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CONSULTANTS IN ENVIRONMENTAL MANAGEMENT

The Modelling of Water Quality in the Nitrate Sensitive Areas of the North Lincolnshire Wolds, Sleaford and Aswarby

Final Report

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Introduction 1

Objectives of the Study

1.1 On the 20 December 1994 the National Rivers Authority (NRA) commissioned Aspinwall & Company to formulate a draft methodology for the modelling of nitrate concentrations in three Nitrate Sensitive Areas (NSA's) in the Anglian Region, namely the North Lincolnshire Wolds, Sleaford and Aswarby (Figures 1 to 3). The methodology should be designed to enable the existing groundwater flow models of the study areas and the WRc Aquifer Nitrate Numerical Assessment Model (ANNA) to be used to, firstly, reproduce historical nitrate concentrations in these areas and, secondly, to examine the potential impacts of the NSA Scheme on future nitrate concentrations.

1.2 The formulation of the draft methodology is referred to as the Phase 1 study. The later nitrate modelling will form part of the Phase 2 study.

Purpose of this Report

1.3 This Report is the outcome of the Phase 1 study. In developing the Phase 2 methodology Aspinwall & Company has had discussions with several organisations, including the Agricultural Development and Advisory Service (ADAS), the Water Research Centre (WRc) and the University of Birmingham (UOB), as well as the NRA.

Structure of this Report

1.4 The Report is subdivided into six main sections. This first Section introduces the objectives of the study, and identifies the main participants involved. Sections 2,3 and 4 present necessary technical background to the study. Section 2 briefly describes the hydrochemical behaviour of nitrate and describes the various nitrate leaching models available to the study; Section 3 describes the various groundwater flow models that exist for the areas under consideration and Section 4 provides details concerning the ANNA model. These descriptions provide the basis for Section 5, which presents the Phase 2 draft methodology for the nitrate modelling. A summary is presented in Section 6.

The Hydrochemical Behaviour of Nitrate, and its Representation in Nitrate Leaching Models 2

Introduction

2.1 This Section aims to summarise the hydrochemical behaviour of nitrate in groundwater, and the means by which it is represented in leaching models. A detailed literature search is considered beyond the scope of this Phase 1 investigation, but reference has been made to established general hydrogeological and modelling texts, such as Freeze and Cherry (Ref 1), as well as papers and reports published by the consultees to the project, and listed below:

- 'Modelling of nitrate leaching: nitrate sensitive areas', a published paper by Ms Eunice Lord, ADAS (Ref 2);
- 'A Groundwater Nitrate Model of the Central Lincolnshire Limestone', a WRc External Report (Ref 3);
- 'The Central Lincolnshire Limestone Model: Simulation of the NSA's', a WRc External Report (Ref 4);
- 'Prediction of Groundwater Nitrate Concentrations', a WRc Report for the NRA (Severn-Trent Region) (Ref 5); and
- 'The ANNA 2.0 User Manual', a WRc User Manual for the NRA (Ref 6).

2.2 At the end of the Section the various leaching models are compared, and the suitability of each model for the forthcoming Phase 2 modelling is briefly examined.

The Hydrochemical Behaviour of Nitrate

2.3 The most common contaminant identified in groundwater is dissolved nitrogen in the form of nitrate (NO_3). As Figure 4 shows, nitrate can originate as nitrate in wastes or fertilisers applied to the land surface. Nitrate can also result from the conversion of organic nitrogen or ammonium occurring naturally in plant residues or within sewage and mineral fertilisers, by means of the processes of ammonification and nitrification. These inputs occur above the water table, within the soil zone.

2.4 The movement of nitrate from the soil zone into the underlying deposits and eventually into surface or ground waters is termed leaching. The quantity of nitrate (normally expressed in kg nitrogen per hectare, N/ha) that is leached from the soil depends on the imbalance between the above mentioned nitrate inputs and the nitrate losses from the soil via crop uptake, denitrification to nitrogen gas and volatilisation to ammonia. The concentration of nitrate in leaching waters depends on the quantity of nitrate and water available for leaching. The sources of water are most commonly runoff and/or potential recharge.

2.5 Ammonification and nitrification can continue to occur in the unsaturated zone, where organic matter and oxygen can still be abundant. A WRc drilling program, undertaken in the late 1970's and early 1980's, showed that nitrate and other solutes move slowly down through the unsaturated zones of the United Kingdom's Cretaceous Chalk and Triassic Sandstone aquifers (Refs 7 and 8). Rates of movement of between 0.5 and 3 metres per annum were typical, though a proportion of rapid nitrate movement through fissures during intense rainfall was also in evidence. In the other major United Kingdom aquifer, the Jurassic Limestone, the rapid movement of water and nitrate through fissures in the unsaturated zone predominates.

2.6 Concentrations of nitrate in the range commonly reported for groundwater are not limited by solubility constraints. This and its anionic form means that nitrate is very mobile and conservative in groundwater. It moves at the speed and direction of the groundwater flow, with little transformation and little or no retardation. A decline in the redox potential of the groundwater or the presence of denitrifying bacteria can cause denitrification, but the occurrence and significance of such processes is little understood.

2.7 In the major United Kingdom aquifers (limestone, chalk and sandstone) saturated groundwater flow is thought to occur predominantly in fissures. The matrix of each of these aquifers is porous and permeable, however, and solutes are able to diffuse into the matrix porewater from adjoining fissures. In limestone the fissure system is particularly well developed, and most of the nitrate reaching the saturated aquifer remains in the fissures. In chalk and sandstone flow paths tend to be more tortuous and diffusion paths shorter, so that diffusion is more significant and can reach equilibrium.

Modelling of Nitrate Leaching

2.8 Three leaching models have been used previously by WRc in its nitrate modelling studies (Ref 5), and each of these are described briefly below.

MODLEACH Leaching Model

2.9 One of the first leaching models produced in the United Kingdom was the WRc leaching model MODLEACH, part of the ANNA suite of executable programs (Ref 6). This model is based principally on the previously mentioned WRc drilling programme. The nitrate profiles obtained by drilling through the unsaturated zones of the major United Kingdom aquifers were analysed using a model of the vertical movement of water and solutes from the soil down to the water table. Runs of the model allowed the annual leaching losses from the overlying soils to be calculated from the profiles. These losses were compared with the historic land use records to derive the simple relationships between cropping, nitrate fertiliser applications and nitrate leaching presented in Table 1.

Table 1: Estimated nitrate leaching losses, WRc MODLEACH model

Land use	Equivalent N leached
Winter cereals	40% N applied*
Peas	50 kg N/ha per annum
Other arable	50% N applied
Cut grass	10% N applied
Grazed grass	15% N applied
Ploughed grass	280 kg N/ha
Woodland/urban	2-3 mg N/l

* reduced by 40 kg N/ha per annum for sowing post 1984, with smaller reductions back to 1978.

2.10 These losses are inbuilt to MODLEACH and incorporate an allowance for the N leached that originates by conversion of organic nitrogen. No allowance is made for N outputs from sewage treatment works.

2.11 MODLEACH requires the following information to run:

- the dimensions of the model area;
- the nodal area (uniform throughout the model);
- the location of active outcrop and confined nodal blocks;
- the years for which land use data are to be input;

- the year the leaching time series is to end;
- the percentage of the catchment or sub-catchment under each of twelve landuses;
- fertiliser applications in kg N/ha for each of these landuses;
- the number of livestock units; and
- details of any non-agricultural land.

2.12 The land use categories used are winter cereals, spring cereals, potatoes, sugar beet, oil seed rape, other arable, temporary cut grass, temporary grazed grass, permanent cut grass, permanent grazed grass, woods and urban. Information on land use areas and livestock units can be extracted from the annual Parish Crop Returns, whilst fertiliser application rates can be taken from the annual Survey of Fertiliser Practice, published by ADAS.

2.13 MODLEACH produces two forms of leaching file. The first, the so-called WRc format file, provides estimates of the catchment-wide average annual potential nitrate inputs (kg N/ha) to the aquifer. Where the distribution of landuse varies significantly across a catchment, the user is advised to run MODLEACH for each sub-area, and compile a WRc format leaching file manually, specifying individual leaching values for given nodes in these local areas. The second MODLEACH leaching file is in so-called ADAS format, and presents the leaching estimates on a nodal basis for just those years for which land use data are input. This output file can also be generated by the ADAS leaching model, described below.

ADAS NSA Leaching Model

2.14 In the early 1990's ADAS developed it's own leaching model to provide estimates of actual present levels of nitrate leaching from NSA's and of the potential effect of changes on farm husbandry or cropping (Ref 2). The ADAS leaching model is based on a field-by-field survey within each of the first ten pilot NSA's of a wide variety of factors relevant in the determination of nitrate inputs and offtakes. Using data collected from field experiments and other sources (Ref 9) ADAS has identified a relationship between the nitrogen balance (in kg N/ha) and N leached for a wide variety of different land uses practised in these NSA's. These relationships were incorporated into the leaching models relational database, and assumed that above a particular nitrogen balance (termed the 'break-point'), the amount of N leached increased more rapidly. It seems likely that the break-point is an indicator of the point at which the crop's nitrogen uptake efficiency falls. Table 2 indicates the break-point for a variety of crops, and the change in N leached that occurs for a unit increase or decrease in the nitrogen balance around this break point.

Table 2: N leached as a function of the nitrogen balance, ADAS leaching model

Land use	Nitrogen offtake (kg/tonne)	At break-point		Gradients (kg/kg N)	
		N balance (kg N/ha)	N leached (kg N/ha)	Upward	Downward
Winter wheat	22	30	35	0.5	0.07
Winter barley	20	30	35	0.5	0.07
Spring barley	19	30	35	0.5	0.07
Oilseed rape	33	150	110	0.7	0.13
Potatoes	2.5	80	80	0.8	0.22
Sugar beet	1.7	50	30	0.3	0.05

2.15 Allowance is made for the carry over of plant residues from year to year, and for the application of manure.

2.16 The ADAS leaching model attempts to take account of nitrate inputs from crops and fertilisers and of the effects of changes in husbandry. It is therefore more demanding in terms of input data than the WRc MODLEACH model. Data required by the ADAS model includes the following:

- soil type;
- field area;
- cropping, yields and approximate organic manure inputs for the three years previous to the current study year;
- intensity of use and date ploughed out for any grass grown within five years of the current year;
- crop and intended manure use for the current year;
- nitrogen fertiliser and manure use;
- crop yields; and
- other details, such as dates of seed drilling, major cultivations, applications of organic manures and harvest, species and growth vigour of cover crops, and grass use.

2.17 Much of this data is collected by ADAS when formulating its advice to farmers participating in the NSA scheme. Data not readily available from farmers (such as nitrogen content of manures or of harvested crop, soil mineral nitrogen in autumn, and crop nitrogen uptake) are inferred from the data supplied, using look up tables. Default values are provided for certain data (yields, manure application rates, and nitrogen uptake in autumn) for cases where detailed information is not available.

2.18 If ADAS is provided with other information, such as the location of the detailed groundwater flow/nitrate transport model grid, it can arrange for the leaching estimates to be in the same form as the MODLEACH ADAS-format file, ready for import into the ANNA nitrate transport model.

ICI/London Economics Leaching Model

2.19 This model uses published data on nitrate leaching collated from lysimeter and field studies at a variety of European sites, including many from within the United Kingdom. A relationship has been derived between the rate of fertiliser application and N leached for each land use, of the general form:

$$N_{leached} = a + (b.N_{applied})^{c}$$

2.20 The best fit parameters a, b and c for the major crops are as shown in Table 3.

Crop	N use range (kg N/ha)	a	b	c
Cut grass	0-700	1	0.011	2.86
Grazed grass	0-700	1	0.024	2.1
Ploughed temporary		115	0.0	1.0
Winter feed wheat (Sept)	0-250	10+SN	0.04	1.6
Winter feed wheat (Oct)	0-250	50+SN	0.05	1.6
Spring barlery	0-225	75	0.06	1.6
Winter oil seed rape	200-300	100	0.06	1.0
Sugar beet	0-200	60	0.015	3.8
Potatoes	100-300	60	0.055	1.6
Peas or beans		80	0.0	1.0
Vegetables	0-400	80	0.25	1.0
Other arable	0-150	80	0.0	1.0
Woods, scrub		3	0.0	1.0
Urban		15	0.0	1.0

SN = seed bed fertiliser nitrogen (kg N/ha/a)

Comparison of the Leaching Models

2.21 All three models described above are essentially 'black-box' models which operate on land use and fertiliser application data to predict nitrate leaching values without undertaking detailed soil nitrate cycling calculations. A comparison of the models undertaken by WRc (Ref 5) for the Wellings NSA indicated that the models N leached estimates agreed quite well (Figure 5). In particular, the ADAS and WRc models gave very similar results from 1975 onwards.

2.22 The Soil Survey and Land Research Centre (SSLRC) has recently undertaken a field study into nitrate leaching from various crop types under various fertiliser regimes. The WRc report that there are large differences between the nitrate leaching measured by SSLRC and that predicted by MODLEACH and, presumably, the two other nitrate leaching models. This poor comparison was assumed to be due to atypical climate conditions during the course of the field studies. During its NSA studies ADAS installed and sampled porous ceramic cups in a number of fields within each NSA. Measured leaching losses compared reasonably well against model estimates for grass without manure and for arable.

Conclusions

2.23 Despite the indifferent comparison with field data, the three leaching models are still considered to provide reasonably realistic estimates of leaching losses. WRc's success in modelling historical nitrate concentrations in a number of the NSA's can be seen to be partly attributable to the long-term reliability of these leaching models.

2.24 The WRc and ADAS leaching models appear to give similar results. However, the WRc model only takes account of cropping patterns and fertiliser applications, whereas the ADAS model also makes allowance for changes in husbandry. The ADAS model can be argued to be on a sounder theoretical footing, and Aspinwall & Company propose that the ADAS model will be the main means of estimating nitrate leaching in the Phase 2 study.

Description of the Groundwater Flow Models 3

Introduction

3.1 This Section presents a description of the hydrogeology of the North Lincolnshire Wolds and the Sleaford/Aswarby area and of the associated UOB groundwater flow models. The main sources of information for this description are a series of UOB reports, the South Humberbank Salinity Research Project Final Report (Ref 10), the Northern and Southern Chalk Modelling Study Final Report (Ref 11)and the Saline Intrusion Study Final Report (Ref 12), for the North Lincolnshire Wolds, and the South Lincolnshire Limestone Catchment Final Report (Ref 13) and the Slea Catchment Groundwater Report (Ref 14), for the Sleaford/Aswarby area. Personal communication with the main originators of these models, Dr. Andrew Spink and Professor Ken Rushton, was also of great assistance.

3.2 At the end of this Section the main features of these models that present difficulties for the later Phase 2 nitrate modelling are identified.

The North Lincolnshire Chalk

Hydrogeological Description

3.3 The Upper Cretaceous Chalk is the main aquifer in North Lincolnshire, comprising a uniform sequence of pure white limestones, with occasional but extensive marl bands. It outcrops as the Lincolnshire Wolds and dips and thickens eastwards beneath a confining cover of Wolstonian and Devensian Glacial Tills (Figure 6). The Chalk is typically 60 to 100 metres thick beneath outcrop, of which up to 50 metres is unsaturated, but in the confined area near the coast the total Chalk thickness is in the order of 250 metres. Running north-south just off outcrop is a buried interglacial cliff, associated with beach sediments of sand and gravel, up to 12 metres thick in places.

3.4 Regional groundwater flow appears to be to the east, towards Waithe Beck, a line of non-perennial springs on the edge of outcrop, the major groundwater abstractions and a number of artesian 'blow wells'. At certain times natural outflow from the springs can amount to as much as 20% of the recharge. Prior to 1950, when groundwater abstraction was less extensive, the discharge to springs and blow wells must have been even more significant.

3.5 The North Lincolnshire Wolds NSA covers much of the outcrop to the west of the large public water abstractions of Little London, Healing and Habrough. These pumping stations are licensed to abstract at average annual rates of 13.6, 18.2 and 13.6 Ml/d respectively. The NSA is used extensively for arable farming, and nitrate concentrations in waters abstracted at the three locations are high (Figure 7). There are three main non-perennial spring outflows upgradient of these abstractions, namely Kirmington, Keelby and Suddle Wood, with peak flows of 35, 35 and 45 Ml/d respectively. No other obvious groundwater outflows are present in the vicinity of the NSA.

Groundwater Modelling

3.6 The time-variant groundwater flow model for the North Lincolnshire Chalk was constructed in three phases. The first phase was undertaken during the South Humberbank Salinity Research Project, and involved construction and calibration of a finite difference model representing the Upper Cretaceous Chalk between the Humber Estuary and the Lud surface water catchment (from Northings 400 to 425). The second phase was undertaken during the Northern and Southern Chalk Modelling Study, and involved extending the earlier model to cover the confined Southern Chalk, down to about the 360 Northings line, extension of the calibration period, and incorporation of more sophisticated modelling routines. In the third and final phase, extra model nodes have been inserted, the model calibration extended and revised again (so that the calibration now covers the period 1960 to 1989 inclusive), and a dispersivity and particle-tracking chloride transport model constructed of the Grimsby area.

3.7 The two earlier versions of the regional groundwater model assume a regular nodal grid, with nodes spaced at 1.414 km grid intervals, at 45 degrees to the Ordnance Survey National Grid. In the latest model, however, the grid spacing in the Grimsby area (including the public abstractions at Little London and Healing) has been reduced to 353 metres. The second phase model is currently used by the NRA for resource management purposes, whilst the third phase model is only currently used to generate input to the transport model. It is the third phase model that is referred to in the rest of this report.

3.8 Transmissivity in the model is allowed to vary with saturated depth, and in the North Lincolnshire Wolds NSA is typically between 400 and 2400 m^2/d. Nearer to the abstractions transmissivity tends to fall to about 2000 m^2/d. A linear transmissivity-depth relationship is usually assumed, implying uniform permeability with depth, but immediately upstream of the springs nodal permeability is allowed to vary with depth, to simulate the effect of fissuring. Nodal springflow is now calculated within the model. Leakage coefficients are used to represent saline inflows from the Humber Estuary and in the vicinity of Immingham.

3.9 Aquifer storage is assumed to be 1-2 % on outcrop, decreasing to 0.01 to 0.001% in the confined. In the vicinity of the buried cliffline the Chalk and the associated beach sediments vary between confined and unconfined conditions. When unconfined the beach sands and gravels are modelled as having a storage of 10%, and are therefore an important source of water during low flow conditions.

3.10 It was recognised during the South Humberbank Salinity Research Project that the volume of recharge estimated by the conventional Penman-Grindley soil moisture balance approach was less than the known outflows from the system. There was a clear need to reappraise the method of recharge estimation, particularly as some recharge is known to occur during the summer. After a number of model simulations the most appropriate recharge model was found to be one which allows a direct recharge of 10% effective precipitation plus 10% actual precipitation in excess of 6 mm. Recharge estimated in this way and based on daily rainfall and monthly potential evaporation readings taken by the Meteorological Office at its station at Binbrook (TF 196958) and, latterly, Waddington (SK 988 653) is then distributed to all other outcrop nodes via a series of recharge factors.

3.11 The most recent model simulates groundwater heads and springflows at various time steps within a month for the period 1961 to 1989. The simulation of the historical water levels and flows for twelve 'control' observation boreholes and the six springs appears reasonable, and the model has been used successfully to examine a number of future resource management options.

The Lincolnshire Limestone

Hydrogeological Description

3.12 The Jurassic Lincolnshire Limestone is the main aquifer in Central and Southern Lincolnshire, comprising varying calcareous strata with shell beds, oolites, pisolites, cementstones, coral knolls and sandy limestones. The

Lincolnshire Limestone forms a north-south outcrop, six to eight kilometres wide, between the Humber Estuary and Kettering (Figure 8). The UOB regional surface-groundwater model only extends as far north as the divide north of Sleaford (Northing 354). The Limestone in this area is typically between 20 and 30 metres thick, of which some 10 to 20 metres are unsaturated. The Limestone dips gently to the east beneath confining Upper Jurassic Estuarine Beds, Kellaways Beds and Oxford Clay (so-called Overlying Beds), and is thought to 'pinch out' before the coast is reached.

3.13 One of the most significant features of the area's hydrogeology is the complex surface water flow environment. Overlying Beds situated above unconfined limestone, particularly in the area of the 'Leg of Mutton' near Sleaford, are an important source of runoff, interflow, runoff-recharge and percolation recharge.

3.14 Groundwater flow in the area around Sleaford and Aswarby is easterly towards the River Slea and its associated gravels and the main public water abstractions in the confined region, namely Clay Hill and Drove Lane, near Sleaford, and Aswarby. Just west of the confined boundary are a number of particularly important springs - Boiling Wells (TF 043 453), Guildhall (TF 055456) and Cobblers Hole (TF 055454). There are no 'wild bores' (artesian boreholes) in the vicinity of Sleaford and Aswarby, though some upward leakage into the Overlying Beds is anticipated in the confined region. Excess water in the confined area east of the abstractions tends to flow south towards the Glens catchment.

3.15 The Sleaford and Aswarby NSA's cover much of the outcrop to the west of the large public water abstractions. Clay Hill and Drove Lane (combined) and Aswarby pumping stations are licensed to abstract at average annual rates of 11.4 and 4.5 Ml/d respectively. The NSA's are used extensively for arable farming, and nitrate concentrations in waters abstracted at the three locations are high (Figure 9).

Groundwater Modelling

3.16 There are currently two time-variant groundwater flow models for the Lincolnshire Limestone. The first model covers the area stretching from Eastings 490 to 530, and Northings 300 to 355, using a one kilometre regular nodal grid. It is essentially an extension of a model developed by the UOB in the 1970's, and has been calibrated against groundwater heads and springflows throughout the Central and Southern Lincolnshire Limestone.

The second model is of more relevance to this study, concentrating as it does on groundwater conditions in the Sleaford/Aswarby area alone. This model employs a variable-density nodal grid, with a minimum nodal spacing of 250 metres in the vicinity of the public abstractions and the Sleaford springs. Flows across the southern boundary in the Sleaford model are defined with reference to the flows within the larger regional model.

3.17 In the Sleaford model permeability is allowed to vary non-linearly with saturated depth. The model transmissivity in the NSAs range from 120 m^2/d in the west to 840 m^2/d at Drove Lane and Clay Hill. In the confined region to the east of the pumping stations the model transmissivity reaches 1300 m^2/d but falls significantly to the east. Enhanced transmissivity (up to 2000 m^2/d) is assumed in the valley of the River Slea between Wilsford and Sleaford, to reflect the effect of runoff-recharge from the 'Leg of Mutton' to the north.

3.18 Aquifer storage is assumed to be 1 % on uncovered outcrop, 0.1 % on outcrop with Overlying Beds and 0.025% in the confined zone.

3.19 The most significant innovation of the Lincolnshire Limestone flow models are their representation of the surface and near-surface flow environment. Each model node is classified as one of nine recharge (geology) types and is within one of seven rainfall zones. The method of recharge estimation at any node depends on the node's recharge type.

3.20 In the Sleaford model there are four recharge types represented, as listed below:

- Outcrop, where recharge is conventional (soil moisture balance) recharge plus local runoff, as determined by the assumed infiltration capacity;
- Overlying Beds, where recharge is only derived from percolation, and is a function of Overlying Beds storage. Conventional recharge is directed to the Overlying Beds, whilst direct runoff and interflow is passed to the next node;
- Edge of Overlying Beds, where recharge is conventional recharge plus received runoff; and
- Confined leakage, where leakage is generally upward and is calculated by the groundwater model.

3.21 There are also three rainfall zones represented in the Sleaford model, namely Cranwell (Zone 1), Barkston Heath (Zone 2) and Culverthorpe (Zone 3).

3.22 Movement of runoff from node to node is determined by a 'director' array. A receiving node may have more than one feeder node, and a delay in the transfer of runoff can be introduced.

3.23 The semi-distributed surface water model enabled the representation of the runoff-recharge mechanisms observed in the River Slea - Leg of Mutton area. It also implied that it is feasible for the NSA's to extend beneath the Overlying Beds where the limestone is still unconfined.

3.24 The model simulated groundwater heads and springflows at fifteen day time steps for the period 1970 to 1993. The models performance is tested by comparing field and modelled groundwater head hydrographs at fourteen boreholes and flows at seven gauging sites. The simulation is generally adequate.

3.25 The UOB went on to use the model to calculate groundwater fluxes (velocity multiplied by saturated depth) for each node, and then to estimate the approximate positions of the Sleaford and Aswarby groundwater catchments for August 1989 and January 1990. It was not possible to identify separate catchments for the Clay Hill, Drove Lane and the individual Slea springflows, despite the use of the finer model grid. The fluxes were however used to indicate fissure flow velocities of about 100 m/d in January 1990, consistent with a recharge-nitrate response of about 0.5 months.

Conclusions

3.26 Both the North Lincolnshire Chalk model and the Sleaford Limestone model are time-variant models, incorporating variations in permeability with depth that result in marked seasonal variations in groundwater velocity and nitrate transport.

3.27 The feasibility of linking these two groundwater models within a steady-state nitrate transport model such as ANNA is discussed in detail in Section 5. It is sufficient here to state that the nature of the hydrogeological environments and the method of groundwater flow modelling employed requires some revisions to the ANNA program code.

3.28 The linking of the Sleaford flow model and the ANNA nitrate transport model will present particular difficulties. The flow model incorporates a variable nodal grid spacing and a complex semi-distributed surface water modelling routine, which can result in recharge occurring some distance and time away from the associated rainfall event.

Description of the WRc Aquifer Nitrate Numerical Assessment Model 4

Introduction

4.1 This Section presents a description of the WRc Aquifer Nitrate Numerical Assessment (ANNA) model. The main sources of information for this description are the original WRc nitrate transport modelling report (Ref 5), the WRc User Manual (Ref 6) and personal communication with one of the main originators of the program code, Dr David Oakes.

4.2 At the end of this Section attention is given to certain aspects of the model which limit it's practical application to real problems.

Description of ANNA

4.3 Over the last ten years WRc has developed a suite of computer programs on behalf of the NRA for simulating the areal and temporal variations in nitrate concentrations in groundwater. Though one of these programs, the nitrate transport module, is given the name ANNA, ANNA is a more general term which can be used to refer to the whole suite of programs; certainly a full nitrate numerical assessment would usually involve running all of these programs.

4.4 Defined in this way ANNA comprises the following five programs:

- MODLEACH, the nitrate leaching program described in Section 2;
- HMAT, a steady state groundwater flow model;
- ANNA itself, a mixing-cell nitrate transport model;
- VGACOL, a program used to prepare output from the program ANNA for display; and
- DISPLAY, a program used to display the output processed by VGACOL, either on the screen, as hard copy or to a results file.

4.5 It has always been intended that the existing UOB models will be used to represent groundwater flow in the North Lincolnshire Wolds, Sleaford and Aswarby NSA areas (see Section 3), so this description of ANNA will only make reference to HMAT when discussing the form of the flow file expected from HMAT to input into the ANNA transport module. It is also considered not necessary to discuss here the graphical post-processors VGACOL and

DISPLAY. The description will therefore focus mainly on the actual nitrate transport model program ANNA.

4.6 The ANNA program requires prior finite-difference approximation of the steady-state flow equations on a regular nodal grid, either by HMAT or another regional groundwater flow model. ANNA takes the average annual flow rates from the steady-state run, or runs (a historical flow simulation can sometimes conveniently be split into a series of steady states), converts them into quarterly flows using a simple empirical relationship, and then evaluates the average nitrate concentrations for each of the model nodal blocks at the end of each quarterly time-step.

4.7 The nitrate concentrations are estimated using a mixing-cell approach. A nitrate mass balance is calculated for each cell. The nitrate concentrations at the beginning of a particular time step are used to calculate the nitrate mass stored with a given cell. To this is added the nitrate arriving in the recharge waters plus the nitrate mass in water flowing into the cell from adjacent cells. Inputs to a cell are essentially via the fissure system, and the model subsequently solves coupled equations for the concentrations in the matrix and fissures at the end of the time step. Calculation proceeds in order of decreasing water levels, ie down gradient. This allows an efficient method of solution and ensures an accurate water balance.

4.8 To run the ANNA nitrate transport model requires between four and six input files, containing the following information:

- the aquifer data as used by MODLEACH (see Section 2);
- the percentage of effective rainfall (and hence nitrate losses) that is available for recharge (fixed throughout the model);
- the aquifer base elevation and the land surface elevation for each node in metres Above Ordnance Datum (A.O.D.);
- the uniform thickness of the confined aquifer (in metres);
- landuse data as used by MODLEACH (see Section 2), if the WRc leaching file is used;
- the number of groundwater flow files to be used;
- the number and location of output (calibration) nodes (a maximum of seven per run);
- the number of years in the run, and the start year of the run;
- the constant used to relate seasonal flow rates to average annual flow as generated by the steady-state regional groundwater model $^{+}$;
- the fraction of recharge that moves quickly to the water table $^{+}$;

- the solute velocity in the slow phase of the unsaturated zone (m/yr) +;
- the decay parameter (1/yr) for denitrification under confined conditions +;
- the porosity in the joints/fissures and in the blocks/matrix +;
- the diffusion coefficient between the fissures and the blocks (m^3/3 months+);
- the proportion of nitrate input in each quarter +;
- the number of years of effective rainfall, and four quarterly effective rainfall totals (mm) for each year;
- the initial nitrate concentrations in joints and in blocks (mg NO_3/l)+. These can be input from a previous ANNA run, using the warm start option;
- the WRc or ADAS leaching file (see Section 2); and
- the groundwater flow output file from the previous steady-state groundwater flow run, providing an array of node numbers sorted in order of decreasing groundwater head, and a row of data for each node, providing the modelled groundwater head (metres A.O.D.), the flow to/from adjacent nodes (north, east, south and west, m^3/yr), abstraction (m^3/yr) and spring discharge (m^3/yr).

+ indicates that the input is assumed to be constant throughout the model.

4.9 The ANNA model has the means to take some account of certain complexities in the hydrogeological environment, as outlined below:

- runoff (and hence nitrate leaching losses) can be expressed as a simple percentage of effective rainfall;
- steady-state average annual flow rates between the various model nodes can be converted into quarterly flows using the following empirical relationship:

  flow (i)/(average annual flow) = 0.25.(AL +(((1-AL).r(i))/(0.25.r)))

  where flow(i) = flow in quarter i (m^3/quarter);
  r(i) = recharge in quarter i (mm);
  r = average annual recharge (mm); and
  AL = a constant;

- nitrate leaching inputs can be distributed non-uniformly over the four quarterly time-steps;

- the proportion of recharge that travels rapidly (within one time step) down to the water table can be specified;
- a uniform solute velocity in the slow phase (matrix) and the thickness of the unsaturated zone determines the delay between the occurrence of nitrate leaching and its arrival in the saturated zone; and
- some account can be taken in the cells nitrate mass balance of any dual porosity by specifying a diffusion coefficient for fissure/matrix exchange.

The Suitability of the ANNA Model to Represent Nitrate Transport in the NSA's

4.10 The complexity of the two aquifer environments in this study, the North Lincolnshire Chalk and the Sleaford Limestone, has been described in Section 3. For the purposes of this study it must be assumed that the existing groundwater flow models are an adequate representation of this complexity. To be able to simulate nitrate concentrations in the NSAs, ANNA must first therefore be able to represent the main features of the groundwater flow models.

4.11 Compatibility problems between the existing groundwater flow models and the ANNA nitrate transport model have been alluded to earlier. The problems are described in greater detail below:

1) Representation of time-variant flow

4.12 Both the North Lincolnshire Chalk model and the Sleaford Limestone model are time-variant models, incorporating variations in permeability with depth that result in marked seasonal variations in groundwater velocity and nitrate transport. This seasonal variability is very well demonstrated by the groundwater flux analyses presented in the Sleaford Groundwater Report (Ref 14).

4.13 The ANNA nitrate transport model is a steady-state model, and is only able to introduce seasonal variations in groundwater flow (and hence nitrate transport) by means of an empirical equation. This equation has been described earlier, and computes quarterly groundwater flows based on the steady-state flows from the flow model, quarterly recharge and a constant. It is considered that the seasonal flows calculated in this way are likely to be different from those derived from the time-variant groundwater flow models. Instead, it is desirable that the transient flows calculated by the UOB models could be used directly in ANNA.

2) Input of a variable model grid

4.14 The North Lincolnshire Chalk model and the Sleaford groundwater flow model incorporate a variable grid spacing, to allow them to simulate both the regional groundwater flow and the detailed flow conditions around the public water abstractions and the springs. The ANNA model assumes only constant grid spacing, and is therefore currently incompatible with these two models.

3) Simulation of the complex surface-water environment

4.15 The Sleaford model incorporates a semi-distributed surface water modelling routine to represent surface and near-surface flows (runoff and interflow) and complex recharge conditions (conventional recharge, percolation recharge and runoff-recharge). There are two main effects of this - runoff generation is governed by infiltration capacity and can become recharge some distance away from where it originated, and delayed percolation recharge can occur in those parts of the Lincolnshire Limestone covered by Overlying Beds.

4.16 The ANNA model, meanwhile, assumes uniform quarterly recharge across outcrop areas, with provision for only a single runoff coefficient and a single unsaturated flow delay factor. In the Sleaford area this is a gross simplification of reality.

4) Potential for Numerical Dispersion

4.17 The mixing-cell approach to nitrate transport modelling has been widely used in the past, particularly in relation to diffuse pollution, but with advances in computing power more sophisticated methods of solution have become available. The most accurate method of solution currently available is particle tracking, as described in Bear and Verruijt (Ref 15) and similar to that used by the UOB in its Northern and Southern Chalk saline intrusion study (Ref 12). The WRc has compared its mixing cell solution for a test problem with that derived from particle tracking (Ref 5), and demonstrated that the mixing cell analysis can be very accurate, provided that the Courant number is generally less than one

i.e. $v \,.\, \delta t / \delta x < 1$

where v = solute velocity (m/d),
t = time step (d), and
x = grid interval (m).

This condition is equivalent to requiring the advance of the nitrate front during one time step to be less than one grid square. The WRC comparison also showed that the mixing cell solution is some 4500 times faster to compute than that from particle tracking.

4.18 The Lincolnshire Limestone has relatively high groundwater velocities, and together with limited fissure-matrix diffusion, the large ANNA time step and the 250 metre nodal spacing may result in the occurrence of so-called numerical dispersion. A solute velocity of 3 m/d would be sufficient to cause problems. In this instance the modeller should reduce the time step and/or increase the nodal spacing.

Conclusions

4.19 It is apparent that in their current form the North Lincolnshire Chalk and Sleaford Limestone models and the ANNA model are incompatible. Three main areas of difference have been identified - the groundwater models are time-variant (ANNA is steady-state with a seasonal approximation), they assume variable grid spacing (ANNA requires uniform grid spacing) and the Sleaford model also incorporates a complex surface water modelling routine (ANNA assumes simple, uniform recharge conditions). A further potential problem, that of numerical dispersion, has also been identified.

4.20 The next Section proposes a draft methodology for the Phase 2 study that takes account of these difficulties. Extension of the groundwater flow modelling, tracking of the flows within the Sleaford surface water routine, and the expansion of ANNA's capabilities are some of the items of work discussed.

Draft Methodology for the Phase 2 NSA Water Quality Modelling Study 5

Introduction

5.1 This Section presents a draft methodology for the Phase 2 study. It is conceivable that some changes to this methodology will be necessary before commencement of the Phase 2 study, but it is hoped that the methodology does at least identify the main issues to be resolved.

Description of the Phase 2 Draft Methodology

5.2 The draft methodology is presented as a series of tasks, with the suggested main participants highlighted. The modelling of the Sleaford/Aswarby NSA's should be undertaken simultaneously, and not split as suggested in the original Proposal (Ref 16). The modelling of the North Lincolnshire Wolds NSA could be treated as a separate sub-project, though the modelling of Sleaford/Aswarby and the North Lincolnshire Wolds will require the same eleven tasks, as listed below.

5.3 In accordance with the successful Project Proposal (Ref 16) it is suggested that the overall process is managed by Aspinwall & Company (with regular liaison with the NRA), though because the scope of the project has changed some revisions of the projected fees may be necessary.

Task 1: Extension of the Groundwater Flow Modelling (UOB and NRA)

5.4 On commencement of the Phase 2 study the UOB and the NRA are asked to explore the possibility of extending the calibration period of the Lincolnshire Limestone and Sleaford Limestone models back to 1960, and of all the models forward to 1995. This is necessary to provide the required groundwater flow information for the later nitrate transport modelling. The NRA would have to provide additional rainfall, potential evaporation and abstraction data, but no additional model calibration is anticipated.

Task 2: Calculation of Nodal Flows (UOB)

5.5 UOB will be asked to output the average monthly nodal flows (groundwater inflows and outflows, abstraction and storage gain/release) from its groundwater models to a series of ANNA-style ASCII flow files, one for each model and each month, together with matrices indicating the node numbers in order of decreasing groundwater head. Nodal transmissivities will not be required.

5.6 The UOB should also give an indication of typical winter average flow velocities, so that Aspinwall & Company can make a judgement whether the proposed ANNA time step of one month is sufficiently small to avoid problems of numerical dispersion.

Task 3: Further Development of the ANNA Model (WRc and Aspinwall & Company)

5.7 To take account of the complexities of the hydrogeological environments and groundwater models of the two areas Aspinwall & Company propose that some additional capabilities are programmed into ANNA. This programming will be undertaken by WRc and would include the following:

- accommodation of variable model grids;
- replacement of any requirement for a runoff coefficient or seasonal nitrate leaching factors with the ability to input monthly (dependent on the Task 2 findings) nodal recharge and nitrate loading;
- replacement of the empirical quarterly flow equation with the ability to input monthly nodal flows and storage gain/release; and
- ability to calculate nitrate mixing on a monthly basis.

5.8 WRc should regularly advise Aspinwall & Company regarding the progress of the programming, and the results of any test runs, including typical PC run times.

Task 4: Establishment of Basic Model Layout (UOB and Aspinwall & Company)

5.9 The UOB will pass over to Aspinwall & Company copies of the model grids associated with the North Lincolnshire Chalk and Sleaford Limestone groundwater models and superimposed on 1:25000 Ordnance Survey topographic maps. The UOB should also provide information to Aspinwall & Company concerning the extent of the confining cover, the elevation of the effective base of the aquifer and the land surface at each model node, nodal areas and the approximate thickness of the confined aquifer. It is understood that this nodal information is not immediately available and will require significant additional work by the UOB.

Task 5: Calculation of Historic Nitrate Leaching (ADAS)

5.10 ADAS will first be asked to generate nitrate leaching estimates (in kg N/ha) for each NSA outcrop node where ADAS field-by-field surveys and leaching model results are available. Geographically referenced nitrate leaching estimates should be provided to Aspinwall & Company for every fifth year during the period 1960 to 1995 inclusive, in a series of ASCII files whose format is to be agreed with Aspinwall & Company. It is understood that the historical data for this analysis is available for Sleaford, and using recent data can be synthesized for the Aswarby and North Lincolnshire Wolds NSA's.

5.11 ADAS will then use the NSA nitrate leaching estimates and Parish Crop Returns to obtain model-wide estimates of annual nodal nitrate leaching for the given years. The annual nodal leaching estimates will be placed in ASCII leaching files, one for each model area.

Task 6: Calculation of Historic Nodal Recharge (UOB)

5.12 The UOB should pass on to Aspinwall & Company listings of monthly nodal recharge for the Lincolnshire Chalk model, covering the models entire historic calibration period. These should be provided as a series of ASCII files, one per month, in a format to be agreed.

5.13 To obtain the same information for the Sleaford model requires more effort, because of the complex surface water modelling. A tracking routine needs to be constructed and inserted into the Sleaford surface water modelling routine by the UOB, so that the quantity and origin of any monthly nodal recharge during the time-variant simulation can be established. In writing this routine it is important to be aware that at some nodes, e.g. percolation recharge and runoff-recharge nodes, the recharge will be a complex mix of waters, originating from a variety of sources and at a variety of times.

5.14 The results of this tracking routine should be accumulated and output in the same manner as for the North Lincolnshire Chalk. It is anticipated that the majority of the aquifer recharge in both areas will occur over the period October to March inclusive.

Task 7: Calculation of Historic Nitrate Loading in Recharge Waters (Aspinwall & Company)

5.15 A program will be written by Aspinwall and Company to take account of the monthly variation in nitrate input and the distribution of nitrate in surface and near-surface waters in the Sleaford model.

5.16 It is suggested that the annual nitrate leaching estimates produced in Task 5 are assumed to occur entirely in the period October to March, though other seasonal variations can be accommodated. The program will then use the results of the UOB tracking routine to redistribute the nitrate leaching to take account of where and when the recharge actually occurs. The results will be ASCII nitrate loading files, one for each model, indicating distributed monthly nodal nitrate loading in recharge waters for the period of the proposed model calibration.

5.17 There is no evidence to indicate whether or not any denitrification occurs during the recharge process. However, to simplify the calculations the program will need to assume that there is no alteration or loss of nitrate during runoff-recharge or percolation recharge, and that there is thorough mixing of the various originating waters during this recharge.

Task 8: Construction and Calibration of the ANNA Models (Aspinwall & Company)

5.18 The monthly nodal recharge, flows and nitrate loading (from Tasks 6, 2 and 7 respectively) will be input into nitrate transport models set up by Aspinwall & Company using the revised ANNA code (from Task 3). The models will be used to simulate monthly nitrate concentrations for the period 1960 to 1990. The simulated nitrate concentrations will then be compared against observed nitrate concentrations for up to seven boreholes and/or springs per model, the locations to be agreed between the NRA and Aspinwall and Company. Calibration of the nitrate transport models will proceed until an adequate match between observed and simulated nitrate concentrations has been achieved, using an agreed and realistic set of flow and transport parameter values.

5.19 In calibrating the nitrate transport models the following starting assumptions will be made, subject to agreement with the UOB and the NRA:

- all recharge will be assumed to instantly (within the monthly time step) reach the water table in the Sleaford Limestone, whilst 50%

instantaneous recharge will be assumed to occur in the North Lincolnshire Chalk;

- flow in the slow phase of the chalk's unsaturated zone is assumed to occur at the rate of 1 m/yr;
- the decay parameter (1/yr) for denitrification in the two models is negligible (0.1);
- the porosity in the joints/fissures and in the blocks/matrix of the limestone and chalk is 0.01 and 0.2, and 0.005 and 0.3 respectively (D Oakes, Pers. Com);
- the initial (1960) nitrate concentration in the fissures and the blocks is 7 mg NO_3/l;
- there is no nitrate in any saline inflows to the North Lincolnshire Chalk; and
- the diffusion coefficients between the fissures and the blocks in the limestone and chalk are assumed to be 1.0×10^{4} m^3 and 1.0×10^{6} m^3 respectively.

5.20 It is proposed to effect an adequate calibration mainly by changing the diffusion coefficients. Agreement will be sought with the NRA on the value of the other parameters prior to commencement of the modelling, and will thereafter only be changed if calibration proves impossible to achieve by modifying diffusion coefficients alone, or during a brief sensitivity analysis undertaken at the end of Task 8.

Task 9: Prediction of the NSA Effects on Nitrate Leaching (ADAS and Aspinwall & Company)

5.21 ADAS and Aspinwall & Company will repeat Tasks 5 and 7 to predict nitrate loading for the 1995 to 2025 period, assuming a repeat of the historic flows and a number of NSA management scenarios identified in the Proposal (Ref 16) and summarised below. Initial (1990) nitrate concentrations will be input using ANNA's warm start-up facility.

5.22 For Sleaford (Pilot NSA scheme) the scenario's are as follows:

- Scenario 1: continuation of 1990 land use patterns and nitrate application rates;
- Scenario 2: observed NSA management since 1990;
- Scenario 3: 50% NSA is grassland; and
- Scenario 4: 100% NSA is grassland.

5.23 For Aswarby and the North Lincolnshire Wolds (new 1994 NSA scheme) the scenario's are as follows:

- Scenario 1: continuation of 1990 landuse patterns and nitrate application rates;
- Scenario 2: 100% take-up of the NSA Basic Scheme Option B, but retaining 1990 grass cover;
- Scenario 3: 25% is premium arable Option C, but retaining 1990 grass cover, with the remainder put over to Basic Scheme Option B;
- Scenario 4: As 3 except 50% is premium arable Option C; and
- Scenario 5: 100% is premium arable Option C.

Task 10: Prediction of the NSA Effects on Nitrate Concentrations (Aspinwall & Company)

5.24 Aspinwall & Company will input the revised loading file into the two ANNA models to predict future nitrate concentrations under the various NSA management options for the seven observation points.

Task 11: Publication of Draft and Final Reports (ADAS, WRc, UOB and Aspinwall & Company)

5.25 Aspinwall & Company will submit a draft report to the NRA documenting the Phase 2 study and its findings. A critical evaluation of the weaknesses and limitations of the modelling and its ability to simulate historical nitrate concentrations and predict future nitrate concentrations will be presented. Hard copies of all ANNA input and output files for the calibration and prediction runs will be included, with annotation as appropriate.

5.26 To assist Aspinwall & Company in the writing of this report, ADAS, WRc and the UOB are each asked on completion of their tasks to submit a short report to Aspinwall & Company, describing their work and discussing any findings.

5.27 Amendments to the draft report will be made on advice of the NRA. Three copies of the Final Report will then be issued to the NRA.

Conclusions

5.28 It is apparent that there is a considerable amount of work to do before the leaching models, the groundwater models and the ANNA nitrate transport model can be used together to predict future nitrate concentrations in the NSA's. This is unsurprising, given the complexity of the chalk and limestone hydrogeological environments and the fact that no one party developed the software or has attempted the whole process (nitrate leaching estimation to time-variant groundwater flow and nitrate transport modelling) before.

5.29 Aspinwall & Company believe that the process is achievable, using the methodology (or similar) suggested here. Critical to the success of the project is the further development of the ANNA nitrate transport model.

5.30 The project can be viewed as a pilot study, and its methodology and findings will assist the NRA in its water quality modelling of other NSA's and aquifers.

Summary 6

6.1 This Phase 1 Report presents and justifies a draft methodology for the Phase 2 modelling study of the water quality in the NSA's of Sleaford, Aswarby and the North Lincolnshire Wolds. It firstly summarises the hydrochemical behaviour of nitrate, and identifies that the modelling of nitrate water quality requires an understanding of three main processes - nitrate leaching/recharge, groundwater flow (especially in the saturated zone) and nitrate transport. The method of modelling each of these processes is then considered.

6.2 There are three models that have been used to estimate nitrate leaching in the United Kingdom. They are all essentially 'black-box' models which operate on land use and fertiliser application data to predict nitrate leaching values. The WRc MODLEACH model and the ADAS NSA model are the two models most commonly used and appear to give similar estimates. However, the WRc model only takes account of cropping patterns and fertiliser applications, whereas the ADAS model also makes allowance for changes in husbandry. The ADAS model can be argued to be on a sounder theoretical footing, and Aspinwall & Company propose that the ADAS model will be the main means of estimating nitrate leaching in the Phase 2 study.

6.3 Groundwater flow in the two aquifers is complex, and this is reflected in the design of the UOB groundwater flow models. Both are transient, variable grid models with a permeability-depth function, but the Sleaford model also incorporates a semi-distributed surface water modelling routine to simulate the occurrence of runoff-recharge and percolation recharge on outcrop. These surface and near-surface flow mechanisms mean that recharge can occur some distance and time away from the associated rainfall event. Despite the complexity of the aquifer environments the two models have adequately represented observed groundwater heads and springflows and for the purposes of this study require no further calibration, though the Lincolnshire Limestone modelling should be extended back to 1960 if at all possible. The UOB will also be asked to develop a means of tracking the quantity and origin of any monthly nodal recharge in the Sleaford model, so that any nitrate leaching can be transferred to the aquifer in accordance with the surface water modelling routine.

6.4 The nitrate transport modelling is to be achieved using the WRc mixing-cell model ANNA. Problems in the use of ANNA within this study have been identified, including its current inability to interact with time-variant, variable grid, variable recharge flow models and the potential for numerical dispersion, particularly in relation to the Lincolnshire Limestone. An important element of the Phase 2 work will be WRc's further development of the ANNA model to rectify these limitations.

6.5 It is apparent that there is a considerable amount of work to do before the leaching models, the groundwater models and the ANNA nitrate transport model can be used together to predict future nitrate concentrations in the NSA. Aspinwall & Company believe that the process is, nevertheless, achievable and worthwhile, using the methodology (or similar) suggested here.

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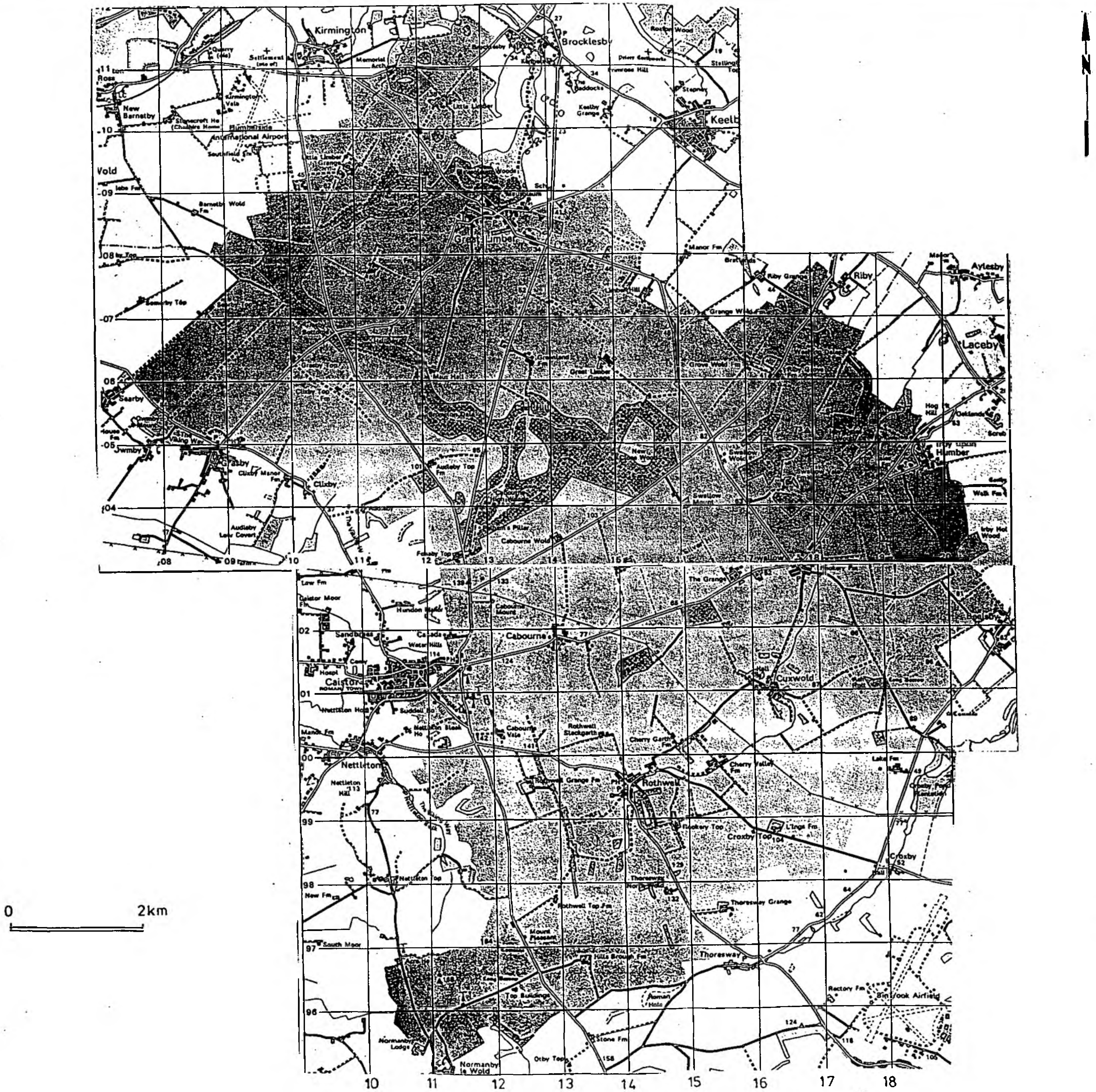
Figure 1

North Lincolnshire Wolds Nitrate Sensitive Area

Aspinwall&company Ltd
May, 1995



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client
NRA

project
NSA WATER QUALITY MODELLING

drawing
FIGURE 1
NORTH LINCOLN WOLDS NITRATE SENSITIVE AREA (MAFF)

scale AS SHOWN	con no. NR0520B
drawn ShS	drafted-drg no. DAH1887A
checked	date FEB 1995

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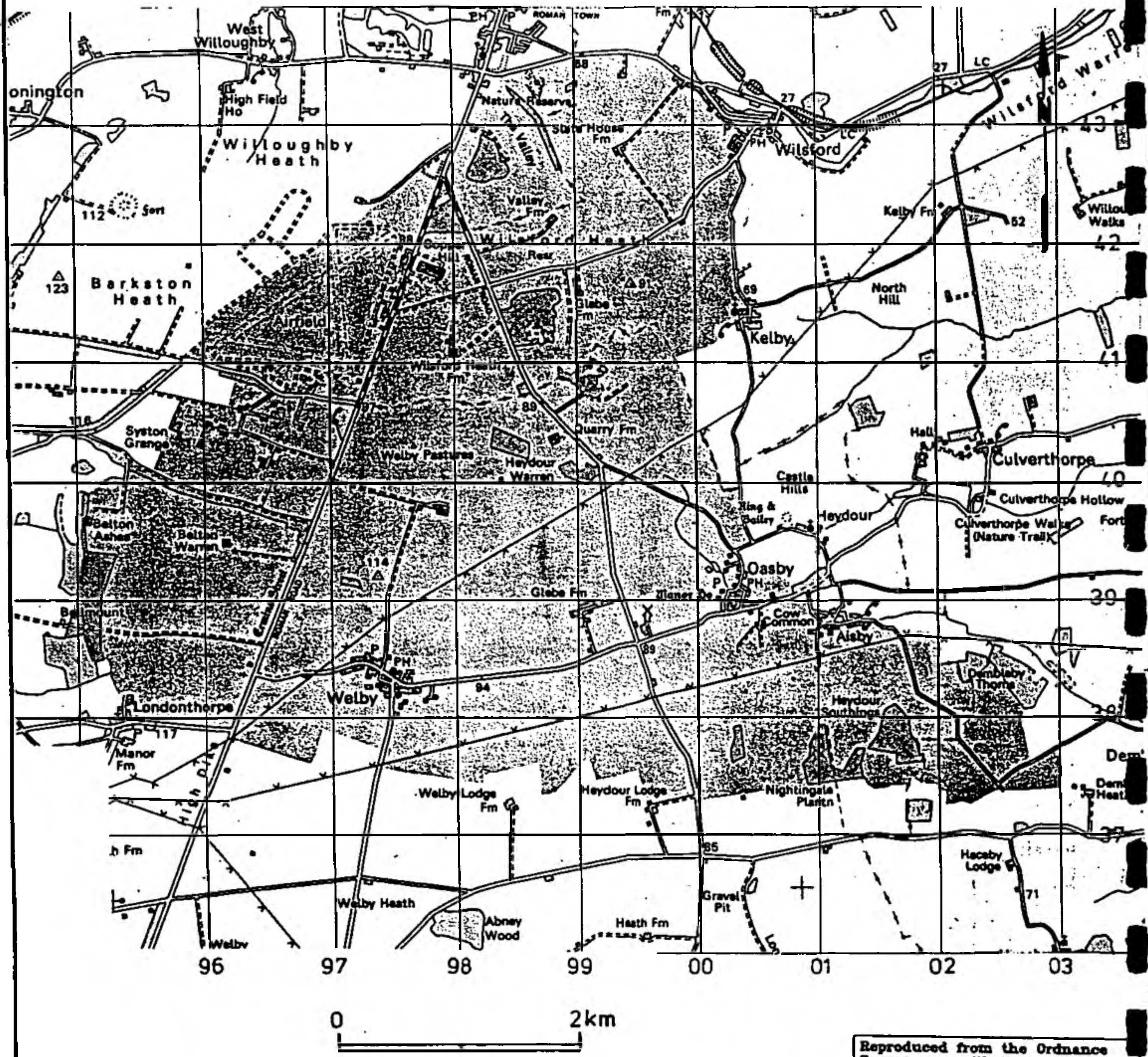
100 WELLINGTON STREET, LEEDS LS1 4LT TEL (0532) 372106
MARION HOUSE, VENTRY LANE, BELFAST BT2 7JP TEL (01232) 245127

Figure 2

Aswarby Nitrate Sensitive Area



ASWARBY NITRATE SENSITIVE AREA (MAFF)

can no. NR0520B	scale 1:50,000	Aspinwall & company — CONSULTANTS IN ENVIRONMENTAL MANAGEMENT	client NRA
drawn ShS	drafted-drg no. DAH1888A	WALFORD MANOR, BASCHURCH, SHREWSBURY SY4 2HH; 16 CRUCIFIX LANE, LONDON BRIDGE, LONDON SE1 3JW; 13 MELVILLE STREET, EDINBURGH EH3 7PE; 100 WELLINGTON STREET, LEEDS LS1 4LT; MARION HOUSE, VENTRY LANE, BELFAST BT2 7JP	project NSA WATER QUALITY MODELLING
checked	date FEB 1995		drg. FIGURE 2

Figure 3

Sleaford Nitrate Sensitive Area

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1 May, 1995

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project
NSA WATER QUALITY MODELLING

drawing
FIGURE 3
SLEAFORD NITRATE SENSITIVE AREA (MAFF)

scale AS SHOWN	con no. NR0520B
drawn ShS	drafted-drg no. DAH1889A
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100 WELLINGTON STREET, LEEDS LS1 4LT TEL (0532) 373108
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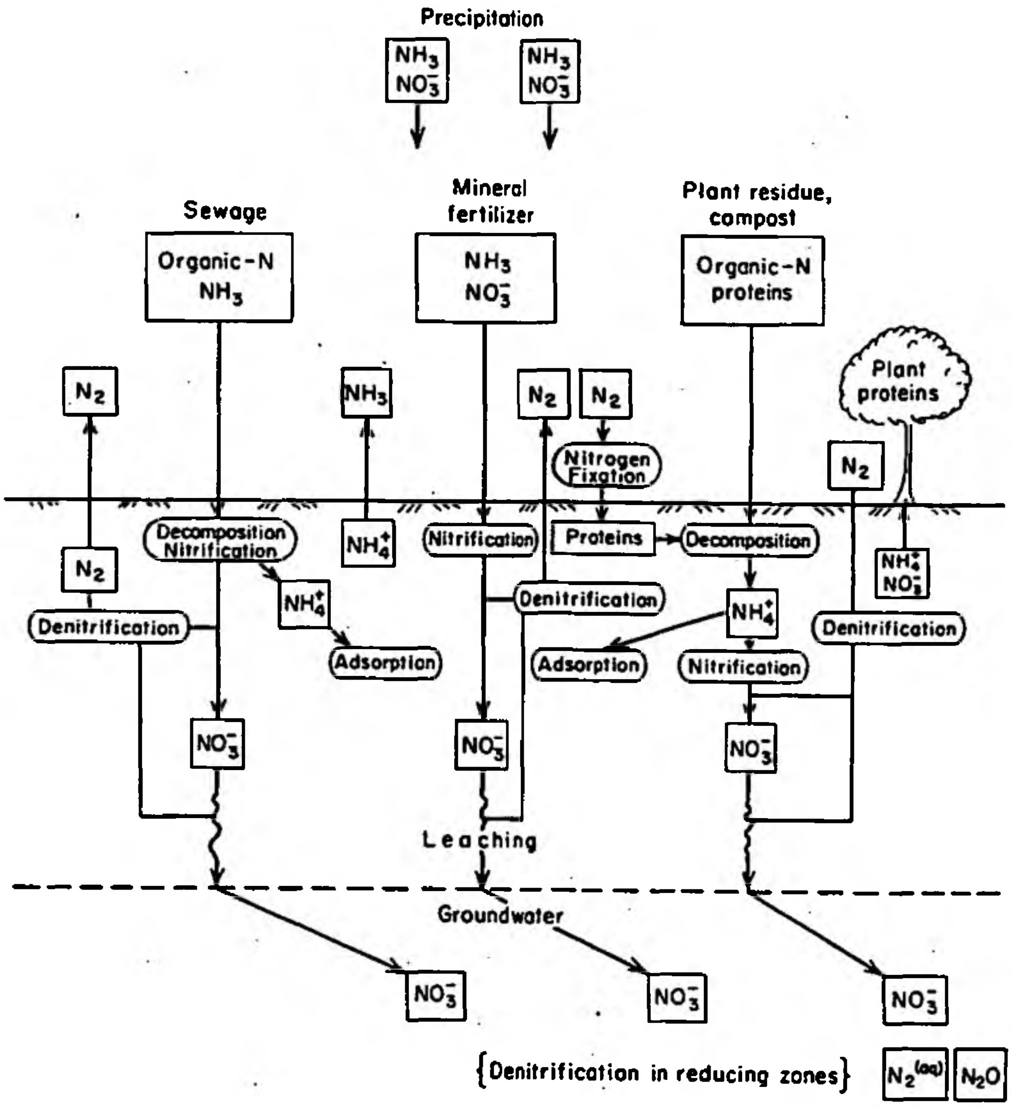
Figure 4

Nitrogen in the Subsurface Environment



NITROGEN: THE SUBSURFACE ENVIRONMENT (FREEZE AND CHERRY)

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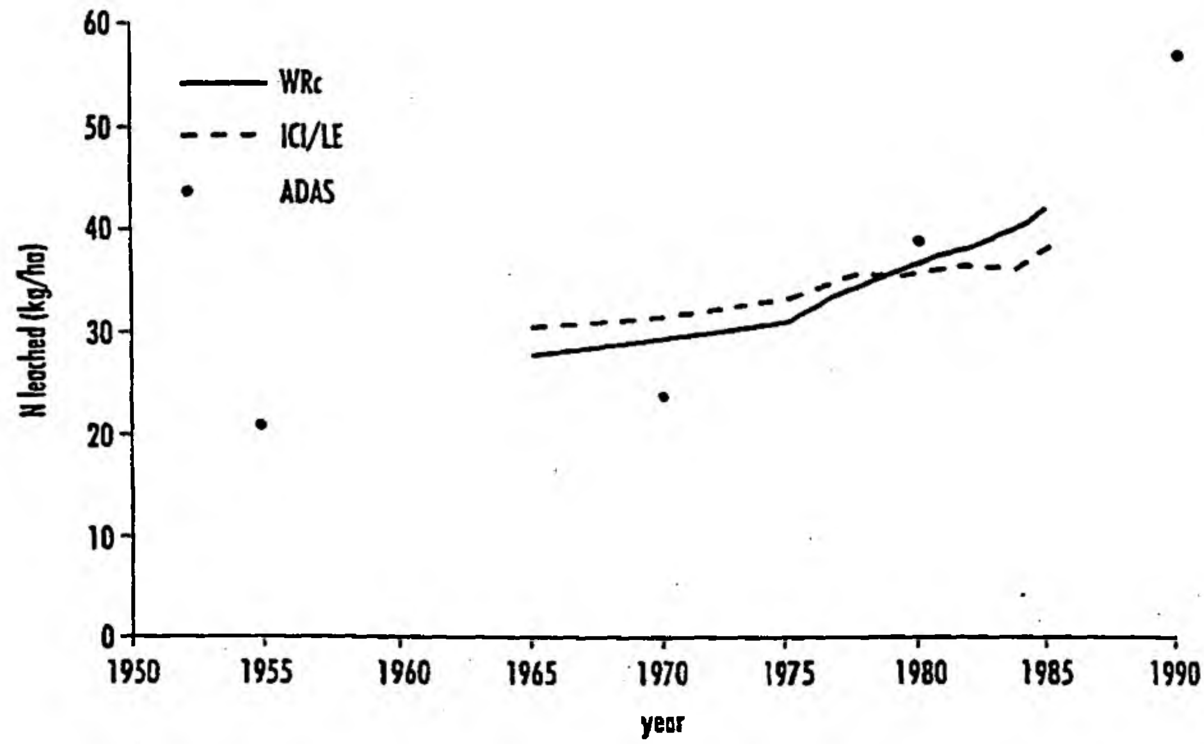
drawn ShS	drafted-drg no. DAH1890A	CONSULTANTS IN ENVIRONMENTAL MANAGEMENT	project NSA WATER QUALITY MODELLI
checked	date FEB 1995	WALFORD MANOR, BASCHURCH, SHREWSBURY SY4 2HH 16 CRUCIFIX LANE, LONDON BRIDGE, LONDON SE1 3JW 13 MELVILLE STREET, EDINBURGH EH3 7PE 100 WELLINGTON STREET, LEEDS LS1 4LT MARION HOUSE, VENTRY LANE, BELFAST BT2 7JP	drg. FIGURE 4

Figure 5

Comparison of UK Leaching Models for Wellings NSA



COMPARISON OF UK LEACHING MODELS
FOR WELLINGS NSA (WRc)

can no.	scale		client
NR0520B	AS SHOWN	Aspinwall&company — CONSULTANTS IN ENVIRONMENTAL MANAGEMENT	NRA
drawn: ShS	drafted–drg no.: DAH1891A	WALFORD MANOR, BASCHURCH, SHREWSBURY SY4 2HH; 16 CRUCIFIX LANE, LONDON BRIDGE, LONDON SE1 3JW; 13 MELVILLE STREET, EDINBURGH EH3 7PE; 100 WELLINGTON STREET, LEEDS LS1 4LT; MARTIN HOUSE, VENTRY LANE, BELFAST BT2 7JP	project: NSA WATER QUALITY MODELLING
checked	date: FEB 1995		drg.: FIGURE 5

Figure 6

Hydrogeological Features of the Lincolnshire Chalk

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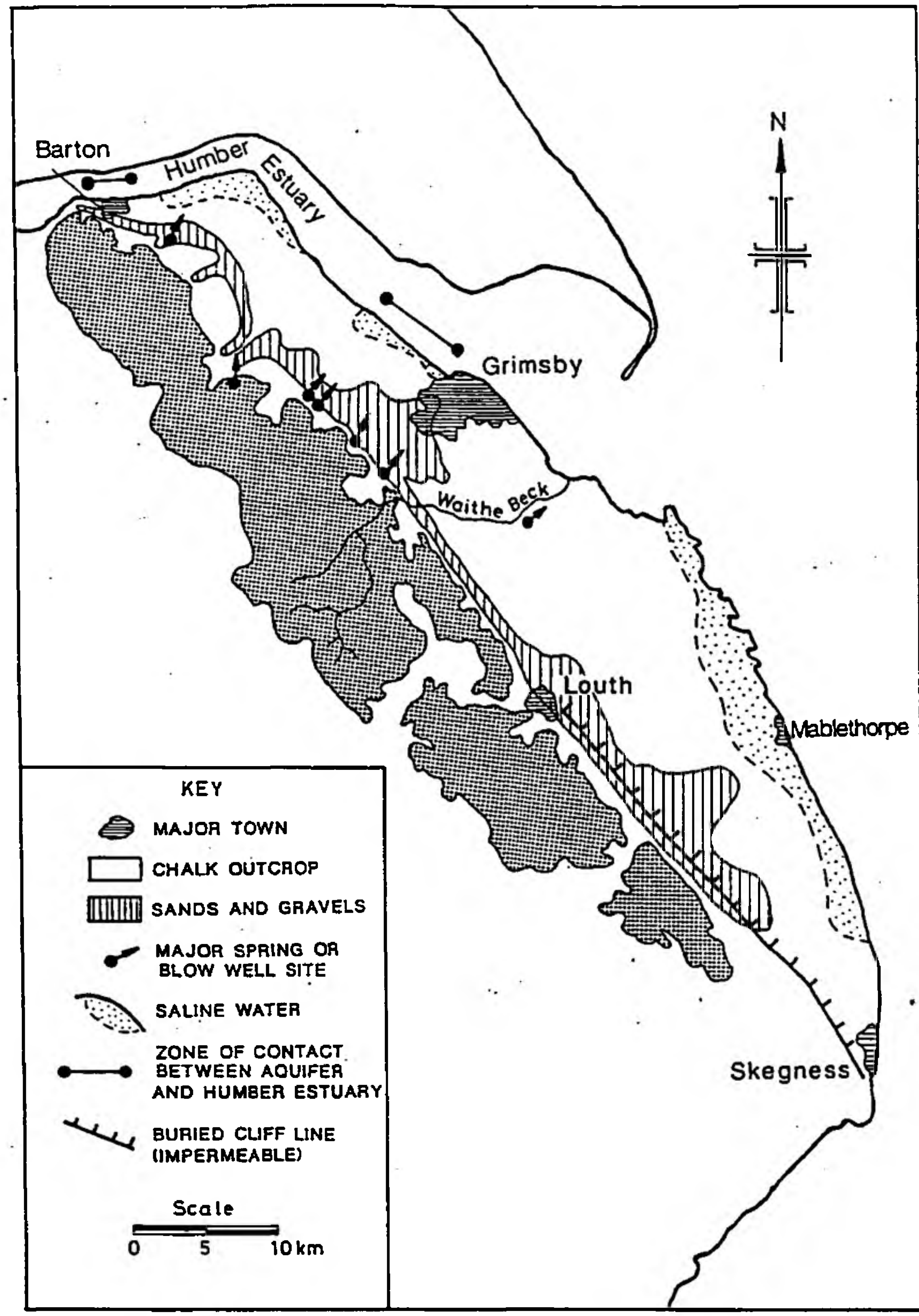
May, 1995



HYDROGEOLOGICAL FEATURES OF THE LINCOLNSHIRE CHALK (UOB)

can no. NR0520B	scale NTS	Aspinwall&company — CONSULTANTS IN ENVIRONMENTAL MANAGEMENT	client NRA
drawn ShS	drafted–drg no. DAH1892A	WALFORD MANOR, BASCHURCH, SHREWSBURY SY4 2HH; 16 CRUCIFIX LANE, LONDON BRIDGE, LONDON SE1 3JW; 12 MELVILLE STREET, EDINBURGH EH3 7PE; 100 WELLINGTON STREET, LEEDS LS1 4LT; MARION HOUSE, VENTRY LANE, BELFAST BT2 7JP	project NSA WATER QUALITY MODELLI
checked	date FEB 1995		drg. FIGURE 6

Figure 7

Nitrate trends in the Lincolnshire Limestone

Figure 7a: Nitrate trends at Aswarby Raw No. 1

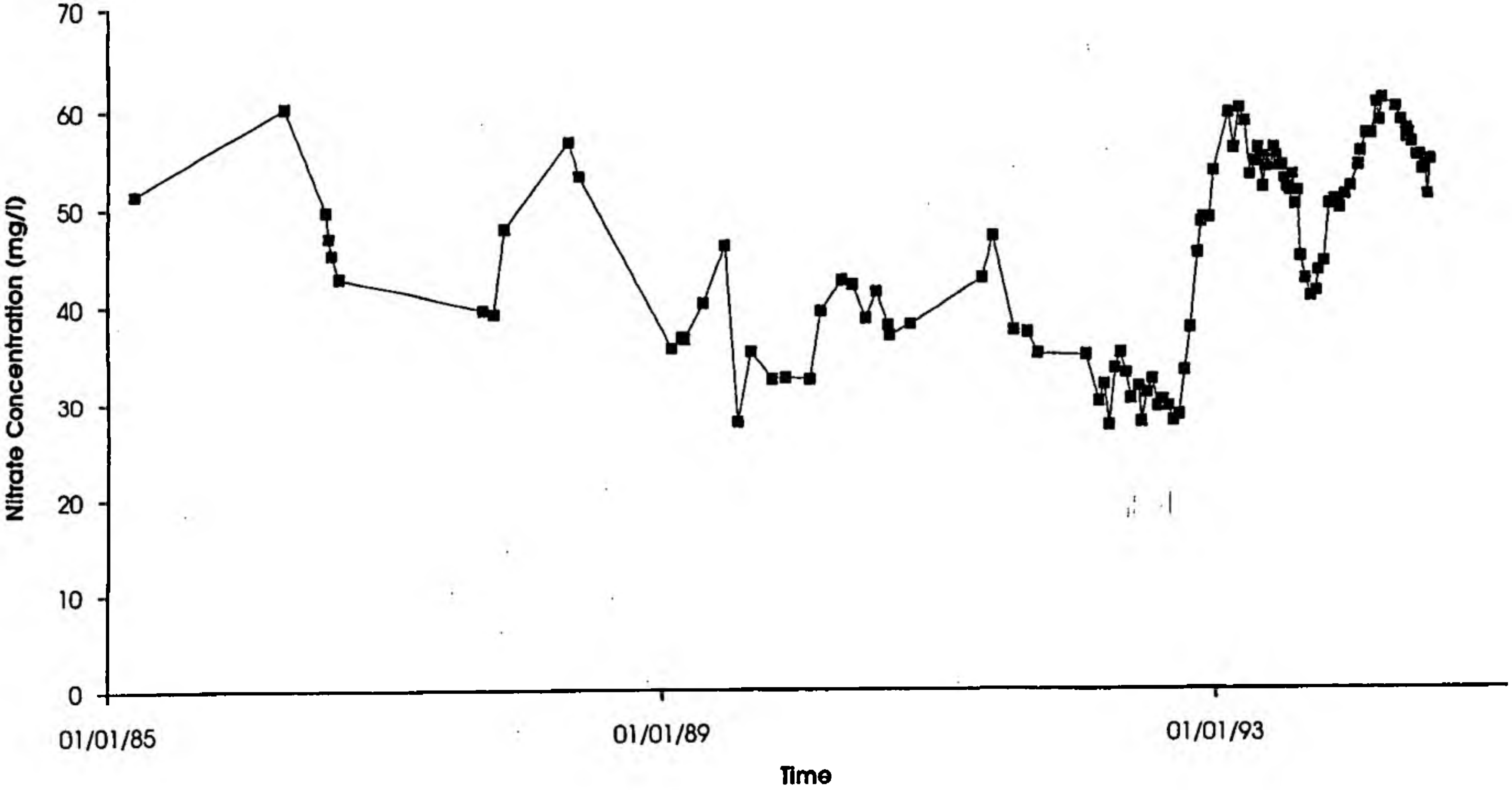


Figure 7b: Nitrate trends at Clayhill

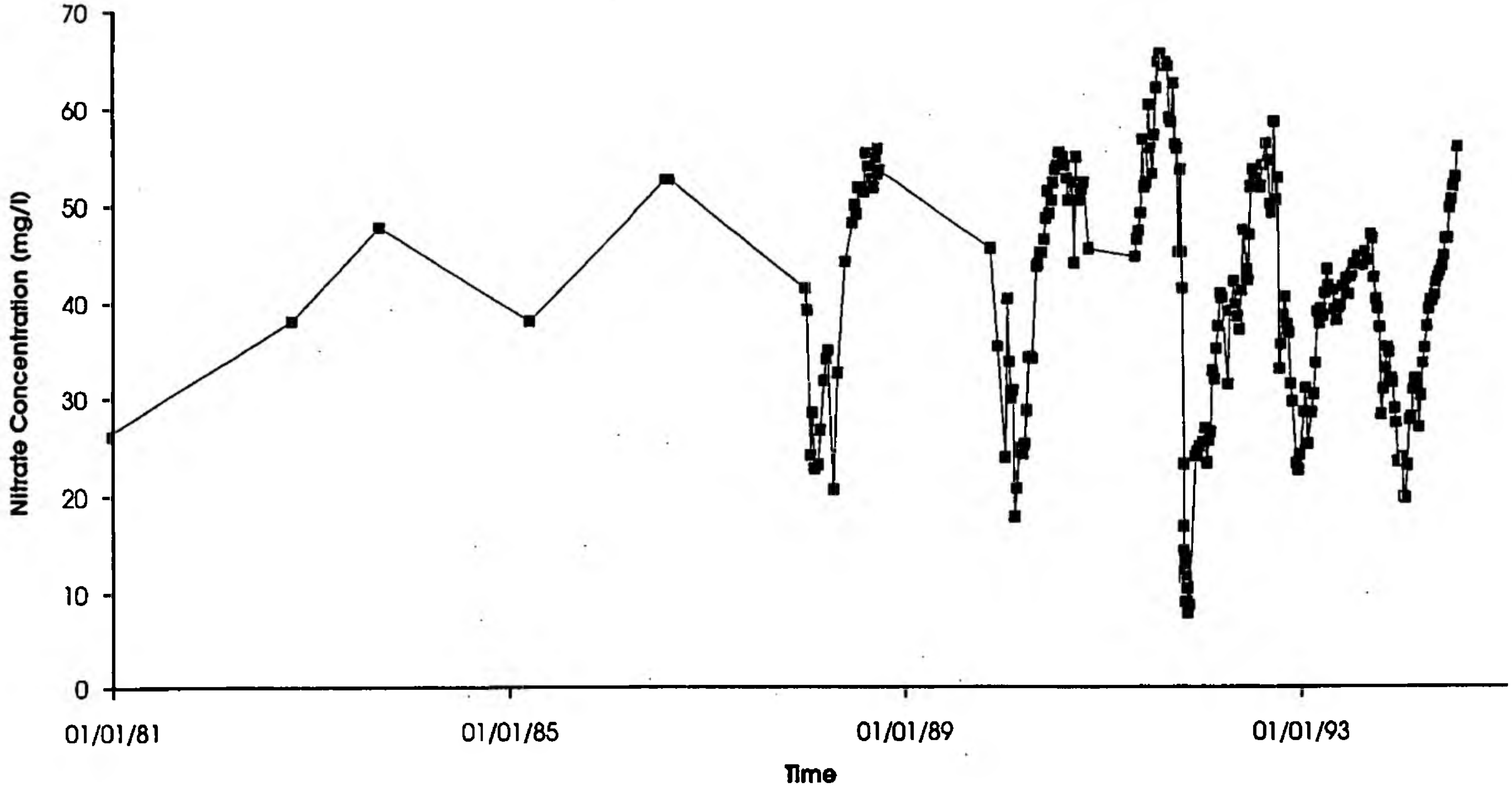


Figure 7c: Nitrate trends at Drove Lane No. 1

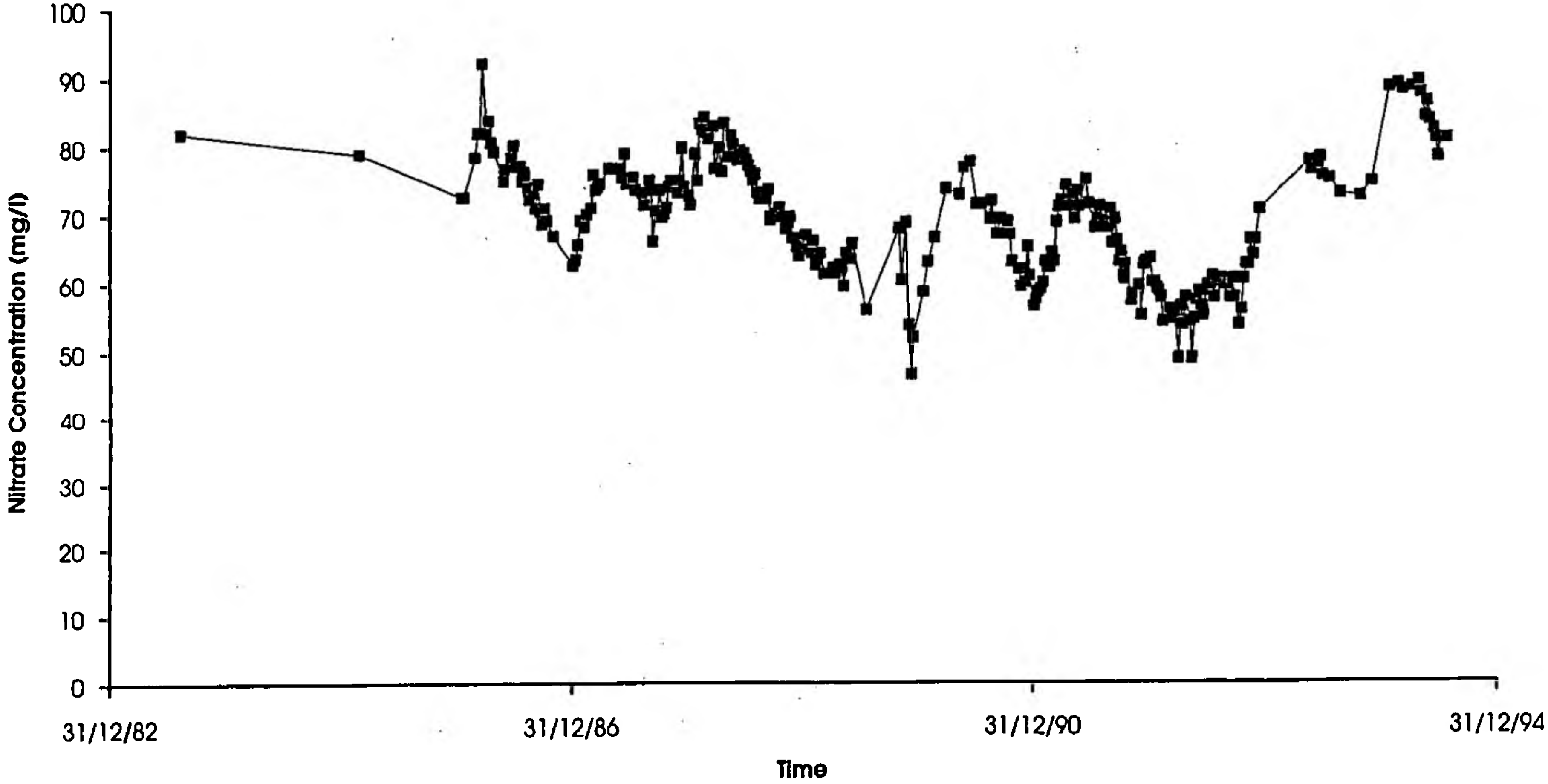
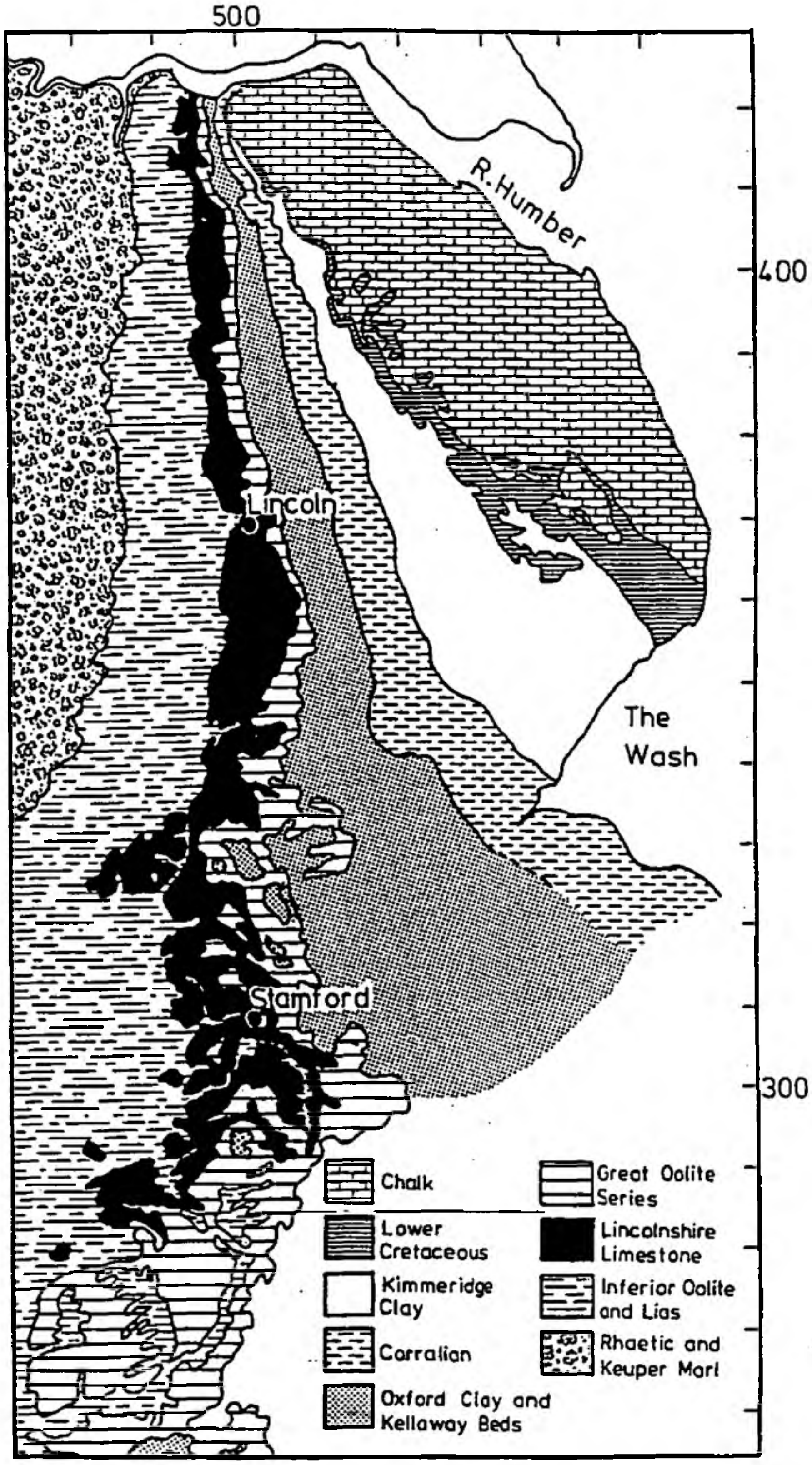


Figure 8

Hydrogeological Features of the Lincolnshire Limestone



HYDROGEOLOGICAL FEATURES OF THE LINCOLNSHIRE LIMESTONE (UOB)

can no. NR0520B	scale AS SHOWN	Aspinwall&company CONSULTANTS IN ENVIRONMENTAL MANAGEMENT WALFORD MANOR, BASCHURCH, SHREWSBURY SY4 2HH 16 CRUCIFIX LANE, LONDON BRIDGE, LONDON SE1 3JW 13 MELVILLE STREET, EDINBURGH EH3 7PE 100 WELLINGTON STREET, LEEDS LS1 4LT MARION HOUSE, VENTRY LANE, BELFAST BT2 7JP	client NRA
drawn ShS	drafted-drg no. DAH1893A		project NSA WATER QUALITY MODELLING
checked	date FEB 1995		drg. FIGURE 8

Figure 9

Nitrate trends in the Lincolnshire Chalk

Figure 9a: Nitrate trends at Habrough No. 1

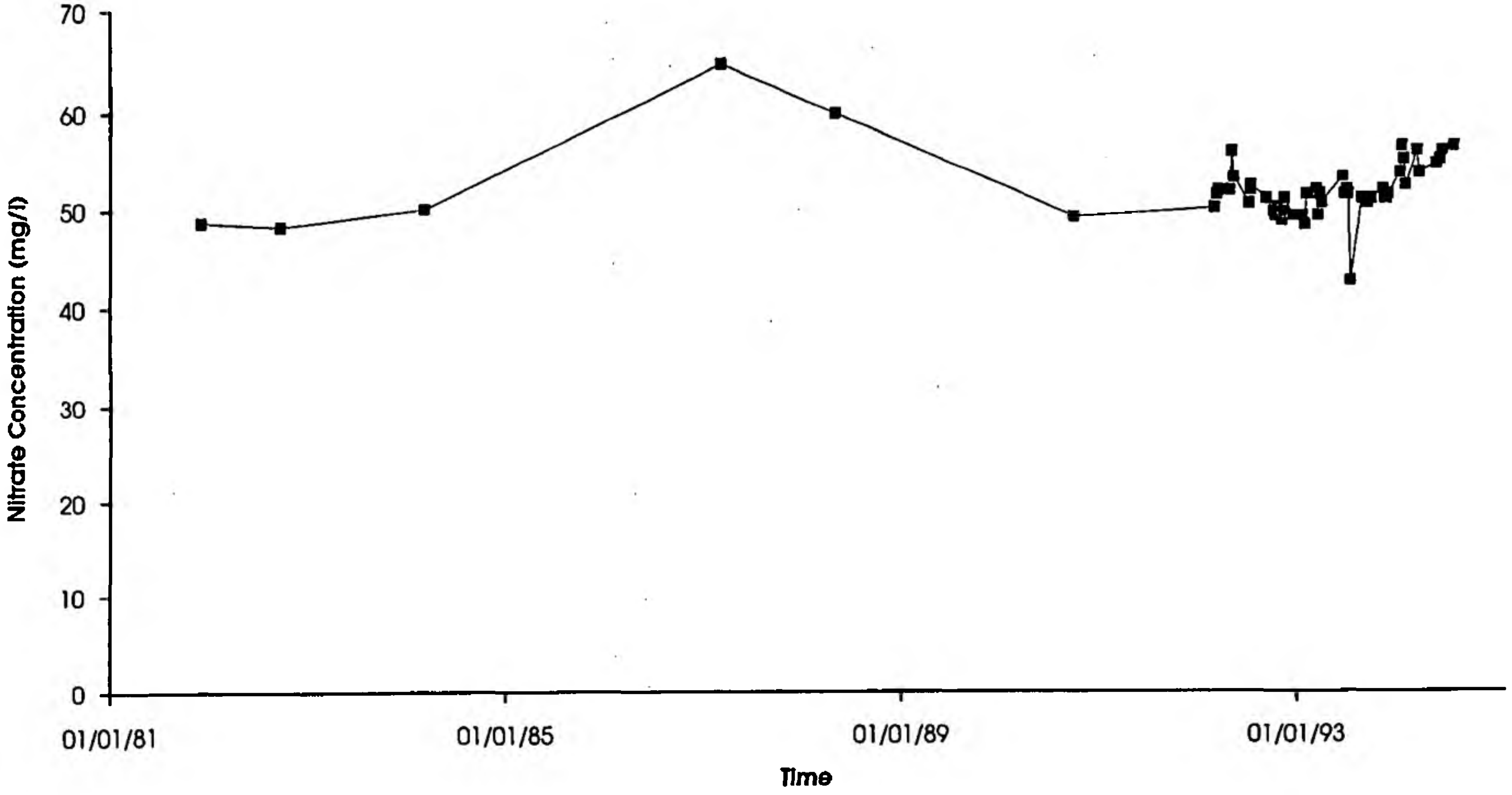


Figure 9b: Nitrate trends at Healing No. 7

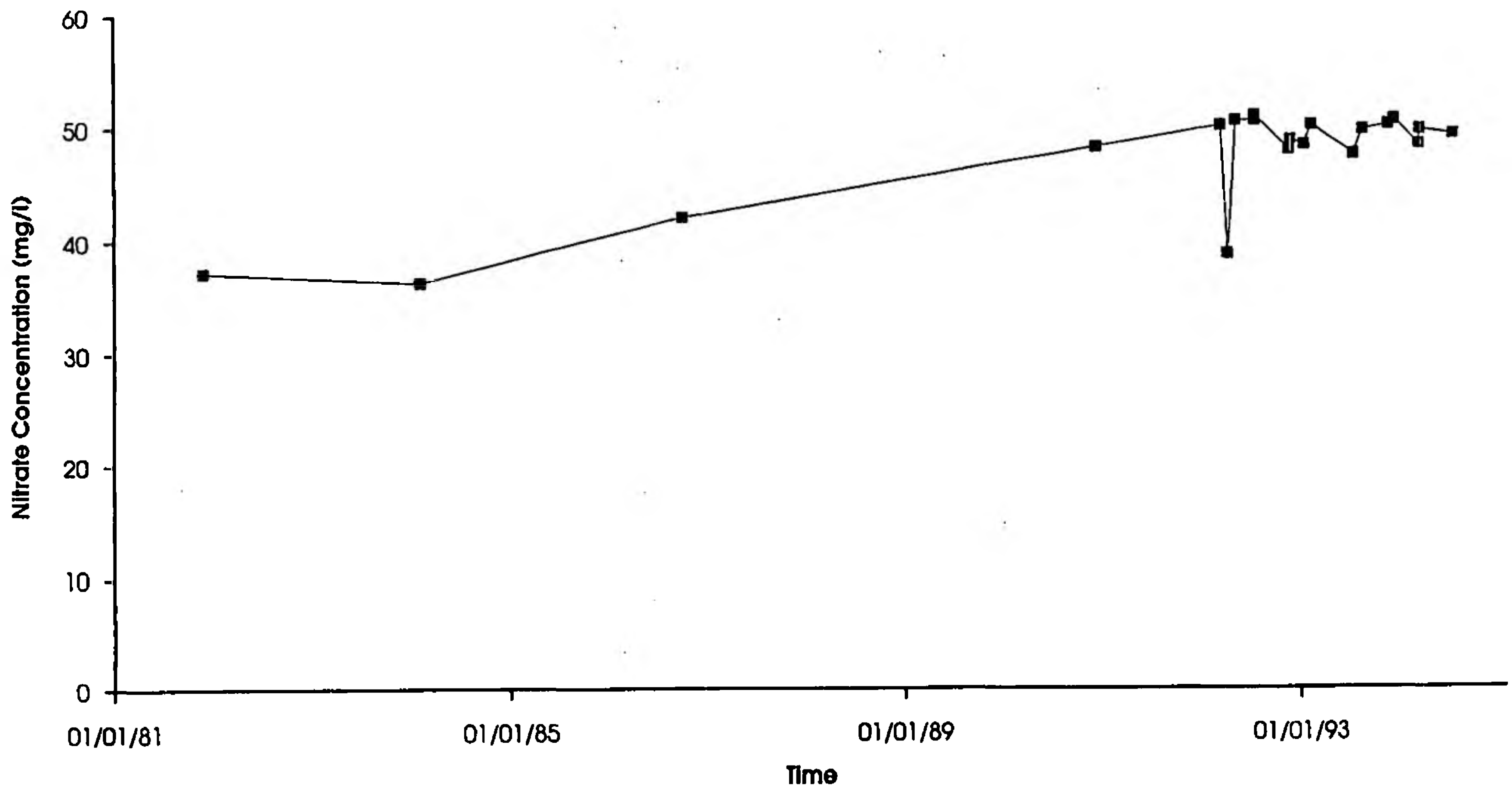


Figure 9c: Nitrate trends at Little London No. 1