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An Investigation into the Flow Interactions between the Spilsby Sandstone and the overlying aquifers of East Lincolnshire

A J Mason

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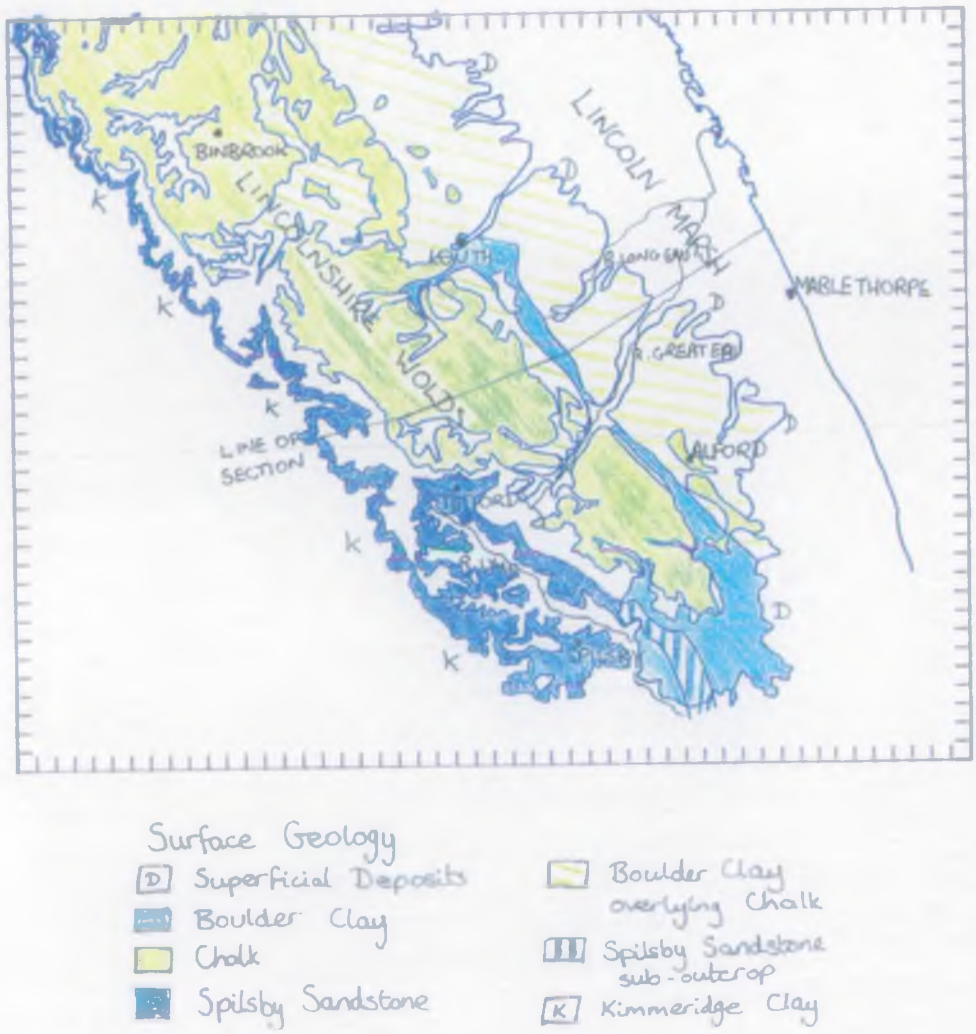
National Rivers Authority
Anglian Region

# EXECUTIVE SUMMARY

## Introduction

The Spilsby Sandstone outcrops along the western edge of the Lincolnshire Wolds from Grasby in the north to the town of Spilsby in the south. The sandstone dips eastwards beneath the Lincolnshire Chalk, although it is separated from it by the Tealby and Langton Series. The Tealby and Langton Series comprises clay, ironstone, limestone and sandstone beds, which are generally continuous above the Spilsby Sandstone.




The major geological feature is a buried chalk cliff extending from the region of Welton le Marsh in the south northwards throughout the area of study. The buried cliff comprises Boulder Clay and Sands and Gravels and forms an impeding boundary to groundwater movement from the Chalk outcrop in the west, to the confined Chalk to the east of the buried cliff.

## Project Objective

The project objective is to gain a further understanding of the flow mechanics between the Spilsby Sandstone and overlying aquifers, by developing a model to simulate groundwater heads and flows in a one-dimensional, multi-layered aquifer system.

## Methods of Investigation

An extensive understanding of the geology in the area of study was gained from background reading.

An understanding of the work of the Internal Drainage Boards, and what effect, if any, pumping had on the water balance, was gained from a visit to the Alford Drainage Board catchment, in the area of the low-lying Lincoln Marsh.

A model was developed around the successive over-relaxation iteration method for solving the one-dimensional groundwater differential equation. Incorporated into the model were the following physical features:

changes in transmissivity, storage, net inflow and vertical permeability due to spatial variations,

changes between confined and unconfined conditions

spring flow at outcrop when water levels reached ground level.

A number of simulation runs were made using different combinations of the transmissivity across the buried cliff, vertical permeabilities and the quantity of water pumped by the drainage boards. Comparison of the simulated results to field data determined the combination of the variables which gave the 'best-fit' solution.

Conclusions

The value of the transmissivity across the buried cliff which was considered to give the 'best-fit' solution was 100 $m^2/d$ (the Chalk has a transmissivity in the order of 1000 $m^2/d$). This value was concluded to be the contribution to groundwater movement made by the Sands and Gravels.

A significant quantity of water (0.09 mm/d) was determined to flow upwards through the Tills from the underlying Chalk. This value was assumed to be the best approximation using the limited data available.

The vertical permeability of the aquitard was found to decrease from $5 \times 10^{-4}$ m/d at the Chalk outcrop to $0.25 \times 10^{-4}$ m/d to the east of the buried cliff.

The largest proportion of inflow to the aquifer system is recharge from rainfall to the Chalk. Of this, it is estimated that 24% reemerges as baseflow to streams, 22% leaks down to the

Spilsby Sandstone and 21% leaks upwards through the Tills.

Although 22% of Chalk water flow down to the Spilsby Sandstone and then some of it reemerges to the confined Chalk, the largest proportion of water flowing to the confined Chalk is through the Sands and Gravels of the buried cliff.

Recommendations

The results obtained in this study, due to the lack of available field data and time available, are far from conclusive. It is therefore recommended that an extensive investigation should commence to further the findings of this study.

The initial investigation should be concentrated in the region modelled in this study and include the following:

An increase in the number of water level observation boreholes, in particular those monitoring levels in the confined Spilsby Sandstone, Carstone and Roach Rock and in the Superficial Deposits. The later would then be used to determine if hydraulic continuity existed between the Deposits and the Chalk.

An extension of the model to simulate the Carstone and Roach Rock aquifers and time-variant situations.

A re-assessment of the parameter values used in the model, with comparisons being made to more recent field data.

Gauging of the water pumped by the Internal Drainage Boards to gain a better estimate of the upflow through the Tills.

A chemical analysis of the water in the Tills to determine its origin.

THE UNIVERSITY OF BIRMINGHAM

SCHOOL OF CIVIL ENGINEERING

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BY

A.J.MASON

FOR

NATIONAL RIVERS AUTHORITY,

ANGLIAN REGION

# AN INVESTIGATION INTO THE FLOW INTERACTIONS BETWEEN THE SPILSBY SANDSTONE AND THE OVERLYING AQUIFERS OF EAST LINCOLNSHIRE

SEPTEMBER 1992

CONTENTS

APPENDICES



TABLES



FIGURES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

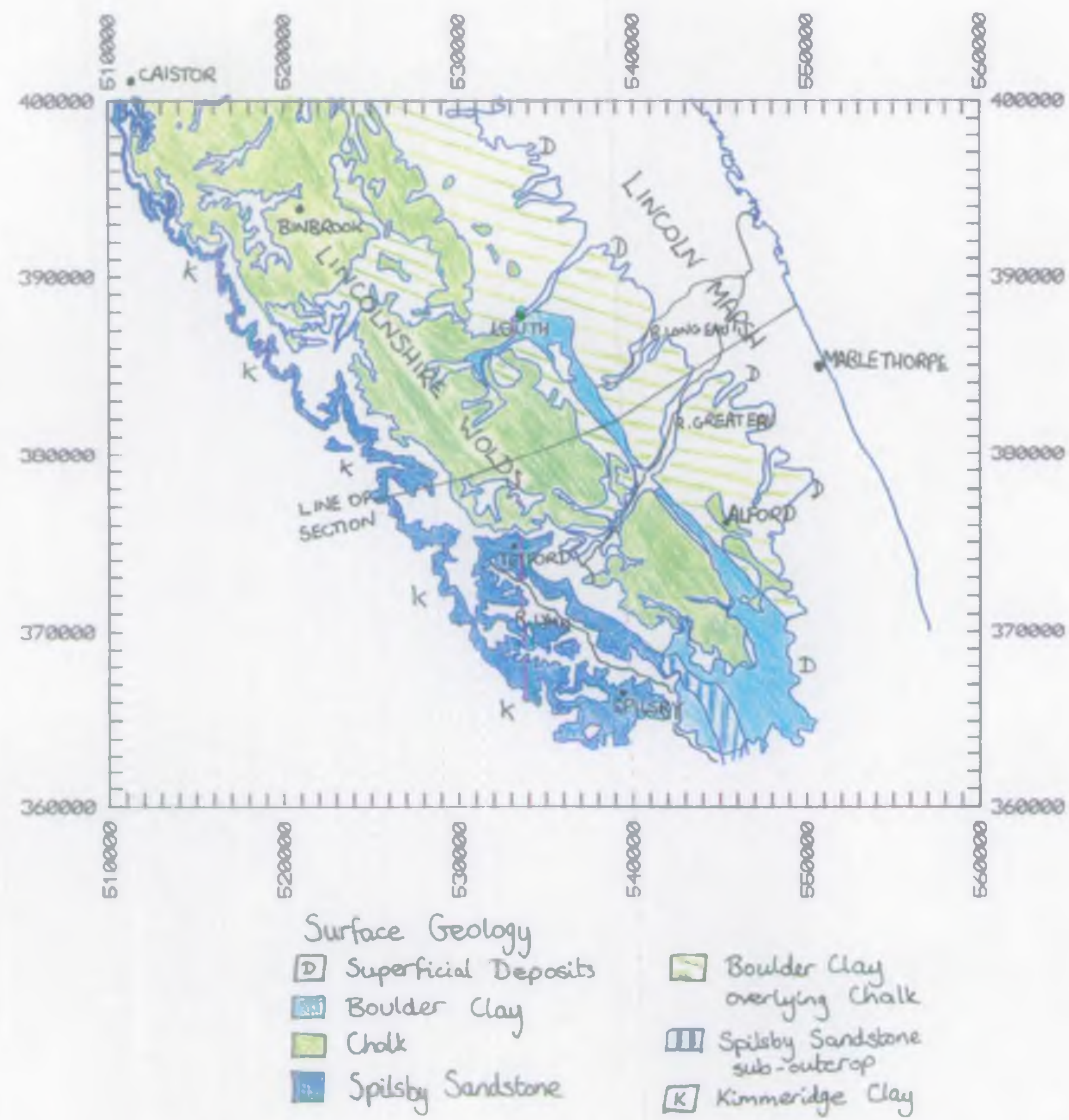
The Spilsby Sandstone outcrops along the western edge of the Lincolnshire Wolds from Grasby in the north to the town of Spilsby in the south. The sandstone dips eastwards beneath the Lincolnshire Chalk, although it is separated from it by the Tealby and Langton Series. The Tealby and Langton Series comprises clay, ironstone, limestone and sandstone beds which are generally continuous above the Spilsby Sandstone. The location and surface geology of the area of study is shown in Fig 1.

The Spilsby Sandstone is an important aquifer for Public Water Supply and boreholes give relatively good yields. However, the aquifer is largely 'confined' and it is unclear where the main inflows to the aquifer originate. The aquifer outcrop is relatively narrow and a large proportion of the recharge to this area probably reappears as springflow (Groundwater Development Consultants Limited, 1989).

An investigation by Groundwater Development Consultants Limited (1989) developed a two-dimensional model of the Spilsby Sandstone with vertical leakage. The study suggests that significant quantities of recharge to the Spilsby Sandstone are obtained from overlying deposits, including the Chalk, via vertical leakage. The model provides only an approximate representation of vertical

# Figure 1

## Location Map



flows between the Chalk and the Spilsby Sandstone.

The Chalk aquifer has been represented in two studies; one as a two-dimensional model, the other as a one- dimensional strip model. Both studies were undertaken by the University of Birmingham (1989 and 1982 respectively). The two-dimensional model allowed a fixed quantity of water to leak out from the base of the Chalk. The strip model only represented flows in the Chalk. Both studies suggest that the majority of Chalk recharge reappears as baseflow to springs or is abstracted for water supply.

## 1.2 Project Objective

The project objective is to gain a further understanding of the flow mechanics between the Spilsby Sandstone and overlying aquifers, by developing a model to represent flows in a one-dimensional multilayered aquifer system.

## 1.3 Methods of Investigation

An extensive understanding of the geology in the area of study has been gained from the background reading of The Spilsby Sandstone Investigation (Groundwater Development Consultants Limited, 1989), The Southern Chalk Hydrogeological Investigation (University of Birmingham, 1982), British Regional Geology, Eastern England (Institute of Geological Sciences, 1980) together with analysis of borehole logs.

An understanding into the work of the Internal Drainage Boards, and what effect, if any, pumping had on the water balance was gained from a tour of the Alford Drainage Board catchment, with the Boards' area manager.

A one-dimensional model, incorporating leaky vertical flows, was developed to observe representative strips of the Spilsby Sandstone and overlying aquifers. Analysis of model behaviour to variations in recharge, abstractions, storage and transmissivity were made. Comparisons were then made between these variations and field data.

## 1.4 Acknowledgements

The assistance of the staff of the National Rivers Authority, Anglian Region and the staff of Alford Drainage Board is gratefully acknowledged.

I would particularly like to acknowledge the assistance of the following:

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Geoff Mason and David Seccombe, National Rivers Authority, for their help in compiling this report,

Mike and Hilary Mason, my parents, for providing the financial support throughout the course.

# CHAPTER 2

# GEOLOGY

## 2.1 Introduction

The Spilsby Sandstone outcrops along the western edge of the Lincolnshire Wolds and underlies much of the county to the east. The outcrop is several kilometres wide at the southern end of the Wolds around the town of Spilsby, but narrows northwards until it disappears near Grasby.

The Spilsby Sandstone rests unconformably on Kimmeridge Clay. It is overlain by the Tealby and Langton Series which consist of clays, ironstones, limestones and sandstones: these in turn are overlain by the Lincolnshire Chalk. The geological succession is summarised in Table 2.1. and is represented as a cross-section in Fig 2.

### Lincolnshire Wolds

The Lincolnshire Wolds are an area of high ground, rising up to 150m aOD. It is a belt of dissected Chalk upland, up to 15km wide and about 70km long trending north-west.

The Chalk escarpment is best developed in the central area, where it is fretted by streams; in the south it gradually ceases to be a prominent feature and its drainage is less mature, while in north Lincolnshire it is lower and more regular and has few streams.

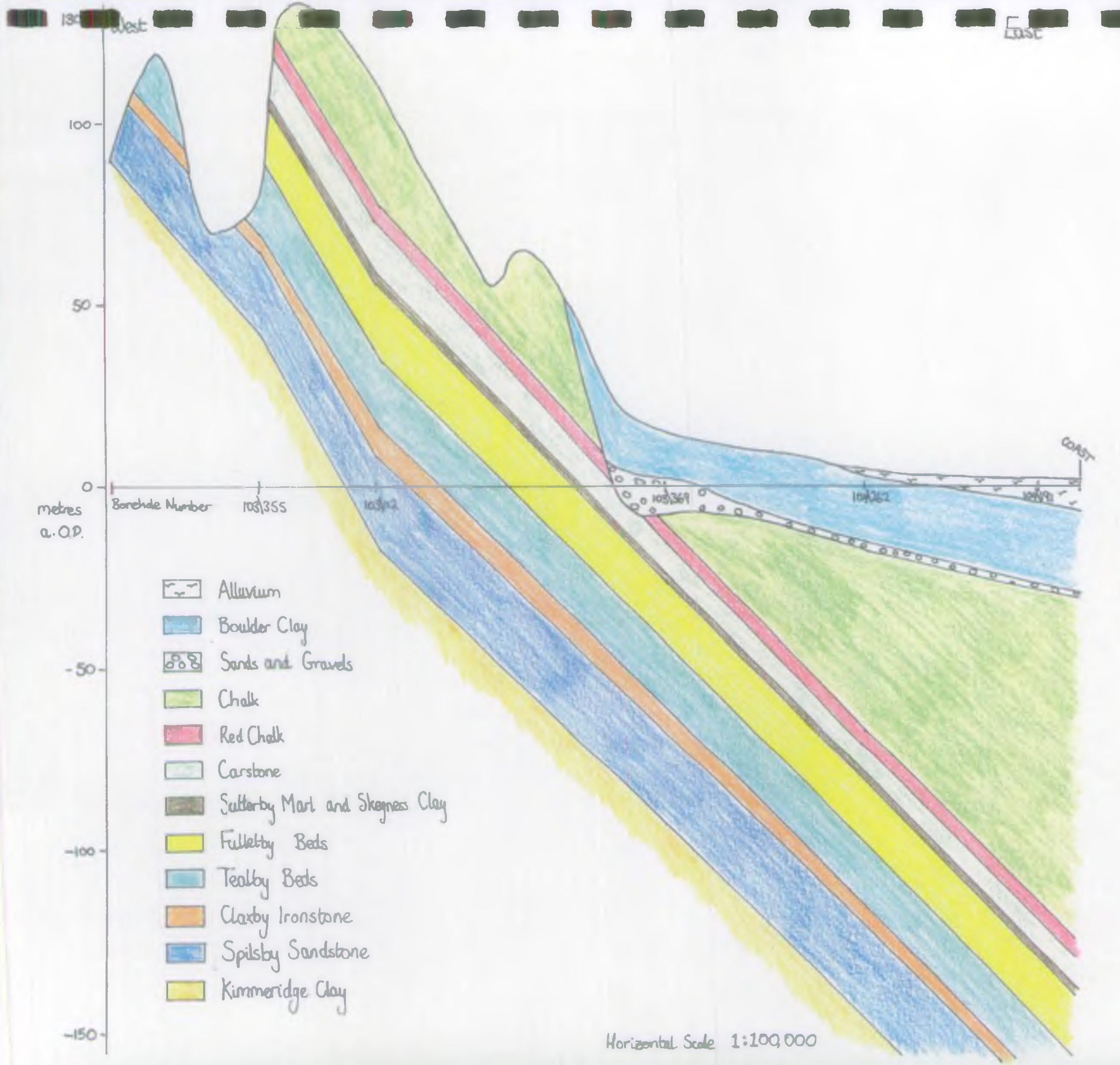


Figure 2.

Geological Cross-section

West to East

Table 2.1

Geological Succession

| Period | Stage | Lithological Division |
|---|---|---|
| Quaternary | Flandrian | 'Estuarine Deposits' |
| | Devensian | Tills, Sands and Gravels |
| | Ipswichian | |
| | Wolstonian | |
| | Hoxnian | |
| Tertiary | Not Represented | |
| Upper Cretaceous | Senonian | Flamborough Chalk Formation |
| | Turonian | Burnham Chalk Formation |
| | Cenomanian | Welton Chalk Formation |
| | | Ferriby Chalk Formation |
| Lower Cretaceous | Albian | Red Chalk<br>Carstone |
| | Aptian | Sutterby Marl<br>Skegness Clay<br>Fulletby Beds |
| | Barremian | Upper Tealby Clay<br>Tealby Limestone |
| | Hauterivian | Lower Tealby Clay<br>Claxby Ironstone |
| | Valanginian<br>Ryazanian<br>Purbeckian | Upper Spilsby Sandstone |
| Upper Jurassic | Portlandian | Lower Spilsby Sandstone |
| | Kimmeridgian | Kimmeridge Clay |

Lincoln Marsh

The fenlands of south-east Lincolnshire pass north-eastwards in to a flat marsh region up to 15km wide, extending along the coast to the Humber. This is underlain by marine silts which rest upon glacial deposits.

Drainage

The River Bain rises to the east of Louth running southwards along the western edge of the Wolds to the confluence with the River Witham at Tattershall and thence to the Wash. Numerous small streams run off the Wolds eastwards across the Lincoln Marsh to the coast. Internal Drainage Boards[1] are responsible for draining the lowlying Lincoln Marsh into rivers and tidal outfalls.

Coast

Much of the Lincolnshire coast is formed of accreting marine alluvium. Between Mablethorpe and Skegness, low cliffs consisting of glacial and later deposits are suffering erosion.

## 2.2 Upper Jurassic

### Kimmeridge Clay

The Kimmeridge Clay underlies the whole area of study, and comprises blue clays containing smooth ammonites in abundance. Exposures of fissile bituminous shale with abundant ammonites in

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[1] A site visit to Alford Drainage Board is summarised in Appendix 1

the middle and upper parts of the Clay are common at the foot of the Wolds scarp, particularly just below the Spilsby Sandstone.

**Lower Spilsby Sandstone**

The Lower Spilsby Sandstone until recently regarded as Lower Cretaceous in age is now included within the Upper Jurassic on fossil evidence. For convenience, it is included in the description for the Spilsby Sandstone unit, below.

## 2.3 Lower Cretaceous

**Spilsby Sandstone**

The Jurassic clays are overlain in the southern Wolds by the Spilsby Sandstone which comprises up to 25m of fine- to medium-grained sandstone, strongly glauconitic in the lower part, largely uncemented but with calcareous cemented masses varying in size from 1 to 3m. Phosphatic nodule beds with both derived and indigenous fossils are developed at two horizons. The lower layer at the base of the Spilsby Sandstone contains derived Kimmeridgian ammonites and a contemporaneous Upper Jurassic fauna. The other nodule bed occurs within the middle of the Spilsby Sandstone and is taken as the base of the Cretaceous.

**Claxby Ironstone**

The Spilsby Sandstone is overlain by the Claxby Ironstone, a brown to purple oolitic ironstone up to 5m thick. This bed becomes shaley south-eastwards, comprising the deeper water Hundleby Clay facies, but limonite ironstone intercalations are still present as far south as Spilsby. The Claxby Ironstone contains a particularly rich fauna.

**Tealby Beds**

Above the Claxby Ironstone are the Tealby Beds, nearly 30m thick and consisting of the Lower and Upper Tealby Clays separated by the Tealby Limestone. The Lower Tealby Clay is a dark plastic Clay, often richly glauconitic, with ammonites, belemnites and bivalves. The Tealby Limestone is about 4m of argillaceous or sandy yellow-weathering limestone with clay partings and scattered fossils.

The Upper Tealby Clay is greenish when unweathered, but becomes light coloured and ferruginous in its upper part, grading into the overlying Fulletby Beds. The Tealby fauna include belemnites and ammonites.

**Fulletby Beds**

The succeeding Fulletby Beds, about 20m thick, show a reversion to iron deposition. The facies is dominantly clayey, variably sandy and ferruginous with abundant dark brown or black polished limonite ooliths. The iron content reaches a maximum in a central cemented member, the Roach Stone, which is a ferruginous sandstone some 4 to 5m thick and locally a low-grade iron ore. The fauna includes some rhynchonellids and belemnites.

**Skegness Clay and Sutterby Marl**

In the area of study the Fulletby Beds are succeeded by the Skegness Clay and overlying Sutterby Marl, both up to about 2m thick. The former contains lower Aptian Ammonites; the latter contains Upper Aptian belemnites with derived Lower Aptian ammonites in a basal nodule bed.

**Carstone and Red Chalk**

The Carstone is a sandstone, averaging about 7m in thickness. It is generally fine-grained in its lower part and coarse and gritty in its upper. There are indications of a stratigraphic break in the middle part, and only the coarse gritty part is now regarded as Carstone. This discontinuous bed, with the overlying Red Chalk into which it passes, transgresses across the underlying Lower Cretaceous rocks northwards until beyond Caistor they overlie the eroded surface of the Upper Jurassic clays.

North of Tealby it is exceptionally coarse and contains numerous phosphatic nodules and fragmentary casts of ammonites. Where present, the Carstone maintains a gradual transition into the overlying Red Chalk. In northern Lincolnshire it is missing locally, but the lower part of the Red Chalk is conglomeratic, with quartz grains and phosphatic nodules in fair abundance.

The Red Chalk is an impure limestone, varying in colour from pink to brick-red, containing rounded quartz grains and numerous fossils. It represents a condensed deposit which accumulated slowly. Its colour may be due to red mud washed from a low-lying lateritised contemporary land area, or alternatively it has been suggested that the ferruginous material could have been derived from the exposed Keuper Marl on rising North Sea salt intrusions. It is continuous throughout Lincolnshire, being 5.5m thick at the southern extremity of the Lincolnshire Wolds but gradually decreasing in thickness northwards.

## 2.4 Upper Cretaceous

### Introduction

Following a brief uplift towards the end of the Lower Cretaceous a general subsidence began at the time of Red Chalk deposition, and subsequently a uniform sequence of pure, white limestones known as the Chalk was deposited.

The total thickness of the Chalk in Lincolnshire is extremely variable as it has been subjected to significant erosion. The total thickness in the area of study could be about 250m.

The Chalk of the region belongs to an ill-defined lithofacial and faunal 'Northern Province' which extends southwards across The Wash in to north Norfolk. In marked contrast to the massive 'earthy' Chalk of the complementary 'Southern Province', the northern Chalk is for the most part relatively hard and thin-bedded. Further points of distinction are the complete absence of flints in the higher parts of the northern succession and the presence within its flinty sequence of courses of continuous thick tabular flints.

Furthermore, since it is not possible at present to identify the horizon in the Northern Province corresponding to the base of the Upper Chalk, the tripartite subdivision in southern England into Lower, Middle and Upper Chalk is not applicable. A new lithostratigraphical classification has recently been erected for the Northern Province (Wood and Smith, 1978). This comprises, in ascending order, the Ferriby, Welton, Burnham, and Flamborough Chalk Formations. These formations can be divided into 11 Zones named after characteristic fossils, and summarised below in Table 2.2.

**Table 2.2**

**Northern Province Lithostratigraphical Divisions**

| Lithostratigraphical division | Zones |
|---|---|
| Flamborough Chalk Formation | *Inoceramus lingua* |
| | *Marsupites testudinarius* |
| | *Uintacrinus socialis* |
| | *Hagenowia rostrata* |
| Burnham Chalk Formation | *Micraster cortestudinarium* |
| | *Sternotaxis* [*Holaster*] *planus* |
| | *Terebratulina lata* |
| Welton Chalk Formation | *Inoceramus labiatus* |
| | *Sciponoceras gracile* |
| Ferriby Chalk Formation | *Holaster trecencis* |
| | *Holaster subglobosus* |

**Ferriby Chalk Formation**

The thickness of the Ferriby Chalk Formation is about 25m. It can be subdivided into two zones. The lower zone being *Holaster subglobosus*, and the upper being the *Holaster trecencis*.

The base of the Ferriby Chalk Formation is marked by the Sponge Bed. The Sponge Bed is a pinkish and yellowish pink chalk which is about 10cm thick throughout the Wolds.

Succeeding the Sponge Bed is the *Inoceramus* Bed, which is about 2m of hard whitish grey chalk lying on a basal layer of green coated nodules.

Overlying the *Inoceramus* Bed is about 10m of hard bluish grey chalk with thin bands of greenish grey marl.

Above the bluish grey chalk lies the Totternhoe Stone, about 1m of a hard bed of dark grey fossiliferous chalk.

Overlying the Totternhoe Stone is 3-4m of whitish grey chalk containing in some regions the Lower and Upper Pink Chalk bands.

The top of the Ferriby Chalk Formation is marked by the Belemnite or Plenus Marl, a layer of dark grey laminated clay about 30 cm thick.

**Welton, Burnham and Flamborough Chalk Formations**

The average thickness of the Welton Formation is about 50m . The average thickness of the Burnham and Flamborough Formations have not been specified in the area of study. The formations will be described below in their zonal subdivisions.

The base of the *Sciponoceras gracile* Zone is marked by a complex of variegated laminated marls collectively known as the 'Black Band'. The Black Band is overlain by a thin layer of buff-coloured chalk.

The *Inoceramus labiatus* Zone is a hard thin bed of pebbly bioclastic chalks with marly partings at some horizons.

The lower part of the *Terebratulina lata* Zone is a hard thin bed of chalk with scattered courses of predominately small, burrowfill nodular flints. The upper part of the *Terebratulina lata* Zone is the 'Columnar Bed', so-called because of the very close-set vertical jointing which it exhibits.

The *Sternotaxis planus* Zone extends up to a thin marl, about 70m above the Black Band. The thin marl marks a change from thin bedded chalks with close-set courses of tabular flints to more massive chalks with nodular flints.

The base of the *Micraster cortestudinarium* Zone is marked by a layer of marly chalk packed with small pycnodonteine oysters. Above the oyster bed there is a horizon of locally iron stained chalk, and somewhat higher in the succession there is a change back to courses of lenticular and tabular flints.

The junction between the flinty and flintless chalk falls within the *Hagenowia rostrata* Zone. The flinty *Hagenowia rostrata* chalk is characterised by tabular and lenticular flints, but these are replaced in the higher part of the succession by small nodular burrowfill type flints. The overlying flintless *Hagenowia rostrata* chalk is characterised by an abundance of the diminutive thin-tested echinoid *Hagenowia blackmorei anterior*.

The *Uintacrinus socialis* Zone consists mostly of massive chalk, with thin bands packed with oysters.

The *Marsupites testudinarius* Zone comprises alternations of blocky and flaggy chalk with marl bands and numerous rusty pyrite nodules.

The *Inoceramus lingua* is similar to the *Marsupites testudinarius* Zone below, but the marl seams are thicker and more numerous.

## 2.5 Quaternary Period

**Introduction**

Tertiary deposits are absent from the area, but many varied Quaternary deposits occur and which are summarised in Table 2.3 below.

The Tills are the most widespread and characteristic of the glacial deposits, being heterogeneous accumulations of erratic rock fragments commonly transported from a considerable distance and including large boulders, set in a clayey, silty or, more rarely, sandy matrix. Sands and Gravels are also common in the region.

During the Ipswichian interglacial stage, the sea level rose approximately 14m. This rise in sea levels resulted in the now-buried Chalk cliff extending from the region of Welton le Marsh in the south northwards throughout the area of study.

**Table 2.3**

**The Pleistocene Deposits**

| **Stage** | **Major Stratigraphical Units** |
|---|---|
| Flandrian | Estuarine Deposits |
| Devensian | Cover sands |
| | Upper Marsh Till |
| | Tattershall Gravels |
| | Lower Marsh Till |
| Ipswichian | Fen margin gravels<br>? Kirmington fossiliferous gravels |
| Wolstonian | Calcethorpe, Welton, Belmont, Wragby and Heath Tills<br>Welton gravels |
| Hoxnian | ?? Kirmington fossiliferous deposits |

**The Pleistocene Deposits**

Much of the material was derived from the destruction of clay outcrops. The mixture of clay with entrained stones and rocks is commonly called Boulder Clay. Among the smaller stones , chalk and flint are almost universally present, the former in the form of pebbles of various sizes or of innumerable widely disseminated pellets. These have led to the establishment of the descriptive title of "Chalky Boulder Clay" for these deposits. Locally,

however, the source of the rocks were sands or chalk, and to cover the range of lithology the alternative word Till is now used.

Two glacial periods are well known in Lincolnshire. The first of these, named the Wolstonian glaciation was responsible for the deposition of the main Boulder Clay. The second was the Devensian glaciation, which covered East Lincolnshire up to the Wolds.

Generally speaking the Devensian Boulder Clays east of the Wolds are coloured brown or various shades of brown tinted more or less deeply with purple. Over the remainder of the county the colour of the Wolstonian Tills is predominantly grey and blue.

**Estuarine Deposits**

The Estuarine Deposits are a sequence of peats, clays and silts deposited in a broad transgressive tract along the whole of the coastline of the area. The transgression which resulted in the deposition of these Estuarine Deposits also produced erosional thinning of the underlying Marsh Tills. The Estuarine Deposits are believed to reach a maximum thickness in excess of 15m in the vicinity of North Somercotes (TF 42 96)

**Sand Deposits and River Alluvium**

The Sands Deposits and River Alluvium are very recent deposits and occur in the form of dunes along part of the coastline, and as alluvial deposits of the present day river system.

## Off-shore Geology

The Marsh Tills thicken gradually away from the coast and may reach over 50m in thickness up to 100km into the North Sea. Submarine exposures of Chalk would not appear to occur within 45km of the coast.

## CHAPTER 3

## HYDROGEOLOGY

### 3.1 Introduction

The hydraulic relationship between the Spilsby Sandstone and the overlying aquifers is potentially complex. The related aquifer systems can be defined as:

Table 3.1

The Aquifer System

| Period | Geological Unit | Hydrogeological Unit |
|---|---|---|
| Quaternary | Estuarine Deposits<br>Boulder Clay | Aquitard |
| | Sands and Gravels<br>Chalk Boulder Clay | Aquifer |
| Upper Cretaceous | Chalk | Aquifer |
| Lower Cretaceous | Red Chalk | Local aquifer |
| | Carstone | Aquifer |
| | Sutterby Marl<br>Upper Roach Ironstone | Aquitard |
| | Roach Rock | Aquifer |
| | Lower Roach Ironstone<br>Upper Tealby Clay | Aquitard |
| | Tealby Limestone | Local aquifer |
| | Lower Tealby Clay<br>Claxby Ironstone | Aquitard |
| | Upper Spilsby Sandstone | Aquifer |
| Upper Jurassic | Lower Spilsby Sandstone | |
| | Kimmeridge Clay | Aquitard |

### 3.2 Hydrometric Relationships

Groundwater movement through a strata can be represented by Darcy's Law:

$$v_i = k_i \frac{\partial h}{\partial x_i}$$

where $k_i$ is the hydraulic conductivity in the direction of the Cartesian coordinate axis i.

The magnitude of flow is determined by the magnitudes of the hydraulic conductivity and the groundwater head gradient.

The hydraulic conductivity can vary greatly throughout the strata and with direction of axis.

The groundwater head gradient is a measure of the rate of change of head with respect to distance. The groundwater head is dependent on the ability of the aquifer to store water (the coefficient of storage) and on the extent to which water can flow through it (transmissivity). In the area of outcrop, the coefficient of storage is high, and decreases with confinement and as the aquifer becomes saturated.

Values for the storage coefficients and transmissivity (permeabilty times the saturated thickness) are determined, in the field, by pumping tests. In this investigation, historic pumping test data, although sparsely located in the area of study, gave a good approximation to the magnitude of the coefficients. The range of the values obtained from the historic data are summarised in Table 3.2

Table 3.2

Aquifer Parameters

| Aquifer Unit | Transmissivity | Storage Coefficients |
|---|---|---|
| Chalk | 600-3000 | 0.01 (outcrop)<br>$39-4\times10^{-5}$ (confined) |
| Carstone/Roach | 170 ? | not known |
| Spilsby Sandstone | 40-400 | 0.1 (outcrop)<br>$2-3\times10^{-4}$ (confined) |

### 3.3 Spilsby Sandstone

The Spilsby Sandstone is the most important of the Lower Cretaceous aquifer units. Over the whole of the area of study the base of the Spilsby Sandstone aquifer is effectively delineated by the great thickness of the Kimmeridge Clay.

Down-dip from the outcrop, the Spilsby Sandstone aquifer is generally confined by the clays of the Tealby Series. North of the Caistor Monocline, however, the Tealby Series are not present and the Spilsby Sandstone may be in hydraulic continuity with the Carstone (George, 1979).

To the south of the area of study, superficial deposits cover the Spilsby Sandstone sub-drift outcrop. The contact lies below present sea level, with the drift deposits being nearly saturated, the relationship between the superficial groundwaters and those in the Spilsby Sandstone could be important in respect of groundwater movement through the south of the area of study.

### 3.4 Tealby and Fulletby Beds

Above the Spilsby Sandstone, the Tealby and Fulletby Beds contain only minor aquifers, namely the Tealby Limestone and Roach Rock

The Tealby Limestone is a rather thin and impersistant aquifer. George (1979) states that, in a report by Jukes-Brown (1893), the water of the Tealby Limestone is generally of very poor quality and low yield, indicating long residence times and poor aquifer characteristics. An investigation into this result is beyond the scope of this project.

The Roach Rock is an important aquifer from which private boreholes obtain small supplies of water, is separated from the Spilsby Sandstone by the Tealby Clay and from the Carstone by the Sutterby Marl.

### 3.5 Carstone and Red Chalk

Only one relatively modest development at Binbrook (TF 21 95) exploits the Carstone for Public Water Supply. There are many private boreholes which obtain small supplies of water from the Carstone.

The Red Chalk separates the Chalk and Carstone, and is often considered to be an aquitard. However, locally where it has been subjected to fracturing or jointing it may be considered as an aquifer.

Water level hydrographs (Figs 3. & 4.) for the Chalk and the Carstone at Burwell (TF 35 79), in the area of the Chalk outcrop, indicate that hydraulic continuity exists between the Carstone and overlying Chalk.

## 3.6 The Chalk

The major aquifer in north-east Lincolnshire and south Humberside is the Chalk. The Chalk is a limestone unit in which the potential for groundwater flow depends upon the degree to which the rock has been subjected to fissure development.

The University of Birmingham (1982) concluded that in the confined region to the east of the buried cliff, the chalk only forms an aquifer in its upper 10m or so, the zone of maximum fissure development. Below this, the Chalk can be regarded as an aquitard. The depth of fissuring was deduced from hydrochemical data and available pumping tests.

## 3.7 Tills and Sands and Gravels

To the east of the Wolds, the Chalk is overlain by Tills and the associated Sands and Gravels, with which it is in hydraulic continuity. The Tills and the Sands and Gravels can substantially extend the potential for groundwater flow and storage at the top of the chalk aquifer unit.

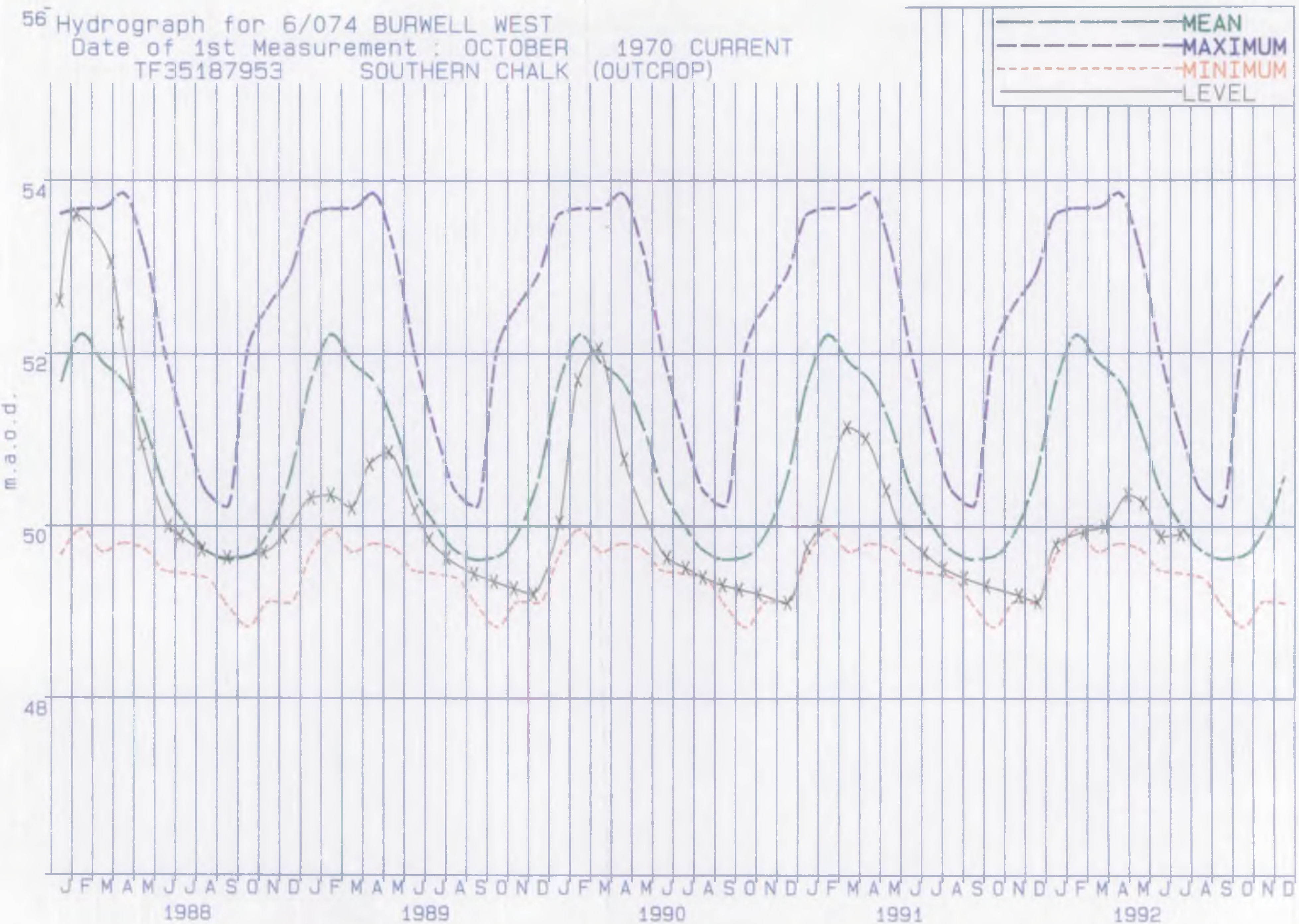
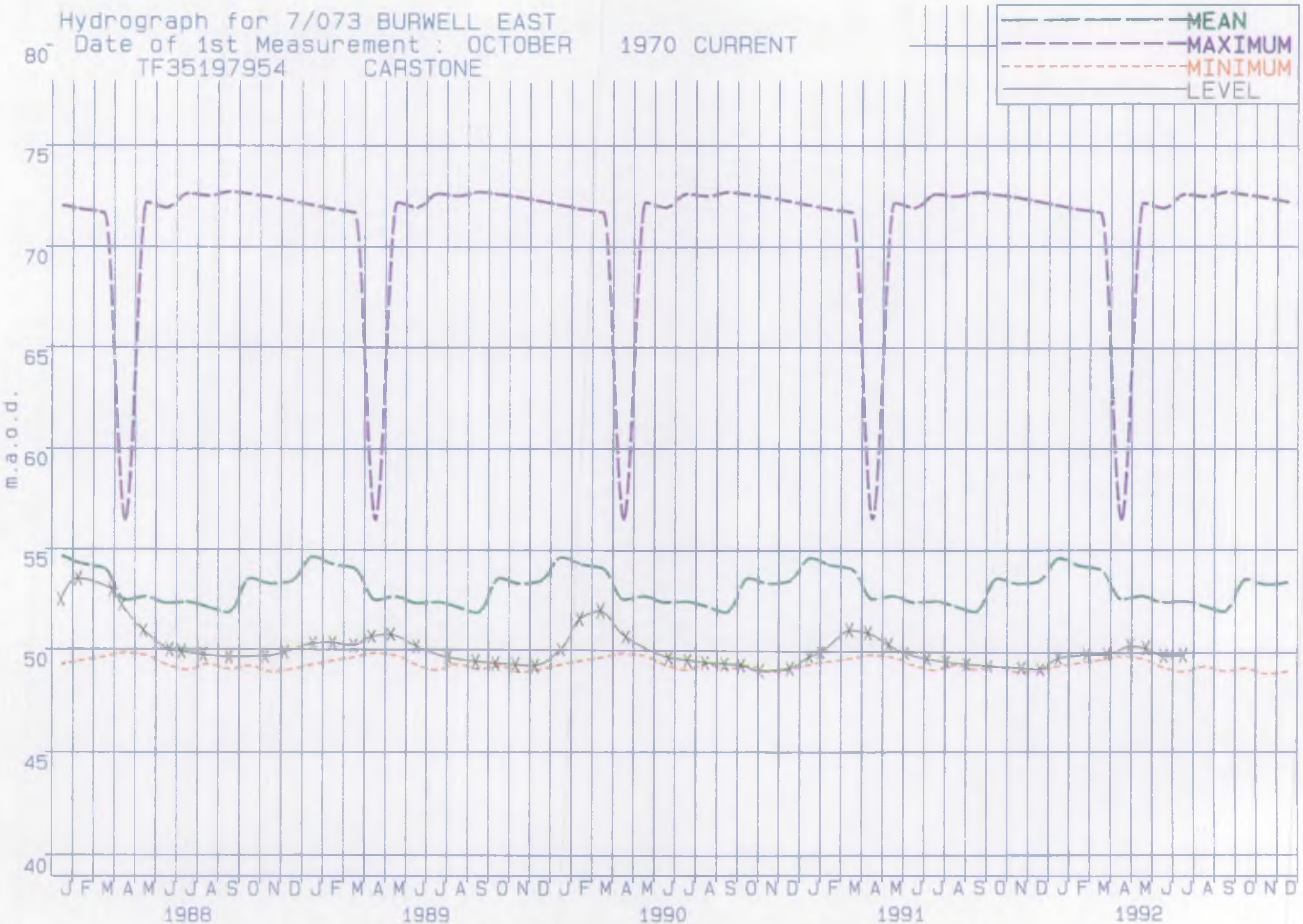

Hydrograph for 6/074 BURWELL WEST
Date of 1st Measurement : OCTOBER 1970 CURRENT
TF35187953 SOUTHERN CHALK (OUTCROP)
MEAN
MAXIMUM
MINIMUM
LEVEL
56
54
52
50
48
m.a.o.d.
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1988
1989
1990
1991
1992

Figure 3.



Hydrograph for 7/073 BURWELL EAST
Date of 1st Measurement : OCTOBER 1970 CURRENT
TF35197954 CARSTONE
MEAN
MAXIMUM
MINIMUM
LEVEL
m.a.o.d.
80
75
70
65
60
55
50
45
40
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1988
1989
1990
1991
1992


Figure 4.

### 3.8 Piezometric Relationships

Fig 5 indicates the relationships between the piezometric heads of the Chalk and the Spilsby Sandstone along the cross-section described previously (Fig 2.).

The head in the Spilsby Sandstone falls slowly away from the outcrop as the strata becomes quickly confined, the gradient declining and the head remaining at, or just above ground level over much of the coastal plain.

In the Wolds, the piezometric level in the unconfined Chalk is higher than the levels for the underlying aquifers; the deepest aquifer, the Spilsby Sandstone, having the lowest piezometric surface. Down-dip, the relationship is reversed, and the piezometric surface in the Spilsby Sandstone lies above the levels in the Carstone, Roach and Chalk (in that order), (Groundwater Development Consultants Limited, 1989). The cross-over in piezometric surfaces occurs close to the Pleistocene cliff line where the Chalk groundwater discharges as springs or flows into the glacial deposits.

The main implications of this piezometric relationship are that downward groundwater leakage occurs from the Chalk to underlying aquifers to the west of the cliff line, and that the reverse is true to the east.

The Boulder Clay overlying the Chalk has previously been considered as impermeable. However, a water balance

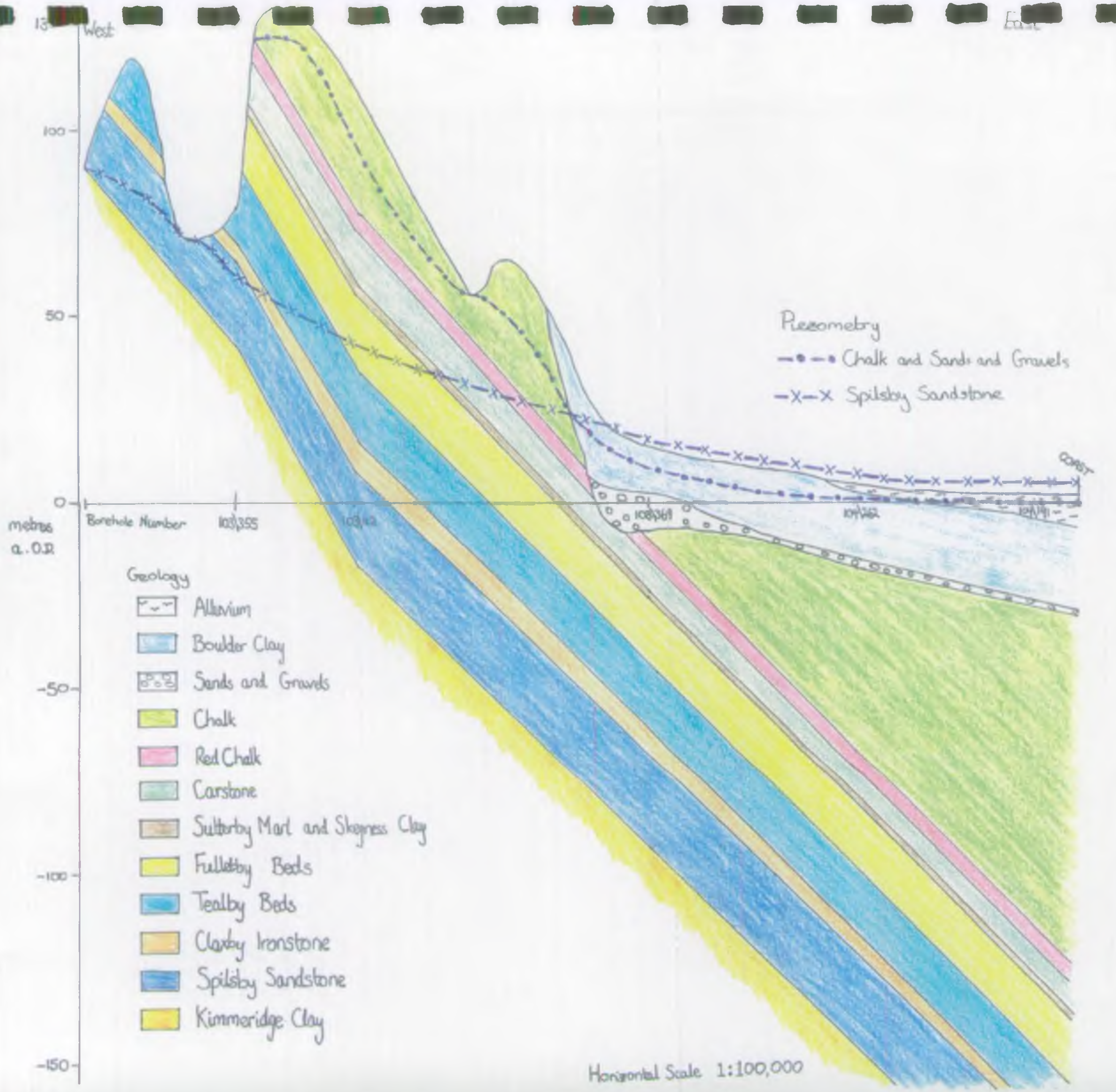



Figure 5.

Piezometric Relationships

approximation, in section 4.4, suggests that significant amounts of water flows up through the Boulder Clay, probably originating from the Chalk and overlying Sands and Gravels. This water is then abstracted by the Internal Drainage Boards.

### 3.9 Flow Directions

The direction of the flows within the aquifer system are shown in Fig 6.

The extent to which groundwater can flow is greatest, by definition, in the aquifers. However, the contributions of vertical flow through the aquitards add another dimension to the possible flow paths.

Recharge enters the aquifer system at the outcrop area and flows down-dip eastwards to the coast. Vertical flow between aquifers are from the higher piezometric head to the lower, with the magnitude of flow being determined by the hydraulic conductivity per unit thickness of the aquitard and by the difference is heads of the aquifers.

To the west of the buried cliff, vertical flow is downwards from the Chalk through to the Spilsby Sandstone. Conversely, to the east, vertical flow is upwards from the Spilsby Sandstone to the Chalk.

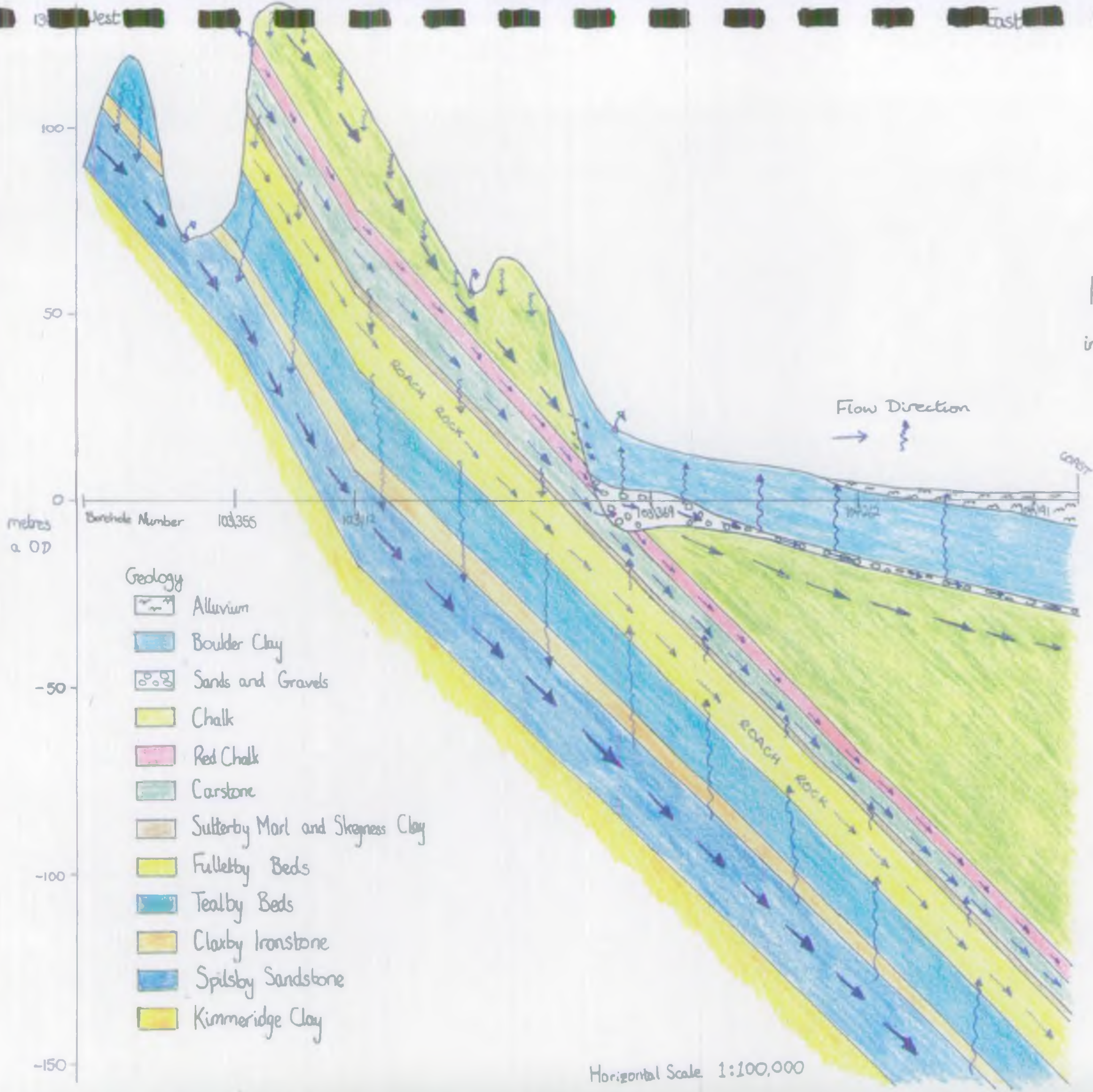



Figure 6.

Flow Directions

in the Aquifer System

# CHAPTER 4

# WATER BALANCE

## 4.1 Introduction

The groundwater balance for the aquifer system can be represented by the equation

$$I - O = \Delta S$$

where I denotes total aquifer inflow, O total aquifer outflow and $\Delta S$ the change in aquifer storage. Positive values of $\Delta S$ indicate an excess of inflow over outflow which will result in an overall rise in water level, and negative $\Delta S$ values indicate that groundwater is being mined.

### Inflow

Inflow to the aquifer system occurs naturally in at the outcrop area in the form of recharge from rainfall. Another source of inflow is vertical leakage from other aquifers.

### Outflow

Outflow from the aquifer system occurs as baseflow to streams and as vertical leakage to other aquifers. Abstractions for public and private water supply are a source of artificial outflow.

## 4.2 Recharge from Rainfall

Recharge from rainfall can be represented in a simplified form by the following equation:

Recharge = Rainfall - Evaporation - Runoff

- Soil Moisture Storage

This equation was utilised in both the Northern Chalk Model (University of Birmingham) and the Spilsby Sandstone Investigation (Groundwater Development Consultants Limited, 1989) to calculate mean annual recharge to the Chalk and Spilsby Sandstone, respectively.

The Northern Chalk model provided a mean annual volume of recharge to the Chalk outcrop. For the purpose of this study, the recharge was convertedto a mean daily equivalent depth (m/d) by dividing through by the outcrop area:

| | |
|---|---|
| Mean daily recharge | = 219,000 $m^3$ |
| Outcrop area | = 342 $km^2$ |
| Mean daily equivalent depth | = 0.64 mm/d |

Similarly, the Spilsby Sandstone Investigation, provided a mean daily equivalent depth of recharge to the Spilsby Sandstone:

| | |
|---|---|
| Mean daily recharge | = 26.7 $m^3$ |
| Outcrop area | = 63 $km^2$ |
| Mean daily equivalent depth | = 0.74 mm/d |

For the purpose of this study, the error introduced into the estimate of the recharge due to variations in rainfall and landuse, was considered to be small.

## 4.3 Spring Flow

Water originating from the Chalk is thought to make up a large proportion of baseflow to streams and rivers. Assumptions were

therefore made to estimate this component of baseflow. Where the Chalk is absent, baseflow is made up, in varying proportions, of waters from the Lower Cretaceous.

Spring flow data was collected for the streams crossed by the representative strip model of the aquifer system. This was converted to an equivalent depth by dividing through by the catchment area.

The daily effective precipitation was calculated using data from MORECS. It was then assumed that the run-off component was approximately equal to 2% of the effective precipitation. The values for effective precipitation for grass and real land use were calculated as 0.37mm/d and 0.46mm/d respectively.

It was assumed that the baseflow component was approximately equal to the spring flow less run-off. Again this was represented as an equivalent depth.

In the eastern area, the impact of pumping, if any, by the Internal Drainage Boards was taken into consideration.

Previous studies have not considered the contribution of water from the Tills when calculating the water balance. In this study, it was assumed that if the Tills did contribute a quantity of water then it could be argued that it was approximately equal to the water pumped less run-off (cf baseflow).

Data was obtained on pump capacities[1] and design annual run time (1000hrs/yr). The annual quantity of water pumped out of the catchment was then determined. By subtracting the volume of run-off in the pump's catchment from the volume of water pumped, the approximation to the contribution from the Tills was made.

However, for the Theddlethorpe and Trusthorpe Pumping Station Catchments, some water is discharged under gravity to tidal outfalls. No reliable estimate can be made to quantify the amount of water flowing out through these outfalls.

### 4.4 Baseflow Calculations

Using the above assumptions, estimates of baseflows to streams in the area spanned by the modelled cross-section can be calculated as shown below:

| | | |
|---|---|---|
| Goulceby Beck, | mean daily flow | = 1296 $m^3/d$ |
| | catchment area | = $3 \times 10^6$ $m^2$ |
| | equivalent depth | = 0.00043 m/d |
| | rainfall runoff | = 0.00005 m/d |
| | Approx. Baseflow | = 0.00038 m/d |
| Scamblesby Beck, | mean daily flow | = 1296 $m^3/d$ |
| | catchment area | = $3.3 \times 10^6$ $m^2$ |
| | equivalent depth | = 0.00039 m/d |

[1] Pump capacities and catchment areas are included in Appendix 1.

| | | |
|---|---|---|
| | rainfall runoff | = 0.00005 m/d |
| | Approx. Baseflow | = 0.00034 m/d |
| Burwell Beck, | mean daily flow | = 1382 $m^3/d$ |
| | catchment area | = $8 \times 10^6$ $m^2$ |
| | equivalent depth | = 0.00017 m/d |
| | rainfall runoff | = 0.00005 m/d |
| | Approx. Baseflow | = 0.00012 m/d |
| Muckton Beck, | mean daily flow | = 1037 $m^3/d$ |
| | catchment area | = $3.3 \times 10^6$ $m^2$ |
| | equivalent depth | = 0.00031 m/d |
| | rainfall runoff | = 0.00005 m/d |
| | Approx. Baseflow | = 0.00026 m/d |

An estimation of baseflows (and upward leakage through the Tills) for the region can be obtained using the data for the Anderby catchment, as follows:

Total Pump Capacity = 4680 l/s

Design Pumping = 1000 hrs p.a.

Therefore the total volume pumped in one year

= $4680 \times 1000 \times 60 \times 60$

= $2.142 \times 10^{10}$ l

The equivalent daily mean flow

= 46159 $m^3/d$

The total catchment area

$= 3612$ ha

Thus the equivalent depth of mean daily pumping

$= 46159/3612\times10^4$

$= 0.00128$ m/d

Similarly, the equivalent depths for Ingoldmells (including Skegness) and Chapel St. Leonards (New Station) are 0.00132m/d and 0.00119m/d respectively. Assuming that the pumps were designed to have ⅔rds backup, then the average equivalent depth of mean daily pumping is 0.00055.

Total effective precipitation for the catchment using MORECS

$= 0.00046$ m/d

Thus the assumed baseflow including upflow

$= 0.00055 - 0.00046$

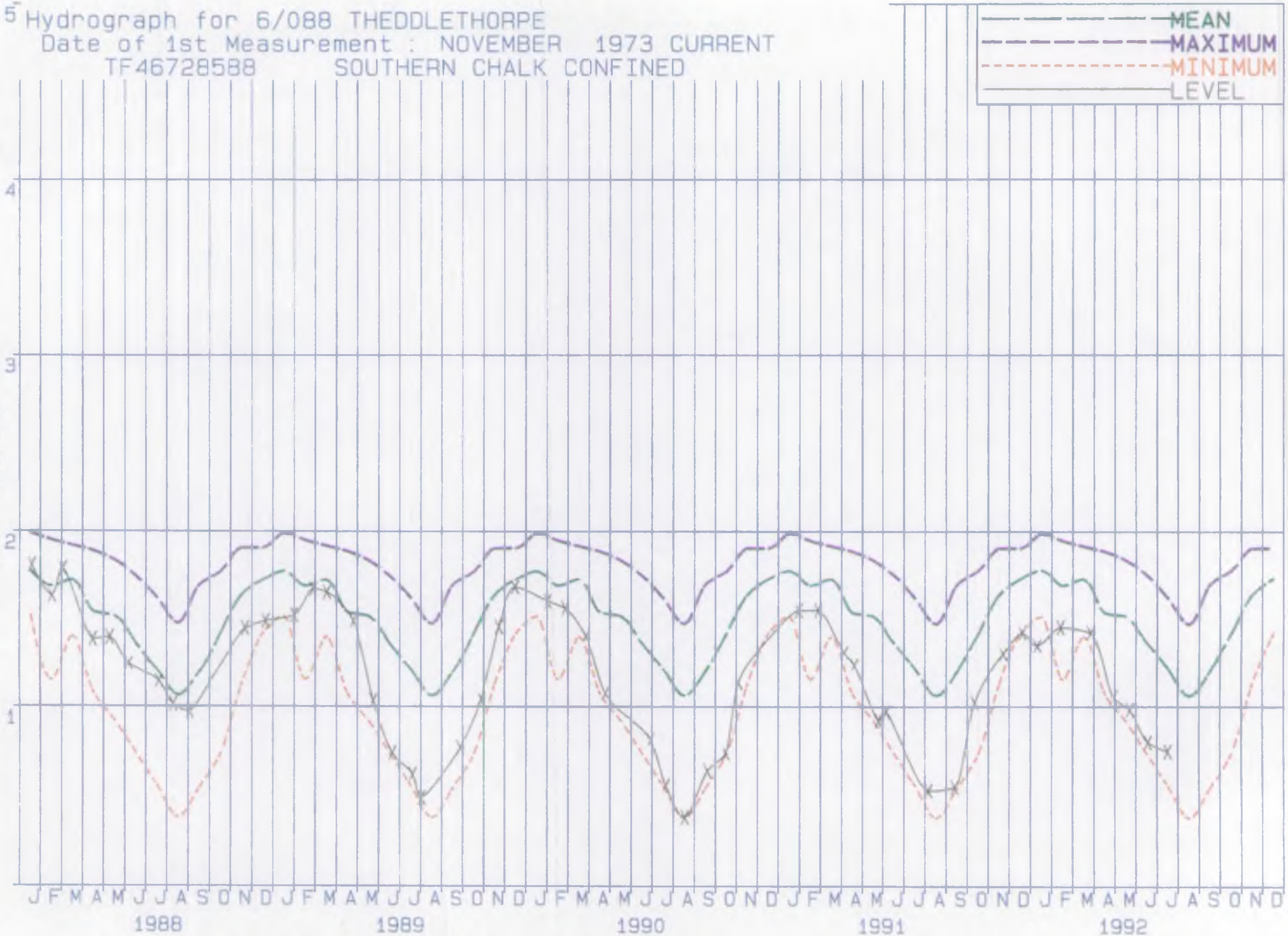
$= 0.00009$ m/d

## 4.5 Abstractions

Abstractions of groundwater artificially lower the water levels around the boreholes. The greatest drawdown occurs in the close proximity of the borehole. Smaller drawdowns can be observed at some distance from the borehole.

The effect of increasing abstractions on water levels is very apparent in the Theddlethorpe hydrograph (Fig 7.). This borehole shows the effect on water levels in the confined Chalk, from increased summer season abstraction.

Figure 7.



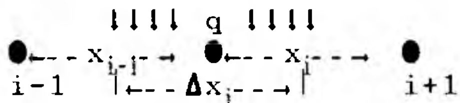
Hydrograph for 6/088 THEDDLETHORPE
Date of 1st Measurement : NOVEMBER 1973 CURRENT
TF46728588 SOUTHERN CHALK CONFINED
MEAN
MAXIMUM
MINIMUM
LEVEL
m.a.o.d.
5
4
3
2
1
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1988
1989
1990
1991
1992

4.6 Model Representation of Inflows and Outflows

In a one-dimensional model, all inflows and all outflows have to be entered as equivalent depths (m/d). For ease of input, data was entered as a net inflow to a node, ie inflow less outflow.

However, at nodes coinciding with outcrop boundaries, abstraction or baseflow points, adjustments to the inflows and outflows have to be made.

The model representation of recharge, q, to node i, is:




where $\Delta x_i = \frac{1}{2}(x_{i-1} + x_i)$

However, at an outcrop boundary, the recharge btween nodes i-1 and i, say, is zero, and between nodes i and i+1, q. The model, however, still interprets this as recharge over the whole length $\Delta x_i$, hence the recharge, q, has to be modified to $q \times \frac{1}{2} x_i / \Delta x_i$.

For baseflows and abstractions, the contributions to the outflow may be from a number of nodes, ie the catchment area, or radius of influence. Therefore the mean outflow over the contributing nodes, $q_0$, has to be modified to represent outflow at a single node as, $q_0 \times \left[ \frac{\text{Range of contributing nodes}}{\Delta x_i \text{ of outflow node}} \right]$

Therefore the baseflows can be modified to:

| | |
|---|---|
| Goulceby Beck (node 7, Spilsby Sandstone), | q= 0.00217 m/d |
| Scamblesby Beck (node 9, Chalk) | q= 0.00037 m/d |
| Burwell Beck (node 16, Chalk) | q= 0.00019 m/d |
| Muckton Beck (node 21, Chalk) | q= 0.00150 m/d |
| Maltby le Marsh Abstraction (node 33, Chalk and Spilsby Sandstone) | q= 0.00011 m/d |

These values of baseflow can be expressed as a proportion of recharge (Table 4.3). The to the Spilsby Sandstone is 1.104 $m^2/d$ and to the Chalk 5.030 $m^2/d$. The units $m^2/d$ are equivalent to m3/d per unit width, hence, three-dimensional flows can be calculated by multiplying by the width (north-south) of the aquifer (m).

Table 4.3

**Streamflow as % of Recharge**

| Stream | Baseflow $m^2/d$ | % of Recharge |
|---|---|---|
| Goulceby Beck | 0.380 | 34.4 Spilsby Sandstone |
| Scamblesby Beck | 0.323 | 6.40 Chalk |
| Burwell Beck | 0.192 | 3.80 Chalk |
| Muckton Beck | 0.702 | 14.0 Chalk |
| Maltby le Marsh (Abstraction) | 0.080 | 7.20 Spilsby Sandstone<br>1.60 Chalk |

## 4.7 Outflows to the North Sea

The University of Birmingham (1982) deduced that natural outflow from the Chalk aquifer occurred at some distance (> 50km) from the coast, into the North Sea. No direct evidence of such an outflow existed.

Groundwater Development Consultants (1989) deduced that an outflow of $2.1\times10^3$ $m^3/d$ from the Spilsby Sandstone to the sea occurred. This figure was introduced into the Spilsby Sandstone model to give a better simulation of the piezometric surface.

# CHAPTER 5

# AQUIFER MODELLING

## 5.1 Introduction

Groundwater modelling is used to assist in the investigation into understanding the flow interactions between the Spilsby Sandstone and the overlying aquifers. Numerical modelling provides an efficient method to represent groundwater heads and flows throughout the aquifer system.

## 5.2 Basic Principles

The model was based on the one dimensional groundwater differential equation, with an addition term to represent vertical leakage between aquifers:

$$T \frac{\partial^2 h}{\partial x^2} = S \frac{\partial h}{\partial t} - q + \text{a vertical leakage term}$$

writing the differential equation in finite difference notation:

$$\left[\frac{T_{i-1}}{x_j} h_{i-1} - \left(\frac{T_{i-1}}{x_j} + \frac{T_i}{x_i}\right) h_i + \frac{T_i}{x_i} h_{i+1}\right]_{t+\Delta t} = \frac{S_i}{\Delta t}(h_{i,t+\Delta t} - h_{i,t}) + qnet_i$$

where $x_i = 0.5 \times (\Delta x_{i-1} + \Delta x_i) \times \Delta x_i$
$x_j = 0.5 \times (\Delta x_{i-1} + \Delta x_i) \times \Delta x_{i-1}$
$qnet_i$ = net inflow to node
and $\Delta x_i$ = distance between nodes i and i+1

The differential equation can be rearranged to produce the Gauss-Seidel iterative relationship, below. This iterative relationship uses updated values as soon as they are calculated.

$$h^{(n+1)}_{i,t+\Delta t} = \frac{S}{\Delta t} h_{i,t} + \frac{T_{i-1}}{x_j} h^{(n+1)}_{i-1,t+\Delta t} + \frac{T_i}{x_i} h^{(n)}_{i+1,t+\Delta t} + qnet_i$$

To develop the iteration formula, replace the right hand side of the equation by the term R. Then add and subtract the value for $h_{i,t+\Delta t}$ at the $n^{th}$ iteration.

$$h^{(n+1)}_{i,t+\Delta t} = [\ R - h^{(n)}_{i,t+\Delta t}] + h^{(n)}_{i,t+\Delta t}$$

The term in brackets [], gives a measure of the change which has been introduced over a single iteration. It can be argued that, if this moves the new value closer to the true solution, then a larger change would speed convergence. Within certain limits, this is the case and successive over-relaxation (SOR) aims to exploit this fact. Increasing the change in the above equation by a factor $\omega$, greater than one and less than two (to avoid difficulties), gives the process its name of *over-relaxation* and provides a rule by which new iterations are defined:

$$h^{(n+1)}_{i,t+\Delta t} = \omega R + (1-\omega)h^{(n)}_{i,t+\Delta t}$$

Convergence

With any iterative scheme there must be a test which is applied to decide that the process has come sufficiently close to the true solution. The basic finite difference equation represents a flow balance and is therefore considered a reliable test for convergence. The rate of convergence can be accelerated by a particular choice for $\omega$. Typical values for $\omega$ in groundwater modelling range from 1.5 to 1.7.

## 5.3 Model Development

The aquifer system is represented by the model as layers of nodes. Parameter values at these nodes will determine the groundwater heads and flows between adjacent nodes (in both vertical and horizontal directions). The parameter values; namely transmissivity, storage coefficient, net inflow and vertical permeability, can vary from node to node.

The model was developed around the SOR iteration procedure for solving the one-dimensional groundwater equation, to represent groundwater flow in a multilayered aquifer system.

Once the SOR iteration routine had been set up, the following physical features were then incorporated into the model:

changes in transmissivity, storage and vertical permeabilities due to spatial variations,
changes between confined and unconfined conditions,
spring flow at outcrop when water levels reached ground level.
changes in net inflow due to spatial variations.

As the aquifer system was represented by the model as layers of nodes, the freedom to choose the number of layers and the spatial variation of nodes was incorporated into the model.

The model generated data for groundwater levels in each of the aquifer layers, vertical leakage between layers and horizontal flow between adjacent spatial nodes.

Three output files were generated by the model to produce records of parameter values used, groundwater heads and flows, and data for use with spreadsheet programmes.

The model was designed to allow the user to input and change data with ease. This was done by allowing the user to define data files, from which the data variables can be read. The model manual is included as Appendix 4.

The strip of Chalk aquifer modelled in the Southern Chalk Investigation was extended from a one layer system to include the Spilsby Sandstone aquifer and then to include the other aquifers lying between the Chalk and the Sandstone.

Reproducing the Chalk model under the same conditions enabled the multi-layered model to be validated[1]. Once validified the model was modified to represent the Chalk aquifer with a more representative set of nodal points.

Further modifications to the model were made to represent unconfined flow in the outcrop area and spring flows into nearby watercourses.

### 5.4 Model Representation

The model representation of the cross-section (Fig 2.) of the aquifer system is shown in Fig 8. and detailed below:

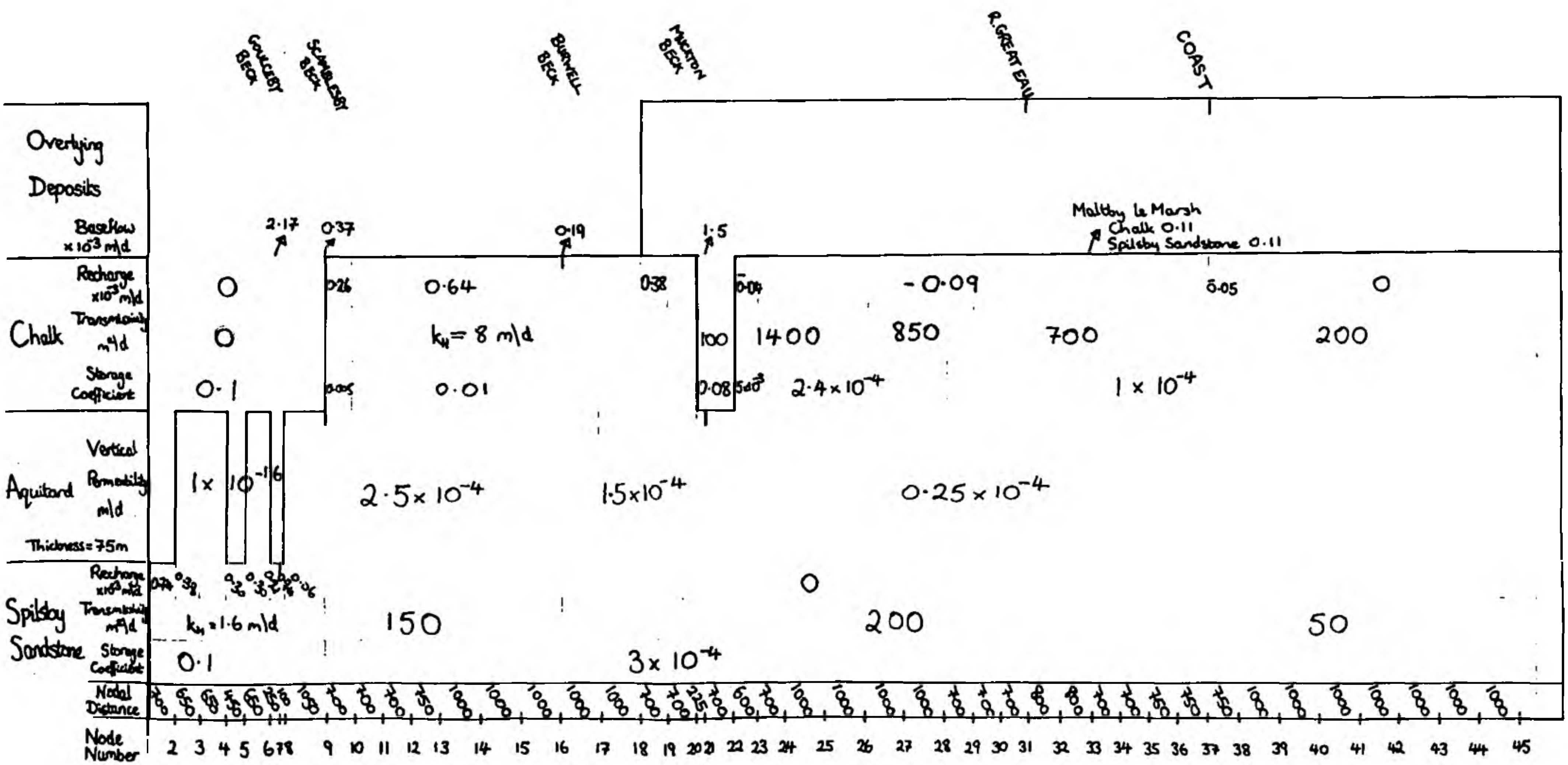
Fig 8. indicates the variations in the parameter values for the Chalk and Spilsby Sandstone aquifers, and the variation in vertical permeability of the aquitard.

---

[1] Validation of the model is explained in Appendix 2

# Model Representation of Cross-Section

Figure 8.




Parameter values shown to right of node

The locations of the nodes were chosen to coincide with points of interest, namely, changes between confined and unconfined conditions, streams and abstraction points, observation boreholes and the buried cliff.

The University of Birmingham's (1982) assumption that fixed heads existed at the buried cliff line and at the coast, was considered unrepresentative of the aquifer system (as this effectively modelled the confined and unconfined halves of the aquifer as two independent systems).

Once the spatial nodes had been determined, values for the transmissivity, storage coefficients and effective recharge were entered using best approximations from the limited field data available.

The values for the vertical permeabilities were originally taken from those used in the Spilsby Sandstone Investigation (Groundwater Development Consultants Limited, 1989).

### 5.5 Model Assumptions

During the course of model development, assumptions were made that no-flow boundaries existed at both the western and eastern boundaries. The no-flow boundary condition was considered acceptable at the eastern boundary because the groundwater gradient under the sea was shallow and hence flows were small. It was also considered that any flow across these boundaries could be modelled as a net inflow into the boundary node.

Estimates to express the effect of abstractions and spring flows as effective recharge (m/d) were made, but due to the available field data were only considered to be the best possible estimates.

Initial values for transmissivities and storage coefficients were approximated from the available field data for the nearest boreholes.

Initial heads in the unconfined Chalk were taken from the Southern Chalk Investigation. In the confined Chalk, initial heads were estimated by a linear approximation between observation water levels and an assumption that a zero water level was present at the coast. Initial heads in the Spilsby Sandstone were estimated from field data for both the Sandstone and the Chalk.

## 5.6 Sensitivity Analysis

To test the sensitivity of the modelled system to the input parameters, a number of simulated runs were made. Each run was made using different combinations of vertical permeability for the leaky layers lying between the Chalk and the Spilsby Sandstone, transmissivity across the buried cliff and the quantity of water abstracted by the Internal Drainage Boards. The range of values tested initially were:

| | |
|---|---|
| Vertical permeability | 0.75 to $5x10^{-4}$ m/d |
| Buried cliff transmissivity | 0, 100, 200, 400 $m^2$/d |
| Quantity of pumped water | 0.09, 0.18, 0.36 mm/d |

The simulated heads were compared to the water levels in the observation boreholes and the 'best-fit' solution determined. The observation nodes and levels used in the 'steady-state' single time step simulation were:

(1,12) 80m aOD (1,16) 49.8m aOD (1,17) 36.4m aOD

(1,23) 7.35m aOD (1,33) 1.1-1.4m aOD (seasonal variations)

(2,23) 63m aOD (2,16) 32.3m aOD.

# CHAPTER 6

# RESULTS AND CONCLUSIONS

## 6.1 Results

The results from the sensitivity analysis show that the model is more sensitive to variations in the transmissivity across the buried cliff and in the quantity of water pumped by the Internal Drainage Boards, and less sensitive to variations in the vertical permeability of the aquitard. The results of the simulated runs are summarised in Table 6.1.

If the transmissivity is too high, then the simulated results in the confined Chalk region were too high. Conversely, with a transmissivity of zero, the simulated results in the confined Chalk region close to the buried cliff were too low.

If the quantity of pumped water was too high, then the simulated heads in the confined Chalk were too low (increasingly so further east). Conversely, if the quantity of pumped water was zero, then the simulated heads were too high.

Variations in vertical permeabilities could 'tune' the simulated results closer to the observed values. This tuning was considered unnatural, so variations in vertical permeabilities were made in 'blocks' corresponding to the Chalk outcrop, the buried cliff region and the confined Chalk region. The simulated vertical permeabilities were observed to decrease from the outcrop,

Table 6.1

Model Sensitivity Analysis

| Run | Trans | Quantity | Aquitard Permeability | | | Comments |
|---|---|---|---|---|---|---|
| Run | across cliff | of pumped water | West *10-4 | Buried Cliff *10-4 | East *10-4 | East of the Buried Cliff only |
| 1 | 0 | 0.36 | 2.5 | 1.5 | 1.5 | Too low |
| 2 | 100 | 0.36 | 2.5 | 1.5 | 1.5 | Better than 1 |
| 3 | 100 | 0 | 2.5 | 1.5 | 1.5 | Too high |
| 4 | 100 | 0.18 | 2.5 | 1.5 | 1.5 | Better than 2 |
| 5 | 200 | 0.18 | 2.5 | 1.5 | 1.5 | Good near cliff |
| 6 | 200 | 0.36 | 2.5 | 1.5 | 1.5 | Too low at coast |
| 7 | 400 | 0.36 | 2.5 | 1.5 | 1.5 | Better at cliff than 6 |
| 8 | 200 | 0.09 | 2.5 | 1.5 | 1.5 | Too high at cliff |
| 9 | 200 | 0.09 | 3 | 1.5 | 1 | as 8 |
| 10 | 200 | 0.09 | 4 | 1.5 | 0.5 | as 8 |
| 11 | 200 | 0.09 | 5 | 2.5 | 0.25 | Better than 8 |
| 12 | 100 | 0.09 | 5 | 2.5 | 0.25 | Best fit |

eastwards to the coast.

It should be noted that in the time available, only a single time step simulation could be modelled. Under this condition, with three variables and minimal observation data, it is possible to get more than one 'best-fit' solution to the differential equation. Further work involving time variant simulations would eliminate this possibilty.

The overall water balance for the aquifer system can be summarised as:

| Inflows | Veritcal Flow | Outflows | |
|---|---|---|---|
| | | Chalk | Spilsby Sandstone |
| Recharge to Chalk 5.030 $m^2/d$ | Downward 1.118 $m^2/d$ | Baseflow 1.217 $m^2/d$ | Baseflow 0.380 $m^2/d$ |
| | | Maltby le Marsh 0.110 $m^2/d$ | Maltby le Marsh 0.110 $m^2/d$ |
| Recharge to Spilsby Sandstone 1.104 $m^2/d$ | Upward 0.047 $m^2/d$ | Tills 1.073 $m^2/d$ | |
| | | Total outflow 2.4 $m^2/d$ | Total outflow 0.49 $m^2/d$ |

The overall net inflow to the Chalk is 2.57 $m^2/d$<br>
net inflow to the Spilsby Sandstone is 1.685 $m^2/d$<br>
net inflow to aquifer system is 3.184 $m^2/d$.

The total flow across the buried cliff (through the Sands and Gravels) is 0.684 $m^2/d$ and through the Spilsby Sandstone in the buried cliff region is 0.551 $m^2/d$.

## 6.2 Conclusions

The values of the transmissivity and quantity of pumped water

that were considered to give the 'best-fit' solution are 100 $m^2/d$ and 0.09 mm/d respectively. For the vertical permeability the values considered to give the 'best-fit' solution are $5\times10^{-4}$m/d in the Chalk outcrop, $2.5\times10^{-4}$m/d in the region of the buried cliff and $0.25\times10^{-4}$m/d in the confined Chalk area.

The value for the transmissivity across the buried cliff of $100m^2/d$ is concluded to be the contribution to groundwater movement made by the overlying Sands and Gravels.

It is apparent that there is vertical leakage through the Tills and that this value is likely to vary considerably with time (increased pumping in winter and water retention during dry periods). It was considered that 0.09mm/d was the best approximation for the single time step.

The results for the horizontal flows in the buried cliff region indicate that a proportion of chalk recharge flows through the Sands and Gravels to the confined Chalk. Chalk recharge also flows downwards to the Spilsby Sandstone and then some reemerges in the confined Chalk via upward flow.

Although the overall net inflow to the aquifer system is not conclusive over a single time step, it does however, indicate an imbalance of flows which would lead to an increase in groundwater levels in time. This imbalance could be overcome in a time variant simulation.

# CHAPTER 7

## RECOMMENDATIONS

The results obtained in this study, due to the lack of available field data and time available, are far from conclusive. It is therefore recommended that an extensive investigation should commence to further the findings of this study.

The initial investigation should be concentrated in the region modelled in this study and include the following:

An increase in the number of water level observation boreholes in particular those monitoring levels in the confined Spilsby Sandstone, Carstone and Roach Rock and in the Superficial Deposits. The later would then be used to determine if hydraulic continuity existed between the Deposits and the Chalk.

An extension of the model to simulate the Carstone and Roach Rock aquifers and time-variant situations.

A re-assessment of the parameter values used with comparisons being made to more recent field data.

Gauging of the water pumped by the Internal Drainage Boards to gain a better estimate of the upflow through the Tills.

A chemical analysis of the water in the Tills to determine its origin.

The model should then be extended to simulate representative strips of the aquifer system further north where the Spilby Sandstone outcrop diminishes in area, further south to include

the R. Lymn catchment and the superficial deposits lying in contact with the Spilsby Sandstone and the area of Chalk outcrop to the east of the buried cliff, and sections in the north-south direction.

Reassessment of the Northern Chalk Model (University of Birmingham, 1987), to allow for leakage from the Chalk outcrop across the buried cliff and for leakage through the Tills should also be carried out.

CHAPTER 8

# BIBLIOGRAPHY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## APPENDICES

## APPENDIX 1

## ALFORD DRAINAGE BOARD

### History

The Drainage Boards have evolved from the Commission of Sewers which was set up by the crown in the 13th century. The Statute of Sewers, passed in 1531, is now regarded as the foundation for land drainage. The Commissioners and the drainers of the Lindsey Marsh had three main basic tasks; one, to keep secure the defences against the sea, two, to embank the rivers and streams to stop the water being carried from the highlands spilling out onto the lowlands and to provide adequate outfalls to the sea, and three, to evacuate the water from lowlying lands by creating artificial channels with sluices to allow the water to drain off when tide and river levels allowed. One other important task was in summer periods when the water level fell or droughts occurred. Many of the channels were originally engineered with outlets from the rivers and with retention gates, in order to transport and provide water for the rich marsh pastures in dry seasons.

### Geography

The majority of the drains in the rateable catchment of the Alford Drainage Boards (Fig 9.) are on the Marshes to the East of the Buried Cliff. The average elevation of the land in the area is 0.6m aOD. The drains in the vicinity of the town of Alford lie in a small area of Chalk outcrop. The average elevation of the town of Alford is 9m aOD.

The Great Eau, Long Eau and Woldgrift, which are spring fed and now managed by the NRA, are at a higher elevation then the drains.

Each pumping station has a catchment area in which all drainage channels flow to that pumping station. This area if often larger than the rateable catchment, (27,758ha and 22,275ha respectively, for the Alford Drainage Board Catchments) as water flows from higher ground into the lower ground of the rateable catchment.

**Theddlethorpe Catchment**

The main drain in the catchment is the Mablethorpe Cut (subdivided in to Upper, Middle and Lower Cuts), to which all the drains in the catchment drain.

During dry conditions the Upper Cut is syphoned under the Great Eau, at the site of the pumping station, into the Middle Cut and then to Mablethorpe where it flows out to sea at low tide under gravity. During wetter periods the penstocks at Bleak House (TF 49 87) are closed and water from the Upper and Middle Cuts is pumped into the Great Eau and thence to the sea.

The pumps, under normal conditions have start up and stop levels, and also have a temporal control for regulated use during the different electricity rating periods, (-0.2m start, -0.6m stop, during off-peak times). Each pump is designed to operate 1000hrs/yr. However, since 1989 the three pumps have only been in operation for a total of 225hrs (pump 3 has not yet been

used).

## Mablethorpe Tidal Outlet

At the Mablethorpe tidal discharge, the normal level in the Lower Mablethorpe Cut for discharge is 0.4m. Due to the drought the current level is maintained at about 0.6m.

## The Drains

The Alford Drainage Board maintains 250 miles of open drains and about 18 miles of culverts. The drains are dug with a bed slope of about 1 in 3000 and with banks having about 1m free-board (ie 1m of bank above the normal water level).

Analysis of the banks indicate a thin band of blue clay overlying running silty sand, or silt overlying marl. In the area of the South Somercotes Ings (TF 41 92) pockets of running sand were found when the drains were dug.

A seepage face of about 30cm was clearly visible in a recently cut channel.

Matting of the beds and erecting toe-boards up the banks help to prevent erosion.

Deweeding can be carried out up to 3 times a year and desilting and other maintenance is carried out at a rate of about 25miles/year.

**Spring Flows**

Spring flows in the Theddlethorpe catchment are characterised by area of boggy land and quite often plantations. Boggs Plantation and the western branch of the Dowse Fen Drain are two such areas, with the bogginess being about 40cm deep. The area has a layer of peat about 25cm thick overlying a shingle-sand layer.

**Mill Rundle Drain, Alford**

The drain lies on an area of Chalk outcrop and is now maintained as a conservation area. Analysis of the bank, which is about 3m deep, shows hard Marl, with particles of blue Clay, overlying Chalk and Gravels. In places, there are small bands of peat.

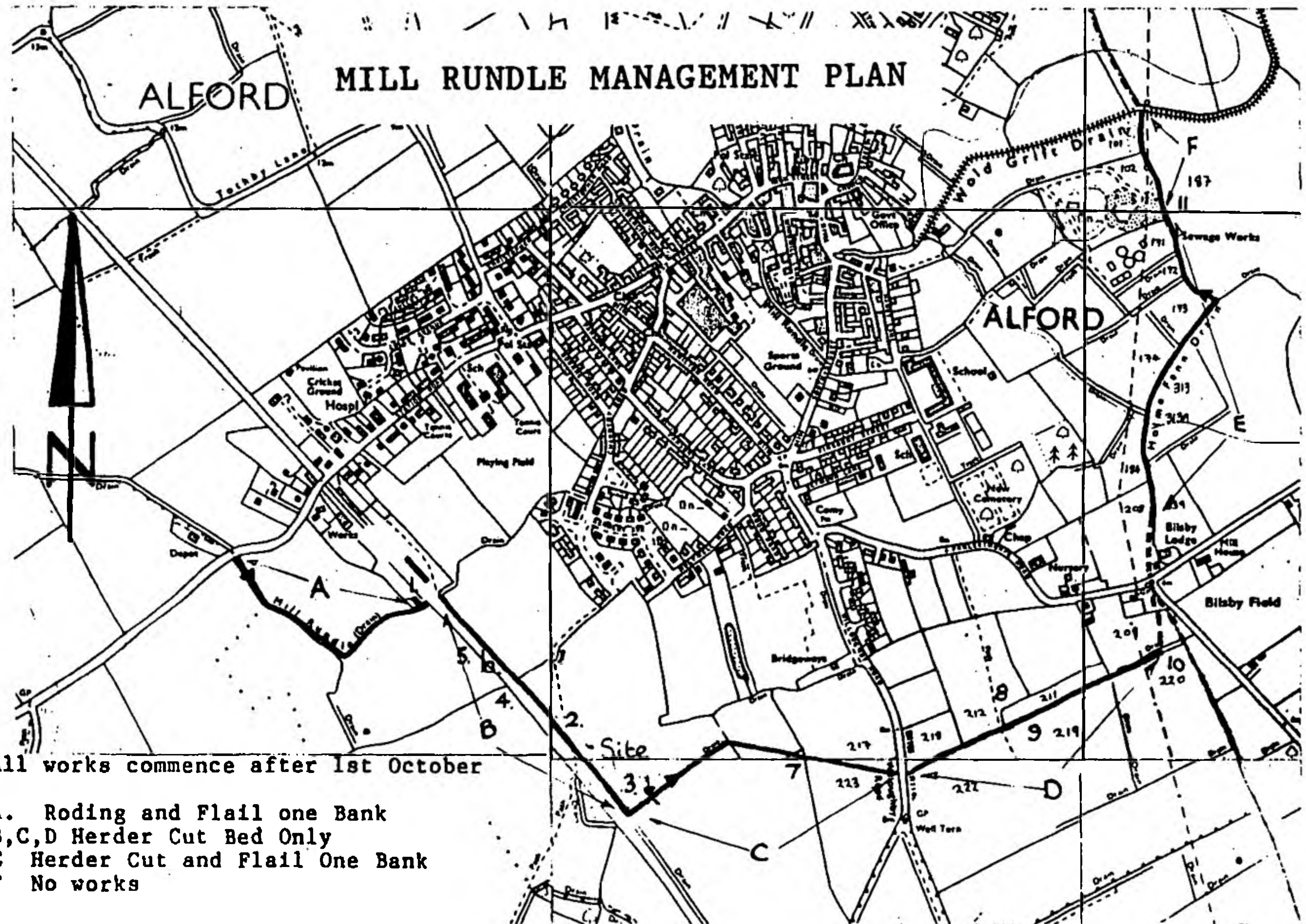
At site 3 in Fig 10, upflow is clearly visible. The surrounding weeds have been discoloured, brown. This may suggest the presence of iron in the water. An Anglian Water Services chemical analysis of the water determined that it was originating from about 20m below ground. Confirmatory analysis has not been carried out.

This site was where a concrete bridge had to be demolished after cracks appeared, only a couple of months after completion.

## PUMPING STATIONS IN ALFORD DRAINAGE DISTRICT

| | Name | Area ha | Pumps/Type No/Size | Motor/ Power | Capacity ltrs/sec | Outfall and destination of pumped water | Operation Commenced |
|---|---|---|---|---|---|---|---|
| 1 | Theddlethorpe | 4760 | Gwynnes<br>2-900mm AFV<br>NEI-APE Ltd<br>1-800mm AFS | Electric<br>108Kw<br>Electric<br>110Kw | 4100<br><br>1850 | To River Great Eau thence to Saltfleet Haven | 1956<br><br>1989 |
| 2 | Fulbeck | 354 | Beford Pump Co.<br>2-600mm AFS | Electric<br>46Kw | 1640 | To Mablethorpe Outfall | 1990 |
| 3 | Trusthorpe | 3611 | Gwynnes<br>3-900mm AFV | Electric<br>108Kw | 5350 | To Trusthorpe sea outfall | 1956 |
| 4 | Boygrift | 2185 | Gwynnes<br>3-675mm AFV | Electric<br>82Kw | 3483 | Boygrift Basin to sea outfall | 1966 |
| 5 | Anderby<br>(Standby Only) | 3612 | Gwynnes<br>2-1050mm CFH | Ruston 10HRC<br>Diesel-116Kw | 4588 | Anderby Creek Outfall to sea | 1945 |
| 6 | Anderby (New) | 3612 | Bedford Pump Co.<br>3-800mm MFS | Electric<br>90Kw | 4680 | Anderby Creek Outfall to sea | 1992 |
| 7 | Chapel Basin | 0.4 | Flygt<br>1-75mm CFS | Electric<br>1.3Kw | 17 | Chapel Basin to sea | 1981 |
| 8 | Ingoldmells<br><br><br>(Skegness D.D. 1080 ha) | 2975 | Gwynnes<br>2-900mm AFV<br>1-750mm AFV | Electric<br>149Kw<br>Paxman<br>Diesel 131Kw | 5438 | Ingoldmells Basin to sea | 1966 |
| 9 | Wyche | 855 | Bedford Pump Co.<br>2-450mm AFS | Electric<br>30Kw | 1220 | To Wyche system thence via Willoughby High Drain to Chapel Pumping Station | 1989 |
| 10 | Nursery<br>(Habertoft) | 88.3 | Brit. Guinard<br>1-250mm AFS | Electric<br>7.5Kw | 159 | To Wyche system thence via Willoughby High Drain to Chapel Pumping Station | 1986 |
| 11 | Boothby | 58.5 | Brit. Guinard<br>1-150mm CFS | Electric<br>4Kw | 65 | To Wyche system thence via Willoughby High Drain to Chapel Pumping Station | 1986 |
| **Operated by National Rivers Authority** | | | | | | | |
| 12 | Chapel St.<br>Leonards<br>Old Station | 6560 | Gwynnes<br>2-1050mm CFH<br>1-900mm AFV | Ruston 10RHC<br>Diesel 116Kw<br>Electric 200Kw | 6900 | Chapel Basin to Sea | 1946 |
| 13 | New Station | | NEI-APE Ltd<br>3-1000mm AFV | Electric<br>200Kw | 7890 | Chapel Basin to Sea | 1986 |

# Alford Drainage Board




All works commence after 1st October

A. Roding and Flail one Bank
B,C,D Herder Cut Bed Only
E Herder Cut and Flail One Bank
F No works

Any emergency works as required.

Figure 10.

Mill Rundle Drain, Alford

ALFORD DRAINAGE BOARD CATCHMENT

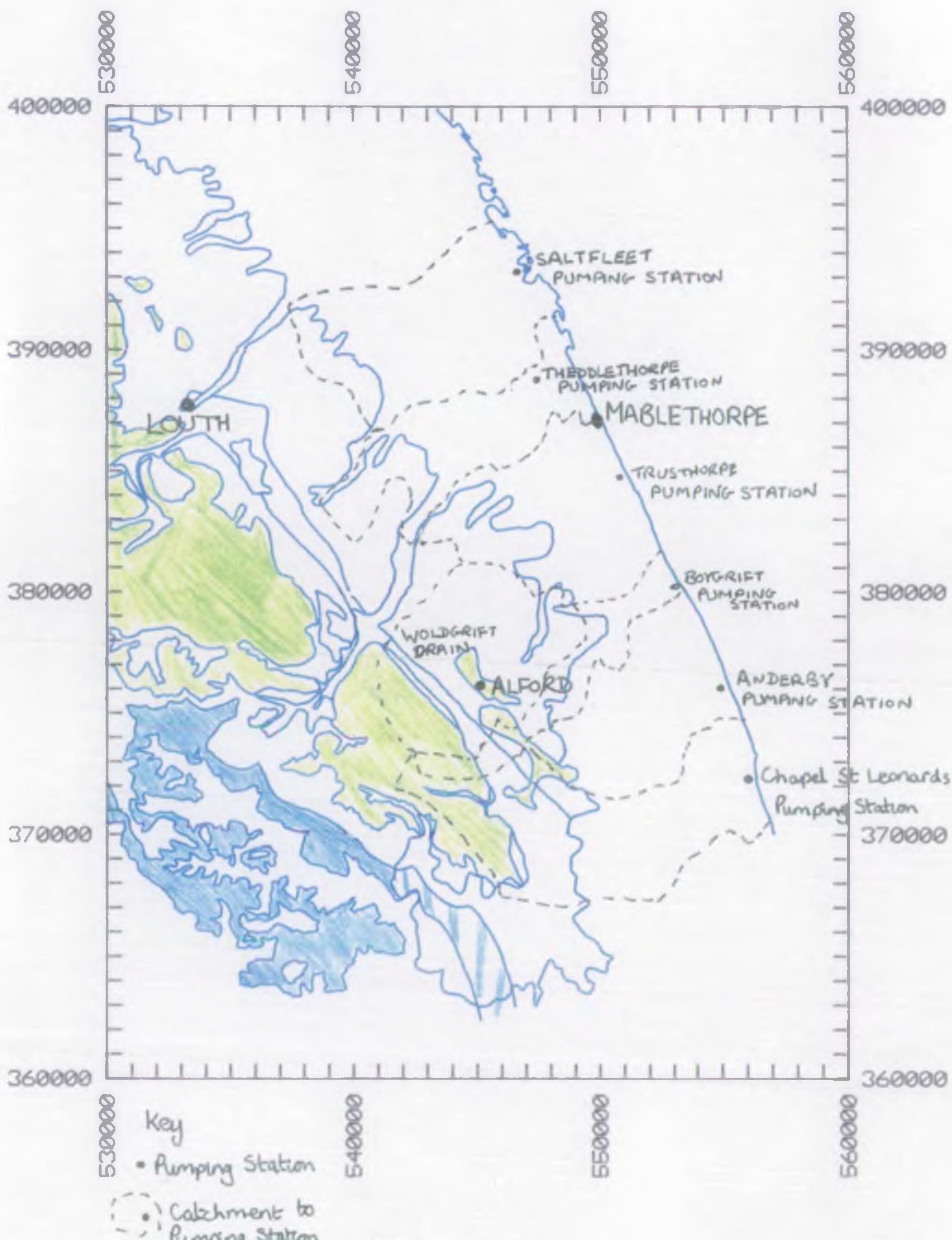



Figure 9

## APPENDIX 2

## MODEL VALIDATION

To validate the model two solutions were considered.

Firstly, an analytical solution to a simple feasible aquifer system. Secondly, a comparison to a previous model, namely the one used in the Southern Chalk Investigation (University of Birmingham, 1982)

### The Analytical Solution

Consider a simple two layered aquifer with recharge, q, to the top layer and abstractions equal to the recharge from the bottom layer.

The boundary conditions are a no-flow boundary at x=0 and a fixed head in both layers at x=L.

The general steady state equation for the top layer, a, is :

$$T^a \frac{d^2h^a}{dx^2} = -q + \frac{k}{m}(h^a - h^b)$$

similarly for layer b,

$$T^b \frac{d^2h^b}{dx^2} = q - \frac{k}{m}(h^a - h^b)$$

Adding the two equations and rearranging,

$$\frac{d^2h^a}{dx^2} = -\frac{T^b}{T^a} \frac{d^2h^b}{dx^2}$$

integrating twice and applying the no-flow boundary condition

$$\frac{dh^a}{dx} = \frac{dh^b}{dx} = 0 \text{ at } x=0$$

$$h^a = -\frac{T^b}{T^a} h^b + C \qquad \text{where C=constant of integration}$$

applying the fixed head boundary condition at x=L

$C \quad = H^a + \frac{T^b}{T^a} H^b$ where $H^a$ and $H^b$ are the fixed heads

Now substituting for $h^b$

$$\frac{d^2h^a}{dx^2} = -\frac{q}{T^a} + \frac{k}{mT^a}\left( h^a + \frac{T^a h^a}{T^b} - \frac{T^a C}{T^b}\right)$$

rearranging as

$$\frac{d^2h^a}{dx^2} - \frac{k}{mT^a}\left(1+\frac{T^a}{T^b}\right)h^a = -\frac{q}{T^b} - \frac{kC}{mT^b}$$

This is the general second order differential equation

$$h'' - D^2 h = K$$

which has the solution

$$h = A\cosh(Dx) + B\sinh(Dx) - \frac{K}{D^2}$$

since $h'=0$ at $x=0$, => $B=0$

$$h^a = A\cosh(Dx) - \frac{K}{D^2}$$

where $D^2 = \frac{k(T^b+T^a)}{mT^aT^b}$ , $K = -\frac{q}{T^a} - \frac{k}{m}\left(\frac{H^a}{T^b} + \frac{H^b}{T^a}\right)$

and A is determined from the boundary condition

$$h^a = H^a \quad \text{at } x=L$$

Hence $h^b = \frac{T^a}{T^b}(C - h^a)$

This solution was then used to validate the values generated by the model under the same conditions.

The analytical problem to the following parameter values

$T^a=750$, $T^b=250$, $H^a=25$, $H^b=15$
$q=10^{-3}$, $L=10000$, $k=10^{-4}$, $m=20$

gives the solution

| at x= | 0 | 2000 | 5000 | 8000 | 10000 |
|---|---|---|---|---|---|
| $h^a$= | 54.62 | 53.66 | 48.33 | 37.07 | 25 |
| $h^b$= | -73.86 | -70.98 | -54.99 | -21.21 | 15 |

the values generated by the model, with the dummy storage variable, $S=10^{-16}$, are

| | | | | | |
|---|---|---|---|---|---|
| $h^a$= | 54.60 | 53.64 | 48.30 | 37.07 | 25.00 |

$h^b$= -73.78 -70.90 -54.90 -21.18 15.00

these values compare favourably with the analytical values. Hence the model was taken as valid.

**Model Comparison**

The model was set up to reproduce the values generated in the one-layered Southern Chalk model. The model had two layers, but a vertical permeability of $10^{-15}$ ensured no vertical leakage and hence the model could represent the single chalk aquifer.

Other than the head value at the ground water divide boundary, the model reproduced the results generated in the Chalk model. The boundary discrepancy, which was less than 0.5%, was due to the methods used at the boundary:

Pictured as an imaginary node, boundary node and the first internal node, the model set the boundary condition as the imaginary node's head was equal to that of the first internal node ie a no-flow boundary. However, the Southern Chalk model was set up with the imaginary node equal to the initial head of the first internal node, which, for a time variant problem is incorrect.

APPENDIX 3

MODEL RESULTS

The output generated by the model for the best fit simulation is shown below. Two output file are shown, the first contains all the calculated values for heads, vertical and horizontal flows for the two-layer model. The second output files contains all the input aquifer parameters.

Calculated Output File

```
RUN 12 (Best Fit)
 Node          1        2        3        4        5        6        7        8
   9
 Node         10       11       12       13       14       15       16       17
   18
 Node         19       20       21       22       23       24       25       26
   27
 Node         28       29       30       31       32       33       34       35
   36
 Node         37       38       39       40       41       42       43       44
   45

Layer  1
  Head     65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00
71.49
  Head     79.66   83.95   80.01   75.31   72.55   61.16   50.03   36.34
27.04
  Head     18.26   14.01   12.97    7.68    7.25    6.76    6.10    5.50
 4.63
  Head      3.84    3.34    2.77    2.26    1.72    1.24     .95     .71
  .52
  Head       .38     .07    -.34    -.72   -1.09   -1.44   -1.76   -2.02
-2.14

Hor.Flow          .000    .000    .000    .000    .000    .000    .000
 .000 -6.671
Hor.Flow        -3.907   3.776   4.011   1.665   6.608   5.448   5.480
2.704  2.711
Hor.Flow          .887    .461    .756   1.017    .976    .920    .842
 .738   .672
Hor.Flow          .612    .563    .518    .472    .421    .285    .237
 .184   .123
Hor.Flow          .084    .081    .077    .074    .070    .064    .051
 .025

Vert.Flow  .0000  .0000  .0000  .0000  .0000  .0000  .0000  .0000
-.0498
Vert.Flow -.0937 -.1335 -.1410 -.1697 -.2100 -.1638 -.1186 -.0278
-.0097
```

```
Vert.Flow  .0044  .0004  .0004  .0014  .0014  .0018  .0023  .0025
.0027
Vert.Flow  .0023  .0018  .0018  .0020  .0022  .0022  .0021  .0022
.0023
Vert.Flow  .0024  .0026  .0008  .0006  .0007  .0008  .0009  .0010
.0010

Layer  2
  Head      68.02  70.00  72.00  73.99  72.00  68.99  66.92  65.03
62.95
  Head      59.57  55.35  50.84  46.22  41.05  36.60  32.24  27.99
23.60
  Head      20.13  16.78  15.83  14.23  13.58  13.23  13.04  12.93
12.72
  Head      12.12  10.91  10.38  10.14  10.00   9.86   9.92   9.94
 9.91
  Head       9.82   8.91   2.00   1.13   1.01   1.00   1.00   1.00
 1.00

Hor.Flow        -.309  -.344  -.352   .522   .533   .915  2.024
 .207   .723
Hor.Flow         .906   .966   .924   .775   .668   .653   .849
 .879   .990
Hor.Flow         .958   .849   .456   .215   .100   .038   .023
 .041   .121
Hor.Flow         .344   .151   .069   .036   .034  -.018  -.004
 .007   .024
Hor.Flow         .061   .345   .044   .006   .001   .000   .000
 .000


Aquifer Parameter Output File

Node         1         2         3         4         5         6
  7         8
Node         9        10        11        12        13        14
 15        16
Node        17        18        19        20        21        22
 23        24
Node        25        26        27        28        29        30
 31        32
Node        33        34        35        36        37        38
 39        40
Node        41        42        43        44        45
Delta X
             700.      650.      650.      450.      650.      250.
   100.     1050.
             700.      700.      700.      750.     1000.     1000.
  1000.     1000.
            1000.      700.      700.      225.      700.      600.
   700.     1000.
            1000.     1000.     1000.      700.      700.      700.
   800.      800.
             700.      700.      750.      750.      750.     1000.
  1000.     1000.
            1000.     1000.     1000.     1000.
 Layer  1
Storage coefficients
```

```
           .1000     .1000     .1000     .1000     .1000     .1000
 .1000     .1000
           .0050     .0100     .0100     .0100     .0100     .0100
 .0100     .0100
           .0100     .0100     .0100     .0800     .0800     .0050
 .0002     .0002
           .0002     .0002     .0002     .0001     .0001     .0001
 .0001     .0001
           .0001     .0001     .0001     .0001     .0001     .0001
 .0001     .0001
           .0001    .0001     .0001     .0001     .0001
Transmissivity (-ve= -kx)
             .0        .0        .0        .0        .0        .0
  .0         .0
           -8.0      -8.0      -8.0      -8.0      -8.0      -8.0
-8.0       -8.0
           -8.0      -8.0      -8.0     100.0     100.0    1400.0
1400.0     1400.0
         1400.0     850.0     850.0     850.0     700.0     700.0
700.0      700.0
          700.0     700.0     700.0     700.0     200.0     200.0
200.0      200.0
          200.0     200.0     200.0     200.0     200.0
Effective Recharge
        .00E+00   .00E+00   .00E+00   .00E+00   .00E+00   .00E+00
 .00E+00   .00E+00
       -.11E-03   .64E-03   .64E-03   .64E-03   .64E-03   .64E-03
 .64E-03   .45E-03
        .64E-03   .38E-03   .00E+00   .00E+00  -.15E-02  -.40E-04
-.90E-04 -.90E-04
       -.90E-04  -.90E-04  -.90E-04  -.90E-04  -.90E-04  -.90E-04
-.90E-04 -.90E-04
       -.20E-03  -.90E-04  -.90E-04  -.90E-04  -.45E-04   .00E+00
 .00E+00   .00E+00
        .00E+00  .00E+00  .00E+00  .00E+00  .00E+00
Vertical Permeability
        .10E-15   .10E-15   .10E-15   .10E-15   .10E-15   .10E-15
 .10E-15   .10E-15
        .50E-03   .50E-03   .50E-03   .50E-03   .50E-03   .50E-03
 .50E-03   .50E-03
        .25E-03   .25E-03   .25E-03   .25E-04   .25E-04   .25E-04
 .25E-04   .25E-04
        .25E-04   .25E-04   .25E-04   .25E-04   .25E-04   .25E-04
 .25E-04   .25E-04
        .25E-04   .25E-04   .25E-04   .25E-04   .25E-04   .25E-04
 .25E-04   .25E-04
        .25E-04  .25E-04  .25E-04  .25E-04  .25E-04
Aquitard Thickness  75.
 Layer  2
Storage coefficients
           .1000     .1000     .1000     .1000     .1000     .1000
 .1000     .1000
           .0100     .0003     .0003     .0003     .0003     .0003
 .0003     .0003
           .0003     .0003     .0003     .0003     .0003     .0003
 .0003     .0003
           .0003     .0003     .0003     .0003     .0003     .0003
 .0003     .0003
```

```
         .0003     .0003     .0003     .0003     .0003     .0003
.0003     .0003
         .0003     .0003    .0003     .0003     .0003
Transmissivity (-ve= -kx)
          -1.6      -1.6      -1.6      -1.6      -1.6      -1.6
-1.6      -1.6
         150.0     150.0     150.0     150.0     150.0     150.0
150.0     200.0
         200.0     200.0     200.0     200.0     200.0     200.0
200.0     200.0
         200.0     200.0     200.0     200.0     200.0     200.0
200.0     200.0
         200.0     200.0     200.0     200.0      50.0      50.0
50.0      50.0
          50.0      50.0      50.0      50.0      50.0
Effective Recharge
      .74E-03   .33E-03   .10E-15   .30E-03   .30E-03   .21E-03
-.14E-02  .60E-04
      .00E+00   .00E+00   .00E+00   .00E+00   .00E+00   .00E+00
.00E+00   .00E+00
      .00E+00   .00E+00   .00E+00   .00E+00   .00E+00   .00E+00
.00E+00   .00E+00
      .00E+00   .00E+00   .00E+00   .00E+00   .00E+00   .00E+00
.00E+00   .00E+00
     -.11E-03   .00E+00   .00E+00   .00E+00   .00E+00   .00E+00
.00E+00   .00E+00
      .00E+00   .00E+00   .00E+00   .00E+00   .00E+00
```

APPENDIX 4

MODEL MANUAL

## Introduction

The model has been written with the users interests in mind. For ease use, the model has been set up to read all input variables from named data files and to output the results to a user defined file.

## Programme Set Up

Copy the programme from the disk to the chosen directory on the hard disk. The programme can be run from the data disk directory by typing c:mace. This will enable data files to be run from diskette files without having to unnecessarily copy the programme several times.

Data files can now be prepared in the following format:

The only file prompted for by the model is the start up file, namely START.DAT

## START.DAT

Data for this named file has to be entered in the following format:

```
aaaaaa.OUT     1 Results Output file name
bbbbbb.DAT     2 Delta X file name
cccccc.DAT     6 Transmissivity Data file name
dddddd.DAT     3 Aquitard Parameters file name
eeeeee.DAT     4 Groundwater Head Data file name
ffffff.DAT     5 Storage Coefficients file name
gggggg.DAT     7 Effective Recharge Data file name
hhhhhh.OUT     8 Parameters Output file name
1 Title(max 16 Chars)
2 Number of Layers (integer)   dimensioned up to 6 but not tested.
```

3Number of Nodes (integer) dimensioned up to 50 6 layers, each 50 nodes.
5Time Step (real.d2)
1Run Time (real.d2)
4SOR factor (real.d2) re-1, 2 dec. pl.
6Accuracy (real.d7)

**DeltaX.DAT**
Distance between successive nodes (Number of nodes -1)

**Trans.DAT**
Transmissivity between successive nodes (Number of nodes)
*Enter negative permeability for unconfined conditions*
Repeat for each layer

**Aqui.DAT**
Vertical permeability (Number of nodes)
Aquitard thickness
Repeat for each aquitard

**Head.DAT**
-1 for fixed heads,
1 for free heads (number of nodes)
Repeat for each layer
Initial heads (number of nodes)
Repeat for each layer
Maximum head levels (Number of nodes)
Repeat for each layer

**Store.DAT**
Storage coefficients (Number of nodes)
Repeat for each layer

**Rech.DAT**
Effective recharge (Number of nodes)
Repeat for each layer

A listing of the groundwater model and examples of data input files are included below:

## The Groundwater Model

```
c       GROUNDWATER MODEL
        implicit double precision (a-h,o-z)
        dimension hint(6,0:50),h(6,0:50),stat(6,49)
        dimension store(6,49),tran(6,0:49),uncon(6,0:49)
        dimension qnet(6,49),q(6,49),ts(6,49),r(6,49)
        dimension bk(5,49),b(5),x(0:49),dx(49)
        dimension vertf(49),horif(49),stream(6,49),hmax(6,49)
        character*32 fname,deltax,aqui,heads
        character*32 stores,trans,rech,outname
        character*32 title
        open(10,file='start.dat',status='old')
        read(10,'(a)')fname,deltax,aqui,heads
        read(10,'(a)')stores,trans,rech
        read(10,'(a)')outname,title
        read(10,'(i2)')lay,nod
        read(10,*)w,dt
```

```
      read(10,'(i5)')irun
      read(10,*)error
      close(10)
      open(20,file=fname,status='unknown')
      open(25,file=outname,status='unknown')
      open(28,file='super.out',status='unknown')

c     VARIABLES   description
c     h(layer,node)-groundwater head
c     store(l,i)-storage coefficient
c     tran(l,i)-transmitivity
c     qnet(l,i)-net inflow to node i
c     q(l,i)-recharge/abstraction
c     bk(l)-permeability between layers l and l+1
c     b(l)-thickness between layers l and l+1
c     ts(l,i)-tran/store divisor
c     r(l,i)-iteration relationship
c     w-SOR factor
c     n-iteration number
c     itime-run time

c     (AQUIFER PROPERTIES)   Set up mesh
      open(30,file=deltax,status='old') - mesh intervals
      read(30,*)(x(i),i=1,(nod-1))
      close(30)
      x(0)=x(1)
      x(nod)=x(nod-1)
      itime=0
      irun=nint(irun/dt)

c     (INITIAL CONDITIONS)   Read in vertical permeability values
      open(40,file=aqui,status='old')   for aquitard, and thickness
      do 4 l=1,(lay-1)
4     read(40,*)(bk(l,i),i=1,nod),b(l)
      close(40)
```

```
c     OUTPUT VARIABLES TO FILE
      write(25,899)(i,i=1,nod)
899   format('Node',8i9)
      write(25,900)
900   format('Delta X')
      write(25,910)(x(i),i=1,nod-1)
      write(28,'(f7.0)')(x(i),i=1,nod-1)
910   format(8x,8f9.0)

c     INITIAL HEADS
      open(50,file=heads,status='old')
      read(50,*)((stat(l,i),i=1,nod),l=1,lay)   status (based on free head) -1 for fixed, +1 for free
      read(50,*)((hint(l,i),i=1,nod),l=1,lay)   initial heads
      read(50,*)((hmax(l,i),i=1,nod),l=1,lay)   max head, related
      close(50)                                 to springflow - any head > hmax
                                                appears as springflow.
c     STORAGE COEFFICIENTS
      open(60,file=stores,status='old')
      read(60,*)((store(l,i),i=1,nod),l=1,lay)   reading storage values.
      close(60)
      do 6 l=1,lay
      do 5 i=1,nod
```

```
      uncon(l,i)=-1                      | Setting up parameters for later.
      stream(l,i)=-1
5     h(l,i)=hint(l,i)                   initial condition for first iteration.
6     continue

c     RECHARGE                                            -ve is net outflow
      open(80,file=rech,status='old')
      read(80,*)((q(l,i),i=1,nod),l=1,lay)   reading in recharge.
      close(80)

c     TRANSMISSIVITY
      open(70,file=trans,status='old')
      read(70,*)((tran(l,i),i=1,nod),l=1,lay)   reading in T
      close(70)
      do 15 l=1,lay

c     OUTPUT VARIABLES TO FILE
      write(25,458)l
      write(25,920)
920   format('Storage coefficients')
      write(25,930)(store(l,i),i=1,nod)
930   format(4x,8f9.4)
      write(25,940)
940   format('Transmissivity (-ve= -kx)')
      write(25,950)(tran(l,i),i=1,nod)
950   format(4x,8f9.1)
      write(25,960)          Net inflow to node
960   format('Effective Recharge')
      write(25,970)(q(l,i),i=1,nod)
970   format(4x,8e9.2)
      if(l.lt.lay)write(25,980)
      if(l.lt.lay)write(25,990)(bk(l,i),i=1,nod)
      if(l.lt.lay)write(25,1000)b(l)
980   format('Vertical Permeability')
990   format(4x,8e9.2)
1000  format('Aquitard Thickness ',f4.0)

      do 10 i=1,nod           sets distance between midpoints of mesh.
      dx(i)=0.5*(x(i)+x(i-1))
      if(tran(l,i).lt.0.)uncon(l,i)=-1*tran(l,i)          } calcs unconfined
      if(uncon(l,i).gt.0.)tran(l,i)=uncon(l,i)*h(l,i)    }  T(=kh)
      tran(l,i)=tran(l,i)/x(i)       }  T/Δx
10    store(l,i)=store(l,i)/dt       }  S/Δt   constants in equation
15    tran(l,0)=tran(l,2)
                        no flow boundary condition
c     LEAKY FACTORS
      do 33 l=1,(lay-1)               Vertical permeability
      do 32 i=1,nod                   aquitard thickness
32    bk(l,i)=bk(l,i)/b(l)
33    continue

c     ITERATION PROCEDURE
      write(6,*)'Starting Iteration Procedure'
      n=0
100   do 300 l=1,lay
      do 200 i=1,nod
```

```
c       FIXED HEADS                                  misses out procedure for
        if(stat(l,i).lt.0.)goto 200                  fixed heads

c       NET INFLOW                                     leaky term from above
        if(l.gt.1.and.l.lt.lay)qnet(l,i)=bk(l,i)*(h(l-1,i)-h(l,i))
        if(l.gt.1.and.l.lt.lay)qnet(l,i)=qnet(l,i)+q(l,i)-
leaky term  + leaky -(bk(l,i)*(h(l,i)-h(l+1,i)))        recharge
bottom
        qnet(l,i)=q(l,i)-(bk(l,i)*(h(l,i)-h(2,i)))  -  net inflow top layer
        qnet(lay,i)=q(lay,i)+bk(lay-1,i)*(h(lay-1,i)-h(lay,i)) - net
                                                                 inflow bottom
c       BOUNDARY CONDITIONS                                      layer
        h(l,0)=h(l,2)              } no flow
        h(l,nod+1)=h(l,nod-1)      } boundary condition
        if(uncon(l,i).gt.0.)tran(l,i)=uncon(l,i)*h(l,i)/x(i) } updates
        tran(l,0)=tran(l,2) - boundary condition              } unconfined
                                                                T
c       ITERATION RELATION
        ts(l,i)=tran(l,i-1)/dx(i)
       +     +tran(l,i)/dx(i)+store(l,i)
        r(l,i)=store(l,i)*hint(l,i)
        r(l,i)=r(l,i)+qnet(l,i)
        r(l,i)=r(l,i)+tran(l,i-1)*h(l,i-1)/dx(i)
        r(l,i)=r(l,i)+tran(l,i)*h(l,i+1)/dx(i)
        r(l,i)=r(l,i)/ts(l,i)
        h(l,i)=w*r(l,i)+((1-w)*h(l,i))

        if(h(l,i).gt.hmax(l,i))stream(l,i)=h(l,i)-hmax(l,i)) streamflow
        if(h(l,i).lt.hmax(l,i).and.stream(l,i).gt.0)     { if head reaches
       +    stream(l,i)=-1                               { max head
        if(h(l,i).gt.hmax(l,i))h(l,i)=hmax(l,i)           (ground level)

 200    continue
 300    continue

c       TEST CONVERGENCE
        do 400 l=1,lay
        do 350 i=1,nod
        if(stat(l,i).lt.0.)goto 350 - skips if fixed head
        if(stream(l,i).gt.0.)goto 350 - skips if max head reached
        delta=store(l,i)*hint(l,i)+qnet(l,i)
       +      +tran(l,i-1)*h(l,i-1)/dx(i)
       +      +tran(l,i)*h(l,i+1)/dx(i)
       +      -ts(l,i)*h(l,i)
        delta=abs(delta)
        if(delta.gt.error)goto 500
 350    continue
 400    continue

c       TIME+1 TO TIME               increases time step
        itime=itime+1                )
        do 420 l=1,lay               }
        do 410 i=1,nod               )
        hint(l,i)=h(l,i)
 410    continue
 420    continue
        write(6,*)n+1
        n=0
        if(itime.lt.irun)goto 100 - continues run if end time not reached
```

```
c      OUTPUT ROUTINE
       write(20,'(a)')title
       write(20,450)(i,i=1,nod)
450    format(1x,'Node',3x,9i7)
       do 490 l=1,lay
       do 455 i=1,nod
       if(i.lt.nod)horif(i)=-tran(l,i)*(h(l,i+1)
      +        -h(l,i))
       if(l.lt.lay)vertf(i)=-bk(l,i)*(h(l,i)-
      +        h(l+1,i))*dx(i)
455    continue
       write(20,458)l
458    format(' Layer ',i2)
       write(20,459)(h(l,i),i=1,nod)
459    format(2x,'Head',3x,9f7.2)
       write(20,460)(horif(i),i=1,nod-1)
460    format('Hor.Flow',5x,9f7.3)
       write(20,*)
       if(l.lt.lay)write(20,470)(vertf(i),i=1,nod)
       if(l.lt.lay)write(28,'(f7.3)')(vertf(i),i=1,nod)
470    format('Vert.Flow',9f7.4)
490    write(20,*)
       open(99,file='newhead.dat',status='unknown')
       write(99,*)((stat(l,i),i=1,nod),l=1,lay)
       write(99,*)((h(l,i),i=1,nod),l=1,lay)

c      STREAM FLOW OUTPUT
       do 492 l=1,lay
       do 491 i=1,nod
491    if(stream(l,i).gt.0.)write(20,1050)l,i,stream(l,i)
492    continue
1050   format('Head-Datum at node (',i2,',',i2,') = ',f8.5)
       goto 510

c      not accurate
500    n=n+1
       goto 100

c      SUPER CALC OUTPUT FILE
510    do 530 l=1,lay
       write(28,555)(h(l,i),q(l,i),i=1,nod)
555    format(f7.3,3x,e12.4)
       if(l.lt.lay)
      + write(28,'(e12.4)')((-1*bk(l,i)*(h(l,i)
      +        -h(l+1,i))),i=1,nod)
       if(l.gt.1.)
      + write(28,'(e12.4)')(bk(l-1,i)*(h(l-1,i)-h(l,i))
      + ,i=1,nod)
530    continue
600    end
```

- (beside horif line) horizontal flows (m2/d)
- (beside vertf line) vertical flows (m2/d)
- (beside open newhead.dat) sends new head data to file was going to be used for time varient.
- (beside format 1050) outputs difference in calculated head and max head (if >0)
- (beside SUPER CALC section) output file for use with SuperCalc spreadsheet.

**Data Input Files**

START.DAT
output12.out
deltax.dat
aqui2.dat

```
heads.dat
store.dat
trans.dat
rech5.dat
var12.out
RUN 12 (Best Fit) q
2
45
1.7
1.0
1
0.0000003
endfile
```

DELTAX.DAT

```
700
650
650
450
650
250
100
1050
700
700
700
750
5*1000
700
700
225
700
600
700
4*1000
3*700
2*800
2*700
3*750
7*1000
endfile
```

AQUI2.DAT

```
8*1e-16
8*5e-04
3*2.5e-04
26*0.25e-04
75
endfile
```

HEADS.DAT

```
45*1
45*1
8*65
70
80
85
80
```

75
73
61
50
36
27
18
14
13
7.77
7.35
6.85
6.14
5.43
4.72
4.01
3.51
3.01
2.51
1.95
1.4
1.13
.86
.57
.28
0
-.38
-.76
-1.14
-1.52
-1.9
-2.28
-2.66
68
70
72
74
72
69
67
65
63
60
55
50
45
40
36
32.5
28
24
20
16
8*13
10*10
7*1
18*999
999

```
999
999
24*999
6*999
68
38*999
endfile
```

**STORE.DAT**

```
8*.1
0.005
10*0.01
2*0.08
5e-03
5*2.4e-04
18*1e-04
8*.1
0.01
36*3e-04
endfile
```

**TRANS.DAT**

```
8*
11*-8
2*100
4*1400
3*850
8*700
9*200
8*-1.6
7*150
21*200
9*50
endfile
```

**RECH5.DAT**

```
8*
-.11e-03
6*0.64e-03
0.45e-03
0.64e-03
0.38e-03
2*
-1.5e-03
-0.04e-03
10*-0.09e-03
-0.2e-03
3*-0.09e-03
-0.045e-03
8*
0.74e-03
0.33e-03
1e-16
2*0.3e-03
0.21e-03
-1.43e-03
0.06e-03
24*
```

```
-0.11e-03
12*
endfile
```