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The future sustainability of groundwater resources in East Yorkshire - past and present perspectives.

Trevor Elliot[1], Paul L. Younger[2] and Darminder S. Chadha[3]

[1] Chemistry Manager, Water Resource Systems Research Laboratory (WRSRL), Department of Civil Engineering, Cassie Building, University of Newcastle, Newcastle upon Tyne NE1 7RU, UK.

[2] Lecturer in Water Resources, Department of Civil Engineering, Cassie Building, University of Newcastle, Newcastle upon Tyne NE1 7RU, UK.

[3] Principal Water Resources Planner, Environment Agency (formerly National Rivers Authority), North East Region, Coverdale House, Aviator Court, Amy Johnson Way, Clifton Moor, York YO3 4UZ, UK.

Introduction

The E. Yorkshire Chalk is an important regional aquifer with a large potential for water supply to the Humberside region and the City of Hull. Although there are more than a dozen long-established pumping wells in the Yorkshire Chalk, these currently abstract a quantity equivalent to only 7% of the total recharge the aquifer receives. The classical notion of "safe aquifer yield" equates the quantity of groundwater available for development with the long-term (pre-development) recharge rate to the aquifer. Indeed, the current groundwater protection policy for England and Wales adopts this notion as a basis for planning aquifer resource management. Given that 93% of the natural recharge to the Yorkshire Chalk aquifer is still untapped, application of the "safe aquifer yield" concept could lead the incautious hydrogeologist to conclude that it is a secure, under-developed resource. Yet the aquifer is already displaying some early symptoms of hydrological stress, eg: all-time low piezometric levels during recent droughts; pollution from agricultural sources; and degradation in water quality due to saline water ingress. These are hardly the characteristics one would normally associate with a secure, under-developed resource.

Equating the "safe yield" of any aquifer to its long-term natural recharge rate is wrong (Bredehoeft et al., 1982). Any substantial groundwater abstraction is matched by some loss of storage, an increase in aquifer recharge (induced from from wetlands, rivers, etc.) and/or a decrease in natural groundwater discharge, the latter being the more common response. Hence the task of rational groundwater resources management is the definition of a *sustainable* level of abstraction which induces *acceptable* changes in storage, recharge and/or discharge. At the planning stage, this necessarily involves the resources manager in predictive groundwater modelling of some sort. However, it is all too easy to derive a poorly-posed predictive model by simplistically assuming the long-term persistence of current hydraulic conditions in the aquifer boundary zones. A way of increasing the trustworthiness of predictive models is to establish their consistency with much longer-term changes in aquifer hydraulics, ie adopt a palaeohydrogeologic perspective. A key means of establishing this longer-term aquifer response to changing boundary conditions is to study the present-day distribution of diagnostic hydrochemical facies. In this paper, we first outline the hydrogeological setting of the Yorkshire Chalk aquifer, which provides a framework within which we make an evaluation of the regional resources of the aquifer and important present and past controls on water quality. From this we show how regional hydrochemical patterns further can be used as a guide for evaluating the sustainability of both present and future aquifer management strategies.

Hydrogeological setting

The Yorkshire Chalk north of the River Humber underlies an area of some 1800 km^2 (Figure 1). The eastern half of this area is overlain by a complex sequence (≤ 45m) of Quaternary tills and associated sediments which form a low-lying (< 20 mAOD) plain known as Holderness. Where the Chalk outcrops as the crescent-shaped belt of low hills called the Yorkshire Wolds, the ground surface rises as high as 240 mAOD but is deeply incised by a network of relict steep-sided, narrow valleys, most of which are perennially dry. The Wolds reflect the Chalk outcrop of an open south-easterly plunging syncline. It is generally considered that during the Ipswichian transgression of the sea cut a coastline in the Chalk from NE of Bridlington all along the eastern flanks of the Wolds running inland via Great Driffield (Figure 1), and meeting the Humber east of Hessle, although its age is contended by Eyles et al. (1994). The cliff was subsequently buried by later glacial deposits and is now stranded above the present shoreline, but the succession with buried marine beds is exposed at Sewerby south of Flamborough Head. Natural groundwater discharge occurs along the line of this buried cliff in Holderness. By virtue of the general geological structure most drainage is directed east and south towards lower lying areas of the Hull Valley where it discharges as an extensive area of artesian flow between the buried cliff line and the River Hull; but in the north there is direct flow towards the North Sea.

The Yorkshire Chalk is a relatively hard, pure limestone, with low matrix permeabilities (< 10^{-3} $m.d^{-1}$). High yields from pumped wells demonstrate that groundwater flow in the Chalk occurs predominantly in fissures, high permeabilities giving transmissivities of 10000 $m^2.d^{-1}$ or more. Outcrop examination reveals the ubiquitous presence of sub-vertical extensional joints and sub-horizontal bedding-plane discontinuities; where groundwater circulation is (or has been) vigorous, their apertures are commonly enlarged. Higher permeabilities are often encountered in valley-axes, low permeabilities below interfluves. Previous studies also suggest that zones of fissure enlargement in the Yorkshire Chalk are essentially stratiform, so that it has a "layered" permeability structure. The layered permeability structure becomes even more pronounced as the main springs are approached: transmissivities of >10000 $m^2.d^{-1}$ occur behind the line of the buried cliff located beneath the feather-edge of the overlying till deposits, presumably reflecting the concentration of groundwater flow in this area immediately west of the historic natural springline. To the east of the historic springline, fissure apertures are generally less well-developed. Transmissivities of <50 $m^2.d^{-1}$ are found generally in the confined Chalk of the Holderness peninsula.

While many major springs still flow, particularly around Great Driffield with winter discharges of as much as $1m^3.s^{-1}$ acting as the source of the River Hull, over the last century most of the springs between Beverley and Hull have dried up mainly due to sustained groundwater abstraction at Cottingham since the 1930s. Here groundwater abstraction is considered to be in a state of imbalance. The recognised hydrologic zonation of the Chalk used throughout this paper is shown in Figure 1.

Symptoms of aquifer stress

At present the public water supply of the area underlain by the Yorkshire Chalk is met from the aquifer and through importing up to 90 $Ml.d^{-1}$ from the River Derwent to Hull. Potential future climate change impacts on groundwater resources in the E. Yorkshire Chalk have been presented by Younger et al. (1997). Projections of the primary climate variables daily rainfall (P) and temperature (T) for E. Yorkshire over the next 50 years have been derived based on an equilibrium Global Circulation Model (GCM) of the climatic effects of present-day ($1xCO_2$) and perturbed ($2xCO_2$) equivalent greenhouse gas (GHG) concentrations in the atmosphere, coupled with estimates of the effects of various transient GHG emissions scenarios on global temperature warming (cf Barrow et al., 1994). Emissions scenarios were chosen to provide an “envelope” of potential climate impacts on global warming (Figure 2a) Potential evaporation (PE) estimates were then derived from the projected T data (Blaney-Criddle formulation), and effective recharge assessed as a function of P, T, and PE using standard soil water budget approach. For E. Yorkshire the projections suggest initially a slight increase in both summer and winter aquifer recharge (Figure 2b). The initial prognosis for recharge to the aquifer in the near-future would seemingly bolster the concept of aquifer as a secure resource, although predicted global temperature rises beyond 2045 AD might bring more severe impacts as evapotranspiration may outpace rainfall increases, and crucially the assessment did not address potential changes in rainfall variability.

However, increasing concern over the long-term sustainability of the Chalk aquifer has already been provoked by a series of extremely dry years, which has resulted in Chalk groundwater levels reaching unprecedented low-stands. West and north of Great Driffield decline in aquifer levels can be directly related to spring discharges. During drought conditions in late summer, aquifer levels drop to the same level as artesian spring heads resulting in drying and downward migration of springs and streams. As part of the management of abstractions in the area some boreholes have control level restrictions whereupon they cease abstraction, which allows the streams to flow over longer periods and protects the environment.

Another limitation on groundwater use is imposed by water quality considerations relating to agricultural pollution. Around 90% of the land overlying the outcrop Yorkshire Chalk is given over to arable agriculture: cereal crops occupy about 60% of the land, with the remainder (generally the steep flanks of dry valleys) permanent grassland pasture and woodland. Significant amounts of nitrogenous fertilisers are applied seasonally to the arable land, and intermittently to grasslands; between 1955 and 1971 fertiliser application rose steadily. It is now generally recognised that there is a rising trend of nitrate concentrations in most public water supply sources as a result of recent historical agricultural activities. 85% of the headwaters of the River Hull derive their water from the Chalk groundwater spring flow, correspondingly showing a rise of nitrate at Hempholme Lock (just above the tidal limit of the Hull) where Yorkshire Water take their public supply, and the River Hull has been designated a Nitrate Vulnerable Zone (NVZ). Some Chalk escarpment springs used for public water supply already have >11.3 mg/l NO_3-N, exceeding the EC Maximum Admissible Concentration for drinking water supply. Some sources are now being blended with low-nitrate waters from other boreholes, and the Environment Agency are already engaged in schemes such as Nitrate Sensitive Areas and NVZs to safeguard the aquifer from pollution through working with farmers and UK MAFF (Ministry of Agriculture, Fisheries and Food) to manage land-use.

Save for a small area of Chalk which drains westwards to contact springs on the escarpments, on the regional-scale the boundaries of the usable body of fresh groundwater in the aquifer are more generally defined by the presence of bodies of saline water. Where the local rate of groundwater abstraction exceeds the rate of replenishment (by regional freshwater flow and local recharge), then the interface between fresh and saline waters may invade the abstraction zone (saline intrusion). Historical over-abstraction in the Hull area has induced saline intrusion, although the remnant effects of saline water ingress in the geological past (when sea-level was higher) might explain the presence of other bodies of saline groundwater in the aquifer. A rational aquifer management scheme which would fully integrate the constraints imposed by both water quantity and quality necessarily rests on an understanding of the present regional distribution of general water types in the aquifer. As this distribution to some extent records the effects of previous changes in aquifer flow regime, an understanding of it will hopefully provide a means to judge proposed changes in aquifer flow regime in the future (eg increased/decreased abstraction, artificial recharge etc). The remainder of this paper is devoted to presenting our current understanding of the regional hydrochemistry of the Yorkshire Chalk in relation to the hydrogeological framework presented above.

Sources of regional saline waters

The interpretations which follow are based upon a scrutiny of a large body of archival data held by the Environment Agency for 198 borehole and/or spring sites in the Chalk. Details are presented in Elliot et al. (submitted). A further hydrochemical sub-division of the initial hydrologic zonation of the groundwaters is made simply on the basis of water salinities. Figure 3 shows the relationships between Cl^- and Total Dissolved Solids (TDS) in Yorkshire Chalk groundwaters, and suggests that the sampled groundwaters can be assigned to three categories reflecting the sources of salinity:

Fresh groundwaters:	TDS < 700 $mg.l^{-1}$ and Cl < $mg.l^{-1}$
Slightly saline groundwaters:	700 < TDS < 1000 $mg.l^{-1}$, and 40 < Cl <150 $mg.l^{-1}$
Moderately saline through brackish waters:	TDS > 1000 $mg.l^{-1}$, Cl > 150 $mg.l^{-1}$

The first two salinity categories are adequate for drinking and irrigation water requirements, whereas the third category waters are of poorer quality. The spatial distribution of this latter category is shown in Figure 4, and is associated with the southern portion of AS zone adjacent to City of Hull, and the following portions of the C zone:

- around Flamborough Head
- small pocket around Meaux Abbey
- broad south-eastern region towards Spurn Head
- in a broad area around Atwick (NW of Hornsea).

A brine-discrimination plot (Figure 5) suggests that moderately saline to brackish groundwaters from the AS and C zones follow a mixing-trend between freshwaters and seawater. This is supported by chloride-correlation plots for Ca, Mg, Na, K and SO_4, Li and F (Elliot et al., submitted). Limited Br data from central Hull yield Br/Cl ratios of $2.75x10^{-3}$ (Chambers and Fargus) and $4.15x10^{-3}$ (Needlers Ltd.) both close to the characteristic seawater ratio of $3.46x10^{-3}$ as the source of saline intrusion in the Hull area (AS zone). So if the saline end-member is indeed a seawater, is it modern, ancient or a combination of the two? Certainly the few published radiocarbon ages obtained for the confined (C) Yorkshire Chalk (1600a BP at Sunk Island, 17900a BP at Hollym) suggest that there are waters of considerable age in the aquifer.

Sporadic monitoring throughout the Hull area has yielded a chronology of the development and gradual control of saline intrusion problems in the AS zone (Chadha, 1986). Increasing salinity first became a problem in 1914; there is evidence in central Hull for gradually increasing Cl^--concentrations over a period of nearly thirty years prior to the first areal salinity survey mapped by the Institute of Geological Sciences in May 1951. Subsequent analyses in November 1967 and May 1973 confirmed the earlier survey, and suggested that the saline front had become firmly established with little change in the overall situation. Yorkshire Water Authority monitored the situation with re-sampling in July 1976, April 1977, September 1978 and November 1978. Significantly, the period August 1976-April 1977 was one of extreme regional groundwater fluctuation following drought; during extreme low groundwater levels (>10m below sea level) hydraulic gradients reversed but apparently did not induce further saline water from the Humber Estuary on a large scale suggesting now only limited hydraulic continuity between the Estuary and the Chalk aquifer. At the Hessle borehole only 300m inland from the Estuary, Cl-concentrations fluctuated from 262 $mg.l^{-1}$ (July

1976) down to 4mg.l^{-1} (September 1977). Following the introduction of appropriate management schemes, a more recent salinity survey in February 1986 suggests that the saline front is at least stable if not retreating towards the shore with some indication of a contraction of the outlying 50 mg.l^{-1} isochlor towards Hull (Chadha, 1986).

At Atwick on the eastern coast depth samples collected from a standing water column show increasing salinity, eg:

Depth (m)	*TDS (mg.l^{-1})*	*Cl (mg.l^{-1})*
40	2858	1230
50	5161	2650
60	5587	2890
70	8500	4660
80	9194	5840

This clearly indicates the presence of a saline water body beneath this coastal region, although the 35m-thick till blanket suggests that this is not a simple reflection of modern seawater intrusion. Away from the shores of the Humber Estuary and the North Sea, the source of salinity in the groundwaters is open to more doubt. Given that in the River Hull at Beverley is $Cl^{-} \leq 50$ mg.l^{-1} at high tide, it is obvious that higher values than this in adjacent groundwaters cannot be attributed to induced river infiltration (Figure 3). The moderately saline waters of the UC and AS zones in the Hull area are generally in such close proximity to modern seawater that a simple invocation of intrusion within the last century or so is obvious, the modern component presumably pre-dating the1950s. However, at least one groundwater in the central Hull (AS zone) has been radiocarbon-dated to 6800a BP. It is possible that older marine waters which may have entered the aquifer during earlier Holocene and/or Quaternary episodes or even "connate" waters deposited with the Chalk might account for the saline components of waters in the AS and C zones. Lloyd and Howard (1979) suggest that seawater intrusion in the North Lincolnshire Chalk aquifer to the south of the Humber Estuary took place during the Ipswichian interglacial during formation of the marine cliff and wave-cut Chalk platform.

Are "old" seawaters a major component of present slightly and moderately saline groundwaters in the the aquifer ? A mixing trend with seawater is clearly inferred from minor Sr-contentrations (Figure 6a), however enhanced Sr-contents of tens of mg.l^{-1} for depth samples from Hollym in the distal saline C zone are far in excess of a seawater concentration (8 mg.l^{-1}), which may reflect the effects of increased water residence times and significant Chalk (860ppm Sr) rock-water interaction and is supported by the radiocarbon age for these waters. Another strand of evidence comes from iodide considered an indicator of groundwater residence time (Lloyd et al., 1982); the source of the iodide is taken to be from Chalk (2-5ppm I) rock-groundwater interaction. Waters from the confined (C) zone plot predominantly along a mixing-line towards a source with an $I/Cl \approx 2.5x10^{-4}$, considerably greater than that of modern seawater (Figure 6b). It seems likely that the saline end-member is indeed an evolved, I-enriched fossil seawater, probably with an age > 19000a as it underlies Devensian till (with the "controversy" over the age of the buried cliff (Eyles et al., 1994), it need not be concluded necessarily that this old seawater was intruded during the cutting of the buried cliff in the Ipswichian). The sample from the AS zone dated at 6800a BP shows only moderate enrichment in iodide ($I/Cl=4.5x10^{-5}$), in line with other waters from this area; their intermediate I/Cl ratios could reflect mixing of both recent and old saline components with freshwaters (Figure 6b). The sample from the Smith and Nephew borehole in Hull yields $I/Cl \approx 7.1x10^{-6}$, much closer to the modern seawater value, an interpretation bolstered by its high tritium value. It is concluded therefore that the source of salinisation in the aquifer is due to admixture with freshwaters of at least two components of seawater:

- an ancient I-enriched saline component strongly represented in the C zone beneath Holderness;
- a modern unevolved seawater component affecting sites around the Hull area.

Implications for sustainable groundwater management

The E.Yorkshire Chalk is a high transmissivity and low storage aquifer. Eighty-five per cent of baseflow to the River Hull is provided by groundwater, and any exploitation in the unconfined zone will result in a corresponding reduction of springflow. This will be worst during drought and low water table conditions. Moreover, in the unconfined zone diffuse pollution is a major threat with increasing nitrate (and potentially pesticide) contents. Long-term implications are that full water treatment may have to be imposed to meet stringent EC water quality standards.

Nevertheless, the regional hydrochemistry further illustrates that plans for long-term management of the Yorkshire Chalk cannot be rationally based simplistically on regulatory water quality targets alone. The evidence presented clearly shows the marked importance of both the recent management of the aquifer (eg dynamic movement of the 50 $mg.l^{-1}$ isochlor around Hull) and the palaeohydrogeology of the aquifer on the evolution and distribution of groundwater quality within the artesian and confined zones of the aquifer. Thus, analyses of aquifer conditions which (especially in relation to saline intrusion) over-emphasise current anthropogenic causes of water quality degradation will not however provide an adequate basis to achieve compliance with overall quality targets in the regional aquifer. Rather, a successful plan will need to take into account the degree to which various waters currently encountered in the aquifer are complex mixtures between modern recharge waters, modern seawater and ancient seawaters (which entered the aquifer many millennia ago). Only a management plan which concomitantly builds upon a sound understanding of this past can be expected to produce options for sustainable aquifer management into the future.

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Figure captions

1. Location and schematic hydrogeological map showing the area underlain by East Yorkshire Chalk, with important localities and geographical areas as mentioned in the text, and with the edge of the confining till marked. Dominant groundwater flow directions are shown. Recognised hydrologic zones are: UC = the unconfined Chalk aquifer; A = the "zones of artesian overflow", ie the 3 - 5km wide semi-confined area on the Chalk dip slope west of the River Hull and beneath the feather-edge of the Holderness drift sequence, through which spring discharges emerge (or formerly emerged) - AN = "artesian overflow zone" *north* of Beverley, where springs are still active), AS = "artesian overflow zone" *south* of Beverley, where most springs are now dry; C = the truly confined area of the aquifer where it is perennially fully saturated with non-saline water beneath the Holderness drift east of the River Hull.

2. (a) Global temperature rise (^oC) for the Greenhouse Gas (GHG) emissions scenarios IS92a and FFEF over the future period 1990-2100 (Barrow et al., 1994). IS92a is a "Business-As-Usual" scenario adopted by the Intergovernmental Panel on Climate Change (IPCC) as the most likely future GHG emission scenario having eg only partial implementation of the Montreal Protocol for chlorofluorocarbons emissions; FFEF represents the Greenpeace International Fossil Free Energy Future with complete phase out of nuclear power and fossil fuels by 2010 and 2100, respectively. The terms LOW, MID, HIGH refer to model climate sensitivities to GHG forcing employed for that scenario, namely a predicted global temperature rise of 1.5^oC, 2.5^oC and 4.5^oC, respectively, for a doubling of CO_2 in the atmosphere; (b) comparison of the projected effects of global temperature rise on effective recharge rates (mm per annum) to a hypothetical spring catchment in the recharge zone of the East Yorkshire Chalk aquifer over the future period 1996-2045 (Younger et al., 1997).

3 Total Dissolved Solids (TDS) plotted against Cl^--concentrations defining the further hydrochemical subdivision of the E. Yorkshire groundwaters which is related to their hydrologic zonation.

4. Schematic hydrogeological map showing the area underlain by East Yorkshire Chalk, with important hydrologic zones are marked as UC, AS, AN and C (see Figure1). Moderately saline to brackish water hydrochemical zones are shown as cross-hatched areas.

5. Brine discrimination plot of the E.Yorkshire Chalk groundwaters based on the major ion ratios (all chemistries in mmol/l), originated by Hounslow (1995) to discriminate between oil-field brine, evaporite dissolution and seawater sources for saline waters.

6. (a) Sr and (b) I plotted vs. Cl, used as indicators of groundwater residence times (see text).

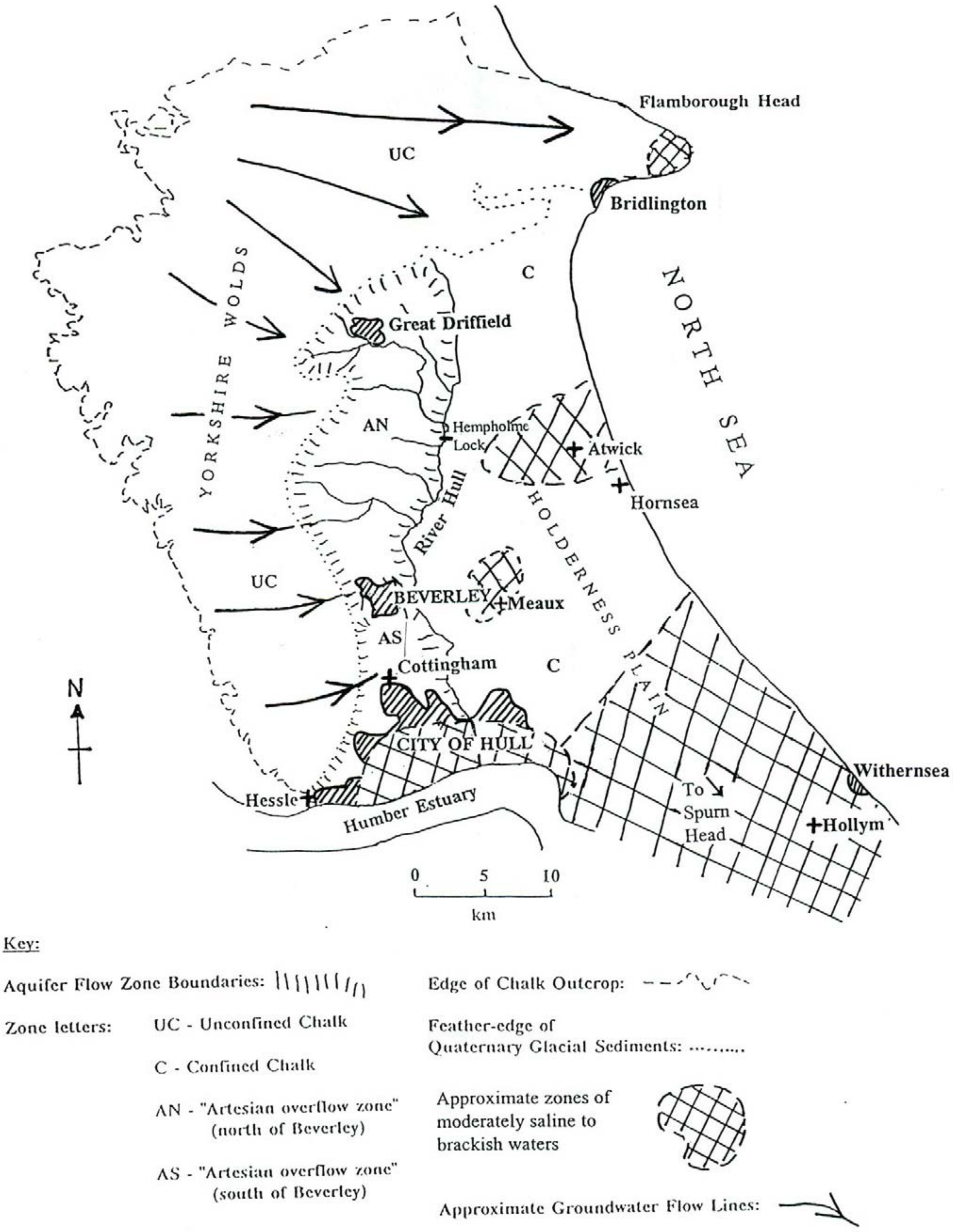
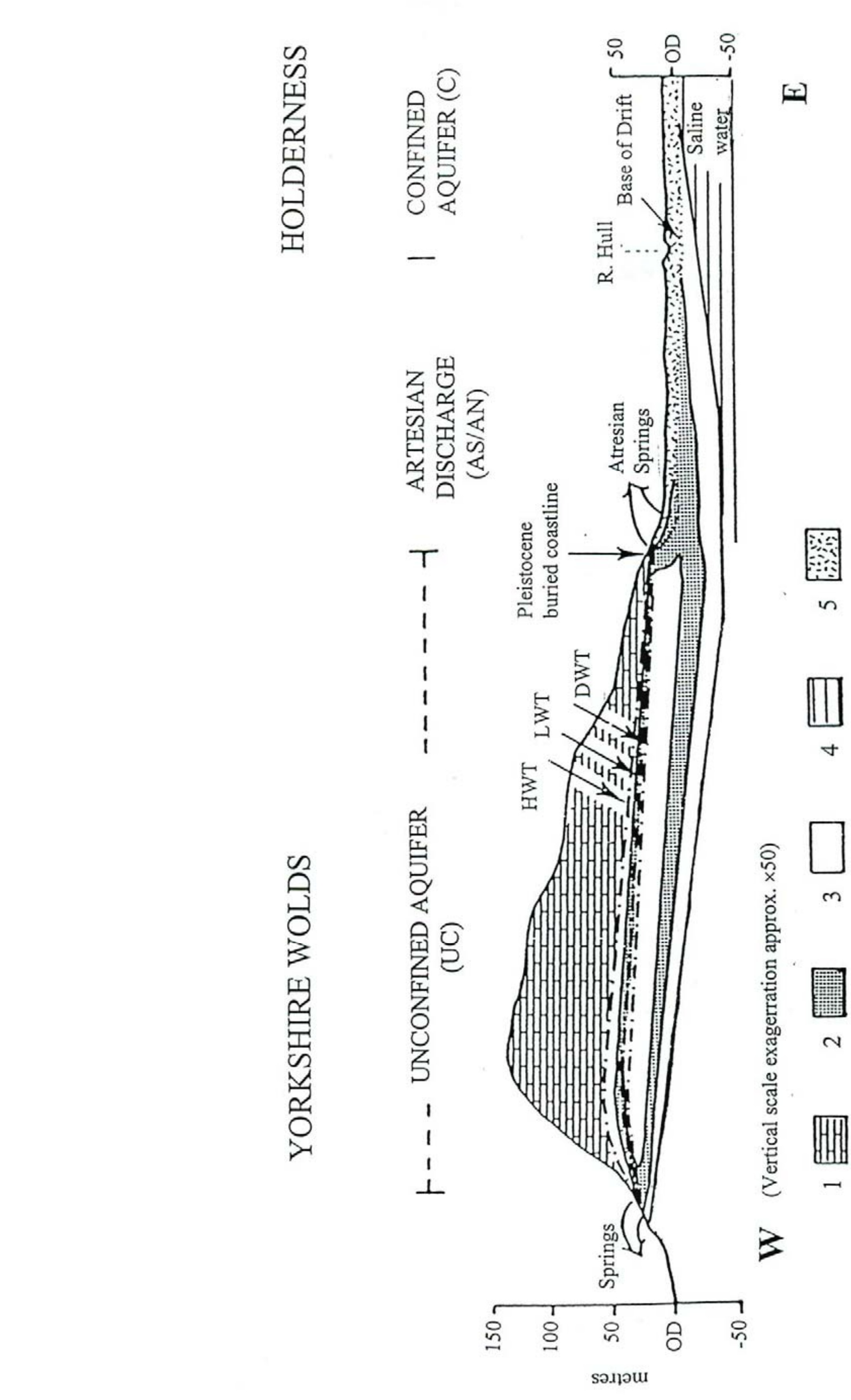
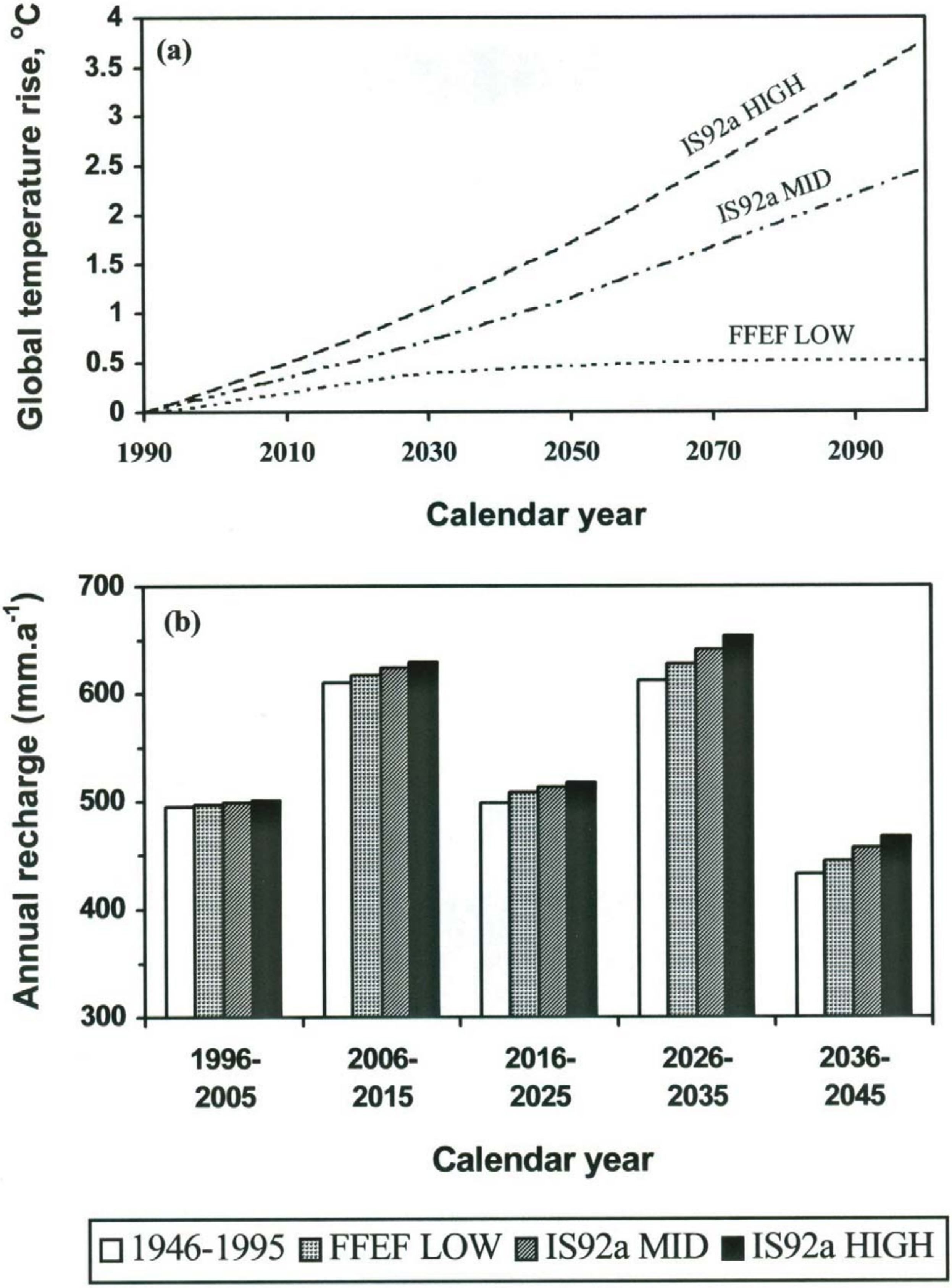

Flamborough Head
UC
Bridlington
C
NORTH SEA
YORKSHIRE WOLDS
Great Driffield
AN
Hempholme Lock
Atwick
Hornsea
River Hull
HOLDERNESS PLAIN
UC
BEVERLEY
Meaux
AS
Cottingham
C
CITY OF HULL
Withernsea
Hessle
Humber Estuary
To Spurn Head
Hollym
N
0 5 10
km
Key:
Aquifer Flow Zone Boundaries:
Zone letters:
UC - Unconfined Chalk
C - Confined Chalk
AN - "Artesian overflow zone" (north of Beverley)
AS - "Artesian overflow zone" (south of Beverley)
Edge of Chalk Outcrop:
Feather-edge of Quaternary Glacial Sediments:
Approximate zones of moderately saline to brackish waters
Approximate Groundwater Flow Lines:

Figure 1



YORKSHIRE WOLDS
HOLDERNESS
UNCONFINED AQUIFER (UC)
ARTESIAN DISCHARGE (AS/AN)
CONFINED AQUIFER (C)
Springs
HWT
LWT
DWT
Pleistocene buried coastline
Atresian Springs
R. Hull
Base of Drift
Saline water
150
100
50
OD
-50
metres
W
E
(Vertical scale exagerration approx. ×50)
1
2
3
4
5

Figure2



Global temperature rise, °C
4
3.5
3
2.5
2
1.5
1
0.5
0
(a)
IS92a HIGH
IS92a MID
FFEF LOW
1990
2010
2030
2050
2070
2090
Calendar year
Annual recharge (mm.a^{-1})
700
600
500
400
300
(b)
1996-2005
2006-2015
2016-2025
2026-2035
2036-2045
Calendar year
1946-1995
FFEF LOW
IS92a MID
IS92a HIGH

Figure 3

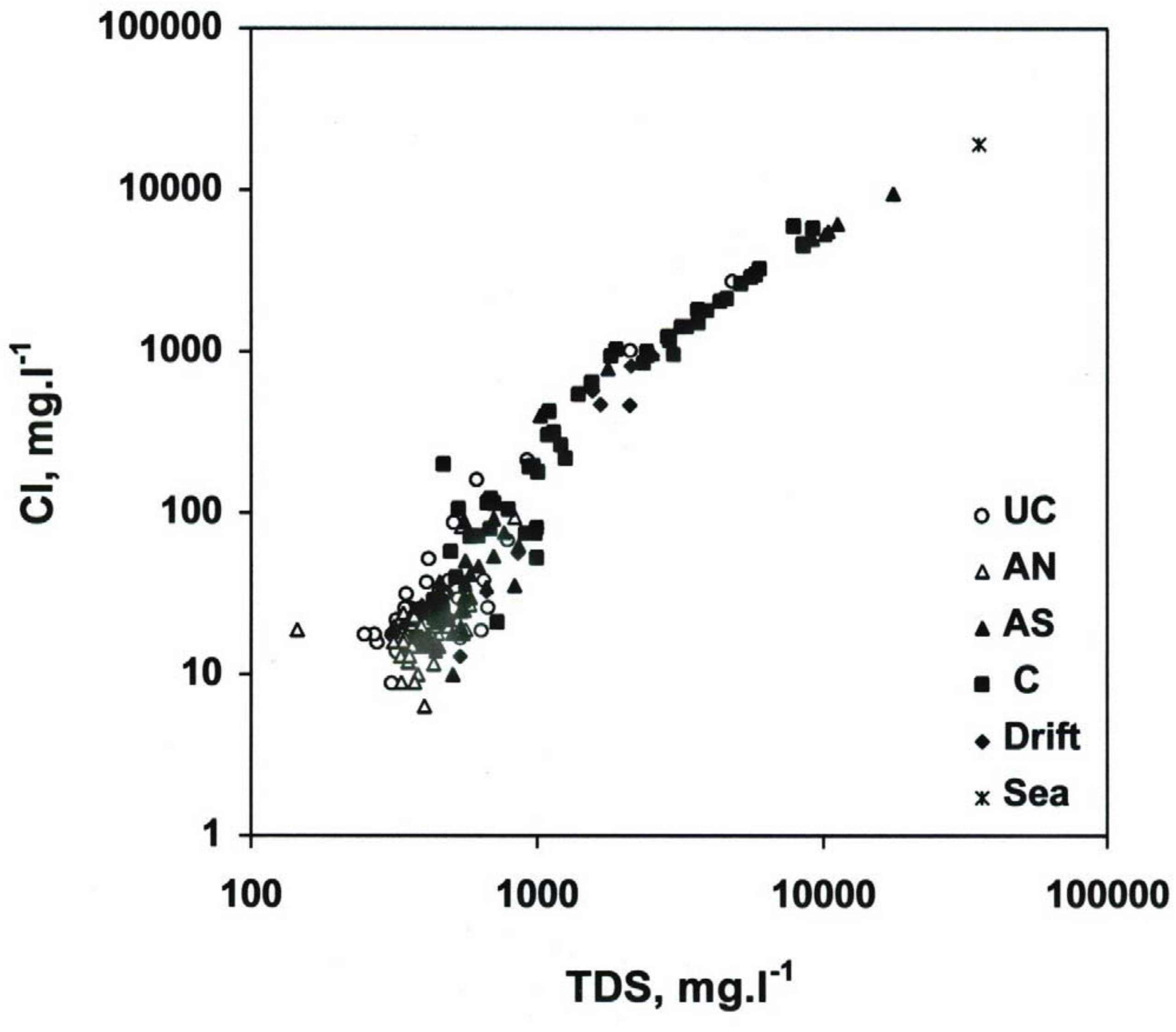
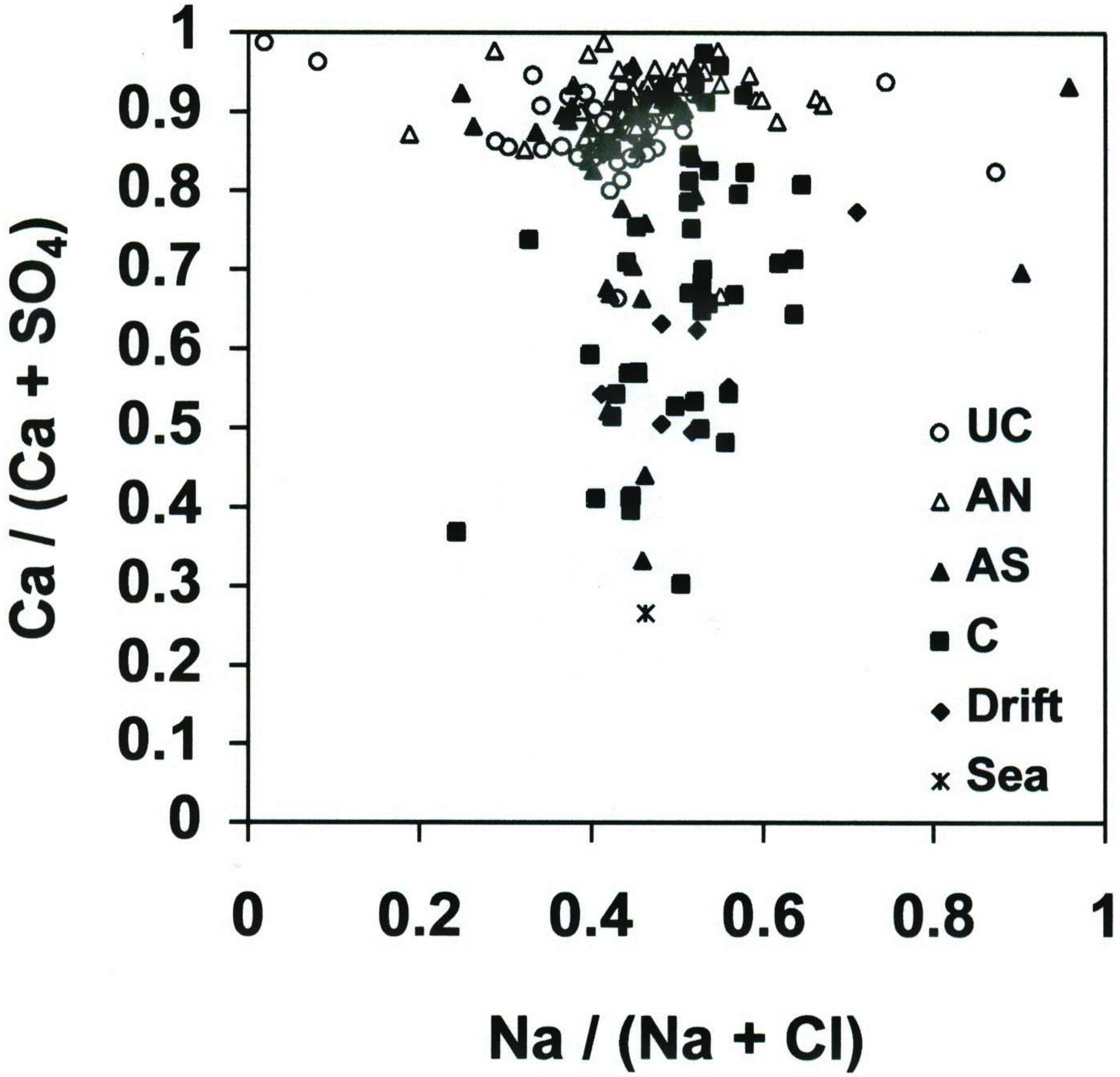

100000
10000
1000
100
10
1
Cl, mg.l-1
100
1000
10000
100000
TDS, mg.l-1
UC
AN
AS
C
Drift
Sea

Figure 4



Ca / (Ca + SO4)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
Na / (Na + Cl)
UC
AN
AS
C
Drift
Sea

Figure 5

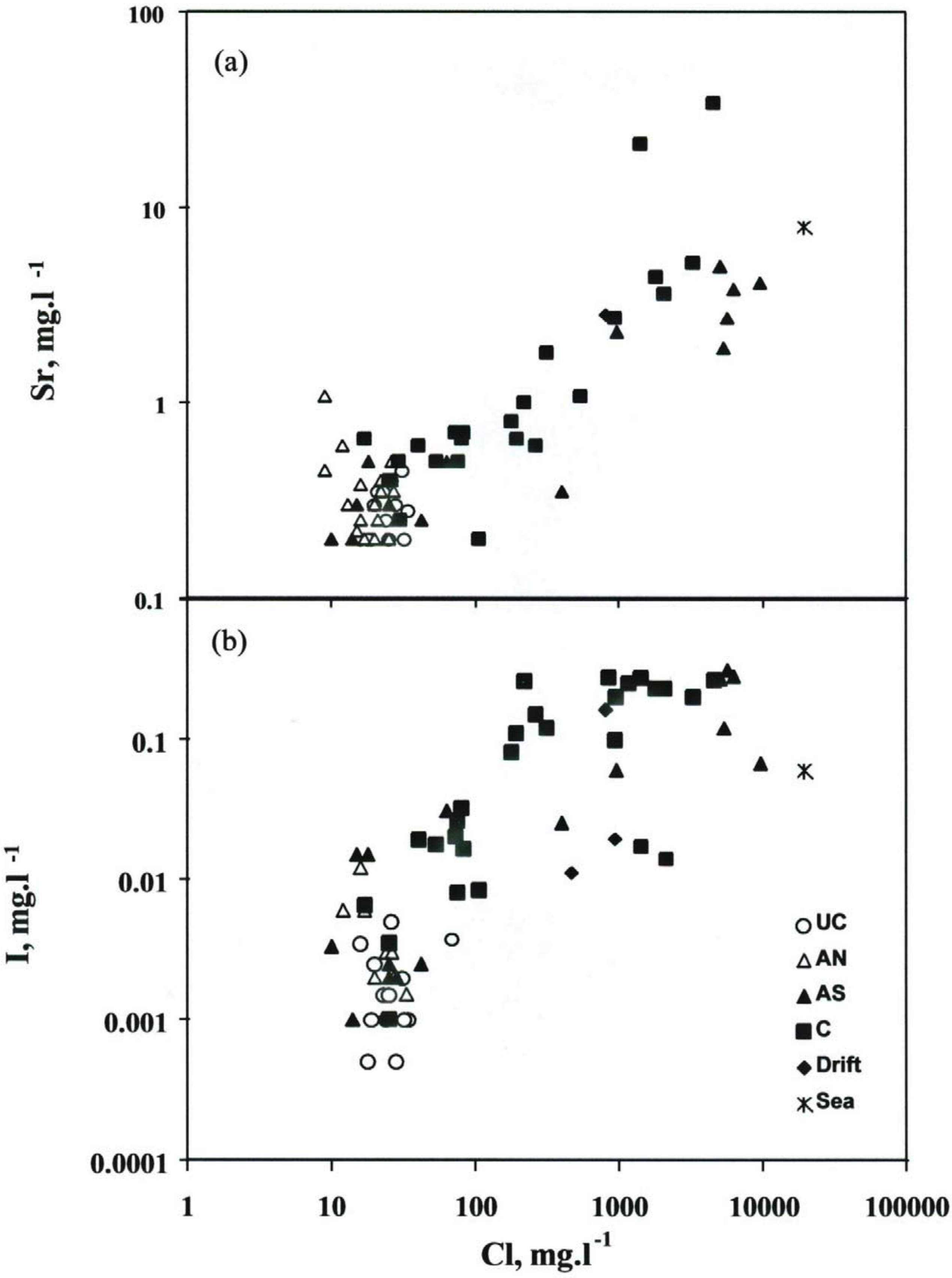

(a)
(b)
100
10
1
0.1
0.01
0.001
0.0001
Sr, mg.l -1
I, mg.l -1
1
10
100
1000
10000
100000
Cl, mg.l-1
UC
AN
AS
C
Drift
Sea

Figure 6