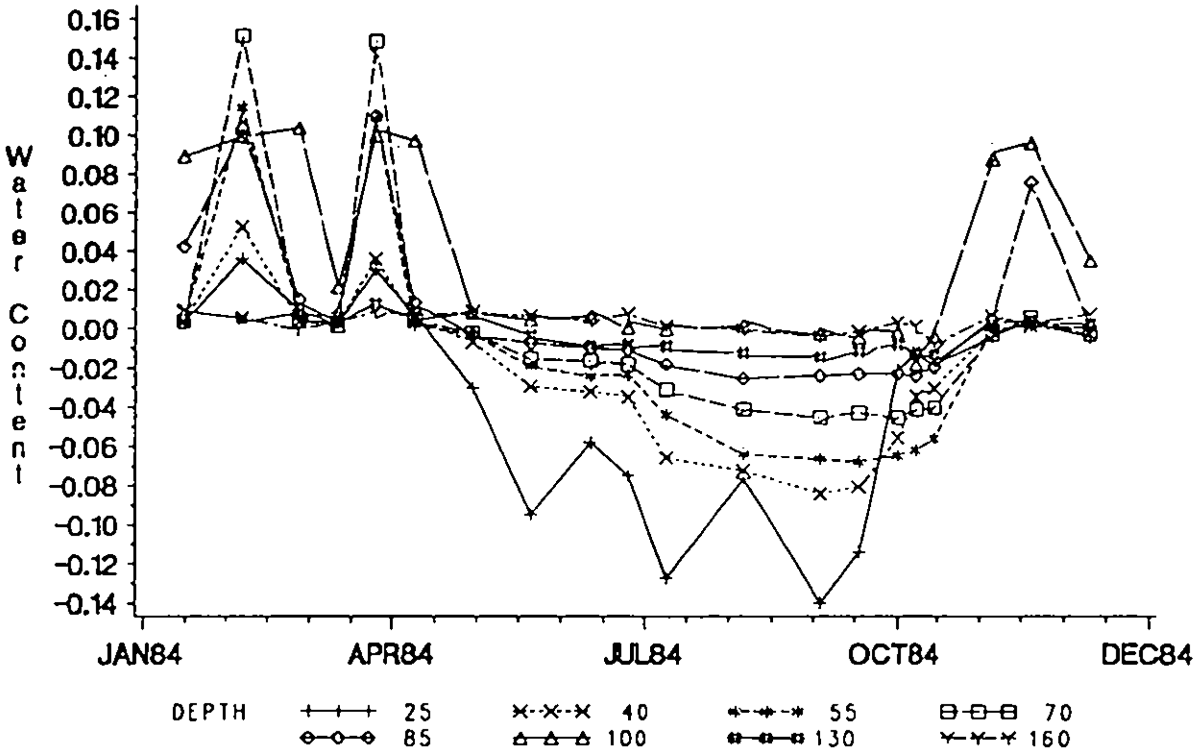

Fig. 19 Time series of soil water content change relative to the standard values for each measurement depth at Scawby in 1984.

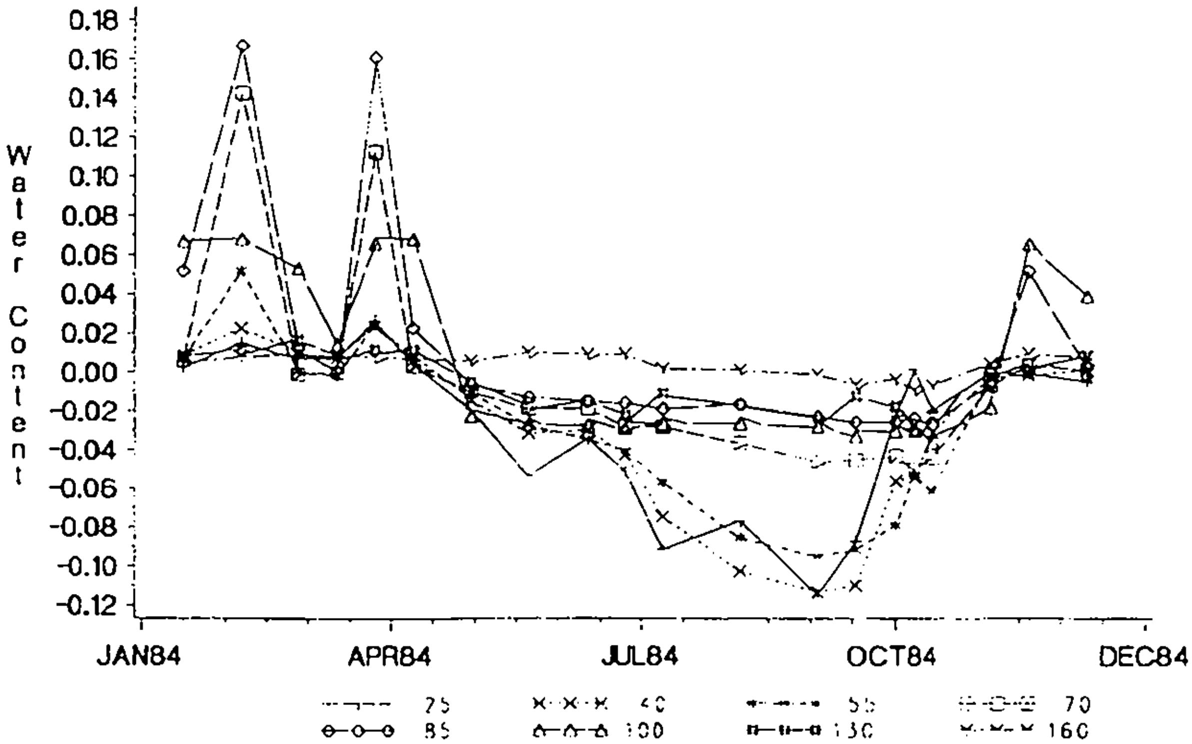

Fig. 20 Time series of soil water content change relative to the standard values for each measurement depth at Redbourne in 1984.

evaporation, was even greater, some 57 mm. Over the following two weeks 66 mm of drainage was calculated. The examples cited are the most extreme but several others occurred each year. Therefore it seems likely that in winter both sites were affected by lateral water fluxes, both into and away from the measured soil profiles.

In summer shallow ZFPs were identified quite readily at both sites. At Redbourne the ZFP usually attained a depth of 0.55 m but in 1985 and 1987 it reached 0.7 m. The ZFP reached 0.85 m in 1984 at Scawby but only 0.55 m in the following two years. Below the ZFP, the profile between 0.85 and 1.3 m, at each site apparently drains slowly, resulting in volumetric water content decreases of about 0.03 (Fig. 19, 20). The quantities of drainage involved are very small, on average 0.28 mm d^{-1} and 0.18 mm d^{-1} at Redbourne and Scawby respectively. Evidently the drainage process is very different from that described in the winter months. The soil at these depths is not saturated and therefore the water movement is unlikely to be lateral. It most probably occurs due to drainage to a slowly falling water table.

5.4.2 Water Balances

A water balance has been calculated for each of the Northern Limestone sites, although, as indicated in the foregoing discussion, the interpretation of the figures in terms of groundwater recharge is problematic. The results are listed in Table 11.

The data for Scawby in 1985 are not considered to be very reliable. A ZFP was observed on only three measurement occasions during the wet summer. Thus much of the water balance was calculated using potential evaporation rates rather than independently determined rates. This resulted in negative drainage of 72 mm between mid-June and late October being calculated. If the actual 1985 drainage estimate of 60 mm is increased by 72 mm, the 132 mm total is of the same order as that for Redbourne (138 mm).

MORECS potential evaporation estimates for grid square 108, in which Redbourne was located, were greater by 12 to 24 mm a^{-1} than for square 100 in which Scawby was sited. There was more rainfall at Scawby than Redbourne however. Given these differences in input to the water balance calculation for the sites and the likelihood of lateral water movement into/away from them, the drainage results were not expected to be similar. However in 1984 the calculated drainage at both sites was almost identical (Table 11).

5.4.3 Recharge to the Northern Limestone

There is insufficient evidence available to determine whether net drainage from these sites (i.e. allowing for lateral movements of water) should be regarded wholly as recharge to the aquifer, or whether some of it flows to springs or streams. If the possibility that some of the drainage appears as surface water can be discounted, then, despite the evidence for lateral water

Table 11 Water Balance results for the Northern Limestone

YEAR	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm	DRAINAGE/ RAINFALL %
REDBOURNE						
1983a	25	532	549	464	42	8
1984	20	589	603	436	167	28
1985	19	673	576	501	138	20
1986	21	683	611	534	166	24
1987	21	702	546	498	227	38
MEAN (1984-1987)		662	384	492	175	26
REDBOURNE (recalculated over shorter period)						
1984b		564	593	426	150	27
1985		672	576	501	138	20
1986c		630	599	522	157	25
MEAN (1984-1986)		643	610	500	155	24
SCAWBY						
1984b	20	581	587	446	151	26
1985	18	646	565	548	60	9
1986c	20	594	575	512	110	19
MEAN (1984-1986)		628	596	519	111	18

a From 1st March 1983
b From 16th January 1984
c To 6th December 1986

movement, the mean drainage value might be regarded as a guide to recharge amounts and in particular, the timing of recharge at these locations, though not for the aquifer as a whole.

5.5 NORTHERN CHALK

5.5.1 Sites, soil water behaviour and ZFPs

The site at Normanby le Wold was located close to the edge of the chalk escarpment whilst Croxby was about 7 km to the east on a west facing chalk slope. Both sites were grassed. Soil water data were available from November 1982 from Croxby, and these included tensiometer and gypsum block measurements. Monitoring commenced in March 1983 at Normanby.

Shallow rendzina soils, about 0.4 m deep, were described at both sites. Below this, weathered chalk was reported at Normanby which was "hard" at 1.3 m although softer chalk occurred at about 1.6 m. At Croxby a crumbly marly band was observed in the chalk between about 0.9 and 1.6 m depth.

Croxby

The water content time series plot for Croxby (Fig. 21) displays a very regular seasonal pattern. The dry summer of 1983 appears to have resulted in more soil drying above 0.6 m depth then in other years, but had little impact on the lower part of the profile. In the summer of 1987, the upper 0.3 m of the profile remained distinctly wetter than in other years. The water content of the weathered chalk at the base of the profile remained at about 0.3 throughout the year. At 1.3 m the silt marl band appears to have been distinctly wetter than the chalk above and below.

The tensiometer measurements at Croxby indicate that total potentials remained high at 2 and 3 m all summer i.e. the chalk at that depth was almost saturated, and in winter it was saturated. The gypsum blocks also recorded high potential at these depths. This is a very different situation to that observed at other chalk sites where potentials fall markedly during the summer months (Gardner *et al.*, 1990). In general, the hydraulic potential profiles recorded by the gypsum blocks pivoted about the data from the block at 0.7 m depth (Fig. 22). It may have been producing satisfactory data, but the combination of it and the block at 1.0 m is difficult to decipher. In 1983, the apparent fall in potential at 1.0 m has been ignored in determining ZFP depths, in view of the measurements recorded on 22nd August, (Fig. 22). The gypsum block derived ZFP depths shown in Fig. 7 for 1984 are very tentative but coincide quite well with those derived from the neutron probe data, which indicate that a ZFP fell to 1.6 m in late summer i.e. lower than in the rather drier summer of 1983. The tensiometers showed the development of a ZFP in the first part of the summer in both 1983 (Fig. 23) and 1984 but thereafter it was necessary to rely on interpretation of the neutron probe data as the data from the tensiometers above 2.0 m was incomprehensible.

In the subsequent wetter years of 1985, 1986 and 1987 the ZFP was almost as persistent; it was found to have been neutralised on only one occasion each summer and to have been re-established within two or three weeks. In 1987 for example, rainfall caused re-wetting of the upper part of the profile on several occasions during the summer yet it seems fairly clear that below this, the ZFP continued falling and reached 1.6 m at the beginning of October (Fig. 24).

Normanby le Wold

The pattern of ZFP development was rather different at Normanby le Wold. Plant abstraction of soil water apparently extended only to between 0.7 m and 1.0 m depth. The determination of the ZFP depths for 1983 from the neutron probe data was described in detail in section 4.1. In that year the maximum ZFP depth achieved was 0.7 m; in 1985 and 1987 it briefly attained 0.85 m depth and in 1984 and 1986 it reached 1.0 m. The shallower ZFPs were more readily destroyed by rainfall than at the Croxby site, and consequently the ZFP periods for this site were rather shorter. As discussed in section 4.1, there were small decreases in water content in the profile below the ZFP, due to drainage, in summer 1983 followed by a period in autumn of no drainage as the soil wetted up. This pattern of events was repeated in the following years.

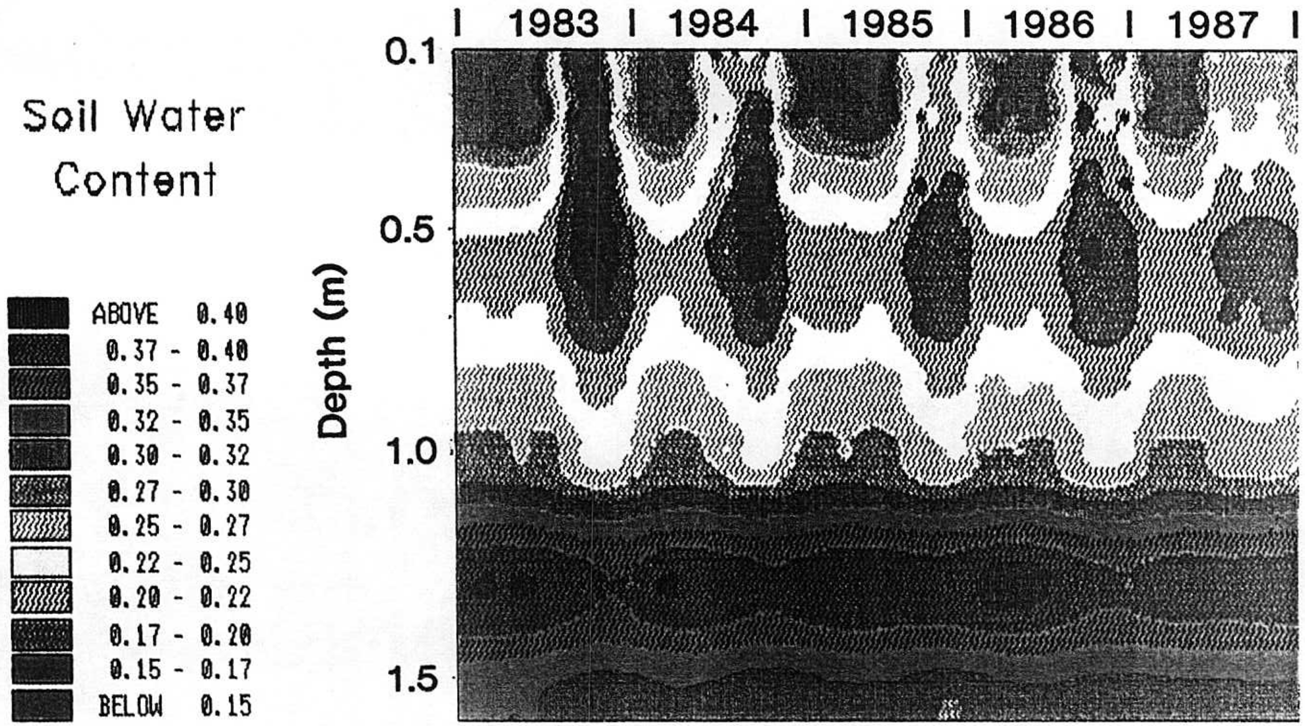

Fig. 21 Soil water content time series for Croxby, 1983 to 1987 inclusive.

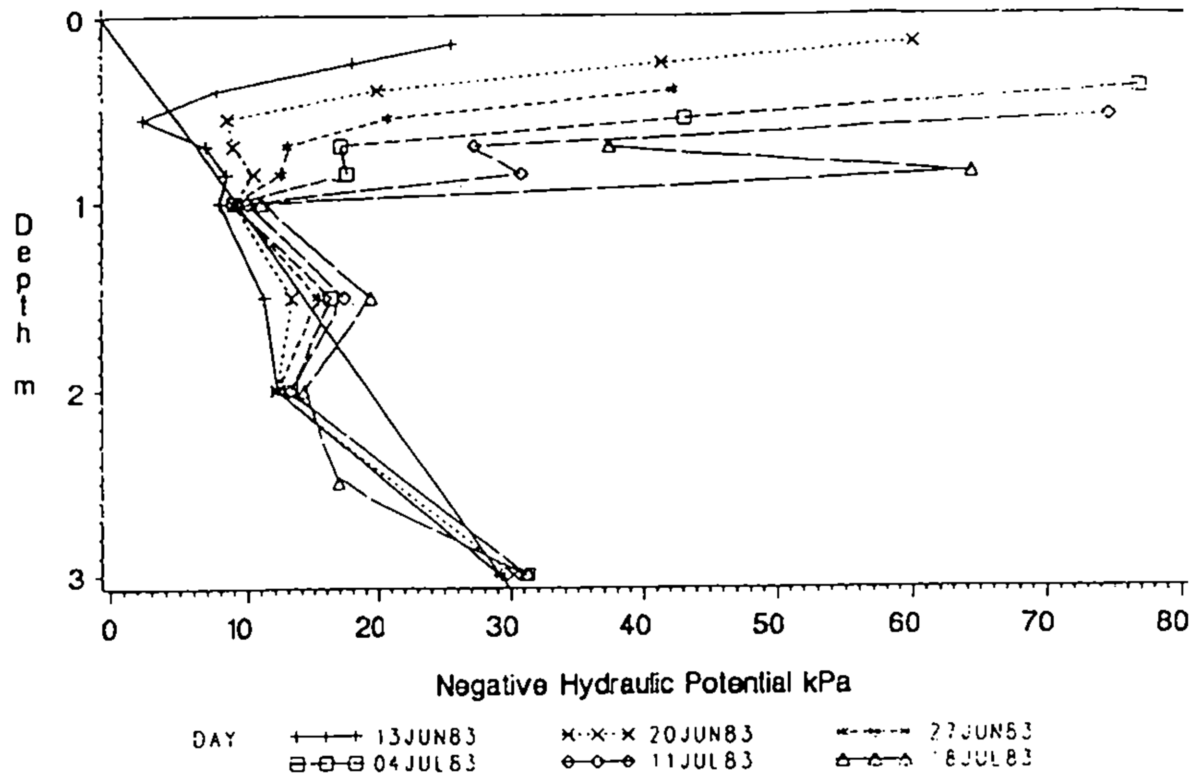

Fig. 22 Tensiometer soil water potential data, recorded at Croxby between 13th June and 18th July 1983.

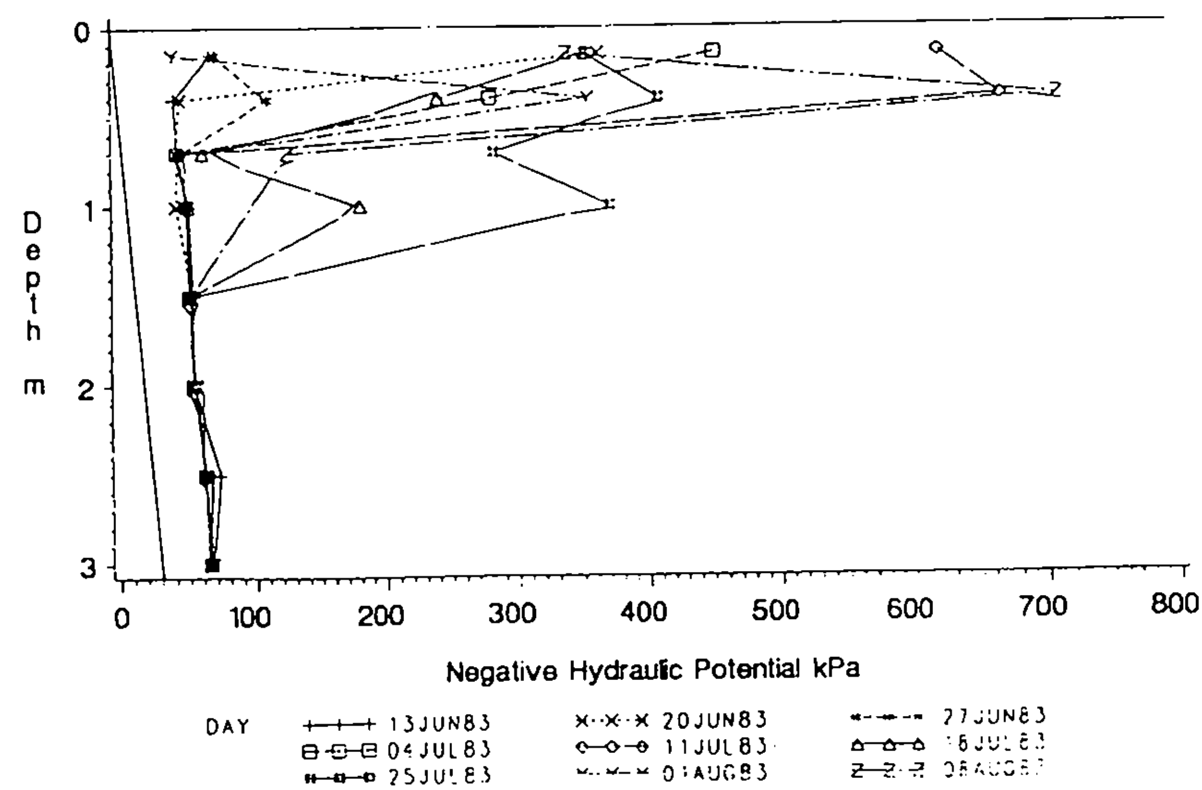

Fig. 23 Gypsum block soil water potential data recorded at Croxby between 13th June and 8th August 1983.

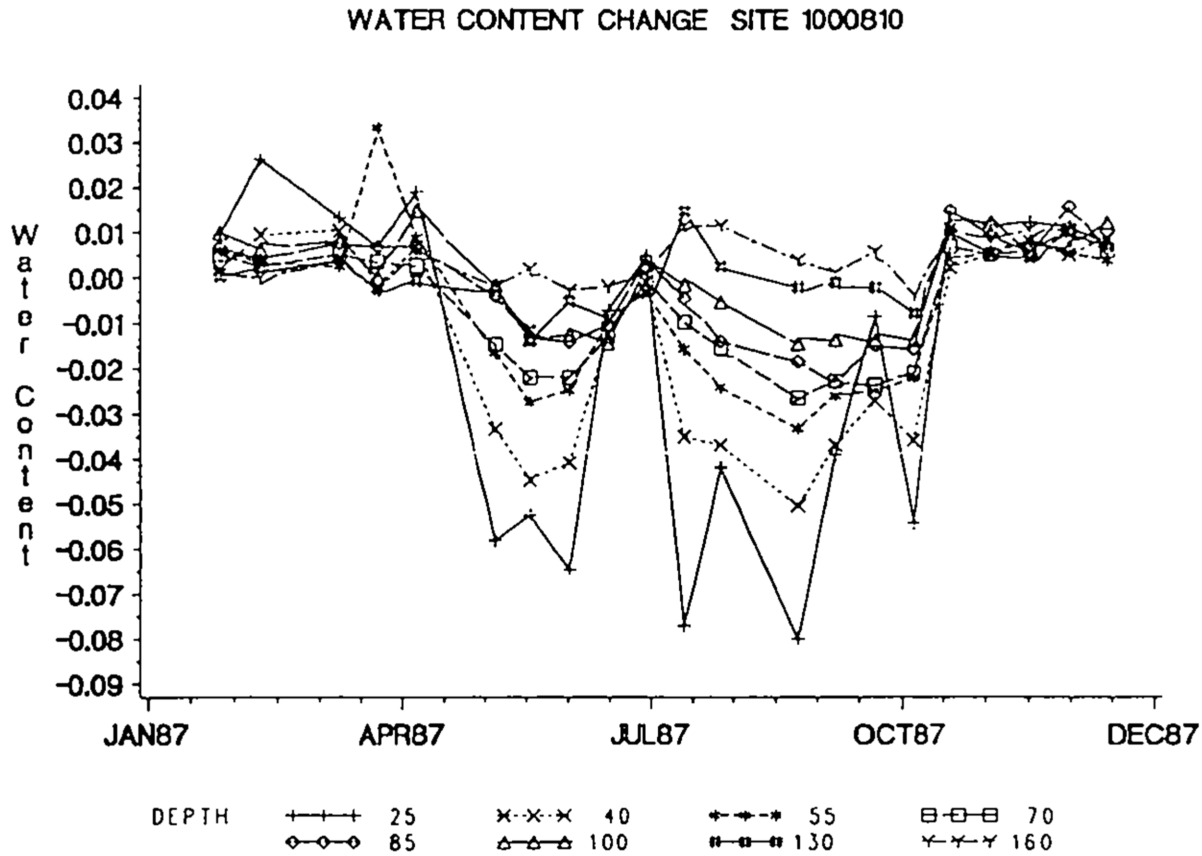

Fig. 24 Time series of soil water content change relative to the standard values for each measurement depth at Croxby in 1987.

5.5.2 Water Balances

Both sites were located in MORECS grid square 109 and hence the same potential evaporation estimate was input to each water balance. Rainfall at the two sites differed by about 37 mm a^{-1} over the measurement period of March 1983 to December 1987, more rainfall always occurring at Croxby. The average difference of 40 mm a^{-1} in the drainage results, greater drainage being estimated for Croxby, can therefore be accounted for by the difference in rainfall (Table 12). If the data for 1985 are excluded, the corresponding rainfall and drainage difference figures are both the same, 46 mm a^{-1}, little different to those for the five year period.

Table 12 Water Balance results for the Northern Chalk

YEAR	NO OF READINGS	RAINFALL mm a^{-1}	EVAPORATION POTENTIAL mm a^{-1}	EVAPORATION ACTUAL mm a^{-1}	DRAINAGE mm a^{-1}	DRAINAGE/ RAINFALL %
CROXBY						
1983		543	541	411	134	25
1984	19	657	585	480	182	28
1985	18	618	570	520	100	16
1986	22	742	610	542	206	28
1987	21	674	551	473	194	29
MEAN (1984-1987)		673	579	504	170	25
NORMANDY LE WOLD						
1983a	25	468	541	406	65	14
1984	20	604	585	475	133	22
1985	19	610	570	526	79	13
1986	20	710	610	505	215	30
1987	21	660	551	525	128	19
MEAN (1984-1987)		646	579	508	139	22

a Totals Calculated From 1st March 1983

Figs. 25 and 26 show the water balance results for 1984 from each site, plotted cumulatively. For Croxby, long intervals in the neutron probe data in May and June meant that potential evaporation rates were used in the water balance causing a negative drainage estimate of some 30 mm. Drainage at Normanby was probably underestimated by a similar quantity for negative drainage was calculated after the end of the ZFP period.

Whilst differences in rainfall quantity are evidently a determining factor in the drainage difference between the sites, the soils at each are important in determining the distribution of drainage during the year. At Normanby le Wold, in summer, the ZFP was shallower and usually less persistent than at Croxby. Over the five year measurement period there were only 391 ZFP

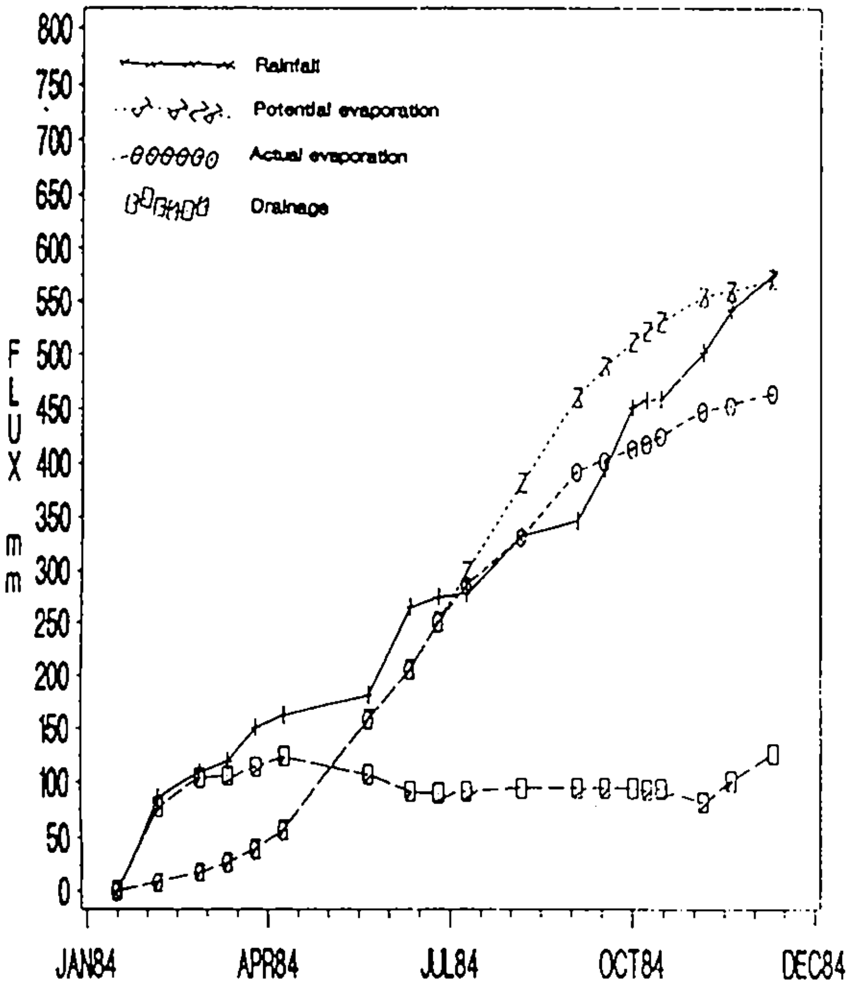

Fig. 25 *The cumulative values for the 1984 water balance components for Croxby.*

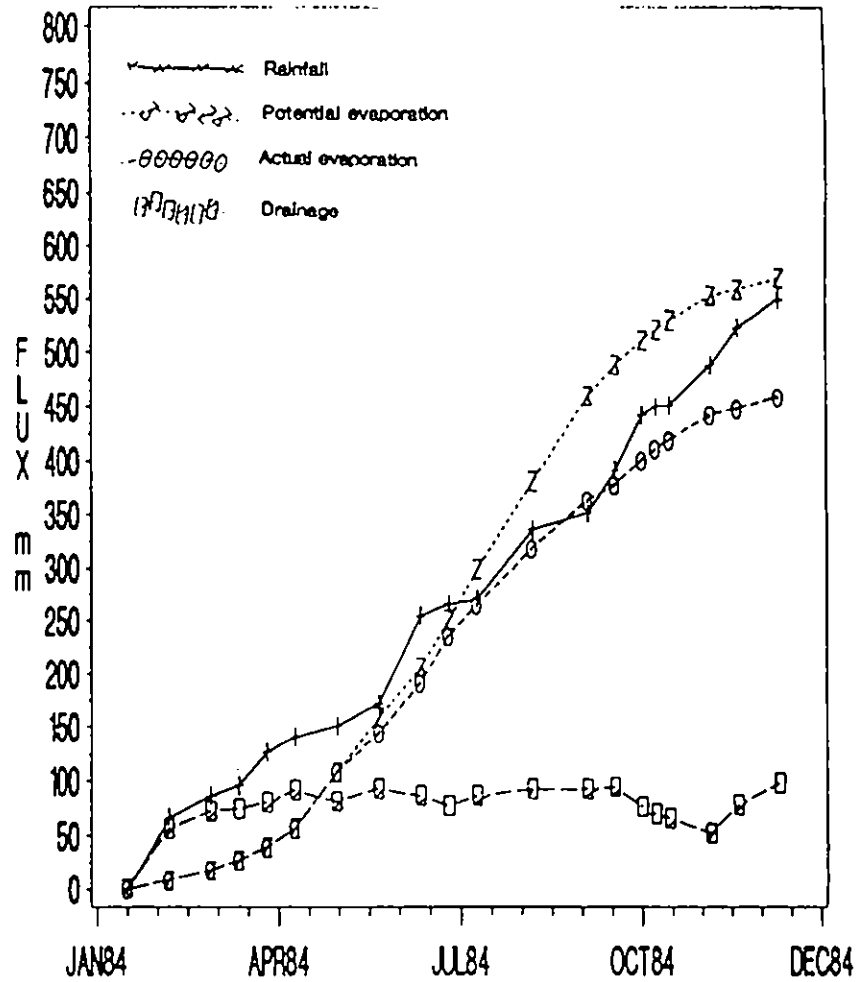

Fig. 26 *The cumulative values of the 1984 water balance components for Normanby le Wold.*

days at Normanby, compared with 566 days at Croxby. However drainage during the ZFP periods amounted to 106 mm at Normanby, 17% of the total recorded. During the longer ZFP periods at Croxby, only 43 mm drainage occurred, 5% of the total drainage. Thus, whilst drainage essentially ceases entirely in summer at Croxby, summer drainage is an important component of the water balance at Normanby.

The ZFP depth data for Normanby le Wold in 1983 and 1984 are a little tentative. The ZFP may have descended further in both years. Recalculation of the water balance for the site in those years, assuming that the ZFP does eventually reach the base of the profile, 1.6 m, produces an increase of only 17 mm in 1983 and 6 mm in 1984 in calculated drainage. The water balance calculations for 1985 are considered to be satisfactory for Croxby as there was a persistent ZFP for much of the summer. At Normanby a ZFP was present for shorter periods during this year and so potential evaporation had to be relied upon for a large part of the time when it may well have been inappropriate.

5.5.3 Recharge to the Northern Chalk

There is nothing in the information and the soil water data provided for the two sites on this aquifer outcrop to indicate that drainage fluxes from the profile do not ultimately form recharge at the water table below. Mean annual drainage rates vary from 142 to 188 mm a^{-1} (4 year mean excluding 1985 data) at the two sites and so it can be assumed that aquifer recharge averages about 165 mm a^{-1} below grassed parts of the aquifer. No data is available for arable areas on the Lincolnshire chalk. However, evidence from paired arable and grassed plots on chalk in Cambridgeshire and Hampshire indicates that arable cultivation has little impact on drainage fluxes (Wellings, 1984: Cooper, 1987). Thus it is probably reasonable to regard the figure of 165 mm a^{-1} as representative of the aquifer as a whole.

5.6 SOUTHERN CHALK

5.6.1 Sites, soil water behaviour and ZFPs

Three sites were located on the Southern Chalk outcrop; Ulceby Cross which was set up in 1974; Driby, some 3 km to the north-west, which was established at the same time, and Claxby, about 4 km south-east of Ulceby Cross, where measurements commenced in spring 1984. At the Ulceby Cross and Claxby sites chalk soils were described; weathered chalk was encountered at about 0.5 m and 0.3 m depth respectively. Hard chalk occurred below 0.8 m depth at Claxby. The chalk was covered by drift described as "boulder clay" at the Driby site. A 0.2 m loam top soil, becoming more sandy with depth, was reported over boulder clay with bands of coarse chalk rubble in a clay matrix and pockets of sand and gravel. The description does not indicate the depth of the drift but it was more than 1.6 m, i.e. the maximum depth of the neutron probe readings. Table 13 lists the standard volumetric water contents determined for these three sites. The values for the Claxby site are notably less than for Ulceby Cross whilst those for Driby are greater by 0.05 or more at most depths.

Table 13 Standard volumetric water contents

Depth (m)	Ulceby	Claxby	Driby
0.10	0.343	.294	0.371
0.25	0.346	.274	0.389
0.40	0.324	.286	0.325
0.55	0.303	.304	0.321
0.70	0.302	.252	0.354
0.85	0.315	.266	0.352
1.0	0.307	.264	0.355
1.3	0.286	.250	0.336
1.6	0.305	.255	0.321

Ulceby Cross

All three sites were under grass throughout the monitoring period. Tensiometers and gypsum blocks were installed at Ulceby Cross in 1983. An "old" and a "new" site are marked on the site plan, the new one being at a greater distance from the reservoir bank. However, there was no indication as to when the site was moved. The early neutron probe data, 1973 to late 1981, only includes readings to 1.3 m depth. Thereafter there is in addition data for 1.6 m depth. It is probable that this change coincided with the move of the site. For the purposes of the analysis here, in the absence of data specifically for 1.6 m depth, the measurements at 1.3 m have been assumed to apply at 1.6 m.

The soil water content time series for Ulceby (Fig. 27) show that summer drying of the profile had little impact below 0.7 m depth, even in the dry summer of 1976. Reasonable tensiometer data were available for summer 1983 and showed the slow progress of a ZFP to 0.55 m depth on 4th July (Fig. 28) after which time the instruments ceased to function correctly. The gypsum block data for this year were good (Fig. 29) and indicate that the ZFP fell to 2 m. A convergent ZFP developed at 0.4 m on 22nd August, a consequence of rainfall in the previous two weeks. The profile wetted up quickly after 12th September.

The data sets collected from both types of instrumentation in 1984 were difficult to understand. It appears that the maximum ZFP depth may have been only 0.95 m in this year.

The ZFP depth data determined from the neutron probe measurements correspond fairly well with the soil water potential data in these two years

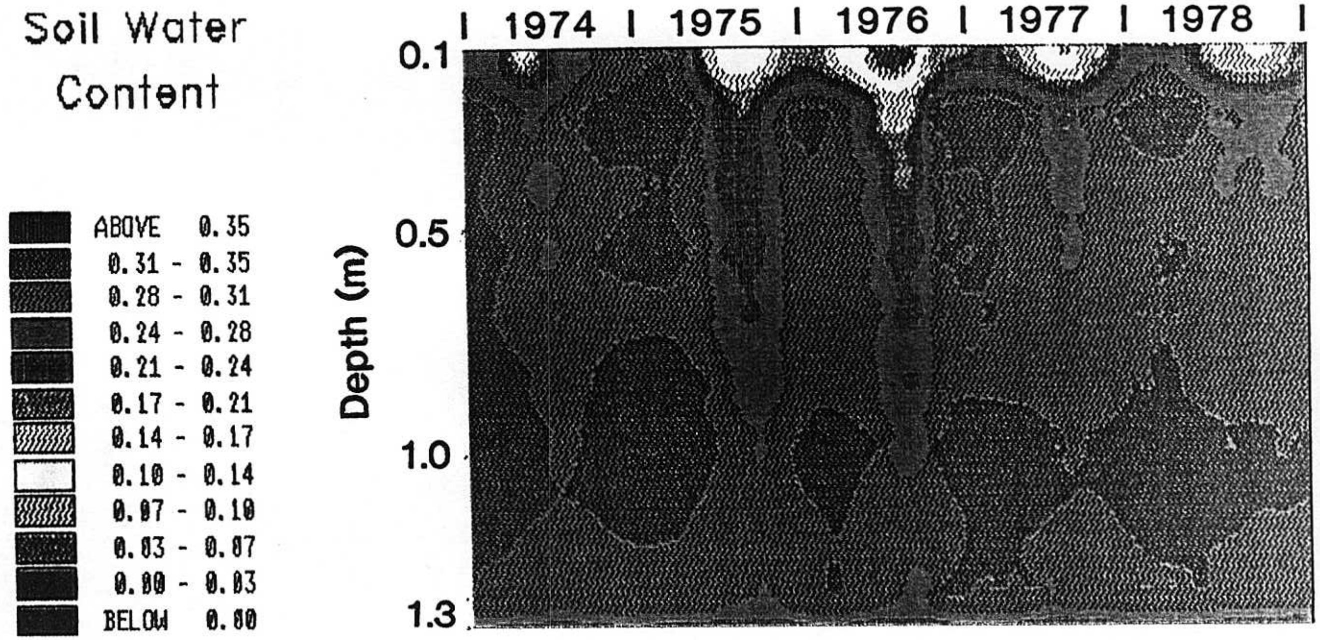

Fig. 27 Soil water content time series for Ulceby Cross, 1974 to 1978 inclusive.

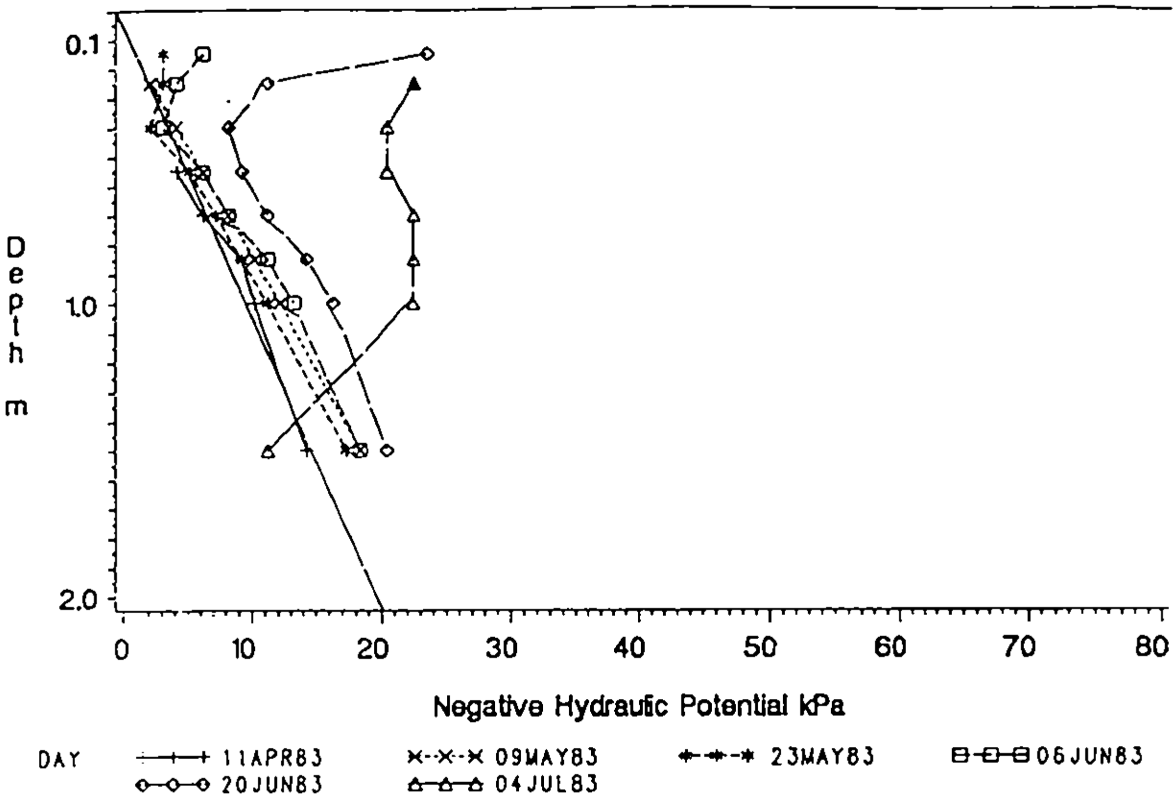

Fig. 28 Tensiometer measurements of soil water potential at Ulceby Cross between 11th April and 4th July 1983.

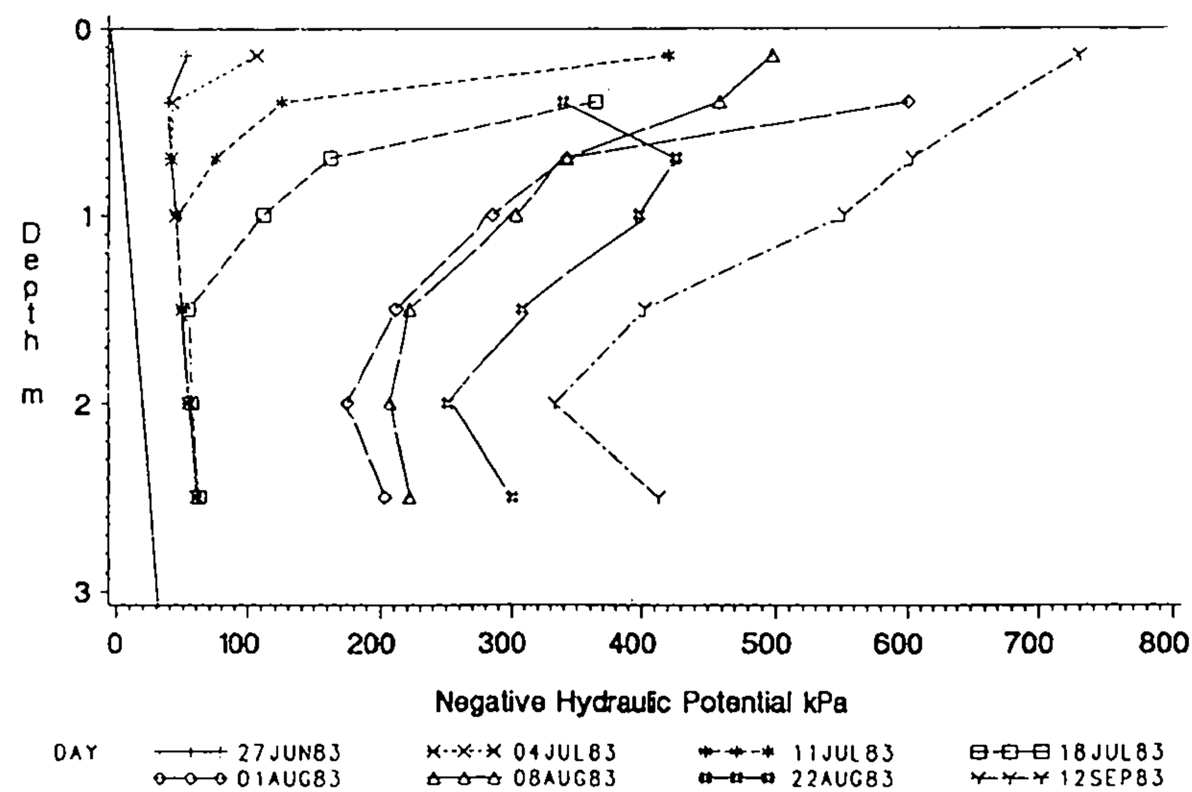

Fig. 29 Gypsum block measurements of soil water potential at Ulceby Cross between 27th June and 12th September 1983.

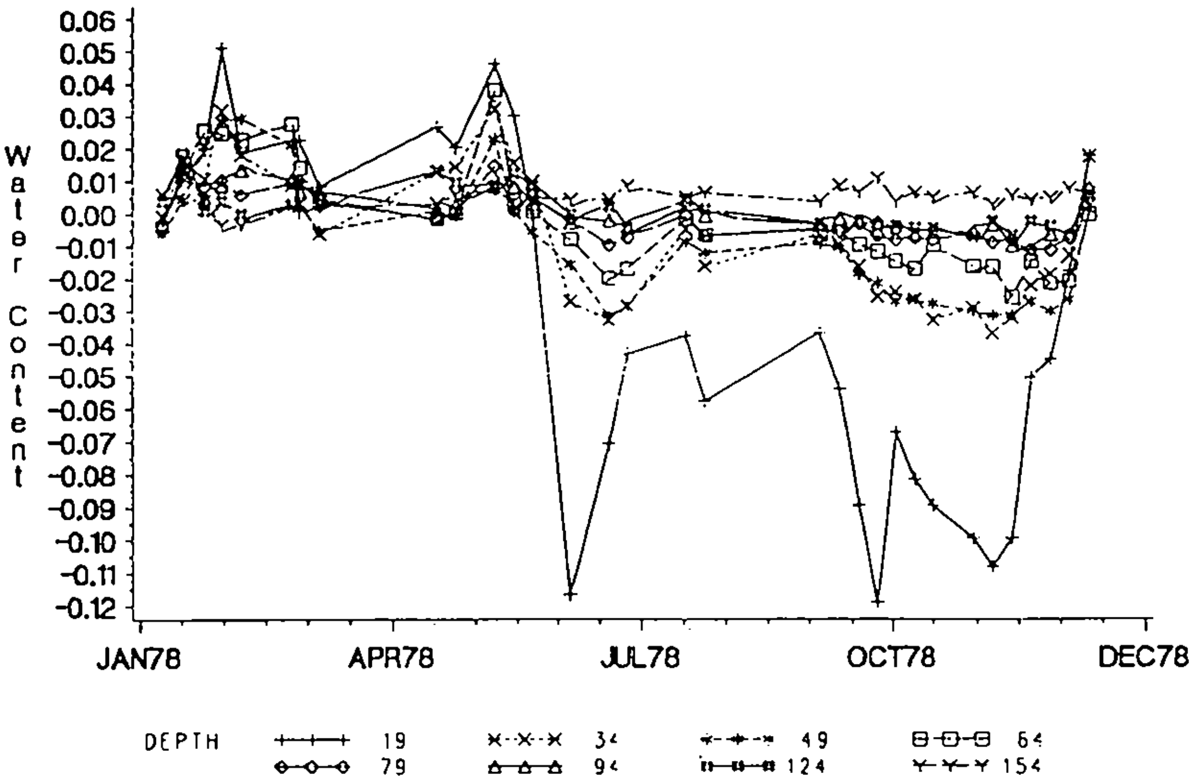

Fig. 30 Time series of soil water content change relative to the standard values for each measurement depth at Driby in 1978.

(Fig. 7). The maximum ZFP depth estimated for other years from the probe measurements was variable; it eventually reached the base of the profile in only some years.

Claxby

At Claxby, the other shallow soil site, the ZFP periods were generally shorter. It was notable that its progress through the profile in spring and early summer was more rapid than at Ulceby. It apparently reached the base of the measured profile in summer 1984 and 1986 but "stuck" at 1 m depth in 1985 and 1987.

Driby

The ZFP estimates for the drift covered chalk site at Driby are a contrast. The ZFP depth never exceeded 0.7 m depth during the thirteen years of measurement. Each summer the ZFP period was at most as long as that at the nearby non-drift sites. Below 0.6 m depth, volumetric water content changes were very small, as illustrated for 1978 in Fig. 30. In 1985 there was a seven week gap in the readings from late July. A ZFP was only observed on the two previous reading occasions, fourteen days apart.

5.6.2 Water Balances

Daily rainfall measurements from the Driby Pumping Station gauge were substituted for the rainfall data provided for the years 1974 to 1982 inclusive, for the Ulceby Cross and Driby sites due to doubts about the data provided (see section 2.1). This resulted in an increase of more than 550 mm in the rainfall total used in the water balance calculations for that period. The water balance results are shown in Table 14.

Ulceby Cross

Table 14 shows that annual soil drainage amounts at the Ulceby site can vary by a factor of more than two, from 126 mm in 1985 to 344 mm in 1980. (The water balance for 1985 was considered satisfactory.) The small drainage total for 1985 thus reflects the wet summer of that year, which caused evaporation at close to the potential rate, and relatively low annual total rainfall amount. In 1980, most of the drainage took place during the winter months (Fig. 31). The summer was quite wet and a ZFP was only present intermittently for the latter part of June, early July, and the whole of August. However, the measurements were weekly and little negative drainage was calculated. Thus, the water balance is believed to be a reasonable representation of the soil water fluxes on throughout those periods.

It is noteworthy that in 1978 and 1979, when total rainfall and actual evaporation amounts were similar to those in 1980, drainage was only 262 and 250 mm respectively. Both years were much drier in the autumn than was the case in 1980 and so it was not until the end of each year that rainfall was sufficient to cause any substantial drainage. In 1980, drainage resumed in October, the soil profile having been thoroughly rewetted by that time.

In 1975 and 1976 drainage amounts were small relative to the mean for this site (161 and 169 mm a^{-1} respectively compared with 217 mm a^{-1}) but still greater than in 1985. The principal contrast between 1975 and 1976 are in the actual evaporation figures which show that there was some 70 mm less evaporation in 1976 than in the preceding year, although the potential evaporation increased by 30 mm. During spring and summer of 1976 soil water use by the grass crop was seriously constrained by the drought conditions.

Claxby

The three complete years of data for Claxby (Table 14), indicate that year to year variation in drainage from this site is again large. The small, 101 mm, total for 1987, only a third of the total for 1986, arises in part due to some negative drainage estimates in the summer months, when there was no ZFP. The water balance for 1985 is considered satisfactory, given the available data; there were intervals of three weeks in the data but a ZFP was present throughout. Drainage in 1986 was more than 150 mm greater than in 1985, accounted for by over 200 mm extra rainfall, which also increased evaporation.

The mean drainage figure of 196 mm a^{-1} for the years 1985 to 1987 may be an underestimate in view of the 1987 summer data. However it is very similar to that for Ulceby Cross, 187 mm a^{-1}.

Driby

The water balance results for this site are believed to reflect fluxes in the soil well except in 1985 and 1987. Small negative drainage amounts were occasionally computed, particularly near the end of ZFP periods, but were insignificant relative to annual totals. Fig. 32 shows the results for 1980.

The small figure for annual drainage from this site in 1985 is considered to be an underestimate for, as described above (section 5.6.1) only one ZFP period was observed and so the water balance calculation relied on use of the potential evaporation data for almost all of the summer resulting in large negative evaporation estimates of 48.6 mm between July and October. Similarly in summer 1987, when, but for a 28 day period in May and June, potential evaporation rates were assumed in the water balance, 59.4 mm of negative drainage were calculated.

The annual quantities of soil water drainage, and the changes through time, are very similar to those computed for Ulceby Cross, except in 1983 and 1984 when 60 mm more drainage occurred at the former site. In fact, the two sites are located in different MORECS grid squares and hence the potential evaporation estimates for the Ulceby Cross site (square 110) are a little greater than those for Driby (square 109). Despite this, the mean annual drainage values for the period 1975 to 1987, excluding 1981 and 1982, are 216 mm for Ulceby and 209 mm for Driby.

This difference is small compared with the results from paired chalk soil and drift covered chalk sites near Cambridge. Cooper *et al.*, (1990) found that the presence of drift led to an increase of 95 mm a^{-1} in drainage quantities, and a different distribution of drainage through the year, summer drainage

Table 14 Water Balance results for the Southern Chalk Sites

YEAR	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm	DRAINAGE/ RAINFALL %
ULCEBY						
1974	28	722	619	492	228	32
1975	30	609	640	466	161	26
1976	32	572	670	396	169	30
1977	49	713	593	507	203	29
1978	33	774	555	510	262	34
1979	31	761	595	510	250	33
1980	37	769	596	511	344	45
1981a	21	416	276	254	218	52
1982b	40	692	605	525	159	23
1983	33	658	576	440	218	33
1984	19	693	607	493	208	30
1985	17	667	589	542	126	19
1986	21	744	634	517	231	31
1987	21	758	576	543	203	27
MEAN (1974-1987 excluding 1981 and 1982)		718	604	494	217	30

a No measurement from 29th June until 4th January 1982
b From 4th January to 6th December 1982

YEAR	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm	DRAINAGE/ RAINFALL %
CLAXBY						
1984a	15	449	537	410	43	10
1985	16	643	590	485	156	24
1986	22	834	634	513	331	40
1987	21	614	569	508	101	16
MEAN (1985-1987)		697	598	502	196	28

a From 9th April 1984

YEAR	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm	DRAINAGE/ RAINFALL %
DRIBY						
1975	29	617	611	491	152	25
1976	30	582	654	406	150	26
1977	50	699	579	478	229	33
1978	33	768	536	498	260	34
1979	30	772	570	483	286	37
1980	39	843	563	475	369	44
1981	43	775	596	523	243	31
1982	38	737	599	498	253	34
1983	33	664	559	494	155	25
1984	18	692	585	546	148	21
1985	17	547	572	556	87	13
1986	19	797	611	546	252	32
1987	21	751	551	534	209	28
MEAN (1975-1987)		719	584	502	215	30

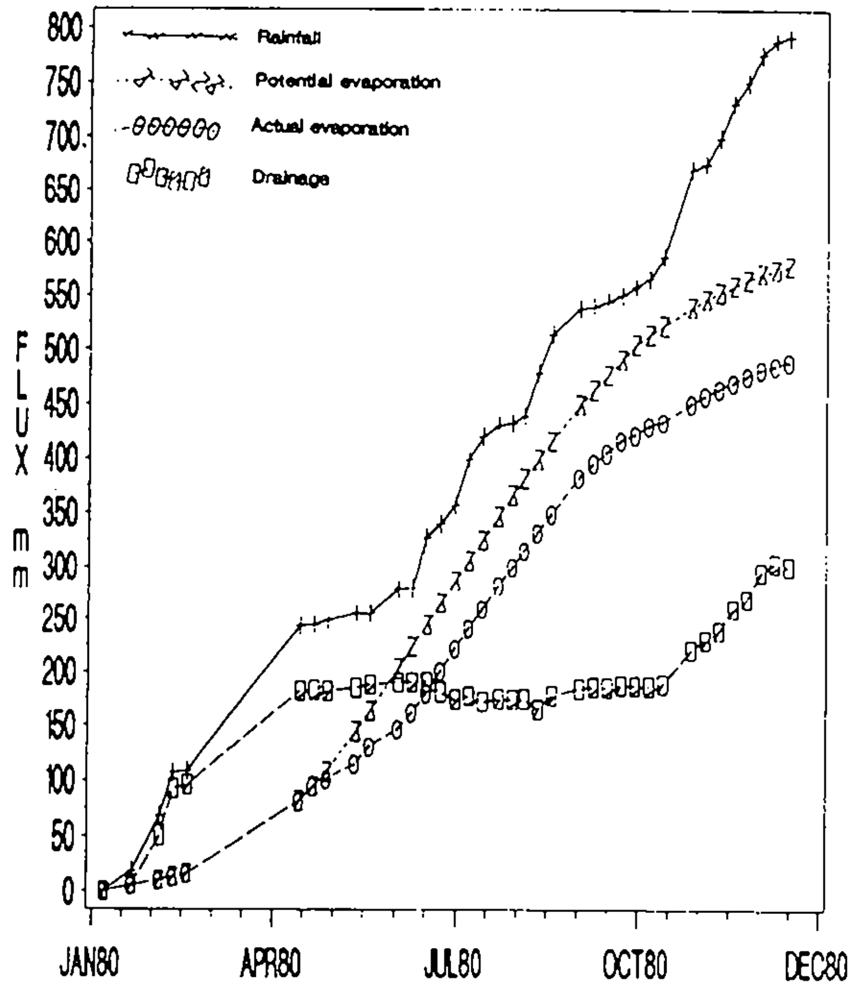

Fig. 31 The cumulative values of the 1980 water balance components for Ulceby Cross

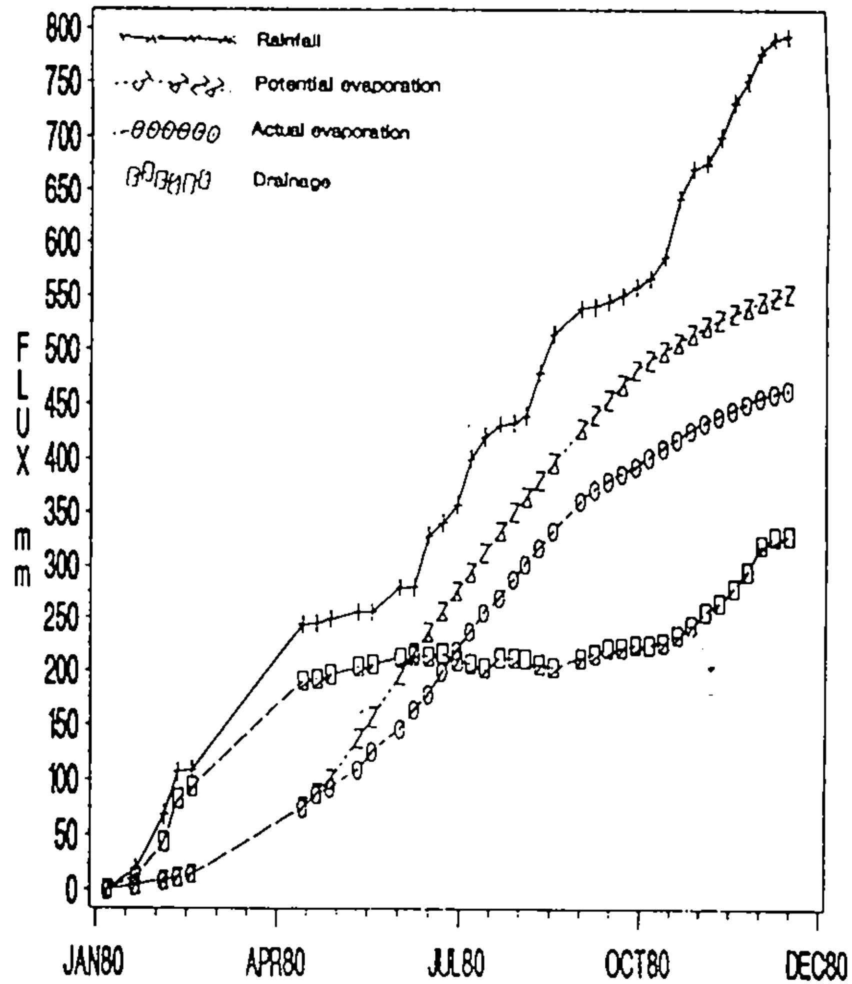

Fig. 32 The cumulative values of the 1980 water balance components for Driby

being much more important. At these two Lincolnshire sites, some difference in the drainage distribution is apparent (Figs. 31, 32). Over the measurement period as a whole, 9% of the drainage at Driby occurred whilst there was a ZFP. The corresponding percentage for Ulceby was 6%. However, as the ZFP periods at Driby tended to be shorter and more intermittent, there were more opportunities for through drainage during the summer months.

5.6.3 Recharge to the Southern Chalk

The water balance calculations have demonstrated that, drainage fluxes from these three sites are very similar (Table 15). There was no evidence, even from the drift covered site, to suggest that soil drainage losses did not percolate vertically downwards towards the groundwater table. Therefore, it can be assumed that the drainage estimates are a good indicator of aquifer recharge. The long term mean annual recharge averages 212 mm a^{-1} between the Driby and Ulceby sites. From the evidence available it seems appropriate to extrapolate this figure to the aquifer as a whole, regardless of drift cover. However, the drift at Driby is apparently quite coarse textured, bands of chalk rubble being incorporated within the boulder clay at shallow depth suggesting that it may not be very deep. A deeper, dense boulder clay drift over chalk might behave differently as was found in Cambridgeshire (Cooper *et al.*, 1990).

Table 15 Water blalance results for the Southern Chalk

SITE	RAINFALL mm a^{-1}	EVAPORATION POTENTIAL mm a^{-1}	EVAPORATION ACTUAL mm a^{-1}	DRAINAGE mm a^{-1}
1983 to 1987 excluding 1981 & 1982				
Ulceby	701	603	494	216
Driby[a] (Drift covered)	712	581	456	209
1985 to 1987				
Ulceby	723	600	534	187
Driby[a]	732	578	545	183
Claxby	697	598	502	196

a Includes negative drainage estimates for 1985

5.7 SPILSBY SANDSTONE

5.7.1 Sites, soil water behaviour and ZFPs

The Spilsby Sandstone site was located at Tetford in a paddock of permanent grass. The soil is described as "sandy soil" above 0.8 m, the uppermost 0.3 m being more loamy. However, below 0.8 m, the soil/parent material is called a sandy loam due to the presence of more "silt and loam". It has been reported (P. Rippon, Pers. Commun.) that there is a perched water table at this site at between 0.6 and 2 m depth.

At 1.3 m and below, water content change was minimal throughout the 5 year period. At 1 m depth, changes were slightly larger and it is probable that in most summers, plant abstraction of soil water extended ultimately to this depth i.e. the ZFP reached 1 m depth.

However, the analysis of the water content time series to determine the ZFP depths was not without ambiguity. The maximum depth achieved by the ZFP may have been only 0.85 m. During the winter months it is notable that at 0.40, 0.55 and 0.70 m depth very marked but ephemeral increases in water content were recorded on several occasions. An example is February 6th 1984 when the volumetric water content increased by between 0.17 and 0.28 at these depths due to 98 mm of rainfall in the preceding three weeks Fig. 6. Three weeks later almost all of the water had been removed from the profile without causing any addition to soil water storage below 0.85 m depth. Similar events took place once in each of early 1985 and 1986, and twice in early 1987 (Fig. 33). This evidence, and the constancy of the water content on each of these occasions suggest strongly that the profile may be temporarily saturated to about 0.55 m depth.

The rapid removal of the relatively large quantity of water stored above 1 m during each of these events may arise as a result of several scenarios. In the absence of more information about this site, and the character of the Spilsby Sandstone, it is not possible to say which is the most probable.

If the layers at and below 1 m depth are saturated due to a perched water table, then water would be expected to move laterally to the edge of the outcrop of less permeable strata that is causing the perching. This could be at a spring line downslope from the site, or lateral movement could transmit the water directly to the River Lymn. Alternatively, on meeting more permeable strata, the water may infiltrate to the aquifer. It is also possible that the less permeable material below 1 m is fissured in places so that the water temporarily held above it can be transmitted directly to the aquifer.

5.7.2 Water Balance

The water balance data for this site have been calculated in two ways:

- assuming simply that all drainage from the profile, throughout the year, was recharge;

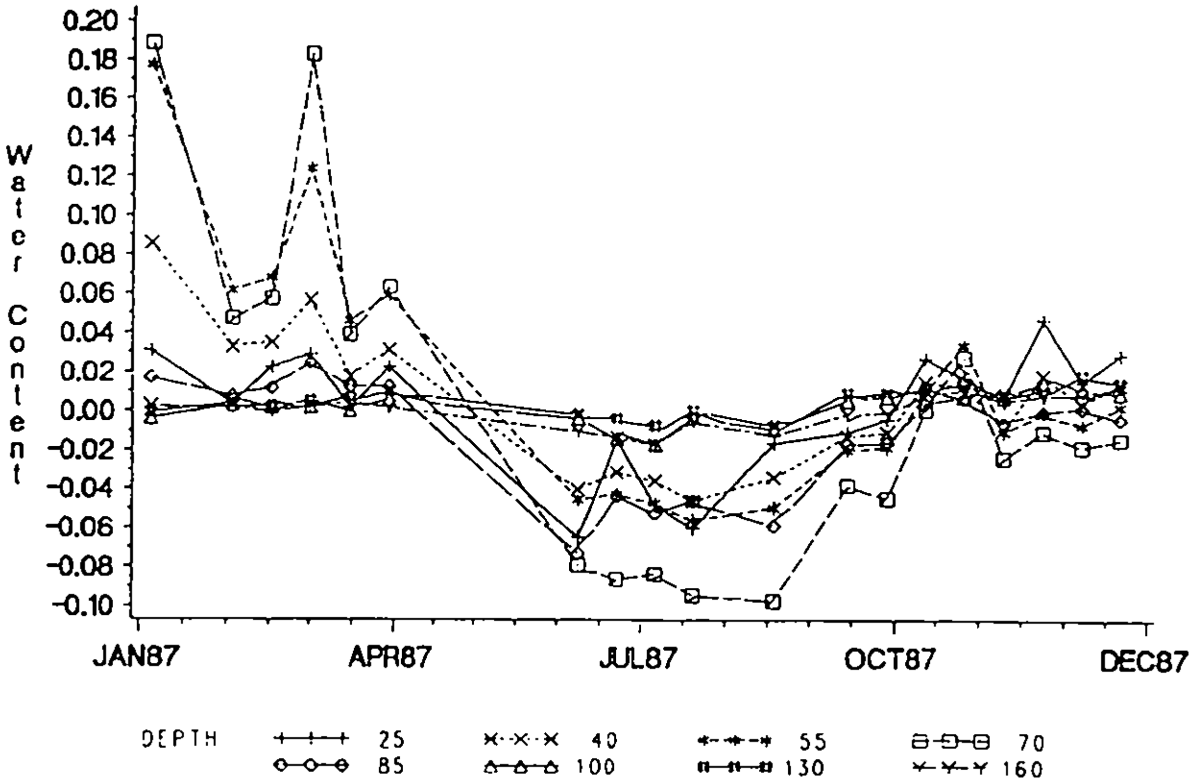

Fig. 33 Time series of soil water content change relative to the standard values for each measurement depth at Tetford in 1987.

assuming that the majority of the water removed from the profile after these events (i.e. all water above 0.85 m), moved laterally to the river. Thus this water has been excluded from the recharge calculation. Water content changes, other than evaporation, at other times, including decreases due to the apparent fall of the level of the perched water table, are assumed to have recharged the aquifer.

First, the water balance in which it was assumed that all soil drainage was recharge, was computed twice, using two alternative sets of ZFP data:

a. maximum ZFP depth of 0.85
b. maximum ZFP depth of 1.0 m.

The results of both computations are presented in Table 16. In fact the difference in terms of drainage at the site was only 3 mm over the five year measuring period. Increasing the ZFP depth increased the number of ZFP days from 414 to 568 over the 5 year period; i.e. from 23% to 31% of the total measurement period.

Table 16 Water Balance results for the Spilsby Sandstone site at Tetford

YEAR	NO OF READINGS	RAINFALL mm	EVAPORATION POTENTIAL mm	EVAPORATION ACTUAL mm	DRAINAGE mm	DRAINAGE/ RAINFALL %
MAXIMUM ZFP DEPTH 0.85 m						
1983	33	699	560	484	219	31
1984	18	700	584	506	192	27
1985	16	803	570	543	224	28
1986	20	776	614	584	215	28
1987	19	754	551	520	275	36
MEAN (1983-1987)		746	576	514	225	30
MAXIMUM ZFP DEPTH 1 m						
1983		699	560	464	239	34
1984		700	584	510	188	27
1985		803	570	546	221	28
1986		776	614	517	169	22
1987		754	551	503	292	39
MEAN (1983-1987)		746	576	521	222	30

For 1983 and 1987, 20 and 17 mm more drainage was calculated when the ZFP was assumed to fall to 1 m depth, rather than 0.85 m respectively; this represented less than 10% of the annual drainage total in both years. The increase in drainage arose because the alternative analysis of the ZFP depths resulted in longer ZFP periods and hence evaporation was assumed to have been at the potential rate for a shorter period of time.

For the intervening years, 1984, 1985 and 1986, the drainage total was larger when the ZFP depth was assumed not to have exceeded 0.85 m depth. In these years the impact of longer ZFP periods due to the deeper assumed ZFP was more than counterbalanced by the smaller amount of drainage from the base of the profile at those times when the ZFP depth was simply increased.

The five year mean annual drainage was 225 mm a^{-1} which represents 31% of the 746 mm a^{-1} mean rainfall. This proportion fluctuated from 27% in 1984 and 1986 to 39% in 1987, assuming that the ZFP reached 1 m depth, and by rather less if it was assumed that the maximum ZFP depth was only 0.85 mm.

The second calculation of the water balance for this site, in which water lost from the profile after extreme wetting events in winter, was assumed not to have recharged the aquifer, provided the results shown in Table 17. The analysis assume that the ZFP reached 1 m depth in summer.

In 1983, the upper part of the profile never wetted as dramatically as in other years. After rainfall there is evidence of redistribution of water through the soil and, in the main, moderate drainage fluxes. However, the 40 mm water loss which may have moved from the profile by lateral seepage averaged 5.8 mm d^{-1}, a faster rate than after some of the better defined events in succeeding years.

The recalculated mean annual recharge total is 125 mm a^{-1}, but fluctuating by 120 mm, from 80 mm a^{-1} to 200 mm a^{-1}, as much as in the alternative analysis.

Table 17 The alternative estimates of annual recharge totals for the Spilsby Sandstone

YEAR	ALL DRAINAGE = RECHARGE mm	WINTER LATERAL SEEPAGE mm	RECHARGE TOTALS mm
1983	239	40	199
1984	188	109	79
1985	221	138	83
1986	169	81	88
1987	292	114	178

5.7.3 Recharge to the Spilsby Sandstone

The site at Tetford was the only one on the Spilsby Sandstone outcrop. Without any indication of how representative it is of the outcrop, it is not possible to extrapolate the results to the outcrop as a whole. This is particularly so because of the uncertainty regarding how much of the water, which apparently drains from the profile during the winter months, recharges the aquifer below. There is, on average, almost 100 mm a^{-1} difference in the annual recharge total depending upon whether all drainage is regarded as recharge, or whether rapid drainage after winter water logging is excluded. It is feasible that even less of the winter drainage forms recharge. Possibly an analysis of the relationship between the soil water data and stream flow would provide a better basis on which to partition winter drainage into lateral seepage and recharge. Summer drainage quantities are small and probably do drain to the aquifer since the lower part of the profile is unsaturated at that time.

Conclusions

Soil water balances have been calculated for 18 of the 19 soil water measurements sites which are located on the Lincolnshire aquifer outcrops. This has been achieved by determining zero flux plane depths from neutron probe measurements and then using the combined zero flux plane / water balance method to calculate soil drainage. Where soil drainage is vertical, drainage fluxes from the base of the soil profile are a measure of recharge to the aquifer.

Zero flux plane depths are more easily determined from soil water potential measurements. However such data was only available from four sites for two years. Use of an alternative method has permitted recharge estimation for all the sites, except one, Ropsley IV where the zero flux plane depths could not be clearly estimated.

The combined method of estimating recharge is very satisfactory where frequent zero flux plane depth estimates are available through the summer. Much of the data from the soil water measurement sites was collected fortnightly or less frequently and consequently, for some years at some sites it was necessary to use estimates of potential evaporation in the water balance calculations for much of the summer. Evaporation from the soils was therefore probably overestimated and the resulting recharge estimates are probably too low. (These have been identified). This was particularly so for 1985 at many sites because of the combination of a wet summer and infrequent measurements.

The principal findings from each of the aquifers regarding recharge are summarised below:

> Lincolnshire Limestone: For the period 1984 to 1987, the difference in annual recharge amounts between the four sites on the Central Limestone: (Rauceby Grange, Dunston Heath grass and arable plots and Navenby) was 30 mm, the same as the variation between rainfall at the sites. Long term mean annual recharge of 134 mm a^{-1} was calculated for the grass site at Dunston Heath, and 152 and 155 mm a^{-1} for the two arable sites at Dunston Heath and Navenby, indicating a slight increase in drainage due to arable cropping. The implication is that, depending on the relative proportion of the two landuses on the Central Limestone outcrop, mean annual recharge is between 134 and 154 mm a^{-1}. The corresponding figures for the period 1983 to 1987 inclusive were 97 and 105 mm a^{-1}.
>
> For the period 1983 to 1987 at Corby Glen on the Southern Limestone, rainfall quantities were very similar to those recorded for the Central Limestone sites, as were recharge. Recharge averaged 107 mm a^{-1} from 1983 to 1987 inclusive. At a second site on the Southern Limestone, Saltby, rainfall was greater by about 55 mm a^{-1} than elsewhere and resulted in a greater recharge estimate of 157 mm a^{-1}. A limited amount of data was available from paired grass and arable sites at a Ropsley where the limestone was drift covered. It suggests that drift cover has no impact on recharge to the aquifer, nor does arable

cropping on drift soils.

A further two sites were located on the Northern Limestone, Redbourne and Scawby, but at both there was evidence suggestive of lateral water movement from the soil profile and so reliable recharge estimates could not be obtained. It is uncertain how representative these two sites are of this part of the aquifer outcrop. If they are not, then the findings from the Central and Southern Limestone might be extrapolated to this area.

The evidence from the Central and Southern Limestone sites indicates that the soils behave similarly and hence, if an estimate of actual evaporation could be obtained for the aquifer as a whole, areal recharge could be estimated by combining it with rainfall data that varied spatially across the aquifer.

2. Lincolnshire Chalk: A long term mean recharge estimate of 216 mm a^{-1} was obtained for Ulceby Cross on the Southern Chalk, almost the same as that for nearby Driby where the chalk was drift covered. However, the distribution of drainage from these sites through the year, differed, with more occurring during the summer months at the site with drift. Across the aquifer as a whole, there is a range of 55 mm in the mean annual recharge estimate for the period 1985 to 1987 when the data from all sites are directly comparable. There is a range of 63 mm a^{-1} in rainfall quantity but the highest rainfall site (Ulceby Cross) does not coincide with the site with the greatest drainage estimate (Claxby). Over a longer period that might not be the case. However the evidence suggests that any areal estimate of aquifer recharge would have to allow for soil variation as well as spatial variability of rainfall across the area.

Spilsby Sandstone: On this outcrop there was only one site for which there are large uncertainties regarding the estimation of recharge. The assumption that soil drainage equates to recharge is probably not valid due to the presence of an impeding layer which causes a seasonal perched water table. Also, how representative this situation is of the aquifer as a whole is unknown. Hence a recharge estimate for this aquifer cannot be derived.

Regarding soil water measurement to obtain recharge estimates for these aquifers in future, several recommendations can be made.

Neutron probe measurements of soil water content are satisfactory for determining zero flux plane depths at these sites but measurements should be at weekly intervals and certainly not greater than a fortnight in length.

2. Soil water potential measurements are a useful adjunct to water content measurements for understanding flow processes in soils. However, this is only the case if good quality data are recorded. This requires careful maintenance and servicing of equipment which in the case of tensiometers can only be achieved by at least weekly site visits. Measurement of soil water potential should only be attempted if this frequency of site visits can be maintained. Vacuum gauge tensiometers are easily damaged by frost and hence their lifetime may be very limited. The use of puncture

tensiometers (Marthaler *et al.*, 1983) may be a good solution, as these are easier to install and maintain than mercury manometer tensiometers, whilst being at least as robust.

It should be established how representative the sites on the Northern Limestone and Spilsby Sandstone are of these aquifers. Depending on this, it may be that the existing sites where lateral movement of water is evident, should be abandoned (for the purpose of recharge estimation) in favour of others. At least one additional site is required on the Spilsby Sandstone. If in fact these sites are typical of the aquifers, the approach to estimating recharge from the soil water measurements should be reconsidered for these sites so that vertical drainage losses from the soils can be separated more readily from lateral movements of water.

l. Although a lot of effort has been put into recording data from the Ropsley group of sites, their usefulness in terms of soil water balance estimation was limited because the measurements are for short periods which often do not overlap and were on different plots. It would be preferable to maintain one or two arable sites for several years continuing measurements right through each year.

References

Bell, J.P., 1976. *Neutron Probe Practice.* Report 19. Institute of Hydrology, Wallingford, UK.

Cooper, J.D., 1979. Water use of a tea estate from soil moisture measurements. *East African Agricultural and Forestry Journal* 43 (Special Issue), 102-121.

Cooper, J.D., 1980. *Measurement of Water Fluxes in Unsaturated Soil in Thetford Forest.* Report 66. Institute of Hydrology, Wallingford, U.K.

Cooper, J.D., Gardner, C.M.K., MacKenzie, N., 1990. Soil controls on recharge to aquifers. *Journal of Soil Science* 41.

Dolman, A.J., Stewart, J.B. and Cooper, J.D., 1988. Predicting forest transpiration from climatological data. *Agricultural and Forest Meteorology* 42, 339-353.

Gardner, C.M.K. and Field, M., 1983. An evaluation of the success of MORECS, a meteorological model, in estimating soil moisture deficits. *Agricultural Meteorological* 29, 269-284.

Gardner, C.M.K., Cooper, J.D., Wellings, S.R., Bell, J.P., Hodnett, M.G., Boyle, S.A. and Howard, M.J., 1990. Hydrology of the unsaturated zone of the chalk of south-east England. *Chalk*, Thomas Telford, London, 611-818.

Giesel, W., Lorch, S., Renger, M. and Strebel, O., 1970. Water-flow calculations by means of gamma absorption and tensiometer field measurements in the unsaturated soil profile. In *Isotope Hydrology 1970.* I.A.E.A., Vienna, Austria, 663-672.

Marthaler, H.P., Vogelsanger, W., Richard, F. and Wierenga, P.J., 1983. A pressure transducer for field tensiometers. *Soil Science Society of America Journal* 47, 624-627.

McGowan, M., 1974. Depths of water extraction by roots. Application to soil-water balance studies. In *Isotope and Radiation Techniques in Soil Physics and Irrigation Studies 1973.* I.A.E.A. Vienna, Austria, 435-445.

McGowan, M. and Williams, J.B., 1980. The water balance of an agricultural catchment. I. Estimation of evaporation from soil water records. *Journal of Soil Science* 31, 217-230.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society A* 193, 120-145.

Stammers, W.N., Igwe, O.C. and Whiteley, H.R., 1973. Calculation of evaporation from measurements of soil water and the soil water characteristic. *Canadian Agricultural Engineering* 15, 2-5.

Thompson, N., Barrie, I.A. and Ayles, M., 1981. *The Meteorological Office Rainfall and Evaporation Calculation System*: MORECS (*July 1981*). Hydrological Memorandum No. 45, Meteorological Office, Bracknell, Berks.

Wellings, S.R. and Bell, J.P., 1982. Physical controls of water movement in the unsaturated zone. *Quarterly Journal of Engineering Geology, London* 15, 235-241.

Wellings, S.R., 1984. Recharge of the Upper Chalk aquifer at a site in Hampshire, England. I. Water balance and unsaturated flow. *Journal of Hydrology* 69, 259-273.

Wellings, S.R., Bell, J.P. and Raynor, R.J., 1985. *The Use of Gypsum Blocks for Measuring Soil Water Potential in the Field.* Report 92, Institute of Hydrology, Wallingford, U.K.