Investigation of Salinity in the River Thurne Catchment of North-East Norfolk

October 1993

I P Holman, University of East Anglia
K M Hiscock, University of East Anglia

Anglian Region Operational Investigation

OI 535/1/A

NRA

National Rivers Authority

Investigation of Salinity in the River Thurne Catchment of North-East Norfolk

October 1993

***I P Holman, University of East Anglia**
K M Hiscock, University of East Anglia

* I P Holman, now Soil Survey & Land Research Centre, Cranfield University, York

Anglian Region Operational Investigation

OI 535/1/A

National Rivers Authority
Anglian Region
Kingfisher House
Goldhay Way
Orton Goldhay
Peterborough PE2 5ZR

Tel: 0733 371811
Fax: 0733 231840

Dissemination Status:
Internal: Released to Regions
External: Public Domain

Research Contractor:
This document was produced under Anglian Region OI Contract 535 by:

School of Environmental Sciences
University of East Anglia
Norwich
Norfolk NR4 7TJ

Tel: 0603 56161
Fax: 0603 507719

NRA Project Leader:
The NRA's Project Leader for Anglian Region OI Contract 535:

David Burgess - RHO, Kingfisher House, Peterborough

Additional Copies:
Further copies of this document can be obtained from R&D Co-ordinator, Anglian Region.

CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This R&D Note summarises the results of a three-year PhD investigation, funded by the Natural Environment Research Council and the National Rivers Authority, into the hydrogeology of the Norwich Crag aquifer in the River Thurne catchment in north-east Norfolk. This low-lying coastal aquifer is subject to saline intrusion as a result of land drainage that has been carried out in the marshland during the past two centuries. Changes in the economics of arable farming and the perception that changes in the land drainage regimes will produce beneficial effects on the water quality of the River Thurne have necessitated the need for an increased understanding of the hydrogeology of this complex, highly managed aquifer.

Section 1 of this Note introduces the catchment and the background to the issues involved in the future management of the catchment.

Section 2 outlines the methodology used in this inter-disciplinary study. Hydrogeological, hydrological, hydrochemical and geophysical techniques have been extensively used.

Section 3 summarizes the results of the three main avenues of research. The hydrogeology of the Crag aquifer is described; the location and the mechanisms controlling the saline intrusion are presented; and the results of a catchment water balance are given. The water balance has been used to assess the available groundwater resource for the catchment and to predict the likely effects of changes in the land drainage regimes on the quantity and quality of water discharged into the River Thurne.

Finally, the principal results have been brought together in Section 4 to demonstrate the links between aquifer structure, saline intrusion and land drainage, and to discuss the possible outcome of some future management options.

1. INTRODUCTION

1.1 Background

Most of the Norfolk Broads and the dykes that drain the associated marshland contain freshwater. Some of them, in the lower reaches of the Broadland rivers, are brackish as a result of tidal influences. However, those in the Thurne catchment, even though they lie upstream of the saline effects of all but the highest tides, are also brackish. This unusual saline nature of the Thurne river system in north-east Norfolk has been reported since the turn of the century, when the source of the salinity was thought to be "probably due to salt springs" within Hickling and Horsey Mere (Gurney 1904).

Following the work of Pallis (1911), it is generally recognised that the source of the salinity is by direct underground communication between the sea and the waters of the Thurne district. The two main potential conduits are the underlying Norwich Crag aquifer, which outcrops beneath the sea, or the peat within the marshes. Goldsworthy (1972) concluded that the peat was the main transmission zone, there being recurrent exposures of peat between the tidemarks on the foreshore between Horsey and the northern end of the Winterton Ness (Lambert et al 1960). Inflow via the Crag aquifer is complicated by the clay layers interbedded both within the Crag and the alluvium. Downing (1959) found two extensive layers occurring at depth within the Crag, while there is a wide clay cover within the alluvium of the Horsey-Martham-Heigham areas.

There has been a general increase in the salinity of the River Thurne over time, although this is difficult to quantify on a year-by-year basis because of the large gaps in the data series. It appears that since the turn of the century the salinity of the Thurne Broads has increased by about a factor of four, from a salt content equivalent to 2½% seawater to about 10% seawater-equivalent and sometimes more today (Roberts 1973). Although there was no monitoring of salinity at the time when land use changes were occurring within most of the catchment, a more recent drainage improvement scheme on the Somerton level coincided with a general increase in the salinity levels within the dykes (Driscoll 1984) and a doubling of salinity levels in Martham Broad.

One of the consequences of the increased salinity levels in the Broads has been the occurrence of algal blooms of *Prymnesium Parvum*. This small free living motile algae lives in waters having a chloride ion concentration of more than 250 mg Cl l^{-1} and produces a potent toxin which can be fatal to fish and some gill breathing invertebrates (Holdway et al 1978). In 1969 *Prymnesium* caused the death of around 250 000 Bream, Pike, Roach, Eel, Rudd and Perch in the Thurne Broads. In an attempt to limit the consequences of *Prymnesium* blooms a fish refuge has been created in Catfield Dyke, which leads into Hickling Broad. At times of high *Prymnesium* populations it is envisaged that fresh groundwater shall be pumped via the IDB drainage pump into Catfield Dyke, thereby creating a freshwater, *Prymnesium* free, zone. This is likely to be only a temporary measure as permanent solutions to the problem are sought. It is considered that a reduction in the chloride concentration of the Broads to around 1000 mg Cl l^{-1} will help to limit the effects of *Prymnesium* by reducing its niche space. It has been advocated that this might be achieved by reducing the salinity of the drainage water being discharged into the river system, principally that of the Brograve pump, by raising the water levels in the dykes (George 1992, Bales et al 1993). This can only occur with a change in the land use of the drainage level from arable to grazing marsh.

Incentives to achieve this are in existence through the auspices of four different schemes. Arable Area payments, designed to compensate farmers for reduced prices (MAFF 1992a), require land to be set-aside either on a rotational or non-rotational basis. Large blocks of less productive marshland could then be set-aside on a permanent basis. In addition to the Area Payments, most of the marshland in the Thurne catchment is within the Broads Environmentally Sensitive Area (ESA). The Broads ESA scheme has been enlarged to 4 Tiers, each of which has a different hydrological requirement (MAFF 1992b). Further incentives for raising dyke water levels are available through the Countryside Stewardship scheme, run by the Countryside Commission, and a European Community aid scheme part-financed by the Guarantee Section of the European Agricultural Guidance and Guarantee Fund.

These schemes will all have the potential, it taken up extensively, of forcing changes to the drainage regimes in parts of the catchment. At present some marshes in the Thurne catchment are being returned to grass and if this continues it may eventually lead to pressure to raise the dyke water levels. The effects of this action on the underlying aquifer and on the surface water chemistry are unknown.

The need is therefore for a study to improve the understanding of the behaviour of the Crag aquifer, of the controls on the saline intrusion and of the nature of the interactions between the surface water and groundwater systems. An understanding of the present system is a necessary prerequisite to implementing changes in the management of the surface water system. Without a knowledge of the importance of each water movement in the system and the interdependence of many of the fluxes, the management of the Thurne catchment as a single integrated unit is not possible. This research project has aimed to provide this information.

1.2 Aims and Objectives

The research project has three main aims. Firstly, while small projects have been carried out investigating the possible behaviour of the Crag aquifer within a small area (for example, Ede and Mansell-Moullin 1981 and Land and Water Research Centre 1992), no information is available as to the behaviour of the Thurne catchment as a single integrated unit, taking into account the hydrogeology, hydrology, meteorology and land use. In addition no information as basic as the height of the groundwater table, location of the catchment boundaries or of the structure of the aquifer existed for the Thurne catchment. As a result, the initial work in this project concentrates on establishing a monitoring network of Crag wells that allows the collection of the basic hydrogeological data. Geophysical surveys, using seismic reflection profiling, are used to define the structure of the aquifer.

Secondly, although much is known about the surface expression of the saline intrusion through the measurement of dyke salinities, no work has been undertaken to delineate the extent of the subsurface saline intrusion and on the controls on this distribution. While the work of Pallis (1911) is very important, it is likely that the distribution of saline groundwater and the relative importance of the mechanisms producing that distribution may have changed. These are therefore investigated.

Finally, each of the fluxes of precipitation, groundwater and surface water are quantified, and any feedback mechanisms which may exist as a consequence of the interdependence of some of the water fluxes are identified.

1.3 Research Area

The area of this research study covers the groundwater catchment of the River Thurne in north east Norfolk (Fig. 1.1), an area of approximately 110 square kilometres centred around 1° 35'E and 52° 45'N. This is part of hydrometric area 34, sub-areas 5,9 and 10. The catchment area forms the north eastern part of Broadland and contains several important Broads including Hickling Broad, Martham Broad and Horsey Mere. It also includes coastal in addition to wetland habitats.

The relief of the area is very subdued, with a height range of about 23 metres. The most striking physical features are the hills of the Flegg Hundreds in the south of the catchment; the loam uplands in the north-west; the coastal dune belt and the alluvial tracts of this part of Broadland.

The River Thurne is largely separated from the aquifer due to the shrinkage of the alluvium which has left the river flowing above the level of the marshes, although the river bed may be in contact with the aquifer. Most of the natural flow of the river is now comprised of discharges of the land drainage pumps and tidal movements. The exceptions to this are the outfall from the sewage treatment works at Ludham and possible groundwater flow into parts of Martham and Hickling Broads (Watson, 1981).

The Crag aquifer can be considered to comprise the Pleistocene Crag and the overlying sands and gravels, given that the deposits are lithologically similar consisting of predominantly quartz sands with horizons of coarser and finer material. The higher land of the catchment is covered by deposits of North Sea Drift and Lowestoft Till, both laid during the Anglian glaciations, although the Lowestoft Till is confined to the hills of the southern watershed. The Lowestoft Till is separated from the underlying, more permeable, North Sea Drift by the Corton Sands.

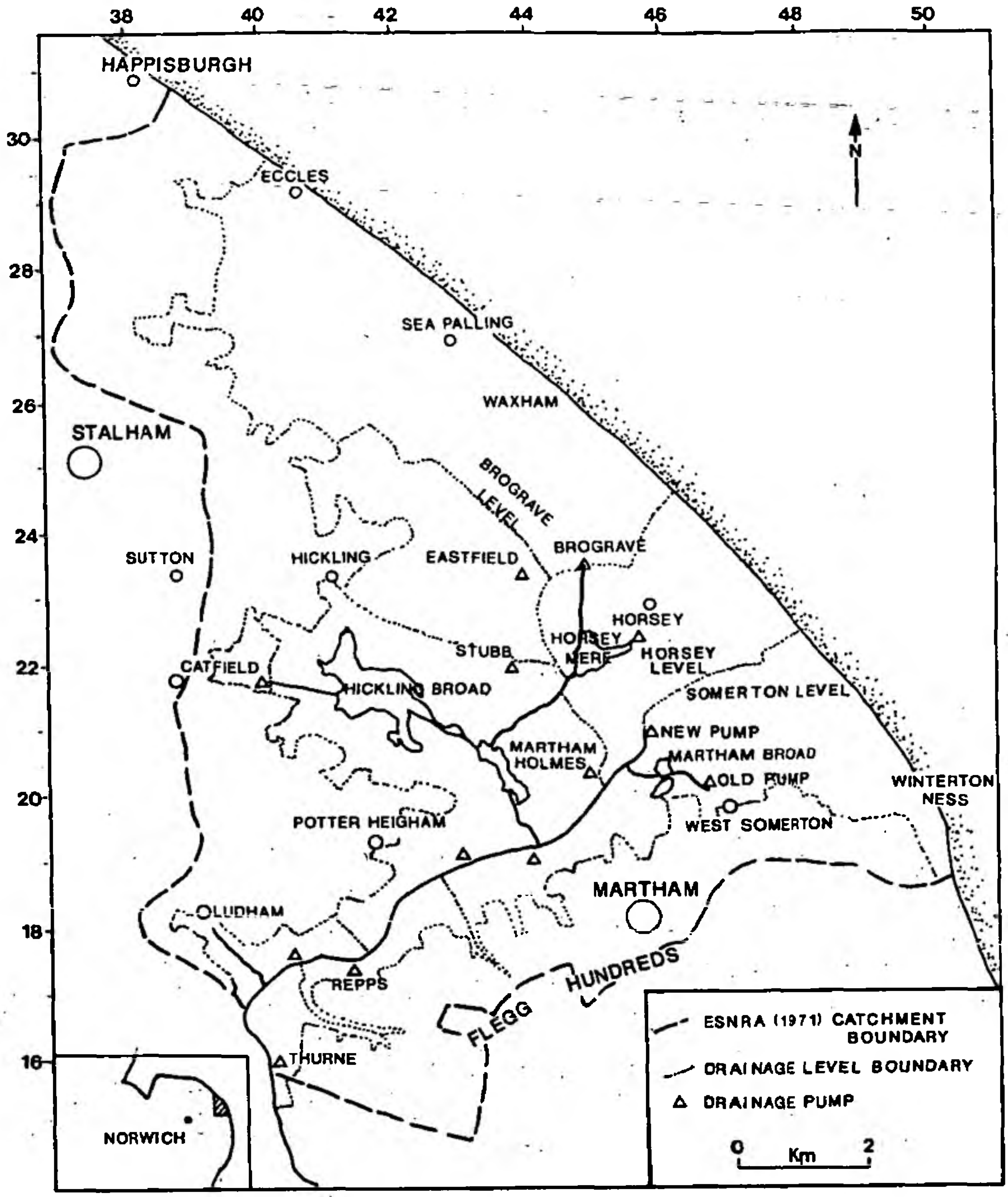

Figure 1.1 Map of the study area showing the River Thurne catchment

2. METHODS

2.1 Hydrogeology

The hydrogeology of the Crag aquifer has been investigated using standard hydrogeological measurements of watertable elevation and geophysical techniques. A network of up to 40 Crag wells and boreholes has been established around the catchment and their elevations accurately determined relative to Ordnance Datum Newlyn (ODN) using standard levelling procedures. The groundwater elevation measurements have an accuracy of ±15 mm. The network has been monitored for two years from April 1991 to April 1993, at weekly to monthly intervals.

High resolution seismic reflection profiling has been carried out to determine the depth of the aquifer, in the absence of borehole data, and to investigate the structure of the Crag. Natural gamma logs have been recorded for two NRA boreholes at Catfield. Electrical resistivity soundings, using the Offset Wenner configuration, have been used to derive porosity values.

2.2 Saline Intrusion Investigation

Surface water samples have been collected to determine the spatial and temporal variation in chlorinity of the drainage ditches in the marshes. A chlorinity survey was carried out in Spring 1991 in the Smallburgh and Happisburgh to Winterton IDB's, while regular, mostly weekly, samples were taken at ten of the land drainage pumps during the period April 1991 to April 1993. All the samples have been analyzed for chlorinity by titration with silver nitrate, to an accuracy of ±10 mg Cl l^{-1}.

In conjunction with the sample collection, regular measurements of dyke water levels at the pumps have been recorded. Water levels were measured from fixed points near to the pumps, the elevations of which were determined relative to ODN using standard levelling procedures to ±10 mm.

The sub-surface extent of the saline intrusion has been investigated using two geophysical techniques which utilise the higher electrical conductivity of saline water. A detailed survey of ground conductivity has been carried out using an EM-34, an instrument which employs an electromagnetic (inductive) technique. Quantitative information on ground conductivity changes in the vertical plane have been provided using electrical resistivity soundings.

2.3 Catchment water balance

Yearly catchment water balances have been produced for the two years of monitoring. Original data have been combined with existing data to produce the calculation :

- Meteorological data - Meteorological Office Rainfall and Evaporation Calculation System (MORECS), squares 121 and 131
- Saline intrusion - drainage water samples, electricity consumption
- River leakage - drainage water samples, electricity consumption
- Open water evaporation - MORECS potential evaporation for grass (PE_O), Penman (1950) conversion factors, length of dyke
- Groundwater abstraction - irrigation returns, NRA (1993)
- Groundwater outflow - drainage water samples, electricity consumption, MORECS effective precipitation (EP)

The water balance of a catchment can be defined as:

$$\Sigma I - \Sigma O \pm \Delta S = 0$$

where ΣI is the sum of all inflows
ΣO is the sum of all outflows
ΔS is the change in storage of water over the time of observations

3. RESULTS

3.1 Hydrogeology

3.1.1 The Geometry and structure of the Crag aquifer

The boundaries of the Thurne groundwater catchment can, as is usual, be taken from the Section 14 report, published by the East Suffolk and Norfolk River Authority (ESNRA 1971). The groundwater catchment was delineated according to the surface water catchment of the River Thurne. The Thurne groundwater catchment has been revised, based upon groundwater level measurements, and has an area of 109 km^2, a decrease of 2.5 km^2 on the Section 14 catchment (Fig. 3.1). Three principal areas of disagreement were found. The watershed is moved northwards at Happisburgh by about 500 m, southwards by about 750 m at Somerton and eastward by about 750 m around Sutton.

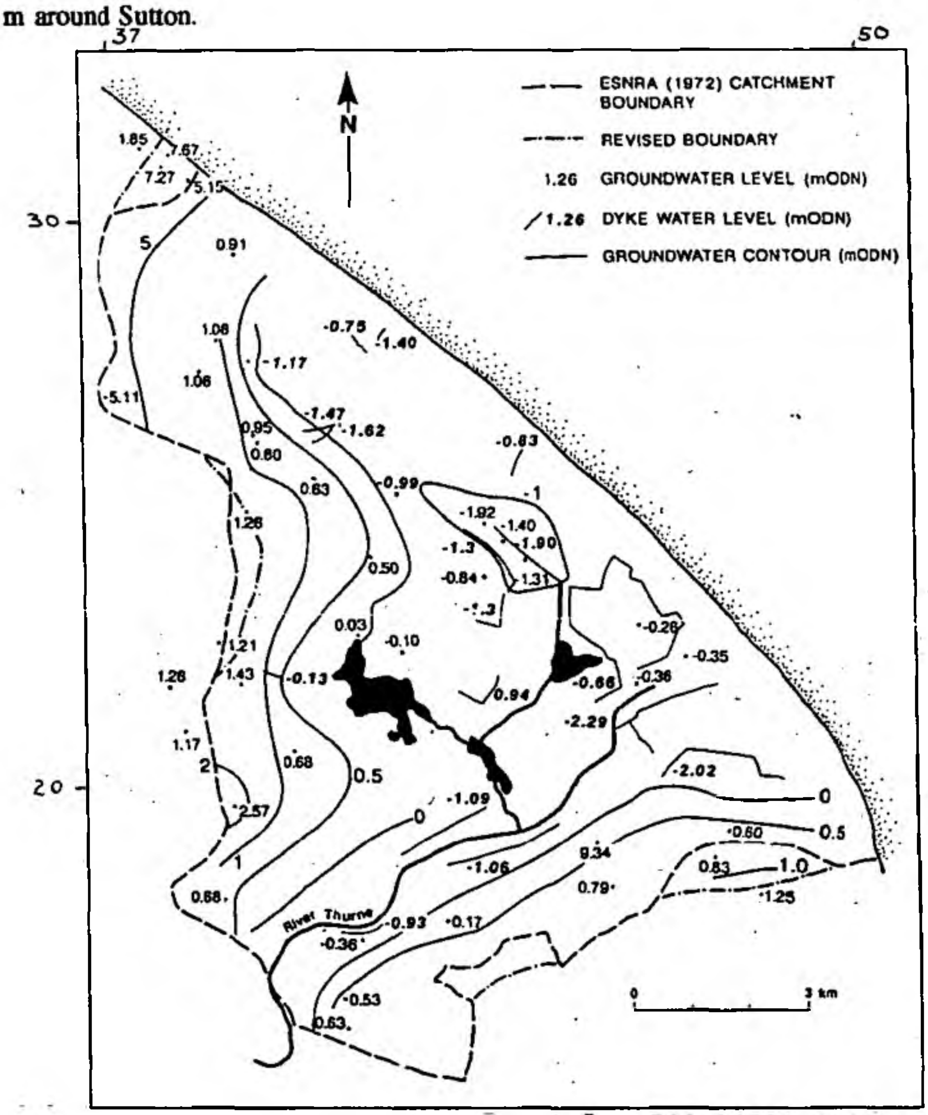

Figure 3.1 Groundwater and surface water elevations on 1st March 1993, and the revised groundwater catchment boundary

A map of the base of the Crag aquifer (Fig. 3.2) has been constructed from well log data and depths determined from seismic reflection profiles. This indicates a general south-easterly deepening of the Crag basin, with a superimposed trough trending in a south-west to north-east direction around Ludham and Catfield. The depths of the Crag base range from around -30 mODN at the western watershed to over -60 mODN within the trough and towards the coast in the middle of the basin, although a localised deepening of the Crag basin appears to occur in the north of the catchment at Happisburgh where depths in excess of -50 mODN are recorded. The map is similar to previous versions (for example, Gibbard & Zalasiewicz 1988).

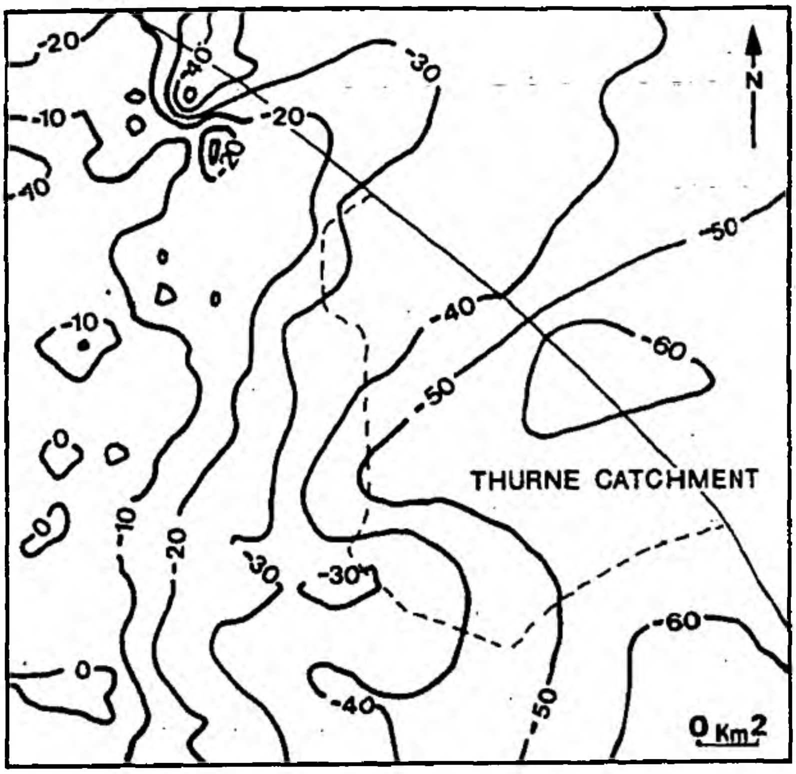

Figure 3.2 Contour map of the base of the Crag

However, very little information is available as to the internal structure of the Crag aquifer, although detailed examinations of the lithology of the Ludham and Ormesby (TG 514143) boreholes have shown significant changes in composition. No work as to the areal extent of observed facies has been undertaken, the only regional work being that of Downing (1959) who suggested the existence of a clay layer within the Crag, based upon borehole records.

Analyses of the Ludham boreholes have indicated that two clay layers (or layers with a higher clay content) exist within the Crag, at depths of around -10 mODN and -19 mODN. These have been correlated with Baventian and the Thurnian deposits. It is considered that the seismic reflection profiles and natural gamma geophysical logs have identified the continuation of these two horizons. The upper seismic reflector, the band of high gamma activity and the clay layer logged in a local gas exploration borehole are considered to be the continuation of the Baventian Clay strata identified at Ludham. The weaker reflector and the thicker region of elevated gamma activity has been correlated with the lower Thurnian Clay horizon, although it seems probable that an increase in the clay content has been detected, rather than the presence of a distinct clay layer. Fig. 3.3a shows a southwest-northeast section through the Crag with the suggested structure of the aquifer.

The depth of the upper clay layer interpreted from the seismic lines has been combined with data from drillers' logs in the region to produce a contour map of this layer within the Crag (Fig. 3.3b). This is similar to that produced by Downing (1959). It is impossible to say whether the strata recorded are a single continuous unit or a number of discrete layers of similar gradient. Nonetheless, in many of the logs the strata recorded change from orange sand above the clay horizon to silver, grey or blue sand beneath, suggesting that the horizon may be acting as an aquitard with chemically reducing conditions found beneath.

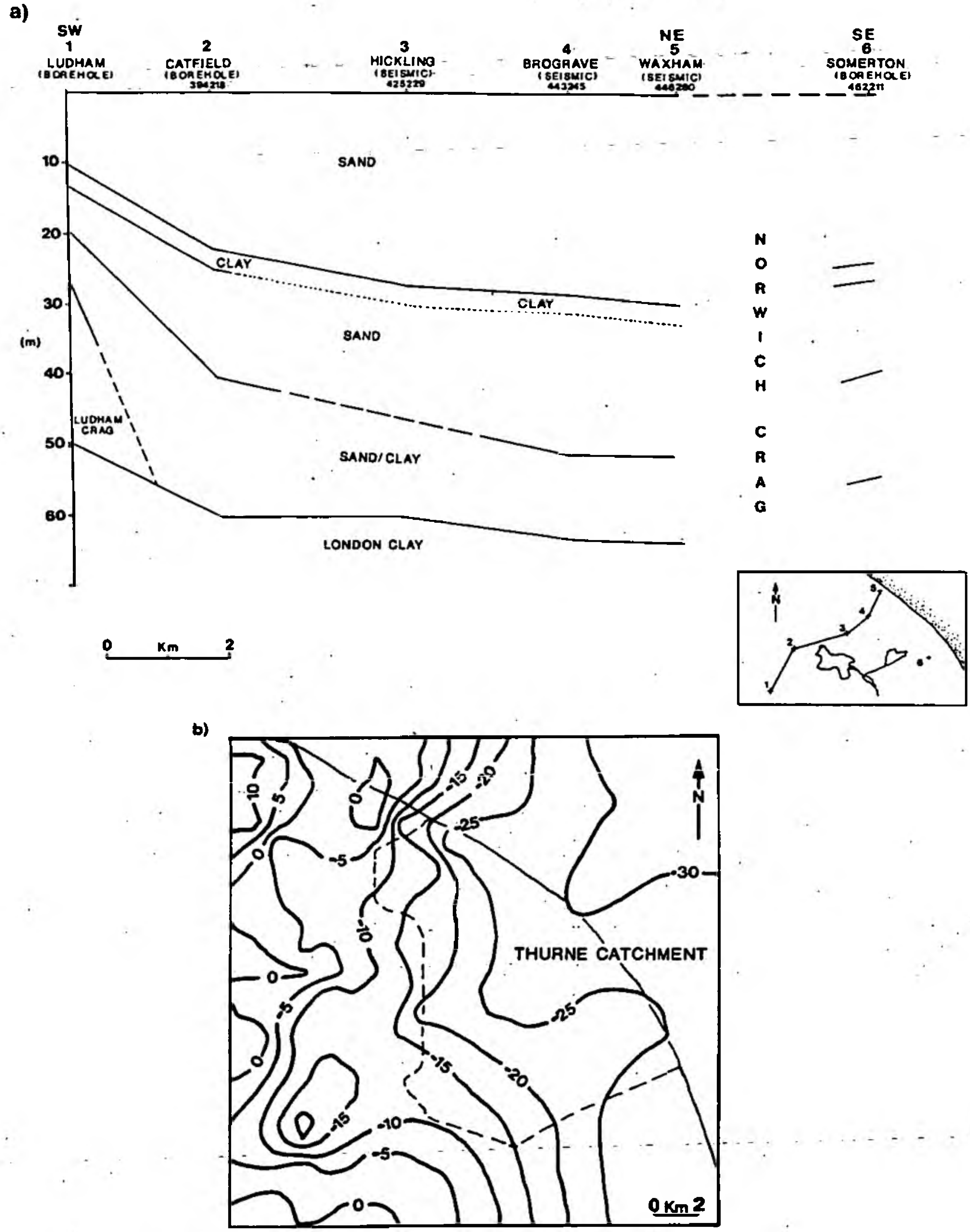

Figure 3.3 Internal structure of the Crag aquifer. (a) A section through the aquifer showing the proposed structure and (b) a contour map of the upper clay layer

3.1.2 Aquifer Parameters

Analyses of NRA pumping tests have shown that all but one of the tests are classified as being unconfined, with several of the pumping tests exhibiting signs of delayed yield, a characteristic of unconfined aquifers. Most of the values of specific yield are in the range 10^{-2} to 10^{-4}. In an unconfined aquifer the specific yield is the same as the effective, or drainable, porosity which is generally less than the total porosity.

When compared with the values of porosity determined from electrical resistivity soundings, which are in the range 25-35%, the specific yield values are much lower than might be expected for an unconfined aquifer. The low specific yield values of these tests may indicate that, although the porosity of the aquifer is fairly high, the sediment particles are small and poorly sorted leading to small pore sizes and, consequently reduced capacity for gravity drainage. Only two pumping tests, beyond the western watershed in the neighbouring River Ant catchment, gave values of specific yield, of 0.12 and 0.25, which are similar to those of porosity.

The transmissivity values range from around 150 $m^2 day^{-1}$ to 1100 $m^2 day^{-1}$. For an aquifer thickness of 50 m this produces hydraulic conductivity values in the range of 3.5×10^{-5} ms^{-1} to 2.5×10^{-4} ms^{-1} (3-22 m day^{-1}), which are consistent with representative values for fine to coarse sands.

3.1.3 The elevation and seasonal fluctuation of the Crag groundwater table

The groundwater head in the catchment is low, generally being below +1 m ODN (Fig. 3.1). The exceptions to this are the northern and southern areas of the western watershed. In the area north of Ludham, groundwater heads in excess of +2 mODN are measured while further north at Happisburgh a groundwater head elevation of over +7 mODN is attained. The groundwater table is below 0 mODN within all the marshes, while there is a slight groundwater mound within Horsey holme. The groundwater table along the length of the southern watershed is below +1 mODN .

The watertable in the areas of high groundwater levels are much higher than in the Chalk aquifer below, which tends to be around +0.5 m ODN. The Chalk aquifer is unconfined beneath about 6 km^2 in the north of the catchment around Happisburgh and will not be a source of recharge into the Crag. Seepage may be possible through the thinning London Clay into the Crag in some areas of the western watershed, particularly around Stalham, where the hydraulic head in the Crag is at a similar elevation to the Chalk piezometric surface.

In general the seasonal groundwater fluctuations were greater in the second year of monitoring (1992/93). South of the River Thurne the fluctuations were less than 0.4 m in both years. Along the western watershed the fluctuations were slightly greater, although they were greatest away from the watershed where a group of three wells had fluctuations in excess of 1 m in the second year. The maximum seasonal fluctuation of 2.43 m was recorded in the second year.

3.1.4 Perched aquifers

The southern hills are capped by the glacial deposits representing the Cromer and Lowestoft advances, and which are separated by the Corton Sands. The Corton Sands, lying upon the less permeable North Sea Drift, are acting as a perched aquifer, with the watertable at around +9 mODN. The aquifer has produced yields of up to 6.8 m^3 hr^{-1} at Sutfield House Nurseries, Martham (Institute of Geological Sciences 1970, Ref. 148/21) while the combined yields of the seven wells at this site (TG 456182) amounted to 91-136 m^3 $week^{-1}$ in summer to 68-91 m^3 $week^{-1}$ in winter, the difference in yield being caused by the weather-related requirements of the nursery. The wells had a seasonal fluctuation in level of 0.6-0.8 m.

Possible minor perched aquifers may exist within the North Sea Drift which covers large areas of the catchment. At Ingham, a trench dug through an area of poorly drained land flowed continuously for seven weeks, yielding 1.3 m^3 day^{-1}, before drying up to leave a cultivatable piece of land. A ditch dug into a similar piece of land nearby also ran for six weeks. The extent of perched aquifers in the North Sea drift cannot be ascertained, but covering 35-40% of the catchment, the North Sea Drift has the potential to contain many.

3.1.5 Recharge mechanisms

The Crag is generally considered to be an unconfined aquifer, although the marshes have been assumed to be impervious so that no recharge occurs to the underlying aquifer (ESNRA 1971). Two sources of recharge exist in the Thurne catchment, derived from rainfall and the surface water bodies.

Rainfall

At the end of the two-year monitoring period on the 29th March, 1993, the groundwater level was still rising in several wells, despite there having been no significant rainfall in the previous two months. All these wells are located within the areas of Norwich Brickearth. It appears therefore, that the Norwich Brickearth is prolonging the recharge by up to at least 17 weeks.

The superficial deposits do not, however, appear to significantly delay the onset of recharge. Minimum groundwater levels in the first year of monitoring occurred in nearly all cases around weeks 24-26 (9th -23rd September). The sites where the minimum groundwater level occur earlier are all located near irrigation boreholes. During the weekend of the 26th week, 62mm of rain fell in Hickling. Most wells responded to this rain in less than eight days, although some of the wells in the marshes had responded within two days. The rapid response of most of the wells to this intense rainfall indicates that either the rainfall was sufficient to satisfy the soil moisture deficit or, more likely, that the intensity of the rainfall event allowed bypass mechanisms (as suggested by Rushton & Ward 1979) to operate so that recharge to the Crag aquifer occurred even though a soil moisture deficit remained.

Surface Water recharge

The river system of the Thurne catchment has been assumed to be a discharge zone for the Crag aquifer in the past (Watson 1981). Drainage of the surrounding marshland (and the associated shrinkage) has left much of the river system standing above the level of the surrounding land. The exceptions to this are the northern edge of Hickling Broad and the southern margin of Martham Broad where they abut higher land. Even in these areas the water level of the Broads are still above the level of the Crag groundwater table (Tables 3.1).

Table 3.1 - The range of groundwater levels near Hickling Broad

	Groundwater level (Summer) m ODN	Groundwater level (Winter) m ODN	Distance from Broad (m)
Broad House (TG414226)	-0.3 to -0.5	0.1 to -0.1	20
Willow Farm (TG420224)	-0.5 to -0.8	0.2 to -0.2	350

Note : Water level of Hickling Broad is about +0.2 to +0.5 mODN.

Groundwater samples taken from two wells in the area north of Hickling Broad both contained low levels of chloride, although only one well had been partially purged by the removal of one volume of water. The low chlorinity of these wells indicates that fresh groundwater occurs close to the Broad.

A geo-electric section, made up of a series of interpretations of electrical resistivity soundings has been constructed through this region north of Hickling Broad to ascertain the subsurface variation in groundwater quality (Fig. 3.4). The section extends from Horsey to Hickling Broad. The saline groundwater is at its shallowest beneath the marshes between Horsey Holme and the promontory of land bordering Hickling Broad. Beneath this spur of land the saline groundwater sinks rapidly beneath the region of high resistivity (fresh groundwater), but does not rise again towards Hickling Broad, so that the brackish water evident in this region is likely to be due to the effect of leakage of water from the Broad. The depth to the brackish groundwater originating in Hickling Broad increases rapidly beneath the higher ground, so that beneath the spur this water is located at about -24 mODN. Assuming an average chlorinity of Hickling Broad of 2000 mg Cl^- l^{-1} (ie. about 10% seawater and equivalent to ρ_s = 1.0025 g cm^{-3}), the hydrostatic balance between the fresh and brackish groundwater requires a fresh groundwater head of 0.06 m above the level of the Broad water surface to produce this observed interface depth. Therefore, either an additional unknown factor is influencing the system, or the system in this area is not in equilibrium. If groundwater levels in this area have been lowered as a result of land drainage, Hickling Broad may have changed from being a groundwater discharge zone to a recharge zone and the body of brackish water is slowly moving so as to attain equilibrium.

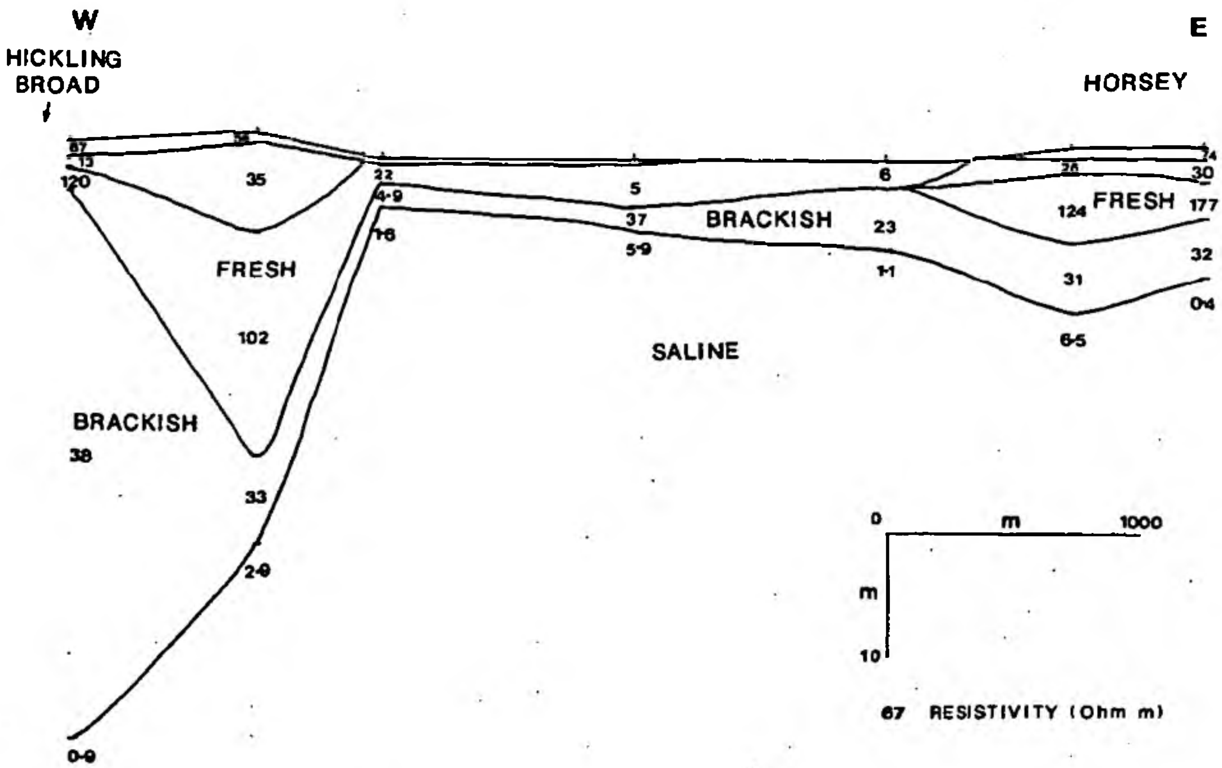

Figure 3.4 A geo-electric section of the area between Hickling Broad and Horsey showing the brackish groundwater originating in the Broad

3.1.6 Groundwater discharge zones

Two main groundwater discharge zones have been identified, within the drained marshland and the cliffs at Happisburgh. Additional groundwater discharge will occur from the sand dunes along the coast.

Drained marshland

Measurements of groundwater levels were recorded in two marshes under contrasting drainage regimes. All the wells exhibited very similar watertable fluctuations that are not related to seasonal changes in drainage regime but are a consequence of groundwater recharge.

During the dry spell in May 1991 the Brograve pump was switched off for a period of two to three weeks (Weeks 8-10). In the following weeks all the wells on the Level exhibited the effect of this action as a lagged pulse of surface water-derived recharge moved away from the dyke (Fig. 3.5). The time lag was greatest where the Holocene deposit changed from peat to a silty peat, which is likely to have a lower hydraulic conductivity. The amplitude of the pulse was lowest at the well furthest from the main drain. Therefore, raising dyke water levels in the discharge zones will allow recharge to the underlying Crag aquifer.

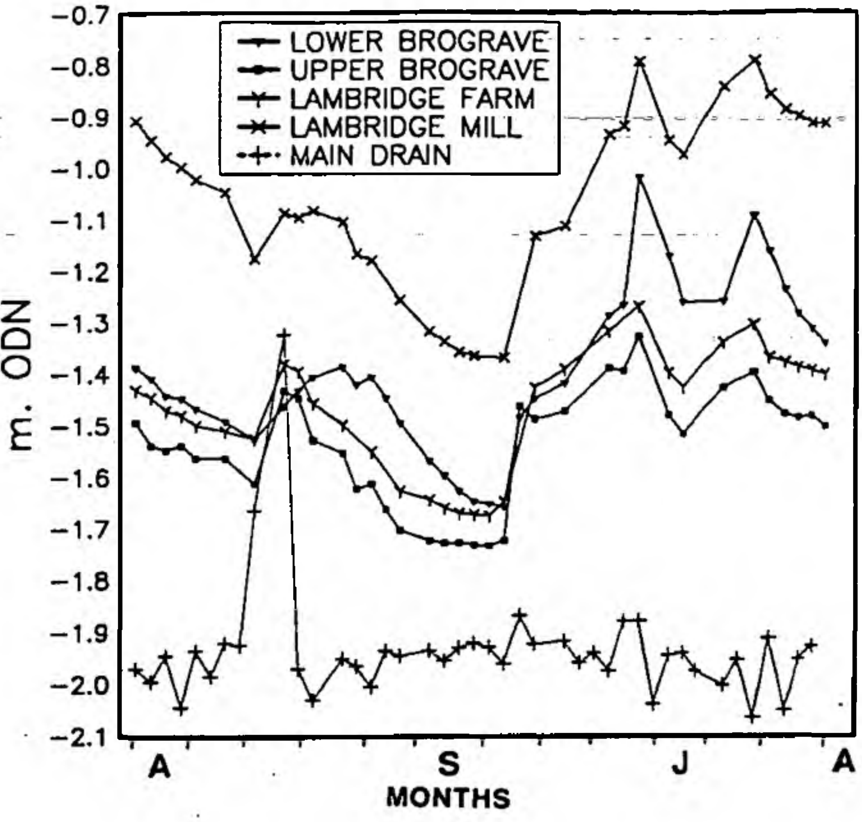

Figure 3.5 Groundwater and surface water levels in the Brograve Level during the period from April 1991 to April 1992

The Horsey estate maintains a high dyke water level through the year, especially during the summer. If deemed necessary the dyke water is augmented with river water via a sluice gate near the pump. Despite the high dyke water level there appears to be little relationship between the dyke water level and the groundwater level in the marsh (Fig. 3.6), which drops significantly below the dyke water level. The underlying Crag aquifer appears to be less sensitive to changes in the surface water regime, than at the Brograve Level.

Happisburgh Cliffs

The coastal village of Happisburgh in the north of the area exhibits the highest water table in the catchment at over +7 mODN. During the first eighteen months of this study it was the only area of the catchment to experience no recovery of groundwater levels, which consistently dropped. The levels did partially recover following the heavy rain at the end of 1992.

Happisburgh is the only part of the catchment that is not separated from the sea by coastal dunes, there being cliffs of up to 10 metres in height. The cliffs at Happisburgh consist of the suite of sedimentary units associated with the Cromer Advance of the Anglian glaciation.The base of the cliffs to about 2.5 mODN is composed of the First Cromer Till and obvious seepage of groundwater occurs from the upper surface of this unit throughout the year. Kazi and Knill (1969) identified other seepage zones, or points, where the depressions within the tills or associated impermeable laminated silty clays act as drains for groundwater seeping from the cliff. These have not been observed, and so it cannot be ascertained whether they might have been related to rainfall episodes, rather than to groundwater discharge. The fall in groundwater levels in the Happisburgh area is due to the combination of the discharge from the cliffs and the general groundwater flow to the marshes, which during the early part of the study were not balanced by recharge.

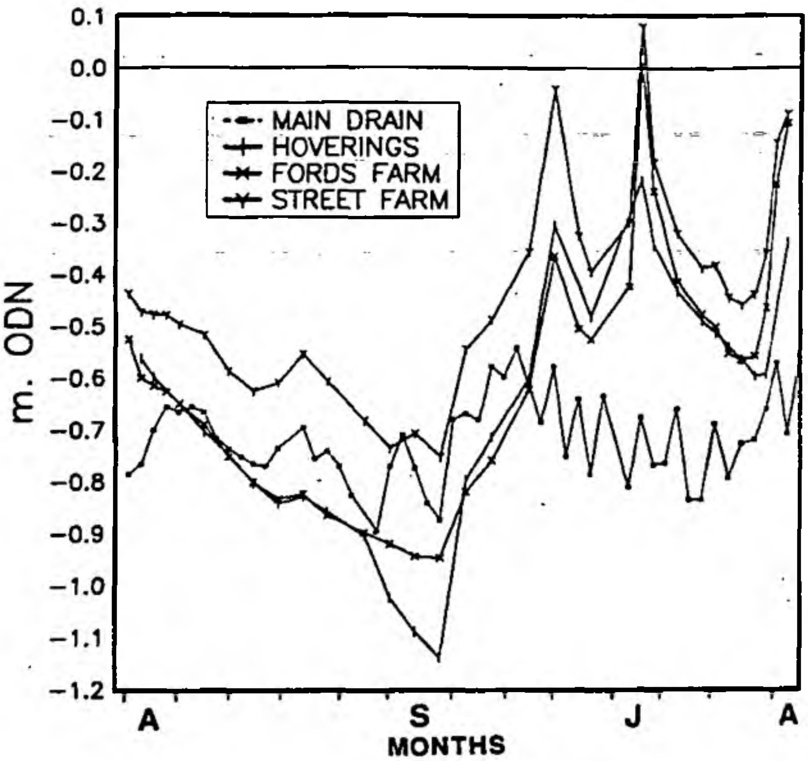

Figure 3.6 Groundwater and surface water levels in the Horsey Level during the period from April 1991 to April 1992

3.2 Location of the saline intrusion

3.2.1 Surface water salinity survey

Seven observations relating to the distribution of salinity in the drainage dykes can be deduced :

1. Dykes that drain land adjoining the uplands are fresh, regardless of their proximity to the coast.
2. Dykes near the dunes often contain water of low salinity.
3. Dykes that drain the marshes which abut the river-level wetlands have varying degrees of moderate salinity. These wetlands are fed by the brackish River Thurne and seepage through the flood protection walls into the drained marshland is probably occurring to some degree.
4. All but one of the marshes near the coast contain dominantly saline dykes.
5. The salinity in these coastal marshes tends to increase with distance away from the sea.
6. The salinity in the coastal marshes tends to increase away from the margins of the higher ground towards the marsh centre.
7. The salinities in the dykes of the neighbouring drainage levels of West Somerton and Horsey are similar despite the difference in land drainage regimes (arable and grazing marsh, respectively) and associated dyke water levels.

3.2.2 Groundwater salinity investigation

Electro-magnetic survey

Figure 3.7 shows the contoured values of measured, uncorrected ground conductivity at an exploration depth of 7.5 m recorded at 149 points around the study area. Although the superficial boulder clay and Holocene deposits have higher conductivities than the Crag they are in general only a few metres thick, so that changes in ground conductivity are primarily a result of changes in the groundwater conductivity within the Crag aquifer. High ground conductivities are measured beneath the marshes at Hempstead, Eastfield, Waxham, Horsey and Somerton. The thin strip of marshland seaward of the Horsey holme which shows high ground conductivity is constrained by the undrained and slightly elevated marshland on the other side of the flood protection wall which maintains a higher groundwater level. All the areas of slightly elevated land have low ground conductivities.

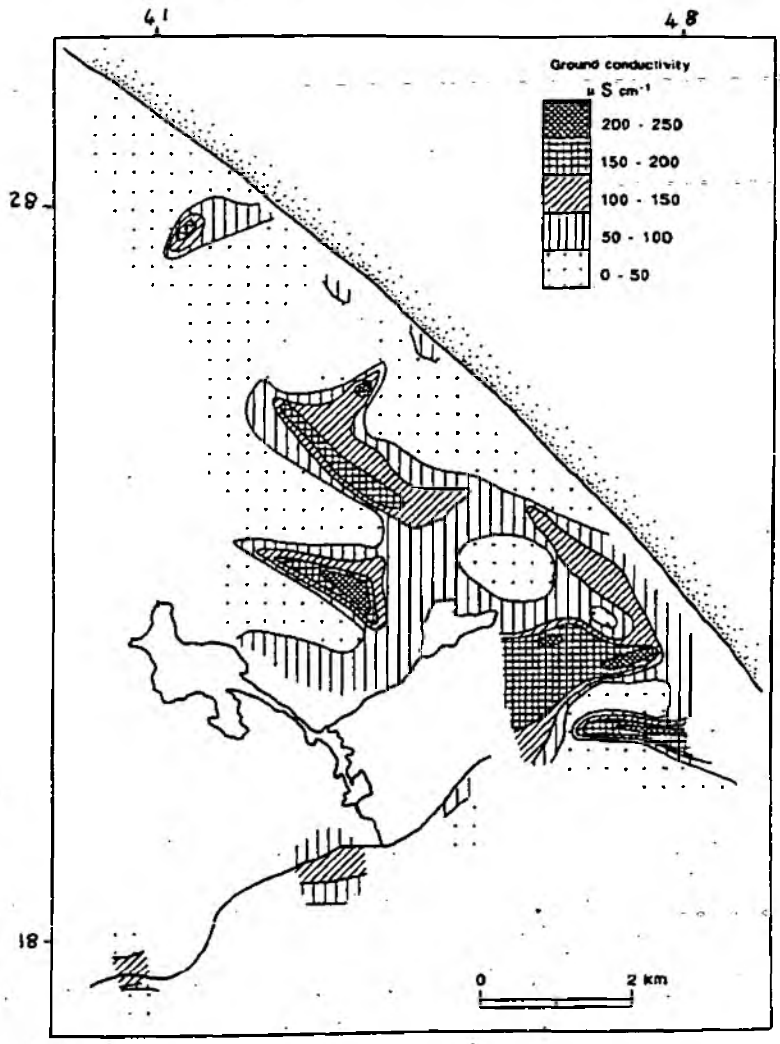

Figure 3.7 Contour map of ground conductivity at an exploration depth of 7.5 m from measurements taken with an EM-34

At an exploration depth of 30m, most areas near the coast have elevated ground conductivities. Only the Horsey and Somerton Holmes have values suggesting the continuing presence of fresh, or slightly brackish, water. The peninsulas of higher land east of Hickling show higher values suggesting the presence of brackish water at this depth. The measurements made in the marshes along the River Thurne suggest that saline water may be present within 30m of the surface.

Electrical Resistivity survey

The results of the electrical resistivity soundings are shown in Fig. 3.10 to depict the depth below sea level to the lowest resistivity layer in the resistivity sounding interpretations, interpreted as being saline groundwater. It has been assumed that this reduction in ground resistivity is due to a change in porewater conductivity and not lithology, since sieve analysis of Crag samples have shown there to be little true clay present (Forbes 1952; Anglian Water Authority 1978). This assumption may not be valid for some of the soundings in the marshes where the saline groundwater is at shallow depth beneath marine alluvium.

The saline interface is shown to be generally located at a depth of less than 10 m under the coastal marshes, although in the marshes north and west of the Hempstead marshes the depth of the interface increases rapidly to over 30 m. The variation in the depth to the saline interface in the coastal marshes is a consequence of the varying proximity of the soundings to the under-drains and dykes. Saline groundwater is evident at very shallow depth under the Hickling marshes, the only inland marshes underlain at shallow depth by the saline groundwater. The dunes and isolated blocks of elevated land cause the interface to be located at a slightly greater depth of 10-15 m. It is under the higher land of the hills of the southern and western watersheds that the saline interface is forced to depths of greater than 20 m, the depth being greater beneath the western watershed where, in some cases, saline groundwater is not detected.

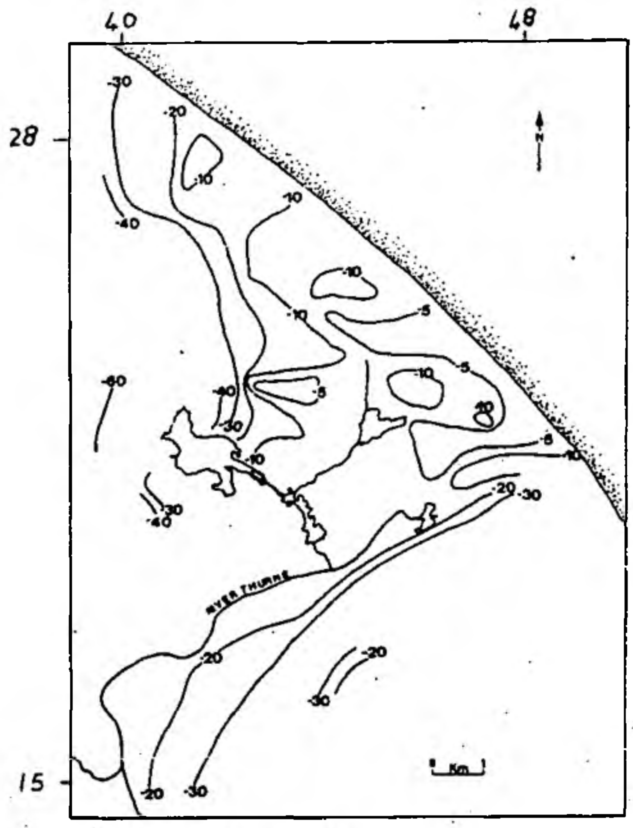

Figure 3.8 Contour map of the depth to the saltwater table, based upon data from electrical resistivity soundings

3.3 <u>Influence of land drainage on saline intrusion</u>

3.3.1 Dyke water level survey

A range of dyke water levels are maintained by the land drainage pumps (Table 3.2). The lowest dyke water levels are maintained by the West Somerton pumps, so that the drained marshes along the River Thurne, such as at Potter Heigham and Martham, have dyke water levels that are over one metre higher.

In that part of the catchment north of the River Thurne the Brograve pump maintains the lowest dyke water level. The main drain has a fairly low gradient up to the area around Marsh Mill (TG410263). Beyond the mill the drain forks, the western branch having to flow over a weir and around to the marsh at Eccles, by which time the dyke water level is above 0 mODN. The part of the main drain below the weir is therefore the lowest point of the watertable in that area (Fig. 3.9).

Stubb and Eastfield pumps in the Smallburgh IDB maintain dyke levels that are around 0.6-0.9 m higher than

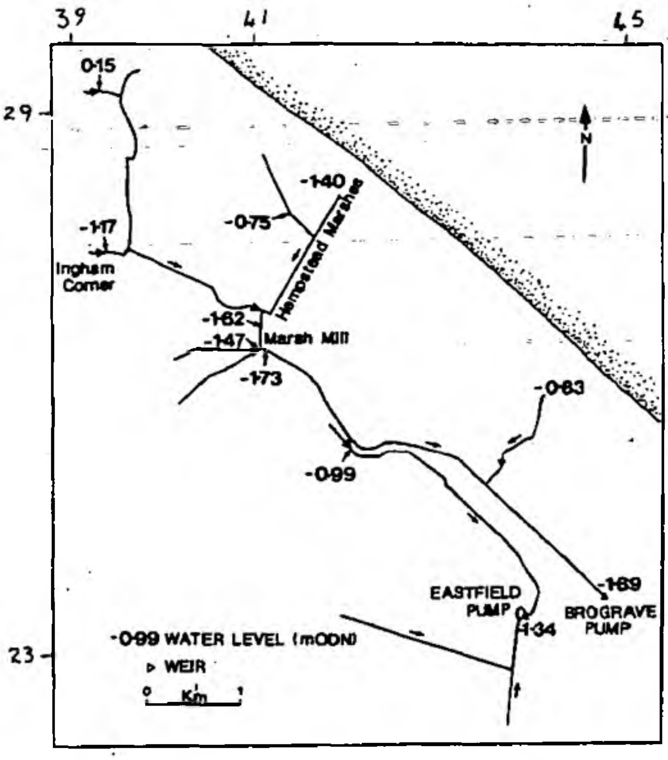

Figure 3.9 Dyke water levels in the Brograve and Eastfield Levels on the 8th March 1993

that of the Brograve pump. Their levels are, however, both lower than that of the Horsey pump. The Stubb and Eastfield drainage levels are the only area of the catchment where an inland drainage pump maintains a lower dyke water level than a pump in the coastal marshes.

Table 3.2 - Mean values (SD in parentheses) and range of values of dyke water levels recorded at the pump inlets during the period April 1991 to April 1993.

Pump	Mean water level (mODN)	Water level range (mODN)	Number of measurements
Brograve	-1.93 (0.10)	-2.07 to -1.33	76
Catfield	-0.11 (0.10)	-0.43 to +0.21	92
Eastfield	-1.34 (0.09)	-1.50 to -1.04	95
Horsey	-0.65 (0.09)	-0.86 to -0.46	92
Martham	-0.99 (0.16)	-1.34 to -0.53	92
Potter Heigham	-0.89 (0.18)	-1.38 to -0.69	90
Repps	-0.83 (0.10)	-1.23 to -0.56	91
Stubb	-1.03 (0.13)	-1.23 to -0.52	96
West Somerton New	-2.31 (0.03)	-2.45 to -2.27	88
West Somerton Old	-2.04 (0.10)	-2.26 to -1.80	38

3.3.2 Composition of the drainage water

All the drainage pumps in the Thurne catchment discharge water having a chlorinity greater than that of fresh groundwater (Table 3.3a and 3.3b). The surface water that is discharged by the drainage pumps is therefore a mixture of three water types: saline water, fresh groundwater and precipitation.

Saline water

All but one of the marshes along the coast and those towards Hickling are underlain at shallow depth by saline groundwater. Further inland along the River Thurne the saline intrusion is located at greater depth. As a consequence the pumps can be spilt into two groups on the basis of their chlorinities. The first group (Group 1), which consists of the Brograve, Eastfield, Horsey, Stubb and both West Somerton pumps, is characterized by high chlorinities in excess of 900 mg l^{-1} Cl^-. The remaining pumps (Group 2) at Catfield, Martham, Repps and Potter Heigham have lower chlorinities.

Table 3.3a Chlorinity data for the Group 1 land drainage pumps of the Thurne catchment (SD in parentheses).

Pump	Mean Chlorinity (mg Cl^- l^{-1})	Chlorinity range (mg Cl^- l^{-1})
Brograve	3590 (870)	1820-5820
Eastfield	1200 (510)	180-3100
Horsey	2170 (600)	790-3550
Stubb	1590 (306)	650-2180
West Somerton New	2230 (550)	1150-3480
West Somerton Old	940 (310)	610-2360

Table 3.3b Chlorinity data for Group 2 land drainage pumps (SD in parentheses)

Pump	Mean chlorinity (mg Cl^- l^{-1})	Chlorinity range (mg Cl^- l^{-1})
Catfield	190 (130)	40-990
Martham	580 (490)	200-3560
Repps	310 (360)	130-2920
Potter Heigham	750 (500)	200-2840

In addition to the difference between the chlorinities of the two groups, the character of the chlorinity variation during the period of monitoring is very different. The chlorinity at the Group 1 pump inlets can be seen to fluctuate greatly about a mean value during the period (Fig. 3.10a). There is little apparent systematic variation with time, although in general the chlorinity is inversely proportional to pumpage, with the highest chlorinity being recorded in periods of low pumpage (Fig. 3.10b). This does not, however, lead to a reduction in the chloride load of the pumps (Fig. 3.11a) which remains as a small proportion of the pump discharge, although there appears to be a trend of increasing chloride load during the second year of monitoring at the Brograve and West Somerton New pumps, and to a lesser extent at Eastfield pump. The proportion of seawater in the total discharge increases slightly with increasing discharge (Fig. 3.11b).

The drainage ditches of the Group 1 pumps are in direct hydraulic contact with the saline intrusion, so that the volume of seawater entering the dyke network is proportional to the hydraulic gradient between the sea and the drainage water. As the gradient remains constant during the year the rate of saline seepage into the network is constant. However, as the rate of freshwater inflow into the network is not constant, the chlorinity of the drainage water fluctuates greatly, being lowest in period of high freshwater inflow. As a consequence of the need to remove the water entering the network, to maintain the desired dyke water level, the rate of flushing of the drainage ditches will be greatest when the pumpage is at its highest. This leads to the chloride load being highest in periods of heavy pumping.

The dyke water of the Group 2 pumps, which are situated along the river, tend to have a more constant chlorinity, with short duration peaks of high chlorinity (Fig. 3.12) associated with over-topping of the river banks. This produces a low background salt discharge with occasional short periods of higher salt discharge.

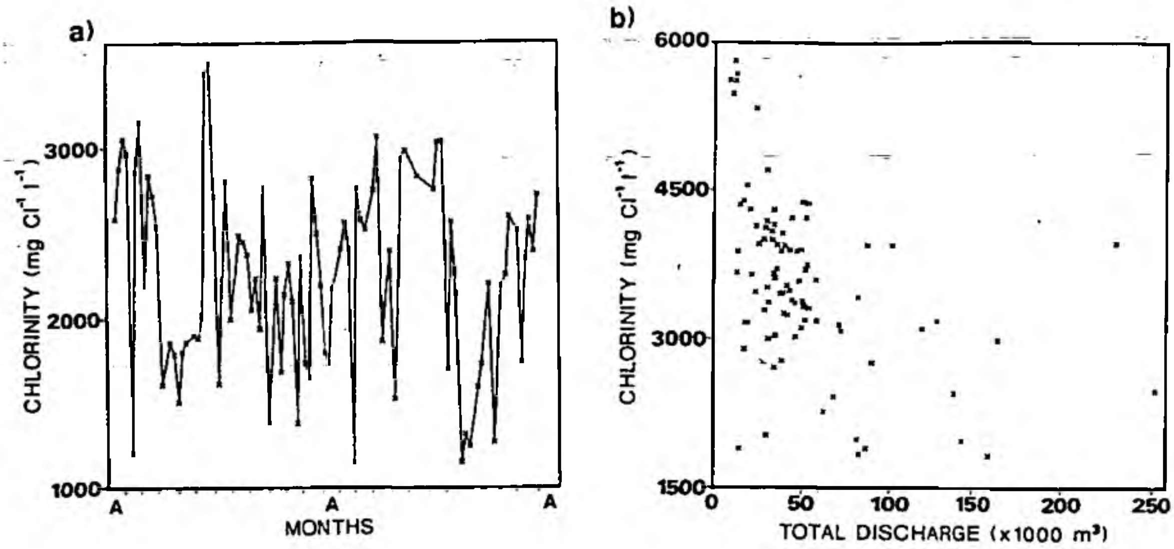

Figure 3.10 The chlorinity of a Group 1 drainage pump against (a) time during the period April 1991 to April 1993 and (b) discharge during the previous week

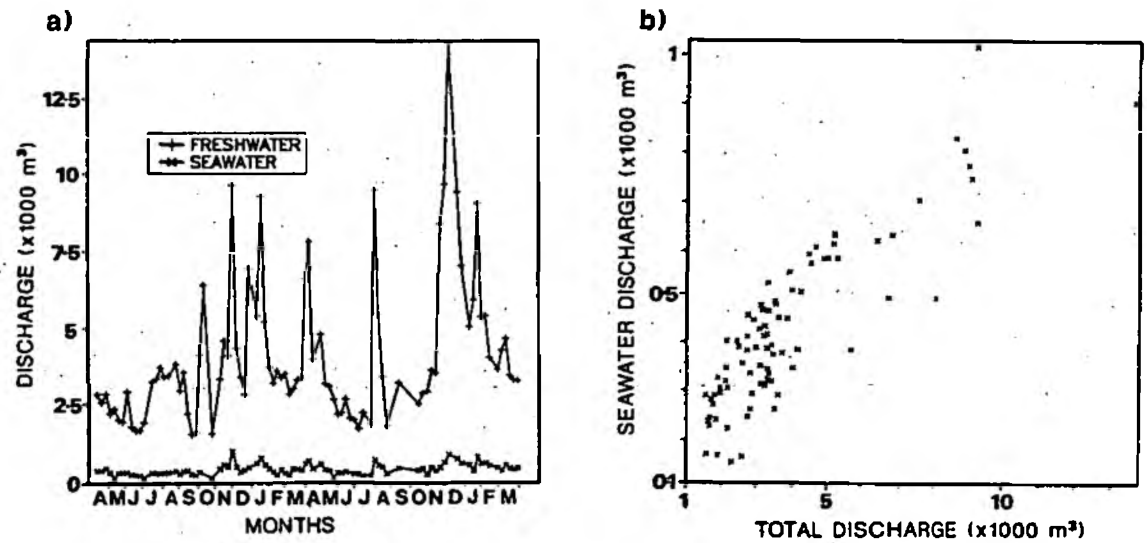

Figure 3.11 The volume of seawater pumped each week by a Group 1 pump during the period April 1991 to April 1993 against (a) time and (b) total discharge

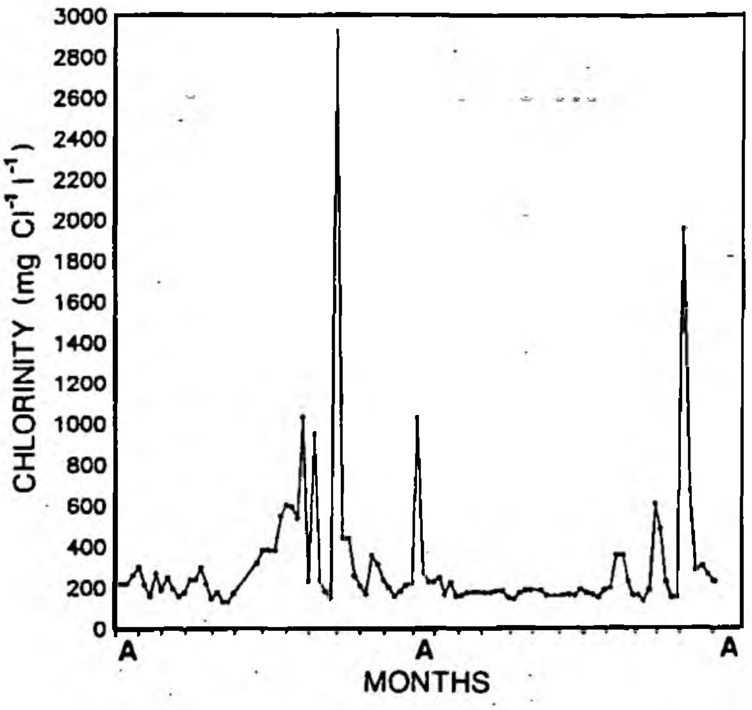

Figure 3.12 Chlorinity of water samples collected at a Group 2 pump during the period April 1991 to April 1993

3.4 Catchment water balance

3.4.1 Water balance results

The results of the catchment water balance are presented in Tables 3.4 and 3.5. It should be noted that the number of significant figures does not imply the degree of accuracy of the figures given.

Table 3.4 Summary of the results of the catchment water balance

	Year 1 Volume (tcma)	Year 2 Volume (tcma)
INFLOWS	60487	73689
OUTFLOWS	59788	78005
STORAGE CHANGE	903	-1958
ERROR	-204	-2358

Table 3.5 Results of the catchment water balance

	Year 1 - 1991/92 Volume (tcma)	Year 2 - 1992/93 Volume (tcma)
INFLOWS		
Rainfall	58795	71624
Saline intrusion	683	1007
River leakage	984	1033
Mains water leakage	25	25
Total Inflows	60487	73689
OUTFLOWS		
Evapotranspiration	47457	59003
Open water evaporation	334	337
Drainage discharge	9892	16417
Groundwater outflow	37	38
Abstraction	400	170
Saline outflow	683	1007
Leakage outflow	984	1033
Total outflows	59787	78005
STORAGE CHANGES		
Surface water	16	19
Soil moisture	763	-1962
Groundwater	125	-15
Total storage change	904	-1958

A number of conclusions can be reached from the catchment water balance, primarily concerning the importance of the land drainage pumps in the cycling of water :

1. The land drainage pumps discharge the equivalent of the potential recharge falling on the entire catchment. This makes land drainage the largest groundwater abstractor in the catchment by at least an order of magnitude.
2. The largest individual groundwater abstractors appear to be the pumps south of the River Thurne, in particular the Somerton pumps and Martham pump. The pumps south of the river abstract an additional volume, over and above the volume provided by rainfall on their drainage levels, equivalent to the potential recharge falling on 30-35 km^2 of upland.
3. The Brograve pump, despite its large drainage level, pumps very little groundwater. This is presumably due to the lack of 'true' upland within its catchment. Only in a small area in the very north of its catchment is groundwater flow not intercepted by the drains of the Eastfield level.
4. Horsey pump discharges little groundwater, as would be expected from its isolated position. A similar situation would be expected for Martham Holmes, for which inadequate data are available.
5. Leakage of river water is as important as the intrusion of seawater into the drainage systems, in terms of volume.
6. The discharge of 'new' water into the River Thurne (ie. not including re-cycled river water) amounts to 10-17 x 10^6 m^3a^{-1} (27-46 x 10^3 m^3day^{-1}).
7. Open water evaporation may be as important as groundwater abstraction. An increase in dyke water levels would further increase this component.
8. In the calculation of the drainage level balance of the Horsey level, actual evaporation for grass (AE_G) was used. During the dry year of 1991/92 this slightly under-estimated

evapotranspiration, while in the wetter year of 1992/93 it produced an over-estimate. On closer examination it was found that AE_G represented the system well during the summer, but during a wet winter was much poorer at representing actual evapotranspiration. It was evident that during this time the marshes on this level were badly waterlogged, and it is considered that this suppressed evapotranspiration. Therefore AE_G appears to represent adequately evapotranspiration in a high watertable marsh, although with a tendency to underestimate in dry years and over-estimate in wet years.

3.4.2 Errors and inaccuracies in the water balance

Meteorological Data - errors are inherent in the areal-averaged rainfall and evapotranspiration values. The variable drainage regimes and soil types around the catchment will produce variations in evapotranspiration that are not reflected in the MORECS data.
Open water evaporation - errors are associated with the measurement of dyke length from the maps and the assumption of a constant dyke width.
Drainage pump discharge - there are errors in the conversion factors for determining the volume of water discharged by the pumps, primarily due to the changes in the river (outflow) elevation, unknown and varying pump efficiencies and the lack of data regarding some of the unvisited pumps.
Saline intrusion and river leakage - volumes have been calculated based upon the assumption that the chlorinity of the dyke water sampled represented the average chlorinity of the water pumped. Leakage was based upon an assumed constant river water chlorinity. In the calculation of saline intrusion it is not possible to differentiate between chlorinity originating from the intrusion and from leakage of river water.
Soil water change - A spatially averaged soil moisture deficit (SMD) was used.
Groundwater storage - the use of a spatially averaged specific yield may be invalid, although the volume of water concerned appears to be small.

3.4.3 Available groundwater resource

The available groundwater resource of the catchment has been determined (Table 3.6) from the volume of recharge falling on the areas of upland, after allowing for runoff as calculated by ESNRA (1971). The total abstraction of this volume of recharge would result in an equivalent reduction in the volume of water discharged by the pumps into the river.

Table 3.6 Available groundwater resource and the reduction in drainage discharge if abstracted

	Groundwater resource (tcma)	Reduction in drainage discharge (%)
Year 1	3450	35
Year 2	3840	23

3.4.4 The effect of raised dyke water levels on drainage pump discharge

A simple steady state numerical model has been created which relates the volume of fresh groundwater discharged by the land drainage pumps that flows into the marshes from the areas of elevated land to the various hydrogeological variables measured. These included groundwater head, dyke water level, hydraulic gradient and the area of the fresh groundwater zone. The model has been calibrated so that the hills of each watershed supply approximately the volume of groundwater required by all the pumps which receive that groundwater.

The effect of raising the dyke water levels of the Brograve and both West Somerton pumps to that maintained in the Horsey level (-0.75 mODN) has then been simulated (Table 3.7). This produced a reduction in the fresh groundwater inflow of approximately 25%:

Table 3.7 The effect of raising the dyke water levels of the Brograve and West Somerton levels

	Groundwater inflow ($m^3 day^{-1}$)
Present dyke levels	9900
Raised dyke levels	6900

Raising the dyke water levels of the Brograve and West Somerton pumps would also reduce the intrusion of seawater into these drainage levels by around 60%, producing an overall reduction of around 40% in the chloride load being discharged by the land drainage pumps into the River Thurne.

4. DISCUSSION

4.1 Mechanisms governing the location of the saline intrusion

From a consideration of the hydrostatic equilibrium between fresh and saline groundwater (the Ghyben-Herzberg relationship), where the fresh groundwater level is low, as in the drained marshlands, saline water will be found at shallow depth. In the dykes, where the local water table is usually at its lowest, the saline water may be at a sufficiently high level to intersect the dyke bed and thereby raise the salinity of the dyke. This will only occur if the water level in the dyke is below sea level. This case is the situation, as shown in Table 3.2, for all the drainage pumps. Drainage, and the associated lowering of the watertable to below sea level, is therefore the predominant factor in explaining the distribution of salinity in the dyke waters of the coastal marshes, with proximity to the areas of higher land being a secondary factor.

In the West Somerton and Horsey Levels, both of which border the sea, it is evident that other factors are important. Prior to the drainage improvement scheme in the West Somerton Level in the 1980's both marshes were dominantly pasture and maintained a high water level, although still below sea level. Data presented by Driscoll (1984) for this period showed that the dyke waters of the West Somerton Level were only slightly brackish with an average chloride ion concentration of 1000-2000 mg $Cl^- l^{-1}$. The dyke waters of the Horsey Level by contrast were significantly more saline. It was only after the drainage improvement scheme that the salinities of the two estates became similar.

Prior to the drainage improvement scheme on the West Somerton Level it is probable that the dykes did not completely penetrate the estuarine clay which forms the Holocene sequence in this area, so that the seepage of saline groundwater from the Crag into the dykes was inhibited, owing to the impervious nature of the clay. Combined with the significant flows of fresh groundwater from the Somerton Hills to the south and from Winterton Ness, this produced a lower dyke water salinity. During the dyke deepening operation the clay was penetrated, such that problems were encountered with 'running sand' (water-saturated unconsolidated sand) in the dyke beds. The penetration of the clay removed the impediment to seepage and the dyke water salinities increased and equalised in the two estates.

All the marshes maintain water levels that are significantly below sea level, yet in many the dykes contain only low levels of salinity or the marshes have a low ground conductivity. Examples of this occur in the marshes of the Eastfield Level to the north of the Eastfield pump, in the Lessingham/Ingham marshes and in the marshes along the River Thurne valley. Fig. 4.1 shows the areas of saline inflow into the dykes, as determined by the dyke water surveys and the areas with high ground conductivity at shallow depth measured during the EM-34 survey, together with the main drains of the pumps. Groundwater flow directions have been drawn on this diagram based only upon the elevation of the water levels in the dykes and assuming a groundwater head above the dyke water level in the areas of higher land. In the north of the area the saline body in the Crag aquifer is seaward of the Brograve main drain; and in the south it is seaward of the Somerton pumps. It is only around Horsey that seawater is intruding significantly inland and this is also the only area where the inland dyke is at a lower elevation than the seaward dyke.

From these observations, it appears that in those areas where seawater intrudes into the dyke network, the dyke water level imposes a new fixed equipotential head on the saline groundwater body (Fig. 4.2). Saline water cannot then intrude further inland into those marshes where the water level is higher, even if that level is below sea level. The dykes of the most deeply drained Levels (West Somerton and Brograve) are thereby acting as flow interceptors for the saline intrusion.

The validity of this fixed equipotential head hypothesis has been tested by predicting the depth to the saline interface at Eastfield Farm where electrical resistivity soundings give an indication of the position of the saline interface. At Eastfield Farm the groundwater head of -0.97m ODN is equivalent to +0.37m relative to the Eastfield Main Drain. This predicts a depth of -15m ODN to the interface, which is slightly greater than that for a sounding nearer the marsh. It appears therefore that the resistivity sounding data support the fixed equipotential head hypothesis.

In the original salinity survey of the Smallburgh IDB, low salinities were measured in the Commissioners Drain

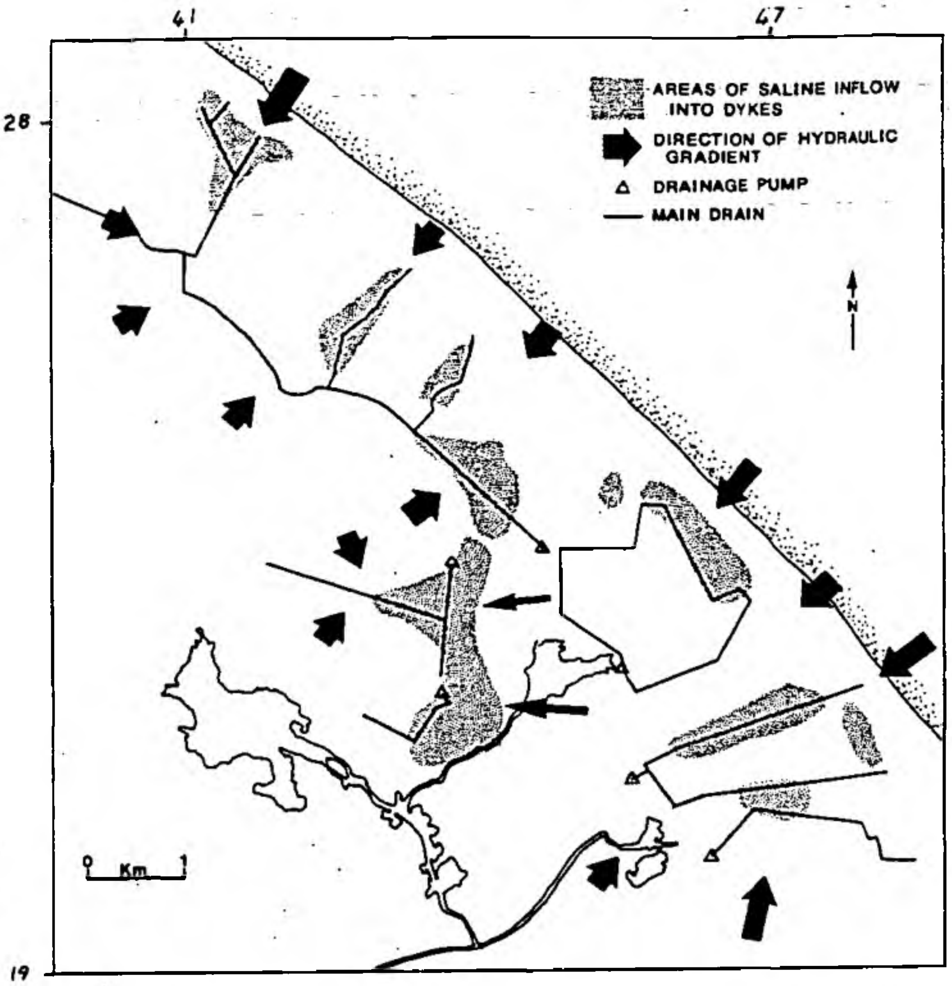

Figure 4.1 The relationship between saline inflow into the dyke systems and the directions of the hydraulic gradients resulting from the dyke water levels

that extends up the marsh between Stubb and Eastfield pumps towards Hickling village. Most of the salinity in the level was attributed to seepage from the high level wetlands of the Brayden marshes and Hickling Broad. However, both the EM and electrical resistivity surveys located saline groundwater at a very shallow depth in this area. A small scale water conductivity survey found that many of the side dykes did show elevated conductivities, with those away from the valley margins having considerably higher conductivities (and therefore salinities) than the Main Drains. Although the Main Drain that runs from the Eastfield pump towards Stubb pump imposes a new equipotential head, the branch of the Main Drain that runs up the valley towards Hickling village is able to maintain a head at levels close to that of the Main Drain so that the intrusion can penetrate up the valley at shallow depth.

Therefore, the above findings suggest that the salinity at any point in the drainage network is dependent on whether the dyke at a point is inland of any dykes that may impose a new equipotential head (Fig. 4.3). If saline water is to seep into the dyke, then the dyke water level must be below the new equipotential head. The degree of salinity will then depend on the hydraulic gradient between the dykes and on the distance from the fresh groundwater inflow of the uplands.

The concept of dykes imposing a new equipotential head has been implicitly shown in previous work (for example Engelen & de Ruiter-Peltzer, 1986; Berger & ten Hoorn, 1986) but it does not appear to have been explicitly stated. Much of the previous work on the hydrogeology of saline intrusion into drained coastal areas has been carried out in Belgium and The Netherlands. In the polder areas of these countries the distribution of surface water levels is very complex, and it is likely that even if certain polder levels are defining equipotential lows, that bypass routes will exist beneath surrounding higher level polders. In the present study, the imposition of a fixed equipotential head that is below sea level allows the Crag aquifer to yield freshwater in wells with

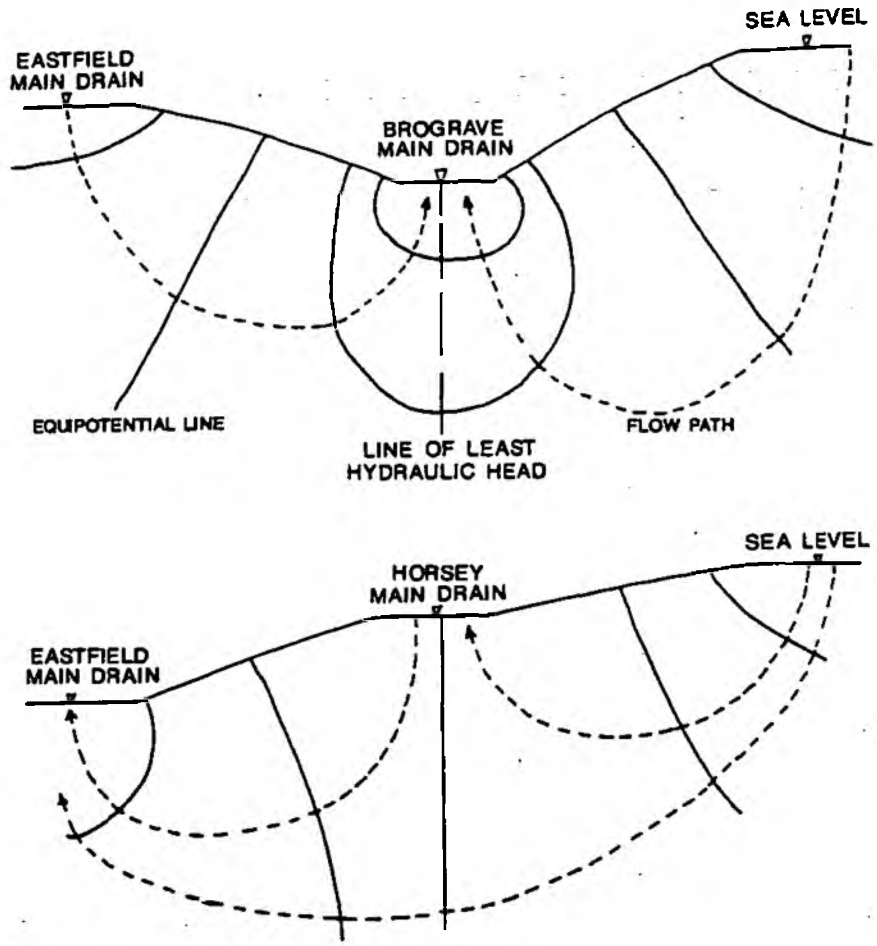

Figure 4.2 The proposed mechanism of fixed equipotential heads imposed by the main dykes of (a) the Brograve pump and (b) the Eastfield pump

negative groundwater heads (relative to sea level).

4.2 The influence of the internal structure of the Crag aquifer on saline intrusion

The Crag aquifer is usually considered as consisting of a sequence of silty, shelly sands, making up a single unconfined aquifer. Layers having an increased silt or clay component have possibly important effects on the vertical permeability of the aquifer, helping to promote and control horizontal groundwater movement (Hiscock, 1993). Due to the likely lateral incontinuity of these clay layers, they were not thought to have further effects, although the total thickness of clay strata within the Crag influences the horizontal permeability (Toynton, 1979).

It has been shown from an examination of borehole logs, seismic reflection data and natural gamma geophysical logs, that the Crag aquifer has two distinct layers within the general thickness of sand. The lower layer, near the base of the Norwich Crag, appears to have an increased clay content within its matrix. It has been correlated with the Thurnian clay horizon of the Ludham borehole. At Ludham, the Thurnian deposit forms the base of the Norwich Crag and overlies the older Ludham Crag. The Ludham Crag, of Pliocene age, has a high transmissivity due to the low content of fine particle. The Ludham Crag sequence within the public supply boreholes at Ludham provide the bulk of the groundwater abstracted. No evidence of the continuation of this deposit towards the coast has been found.

The upper layer identified within the Crag has a composition approaching that of a clay. This layer, likely to be that identified by Downing (1959), has been mapped out to the coast (Fig. 3.3b), suggesting that it is laterally continuous. The lateral continuity of this horizon is significant as it may be hydrogeologically important in

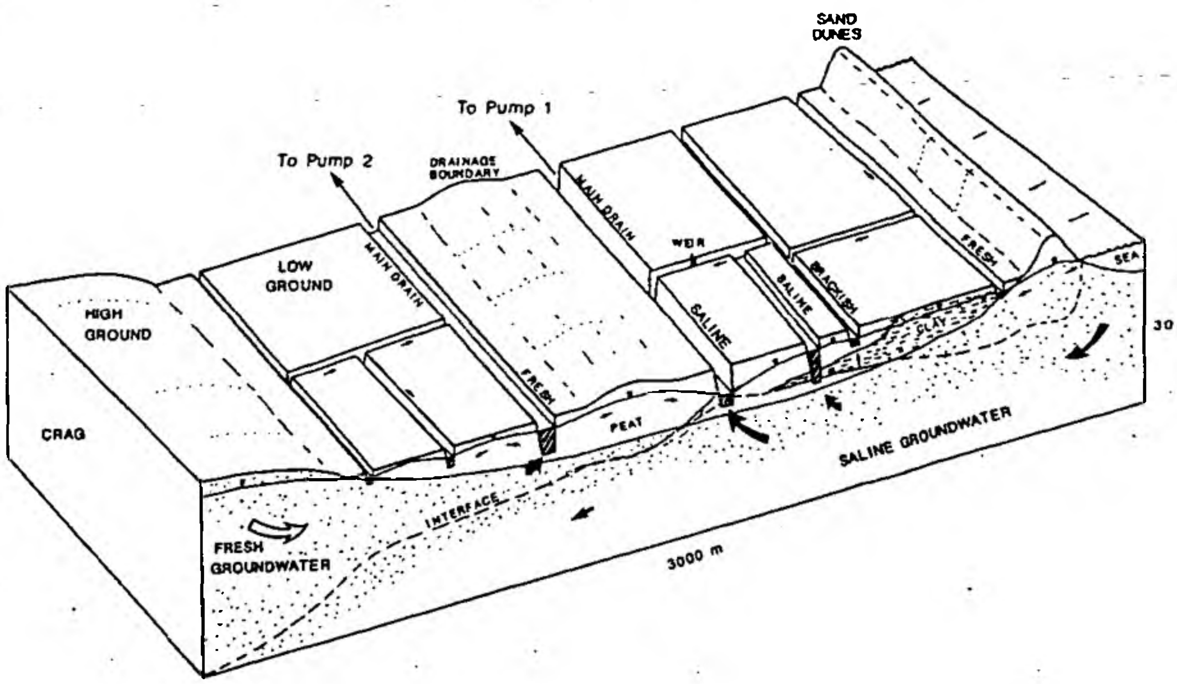

Figure 4.3 Conceptual model of the mechanisms controlling saline intrusion in the Thurne catchment

controlling the position of the saline intrusion in the north of the catchment. Saline water intrudes into the Hempstead marshes but upon advancing inland is soon forced to a depth of around -50m ODN. The location of this coincides with the weir at TG409267, but the increase in water level across the weir, and subsequently to Ingham Corner (Fig. 3.9) of around 0.45 m, is not sufficient to account for this depth. Clearly the dyke water level cannot be controlling the depth of the saline intrusion.

The groundwater head, further north of Ingham Corner, in the Eccles marsh is sufficient to account for the depth of the intrusion, but not sufficient, according to the Ghyben Herzberg equation, to prevent the toe of the intrusion from penetrating into the aquifer beyond this location. Further inland the intrusion should have been detected at a shallowing depth due to the lowered elevation of the dyke water level as Ingham is approached. It is therefore suggested that the saline intrusion is prevented from penetrating into the upper aquifer unit by the high groundwater levels pertaining near the Eccles marsh. Inland the intrusion present in the lower aquifer is not able to flow upward through the clay layer, or at least at a sufficient rate, to produce a detectable decrease in groundwater quality. The slight inconsistency between the depth of the clay layer and the depth of the saline groundwater, as detected by the electrical resistivity soundings, is due to the decrease in resolution of the resistivity interpretation with depth.

In The Netherlands, erosion during glacial times of a similar clay layer separating fresh and salt water Pleistocene aquifers has allowed the salinization of the upper, freshwater aquifer following the development of a well field (Geirnaert *et al.*, 1983). Any groundwater development of the Crag aquifer in the northern area would therefore have to be certain not to penetrate this clay layer. Such an action could lead to salinization of part of the upper aquifer unit in this area.

4.3 Stability of the saline intrusion front

The part of the catchment around Ingham Corner and Eccles is the only area of the catchment where the influence of the upper clay layer is important in controlling the position and depth of saline intrusion. Elsewhere, due to the low groundwater heads within the remainder of the coastal 'uplands', the depth of the intrusion is governed by the groundwater head imposed by the dyke water levels. Although the relative head beneath some of the grazing marsh levels along the river may be sufficient to force the intrusion beneath the clay layer, the head is relative to the dyke water levels of the deeply drained coastal marshes. The dyke water levels of these coastal marshes may be raised in the future so that the inland penetration of the saline groundwater body above the clay layer will be possible.

The position of any salt/fresh groundwater interface in shallow deposits is likely to have changed position during the Pleistocene and Holocene periods as a result of changes in sea level and recharge patterns. At present the interface in the Thurne catchment appears to have attained, or is approaching, equilibrium with the present groundwater head distribution within much of the catchment. It therefore seems unlikely that zones of reduced hydraulic conductivity produced by the deflocculation of clay particles (particularly montmorillonite) within the aquifer matrix will have formed within the Crag. Deflocculation occurs when seawater intrudes a freshwater-saturated aquifer, or vice versa, and can reduce hydraulic conductivity values in the interface zone by a thousand-fold, impeding subsequent shifts of the interface (Goldenberg, 1991).

The distribution of the dyke water levels is not a stable system, with water levels having been lowered or raised in the past due to the desires of landowners. In the 1980's, the availability of grants for deep drainage to enable arable cultivation was the driving motivation, producing a lowering of the dyke water levels in several of the drainage levels, for example Martham, Eastfield and West Somerton. In the 1990's the opposite is occurring, with grants available to those maintaining high dyke water levels in their marshes. As of present, dyke water levels have only been raised along one short length of dyke in the Smallburgh IDB, but for reasons unconnected with the grant schemes. Nevertheless, sizeable areas within the drainage levels of the Eastfield, Potter Heigham and Brograve pumps have reverted to grazing marsh or set-aside land. It appears to be only a matter of time before pressure will be exerted to allow dyke water levels to be raised. This is a very simple exercise, requiring little effort other than the raising of the electrodes that operate the automatic pump controls.

The West Somerton and Brograve pumps impose water levels on the two most important main drains that are acting as flow interceptors. Tables 4.1 and 4.2 show the head differences for the other drainage levels relative to these two main drains.

Table 4.1 Groundwater head imposed by inland drainage pumps relative to that of the West Somerton New pump and the resulting predicted depth of the saline intrusion from a consideration of hydrostatic equilibrium.

Pump	Relative head (m)	Predicted depth to saline intrusion (m)
Martham	1.3	52
Potter Heigham	1.4	56
Repps	1.5	60

Table 4.2 Groundwater head imposed by inland drainage pumps relative to that of the Brograve pump and the resulting predicted depth of the saline intrusion.

Pump	Relative head (m)	Predicted depth to saline intrusion (m)
Eastfield	0.6	24

Comparing the predicted depth of the saline intrusion beneath the Eastfield level and that measured with the electrical resistivity sounding (Fig. 3.8) it appears that there is some similarity. This suggests that the saline intrusion in this area may have reached its equilibrium position.

The predicted depths beneath the river marshes, which are controlled by the West Somerton pumps, are significantly greater than that observed. The West Somerton drainage improvement scheme was carried out in the early 1980's, compared to the mid 1960's on the Brograve level, and it is likely that the intrusion has yet to reach its equilibrium depth beneath the river marshes. The alternative possibility is that the saline intrusion is reaching the river marshes via the Horsey level. As the Horsey level imposes a dyke water level that is higher than that of the river marshes, the depth of the intrusion beneath these marshes must be controlled by the dyke water level in the Martham Holmes level. Unfortunately no information is available regarding the dyke water level controlled by the Martham Holmes pump. To account for the observed maximum depths of the intrusion would require the pump to maintain a level of between -1.12 and -1.34 mODN, similar to that of the Eastfield level.

4.4 Contribution of drainage pump discharges to the catchment water balance

In Section 3.4 it was shown that the water balance of the River Thurne catchment can be defined with three main variables: precipitation; evapotranspiration; and drainage pumping, the latter indicating that land drainage is a very important parameter. All the other water fluxes appear to be at least an order of magnitude smaller. The fluctuation of the groundwater table in the marshes has shown that significant recharge to the Crag does occur through the Holocene deposits. This is an important result as it has the effect of increasing the available groundwater resource of the catchment.

Table 4.3 compares the latest resource assessment for the Thurne catchment (NRA, 1993) with the results of the water balances presented in this study. The availability of groundwater in the drained marshes to support the river has more than doubled the volume of groundwater discharged into the river, and by providing the river's full requirement has resulted in an increase of 70-90% in the available groundwater resource of the uplands.

Table 4.3 Nominally available groundwater surplus in the Thurne catchment. All figures in units of 10^6 m^3a^{-1}

	Effective resource (1)	River requirement (2)	Effluent input (3)	Groundwater input to river (4)	Total abstraction (5)	Balance nominally available (=1-4-5)
NRA (1993)	4.3[1]	2.4	0.3	2.1	0.4	1.8
Year 1	8.7	5.6[2]	0.3	5.3	0.4	3.0
Year 2	9.7	6.2[2]	0.3	5.9	0.4	3.4

Note: 1 - The gross resource (based upon long term average recharge (1961-1990) reduced by 20% to reflect seasonal variation. The effective resource is reliably available
2 - Calculated from drainage pump discharge resulting from potential recharge from marshland and runoff from higher land in addition to effluent input.

4.5 Effect of raising dyke water levels

As mentioned earlier, raising the dyke water levels is a fairly simple operation, requiring the cooperation of the Drainage Board. If either the West Somerton or Brograve pumps raised their water levels to that of the neighbouring Horsey Level, the saline groundwater body would be able to underlie at a more shallow depth many of the inland marshes, as the relative head between the inland and coastal marshes would be decreased. Unfortunately the movements of the saline body would take a long time to re-equilibrate with the new groundwater head distribution, so that the effects of such an action would take many years to be seen.

It has been shown in this study (Section 3.4.4) that raising the dyke water level of the Somerton and Brograve pumps to about -0.75 mODN will produce a reduction in the chloride load discharged by the pumps of about 40%, a similar amount to that found in a modelling study in the Netherlands (Maas, 1991), although the height to which the water levels were raised in this study was not stated. Although there would be a predicted 25% reduction in the freshwater discharge of these pumps, the overall reduction in chloride load will have a beneficial effect on the salinity of the River Thurne. The resulting volume of water discharged by the pumps will continue to be greater than that required to meet the river's full allocation (NRA, 1993), so that the river should not become more prone to tidal surges as a consequence of its reduced discharge. This, however, is a short term view as the overall effect of such an action will be to the likely detriment of the freshwater resource of the Crag aquifer, as the saline intrusion penetrates further inland.

If such decisions are to be taken, it is important that the effects of such actions on other areas, away from the individual drainage level concerned, are taken into account. The presence of the saline groundwater body at shallow depth beneath a marsh is not a problem in itself, provided that it does not 'pollute' the drainage ditches to such an extent that the water is undrinkable for stock. The water within dykes that are subject to saline groundwater inflow often stratify, with the less dense freshwater overlying the denser salty water, thereby continuing to provide drinking water for stock. The solution to the desire to raise dyke water levels in individual drainage levels may be to limit the height to which the water levels may be raised, so that at eventual equilibrium the saline groundwater body will not affect the quality of the dyke water in other drainage levels. A head difference between the coastal and inland dykes of only 0.25 m will, according to the Ghyben-Herzberg equation, allow the saline groundwater body to rise to a depth of not less that 10 m.

If the possible long term derogation of large parts of the aquifer is not acceptable then alternative solutions must be considered. It may be possible to re-design the drainage networks of the Brograve and West Somerton levels so that the pumps maintain the present dyke water levels in the main drains, while the water levels in the side drains are kept at a higher level by weirs. While this would require the installation of several dozens of weirs it would enable the main drains to continue to act as flow interceptors, imparting the present equipotential head, while the side drains contain the high water levels required of many of the grants. Such a scheme would have several disadvantages. The costs of installing so many weirs would be considerable, and as the pump would continue to have to operate with the same lift as at present there would be a lack of savings on pumping costs. It is doubtful whether such a scheme would be acceptable without external funding.

The future management of the surface water network is likely to be driven by the coincident desires of the conservationists and the farmers. Both forces are likely to lead, through raised dyke water levels, to the similar end result of lower drainage pump discharge and river water salinity. Both will be at long term expense of the aquifer. It remains to be seen whether such actions will be allowed.

5. CONCLUSIONS

The Crag aquifer in the River Thurne catchment has a catchment area of 109 km^2, a decrease of 2.5 km^2 on the groundwater catchment derived from the surface water catchment reported in ESNRA (1971). The structure of the Crag aquifer is found to be more complicated than originally thought. The Crag forms an easterly deepening basin, with a maximum recorded depth of -60 mODN, overlying the London Clay, with its axis aligned southwest-northeast through the centre of the catchment. The aquifer itself appears to be sub-divided at around -25 mODN by a clay horizon of probable Baventian age. Evidence of reducing conditions beneath this horizon and its potential importance in preventing the incursion of saline groundwater in the marshes towards the north suggest that it may be more appropriate to consider the Crag aquifer, not as a single unit, but as an aquifer system of at least two layers. A further lithological change to a more clay-rich matrix has been detected towards the base of the aquifer from about -40 mODN.

The Crag has a porosity range of 25-40 % above the Baventian clay, derived from electrical resistivity soundings. In contrast, the specific yield of the aquifer, based upon pumping test data, ranges mainly from 10^{-2} to 10^{-4}, the higher values being found beneath the hills of the southern watershed. Transmissivity values ranged from 150-1100 m^2day^{-1} equivalent to a hydraulic conductivity of $3.5x10^{-5}$ to $2.5x10^{-4}$ ms^{-1}, typical of a fine to coarse sand.

In addition to the main aquifer, perched aquifers occur within the superficial deposits. The main perched aquifer is found within the Corton Sands in the hills of the southern watershed around Martham. Smaller perched aquifers have been identified in the North Sea Drift in the north-west of the catchment.

The elevation of the groundwater table is low, reaching a maximum elevation of around +7 mODN in the far north of the catchment. Elsewhere the watertable is generally found at elevations of less than +1.5 mODN, although in and around the margins of the marshes groundwater levels are below 0 mODN.

The principal source of recharge is rainfall. During two years of monitoring groundwater levels, few of the wells exhibited a groundwater recession rate that was close to the maximum recorded, even during the summer of 1991. Recharge water does appear to reach the watertable within a matter of weeks, if not days, in most parts of the catchment, but the period of time in which the infiltrating water recharges the aquifer varies enormously. The nature of the superficial deposits appear to exert a significant influence on the mean rate of infiltration of the recharging water, but not on the maximum rate.

The surface water bodies of the river system appear to be sites of brackish groundwater recharge. Although most of the river system is surrounded by drained marshland, which acts so as to intercept any leakage, in those areas where the river system abuts higher, undrained land leakage of the brackish surface water into the aquifer is occurring. It cannot be ascertained whether the brackish water body has reached a steady state, or is still rising to attain equilibrium.

In the grazing marsh areas an important groundwater outflow, which can lower the groundwater level to below the dyke water level, is the transpiration of the vegetation. Vegetation is able to transpire effectively during drought periods due to the shallow depth of the watertable beneath the marsh surface. In the deeply drained marshland, groundwater outflow is a result of discharge into the drainage dykes. An additional groundwater outflow occurs in the cliffs at Happisburgh where seepage zones are evident.

The groundwater salinity distribution is controlled by the water level in the drained marshes as maintained by pumping. Seawater may intrude into all the dykes as far inland as the dyke with the lowest water level since this defines a new line of equipotential head for the seawater. Inland of this, the intrusion will gradually increase in depth beyond the reach of any intercepting drainage system.

In areas of the catchment where dykes run inland from the dykes which define the fixed equipotential lines, the surface water gradient governs the depth and inland penetration of the saline intrusion. The shallower the gradient of the water surface, the further the saline groundwater body will intrude, and the shallower its depth.

The Brograve, Somerton and Hickling main drains are acting as flow interceptors to the saline groundwater intrusion by imposing the lowest hydraulic heads. Raising their water levels above that of any drained level further inland risks allowing increased penetration of the saline intrusion.

Individual dyke salinity depends on the saline water within the Crag being able to enter the drains. This occurs if the dyke completely penetrates the Holocene layers or if only peat is present beneath the dyke bed. If clays are present beneath, the salinities are much lower due to the impervious nature of the clay. Superimposed upon this salinity distribution is the freshwater entering the dykes from the marshes themselves via precipitation, and groundwater flow from the uplands and holmes. In general, dyke salinities increase away from the uplands.

At any point, the depth to the saline water can be calculated approximately from the Ghyben-Herzberg relationship provided that the correct equipotential head defined by the dyke water level is known.

The catchment water balance is dominated by three variable: precipitation, evapotranspiration and land drainage discharge. The discharge from the land drainage pumps is equivalent to the potential recharge falling on the entire catchment, making land drainage the largest groundwater abstractor in the catchment by at least an order of magnitude.

Abstraction of the available groundwater resource falling on the higher land will lead to a reduction in the inflow of groundwater into the marshes of 25-35%. Raising the dyke water levels of the West Somerton and Brograve pumps will produce a decrease in fresh groundwater inflow of 25% and a reduction in the intrusion of seawater by around 60%. This will produce an overall reduction of about 40% in the chloride load being discharged into the River Thurne. However, such an action would allow the increased inland penetration of the saline groundwater body, potentially raising the chlorinity of other drainage levels.

6. RECOMMENDATIONS

1. Further work is needed in defining the internal structure of the Crag aquifer, and establishing how this may affect the groundwater flow paths and the position of the saline intrusion.

2. Due to the importance of the land drainage pumps, the calibration of the electricity consumption-discharge relationship is necessary to verify the catchment water balance.

3. Further work is required to determine the effect of raising the dyke water levels on the chloride load and the volume of water discharged by the land drainage pumps. If dyke water levels are raised, either due to changing land use or in an attempt to decrease the chlorinity of the river system, it is unknown what effect this might have on the penetration of seawater or nutrient-rich water from the River Bure into the River Thurne.

4. Finally, the drainage networks must be considered as being part of a single integrated system, rather than as independent units within the catchment. The possible effects of changes in the management of one drainage level on the others must be considered before any changes are carried out.

7. ACKNOWLEDGEMENTS

This work was carried out while Ian Holman was in receipt of a NERC studentship (GT4/90/GS/34) and CASE award from the National Rivers Authority (Anglian Region, ref. 830/53/50). The views expressed in this report are entirely those of the authors and do not necessarily reflect those of the National Rivers Authority. The assistance of the Happisburgh to Winterton IDB, the Smallburgh IDB, the Repps, Martham and Thurne IDB, the Kings Lynn Consortium of IDB's and the numerous landowners and well owners are gratefully acknowledged.

8. REFERENCES

Anglian Water Authority (1978) Salinity Investigation Boreholes near Horsey Mere, Hickling, Norfolk. Unpublished Report, Norfolk & Suffolk River Division, AWA.

Berger, H.E.J. & ten Hoorn, W.H.C. (1986) The shape and position of the salt water wedge in a semi-confined aquifer in non-steady state. In Proceedings of the 9th Salt Water Intrusion Meeting (Delft), edited by R.H. Boekelman, J.C. van Dam, M.C. Evertman & W.H.C. ten Hoorn.

Downing, R.A. (1959) A note on the Crag in Norfolk. Geological Magazine, 96, 81-86.

Driscoll, R.J. (1984) Chloride ion concentrations in dyke water in the Thurne catchment area in 1974 and 1983. Unpublished Report NCC, Norwich.

East Suffolk & Norfolk Rivers Authority (1971) First survey of resources and demands. Water Resources Act, 1963, Section 14.

Ede, A.N. & Mansell-Moulin, M. (1981) Water resources of the Burnley Hall Farms, Norfolk. Unpublished Report for AWA.

Forbes, C.L. (1952) Ludham Borehole : A gravel pack well in the Norwich Crag. Journal of the Institute of Water Engineers, 6, 362-369.

Geirnaert, W., De Jong, S.J. & Sprong, D. (1983) Salinization of a well field caused by a short-circuit between two aquifers. In Geologia Applicata & Idrogeologia. Vol. XVIII, Parte II. Proceedings of the 8th SWIM, (Bari).

George, M. (1992) The Land Use, Ecology & Conservation of Broadland. Chichester: Packard Publishing Ltd.

Gibbard, P.L. & Zalasiewicz, J.A. (1988) Pliocene and Middle Pleistocene of East Anglia. Quaternary Research Association Field Guide.

Goldenberg, L.C. (1991) Permeability decrease in coastal aquifers due to water-rock interactions. In Hydrogeology of Saltwater Intrusion- A selection of SWIM papers. IAH Vol. 11, edited by W. De Breuck, 305-316, Hannover: Verlag Heinz Heise.

Goldsworthy, B. (1972) Horsey Mere - A chemical investigation in four dimensions. Unpublished Undergraduate Project, Univ. of East Anglia.

Gurney, R. (1904) The fresh and brackish water crustacea of east Norfolk. Transcripts of the Norfolk & Norwich Naturalists Society, 7, 637-660.

Hiscock, K.M. (1993) The influence of pre-Devensian glacial deposits on the hydrogeochemistry of the Chalk aquifer system of north Norfolk, U.K. Journal of Hydrology, 144, 335-369.

Holdway, P.A., Watson, R.A, & Moss, B. (1978) Aspects of the ecology of Pymnesium parvum (Haptophyta) and water chemistry in the Norfolk Broads, England. Freshwater Biology, 8, 295-311.

Institute of Geological Sciences (1970) Records of the wells in the area of New Series 1-inch (Geological) North Walsham (148) sheet. Water supply paper of the IGS. London: NERC.

Kazi, A. & Knill, J. (1969) The sedimentation and geotechnical properties of the Cromer Till between Happisburgh and Cromer, Norfolk. Quarterly Journal of Engineering Geology, 2, 63-86.

Lambert, J.M., Jennings, J.N., Smith, C.T., Green, C. & Hutchinson, J.N. (1960) The making of the Broads. Royal Geographical Society, Research Series No.3.

Land & Water Research Centre Ltd. (1992) An assessment of the proposed groundwater abstractions in the Catfield area. Unpublished NRA Internal Report.

Maas, K. (1991) A seepage barrier against salt-water intruion. In Hydrogeology of Salt Water Intrusion. IAH, Vol. 11,edited by W. De Breuck, 17-31, Hannover: Verlag Heinz Heise.

MAFF (1992a) Arable Area Payments - Explanatory Booklet. London: MAFF.

MAFF (1992b) The Broads ESA - Guidlines for Farmers. B/ESA/2. London: MAFF.

National Rivers Authority (1993) Water Resources Strategy Consultation Draft. NRA (Anglian Region) consultation document, April 1993.

Pallis, M. (1911) Salinity in the Norfolk Broads. I. On the cause of the salinity of the Broads of the River Thurne. Geographical Journal, 37, No.3, 284-291.

Roberts, F.N. (1973) The salinity of the waters of Hickling Broad - A historical review. Unpublished Report by the Pollution Prevention Officer, ESNRA.

Rushton, K.R. & Ward, C. (1979) The estimation of groundwater recharge. Journal of Hydrology, 41, 345-361.

Toynton, R. (1979) Waste disposal hydrogeology with special reference to the Chalk of East Anglia. Unpublished Ph.D. Thesis, Univ. of East Anglia, Norwich.

Watson, R.A. (1981) The limnology of the Thurne Broads. Unpublished Ph.D. Thesis, Univ. of East Anglia, Norwich.