Assessing and Improving Sustainability of Urban Water Resources and Systems

AISUWRS Work-package 4:

Field investigations interim report

Groundwater Systems and Water Quality Programme

Commissioned Report CR/04/022N

BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/04/022N

Assessing and Improving Sustainability of Urban Water Resources and Systems

AISUWRS Work-package 4
Field investigations interim report

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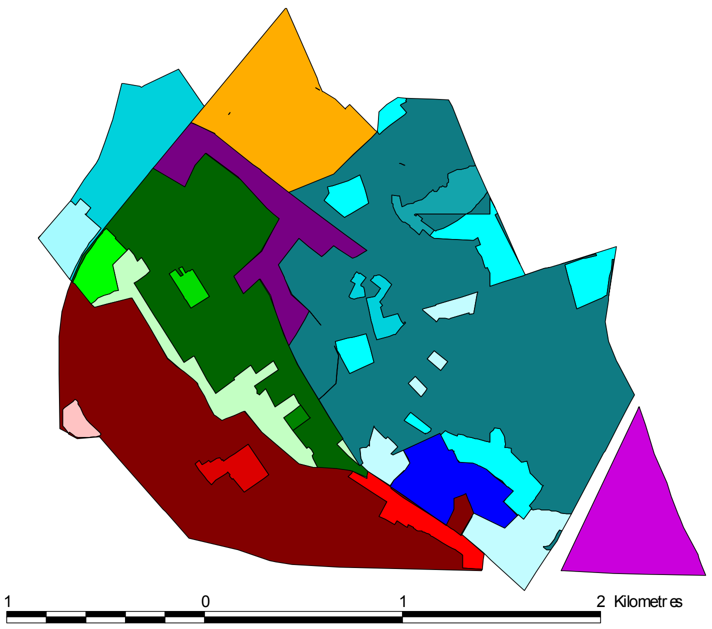

Key words

Groundwater, urban water management, sustainable use.

Plate:

20 proposed UVQ model neighbourhoods in Bessacarr-Cantley study area

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Foreword

This interim field investigations report comprises the first part of Deliverable D10 of the project "Assessing and Improving the Sustainability of Urban Water Resources and Systems" (AISUWRS). It is jointly produced by the UK partners the British Geological Survey and the Robens Centre for Public and Environmental Health of the University of Surrey. This 3-year urban water research project is partly funded by the European Community. It aims to develop an innovative modelling system of the urban water infrastructure that can inform decision support systems for cities that depend on underlying or nearby aquifers for their water supply.

Acknowledgements

The authors would like to thank the project's stakeholders for their practical support in this on-going project, especially the following:

David Craven, Doncaster Metropolitan Borough Council (DMBC) Environmental Health Dept and Bernard Russell, DMBC Neighbourhood Services; Gerd Cachandt, Brian Humphries, Ian Mitchell, Meryl Knapp, Andrew Bardsley and various colleagues at Yorkshire Water (YW); Gordon Smith, Andrew Pearson, and Martin Shepley, Environment Agency (EA), Midlands Region

Contents

FIGURES

TABLES

APPENDICES

Appendix 1	Rueedi, J., and A. A. Cronin. 2003. Construction of 5 Depth Specific Groundwater Sampling Sites in Doncaster, UK. Robens Centre for Public and Environmental Health, Guildford.
Appendix 2	Stuart M E, Whitehead E J and Morris BL. 2004. AISUWRS Work-package 4: Water quality of the Doncaster aquifer. *British Geological Survey Commissioned Report*, CR/04/026N. 40pp. BGS Keyworth England
Appendix 3	Data tabulations for Section 7: Support to components of urban water model array including GIS analysis and interpretation
Appendix 4	Neumann I and Hughes A. 2003. Translation of the Doncaster Groundwater Model into the MODFLOW code. *British Geological Survey Commissioned Report*, CR/03/258N. 27pp. BGS Keyworth England

Summary

Background

This interim report outlines progress to date of the field investigations being undertaken in Doncaster (UK) as part of the European Community 5th Framework Programme-Shared Cost Research Technological Development and Demonstration project AISUWRS (Assessing and Improving Sustainability of Urban Water Resources and Systems). This is one of the four case study cities being examined in Work Package 4 of this project; the others are Rastatt (Germany), Ljubljana (Slovenia) and Mt. Gambier (Australia). The report provides summarises the various components of the field and model preparation investigation programme to date. The in-depth analyses from which this summary is derived are collated as report appendices.

As indicated in the Doncaster case-study WP1 inception report (Morris et al., 2003), a suburban district of Doncaster was chosen for more focused field investigations from within the urban area of Doncaster. This is the district of Bessacarr-Cantley and was chosen due to the fact that it is located down-gradient of the historical town centre of Doncaster and because it comprises several and varied landuse types, principally residential housing.

Monitoring Network

This field investigation programme aims at achieving a better understanding of the groundwater quality and urban water mass balance fluxes in and around Doncaster to support the AISUWRS modelling suite. The monitoring program started in June 2003, with the sampling of 12 regionally dispersed existing boreholes. However, additional sampling points were necessary due to the dispersed nature of these regional wells and the fact that few were in an urban setting and all had screens open over large sections of the aquifer, which meant that vertical variations in groundwater quality were not distinguishable. To this end, in September 2003, five multilevel piezometers (with a total of 33 depth-specific levels), and two shallow piezometers on Bolton Hill, were installed to complement the existing regional wells and to focus in on the study suburb of interest, Bessacarr. All of these regional wells and multilevel piezometers were sampled in November 2003, along with three sewer sampling points and two stormwater sampling points. This sampling consisted of purging the boreholes sufficiently prior to taking standard field measurements at each site (temperature, pH, dissolved oxygen, electrical conductivity, redox potential, field alkalinity). In addition, samples were taken for microbial indicators of faecal contamination (both bacterial and viral), major and minor chemistry. Taken together, new results for ~50 different sampling points were produced during each field session. Regional wells were also logged with a downhole-logging device measuring pressure (which can be converted to water level after adjusting for barometric pressure), temperature and electrical conductivity. This has allowed high-resolution open-hole vertical profiles of groundwater temperature and conductivity to be produced.

The five new sampling sites were constructed in order to better understand groundwater quality patterns and groundwater flow characteristics. The new sampling sites were designed to enable groundwater to be sampled at different depth intervals. Depth profiles are usually an important aspect of detailed groundwater quality investigations because contaminant concentrations in bedded deposits can vary markedly in the vertical direction. In some situations, the entire zone of contamination may occupy only a small part of the total aquifer thickness. Drilling of these new monitoring points started on September 1st 2003 and took 2 to 3 days per hole. Instead of carrying out geophysical logging (as outlined in the proposal), precise drilling logs were taken during drilling and samples of drilling debris were taken regularly, as outlined in detail in the report. This is the main change from the proposed work outline and is due to the fact unfavourable geological conditions were encountered during drilling (Appendix 1). Three spot cores (1-2m length) were taken at the Haslam Park 2 site. The cores were analysed both physically and geochemically by the British Geological Survey. After completing the boreholes and removing the rig, short pumping tests were undertaken. The pumping tests were performed to obtain transmissivities and also to clean the holes from potential groundwater contamination introduced by drilling (e.g. 'mist' used to obtain cores). Following the pumping tests, the installation of multilevel piezometers was started to prevent collapsing and possible contamination of the open holes. HDPE and PVC pipes were installed to reach a maximum of 7 different depths below ground. Each level was packed with sand and the levels were sealed from each other by at least 1.2 metres of clay. One month after installation, the multilevel sites were developed, disinfected and pumped clean.

Groundwater Levels

An analysis of historical groundwater levels obtained from the Environment Agency show that groundwater levels have dropped considerably outside the Doncaster urban area where the pumping stations for public water supply are located. Inside the urban area, groundwater levels have changed slightly during the observation period (1969-2002). Observed vertical gradients in the multilevel piezometers are quite small, apart from Bolton Hill where the medium depth intervals seem to have more elevated water levels relative to the other depth intervals. Small vertical hydraulic gradients possibly originate from the low topography in this region (ground levels are within a few metres above sea level dipping slightly from west to east). Water levels at both shallow and deep levels have been observed to change in magnitude at the same time and this could be due to the influence of nearby groundwater abstractions, a lack of spatially-extended confining layers in the aquifer (e.g. clay bands) and high vertical conductivities. The downward vertical hydraulic gradients indicate recharge conditions in the Bessacarr area but little recharge on the Sandall Beat site near the city of Doncaster. In summary, the results of the monitoring loggers emplaced in the multilevel piezometers may provide valuable groundwater level data inputs for the groundwater flow model.

Microbiological Sampling Results

Faecal indicator (bacterial and viral) monitoring is an important aspect of this fieldwork as this is a useful insight into transport mechanisms in the Sherwood Sandstone as well as assessing how pathogens vary in the urban water cycle. The results from the first two sampling campaigns show higher positive detection rates than previous historical monitoring of open public supply wells. The microbiological sampling results show a higher number of positive detects and larger colony counts during the November 2003 sampling than the Summer 2003 sampling. Knowledge and interpretation of these temporal trends will become more refined as the sampling work continues during 2004. Coliphage sampling has yielded only two positive results for the regional and multilevel sampling to date though the longer-lived SRC spores have been found frequently. Similarly the longer lasting Faecal Streptococci are being detected more frequently than the *E. coli* (or thermotolerant coliforms). This may reflect on the relative frequency and survival times of these indicators in urban sandstone settings but it is still a tentative suggestion. In general, the field assessment of TTC and the laboratory analysis of *E. coli* match well and this is a useful cross check on the methods. The multilevel piezometers are giving interesting depth profiles of contamination to date but it is too early to speculate on exact levels and mechanisms that are giving rise to these profiles. However, it is significant to note that indicators of faecal contamination are being detected at depths of over 50m below ground. The samples from sewer and storm water systems have shown very high counts of bacterial indicators (1.75–4x10^6 *E. coli*) supporting their usefulness as sewage indicators. Furthermore, some enteric viruses were detected in the sewage system indicating a possible risk for groundwater. However, there was only one positive detect in the groundwater samples taken so far.

Hydrochemistry

A developing programme of local groundwater monitoring using both local private supplies and multilevel research boreholes (purpose-constructed for the project) is supplementing available data on the water quality of the project area and its environs. The water quality conceptual model recognises that the Sherwood Sandstone east of Doncaster, as an intensively exploited unconfined aquifer with urban, rural, industrial, agricultural and mining activities at the land surface, is a complex system. The presence of variable Quaternary superficial deposits across the aquifer outcrop/subcrop adds to this complexity. Initial interpretation suggests that there is significant variability both laterally across the aquifer system and with depth. No spatial pattern to the variability indicated by the datasets has yet been discerned. Initial wastewater sampling results indicate that while sewered waters have higher concentrations of major ion constituents than groundwaters in the same general area, the difference is not conspicuous. The relatively small differences in indicator concentrations between wastewaters and the parent groundwater forming the supply to the study area will constrain their interpretative use in mass balance calculations. A mid-term review of the monitoring strategy is required in order to concentrate effort on understanding processes in the Triassic aquifer in the immediate neighbourhood of the study area. Work continues to determine whether different elements of the flow system can be characterised by their chemical compositions, thereby allowing shallow recharge beneath the city to be characterised chemically.

Groundwater Flow Model

The regional resource management model has been translated into the MODFLOW code in order to set up a sub-regional model centred on the Bessacarr-Cantley area only and to facilitate both solute transport modelling and groundwater flow simulations. The overall agreement between the MODFLOW model and the original model is good, both for hydrographs of observation boreholes and for the water balance of the models. Some accommodation has been necessary to take account of the differing modes of discretization and drift thickness assignment and data availability limitations. The translated model has now been adapted to provide a sub-regional model for Bessacarr-Cantley and further discretized into 100m x 100m cells. These are arranged so as to facilitate overlay of the Urban Volume Quality (UVQ), Pipe Line Leakage (PLM) and unsaturated zone outputs when these models are linked. The footprint area of interaction for these latter models has been agreed.

Data Requirements and GIS Analysis

A model parameters appraisal exercise was undertaken to assess data requirements for the forthcoming modelling work packages. The large number of input fields came as a surprise, and site-specific data availability was highly variable, from 65-85% for the groundwater models to <10% for UVQ. A major extension of the data gathering, collation and processing exercise therefore has had to be undertaken as an additional unanticipated field investigation activity. This additional work has been vital to provide real data to inform the models so they can be run in a realistic way. Tasks undertaken in these additional studies include an extended literature and Internet search, a pipe infrastructure analysis, mains leakage calculations, production of a map and associated database showing where the sewer system may be below the water table (all for the PLM) and a land use database transformation to facilitate UVQ modelling.

Urban Volume Quality (UVQ) model

The Urban Volume Quality (UVQ) mass balance model was populated with the urban water quality and quantity information currently available. The pipe system of the project area is very well defined and consists of a separate storm water and sewer network in most of the Bessacarr area. This makes it a straightforward task to separate different neighbourhoods with different sewer and storm water outflows. Furthermore, the detailed digital land use map supplied by Doncaster Metropolitan Borough Council was very helpful in distinguishing between different housing types and densities. However, the differentiation between the different landuses at the household to street level (roof, paved, garden, road), which was assessed from detailed map analysis, are quite approximate, even though they are supported by aerial photographs. Unfortunately, calibration data is still lacking. Limited data exists to estimate sewer outflow volumes measured over one month in August 1993 (the period of a detailed sewer assessment report in Bessacarr). Furthermore, water use was requested for the entire suburb of Bessacarr to pin down at least the approximate sewer amounts produced during this time period and also to assess irrigation patterns during summer. As soon as these data are available the calibration process can be started. The sewer quality measurements that are being regularly sampled at present will provide approximate concentrations of the useful indicator substances in both sewer and storm water network. However, when water volumes are not available, calibration of quality parameters is extremely difficult because of the large number of different sources (bathroom, toilet, roof runoff, etc.) and also the large documented range of concentrations for each of these sources (i.e. ranges can be over several orders of magnitude).

1 Introduction

1.1 BACKGROUND

This project report is produced jointly by the UK partners of the AISUWRS consortium: the British Geological Survey and the Robens Centre for Public and Environmental Health at the University of Surrey. The 3-year AISUWRS urban water research project is partly funded by the European Community 5th Framework Programme for Shared Cost Research, Technological Development and Demonstration. The 5th Framework Programme was conceived to help solve problems and respond to major socio-economic challenges the European Union is facing. It focuses on a number of objectives and areas combining technological, industrial, economic, social and cultural aspects.

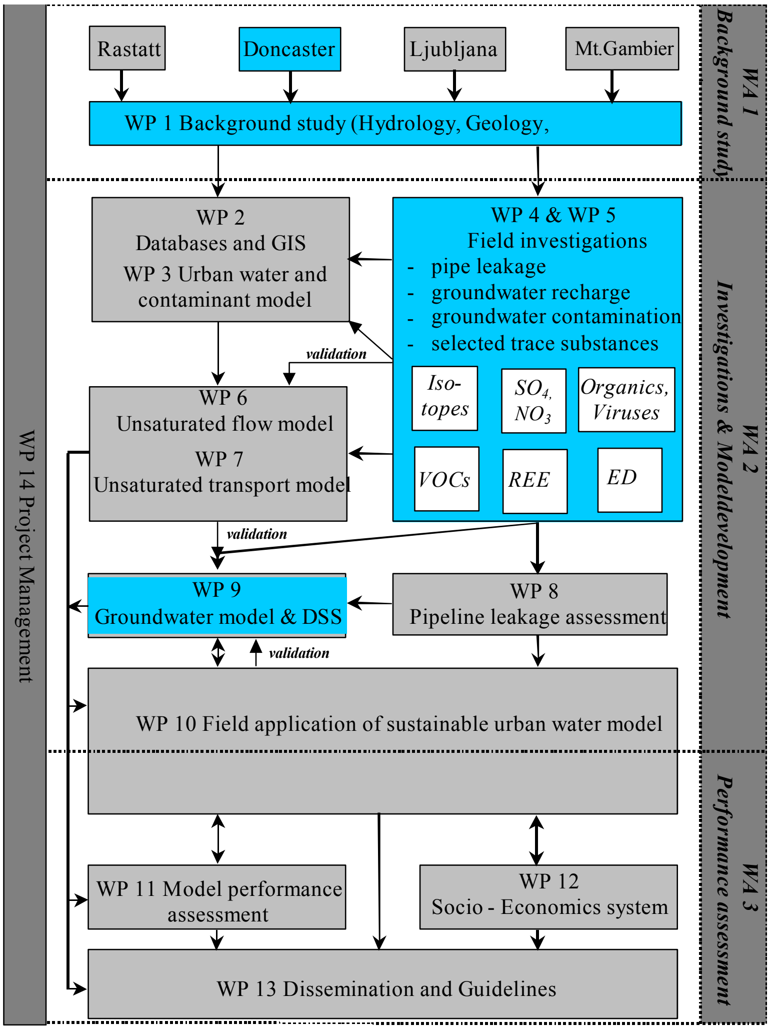
The project is one of a number of European research projects on integrated urban water management that are clustered as the CityNet group. The AISUWRS project aims to develop innovative new modelling techniques and a pilot decision support system (DSS) for cities that depend on underlying or nearby aquifers for their water supply. The objective is to assess and improve the sustainability of urban water resources and systems with the help of computer tools. The AISUWRS project ("Assessing and Improving the Sustainability of Urban Water Resources and Systems") is using case studies of the cities of Doncaster England, Rastatt Germany, Ljubljana Slovenia and Mount Gambier Australia to test and develop an integrated suite of models for urban water management purposes. The European case study cities represent examples of common urban, hydrogeological and water infrastructural settings, so successful application of the models to these situations will be a test of the system's robustness for wider use in the many other cities in Europe and elsewhere that depend on local groundwater for public and private water supply. The roles of the different partners in the project are described in detail in the project's Description of Work (Eiswirth, 2002) and summarised in Table 1

Table 1 Roles of partners in AISUWRS project

Country	Case study city	Partner	Role
Germany	Rastatt	University of Karlsruhe	Rastatt case study, unsaturated zone flow model, groundwater model, development of DSS and application to Rastatt, dissemination, project management
		GKW Consult	Model performance assessment, socio-economics
Slovenia	Ljubljana	Institute for Mining, Geotechnology and Environment, Slovenia	Ljubljana case study, database development, groundwater model and DSS application to Ljubljana
UK	Doncaster	Robens Centre for Public & Environmental Health (Univ. of Surrey)	(jointly) Doncaster case study, groundwater model and DSS application to Doncaster, dissemination
		British Geological Survey	
Australia	Mt Gambier, inputs to the 3 European cities	Commonwealth Scientific and Industrial Research Organisation	Urban water & contaminant model, comparison investigations in Mt Gambier, unsaturated transport and pipeline leakage assessment, groundwater model and DSS application to 4 case study cities

1.2 OBJECTIVES OF THIS REPORT

This interim report details the results of the first 9 months of field investigations in Doncaster, part of Work Package 5, as shown schematically in Figure 1.



WA = working areas, WP = workpackages

Figure 1 Graphical representation of AISUWRS's components (interconnection diagram).

1.2.1 Report layout

Following this introductory section, Chapter 2 outlines the field investigation package and comments on progress, while Chapter 3 describes the siting and construction of the multilevel boreholes in the project's focus area. Chapters 4, 5 and 6 summarise respectively the results of piezometric monitoring, microbiological and hydrochemical sampling/analysis up to 31st of December 2003. The on-going time-consuming collection and interpretation of background data to populate the various models has proven to be an extension of the field investigation tasks, and Chapter 7 summarises various GIS-oriented tasks that contributed to model development. Chapter 8 describes stakeholder consultation activities and finally Chapter 9 outlines the further field investigations work to be undertaken during the second half of Work Package 4, including suggestions on the critical quality indicator and flux parameters that may be emerging from this study.

2 Components of Field investigation programme

2.1 FIELD INVESTIGATION AREA

As indicated in the Doncaster case-study WP1 inception report (Morris et al., 2003), a district of Doncaster has been chosen for detailed field investigations from within the area of initial interest. This is the district of Bessacarr-Cantley (Figure 2), selected for the following reasons:

- Nil or minimal Quaternary cover over the Sherwood Sandstone aquifer
- Well-defined urban boundary and corresponding piped water infrastructure (piped water supply, sewers, surface water drainage, combined sewers)
- Mixture of land uses but predominantly residential and community, with a range of housing types
- Down-gradient of city
- Range of water table depths due to topography.

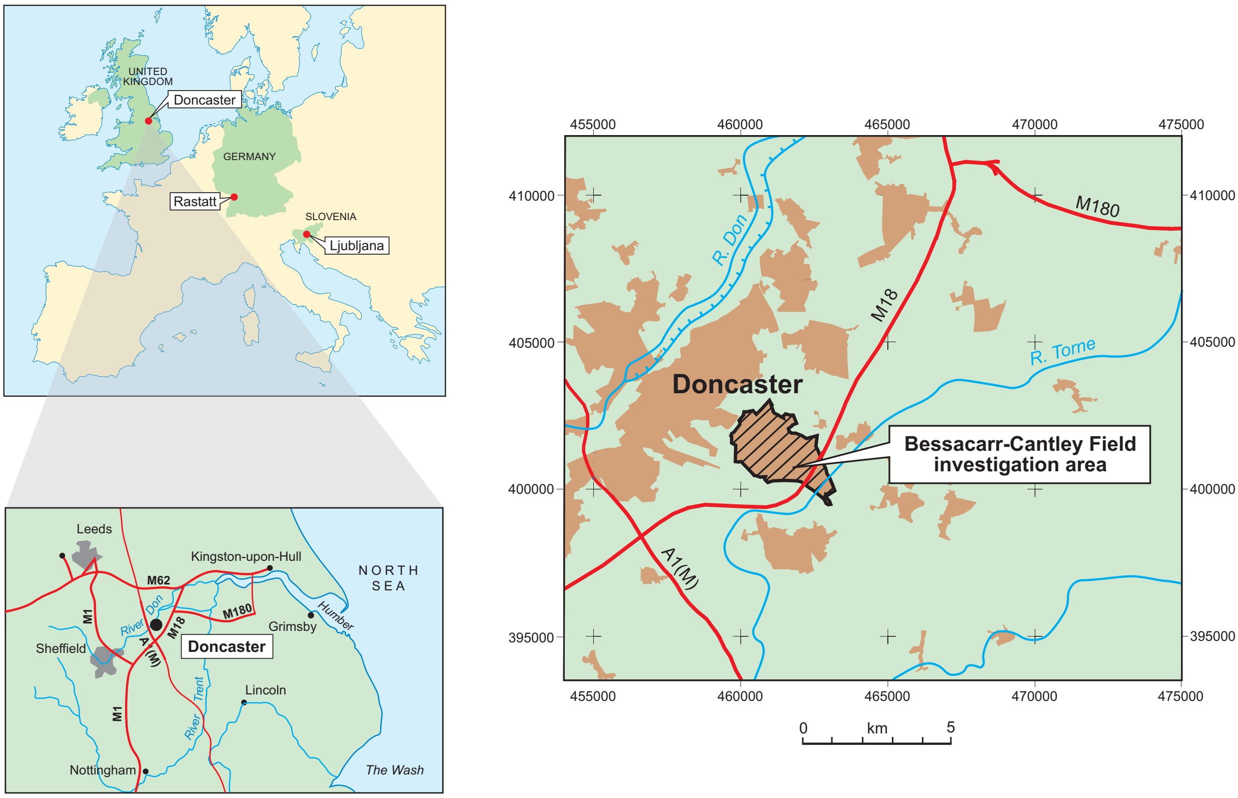


Figure 2 Location of Doncaster

The resultant 7 km^2 area is shown in Figure 3, and is the focus for all future data collection and modelling. Figure 4 shows the simplified land use

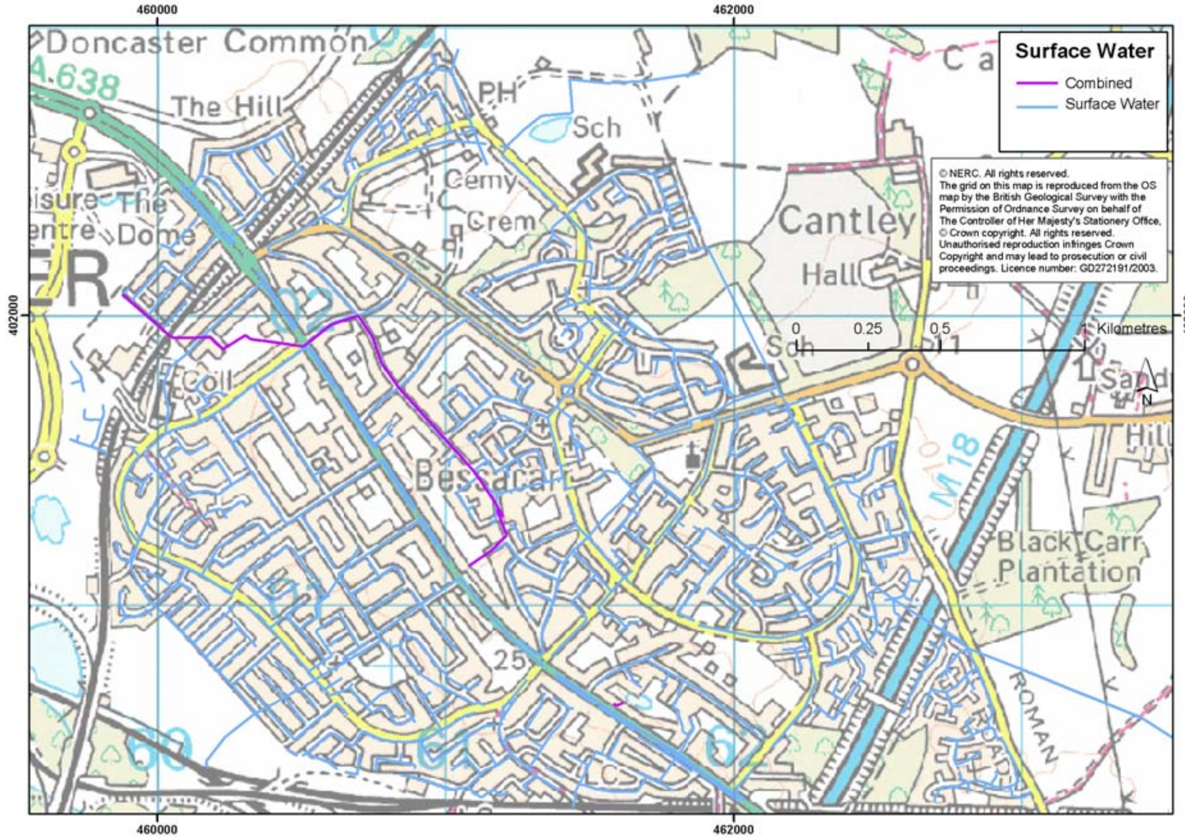


Figure 3 Bessacarr-Cantley detailed investigation area; this example shows the surface water and combined sewer pipe network

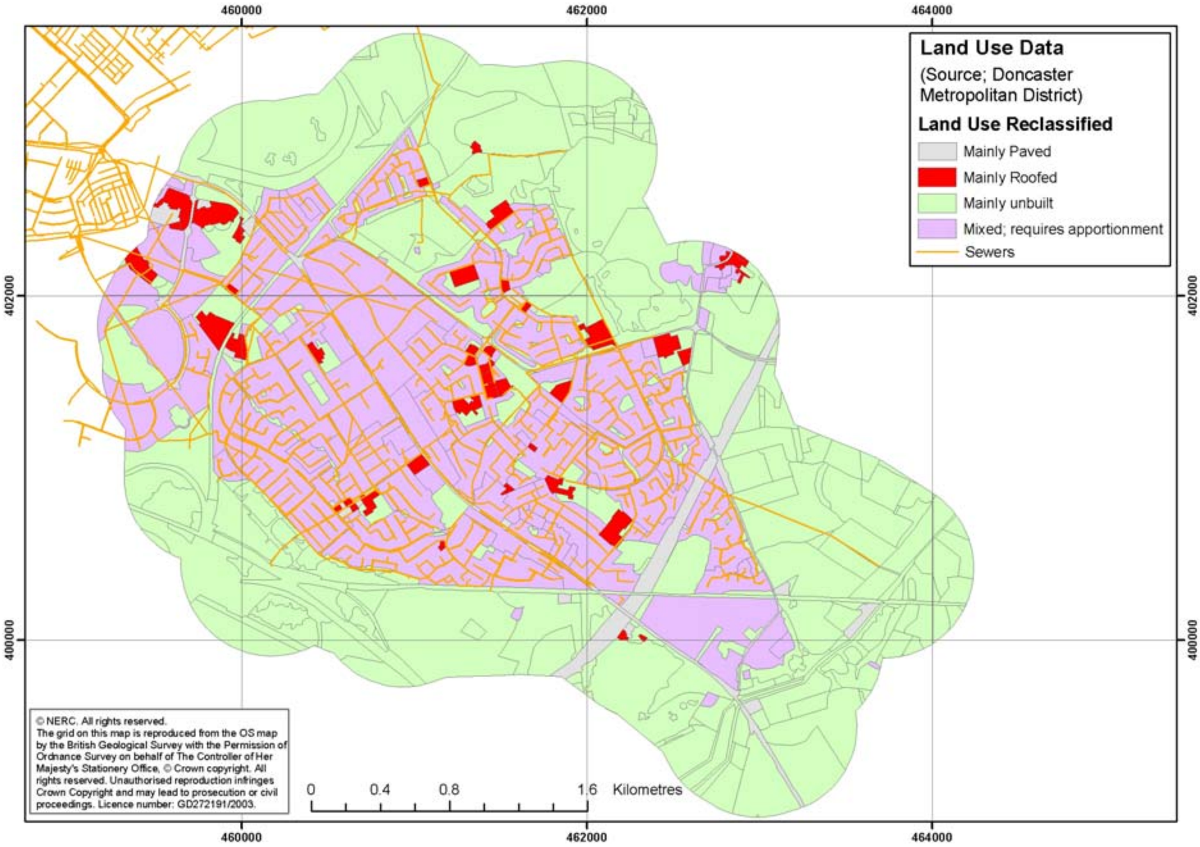


Figure 4 Bessacarr-Cantley investigation area; simplified land use for UVQ purposes

2.2 FIELD INVESTIGATION PROGRAMME

The field investigation program aims to obtain detailed information about the groundwater conditions in and around Doncaster to support the suite of modelling tools. Therefore, at the beginning the main focus was on shallow existing boreholes near the city of Doncaster. As the number of such wells was found to be very limited, some deeper boreholes were added and 5 new multilevel sites were drilled. The aim of the latter is to obtain a detailed insight into vertical penetration of contaminants, something not possible with the existing open regional boreholes

The program started in June 2003 and consists of the following sampling points (Figure 5)

- 12 regional wells
- 5 multilevel piezometers with a total of 33 distinct depth-specific intervals
- 2 shallow piezometers on Bolton Hill
- 3 sewer sampling points
- 2 storm water sampling points

In the first sampling sessions in June/July 2003, only regional wells and sewers were sampled. In the following round in November 2003 all points were sampled except the storm water (due to access problems). For each sampling point the following measurements were performed:

- Temperature, electric conductivity (SEC), pH, redox potential (Eh), alkalinity and dissolved oxygen at the wellhead
- Thermotolerant coliform samples were filtered on-site and incubated over night
- Hydrochemical samples were filtered and preserved for later analysis for major and minor constituents at the BGS Wallingford laboratory
- Selected samples were taken to be analysed for organic contaminant measurement
- Samples for total coliforms, faecal coliforms and faecal streptococci were taken to be analysed the same day in a nearby commercial microbiology laboratory
- Samples for coliphage (bacteriophage with an *E. coli* host) and sulphite-reducing Clostridia (bacterial spores) were taken to be analysed at the Robens Centre
- Selected samples were taken to be analysed for enteric viruses

In total, analyses are produced for about 50 distinct sampling points during each field session. The same program will be continued in February, May and August 2004 to obtain a full set of samples for each season of the year. During 2004 sampling for CFCs (chlorofluorocarbons) and SF_6 (sulphur hexafluoride) will be attempt to identify bulk groundwater ages.

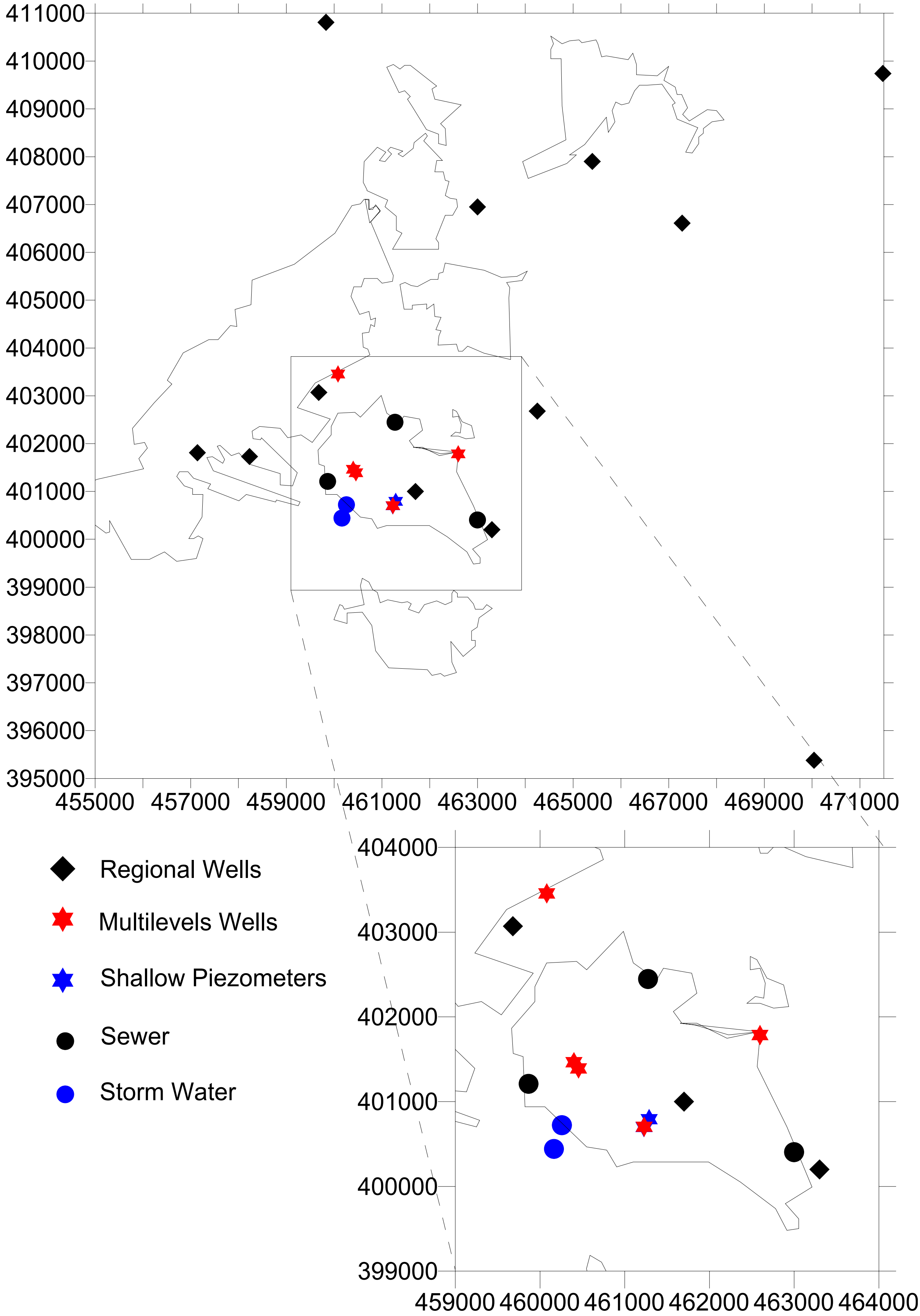


Figure 5 Locations of sampling points of AISUWRS sampling program. Black lines show the boundaries of the urban area.

3 Multilevel boreholes

3.1 INTRODUCTION

Important aims of the field work are to understand the hydrogeology of the area and obtain the required inputs for the models. Testing and validating techniques for assessing groundwater residence times and contaminant concentrations is important as anthropogenic influences on water balance are likely to be significant. UNIS and BGS are jointly undertaking a sampling programme of existing boreholes and new test boreholes in the Doncaster urban area. Hydrochemical and microbiological water quality is being tested; including faecal coliforms, faecal streptococci, coliphage and the USEPA priority viruses (enterovirus, rotavirus, Noro Viruses, Astrovirus and Adenovirus). Furthermore, new sampling sites were constructed to provide insights into groundwater quality patterns and groundwater flow behaviour. The new sampling sites were equipped with multiple depth sampling facilities to permit groundwater sampling at different depth intervals. Similar work was done in the cities of Nottingham and Birmingham (Taylor et al., 2003). By producing depth-specific profiles, we hope to calculate vertical penetration rates of urban contaminants and to study detailed flow processes within the Sherwood Sandstone aquifer. Depth-integrated sampling is usually the preferred approach for detailed groundwater-quality monitoring. However, the depth-integrated approach may be appropriate where the question is whether or not contamination exists at a particular monitoring site. It is often the most appropriate technique for evaluations of water quality for public water supply wells.

Depth profiles are usually important for detailed groundwater quality investigations because contaminant concentrations in bedded deposits can vary markedly in the vertical direction and, in some situations, the zone contributing to the well contamination may occupy only a small part of the total aquifer thickness. This zone could go undetected, or could mistakenly be assumed to represent conditions over the entire aquifer depth, if vertical profiles are not available. When depth-specific sampling is performed, the water sample is drawn from a narrow interval in the borehole in a manner that minimises mixing of water from different depth zones. If this is accomplished, the concentrations in the sample will represent the concentrations in the formation at the depth of sampling. When this sampling approach is used, it is usually necessary to do depth-specific sampling at several depths at each sampling location in order to determine the overall conditions of groundwater quality at the location (Graham 1991). Advantages and disadvantages of drilling techniques and construction (e.g. lining and filling materials) that need to be considered in the planning phase are listed in (Rueedi and Cronin 2003) (see Appendix 1).

3.2 GEOLOGY AND HYDROGEOLOGY

The major geologic formations in the study area are the Mercia Mudstone, the Sherwood Sandstone aquifer and the underlying Permian stratigraphy. The outcrops of the formations are shown in Figure 6. The Sherwood Sandstone Group (formally the Bunter Sandstone) comprises a thick sequence of red, brown and more rarely greenish-grey sandstones of fine to medium grain size with thin layers or lenses of red mudstone and siltstone. South of the study area the Sherwood Sandstone comprises two distinctive lithological units, namely the Nottinghamshire Castle Formation (formerly the Bunter Pebble Beds) and the Lenton Sandstone Formation (formerly the Lower Mottled Sandstones). The units are traceable northwards into the study area but are indistinguishable due to diminishing pebble content. These rounded quartzite pebbles are common in the middle and upper parts of the sandstone but they are increasingly rare and smaller around Doncaster.

In the Doncaster area, fine-grained red sandstone is the dominant feature. However, small quartzite pebbles and rolled mudstone fragments were observed frequently (Gaunt 1994). Some thicker mudstone layers (a few metres) were observed in the north of Doncaster. Cores provide evidence of the lithology, as follows:

- Approximately the lowest 40m of Sherwood Sandstone are characterised by an abundance of thin argillaceous layers and an absence of quartzite pebbles. The sandstone in the lower part of the formation is mainly fine to medium grained, generally thin bedded and locally laminated. The argillaceous layers and laminae are mainly dark red, but a few are greyish green (Gaunt 1994).
- The middle part of the Sherwood Sandstone, from about 40m above the base to 200m, is characterised by fewer argillaceous layers. The sandstone in this sequence is almost entirely red and much of it is medium grained and well sorted. The argillaceous layers have the same characteristics as those in the lower strata, but occur less frequently. Rolled argillaceous fragments are, in contrast, more abundant, occurring both widely scattered and locally concentrated into thin 'marl conglomerate' layers. The largest pebbles recorded are 50mm across but most are well under half this size (Gaunt 1994).
- The upper part of the Sherwood Sandstone, less than 100m thick in the south, is poorly known due to the paucity of cored boreholes and absence of shafts through it. Generally, the appearance is very similar to the lower layers, showing some argillaceous layers and rolled argillaceous fragments as well as rarely noted fine pebbles. The most obvious variation of the upper part of the Sherwood Sandstone is its greyish colour (Gaunt 1994).

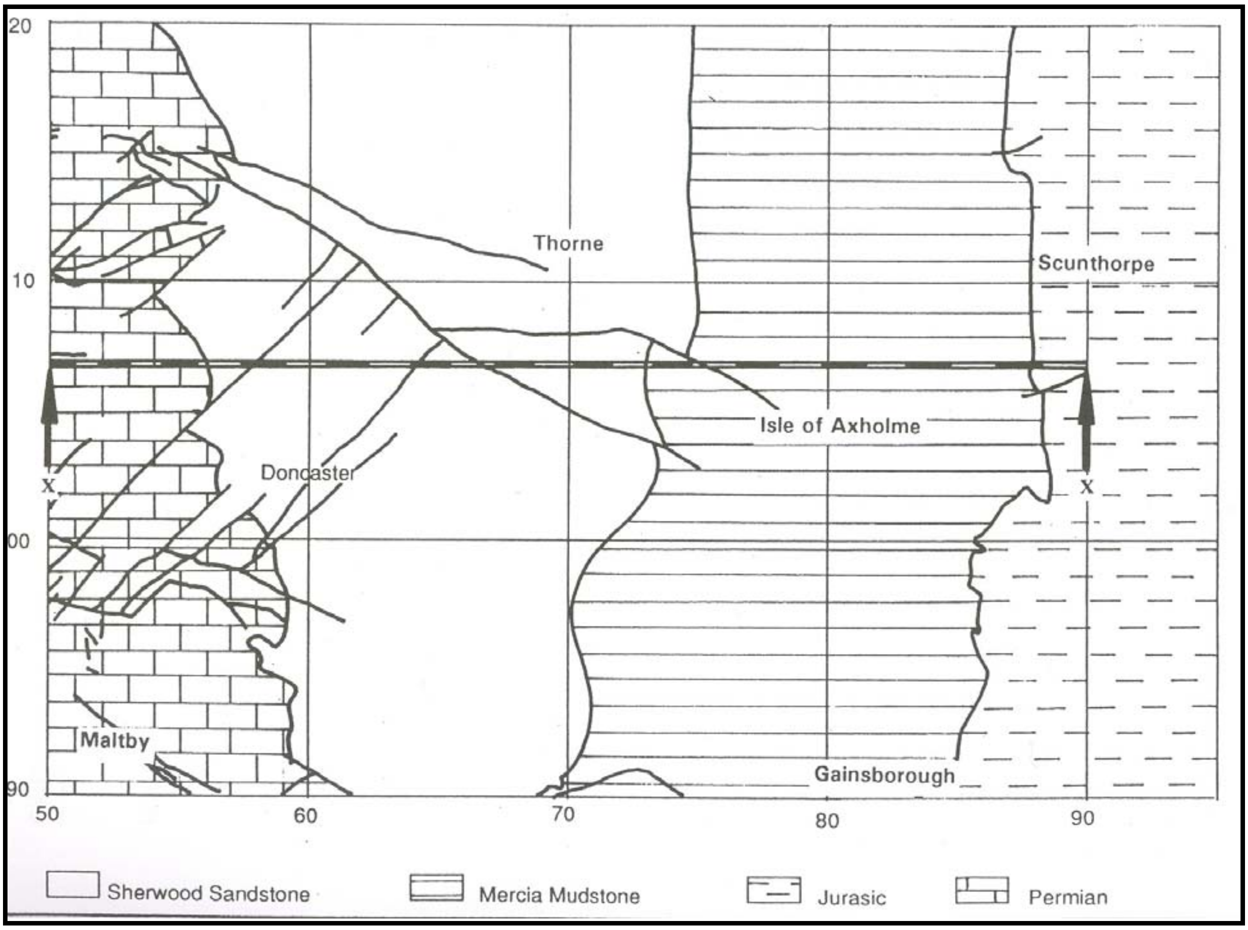


Figure 6 Main outcrop geology features of the Doncaster area (from Brown and Rushton, 1993)).

The Quaternary geology of the area has been rigorously examined and discussed by (Brown and Rushton 1993). The Sherwood Sandstone is overlain by superficial deposits of the Quaternary Ipswichian, Devensian and Flandrian stages (Figure 7). These deposits are widely spread over the area and complex in nature. Deposits range from clay tills and glacial channel deposits, to glacial and fluvioglacial sands and gravels with more recent lacustrine deposits, blown sands and peat. Thicknesses vary up to tens of metres, and these beds strongly affect groundwater recharge and groundwater flow patterns. The variability evidenced in the Figure 7 map shows how important it is to understand the drift geology in this area both for finding suitable locations for the multilevel sites and for the interpretation of the results.

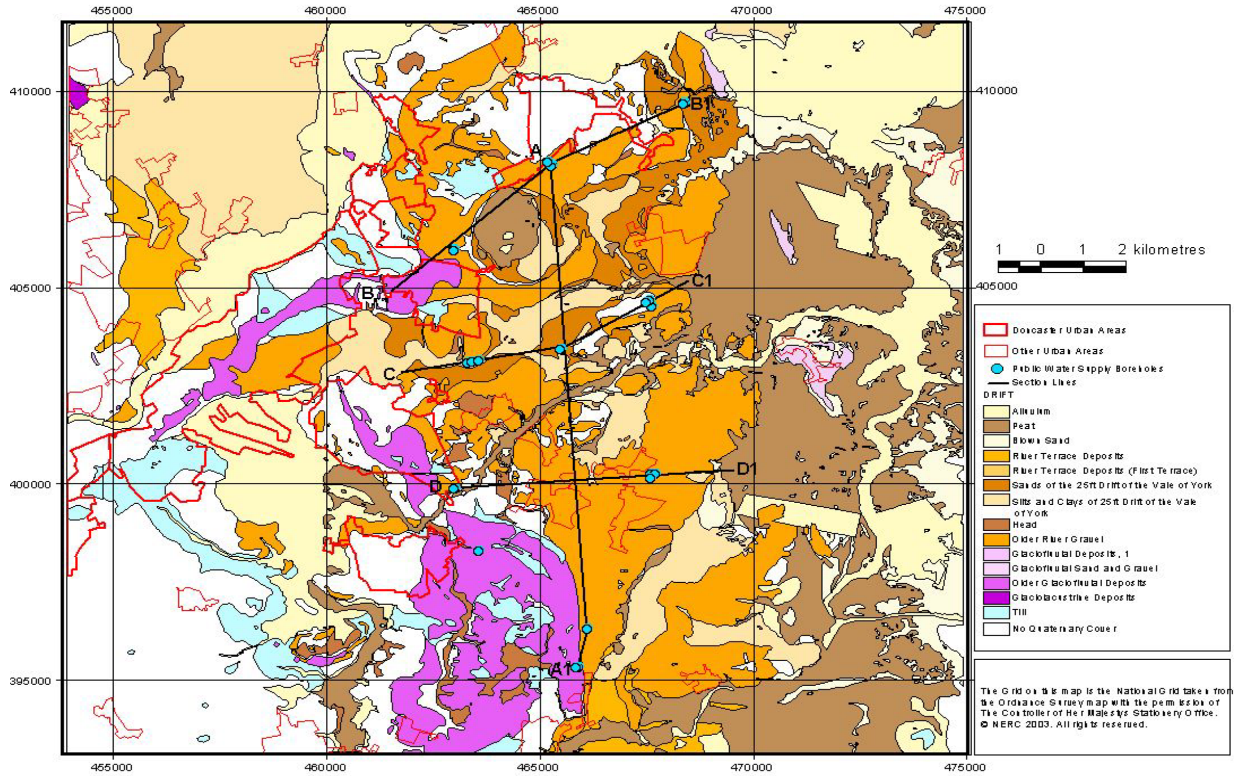


Figure 7 Quaternary geology of the area around Doncaster (from Morris et al., 2003)).

3.3 MULTILEVEL SITES

During the first inspection of possible drilling sites in May 2003 12 locations were identified (Figure 8). However, several of these sites were rejected after it was found they would be located on or close to rather deep glacial channels (A1, D1, D3, D5, D7). Another site was likely to be opposed by local residents for historical reasons and was also dropped. The best match for the chosen siting-criteria was in the Bessacarr area (B1–B4). However, this suburb's housing stock is younger than the city centre. Therefore, it was decided to drill one borehole on Sandall Beat Playing Fields owned by Doncaster Metropolitan Borough Council (DMBC) in order to assess the likely impact of urban recharge from the older centre of Doncaster which is located just upgradient. The other 4 sites were all chosen to be in Bessacarr, namely on the playing fields of McAuley Catholic High School, on Bolton Hill Playing Fields and on Haslam Park, the latter two owned by DMBC. Since there little known about medium scale (tens of metres) variability in the Sherwood Sandstone this project allowed an opportunity to drill 2 sites at a distance of about 80 metres (both on Haslam Park). The latter site was chosen because it is very secure for drilling and sampling and it is totally surrounded by residential properties and so may produce interesting results from water quality sampling.

Drilling started on Monday 01/09/2003 on Sandall Beat site near Doncaster Race Course. After penetrating through some glacial clay and gravel layers, red sandstone was hit at a depth of about 6m below ground. After drilling through a few metres of hard sandstone, the water-bearing layer was reached at a depth of approximately 13m where the permanent casing was inserted and cemented in. The water level then rose up to about 2.5m below ground, indicating confined conditions. This was surprising as confined conditions were only expected below the poorly conductive Quaternary drift layers. However, these layers only reach to a depth of about 6m. Therefore, there must be low conductivity layers in the sandstone preventing groundwater entering the upper layer. Drilling was continued using a $5^{7}/_{8}$" air-hammer (15cm). After penetrating through about 2 metres of hard sandstone, the hammer went through a few metres of soft sand before hitting hard stone again at a depth of about 18m. After that, the drillers observed the hole to cave in slightly. They tested by stopping one hour and observing 1.2m of sand falling into the hole. As the hole was expected to penetrate to the underlying Permian Marl above 60m depth and as excessive volumes of sand were coming up, it was decided to drill to a final depth of 36.7m. After removing the bit the borehole collapsed to a plumbed depth of about 15m. Hence, the sandstone seems to be unconsolidated to depths below only a few metres. This hole was left until the end of the drilling session because a temporary casing had to be manufactured to drill into the existing hole to case out the collapsing layers.

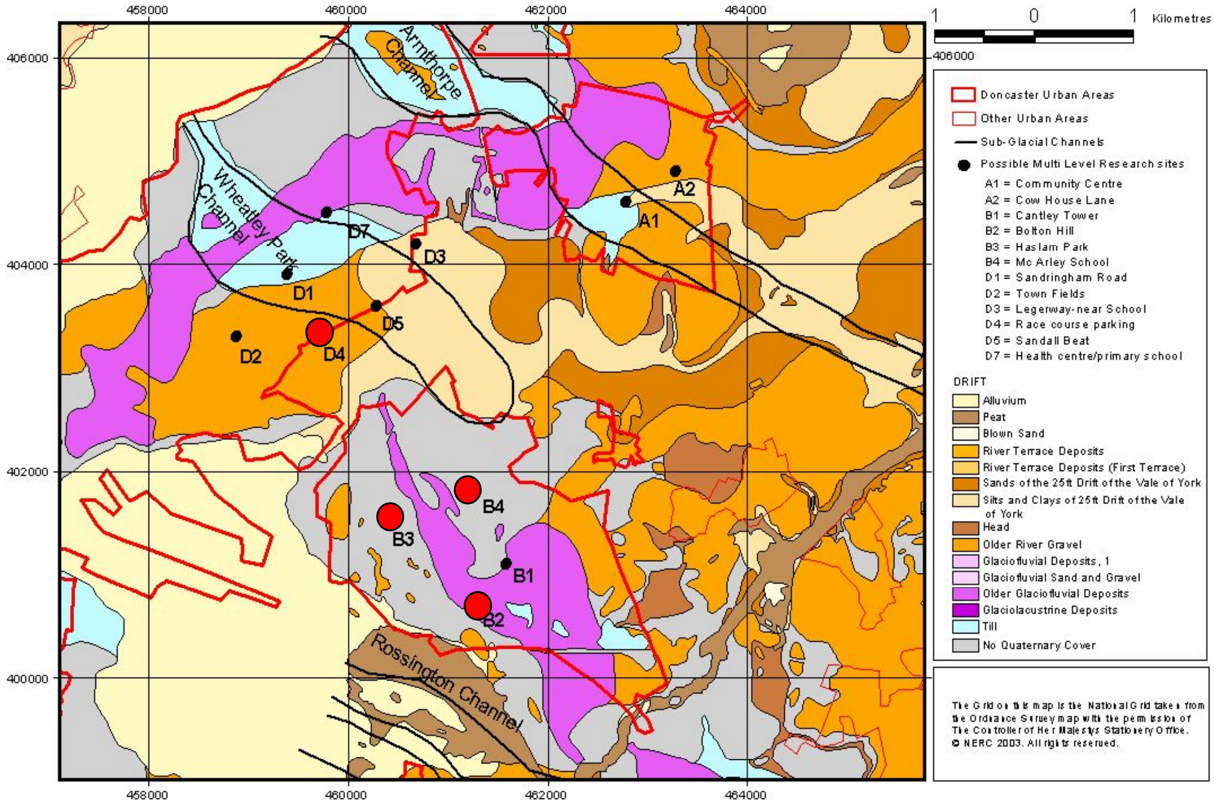


Figure 8 Multilevel drill-sites superimposed on Quaternary geological map; potential sites in black, chosen sites in red

The drilling strategy was altered for the remaining 4 holes and always used a small diameter hammer ($4^3/_4$", 12.2 cm) to penetrate through the top part of the saturated zone where collapsing was a possibility and then continuing with the larger $5^7/_8$" air-hammer (15cm) to complete the hole. These boreholes were sufficiently consolidated to prevent collapsing so that this standard uniform approach (using first the small and then the larger hammer) could be followed at all of these four remaining holes. After reaching the final depth (≈60m), the boreholes were flushed with compressed air to remove remaining drilling debris.

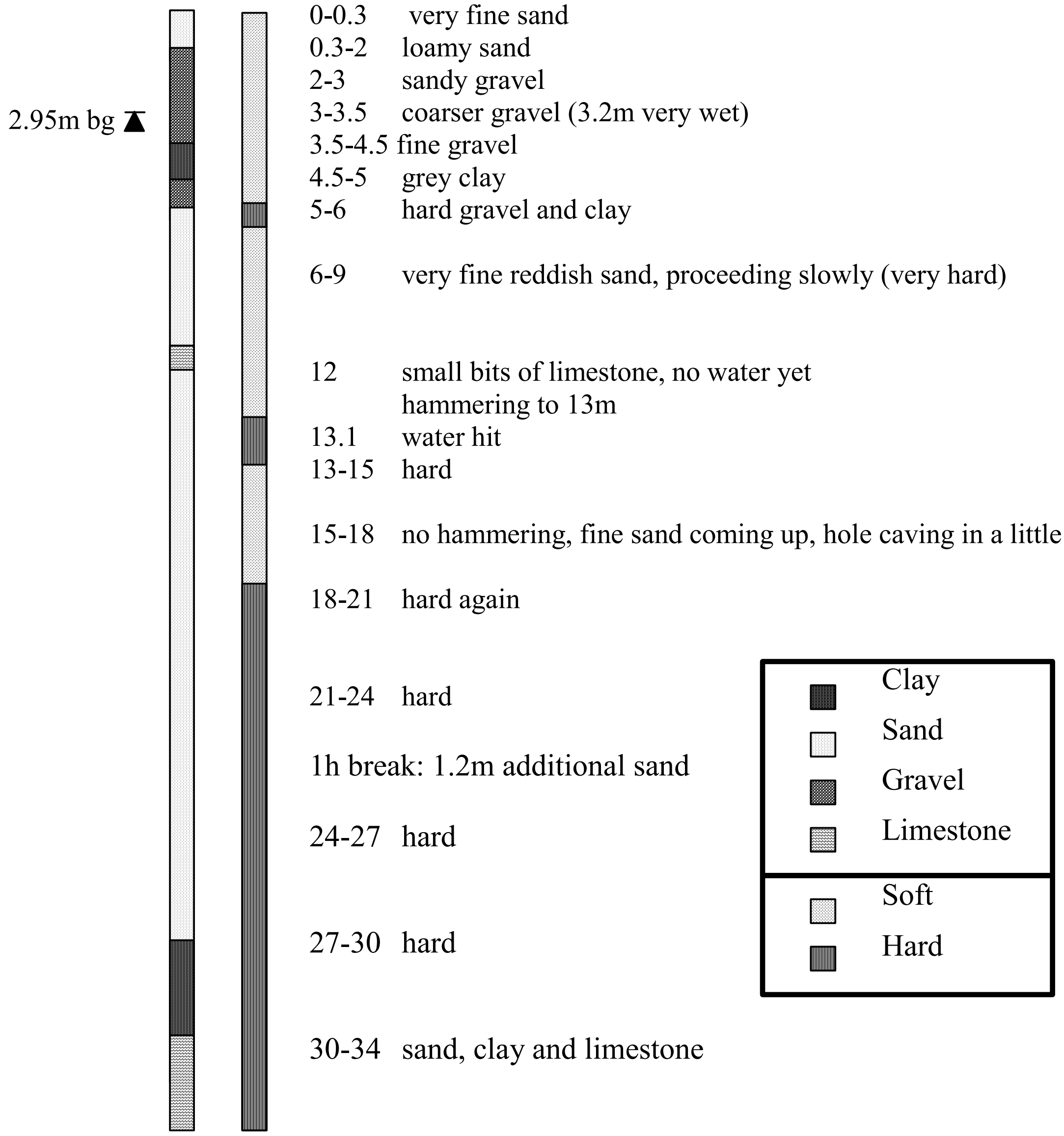
The planned open hole geophysical logging was cancelled because

- the holes were not stable enough to guarantee safe insertion and removal of probes
- of the additional contract costs arising due to the collapsed borehole.

Instead of geophysical logs, precise drilling logs were noted during drilling and samples of drilling debris were taken regularly. The drilling logs show where the hammer bit is hammering indicating hard and soft layers within the sandstone. The subsequent installation of multilevels was based on this information rather than on geophysical logs. Figure 9 shows an example of the detailed logs taken during drilling.

Coring was unsuccessfully attempted at Bolton Hill. The major reasons for taking core samples were (a) for a more detailed view of the sandstone sequence and (b) to obtain pore-water samples for comparison with the measurements to be analysed during the one-year sampling campaign.

Core withdrawal was tried again on Haslam Park 2 site by adding a small amount of mist and reducing air pressure on the core barrel. 3 cores were successfully taken from different depths for analysis.



Notes: Left log shows lithology
Right log depicts rock competence from hammering action of the bit.
Depths given in metres below ground level (mbgl).

Figure 9 Drilling Logs taken at Sandall Beat.

It was found that all samples including the core from 30m below ground are uncemented, merely becoming somewhat more consolidated with depth. This was a surprising finding, not generally reported in previous literature; further south along the strike the Sherwood Sandstone is cemented through much of its thickness, forming for instance stable low cliffs in road cuttings. Generally, the samples consist of medium size sand and contain various silty horizons and mud pellets.

After completing the boreholes and removing the rig, short pumping tests were conducted on all sites except Sandall Beat, designed to:

1. prevent groundwater exchange from one level to another aquifer level
2. clear the boreholes of drill cuttings prior to the installation phase

3. avoid running generators overnight because 3 of the 4 sites are near housing
4. provide a local estimate of transmissivity

To monitor the groundwater levels the automated data loggers (Divers© by Van Essen Instruments) were used for continuous groundwater monitoring. The results and interpretations of all water level data are shown in (Rueedi and Cronin, 2003). The transmissivities obtained are of the order of 3-15 m^2/h (70-360 m^2/d) and are within the range of values documented for this region (Brown and Rushton 1993). They reflect the drilling observations that Bolton Hill is the least consolidated of all the sites.

The design of the multilevel piezometers was adapted from previous experience to meet the requirements of this project (Figure 10). As urban recharge is the major focus of AISUWRS, the depth of boreholes was limited to a maximum of 60m below ground. Considering a thickness of a clay seal of at least 1.5m and the distance between the sampling interval and the seals of about 2.5m, a maximum number of 7-8 levels is possible in a 60m hole. We therefore decided to install 7 levels to allow thicker clay seals to be installed.

As groundwater levels, temperature and conductivity are being monitored online by adding the automated divers into the lowest and the upper-most depth intervals, these two levels needed to have an internal diameter of at least 26 mm. Hence, 42mmOD/35mmID PVC pipes were employed for these levels. For the other levels 21mmID HDPE pipes were installed:

- to enable Low-flow Waterra pumps to be used
- to permit clustering of all pipes around the centre pipe (including the PVC pipe for the shallow level)
- to leave enough annular space to add sand and bentonite

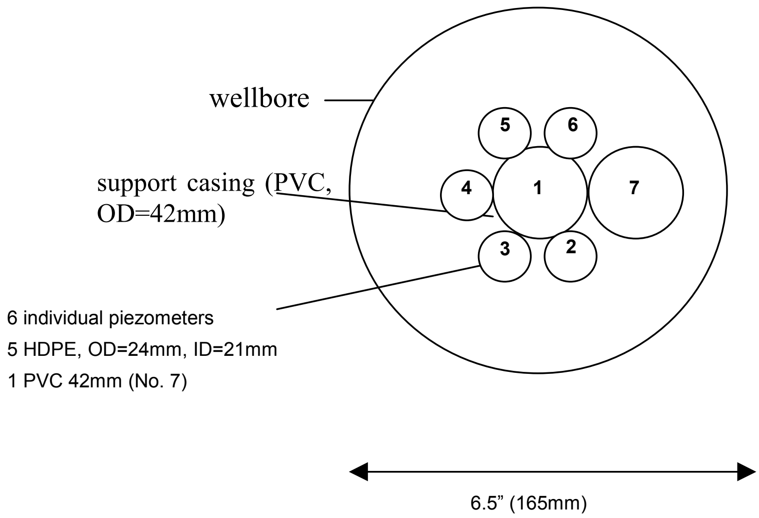


Figure 10 Design of multilevel sampling assembly.

To sample micro-organisms in groundwater properly, all possible sources of micro-biological contamination were minimised during installation (e.g. by dirty hands touching pipes). Furthermore, the water inside the sampling intervals most likely contained a chemical signature influenced by of the added clay seal because the bentonite pellets were dropping through the open hole and because the seals were not active until a few hours after installation (after swelling). Therefore, it was decided to develop the multilevel boreholes 1 month after installation by adding bleach and purging each level.

The bore volume was calculated and to this an extra estimated volume of 15L of water in the sampling interval (from seal to seal) was added. In addition, this volume was bleached (50mg/l free chlorine residual) and left to disinfect the bore for at least 15 minutes. Then a minimum of 3 times the added volume was removed while continuously checking the SEC and water temperature. It was found that a constant level was reached after about 2 volumes and so withdrawing 3 volumes or more was felt to be sufficient.

3.4 CONCLUSIONS

The 5 multilevel sampling sites were successfully installed and cleaned and were sampled for the first time in November 2003. As the first results obtained show quite clear differences between different intervals we are confident that the seals prevent vertical flux between the levels. Results from the first multilevel sampling campaign show considerable differences in conductivity, Eh and dissolved oxygen with depth indicating that the construction was successful. However, it is planned to test the seals both hydraulically and with tracers. These tests will be carried out after the end of the one-year sampling time to avoid adversely influencing any of the samples.

It was noted earlier that one borehole collapsed, leading to additional costs. However, this hole was recovered and a depth interval monitoring point was installed into the collapsing zone. Therefore, this hole could be most interesting from a water quality viewpoint because the collapsing soft zone is expected to have a high hydraulic conductivity. This, in turn, would lead to rapid transport of contaminants in this zone, provided a sufficient gradient is present.

The construction of the multilevel piezometers enables on-line measurement of groundwater levels, temperature and conductivity at the topmost and the lowest level and with a high temporal resolution. It is hoped they will provide important information about groundwater recharge in our study area and enable the elucidation of regional groundwater flow dynamics (both horizontally and vertically).

A more detailed insight into planning and construction of the multilevel sites can be found in (Rueedi and Cronin 2003) (see Appendix 1). One aspect outlined in more detail in this Appendix is that, generally, the observations made during drilling point to the fact that the aquifer is not entirely unconfined, but more likely semi-confined. This previously unreported observation in this region is quite surprising. Furthermore, local residents reported that perched water levels, as observed on Bolton Hill, seem to be quite common features in the area. Both a semi-confined aquifer and perched water levels imply that groundwater recharge cannot reach the aquifer directly in these areas but is delayed in reaching the water table. However, the spatial extent of these features is not known. They will certainly have an impact on the modelling approaches to be applied in this project.

4 Piezometric monitoring

4.1 REGIONAL MONITORING NETWORK

The Environment Agency of England and Wales (EA) operates the current water level monitoring network. Measurements have been monthly since the mid 1980s. A sample of the results is displayed in Figure 11 and shows January water levels measured in the years 1970, 1980, 1990 and 2000 at the stations indicated with black diamonds. It can be seen that the draw-down induced by the numerous pumping wells for groundwater supply lead to a very noticeable composite cone of depression downstream of the city area. The largest cone is visible on the 1990 plot prior to a post-1995 reduction of pumping rates agreed between the EA and Yorkshire Water (YW).

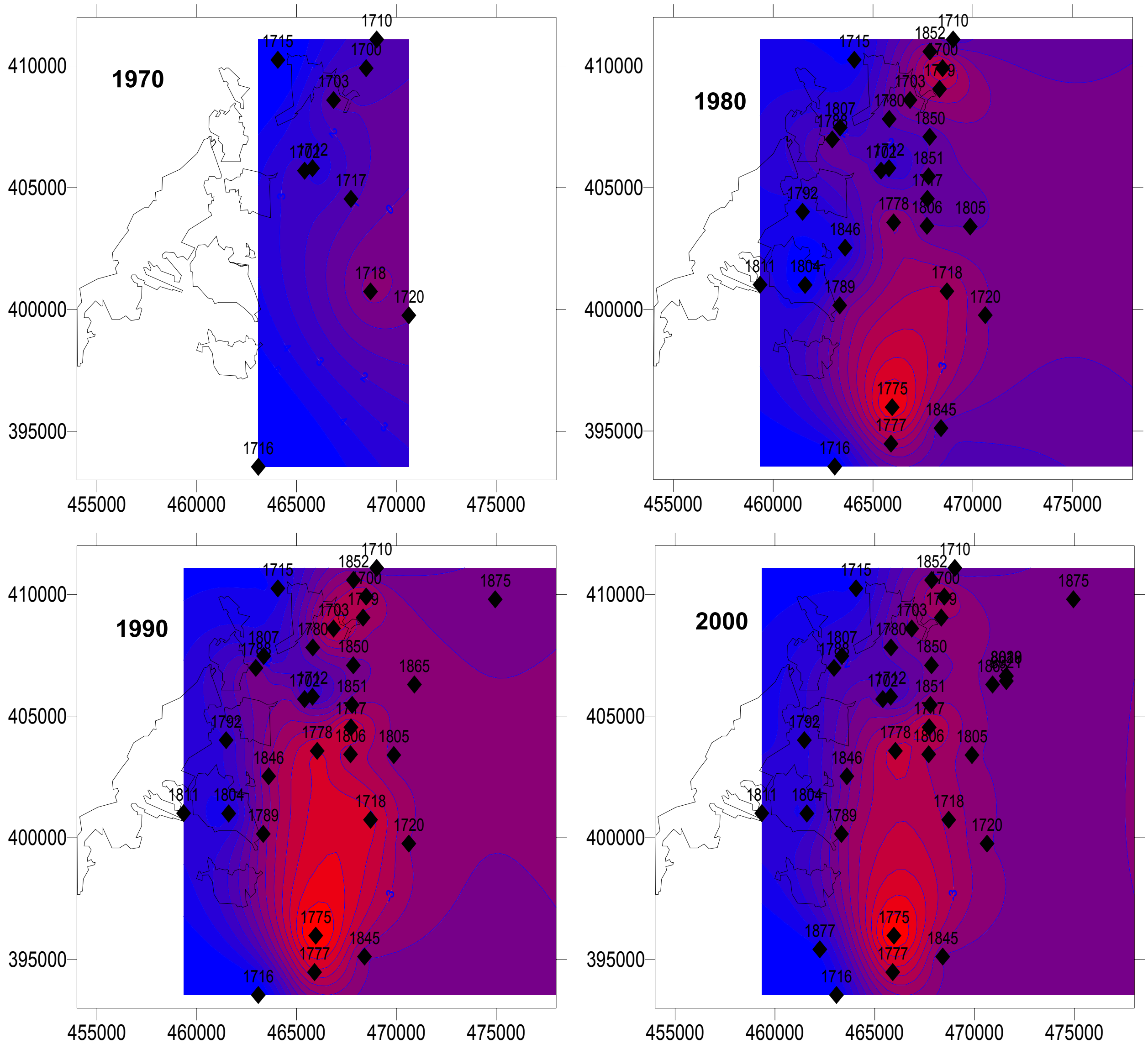


Figure 11 Contour plots of January groundwater levels in 1970, 1980, 1990 and 2000 using kriging. Red areas are low levels and blue areas are high levels. Black diamonds show locations of monitoring including the reference numbers. Boundaries of the urbanised areas are outlined with black lines.

When the water levels are analysed in detail it can be seen that near the pumping wells the groundwater levels have changed considerably over the observation time. Further away from the pumping wells changes in pumping rates have hardly affected groundwater levels – even after decades of pumping (Figure 12 and Figure 13). Fluctuations are of the order of 8m near a pumping well and of the order of 0.5m near the city area (Figure 13).

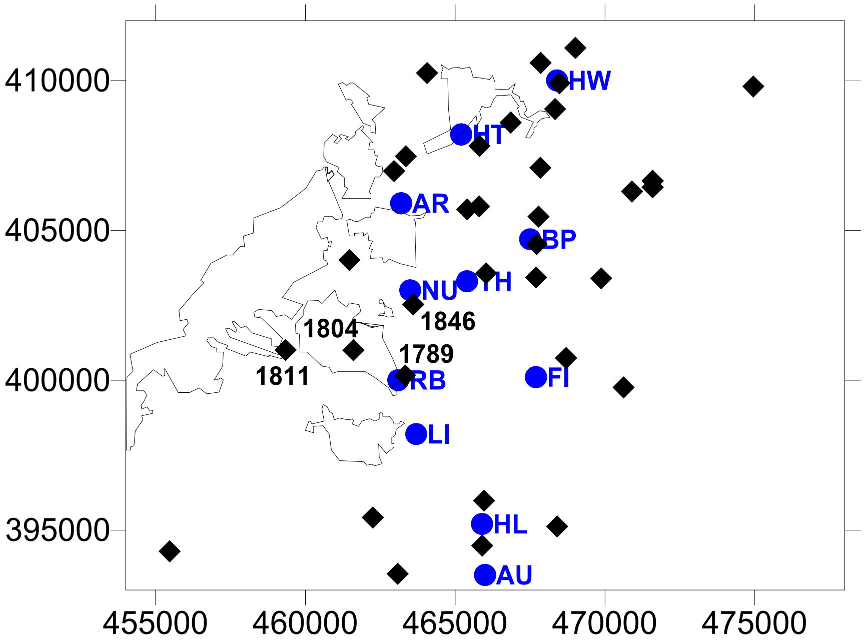


Figure 12 **Water Level Monitoring wells and major abstractions east of Doncaster. The EA Monitoring network is shown with black diamonds, YW water supply pumping stations with blue dots and boundaries of the urbanised areas are outlined with black lines.**

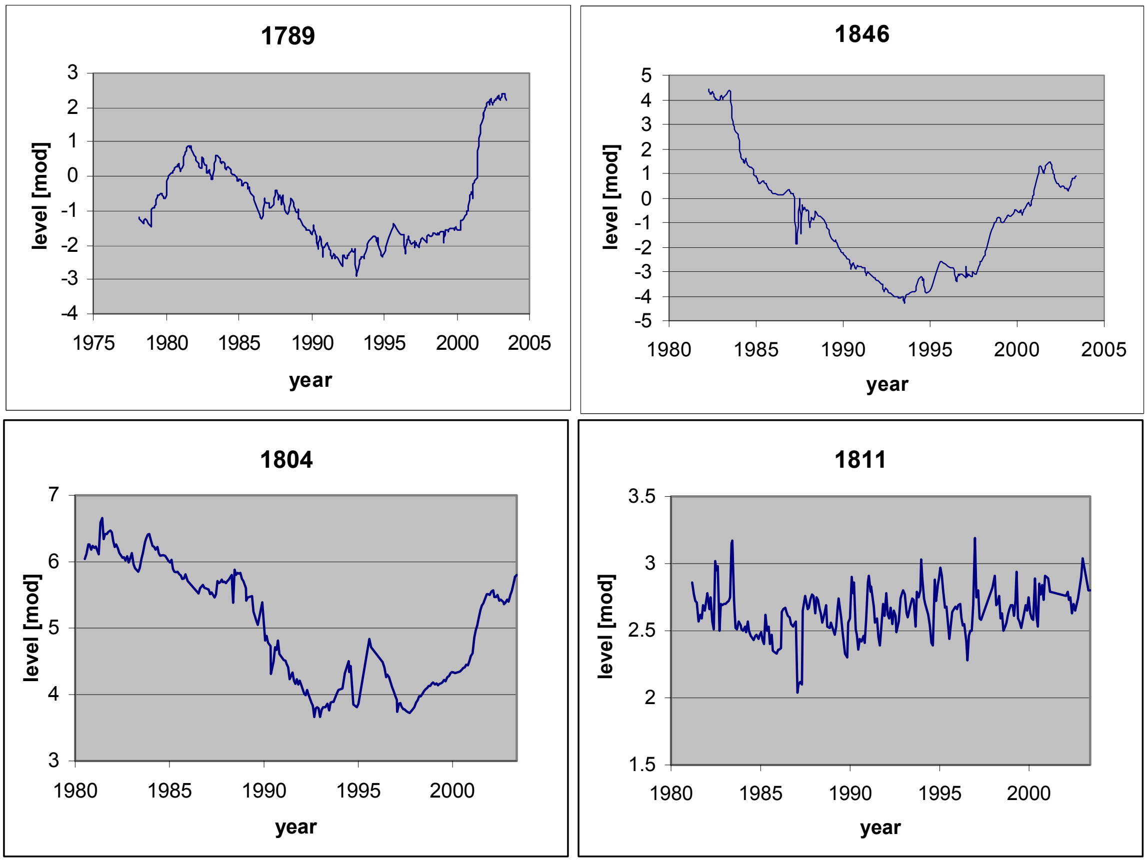


Figure 13 **Water level hydrographs at four monitoring wells 1789, 1846, 1804 and 1811 in and near Bessacarr-Cantley.**

Based on these measurements it is expected that water level changes of the order of 10s to 100s of centimetres occur during our observation period of slightly more than a year.

4.2 MULTILEVEL MONITORING RESULTS

Groundwater levels of each multilevel well are measured manually on each visit and continuously in a selection of ports. The latter have loggers installed to enable on-line recording of the top and bottom levels and use automated Diver© loggers. The Divers measure groundwater levels with a precision of ±2cm, temperature with a precision of ±0.1°C and Electrical Conductivity (EC) with a relative precision of ±1%. The logger use non-vented transducers to measure total pressure in the borehole and as fluctuations in barometric (air) pressure will affect this then the results have to be corrected for any air pressure changes. Therefore, barometric pressure is monitored at the same frequency as groundwater pressure. The recommended correction is based on a simple subtraction. However, it was found that the air pressure signals are still recognisable in the resulting measured groundwater fluctuations. Therefore, the original results are corrected based on a linear regression. This procedure should lead to the smallest possible influence of short-term atmospheric pressure changes. The results of the first month of monitoring, after the wells were constructed, are displayed below for each well. Note that the displayed results from the monitoring equipment are from the initial Diver testing phase.

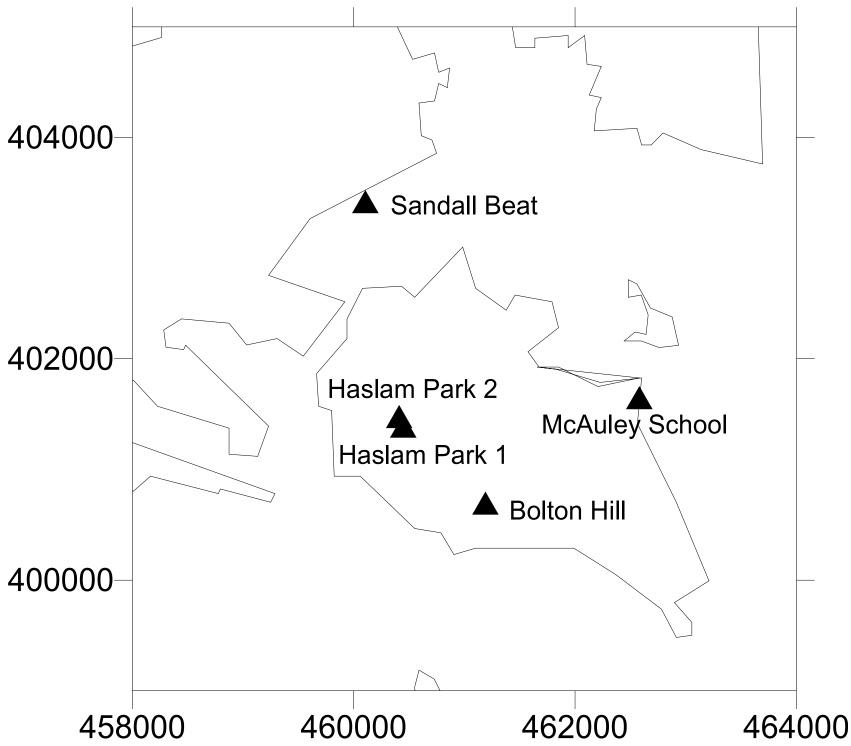


Figure 14 Map showing multilevel monitoring sites. Black lines indicate boundaries of urbanised areas.

4.2.1 Sandall Beat

The Sandall Beat site has shown only small changes in groundwater level at different depth intervals. As the different levels are separated with at least 1m of clay, vertical head gradients (if present), should be clearly observable. Such gradients are quite small even when total pressure changes are observed and corrected for barometric fluctuations (Figure 15). The right hand side plots of Figure 15 show that the monitored water levels coincide well with those obtained manually using a water level dipper. The rising water levels observed could be due to the winter rainfall but more likely they show the recovery of the groundwater after the irrigation pumps at Doncaster racecourse (about 100m away) were switched off.

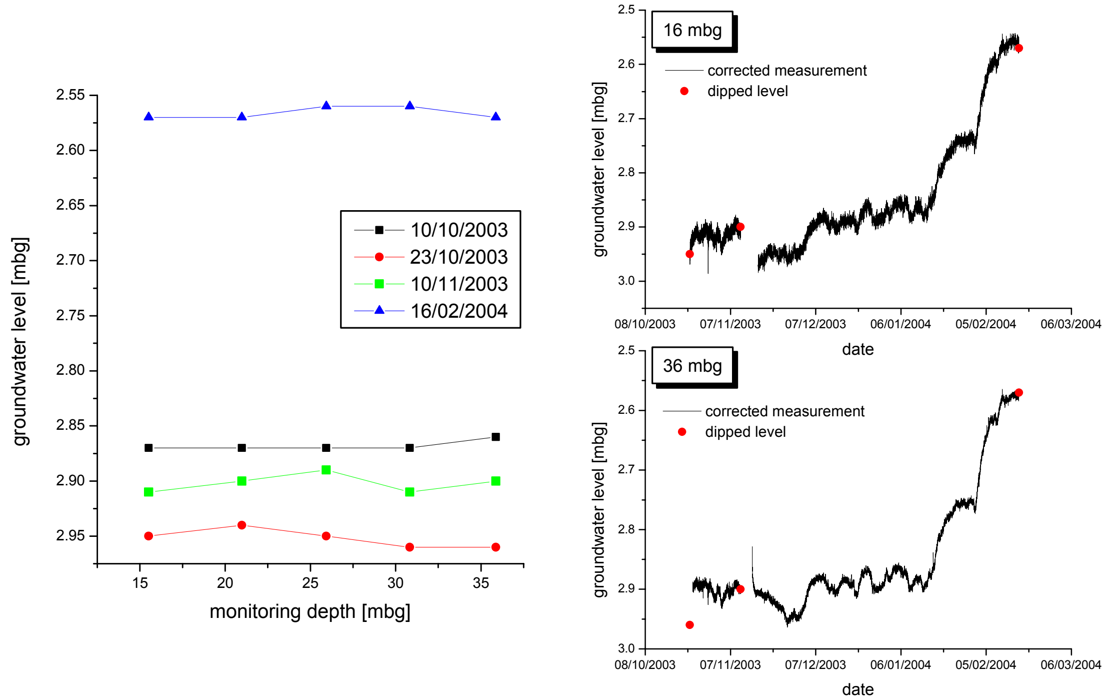


Figure 15 Groundwater levels measured at the Sandall Beat multilevel. Left hand plot shows manually dipped groundwater levels. Right hand plots show the logged water levels after correction for air pressure (black line) and the manually dipped water levels (red circles) for the depth intervals of 16 and 36 mbgl.

4.2.2 McAuley School

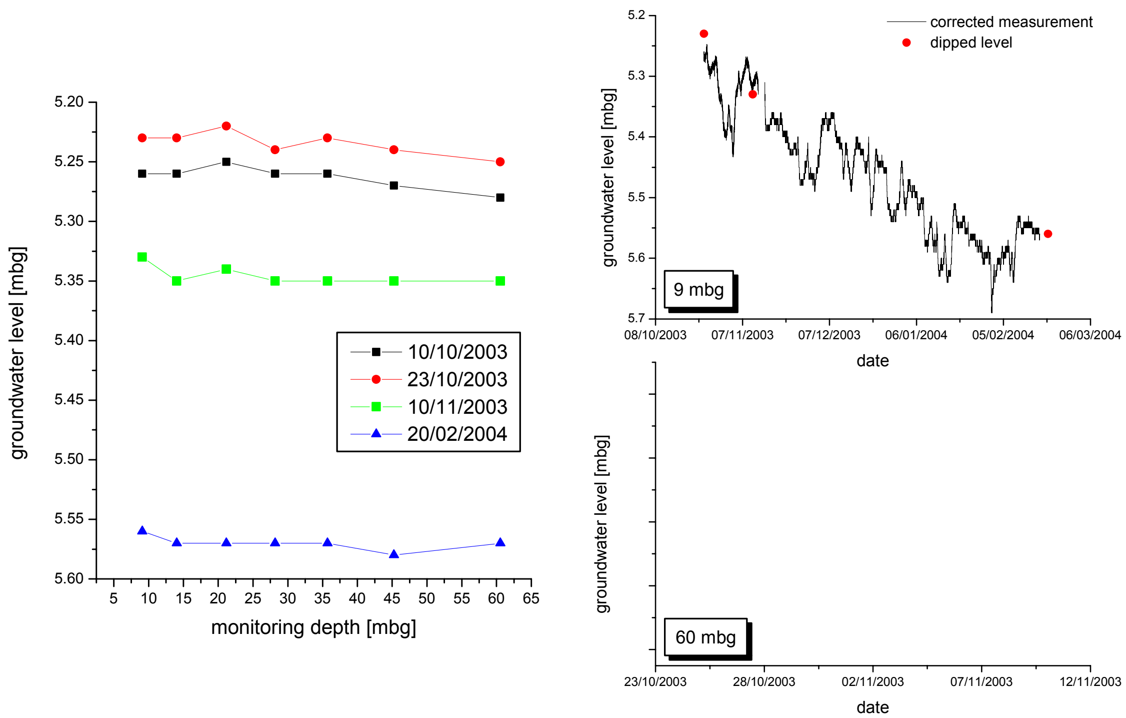


Figure 16 Groundwater levels measured at the McAuley School multilevel. Left hand plot shows manually dipped levels. Right hand plots show the logged water levels after correction for air pressure (black line) and the manually dipped water levels (red circles) for the depth intervals of 9 mbgl. (60mbgl not monitored).

At the McAuley School site, groundwater levels consistently show a decrease with increasing depth indicating local groundwater recharge ((Figure 16). Whether the large fluctuations of the on-line measurements reflect real water pressure fluctuations or are measurement and correction artefacts is difficult to deduce at this early stage of the project. However, a general drop of the water table by about 40cm can be observed.

4.2.3 Bolton Hill

The Bolton Hill site is interesting in terms of water levels because the gradients are far bigger than in the other sites. The left hand side plot of Figure 17 shows considerably higher levels at intermediate depths. The importance of such observations will become clearer as the monitoring continues over the next field sessions. The monitoring results from the topmost level show a decline the water levels of ~ 15cm.

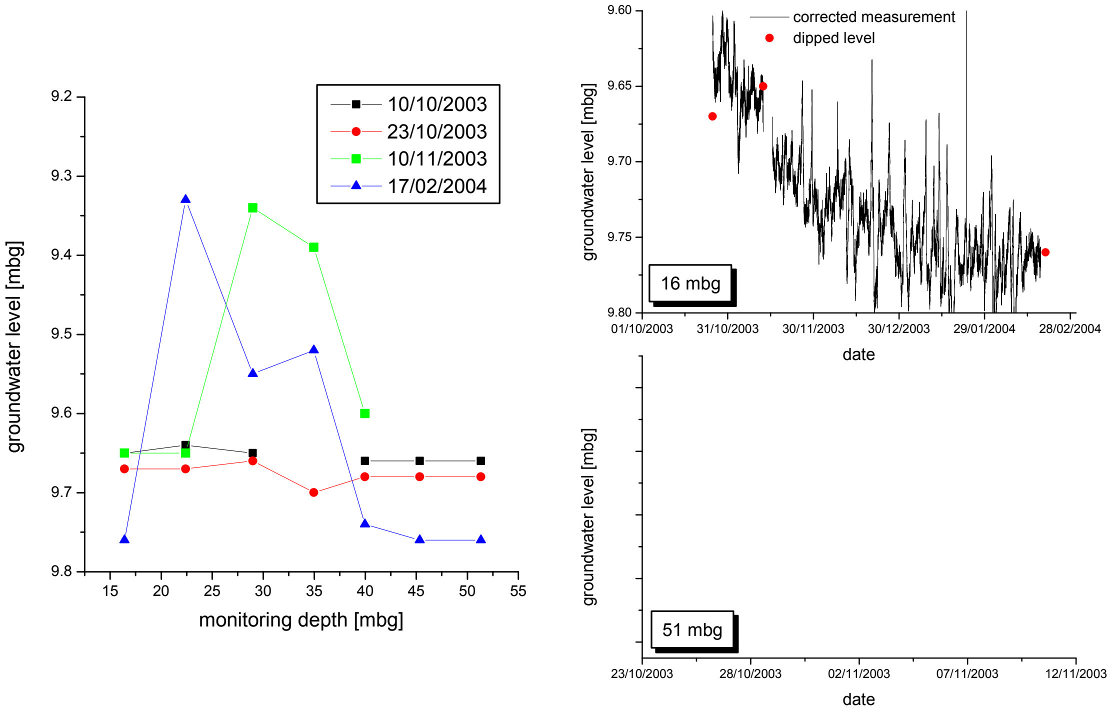


Figure 17 Groundwater levels measured in Bolton Hill multilevel. Left hand plot shows manually dipped levels. Right hand plots show the logged water levels after correction for air pressure (black line) and the manually dipped water levels (red circles) for the depth intervals of 16 mbgl. (51 mbgl not monitored).

4.2.4 Haslam Park

The water level profiles at the Haslam Park sites look quite similar to each other with declining levels during the observation period whereas the gradients remain an almost constant 0.16m/month. The decreasing levels with depth imply that recharge occurs locally.

The right hand side plots of Figure 18 and Figure 19 show that the on-line monitoring devices coincide well with the dipped levels. The disagreement with the dipped levels is only of the order of 1 to3 cm which is within measurement precision.

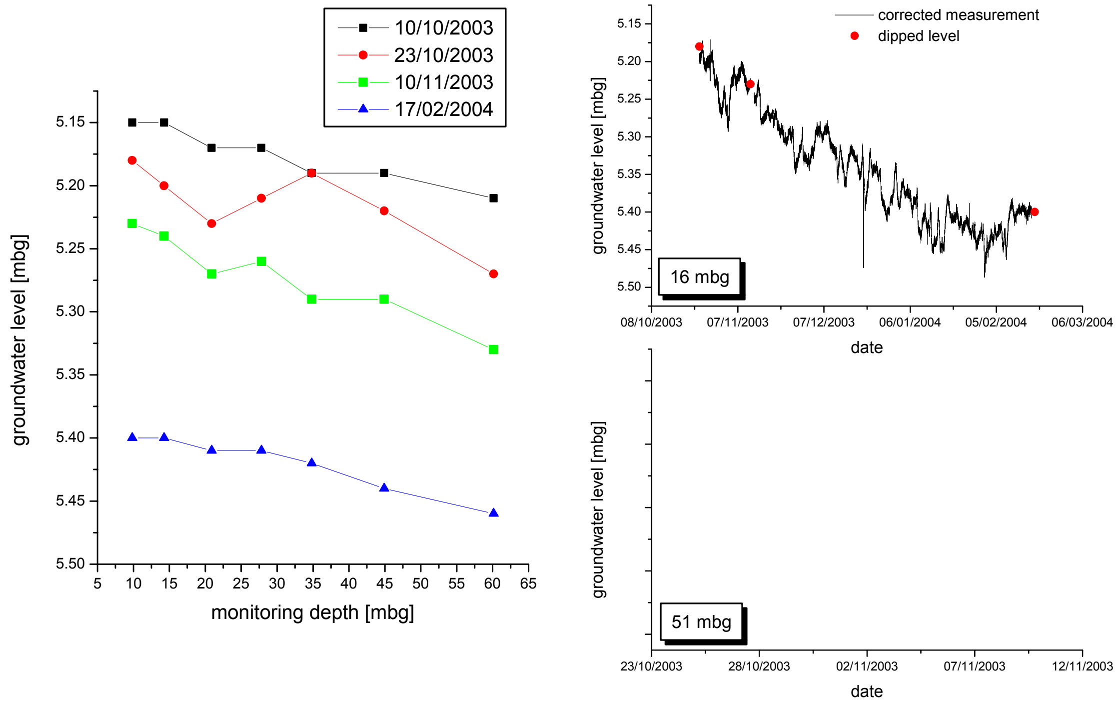


Figure 18 Groundwater levels measured in Haslam Park 1 multilevel. Left hand plot shows manually dipped levels. Right hand plots show the logged water levels after correction for air pressure (black line) and the manually dipped water levels (red circles) for the depth intervals of 16 mbgl. (51mbgl not monitored).

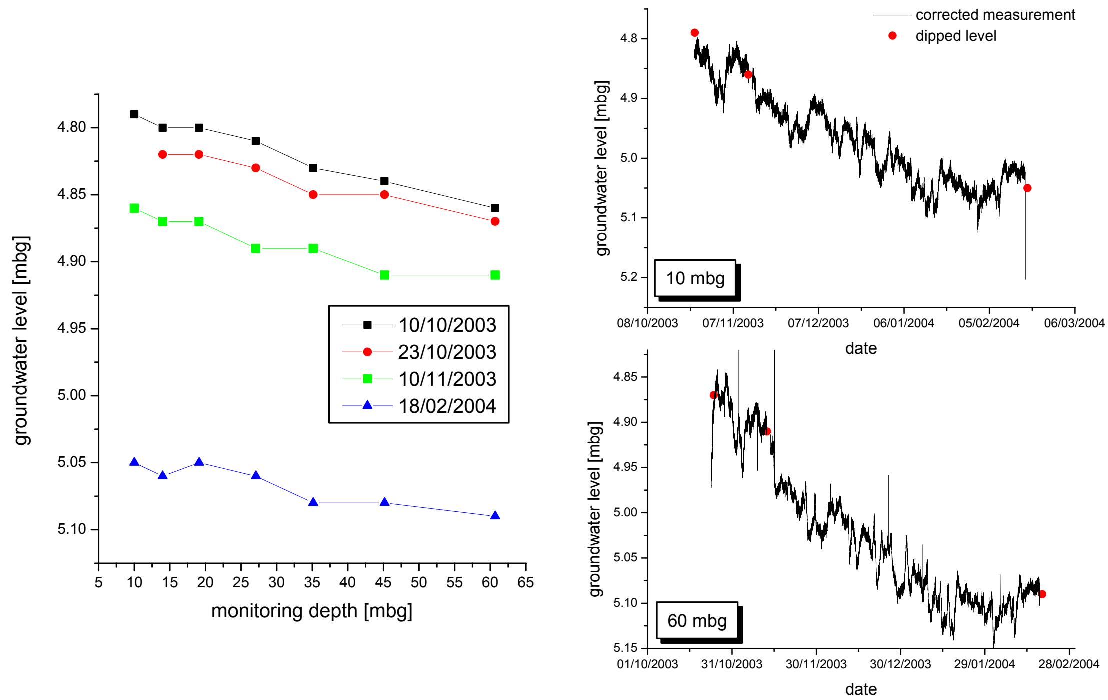


Figure 19 Groundwater levels measured in Haslam Park 2 multilevel. Left hand plot shows manually dipped levels. Right hand plots show the logged water levels after correction for air pressure (black line) and the manually dipped water levels (red circles) for the depth intervals of 16 and 60 mbgl.

4.3 CONCLUSION

Observed vertical gradients are quite small except on Bolton Hill where the intermediate depths show higher water levels. Small gradients with depth are likely to originate from the low topographic variations in this region. Ground levels are within a few metres above sea level dipping from west to east. The simultaneous visible water level changes of shallow and deep levels could originate from a lack of spatially extended confining layers in the aquifer (e.g. clay bands) and high vertical conductivities but it also could be a consequence of improper sealing between the monitoring levels. The latter will be tested with artificial tracers after the water quality sampling program is finished. However, the larger gradients within the Bolton Hill site seem to be a first proof of the reliability of the installed seals.

The downward vertical gradients of water levels within the wells indicate recharge conditions may be occurring in the Bessacarr area but no recharge is observed at the Sandall Beat site on the city-centre side of the study area.

The results of the monitoring loggers will be useful as inputs for the groundwater model. In general the dipped water levels coincide well with the logged levels. However, in some cases the difference is more than the precision uncertainty of ±2cm. Some of these measurements differ by more than 5cm but the overall results show that the equipment produces very accurate results showing decreasing levels in the Bessacarr area and increasing levels at Sandall Beat. More conclusive results will be obtained as the sampling records increase during the project.

5 Microbiological surveillance – a review of historical production well analyses and initial findings from first sampling rounds

5.1 INTRODUCTION

This chapter is one of several forming the interim report on the fieldwork on-going at the AISUWRS UK case study city of Doncaster. The objectives of this chapter are to:

- Set the microbiology context of this report
- Review the historical microbiological sampling from the production boreholes in Doncaster
- Explain the methodology used to sample regional wells and multilevel piezometers in Doncaster as part of the AISUWRS research
- Determine what the data shows
- Draw some conclusions

The data that form the basis of this report come from 2 sources: that collected by the UK AISUWRS team in the Doncaster area and that kindly supplied by Yorkshire Water.

5.2 INDIGENOUS MICROORGANISMS IN THE SUBSURFACE

As the AISUWRS project mainly focuses on faecal indicator bacteria and viruses, indigenous micro-organisms are dealt with to a much lesser degree, though there are some results discussed in Section 5.3 and further analyses planned as part of the AISUWRS field work. This section is to explain the importance of indigenous micro-organisms and to explain why they are so difficult to quantify and identify.

Up to relatively recent times the importance of micro-organisms in the deep subsurface was not recognised, though since the 1980s microbial ecologists have been reporting that micro-organisms do indeed exist in deeper groundwaters and perform significant functions in altering the chemistry of the groundwater (Cullimore 1992). Bacterial counts in several deep groundwaters gave results around 105 cfu/100ml though values may be much higher than this as (crucially) many such bacteria are unculturable (West et al. 1998). This makes it very difficult to easily and economically quantify indigenous micro-organisms. Positive identification of species is equally frustrated by the wide diversity of the micro-organisms, even between wells. It is also very possible that many species are presently unknown.

Bacterial populations may vary with different strata in the subsurface with higher numbers and activity in sandy transmissive aquifer sediments as opposed to those with a high clay content and low transmissivity (Thomas and Ward 1992). Indigenous eukaryotic micro-organisms in aquifers (protists comprising groups such as algae, protozoans and lower fungi) have been reviewed by (Navario et al. 1997). Microbial studies of groundwater to 50m depth have shown viable bacteria, algae, fungi and protozoa with bacteria dominating at depths below 150m (Ehrlich 1998). Micro-organisms have been found unequivocally to depths of 500 to 600m (Thomas and Ward 1992). Indigenous micro-organisms are important in that they may be able to provide a better insight into how faecal contamination and introduced microbial tracers behave with availability of binding sites, predation etc.

Microbes indigenous to the subsurface are able to exist in very harsh environments (Table 2) and it seems that provided there is liquid water, a source of energy and basic nutrients, microbial colonisation of the environment will eventually occur.

Table 2 Microbe groups with the ability to survive under extreme environmental conditions (Cullimore 1992).

Microbe	Extreme Environment
acidophiles	Growth 0 to 5 pH
alkalophiles	Growth 8.5 to 11.5 pH
psychrophiles	Growth range <10 to +15°C
thermophiles	Growth range +45 to +250°C
aerobes	Oxygen concentrations from 0.02ppm to saturated
anaerobes	No O_2 required
barotolerant	Hydrostatic pressures of 400 to 1,100 atmospheres
halophiles	Growth in 2.8 to 6.2 M NaCl

Dissolved oxygen levels in aquifers are important as they help determine microbial activity in the aquifer and also the reduction or oxidation (redox) conditions. Redox reactions are chemical reactions in which a participating element loses or gains electrons (Heim 1992). Microbial activity in the absence of light requires the presence of both electron donors and electron acceptors. The redox potential, Eh, of groundwater is a good qualitative indicator of the overall redox conditions within the aquifer (Walton 1981) and so can give information on reactions involving oxidizable material in the aquifer. Indeed, much of what is known about the distribution of microbial processes in the subsurface has been deduced from groundwater chemistry data (Chapelle 2000).

Thus, redox reactions are generally determined in groundwater by the oxygen content of recharge water and its consumption by bacterially mediated decomposition of organic matter (Drever 1997). Figure 20 shows schematically that oxygenated water entering an organic-rich aquifer will be freed first of its oxygen, then its nitrate, then iron and sulphate and finally methane may appear and this is due to both chemical kinetic and microbially mediated reasons (Appelo and Postma 1993).

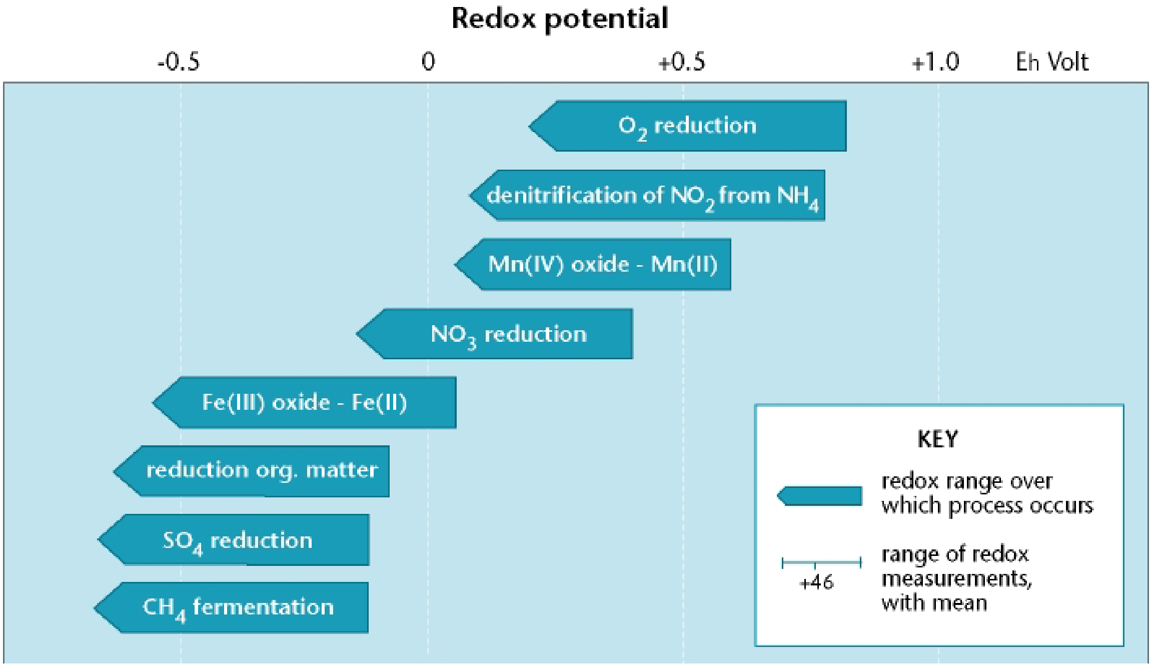


Figure 20 Sequence of microbially mediated redox processes (from Lawrence et al 1997)

British Permo-Triassic sandstones generally contain very little dissolved organic carbon (DOC), typically in the range of 0.1 to 4 mg/l of organic carbon (Edmunds et al. 1982, Tellam 1994). In general, the organic matter in sedimentary aquifers is not easily utilised by bacteria as more easily metabolised materials have already been converted. Also the elevated temperatures and pressures have converted the original organics into less suitable compounds (Drever 1997). Hence it is likely microbial activity in British aquifers will be controlled by the availability of the electron donor, i.e. carbon in organic compounds (West et al. 1998) though much more research is needed on indigenous microbial populations in UK aquifer systems.

Thus, it is clear that there are indigenous micro-organisms in the subsurface and that they act in tandem/vary with geochemical processes such as changing redox conditions. An improved understanding of the properties of indigenous micro-organisms is required to determine how they can affect faecal contamination. Very little is known about indigenous micro-organisms in British aquifers at present.

The authors plan to do some initial background tests such as Total Viable Counts (TVC) to gain a better understanding of the level of indigenous micro-organisms in the Doncaster area though rigorous characterisations will not be possible.

5.3 HISTORICAL MICROBIOLOGICAL SAMPLING FROM THE PRODUCTION BOREHOLES IN DONCASTER

Yorkshire Water (YW) operates 11 public water supply sites forming the Doncaster well field (Figure 21). Each site typically has two or more large diameter boreholes, some of which are fully penetrating. Full details are available in Table 9 of the AISUWRS inception report (Morris et al. 2003).

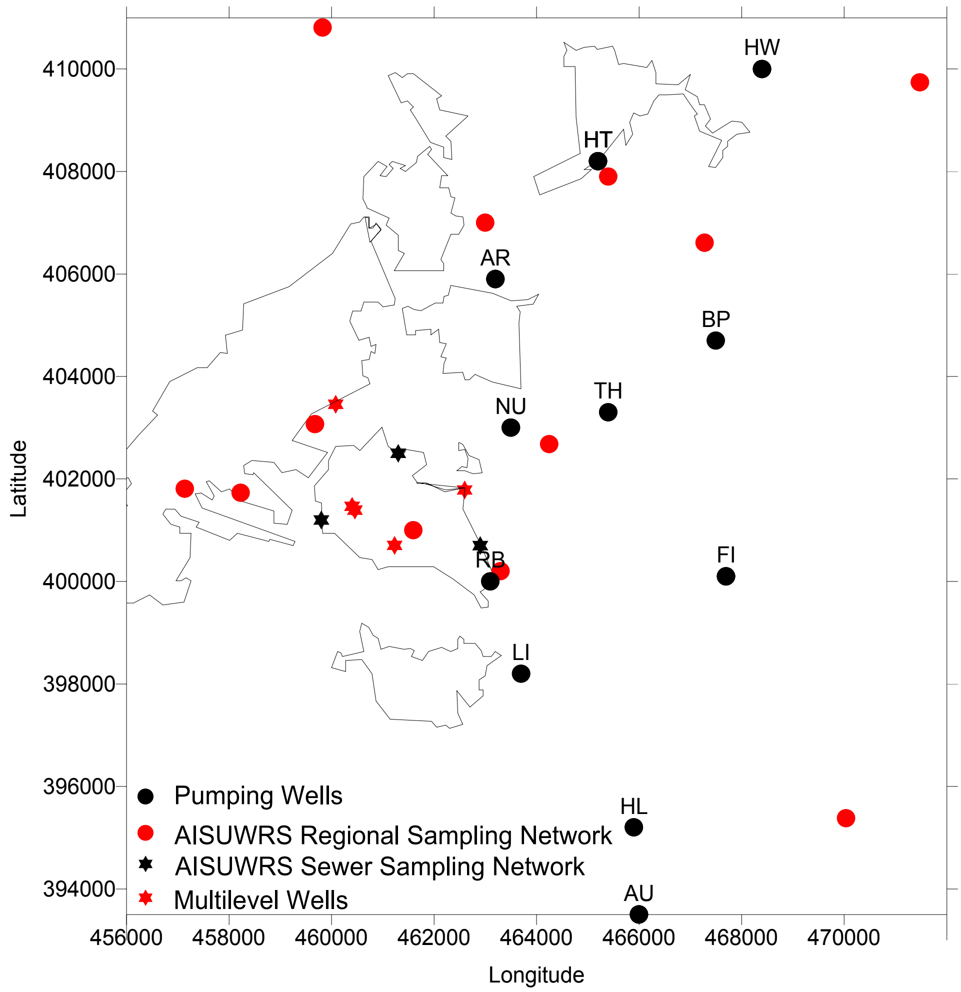


Figure 21 Locations of Yorkshire Water pumping wells, boreholes of regional sampling network, sewer sampling sites and the newly constructed multilevel wells, relative to urbanised areas of Doncaster (black lines).

The data presented in the tables below are all from Yorkshire Water's water quality monitoring records. Table 3 presents microbial parameters that were frequently measured between January 1999 and January 2004.

Table 4 presents the less frequently measured parameters from the time period April 1979 to December 2003.

Table 3 Frequently measured microbial parameters (Jan. 1999 to Jan. 2004) from 21 wells at public supply sites in the Doncaster area (AR, BP, FI, HT, HW, LI, NU, RB, TH); 1 cfu = colony forming units.

Parameters	Value reported	No. of analyses	No. of positive detects	Max. Value
Coliforms presumptive	cfu/100ml[1]	1664	3	4
Total coliforms	cfu/100ml	1703	2	4
Colonies 1 day 37°C	cfu/ml	1689	218	8150
Colonies 2 days 37°C	cfu/ml	8	1	47
Colonies 3 days 22°C	cfu/ml	1691	580	4130
E. coli	cfu/100ml	34	0	0
Faecal coliforms	cfu/100ml	1649	1	1
Turbidity	FTU	1699	208	11.7

Table 4 Less frequently measured microbial parameters (Apr. 1979 to Dec. 2003) from 23 wells at public supply sites in the Doncaster area (AR, BP, FI, HT, HW, LI, NU, RB, TH); 1 cfu = colony forming units,2 pfu = plaque forming units.

Parameters	Value reported	No. of analyses	No. of positive detects	Max. Value
Clostridium perfringens	cfu/100ml[1]	582	7	16
Cryptosporidium	no/l	5	0	0
Faecal Streptococci	cfu/100ml	569	17	10
Microtoxicity 5min	% TF	47	5	19.5
Enteroviruses	pfu/10l[2]	24	0	0
Rotavirus	pfu/10l	24	0	0

The parameters listed in these tables are explained below:

Coliforms presumptive, Total coliforms: The term "coliform bacteria" refers to a vaguely defined group of bacteria which have a long history of use in water quality assessments. Some of the bacteria included in this group are without doubt of faecal origin, whilst others are not, and may even replicate in groundwater systems. These bacteria may be analysed by simple and inexpensive techniques. These are more often used to test the quality of treated water (presence indicates treatment failure). Coliform tests are not used to detect faecal pollution but to screen the general sanitary quality of treated drinking water supplies.

Colonies 1 day 37°C, Colonies 2 days 37°C, Colonies 3 days 22°C: Also known as Total Viable Counts (TVCs) and Heterotrophic Plate Counts, these aim to grow all heterotrophic culturable bacteria at temperatures that reflect environmental conditions (22°C) and human body temperature (37°C). This can give an indication of the level of culturable indigenous micro-organisms in the water.

Faecal coliforms: Thermotolerant coliform bacteria are members of the total coliform bacteria group that grow at 44°C. They tend to be more closely related to faecal or sewage pollution, and do not generally replicate in groundwater systems. This group of bacteria are variously known as *faecal coliforms*, presumptive *E. coli* and *faecal coliforms* (pres.) because in many cases, the majority of *faecal coliforms* found in contaminated groundwaters are *E. coli* though this can vary over quite a range.

E. coli: E. coli is a member of the group of faecal coliform bacteria. It has the important feature of being highly specific to the faeces of humans and other warm-blooded animals. Generally these bacteria cannot multiply in any natural water environment and they are therefore used as specific indicators of faecal contamination. They are generally distinguished from other *thermotolerant coliforms* by the ability to yield a positive indole test within 24 hours at 44.5°C. Now it is more common to use enzyme specific reactions to identify *E. coli*.

Turbidity: An optical property of a water sample causing incident light to be scattered and absorbed - not transmitted. Hence it is an indirect measure of the total suspended, colloidal, and particulate matter in water. Though not a microbiological parameter, it is linked here as increases in turbidity decrease disinfection efficiency.

Clostridium perfringens: Sulphite–reducing clostridia are anaerobic, spore forming, non-motile gram-positive rods of exclusively faecal origin. The spore nature of this organisms means it can survive much longer in water than either coliforms or streptococci, possibly even for years.

Cryptosporidium: *Cryptosporidium spp.* are coccidian protozoan parasites belonging to the Phylum Apicomplexa. It has been recognised as a significant cause of gastro-intestinal disease in humans, particularly in children and the immuno-compromised and has been known to cause large waterborne illness outbreaks from contaminated groundwater supplies.

Faecal Streptococci: Are a group of gram-positive cocci, are non-sporating and non-motile. They belong to the genera Enterococcus and Streptococcus. They have been found to be useful faecal indicators in that they rarely multiply in temperate climate groundwaters, are more resistant to environmental stress and chlorination than coliforms and generally persist longer than coliforms in the environment.

Microtoxicity 5min: This is an alternative test to the use of fish for toxicity assessment. This test uses light-emitting bacteria. The luminescence of the bacteria makes it easy to measure the change in the bacterial population and hence get an indication of the level of pollutant in the sample.

Enteroviruses: Echovirus is a pathogenic virus with associated health effects of fever, respiratory disease, aseptic meningitis and rash. Coxsackie is a pathogenic virus with associated health effects of fever, pharyngitis, rash, respiratory disease, diarrhoea, hemorrhagic fever, conjunctivitis, myocarditis, pericarditis, aseptic meningitis, encephalitis, reactive insulin-dependent diabetes and foot and mouth disease. Both are of concern in groundwater.

Rotavirus: *Rotavirus* is a pathogenic virus of concern in groundwater. Associated health effects include gastro-enteritis (fever, vomiting, diarrhoea). It is the most common cause of infantile gastroenteritis causing high child mortality.

5.4 AISUWRS RESEARCH SAMPLING OF THE REGIONAL WELLS AND MULTILEVELS IN DONCASTER

Samples were collected for bacteriological indicators of sewage contamination as part of the AISUWRS fieldwork in Doncaster to better understand how these contaminants vary in the different points of the urban water cycle (Figure 21). Groundwater quality assessment is a top priority in the UK case study site as this is the resource under threat and the object of protection by the AISUWRS effort. In addition, as groundwater is the main water supply source for Doncaster, serious deterioration in groundwater quality will have major implications for potable water supply in the area. Samples were collected in the following sequence:

Summer 2003	12 regional wells
	3 sewer locations

November 2003	11 regional wells
	3 sewer locations
	33 multilevel piezometer depth intervals (in 5 different holes)
	2 shallow piezometers in the unsaturated zone

Prior to sampling, in order to sample groundwater representative of the aquifer, each multilevel piezometer was purged of a minimum of 3 well volumes of water and until physical parameters (redox potential, pH, electrical conductivity) stabilised. Purging and sampling of groundwater from each piezometer were achieved using a peristaltic pump (Watson Marlow 603S) with a 13mm or 16mm (OD) HDPE rising main. Each multilevel interval has a dedicated rising main that was emplaced during the development and disinfection of each interval, approximately 5 weeks after drilling. Each dedicated rising main is never removed so as to ensure no contact whatsoever with any possible faecal contamination at the surface.

Analysis of thermotolerant coliforms (TTC) in groundwater samples was conducted in the field using membrane filtration and enumerated by culture on membrane lauryl sulphate broth (Anon. 1982). In addition samples for total colifoms, *E. Coli* and *Faecal streptococci* (FS) were collected in sterile polystyrene containers and placed immediately in a refrigerator (powered by a generator in the field). The samples were kept at 4ºC until laboratory analysis less than 24 hours later at a local UKAS accredited laboratory. 100ml samples were analysed for total colifoms and *E. Coli* by isolation using membrane filtration and, as for the field method, enumerated by culture on membrane lauryl sulphate broth. Samples for sulphite-reducing clostridia (SRC) were also taken for later analysis at the Robens Centre for Public and Environmental Health. FS and SRC were isolated from 100ml sample volumes, again using membrane filtration, and selectively enumerated by culture on Slanetz and Bartley agar (FS) and perfringens agar (SRC) respectively (Anon 1994).

Enteroviruses (from 10l samples) were analysed using plaque assay and RT-PCR methods at the Health Protection Agency, Reading. Subsequent sampling will concentrate the 10l groundwater samples in the field using a glass wool trap (Powell et al. 2000, Powell et al. 2003). Enumeration of coliphage from the eluate can be determined by assay of 1ml of sample using a double agar layer technique (Adams 1959).

Certain multilevel depth intervals show interesting depth profiles. Figure 22 shows the contamination profile with depth of one of the multilevel intervals in Haslam Park. The shallow level here shows positive detects of all indicator bacteria but contamination is present at depth also. Continued temporal monitoring is necessary to see how such profiles change with time and how the indicator species values vary. If such profiles as shown in Figure 22 are found to be common throughout the sampling then explaining how such contamination penetrates to depths of several tens of metres will be an important aspect of the AISUWRS work.

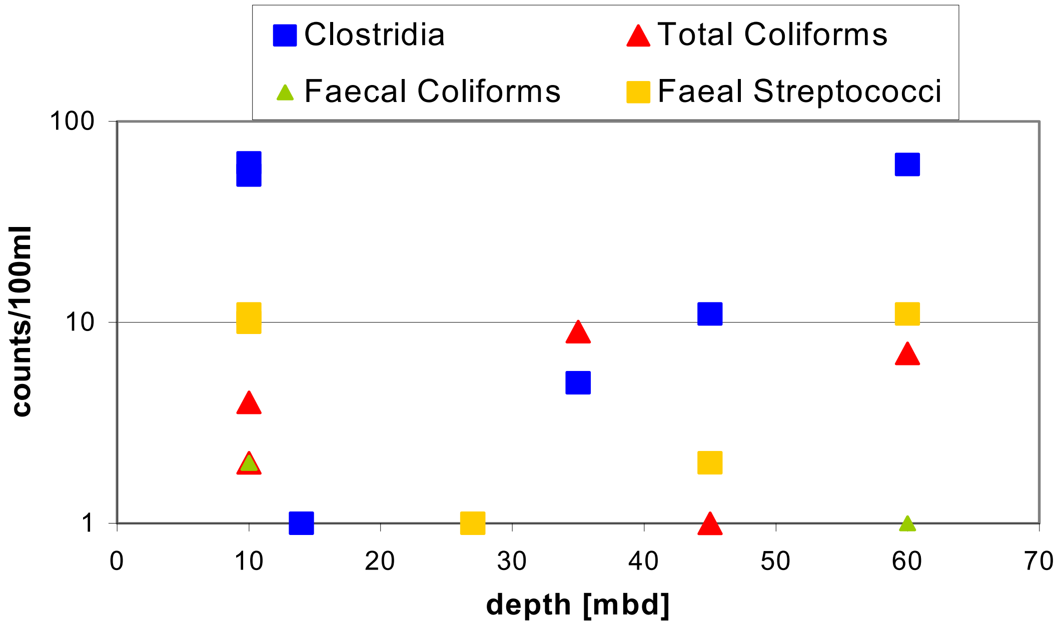


Figure 22 Haslam Park 2 Faecal indicator results, November 2003.

Table 5 Summary of results to date from AISUWRS sampling in Doncaster for microbial indicators of faecal contamination.

	Field TTC assessment	Total Coliforms	E. Coli	Faecal Streptococci	SRC	Coliphage	Entero-virus
	cfu/100ml	cfu/100ml	cfu/100ml	cfu/100ml	cfu/100ml	cfu/ml	PFU
Regional Wells: June 2003							
no. analyses*	10	10	10	10	10	10	3
no. positive detects	2	3	1	4	7	2	0
Max. value	2	19**	1	3	7**	9	0
Sewers: June 2003							
no. analyses	3	3	3	3	3	3	3
no. positive detects	3	3	3	3	3	3	3
Max. value	$3.73 \cdot 10^6$	$2.50 \cdot 10^8$	$6.10 \cdot 10^7$	$5.00 \cdot 10^6$	$2.3 \cdot 10^6$	736	26/10ml
Regional Wells: November 2003							
no. analyses*	11	11	11	11	11	11	0
no. positive detects	0	2	1	3	6	0	-
Max. value	0	18	2	11	8	0	-
Sewers: November 2003							
no. analyses*	3	3	3	3	3	3	2
Sewers - no. positive detects	3	3	3	3	3	3	2
Sewers - Max. value	$6.00 \cdot 10^6$	$7.00 \cdot 10^6$	$4.00 \cdot 10^6$	$7.00 \cdot 10^6$	>30000	>1000	5/10ml
Multilevel Intervals: November 2003							
no. analyses*	33	33	33	33	33	33	11
no. positive detects	13	8	4	13	17	0	1
Max. value	19	200	2	600	120	0	2/10L
Shallow Piezometers: November 2003							
no. analyses*	2	2	2	2	2	2	0
no. positive detects	0	1	0	2	2	0	-
Max. value	0	6	0	22	53	0	-

* Blanks and replicates not included in the summary here

** The shallow well in the Allotments area was not included in this figure as there was obviously gross contamination affecting some results

5.5 WHAT ARE THE DATA SHOWING?

The Yorkshire Water sampling results (Table 3 and Table 4) show large numbers of analyses undertaken with few positive detects. Many of the infrequently monitored parameters (Table 4) have low positive detect rates but this is less surprising as, for example, the virus sampling work has only been carried out 24 times. What is somewhat surprising are the very low positive detection rates in the frequently monitored parameters (Table 3). Total coliforms, normally heavily influenced by environmental organisms and not necessarily of faecal origin, shows only 2 positive detects out of >1700 analyses undertaken between January 1999 and January 2004. Colonies grown at 22°C for 3 days show approximately a 1 in 3 positive detect rate, very low for such an analysis that will allow a plethora of culturable organisms to grow. The method of sampling employed by YW and the locations of where the samples are taken at each well site are currently being followed up.

In contrast to the YW data, the AISUWRS fieldwork in regional wells and multilevel piezometers has shown much higher positive detection rates. The sampling shows higher numbers of positive detects and counts during the November 2003 sampling than the Summer 2003 sampling and these temporal trends will become more apparent as the sampling work continues during 2004. Coliphage sampling has yielded only 2 positive results for the regional and multilevel sampling to date though the longer-lived SRC spores have been found frequently. Similarly the longer lasting Streptococci are being detected more frequently than the *E. coli* (or thermotolerant coliforms). This may reflect on the relative frequency and survival times of these indicators in urban sandstone settings but this is still a very tentative suggestion. In general, the field assessment of TTC and the laboratory analysis of *E. coli* match well and is a useful cross check on the methods. Figure 22 shows that the multilevel piezometers are giving interesting depth profiles of contamination. It is too early to speculate on exact magnitudes and mechanisms that are giving rise to such profiles but it is significant to note that indicators of faecal contamination are being detected at depths of over 50m, as was found with monitoring under the urban areas of Birmingham and Nottingham (Cronin et al. 2003, Powell et al. 2003). Not all multilevel depth intervals showed such trends and only 1 positive detect for enterovius was found. Further monitoring is required to assess how these trends change with time. Sewer-borne wastewater sampling was also undertaken and has confirmed high bacterial loads (~10^6 TTC cfu/100ml) though more dilute viral loads (~10^2 pfu/100ml).

Although the data are preliminary, the results show an interesting picture to date. Further data need to be gathered over the coming months in order to

- Assess the extent and depth of penetration of faecal indicators in the study area
- Better understand the aquifer processes that are producing the observed results
- Assess to what extent and how the urban water cycle is influencing observed trends
- Populate the AISUWRS model suite with the measured data
- Assess how this mass balance approach and the other AISUWRS models mirror what is being observed in the field.

5.6 CONCLUSIONS

- Indigenous microorganisms play an important role in British Permo-Triassic aquifers and research on their occurrence and distribution is being incorporated in the AISUWRS field programme.
- Historical surveillance records of microbial groundwater quality show a low positive detection rate though this may be due to sampling location. However, more investigation of these results is needed.
- Data from the first sampling round in Doncaster (November 2003) show interesting depth profiles for indicator organisms at certain depth intervals of the dedicated multilevel

piezometers. Regional well sampling showed low numbers of positive detects. Sewer sampling revealed bacterial loads in the order of ~10^6 TTC cfu/100ml and viral loads in the order of ~10^2 pfu/100ml.

- Sampling in Doncaster of the multilevel piezometers, regional wells, shallow unsaturated zone piezometers, sewer and stormwater sampling points will continue during February, May and August 2004.
- These data will inform the microbiological transport modelling in the UVQ and the downstream AISUWRS contaminant transport models.
- A better understanding of the urban water cycle in this environment is anticipated.

6 Hydrochemical data collection and monitoring

This topic is covered comprehensively in a separate appended BGS report (Appendix 2). This section therefore contains only a précis of the extensive range of tasks undertaken so far.

6.1 DATA COLLECTION AND COLLATION

Existing water quality data were collected from information provided by Yorkshire Water, the Environment Agency, the UK Acid Deposition Monitoring Network (public domain data) and from an independent BGS-collected dataset. The YW datasets provided results of analyses from both the 11 Doncaster wellfield pumping stations and a combined/treated water from the water treatment works supplying Bessacarr-Cantley.

Collation and interpretation of existing data has been supplemented by a major field monitoring programme with three sampling components;

(i) a network of 11 private boreholes in the vicinity of Doncaster, chosen to provide samples from the upper and middle aquifer

(ii) raw sewage at 3 sewer access manholes at key exit locations from Bessacarr-Cantley

(iii) the five multilevel research boreholes and two shallow piezometers drilled and constructed in September/October 2003 as part of the planned fieldwork.

Monitoring sites, key YW pumping stations and EA water quality sites are shown on Figure 23.

6.2 MONITORING PROGRAMME STRATEGY

A quarterly sampling programme was started during the summer of 2003. By February 2004, three sampling visits had been completed for the private boreholes and wastewaters and two for the multilevels. The analytical results arising from these visits will be supplemented with those from a further two quarterly visits in late spring and summer 2004. With the public water supply analyses referred to above and a small dataset recently identified for atmospheric inputs, these data will together form the basis for the characterisation of the aquifer and urban water system for UVQ and the subsequent solute transport models.

The field sampling strategy for microbiological parameters is described in Section 5 of this report. For the hydrochemical programme, available resources and the cost of analysis dictated a staged approach (Table 6).

Table 6 Determinands and analytical methods; AISUWRS field sampling programme

Characterisation group	Determinand	Method	Suite	Under way?
Field hydrochemical:	pH, temp, Eh, DO_2, SEC	Field meters in in-line cell	A	✓
	HCO_3	Field alkalinity titration		✓
Major and minor constituents; laboratory determinations;	Na, K, Ca, Mg, SO_4, Si, Al, B, Ba, Be, Cd, Co, Cr, Cu, Fe_{total}, La, Li, Mn, Ni, Mo, Pb, P_{total}, Sc, Sr, V, Y, Zn, Zr, (As, Se)	ICP-AES	A	✓
	Cl, TON, NO_3-N, NO_2-N, NH_4-N	Skalar Autom. colorimetry	A	✓
	DOC	Carbon analyser	B	✖
Stable isotopes and residence time indicators	$\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$ in waters	Mass spectrometry	B	✖
	CFCs	GC	B	✖
	SF_6	GC	B	✖
Indicator organics	Phenols, BTEX,PAH, Chlorinated VOCs MTBE	Chromatography	C	optional

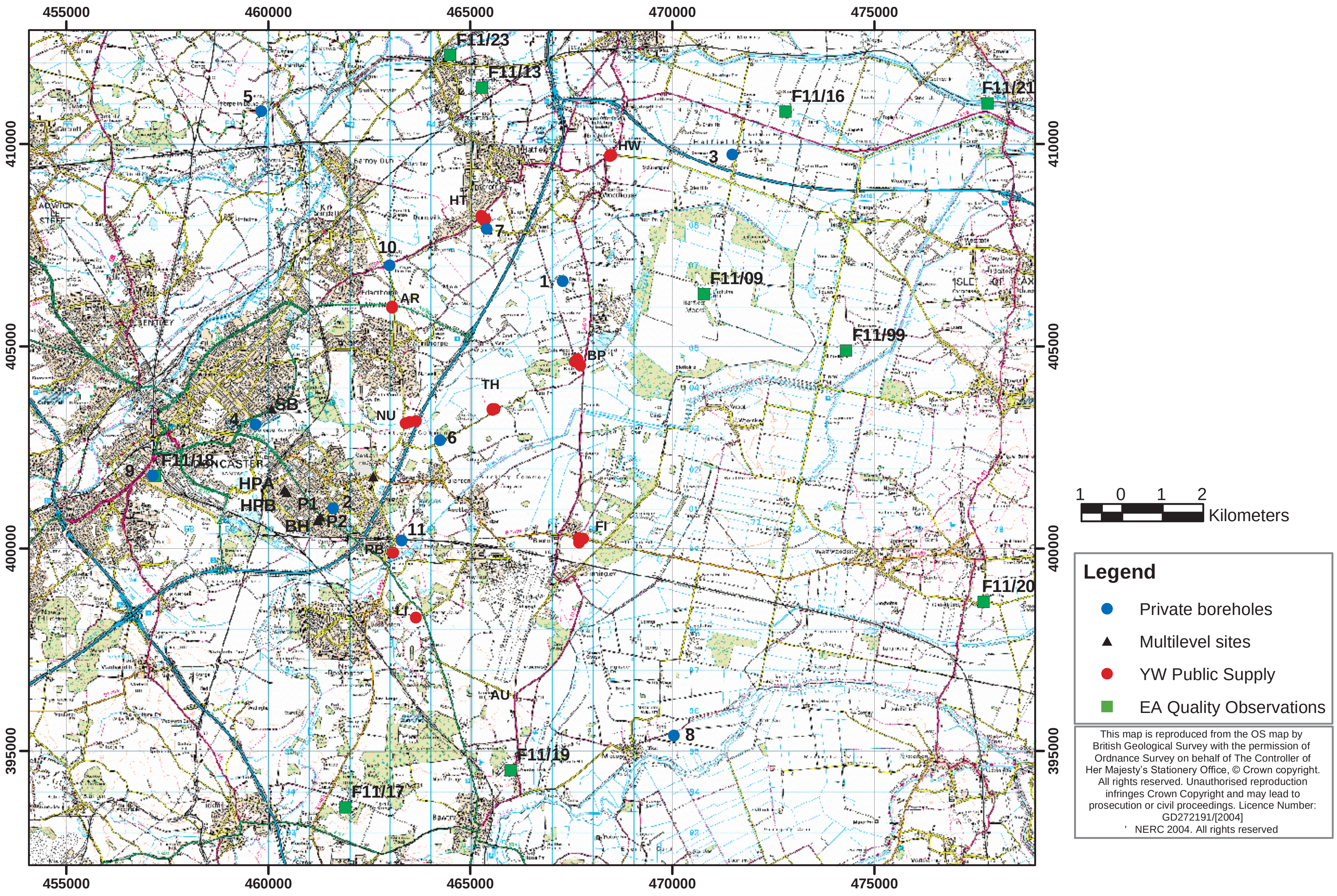


Figure 23 Locations of public supply boreholes, EA groundwater quality monitoring network, private boreholes sampled and multi-level sites

For the five quarterly sampling visits scheduled for WP4, all the analytes in Suite A will be determined. A single sampling of Suite B stable isotopes and residence time indicators is scheduled to take place as part of one of the remaining quarterly site visits. Suite C analyses are optional and relatively high cost. They may be undertaken on a selected subset of sites if remaining funds permit, or the balance of budget used for better characterisation of inorganic indicators.

6.3 DATA ANALYSIS AND INTERPRETATION

This has been undertaken in order to:

(i) characterise the water quality of the aquifer system as recharge receptor

(ii) quantify the water quality of important components of the urban water balance (rainfall, mains supply, wastewater)

(iii) develop a conceptual model of how flow and solute load evolve in the case study's urban area and its surroundings; this model will then inform the method of applying the various solute transport models to the case study area

Appendix 2 details this work, from which the two figures below are drawn for illustrative purposes. Figure 24 shows the urban groundwater quality conceptual model and Figure 25 key results of urban recharge indicators from the YW pumping stations and the monitoring network, used to assess the usefulness of the selected indicator species.

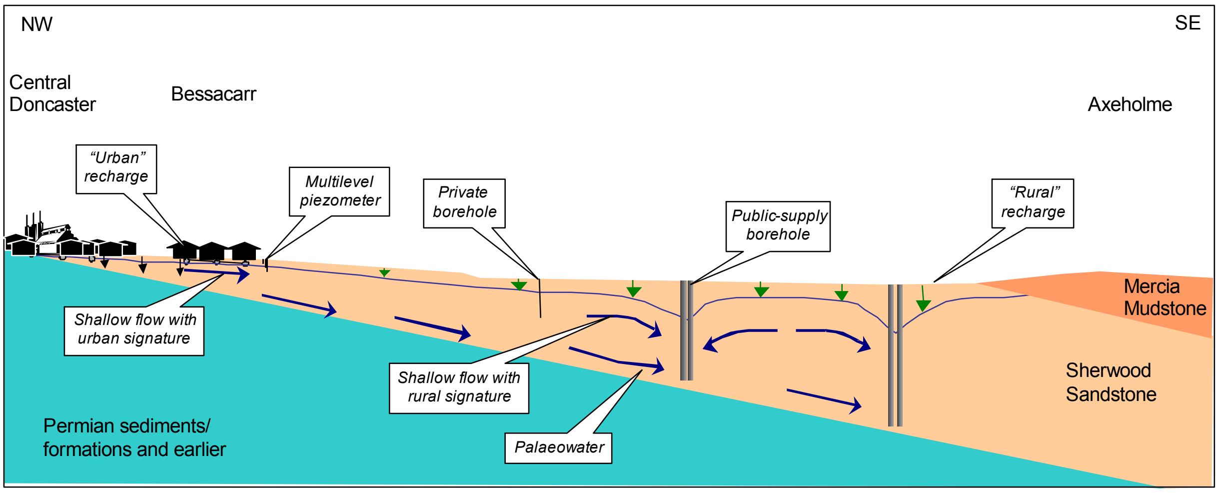


Figure 24 Schematic illustrating the main features of the conceptual model describing groundwater quality influences in the Doncaster aquifer

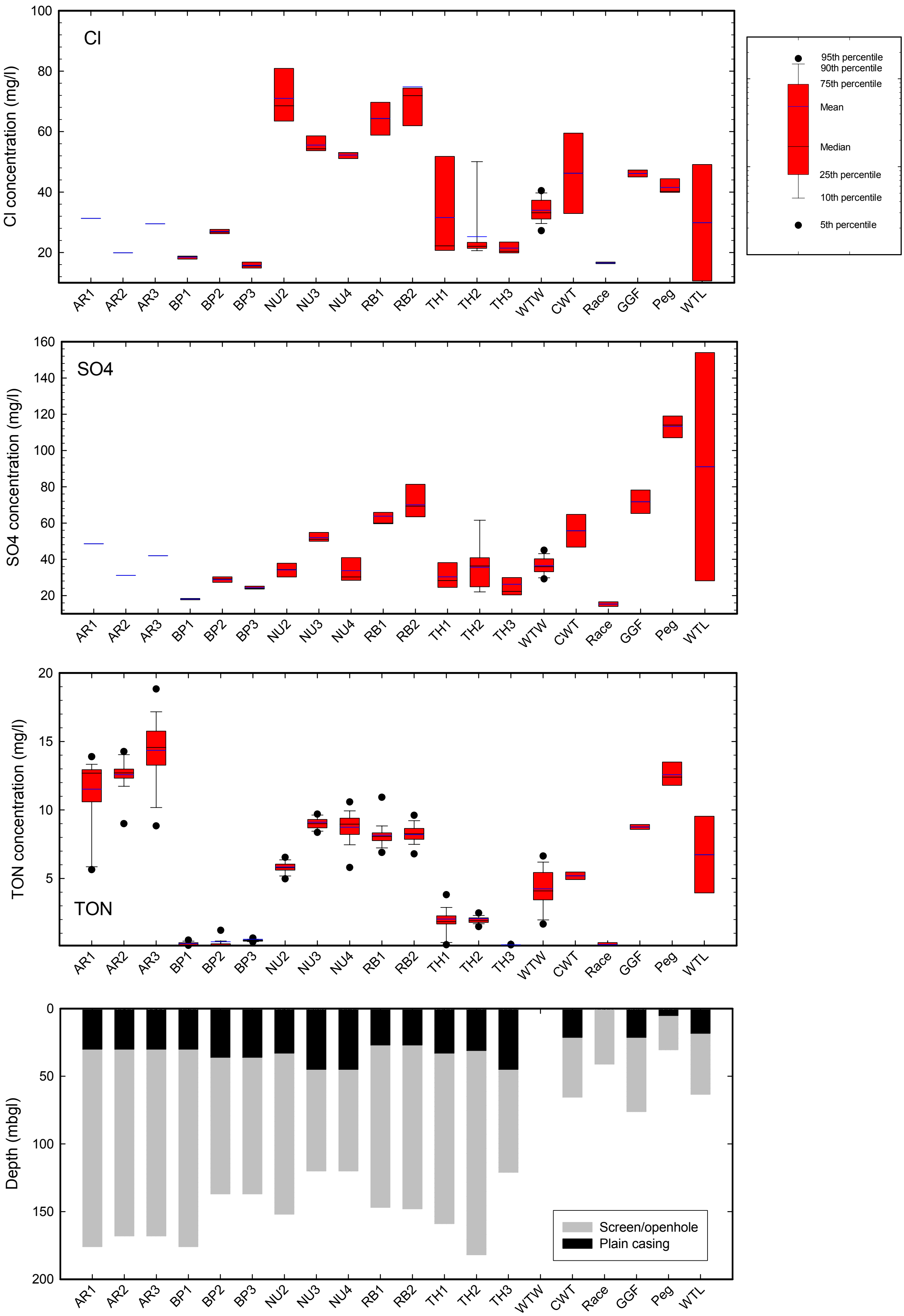


Figure 25 Comparison of key major constituents TON, SO4 and Cl for public supply and private boreholes in the general vicinity of Bessacarr-Cantley

While an understanding of the groundwater characteristics is emerging from the work so far, in this part of the Nottinghamshire-South Yorkshire Triassic sandstone outcrop, recharge processes are complicated by the presence of variable Quaternary superficial deposits, which appear to control both ease of recharge and hydrochemical characteristics of the resulting shallow groundwater.

The data suggest that this complexity manifests itself in a degree of lateral variability in water quality at least as great as that occurring with depth. The implication is that the degree to which the contaminant load arising from different land use activities will affect the underlying saturated aquifer will depend on local recharge conditions at least as much as the magnitude of the loading itself.

At this interim stage of the field programme, the study has succeeded in producing an initial hydrochemical characterisation of the principal constituents of the groundwater circulating in the mains water supply to the study focus area, the wastewater in its sewer system, precipitation, the underlying and surrounding shallow aquifer and the deeper aquifer (Table 7).

Assessment of the originally selected urban recharge indicators of chloride, sulphate, boron and zinc has shown that these are likely to be only partially successful in Doncaster, for the following reasons:

- the wastewater effluent load appears to be dilute
- pollution from other human activities (agriculture, mining) is present within the same catchments, generating similar contaminant types and loadings
- important relatively persistent contaminants found in urban wastewater such as sulphate also occur naturally in the aquifer to a varying extent.

Further work will be needed to unravel this complex system sufficiently to inform the urban water models that are being developed, linked and operated as the principal task of the AISUWRS project.

6.4 CONCLUSIONS FROM THE WORK SO FAR (REPRODUCED FROM APPENDIX 2)

The main conclusions and recommendations from this phase of the programme are:

(i) A developing programme of local groundwater monitoring has complemented an array of water quality data mainly derived from operational public water supply boreholes in the Doncaster wellfield operated by the project stakeholder Yorkshire Water.

(ii) This monitoring array includes a set of local private supplies chosen to try to characterise the shallow Sherwood Sandstone east of Doncaster, and a local array for the focus area of the study (Bessacarr-Cantley district) comprising multilevel research boreholes and wastewater sampling sites.

(iii) Data from the public supply boreholes and from the monitoring network have been evaluated in order to develop and then validate a conceptual model of the flow system and its likely effect on groundwater quality in the urban and periurban area.

(iv) This conceptual model recognises that the Sherwood Sandstone east of Doncaster, as an intensively exploited unconfined aquifer with urban, rural, industrial, agricultural and mining activities at the land surface, is a complex system. The presence of variable Quaternary superficial deposits across the aquifer outcrop/subcrop adds to this complexity.

(v) Initial interpretation suggests that there is significant variability both laterally across the aquifer system and with depth. No spatial pattern to the variability indicated by the datasets has yet been discerned.

Table 7 Ranges and mean concentrations of potential urban recharge indicators

Indicator	Concentration												
	Groundwater								Inputs			Urban outputs	
	PS boreholes vicinity of study area		Private boreholes		ML Piezometers & P1, P2 (0-30 mbgl)		ML Piezometers (30-60 mbgl)		Precip-itation	WTW Supplied water**		Waste water	
	Mean•	Range	Mean*	Range*	Mean	Range	Mean	Range	Mean	Mean	Range	Mean	Range
Chloride (mg/l)	39	15-85	50	17-112	44	10-184	40	12-113	2.1	34	26-41	72	60-85
Sulphate (mg/l)	39	18-97	128	15-323	84	37-153	84	11-165	2.8	36	27-46	90	80-100
Boron (µg/l)	-	<50-50	-	<80-150	-	<80-140	-	<80-100	-	-	-	500	400-600
Ortho-phosphate[§] (µg/l)	14[‡]	5-130[‡]	-	100-500	-	300-600	-	300-600	-	620	<63-950	31000	28000-33000
Zinc (µg/l)	-	<6-230	66	10-320	10	6-16	7	4-16	-	-	-	81	69-99
Potassium (mg/l)	2.6	1.9-2.9	7.8	1.4-32	5.8	1.7-16.2	3.2	1.3-7	0.08	2.7	2.3-2.9	20.2	17-25

The mean is not shown where the majority of the analyses are below the limit of detection

* Excluding Sandall Common Farm (local point source pollution from mine drainage suspected)

** Blended water supplied to study area from Nutwell water treatment works; mix of AR, BP, NU, TH,

• For illustrative purposes only, averages of individual well means were used for this complex dataset

§ BGS data for total P assumed to be PO_4

‡ Data period 4/1979-4/1990 inclusive; no later analyses available

(vi) Initial wastewater sampling results indicate that while sewered waters have higher concentrations of major ion constituents than groundwaters in the same general area, the difference is not conspicuous, and the resulting effluent would be regarded as dilute in comparison with the groundwater receptor.

(vii) These relatively small differences, for instance in chloride and sulphate indicator concentrations between wastewaters and the parent groundwater forming the supply to the study area will constrain their interpretative use in mass balance calculations later in the project.

(viii) Consideration of the analytical results from the monitoring network indicate that a mid-term review of the monitoring strategy is required in order to concentrate effort on understanding processes in the Triassic aquifer in the immediate neighbourhood of the study area. This would imply some revision of the sampling programme, a closer focus on the 5 YW pumping stations either supplying the study area or located in its vicinity, and further inspection of data to assess whether an additional recharge indicator such as potassium, dissolved organic carbon or dissolved organic nitrogen can be identified to replace one or other from the present selection.

(ix) The current minimum detection limits for boron do not permit discrimination of small variations in concentrations below 100µg/l; analysis by ICP-MS needs to be considered if B is to continue to be viewed as an urban recharge indicator.

(x) Work continues to determine whether different elements of the flow system can be characterised by their chemical compositions, thereby allowing shallow recharge beneath the city to be characterised chemically.

6.5 IMPLICATIONS OF RESULTS FOR THE SECOND HALF OF THE WP4 FIELD PROGRAMME

Available data is still being collected as an ongoing field programme task. This was unanticipated in original pre-project planning but is an inevitable outcome of the model parameter prioritisation process described in Section 7.1 Their analysis, together with the initial results of the monitoring programme to date are helping the efficient planning of remaining field activities for this work package. Conclusions already reached that will be actioned during the second half of the field programme include:

(i) Further interpretation of public supply water quality data provided by YW will focus on five pumping stations (AR, BP, NU, RB, TH), four of which, under normal operations, supply Bessacarr-Cantley and one of which is immediately downstream of the study area. A better understanding of the recently acquired combined supply analyses from these wells to the study area is also needed

(ii) The private borehole array selected at the beginning of the field programme to characterise shallow groundwater in the Sherwood Sandstone needs to be rationalised to exclude sites whose water chemistry may be affected by local circumstances not relevant to this project.

(iii) The multilevels appear to be performing well and are providing evidence of depth stratification; the full sampling programme should be continued, to including analytical suite B when appropriate

(iv) The wastewater sampling programme is also proving very informative, and if the opportunity presents itself e.g. during a flow monitoring exercise, sampling should be extended. Although their transience makes the exercise opportunistic, if possible, further stormwater events should be sampled in order to better characterise this part of the urban water system

(v) The performance of the chosen suite of urban recharge indicators is mixed and further data inspection should be made to try to identify an additional parameter that can be assessed within the resources available to this project.

In the continued absence of an AISUWRS-wide data management system, BGS needs to establish a water quality subsidiary database so that the data from the diverse sources referred to above can be interpreted in a holistic way. This will help reinforce confidence in the conceptual model, which is still evolving.

7 Support to components of urban water model array including GIS analysis and interpretation

7.1 MODELLING PARAMETERS APPRAISAL EXERCISE

At the first project coordination meeting held in April 2003 at the University of Karlsruhe, the project partners agreed to collectively produce a single collated list of modelling parameters for the 6 model components of the urban water model array. This action was concerted by IRGO and the resultant list produced as a 6-worksheet Excel spreadsheet in May 2003. This list revealed for the first time the very large number of parameters that would need to be manipulated, both within each model and between the various model components as outputs from one model cascaded down to the next model in the array. Table 8 summarises the distribution between models of the ca.320 input fields as of 30th of September 2003. At that time, the UFM and UTM models were still awaiting development so the entries for these models were estimated; the total number of fields is likely to increase once these models are fully developed.

Table 8 Provisional distribution of input parameters in the urban water model array, Sept 2003

Model name	Short name	No of input fields	% total no. of input fields
Urban volume and quality	UVQ	116	36
Pipeline leakage	PLM	58	18
Unsaturated zone flow model	UFM	20*	6
Unsaturated zone transport model	UTM	8*	3
Saturated zone flow model	SFM	53	17
Saturated zone transport model	STM	63	20
	Totals	318	100%

* *Estimated*

This exercise prompted a reappraisal of the data collection exercise of the WP1 background study, the conclusions from which were:

- There were many input fields for which data needed to be collected but which the field study team was unaware of at the time of the WP1 background study
- This was principally the case in the four models upstream from the SFM and STM that lie outside the UK team's professional area of expertise but which together comprise almost two-thirds of all data requirements.
- A significant further effort was required to populate these input fields that, although an unanticipated additional task, should comprise part of the field investigation phase of WP4 in view of its importance in providing realistic case-study conditions for the testing of the models as a linked array.
- It was accepted, however, that a number of fields could not practicably be populated with case-study specific values within the scope of project resources and likely stakeholder collaboration, so default approximations would need to be employed.
- A clearer classification of the input fields was required to help identify key parameters that data collection and interpretation effort needed to concentrate upon.

As a result, the project team expanded the modeling parameter listings with additional columns to help indicate the importance/sensitivity of the particular field. Data input fields for each model were assessed in three ways:

1. *Data criticality classification*; a simple system assigned in consultation with the model development teams with the intention of helping field study teams to prioritise key parameters for data collection and to identify where the data collection to date was most deficient. Two classes were used:

High; a key parameter which needs city case-study-specific value; the validity or confidence in the resultant model would be compromised without a value for such a parameter

Low; a parameter of secondary importance; it would be useful to have case-study specific value, but generic, assumed or approximate value could be employed

The criticality of particular data fields in the AISUWRS model suite leads directly to the issue of sensitivity analysis of the models, both individually and once they are linked in the decision support system. At the time of this report, this important but complex issue was still under consideration by the team members tasked with the modeling work packages.

Data quality classification; a system completed by the case-study teams indicating the likely quality of the data in terms of its specificity to the study area. The ratings could vary from city to city depending on local circumstances but would tell the model originators (at an early stage) how specific the data will be from a given case-study application, and by comparing returns from all three cities, what a typical city might be able to provide. The results do not assess the relative accuracy of the data but in general, a model run with more fields populated with Class A data, is likely to be more representative of local field conditions. Three classes were used:

Class A; must have, or generate, site specific values e.g. water levels, aquifer node hydraulic conductivity, pipe material class, soil distribution/thickness. Values would be sourced from available data and additional project field studies.

Class B; site specific values unlikely to be available but reasonable approximations can be found from national, regional or company statistics e.g. sewer leakage rates, pipe failure rates, indoor water use, mains water leakage rates unaccounted-for water). Values would be drawn from available data e.g. from water utility stakeholders; field studies to generate these data likely to be beyond scope/resources of this project

Class C; neither site-specific nor local-context values likely to be available e.g. every parameter not covered by Class A or Class B. Values would be defaults comprising working approximations/experimental/empirical estimates obtained from technical literature searches, studies in analogous situations, laboratory studies, project colleagues with a firmer footing in the specialist field which is the subject of the model.

2. *Other model origin;* a column to help the case-study city modelers keep track of data as it cascades as output from one model to input to another, and also as a Quality Assurance (QA) measure. The 'Other model origin?' column would mark the source of the data if it came from another model e.g. leakage rate and x,y coordinate of pipe in the unsaturated zone flow model is supplied by output from the pipe leakage model and does not have to be independently generated for the unsaturated zone flow model

3. *Sources of information:* a column to help cross transfer of data between case-studies where city-specific information is absent or unobtainable for the very large C class in the data quality classification. It would indicate, for instance if one partner had measured field data on, say, kitchen greywater quality or another had good and comprehensive literature for a particular parameter that others might not be aware of. This could also help to produce a convergence in values for some parts of the parameter sets.

After circulating updated lists for other partner use, this exercise was completed for the Doncaster case-study, and the results are shown in Appendix 3A. An analysis of the results was also undertaken (see Table 9 and Figure 26).

Table 9 Analysis of urban water model array data input fields for Doncaster case-study

Model	Short name	Total no. input fields	% High criticality	Class A	%	Classes B & C	%	Class N/ap	%	Sub-total %
Urban volume and quality	UVQ	116	42*	11	9	101	87	4	3	99
Pipeline leakage	PLM	58	81	45	78	8	14	5	9	101
Unsaturated zone flow model	UFM	20	52	16	80	4	20	0	0	100
Unsat. zone transport model	UTM	8	NK	6	75	2	25	0	0	100
Saturated zone flow model	SFM	53	65	45	85	8	15	0	0	100
Saturated zone transport model	STM	63	28	41	65	22	35	0	0	100
	Totals	318	-	164	52	145	46	9	3	-

* Provisional NK Not known at time of report production

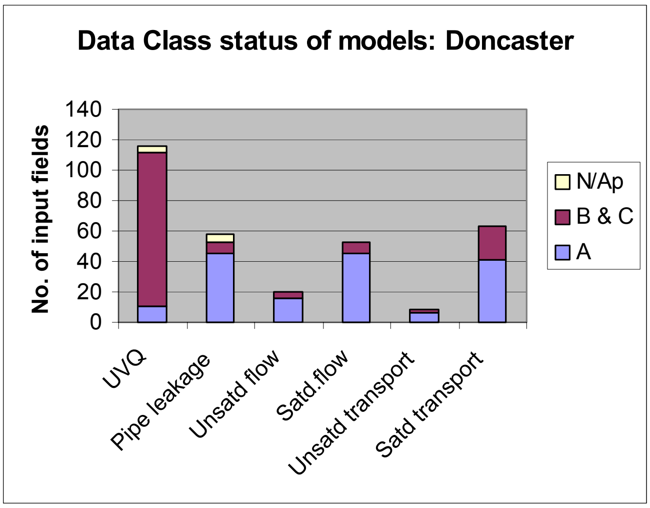


Figure 26 Data Class analysis for the 318 input parameter fields, Doncaster case-study

The analysis showed that UVQ is especially demanding in terms of number of parameters, but the poorest served with site-specific values (only 9% of the total). When collated, the results indicated that for the model array as a whole, it would only be practicable to populate about half of the input fields with site-specific (Class A) values (Figure 27).

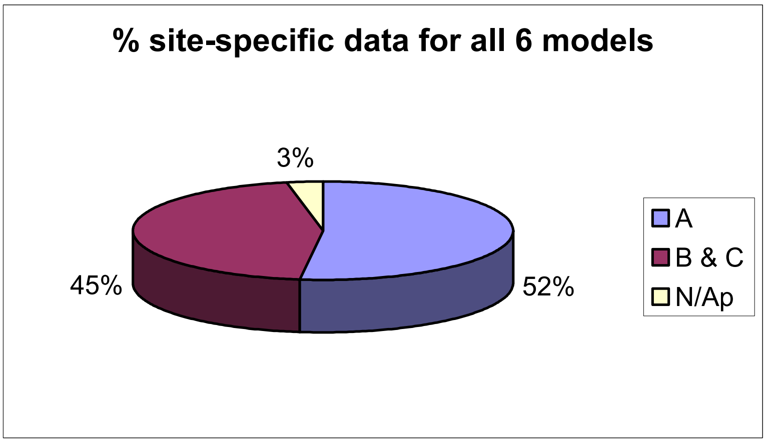


Figure 27 Percentage of input fields in Doncaster case-study likely to be populated with site-specific data

7.2 DATA ANALYSIS & INTERPRETATION ARISING FROM PARAMETER APPRAISAL

In response to the results of the analysis a number of model data provision activities were undertaken and are described in the following subsections

7.2.1 Literature and Internet search

This was conducted to identify High priority Class C parameters (Appendix 3B). The search has been only partially successful, and many important parameters, especially in UVQ, will unavoidably have to rely on generic values, a number of which derive from non-UK settings.

7.2.2 Water infrastructure GIS analysis

This work was undertaken, with the help of YW staff, in part to better understand the water infrastructure of the Bessacarr-Cantley study area in order to employ UVQ and in part to provide data for the development by CSIRO of generic curves employed in the PLM to infer leakage features where CCTV survey defect report analyses are not available. A network analysis for the study area was conducted on pressurized mains, wastewater and surface water systems to assess pipe material, diameter and location for each pipe network. In all three cases a unique asset number related to each reach of pipe subdivides the pipe stock. The analysis was completed for the 3762 pipe assets in the urban pipe infrastructure, and the results are noted in Appendix 3C. The resultant analysis provides a detailed picture of the asset stock, and will allow the CSIRO PLM development team to assess the study area and satisfy themselves that the generic curves, developed for use on those pipe reaches where no CCTV surveys are available, can be applied to the Doncaster setting. Table 10 A,B provides overview statistics of the pressurised water mains, wastewaters and pluvial systems respectively for the study area.

Table 10 Summary statistics for piped water infrastructure, Bessacarr-Cantley

A. Numbers of assets and length

Study area statistics	Area:		4.23 km^2	
	No. of properties		ca.7210	
System	Sub-class	No. of assets	Total length (km)	% total piped water infrastructure
Pressurised mains	-	1135	91.64	41.7
Foul and combined sewer	Foul	1170	54.73	24.9
	Combined	35	2.12	1.0
	Other	9	0.20	<0.1
Pluvial (surface water)	-	1413	71.09	32.3
Total piped infrastructure:		**3762**	**219.78**	**100.0**

B. Pipe materials and length

System								
	Cast iron		*Ductile iron*		*Galv. mild steel*		*Other (PVC, PE)*	
	Assets	km	Assets	km	Assets	km	Assets	km
Pressurised mains	746	65.0	171	12.1	211	14.0	9	0.6
	Vitrified clay		*Concrete*		*Other (PVC, cast iron)*			
	Assets	km	Assets	km	Assets	km		
Foul+ combined sewer	1070	49.5	127	6.9	8	0.4		
Pluvial (surface water)	753	33.3	648	37.5	11	0.3		

Statistically, the average residence is provided for by 12.7m of water main, 7.9m of wastewater sewer and 9.9m of surface water drain (the latter two excluding domestic-to-main connections). The water mains are predominantly cast iron (71%) and ductile iron and galvanized mild steel (13% and 15% respectively). The foul and combined sewers are mainly vitrified clay (87%) with some concrete (12%), while the surface water drains are almost equally concrete (53%) and vitrified clay (47%).

The mains network for the study area is divide into six Demand Management Areas (DMAs) from two Water Supply Zones (WSZs), as indicated in Figure 28. The significance of this division is being investigated in terms of possible differences in mains water inorganic constituents.

WSZ	DMA
Armthorpe 2001	D445 Bawtry Road
	D446 Cantley Manor
	D454 Goodison Boulevard
	D499 Cantley Lane
	D509 Warning Tongue Lane
Doncaster 2001	D453 Stoops Lane

Figure 28 Pressurised mains water system, Bessacarr-Cantley

The wastewater network is a gravity system but of a complex nature. There are some important combined sewer sections, principally in the older-established residential area along the Bawtry Road, that bisects the study area along a NW-SE axis, and some reaches connected by pumping stations in low-lying areas (Figure 29, Figure 30). Network analysis has enabled subdivision of the study area into 9 initial regions in which there is only one sewage and storm water outflow per region, a necessary precursor to neighbourhood selection for UVQ (see Section 8 and Figure 45).

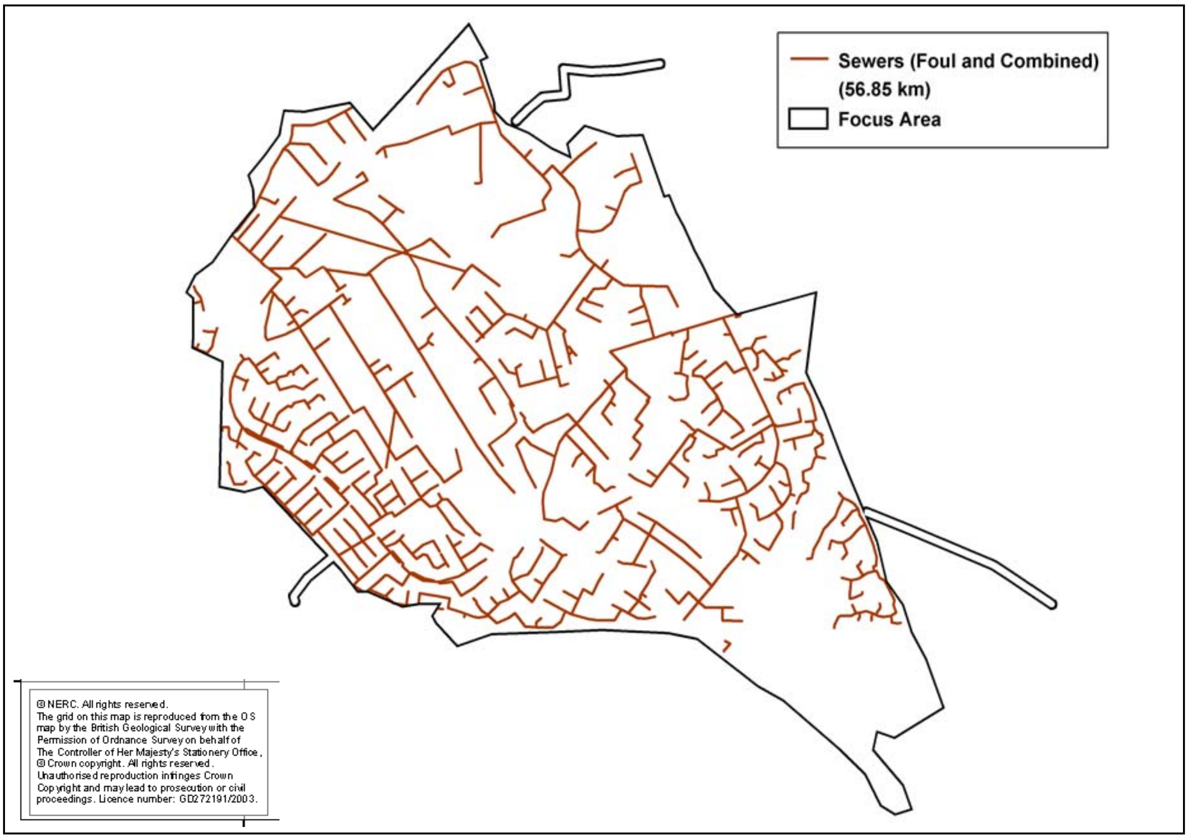


Figure 29 Foul and combined sewer system, Bessacarr-Cantley

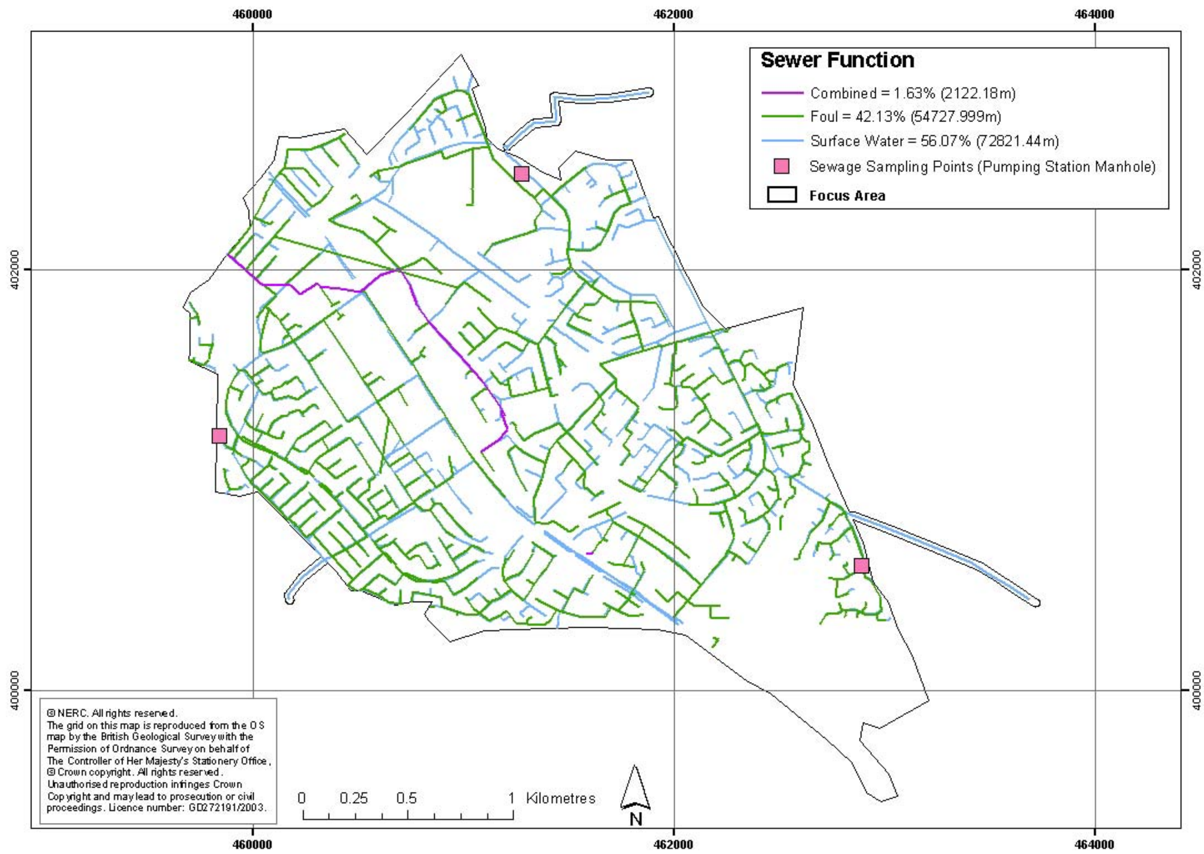


Figure 30 Superimposed foul and surface water drainage systems showing combined reach, Bessacarr-Cantley

CCTV coverage of the sewer system in the study area is confined principally to the older part of the network to the west of Bawtry Road, and comprises less than half of the asset length (Figure 31).

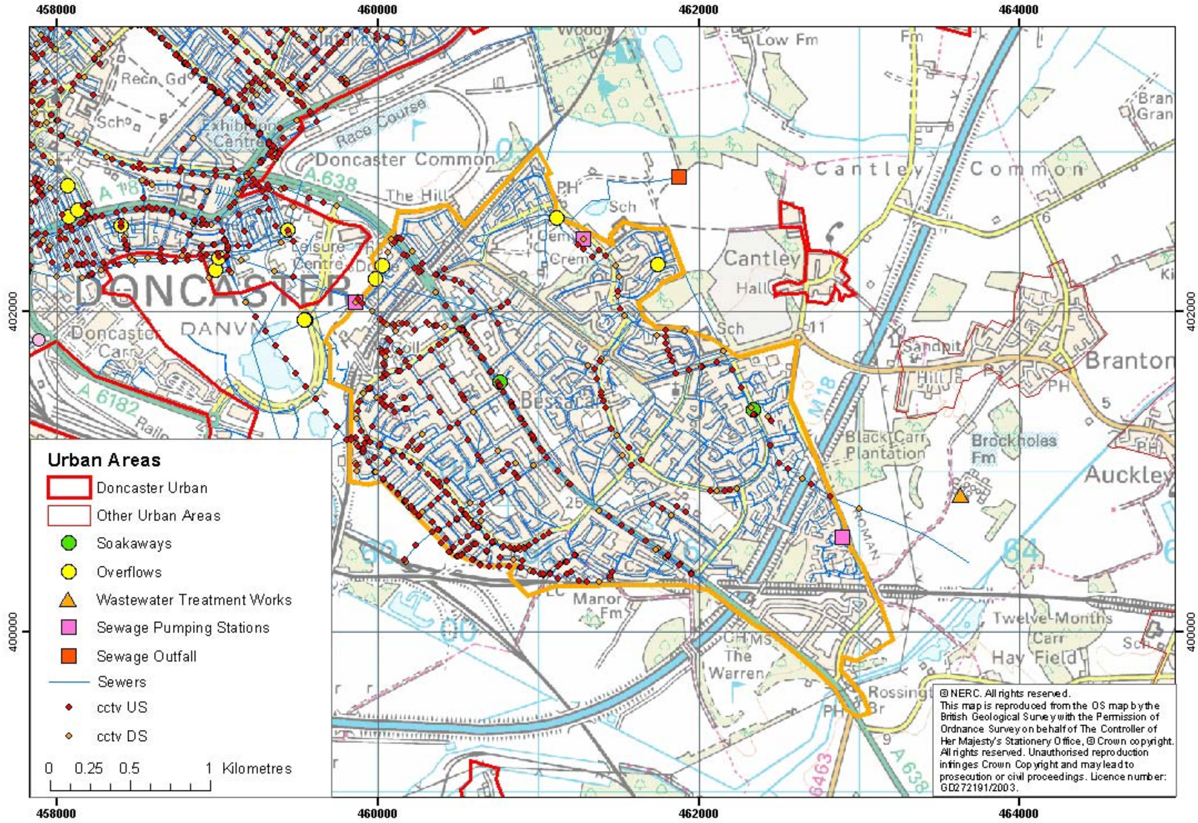


Figure 31 CCTV coverage of foul and combined sewers, Bessacarr-Cantley

7.2.3 Mains leakage estimation

The Class B statistic for leakage has been obtained from the national water regulator website (OFWAT, 2003), see Table 11:

Table 11 Pressurised mains leakage: regional and national statistics

	2000-01	2001-02	2002-03
Total leakage (m^3/km/d)* Yorkshire Water	10	10	10
English water industry average	10	10	11
Total leakage (l/prop/d)** Yorkshire Water	146	141	140
English water industry average	139	146	154

* Total length of main at year end used as denominator
** Total connected properties is used as denominator

To improve the accuracy of this input parameter, which is a potentially important recharge element in an urban setting, site-specific values for the 6 DMAs of the study area were collated from YW night-time flow survey results for approximately 5 years (Table 12), typically from April 1998. Industry–wide standard allowances of 1.75 l/property/hour and 8 l/property/hour for domestic and commercial users respectively are applied to the data, but the results are still considered to be a better approximation to actual leakage than the company-wide averages in Table 11 and are considered now to be a Class A data source

Table 12 Summary mains leakage calculations for Bessacarr-Cantley 4/1998-9/2003

DMA Name	Function	Avg Min Flow	Gross NL	Net NL	Dom Allow	Comm Allow	No. Props Reported	Days Reported
	Units →	*l/hr*	*l/prop./hr*	*l/prop./hr*	*l/hr*	*l/hr*		
D454 Goodison Boulevard	MP total	515509.2	247.9	130.8	220930.5	21696.0	128958	1705
	MP average	8314.7	4.0	2.1	3563.4	349.9	2080	
D453 Stoops Lane	MP total	350624.6	154.7	59.6	203600.3	11936.0	117835	1485
	MP average	6742.8	3.0	1.1	3915.4	229.5	2266	
D499 Cantley Lane	MP total	192581.1	170.1	80.3	90104.8	12000.0	74739	1941
	MP average	2917.9	2.6	1.2	1365.2	181.8	1132	
D445 Bawtry Road	MP total	324435.3	416.0	309.1	78575.0	5208.0	45551	1717
	MP average	5593.7	7.2	5.3	1354.7	89.8	785	
D509 Warning Tongue Lane	MP total	201931.4	180.6	79.2	111281.5	528.0	73886	1996
	MP average	3059.6	2.7	1.2	1686.1	8.0	1119	
D446 Cantley Manor	MP total	199889.6	212.3	101.5	103314.5	1008.0	62113	1932
	MP average	3028.6	3.2	1.5	1565.4	15.3	941	
Approx total no of props in 6 DMAs covering Bessacarr-Cantley during period: 8324								

KEY:

MP	Multiple period
AvgMinFlow	Actual minimum flow reading for the period of record in l/hour
GrossNL	Gross night line flow, calculated as AvgMinFlow/NoPropsReported,, units l/property/hour
NetNL	Net night line flow or net leakage, after allowing for domestic and commercial nightime min. usage. Calculated as (AvgMinFlow-DomAllow-CommAllow)/NoPropsReported, units l/property/hour
DomAllow	Domestic nightime usage allowance, using industry standard of 1.75 l/property/hour X No. of domestic properties. The latter can be deduced as NoPropsReported-(CommAllow/8)
CommAllow	Commercial nightime usage allowance, using industry standard of 8.0 l/property/hour X No of commercial properties. The latter can be deduced as CommAllow/8
NoPropsReported	Total no of properties in DMA at time of period of record, comprising both domestic and commercial properties
DaysReported	No of days in 4 or 5 week period over which meter readings extend i.e. if less than 28 or 35, the record period was interrupted for some reason, such as meter defect.

Collation of these data indicated:

- The range of gross night time flows in the Bessacarr area is 2.6-7.2 l/prop/hour, with an average for all 6 DMAs of 3.8 l/prop/hour and median of 3.1 l/prop/hour
- The range of net night time flows in Bessacarr area is 1.1-5.3, with an average for all 6 DMAs of 2.1 l/prop/hour, and median of 1.4 l/prop/hour
- The leakage control zones cover around 750-2000 properties each, and the 6 DMAs together covered about 8300 properties. This compares satisfactorily with an estimated project area property count of ca.7210 from GIS calculations for UVQ and PLM purposes; the difference being due to a slightly different footprint (Bawtry Road DMA overlaps the study area

southeast of the M18 and south of the railway, see Figure 28) and possibly a few multi-occupancy dwellings (separate properties for metering and billing purposes).

These figures will form the basis for pressurised mains leakage parameters in UVQ and PLM, although it is noted that the domestic and industrial night-time usage figures, which are assumed and use industry-wide nationally agreed standard values rather than measured site-specific readings, account for almost 50% of flow in the corrected (net) leakage calculation total.

7.2.4 Sewer-water table interaction

The northeast and southwest margins of Bessacarr-Cantley are low-lying and adjoin former or present wetland areas. The wastewater division of YW had previously advised that groundwater drainage was recognized as an important feature of Doncaster sewer design. Therefore, it was necessary to test whether any of the study area might have sewer assets located below the water table. In the nodes representing any such areas, the PLM would need to represent a gain from the aquifer rather than a loss to the unsaturated zone, both in terms of volume and solute flux.

The mapping was performed as a GIS operation and three datasets were used:

(i) Water table elevations interpolated from the EA regional water level monitoring network

(ii) Ground elevation, in meters above Ordnance Datum (mean sea-level in the UK)

(iii) Elevation of the sewer invert for each pipe asset at surface access points (SAPs, usually manholes)

Each thematic layer has its data constraints. The water table elevation surface had to be interpolated from a sparse local array of water level observation well locations, only two of which are within the study area (Figure 32). It is a functional but provisional surface pending better resolution of the water table in the study area once the project's five multilevel sites have been leveled in to provide additional water table elevations and once a NextMap digital terrain surface dataset become available. The latter's higher lateral and vertical resolution will provide a more accurate topographic surface.

The ground elevation map was originally derived from the national Digital Elevation Map dataset of CEH, but was found to be unsuitable because absolute elevations, which are important for this application, could not be discriminated with sufficient accuracy. Instead the ground elevation map was constructed from two surveyed datasets, these being spot heights from the OS Landform Profile dataset and SAP elevations from YW records (Figure 33). This map clearly shows the low northeast-southwest trending ridge followed by Bawtry Road, the central half of the study area at 10m or more above sea level and the low-lying area below 8m elevation along the southwest margin.

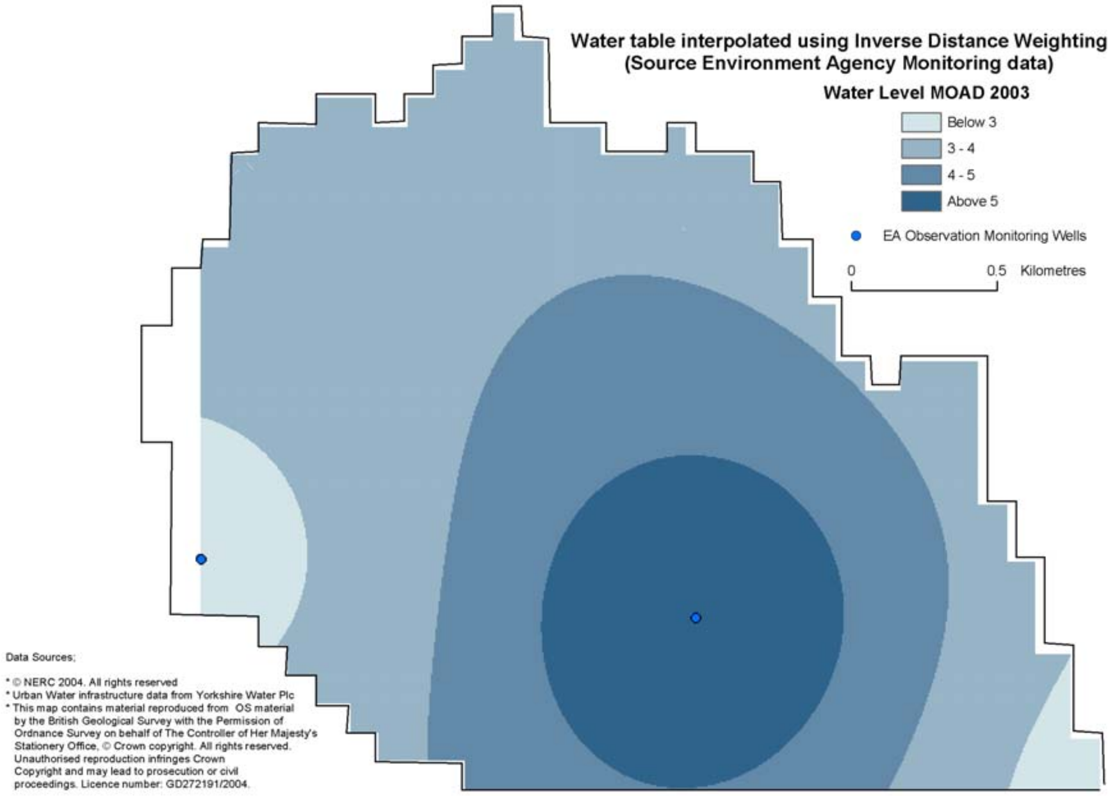


Figure 32 Water table elevation map, Bessacarr-Cantley study area, April 2003 example

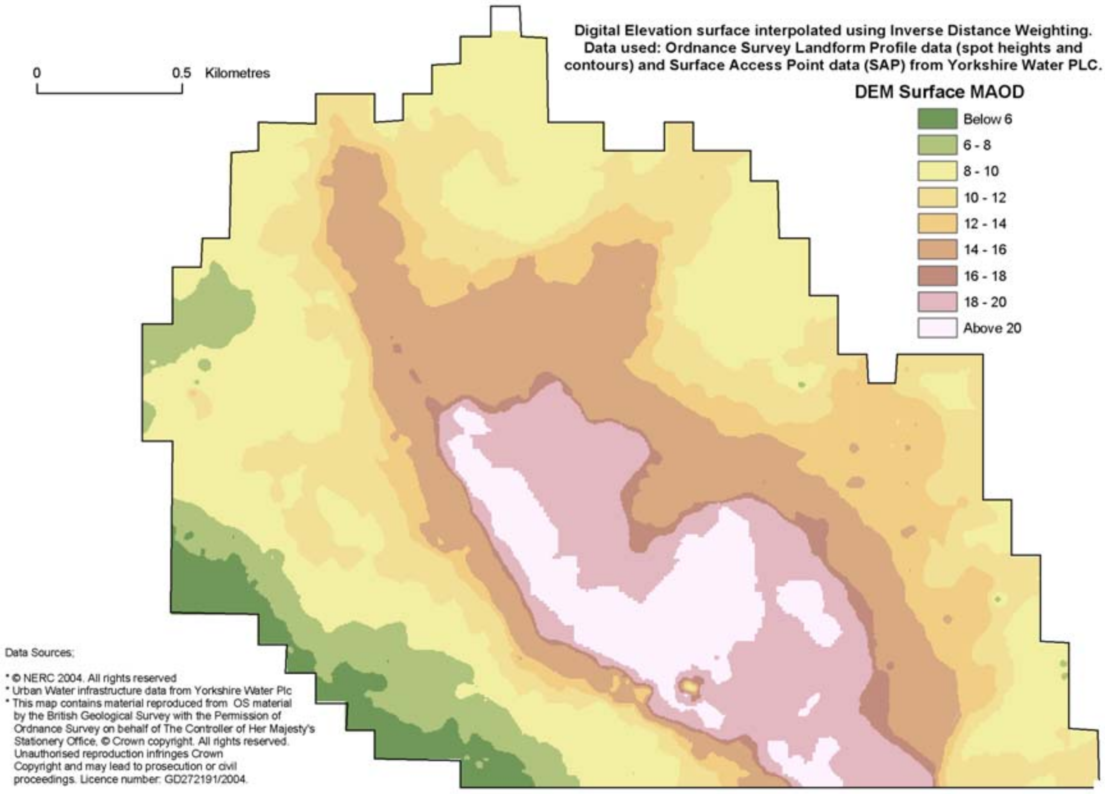


Figure 33 Ground elevation map, Bessacarr-Cantley study area

The sewer invert surface was interpolated from the ground elevation map and the sewer invert level in metres below the SAPs (Figure 34). The provisional water table elevation surface and the sewer invert surface were superimposed within ArcGIS with the 100m x 100m grid to be used in forthcoming PLM, SFM and other modeling work.

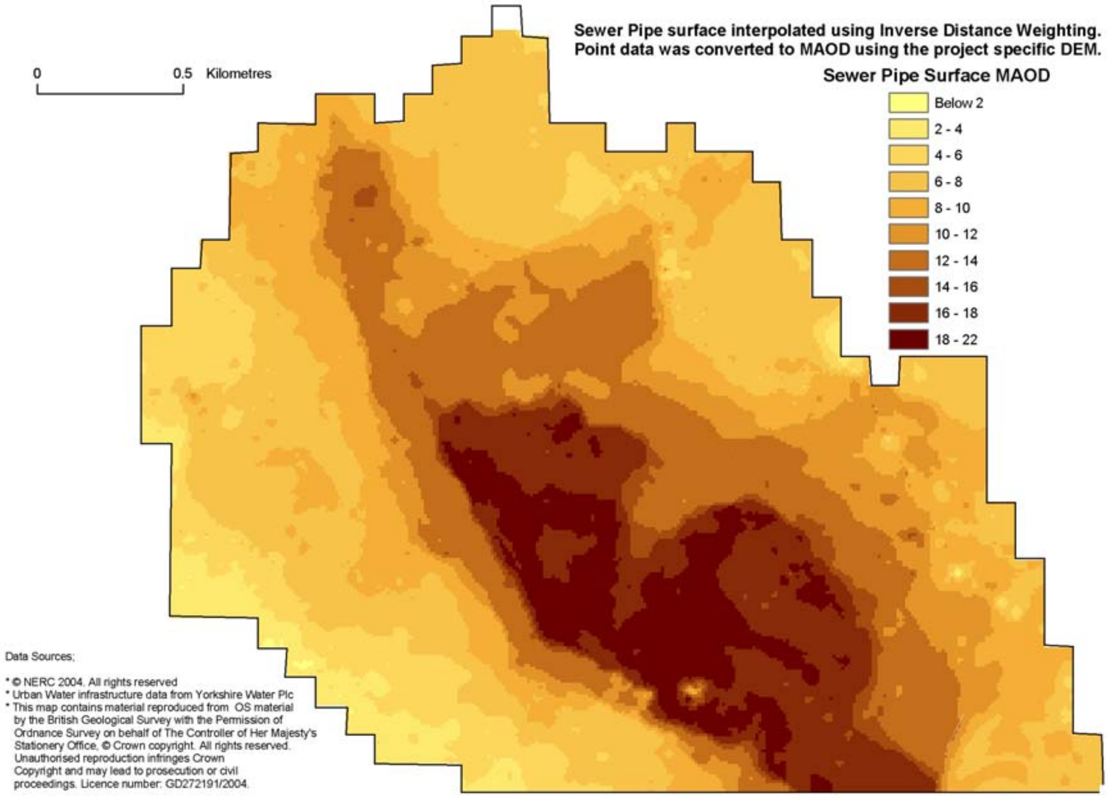


Figure 34 Sewer invert surface, Bessacarr-Cantley study area

The resultant map indicates those nodes where the sewer network was either gaining from or losing to the aquifer/unsaturated zone (Figure 35); the April 2003 dataset indicates a number of nodes on the southwest margin and possibly a small area near McAuley School may currently have gaining sewer reaches.

Figure 35 Bessacarr-Cantley study area nodes with sewer level below water table, April 2003 (provisional version)

Comparison with the September 1997 groundwater elevation map, before the commencement of major reductions in pumping agreed with the EA, indicate that this sewer-gain area may have expanded in recent years, an observation that coincides with recent reports of incipient groundwater flooding problems, both near the study area (in the vicinity of Rossington Bridge pumping station) and further northwest in older-established areas of Doncaster.

7.2.5 Transforming DMBC landuse mapping into urban water infrastructure units

The Planning Department of Doncaster Metropolitan Borough Council (DMBC) provided the project team with a section of the comprehensive and detailed land use dataset compiled for the Council's area. This survey dataset assigns land use to one of 135 categories (Table 13) of which 88 are used within the Bessacarr-Cantley study area or in land adjacent (0.5km buffer zone) and 61 within the detailed study area itself.

Table 13 DMBC Land use categories summary

Land use division	No of sub-categories	No of sub-categories in study area	Aggregation procedure for UVQ polygons
Agriculture, woodland, other green open space	20	12	Consolidated into 1 subcategory 'open space or periurban equivalent'
Water and wetland	8	2	
Rock, coastal land, minerals and landfill	15	0	
Recreation land, buildings	11	9	Buildings and and grounds identified separately as 'roofed', 'paved' and 'open space'
Transport	15	4	Consolidated into 'Paved' and resultant polygons excluded from study area (main roads only)
Residential	24	15	Grouped into two types based on garden size
Community buildings including schools	10	9	Buildings and grounds identified separately as 'roofed', 'paved' and 'open space'
Industrial and commercial	20	9	
Vacant land, Other	12	1	
Totals:	**135**	**61**	

Although the study area boundary is well defined in land use terms between rural/agricultural and urban/residential, the resultant mosaic of categories is complex (Figure 36). Being a suburb of Doncaster, in terms of area the main land use division in Bessacarr-Cantley is residential. Community and commercial uses, principally schools, halls and retail premises, dominate the rest (Figure 37) but only comprise just over half of the land use categories employed.

The complexity of land use categories was therefore simplified (as a precursor to assigning neighbourhoods within the UVQ model) to classes based on likely infiltration characteristics of the land cover (pervious or impervious surface) as shown in Figure 39.

Table 14 Infiltration classes subdividing study area for UVQ land block data input

Infiltration classes:	Approximation to permit UVQ land block data input
Mainly Roofed	Land block average roof area assumed to be =100%
Mainly Paved	Land block average paved area assumed to be =100%
Mainly unbuilt	Land block open space/garden area assumed to be =100%
Mixed; requires apportionment	Approximation not possible; housing stock subcategories inspected separately to derive a roofed/paved/pervious surface apportionment

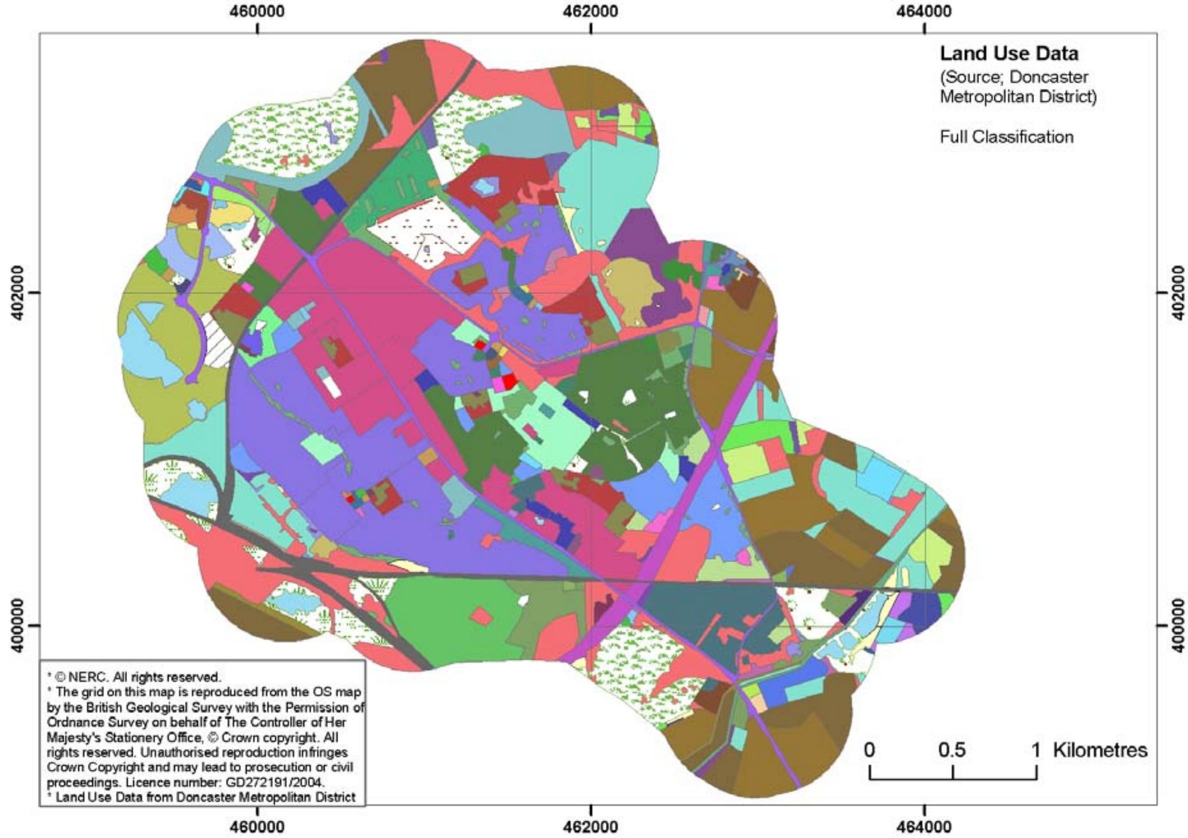


Figure 36 Original DMBC land use classification for study area and 0.5km buffer zone showing complexity of categorisation used for town-planning purposes

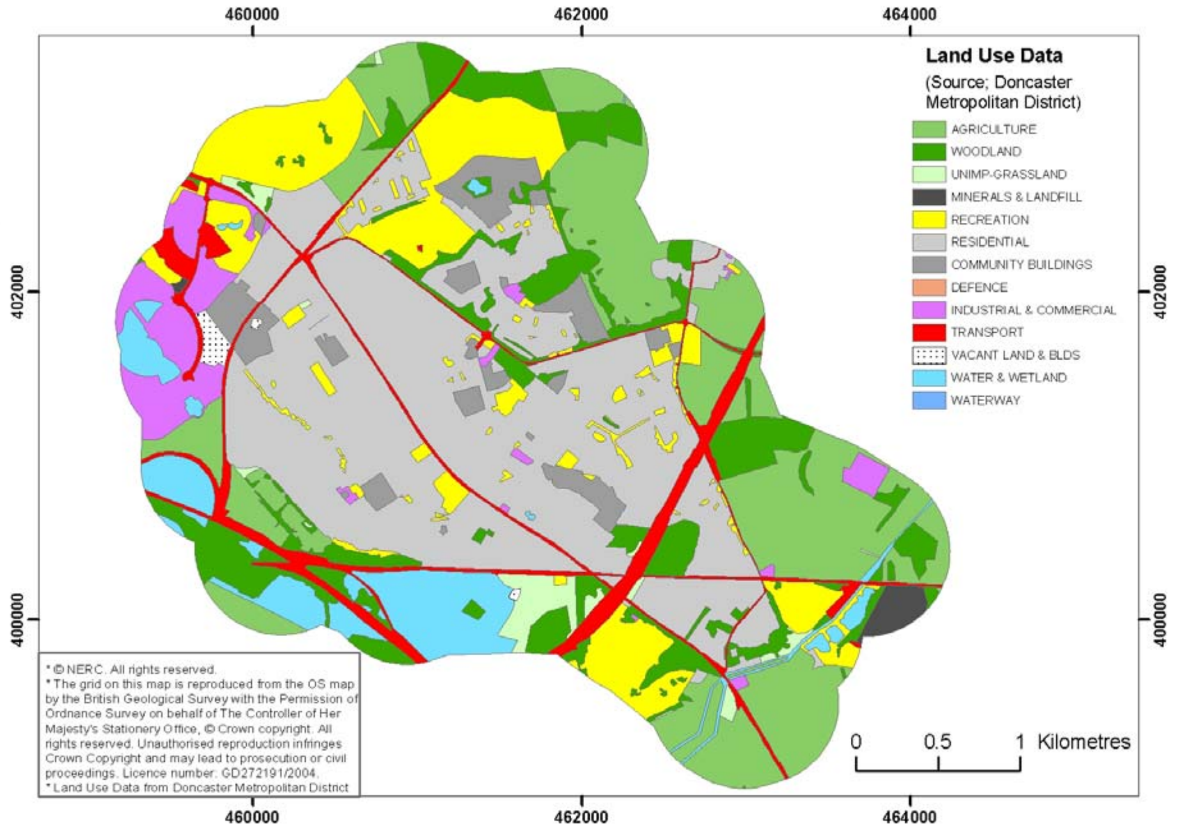


Figure 37 DMBC land use classification of study area and 0.5 km buffer zone simplified to show role of residential and other primary land use divisions

The subcategories, consolidated as mainly roofed, mainly paved and mainly unbuilt, permit assignation within each UVQ land block of pervious and impervious surface (Table 14) for a given land block. Thus, a school property for instance can be divided using existing GIS datasets into school buildings ('mainly roofed'), playgrounds forecourt and car-parking ('mainly paved') and playing fields ('mainly unbuilt'). The resultant reclassification is detailed in Table 15 and illustrated for the study area and a surrounding buffer zone of 0.5 km in Figure 38. The buffer zone is displayed merely to show the general setting of the study area and has not been subsequently employed for UVQ data entry purposes.

Table 15 Reclassification of DMBC land use categories into UVQ-amenable input

DMBC Division	DMBC Primary Category	BGS-assigned infiltration class	BGS-assigned provisional sub-class
Agriculture	Field crops	Mainly unbuilt	Open space or periurban equivalent
Agriculture	Improved pasture	Mainly unbuilt	Open space or periurban equivalent
Agriculture	Minimal tree cover	Mainly unbuilt	Open space or periurban equivalent
Agriculture	Park Woodland	Mainly unbuilt	Open space or periurban equivalent
Agriculture	Ploughed field	Mainly unbuilt	Open space or periurban equivalent
Community Bldgs	Car parking exceeding 500sq.m.	Mainly Paved	Paved, not road
Community Bldgs	College playing fields	Mainly unbuilt	Open space or periurban equivalent
Community Bldgs	Colleges buildings and curtilages	Mainly Roofed	Mainly Roofed
Community Bldgs	hospitals and health centres	Mainly Roofed	Mainly Roofed
Community Bldgs	Institutional buildings	Mainly Roofed	Mainly Roofed
Community Bldgs	other buildings and uses	Mainly Roofed	Mainly Roofed
Community Bldgs	Religious buildings	Mainly Roofed	Mainly Roofed
Community Bldgs	School buildings and curtilages	Mainly Roofed	Mainly Roofed
Community Bldgs	School soft playing areas	Mainly unbuilt	Open space or periurban equivalent
Industrial & Comm.	Car parking areas over 500sq.m.	Mainly Paved	Paved, not road
Industrial & Comm.	Car sales	Mainly Paved	Paved, not road
Industrial & Comm.	Land under development	Mixed; requires apportionment	Outside focus area: will be removed when redefined
Industrial & Comm.	Landscaping areas outside of highway and building curtilage	Mainly unbuilt	Open space or periurban equivalent
Industrial & Comm.	Offices	Mainly Roofed	Mainly Roofed
Industrial & Comm.	Post war estates and business parks	Mainly Roofed	Mainly Roofed
Industrial & Comm.	Retail Road Frontages	Mainly Paved	Paved, not road
Industrial & Comm.	Utilities	Mainly Paved	Paved, not road
Industrial & Comm.	Water	Mainly unbuilt	Open space or periurban equivalent
Recreation	Allotments	Mainly unbuilt	Open space or periurban equivalent
Recreation	buildings and curtilage	Mainly Roofed	Mainly Roofed
Recreation	car parking exceeding 500sq.m.	Mainly Paved	Paved, not road
Recreation	cemeteries	Mainly unbuilt	Open space or periurban equivalent
Recreation	formal playing fields but excluding school playing fields	Mainly unbuilt	Open space or periurban equivalent
Recreation	golf courses	Mainly unbuilt	Open space or periurban equivalent
Recreation	informal open playing areas within housing estates	Mainly unbuilt	Open space or periurban equivalent
Recreation	large public houses	Mainly Roofed	Mainly Roofed
Recreation	public parks	Mainly unbuilt	Open space or periurban equivalent
Residential	Institutional and communal accommodation	Mixed; requires apportionment	Institutional and communal accommodation
Residential	Land under development for housing	Mixed; requires apportionment	Land under development for housing
Residential	Local authority 1980-1990 (& housing associations)	Mixed; requires apportionment	Local authority 1980-1990 (& housing associations)
Residential	Local authority and NCB post war	Mixed; requires apportionment	Local authority and NCB post war

Residential	Local authority non traditional (incl Radburn layout)	Mixed; requires apportionment	Local authority non traditional (incl Radburn layout)
Residential	Local authority pre war	Mixed; requires apportionment	Local authority pre war
Residential	Mansions with park and gardens	Mixed; requires apportionment	Mansions with park and gardens
Residential	Mixed, one time urban edge or main road	Mixed; requires apportionment	Mixed, one time urban edge or main road
Residential	Private 1919-1970, superior quality middle class	Mixed; requires apportionment	Private 1919-1970, superior quality middle class
Residential	Private 1930-1960, semi detached and smaller detached	Mixed; requires apportionment	Private 1930-1960, semi detached and smaller detached
Residential	Private 1970-1990 medium sized houses in larger plots	Mixed; requires apportionment	Private 1970-1990 medium sized houses in larger plots
Residential	Private 1970-present, larger house, complex roofs, larger gardens	Mixed; requires apportionment	Private 1970-present, larger house, complex roofs, larger gardens
Residential	Private 1980-1990 low rise and non conventianal design	Mixed; requires apportionment	Private 1980-1990 low rise and non conventianal design
Residential	Private 1980-1990 smaller houses in smaller plots	Mixed; requires apportionment	Private 1980-1990 smaller houses in smaller plots
Residential	Recently developed housing	Mixed; requires apportionment	Recently developed housing
Transport	Motorways including curtilages	Mainly Paved	Road
Transport	Other roads	Mainly Paved	Road
Transport	Railway corridor	Mainly unbuilt	Open space or periurban equivalent
Transport	Surface formal	Mainly Paved	Paved, not road
Unimproved Grassland,Heathland	Unimproved Grassland	Mainly unbuilt	Open space or periurban equivalent
Unimproved Grassland,Heathland	Weedy dilapidated grassland	Mainly unbuilt	Open space or periurban equivalent
Vacant Land & Bldgs	Vacant land previously developed	Mixed; requires apportionment	Recently developed housing
Water & Wetland	Freshwater marsh	Mainly unbuilt	Open space or periurban equivalent
Water & Wetland	Standing water	Mainly unbuilt	Open space or periurban equivalent
Woodland	Broadleaved woodland	Mainly unbuilt	Open space or periurban equivalent
Woodland	Conifer woodland	Mainly unbuilt	Open space or periurban equivalent
Woodland	Mixed woodlands	Mainly unbuilt	Open space or periurban equivalent
Woodland	Scrub	Mainly unbuilt	Open space or periurban equivalent
Woodland	Undifferentiated young woodland	Mainly unbuilt	Open space or periurban equivalent

Table 15 and Figure 38 show a 'mixed' infiltration class. A further aggregation step was needed for this important 'mixed' group composed of 15 DMBC residential categories comprising the housing stock of Bessacarr-Cantley. These have intricate boundaries (see Figure 39). Each polygon of the housing type is a mixed land use of building, garden, pavement/verge, road and minor open space not readily addressable in GIS terms. The residential aggregation procedure required inspection of each polygon for the numbers of houses and gardens and approximate road, roof and paved areas. These were calculated manually using OS maps and aerial photographs provided by DMBC Planning Department. The results were tabulated and analysed (see Figure 47, Section 8).

This procedure allowed the housing stock to be divided into just two subcategories (large-garden and small-garden) and provides the necessary area statistics for data input at land block and neighborhood scales in a spreadsheet. Gardens were a useful proxy for property count, allowing the OS digital 1:10,000 building polygons to be subdivided where necessary into detached, semi-detached and terraced properties. This device does not work for apartment blocks but fortunately these are not common in the study area. See Section 8 for a description of how the resultant land use classification was then used as UVQ input to define neighborhoods.

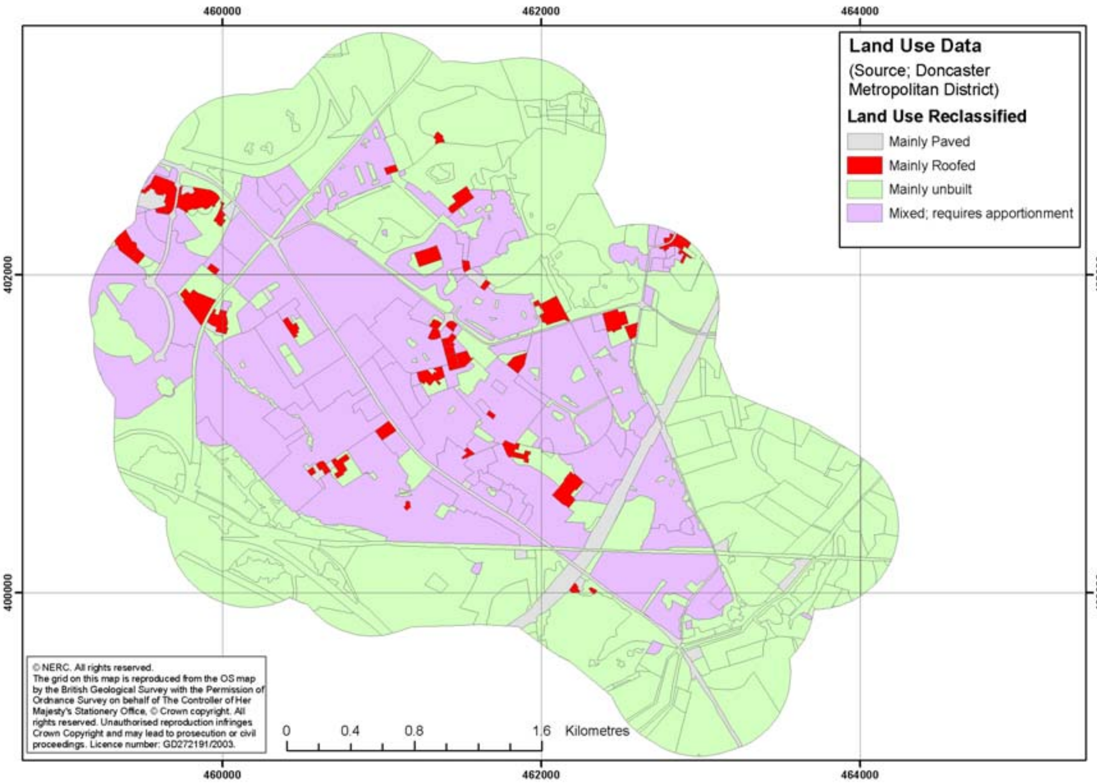


Figure 38 DMBC land use data in process of conversion into form amenable to UVQ data input at land block scale

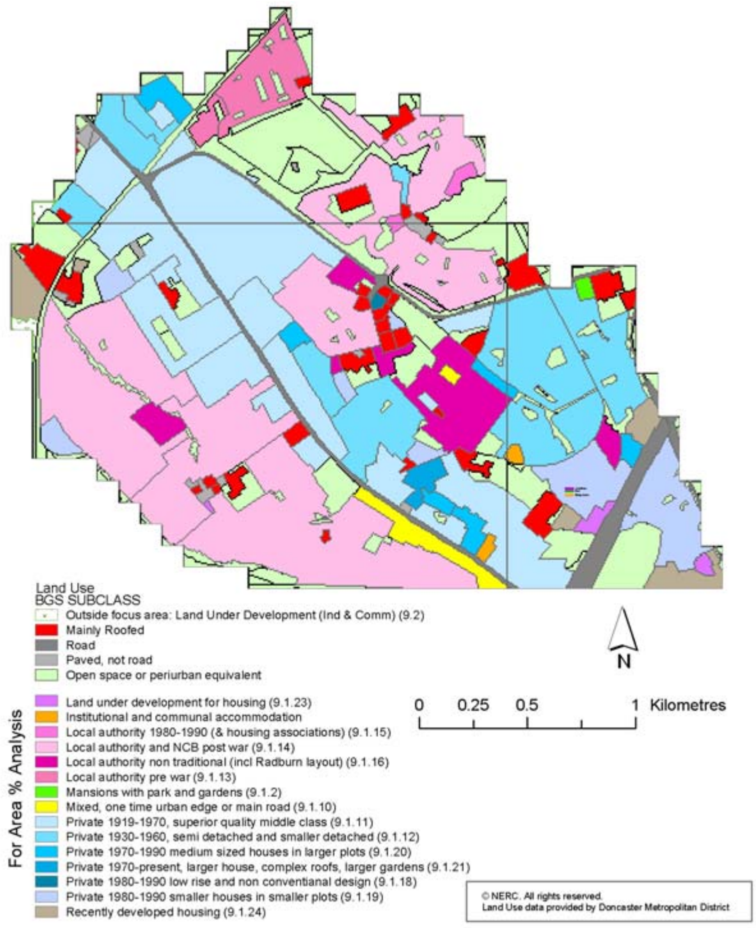


Figure 39 Housing stock of Bessacarr-Cantley; the 15 town planning categories need to be aggregated

7.3 TRANSLATION OF REGIONAL GROUNDWATER FLOW MODEL FOR APPLICATION IN AISUWRS PROJECT

The Doncaster Groundwater Model, originally developed by Brown and Rushton (1993) is a key resource for the AISUWRS project because it is considered to represent an acceptable approximation to the groundwater flow regime in the case study area. It is one of three regional models used for resource management and predictive purposes for the important c.120 km zone of Sherwood Sandstone between Nottingham and York (see Neumann and Hughes 2003 and Chapter 5, Morris et al, 2003 for summary).

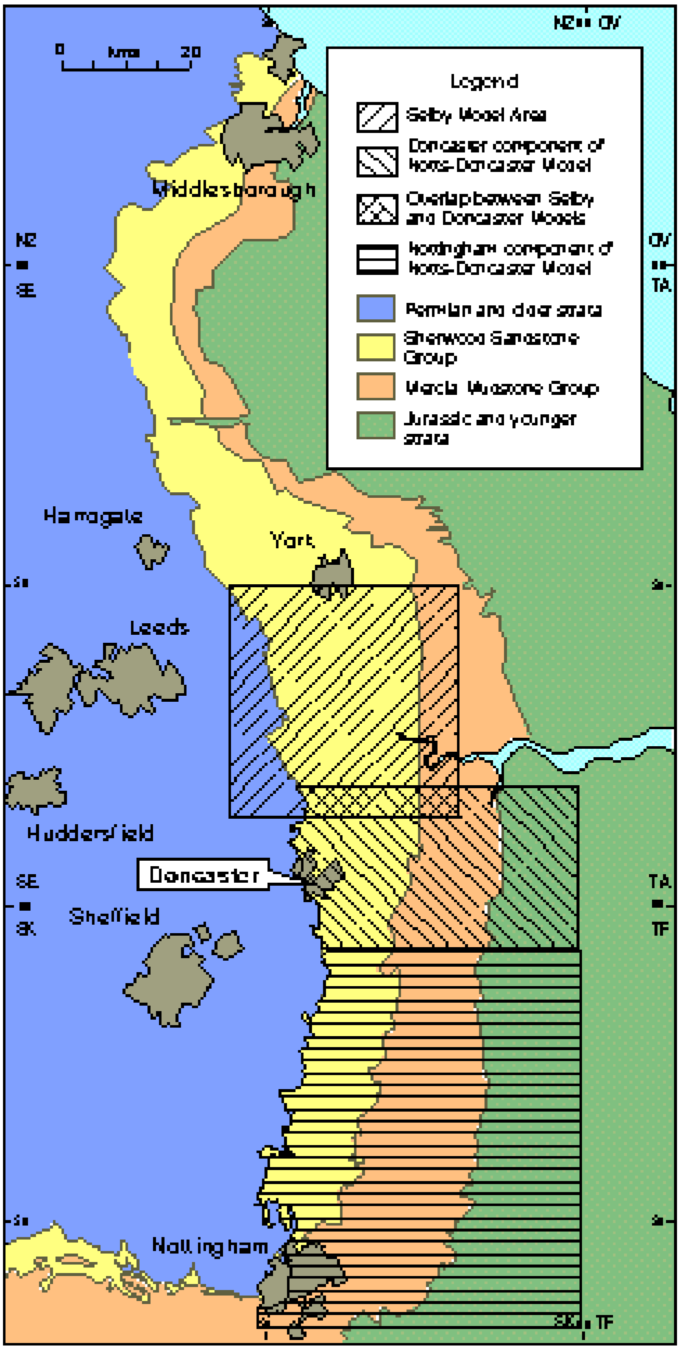


Figure 40 Extent of the original Notts-Doncaster regional groundwater model.

A key preliminary step to setting up the groundwater flow and groundwater transport modules for Bessacarr-Cantley was therefore the translation of the original model code into the MODFLOW code. This will allow a sub-regional model to be set up to focus on the Bessacarr-Cantley area only and facilitate both solute transport modelling and groundwater flow simulations by permitting flexibility in changing input parameters to conduct scenario modelling.

The translation of the original code into a MODFLOW equivalent is described in detail in Neumann and Hughes 2003 (Appendix 4).

A comparison of model results from the original model and the MODFLOW model led to the following observations:

- The overall agreement between the MODFLOW model and the original model is good, both for hydrographs of observation boreholes and for the water balance of the models.
- The original model domain is discretised using a mesh-centred approach, while the MODFLOW code uses a grid-centred approach. This leads to a model area slightly larger by half a cell width all round compared to the original model domain. Due to the different discretization, observation borehole nodal references used in the original model to produce hydrographs are in some cases not identical to the grid cells used in the MODFLOW model.
- Differences exist in the amount of abstraction from boreholes in both models, as an unavoidable consequence of limited data being made available.
- Differences exist in the numerical representation of the southern boundary of the model area. The southern boundary of the MODFLOW model is only a notional boundary in the original model. The southern boundary of the original model is the southern boundary of the full Notts-Doncaster model. Flows over the notional southern boundary were not supplied to BGS and had to be inferred using water balance figures of the original model. This permitted the correct assignment of the total flow amount, but the location of the flows along the boundary unavoidably had to be inferred.
- Differences may exist between both models in the thickness of the drift cover, which is used to infer a leakage rate to and from the overlying stratum and the aquifer. Original input was supplied with rounded values, which led to the assignment of zero thickness for some drift cells. The actual drift thicknesses for those cells are unknown and were approximated in the MODFLOW model to 1m.

To resolve some of the differences in both models, the following would be required:

(i) Update with the original abstraction input data, in order to apply the same borehole abstractions in both models.

(ii) Update with the original, un-rounded model parameter input data, to establish the actual thickness of the drift cover in areas where rounding errors led to the assignment of zero values in the data set provided to BGS.

(iii) Obtain data to model flows across the southern boundary more accurately. Either the flows over the southern boundary would be required or data of the Notts-Doncaster model are needed to establish the flows over the notional southern boundary by running the full Notts-Doncaster model.

7.3.1 Adapting regional model to detailed investigation area

The MODFLOW model has a 1 km x 1 km gridnodes. In the Bessacarr-Cantley area the model has been further discretized into 100m x 100m cells (Figure 41). These are arranged so as to facilitate overlay of the UVQ, PLM and unsaturated zone outputs when these models are linked. A further development is to agree on a fixed ‘footprint’ portion of the discretized grid approximating to the boundary of the detailed study area. The 586 grid squares within this subsidiary area will be those treated spatially in turn by the ground water flow and transport model sets and to which specific input parameters for example in the UVQ and PLM are applied. This footprint area is shown in Figure 42.

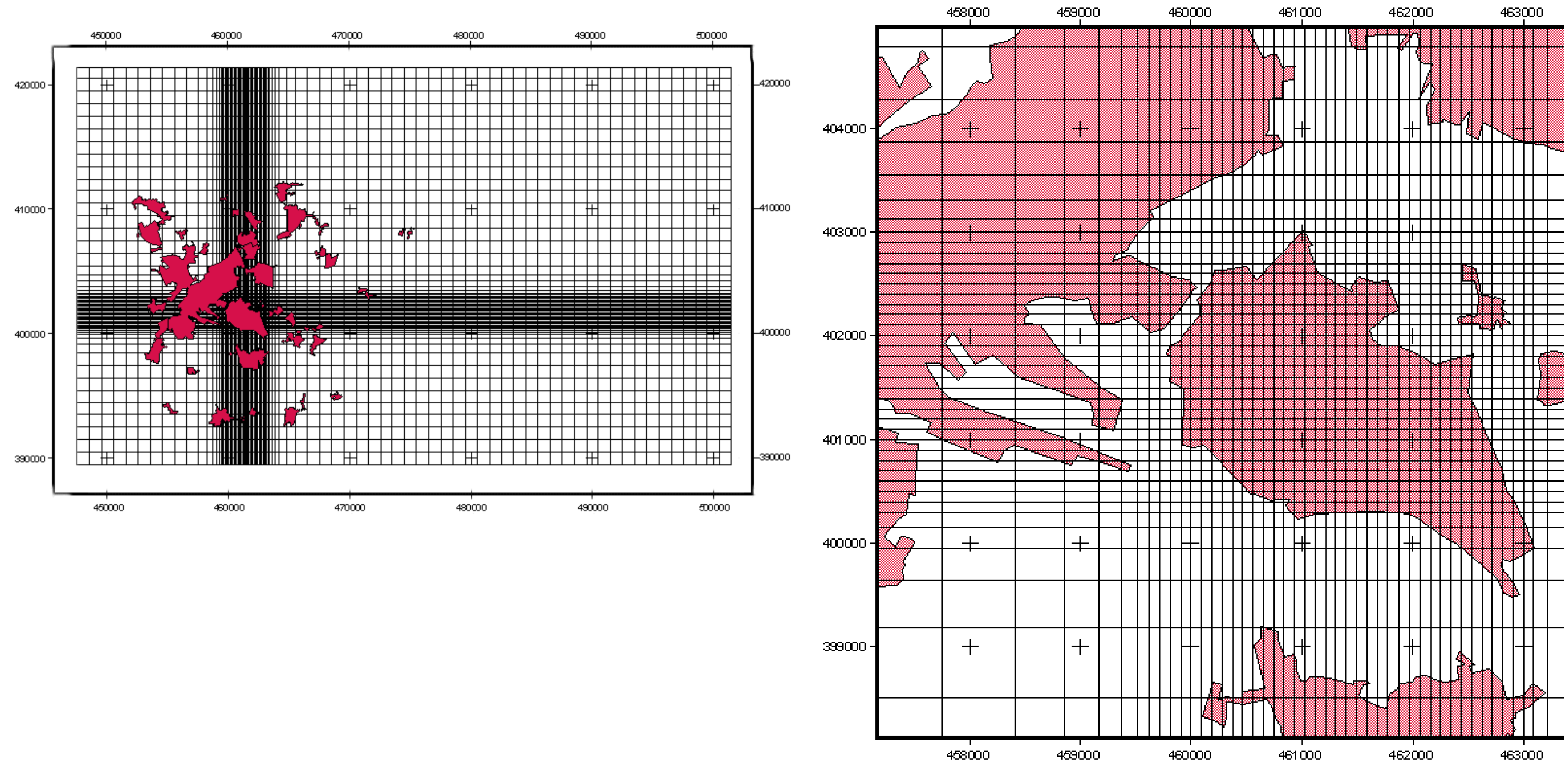


Figure 41 Discretization of groundwater flow model in Bessacarr-Cantley area

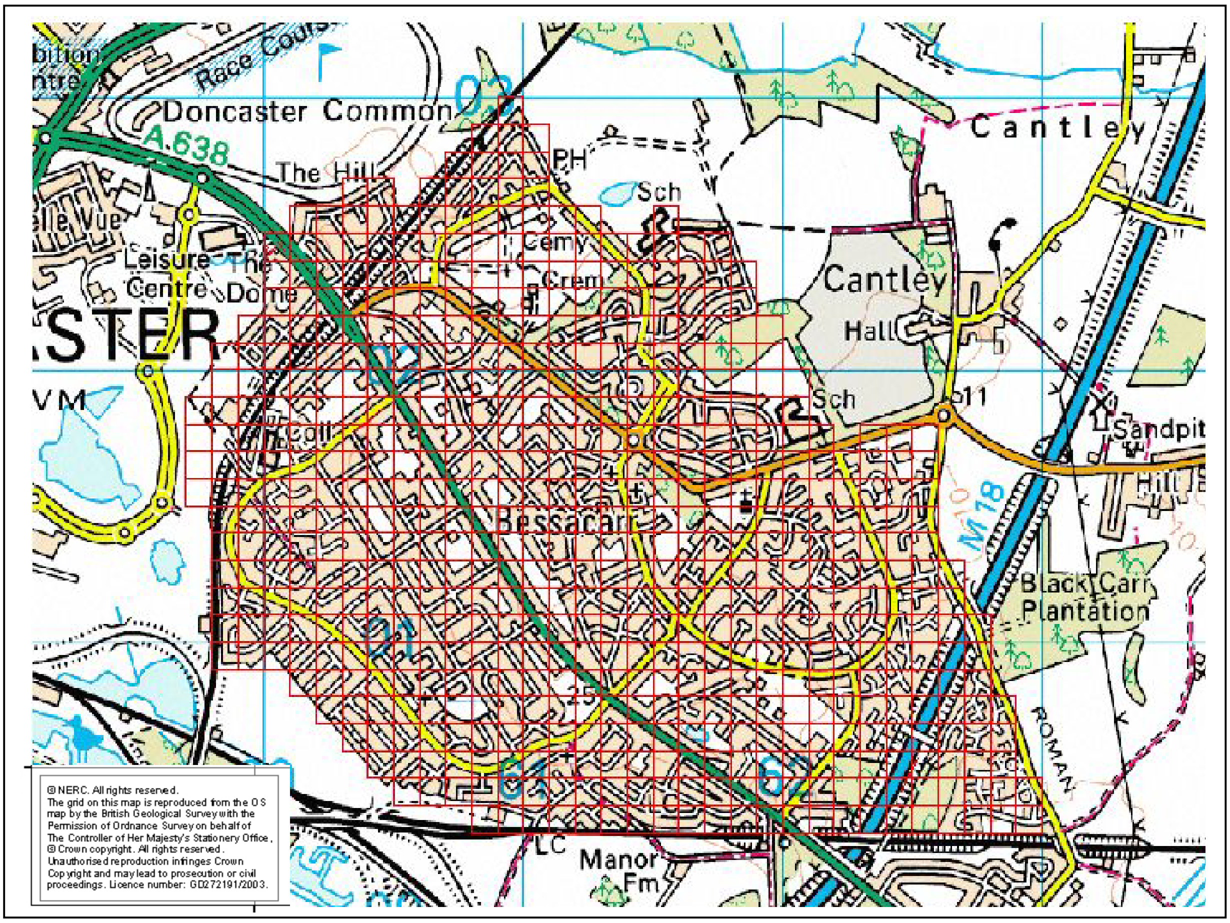


Figure 42 Subsidiary area of discretised groundwater local model grid approximating to Bessacarr-Cantley study area, for future use in main modelling tasks

8 UVQ Model

8.1 INTRODUCTION

UVQ (Urban Volume Quality) is an urban water volume and contaminant balance analysis tool that was developed by CSIRO in Australia to analyse how water and contaminants flow through an urban system. It is a tool to investigate how a wide range of non-traditional practices can improve the water use in terms of quantity and quality. UVQ was initially developed to support the assessment stage of alternative water use scenarios. UVQ uses simplified algorithms and conceptual routines to provide a holistic view of the project area (Mitchell and Diaper 2003, Mitchell et al. 2003). Figure 43 shows the conceptual view of a project area.

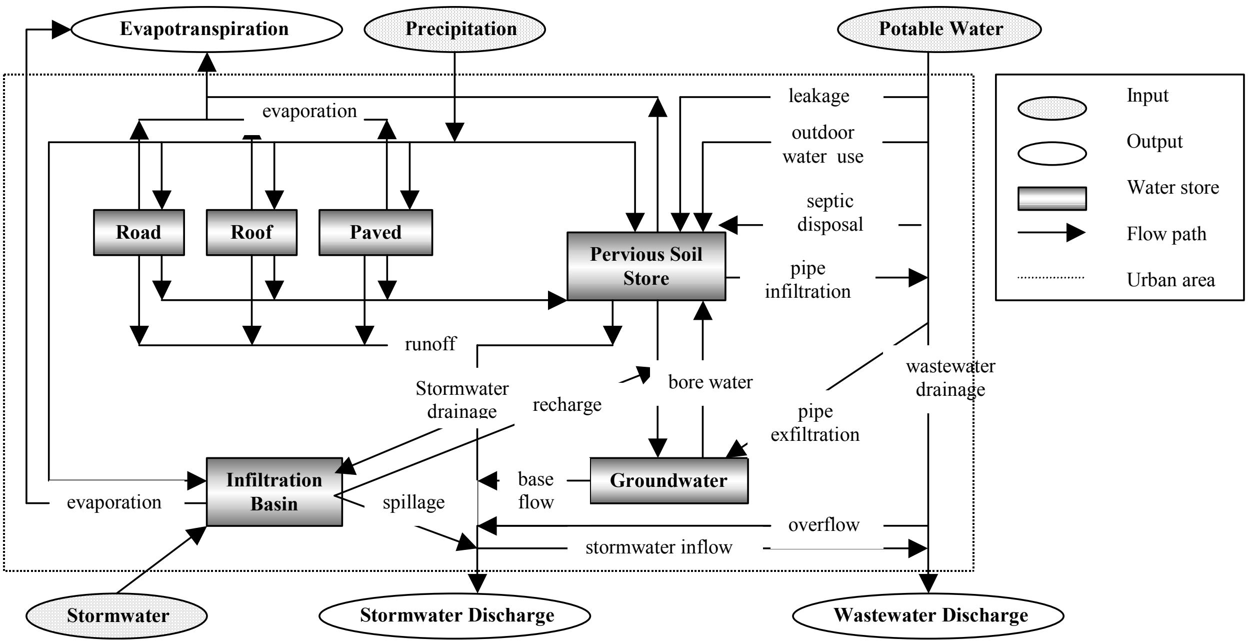


Figure 43 Conceptual picture of UVQ model.

Water quality and quantity aspects as well as sizing of infrastructure are essential assessment considerations for alternative water servicing options. Thus, in addition to providing an integrated approach to water servicing options in an urban area, UVQ also provides a method for tracking water-associated contaminants through the urban water cycle. In essence, it is a mass balance model. It should be noted that UVQ works with on daily time steps and therefore cannot account for short-term storm events.

The model allows direct representation of the effects of alterations to water services on the movement and distribution of contaminants in the urban system. Contaminants are all modelled conservatively, with no conversion or degradation within the existing infrastructure and the calculations are all based on simple mixing and removal processes.

8.2 INPUT DATA

UVQ requires quite a large set of data related to physical characteristics (e.g. land use, number of occupants, water use, road area) and quality aspects (e.g. contaminant concentration in laundry or road runoff). All these data were gathered during the past months of the project. Table 16 contains all data needed as input into UVQ as well as their origin and their current sources to populate the model. It should be noted that the data sources may change during the course of the on-going project.

Table 16 Sources of data needed for UVQ.

Data Field Name	Unit	Data Source
Physical Data		
Neighbourhood Frame		
Area	ha	Analysis of land use map with GIS
Road Area	ha	Analysis of land use map with GIS
Open Space	ha	Analysis of land use map with GIS
Percentage of Open Space Irrigated	%	From Neighbourhood Services (DMBC)
Imported Supply Leakage	%	Yorkshire Water leakage file
Wastewater as Exfiltration	ratio	
Land Block Frame		
Number of Land Blocks		Analysis of land use map with GIS
Block Area	m^2	Analysis of land use map with GIS
Average Occupancy		DMBC population statistics (inception report p.12)
Garden Area	m^2	Analysis of land use map with GIS
Roof Area	m^2	Analysis of land use map with GIS
Paved Area	m^2	Analysis of land use map and digital aerial
Percentage of Garden Irrigated	%	
Proportion of Roof Runoff to Spoon drain	ratio	
Wastewater Output Frame		
Wastewater goes to Neighbourhood		Analysis of sewer and storm water network obtained
Stormwater goes to Neighbourhood		Analysis of sewer and storm water network obtained
Indoor Water Usage		
Bathroom	L/p/day	UVQ tutorial
Toilet	L/p/day	UVQ tutorial
Kitchen	L/p/day	UVQ tutorial
Laundry	L/p/day	UVQ tutorial
Total	L/p/day	
Calibration Variables		
Stormwater Frame		
Maximum Soil Storage Capacity	mm	UVQ tutorial
Soil Storage Field Capacity	mm	UVQ tutorial
Maximum Daily Drainage Depth	mm	UVQ tutorial
Roof Area Max Initial Loss	mm	UVQ tutorial
Effective Roof Area	%	UVQ tutorial
Paved Area Max Initial Loss	mm	UVQ tutorial
Effective Paved Area	%	UVQ tutorial
Road Area Max Initial Loss	mm	UVQ tutorial
Effective Road Area	%	UVQ tutorial
Drainage Factor Ratio	ratio	UVQ tutorial
Base Flow Recession Constant	ratio	UVQ tutorial
Wastewater Frame		
Infiltration Index	ratio	UVQ tutorial
Infiltration store recession constant	day^{-1}	UVQ tutorial
Percentage Surface Runoff as Inflow	%	UVQ tutorial
Dry Weather Overflow Rate	%	UVQ tutorial
Wet Weather Overflow Trigger	kL	UVQ tutorial
Irrigation Frame		
Garden Trigger to Irrigate	ratio	UVQ tutorial
Open Space Trigger to Irrigate	ratio	UVQ tutorial

Data Field Name	Unit	Data Source
Observed Volumes		
Imported Water Wastewater Stormwater	kL/y kL/y kL/y	YW, Sandy Lane Report
Contaminants		
Assumed Values		
Bathroom Contaminant Load	mg/c/day	Literature
Toilet Contaminant Load	mg/c/day	Literature
Kitchen Contaminant Load	mg/c/day	Literature
Laundry Contaminant Load	mg/c/day	Literature
Road Runoff	mg/L	Literature
Pervious Surface Runoff	mg/L	Literature
Roof First Flush	mg/L	Literature
Fertilizer to POS	mg total	From Neighbourhood Services (DMBC)
Evaporation	mg/L	
Groundwater	mg/L	monitoring network
Imported	mg/L	monitoring network
Rainfall	mg/L	
Pavement Runoff	mg/L	Literature
Roof Runoff	mg/L	Literature
Observed Values		
Wastewater	mg/L	Field measurements
Stormwater	mg/L	Field measurements, Literature
Definitions		
Land Block	A single property that may contain building(s), paved areas and garden areas. May also represent commercial, industrial or institutional/community facility sites e.g. school	
Neighbourhood	A number of land blocks, roads and public open space forming a local area or suburb. Can be residential, commercial or industrial	
Study area	An urban area containing a number of neighbourhoods	

8.3 DETERMINATION OF NEIGHBOURHOODS

UVQ is designed to calculate water quantities and qualities produced within a Neighbourhood (see definition in Table 16 above). The sewage and storm water produced will leave a given neighbourhood either to exit the project study area or to reach another adjacent neighbourhood. The program only provides the option of one single outflow path for sewer and storm water, respectively, for each neighbourhood (Figure 44). Therefore, a first criterion for defining the Neighbourhoods is based on the sewer and the storm water network. This first step led to the creation of 9 regions in the Bessacarr study area (Figure 45). Black pointers indicate sewage outflow and blue pointers show where storm water exits the area.

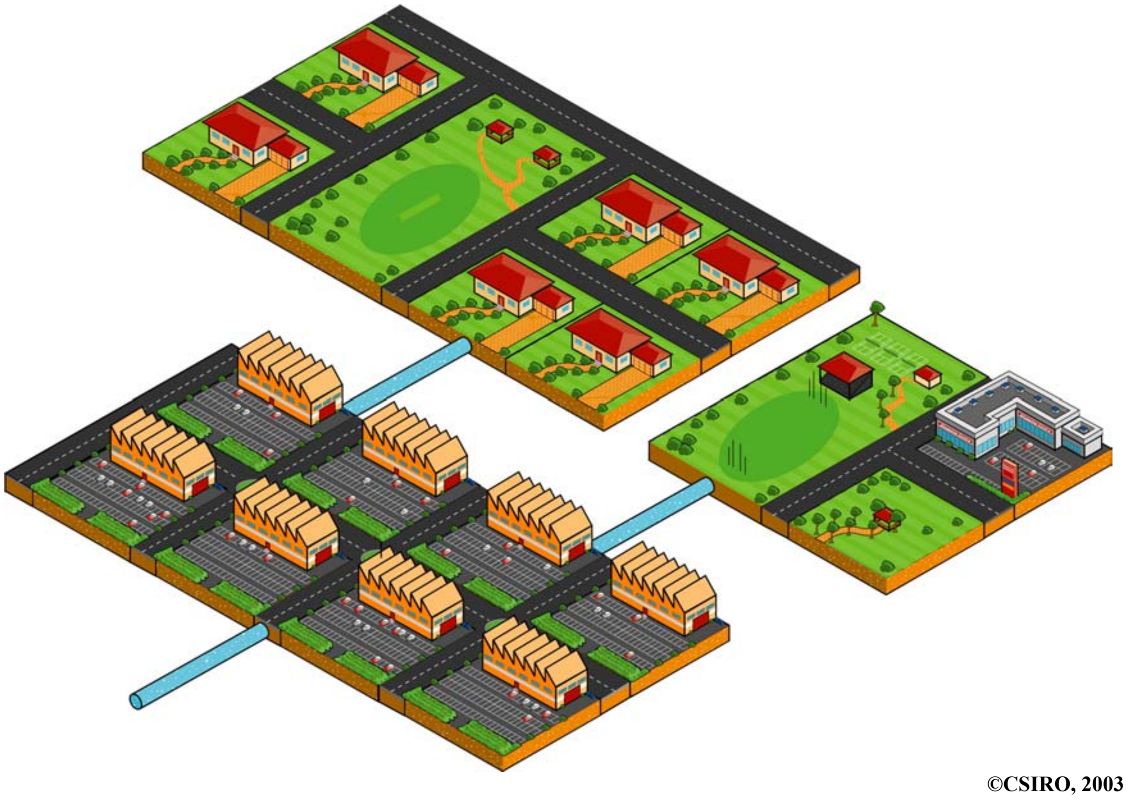


Figure 44 Wastewater system linkage requirements between UVQ neighbourhoods

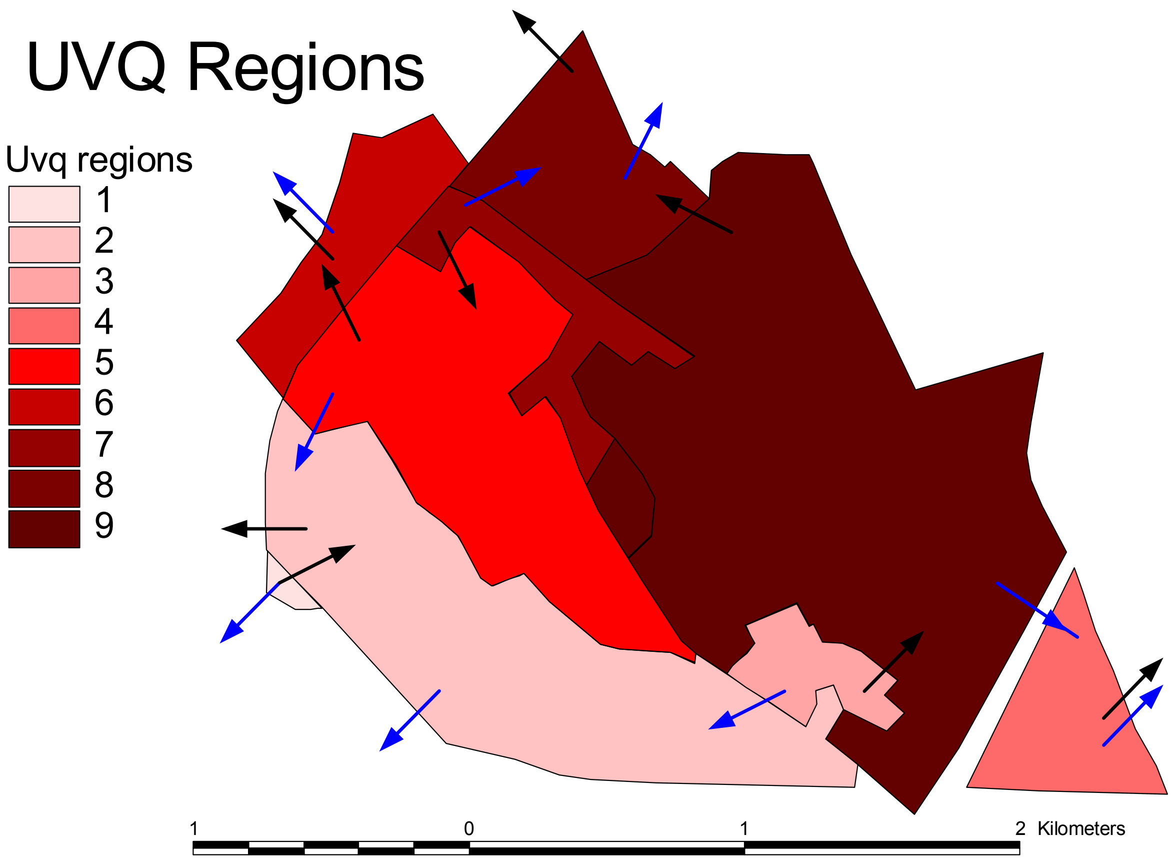


Figure 45 The 9 UVQ regions resulting from first selection based on the restriction that there is only one sewage and storm water outflow from a region. Black pointers indicate sewage water outflow and blue pointers indicate storm water outflow.

The second step takes into account that regions with different land use characteristics have to be distinguished because they produce different wastewater/storm water volumes and qualities. Therefore, the analysis of the detailed land use map obtained from Doncaster Metropolitan Borough Council (DMBC) was used to subdivide each region into land use polygons (Figure 46). The map was used to distinguish between various housing types and densities that are likely to produce different water use patterns (e.g. varying garden irrigation) and different sewage qualities per area.

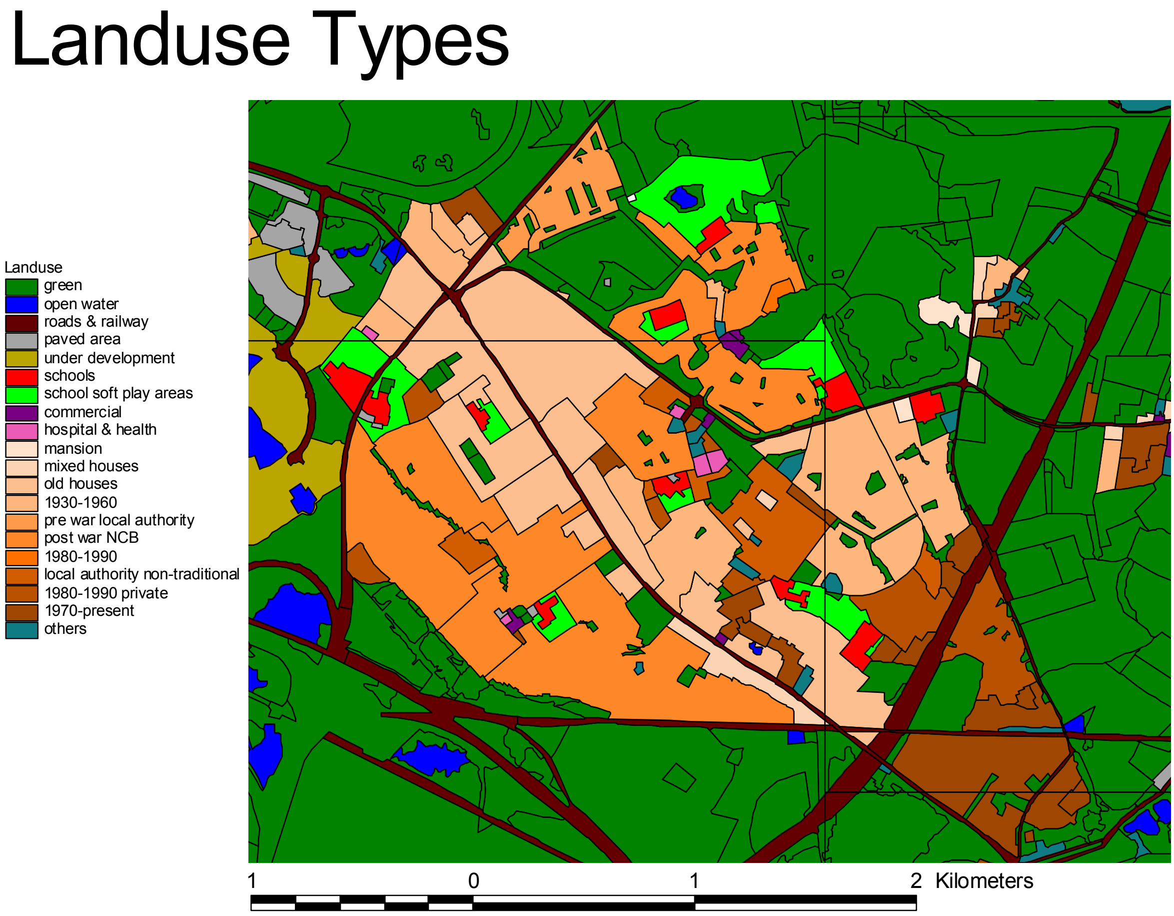


Figure 46 Detailed land use map as provided by Doncaster Metropolitan Borough Council (DMBC)

Therefore, each polygon class area was analysed for its total roof area, number of houses and number of gardens using the 1:10’000 OS map and aerial photos obtained from Doncaster Council. The number of gardens was used as a surrogate for housing unit because at 1:10,000 scale, some building outlines may contain more than one property (e.g. terraced and semi-detached units). Thus a semi-detached unit could be identified as such because there would be a subdivided rear and/or front garden outline.

The residential land-use classes used by DMBC are prefixed 9.1.*. The number of gardens was normalised for each housing class (total number of gardens divided by polygon area) was calculated for each polygon of each of the 15 different sub-types. This was in order to simplify the number of housing classes. The results of the analyses are displayed in Figure 47. It can be seen that the number of gardens per area and thus the number of households per area varies significantly, even within one housing class.

Ideally, each polygon analysed would form a separate neighbourhood in UVQ. However, firstly the model would be too complicated to calibrate due the large number of neighbourhoods involved and secondly there are insufficiently detailed data available to justify the calibration of each neighbourhood.

At the present early stage of experience in using UVQ the number of neighbourhoods involved has been reduced by aggregation, taking the major differences outlined above into account. Two main groups of housing types can be distinguished from the analyses: The older housing areas with more garden area (9.1.10 and 9.1.11) and newer denser housing types (9.1.12-9.1.24) (Figure 48). These two aggregated types are expected to produce distinctively different water fluxes and qualities. If the calibration data are precise enough and this initial selection does not permit a fit, the current selection will be refined to improve the model.

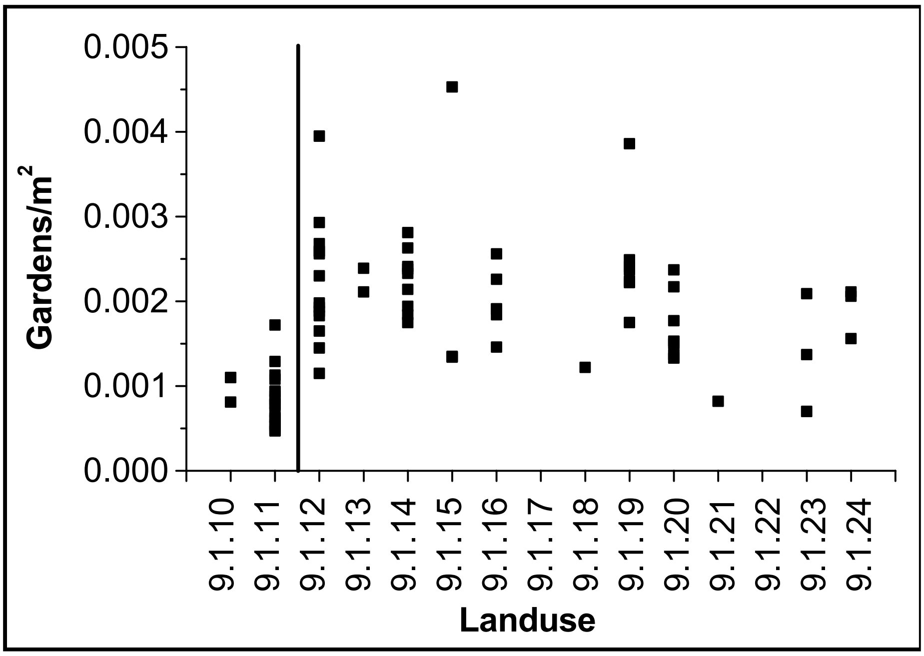


Figure 47 Results of analysis of land use maps for each housing type. Points show the average number of gardens per m^2 of the total polygon area analysed. The line distinguishes old, pre-war, from new houses.

As a separate exercise, the following landuse types were also used to define other neighbourhoods within the 9 water infrastructure regions shown in:

- Schools
- Hospital
- Commercial buildings

This second selection step resulted in a final total of 20 different neighbourhoods to be modelled by UVQ (Figure 48).

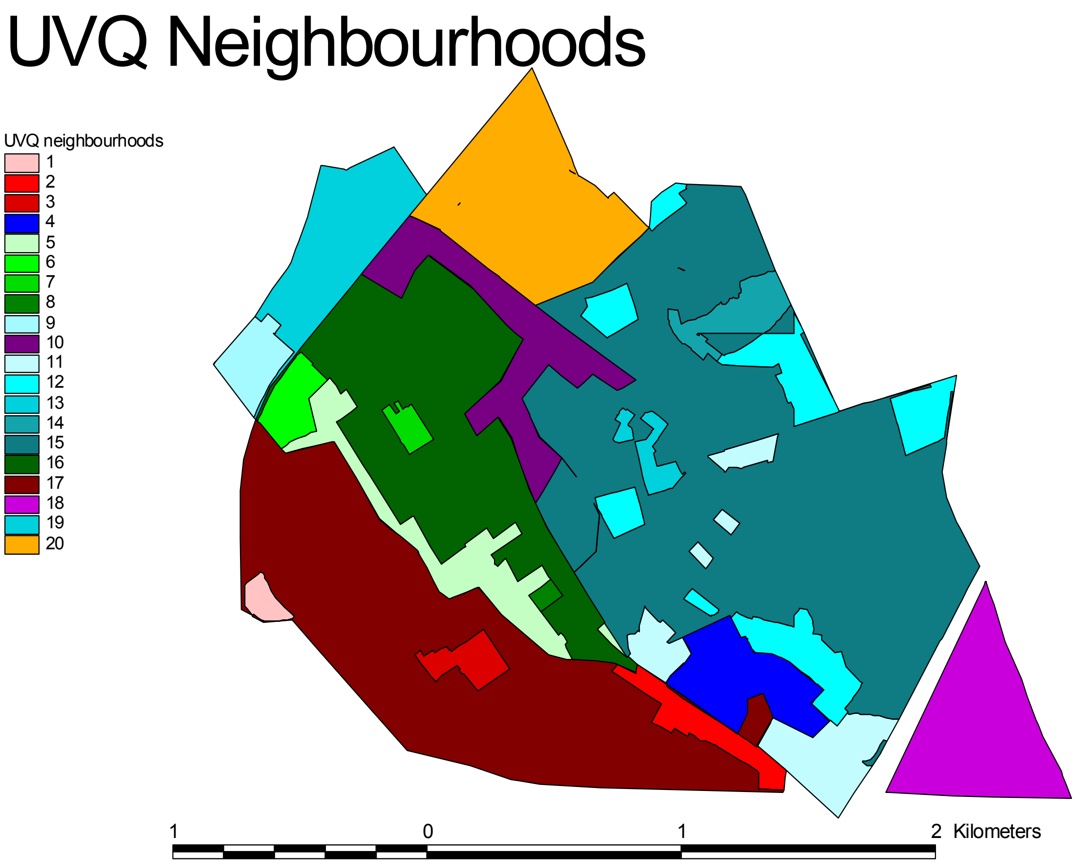


Figure 48 20 proposed UVQ neighbourhoods.

8.4 CONCLUSIONS

The pipe system of the project area is very well defined and consists principally of separate storm water and sewer networks. This makes it a straightforward task to separate different neighbourhoods with different sewer and storm water outflows. Furthermore, the detailed digital land use map from Doncaster Council was most helpful in distinguishing between different housing types and densities (see previous chapter). However, in detail the different land use types (roof, paved, garden, road) as defined from the map analysis are quite difficult to separate, and support was required from aerial photograph cover. These helpful in identifying actual road widths because the OS maps use uniform widths for cartographic reasons. This type of analysis helped to distinguish the approximate paved areas in front of houses and around commercial buildings and schools.

Unfortunately, calibration data are limited to a design study summary of sewer volumes measured over one month in August 1993 (DMBC, 1994). Furthermore, water use was requested for the entire suburb of Bessacarr to pin down at least the approximate sewer amounts produced and to find out more about green space irrigation patterns during summer. As soon as these data arrive the calibration process can be started.

The sewer quality measurements currently being undertaken as part of the on-going field sampling program will provide more information on approximate concentrations of indicator substances and other analytes in both the sewer and storm water network. However, when information on water volumes is missing, calibration of quality parameter is difficult because of the diverse water quality of different water sources (i.e. bathroom, toilet, roof runoff, etc.). The concentrations of water quality parameters coming from these sources can vary over several orders of magnitude (Eriksson et al. 2002).

It is clear already that a precise calibration of the storm water system based on actual measured volumes will not be possible as such data are not available at present. The possibility of a field survey is being explored by the UK team but in the event that this is not practicable, general industry-accepted values may be employed to validate the model assumptions.

9 Stakeholder consultation

9.1 LOCAL CONSULTATION: FIRST PROJECT NEWSLETTER

To keep the consultation process active, and provide some feedback to key members of the project liaison group, a project newsletter scheme has been introduced. The first edition was published in September and widely circulated to contacts within the key data providers and field programme facilitators (Yorkshire Water, Doncaster Council and the Environment Agency). The newsletter was also disseminated to interested collaborators in the Doncaster area such as residents who expressed an interest in the project,as well as McAuley School, on whose grounds one of the multilevel piezometers is located. Further newsletters are planned, at approximately 8-month intervals, to keep stakeholders abreast of progress and retain their interest in the project. The newsletters will also be sent to water industry interested parties as a wider project dissemination aim.

9.2 THE WIDER CONSULTATION PROCESS

An end-user workshop for all of the projects in the CityNet cluster (Care-W, APUSS, AISUWRS, DayWater, CD4WC and Care-S) was undertaken on 16-17 March 2004 in Ghent Belgium. At the invitation of the UK project team, Mr Gerd Cachandt (Yorkshire Water) participated and presented a paper as an AISUWRS project stakeholder participant.

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Robens
Centre for Public and Environmental Health

Construction of 5 Depth Specific Groundwater Sampling Sites in Doncaster, UK

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Robens Centre for Public and Environmental Health
University of Surrey, Guildford, November 2003

Contents

Figures

Tables

Summary

This report comprises the technical background and the practical application of drilling and installing multilevel sampling sites for the AISUWRS (Assessing and Improving Sustainability of Urban Water Resources and Systems) project. It is meant to show the decision processes undergone during site selection and the choice of materials and techniques to be used. This document fulfils the requirements of work package 4 to produce a comprehensive description of all drilling and infrastructure work undertaken in Doncaster as part of the development of a depth-specific water sampling network.

In the first part, the technical background, together with experiences and recommendations, are given to show the connection to previous construction techniques and to compare the applied methods. In the second part, full details are provided about the final drilling and installation works. Furthermore, all results and interpretations of the pumping tests and first conclusions for the local hydrogeology resulting from observations and experiences made so far are included.

1. Introduction

The AISUWRS project will use different computer models to assess and improve the sustainability of urban water resources and systems in 3 European cities: Doncaster in the UK, Rastatt in Germany and Ljubljana in Slovenia, and draw on previous experience in Perth and extend it on Mt. Gambier, both located in Australia. The project aims to analyse these existing urban water supply and disposal scenarios, which vary in their handling of contaminants in the different urban water systems and assess the potential effect of these contaminants on groundwater contamination. Contaminant sources, their flow paths and the sinks will be identified for different urban areas and quantification of the contaminant loads will be undertaken. In addition the AISUWRS project aims to develop a system making use of innovative pipeline and urban water system assessment methods.

The British Geological Survey (BGS) and the University of Surrey (UNIS) will collaborate to investigate the UK case study city of Doncaster, which public water supply relies mainly on water drawn from a well field east of the city tapping the important Sherwood Sandstone aquifer. The city will be a case study for the modelling system produced by the EU partners.

An important part of the field work to understand the hydrogeology of the area and obtain the required inputs for the models will involve testing and validating techniques for assessing groundwater residence times in the city, where anthropogenic influences on water balance are likely to be major. UNIS and BGS agreed to jointly undertake a sampling program of existing fully penetrating boreholes and new test boreholes in the urban area, where microbiological and chemical water quality will be tested including faecal coliforms, faecal streptococci, coliphage and the USEPA priority viruses (enterovirus, rotavirus, Norwalk Like Viruses, Astrovirus and Adenovirus).

The new sampling sites will be equipped with multiple depth sampling facilities to enable groundwater sampling at different depths. Similar work was done in the cities of Nottingham and Birmingham (Taylor et al., 2003). By sampling depth profiles we hope to be able to calculated vertical penetration rates of urban contaminants and to study detailed flow processes within the Sherwood sandstones.

2. Technical Background

2.1. Drilling Methods

Selection of a drilling method from the methods available requires consideration of the study objectives, as well as site conditions and financial constraints. Because a primary purpose of installing the wells is for water-quality sampling, a drilling method that has minimal effect on ground-water chemistry should be the primary consideration for selection of a method.

When considering the installation of wells for sampling ground-water quality, preferred drilling methods are those that minimise

- the possibility of contamination of aquifers and aquifer pore water by foreign drilling fluids
- cross-contamination between aquifers by drilling fluid, pore water, and drill cuttings

In some cases, a method of drilling that minimises the potential for subsurface contamination by the drilling process might severely limit collection of other data at the well that are also important to meet the study-component objectives. This requirement is at odds with the most preferred methods of drilling in order to install wells for water-quality sampling. The study must weigh the cost benefit of data desired against the practical constraints of the drilling methods being considered and the primary objective of collecting ground-water-quality samples that accurately represent ground-water chemistry.

Well-construction information must be documented at the time of well installation, as discussed in the section "Documentation".

2.1.1. Logistical considerations

When drilling is done within a clear project schedule, logistic consideration are of high importance for a successful installation of monitoring wells. The major points to keep in mind are:

- Accessibility of the drilling site
- Ability to obtain permits and approval to drill at the site
- Availability of necessary equipment
- Time available to complete drilling program

2.1.2. Drilling considerations

A second point to consider is the logistics during drilling, particularly when other activities are planned (e.g. geophysical logs, pumping test or well installations)

- Types and competency of water-bearing units to be drilled and sampled
- Types and quality of lithologic and other borehole logs required
- Types and quality of aquifer samples required
- The importance of minimising contamination of aquifers by a drilling fluid
- The importance of minimising cross contamination between aquifers
- The importance of minimising disturbance of aquifers during drilling
- Total depth of drilling anticipated
- Casing diameter and casing material selected for the monitoring well
- Ease of completing the monitoring well as designed, for example ease of installation of filter pack, grouting, and instrumentation

2.1.3. Economic considerations

Last but not least, economic considerations will limit the choice of drilling technique; particularly when the drilling works are performed within a clear project budget. To show the advantages and disadvantages of different drilling methods the most important techniques are listed in Table 1.

Table 1: List of advantages and disadvantages of different drilling techniques (Environment Agency, 2000; Aller et al., 1989; Brandon, 1986; Driscol, 1986; British Standards Institution, 1999).

Method	Advantages	Disadvantages
Cable tool	• Inexpensive • Easily cleaned • Easy to identify lithological changes • Bulk and undisturbed samples possible • Minimum use of drilling fluids • Use of temporary casing allows accurate installation of lining and annular filling	• Slow • Cannot penetrate hard rock • Can smear sides of borehole
Rotary auger	• Rapid • Inexpensive • Easily cleaned • Hollow stem augers allow continuous sampling in unconsolidated materials • Lining can be installed directly into stem augers • No drilling fluids needed	• Cannot penetrate hard rock • Hollow stem augers cannot penetrate where cobbles or boulders are present • Sampling depth and water strikes difficult to identify using solid stem augers • Solid stem augers cannot be used in loose ground (hole collapses) • Unable to install annular fill and seals in collapsing ground
Other rotary drilling	• Can be inexpensive • Fast in consolidated materials • Can be adapted to drill all formation types by changing bits • Continuous samples can be cored in consolidated rock and clay	• Can be expensive • Fluids need to be added (e.g. air, foam, water, mud) • Possible introduction of contaminants (including oil from air compressor) with circulation fluid • Recovery of samples can be slow when drilling at great depth • Can smear sides of borehole • Synchronous casing methods in unconsolidated formation only allow installation of narrow diameter lining

2.2. Construction Materials

Any construction material or sampling equipment which comes into contact with the water sample being collected, can affect the integrity of the sample by leaching compounds into solution, by the adsorption (and subsequent desorption) of compounds from the solution, by gas diffusion through the material and also by solute transfer. This becomes a serious problem when organic compounds are to be monitored (Blakey et al., 1997). It is important to select the appropriate materials, and type, diameter, and length of casing and screen, as these can affect the quality of a ground-water sample. Biased water-quality data can arise from chemical and physical interaction between groundwater and materials used to construct monitoring wells. These biases can result from leaching, sorption/desorption, or volatilisation.

2.2.1. Lining Material

A first point to consider is the choice of the lining material. The most important materials to construct monitoring wells are listed in Table 2.

Table 2: List different rigid lining materials with recommendations from US EPA.

Material	Recommendations
PTFE (Teflon)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leachate impacted hydrogeologic conditions. Virtually an ideal material for corrosive situations where inorganic contaminants are of interest.
Stainless Steel 316	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leach ate impacted hydrogeologic conditions.
Stainless Steel 304	May be prone to slow pitting corrosion in contact with acidic high total dissolved solids aqueous solutions. Corrosion products limited mainly to Fe and possibly Cr and Ni.
HDPE, MDPE, PVC	Recommended for limited monitoring situations where inorganic contaminants are of interest and it is known that aggressive organic leachate mixtures will not be contacted. Cemented installations have caused documented interferences. The potential 'for interaction and interferences from PVC well casing in contact with aggressive aqueous organic mixtures is difficult to predict. HDPE, MDPE and PVC are not recommended for detailed organic analytical schemes. Recommended for monitoring inorganic contaminants in corrosive, acidic inorganic situations. May release Sn or Sb compounds from the original heat stabilisers in the formulation after long exposures.
Low-Carbon Steel Galvanised Steel Carbon Steel	May be superior to PVC for exposures to aggressive aqueous organic mixtures, These materials must be very carefully cleaned to remove oily manufacturing residues. Corrosion is likely in high dissolved solids acidic environments, particularly when sulfides are present, Products of corrosion are mainly Fe and Mn, except for galvanised steel which may release Zn and Cd. Weathered steel surfaces present very active adsorption sites for trace organic and inorganic chemical species.

2.2.2. Borehole Screen

A properly designed borehole screen serves the purpose of allowing water to flow into the borehole whilst minimising the amount of sediment inflow, particularly when used in conjunction with a gravel pack. Many screens can be supplied in a variety of slot sizes and may also incorporate filter wraps to reduce the size of openings. In water well design, it is possible to relate slot size to the formation being screened to ensure that silt is removed from the formation during development of the well to produce a clear inflow of water.

Screen apertures should be selected to minimise fine particles entering the borehole and to optimise flow into the borehole at a velocity which will not cause undue turbulence.

For monitoring boreholes in very fine formations (e.g. predominantly silts or clays) it is very difficult to achieve either of these objectives. If the formation grain sizes are at or below fine sand (0.2 mm) the use of small slots (e.g. 0.25 or 0.5 mm), will do nothing to stop particle entry, but may actually increase entrance velocities and encourage entrainment. If a very small slot size is achieved (e.g. by use of a geotextile wrap) there is a risk of clogging. In these situations, the use of a filter pack (e.g. 0.5 to 2 mm grain size) with as wide an annulus as possible around the screen should be encouraged, rather than reducing the slot size to a point where clogging may occur.

2.2.3. Backfill Materials

The role of a filter material is to support the formation around the screen and, in suitable strata, to provide improved hydraulic characteristics to minimise turbulent flow into a well during pumping. The filter material is typically sand or gravel. It needs to be larger than the effective slot size of the screen, but should not be excessively coarse so that it serves no filtering purpose. For example, the use of 10mm gravel around screens provides very little filtration potential.

Well completion ensures that the hydraulic head measured in the well is that of the aquifer(s) of interest, ensures that only the aquifer(s) of interest contribute(s) water to the well, and prevents the annular space from being a vertical conduit for water and contaminants.

Specific details of well completion require consideration of several hydrogeologic factors, including:

- the depth to water, to the top of the aquifer of interest, and to the zone in the aquifer to be monitored
- the nature of materials that make up the aquifer to be monitored and that overlie the aquifer--for example, whether the materials are consolidated or unconsolidated
- expected water-level fluctuations
- expected direction of the vertical head gradient-downward, upward, or fairly uniform with depth
- whether the aquifer is confined or unconfined
- the design of the monitoring well(s). Completion requirements and practices can differ considerably among wells.

The well casing and/or screen are installed in the borehole as the first step in well completion. After installation of the well casing and, if needed, the well screen, the major elements of well completion consist of the following:

1. **If a well screen is used and a filter pack is required, the primary filter pack is installed around the well screen.**

   The primary filter pack (also commonly called a sand or gravel pack) is material that fills the annulus around and just above the well screen to retain and stabilise material from the adjacent screened unit. A filter pack has a greater grain size than that of the aquifer material in the vicinity of the screen. Filter-pack grain size and gradation are designed to stabilise the hydrologic unit adjacent to the screen and permit only the finest grains to enter the screen during development, resulting in relatively sediment-free water for sampling after development. The primary filter pack should consist of relatively inert material such as quartz, contain no limestone or other calcareous materials such as shell fragments, and contain no organic material such as wood fragments or lignite. Alternatively, filter-pack material of known chemistry (ASTM, 1992) can be used, such as glass beads.

   The primary filter pack commonly is extended up the annulus to a minimum of 5ft above the top of the screen (Hardy et al., 1989), if a secondary filter pack is impractical. The primary filter pack must not intersect multiple water-bearing units, nor cross confining units that otherwise would not be screened. Intersection of such units can result in an artificial, vertical, hydraulic connection along the annulus between these units, and can affect the chemistry of the ground water being sampled.

2. **A secondary filter pack is installed above the primary filter pack.**

   The secondary filter pack is a finer grained material than the primary filter pack, placed in the annulus between the primary filter pack and the overlying annular seal, or between different types of annular seals (ASTM, 1992, p. 124). The purpose of the secondary filter pack is to prevent material used for the annular seal from infiltrating and clogging the filter pack and from affecting ambient water chemistry. The secondary filter pack should consist of inert material, consistent with that of the primary filter pack. A length of secondary filter pack of about 1 to 2ft is recommended (Hardy et al., 1989, p. 16; ASTM, 1992, p.129, Fig. 2 and 3).

3. **Annular seals are installed to about frost level.**

   Annular seal(s) are installed from above the secondary filter pack or the extended primary filter pack to near land surface, in order to seal the annular space between the casing and borehole wall. These seals prohibit vertical flow of water between aquifers and prevent cross-contamination of aquifers by contaminants. They also protect against infiltration of water and contaminants from the surface.

   A 3- to 5-ft plug should be placed above the extended primary or secondary filter pack (ASTM, 1992). The plug is formed from a hydrated material such as bentonite or cement that acts as a sealant. The choice of a sealant material must minimise possible effects on the constituents to be analysed from the well. Penetration of the sealant into the underlying filter pack should be limited to less than a few inches (Hardy et al., 1989).

   The remaining upper part of the annulus is grouted to below the frost line. The grout prevents movement of ground water and surface water within the annular space between the well casing and borehole wall. It also maintains the structural integrity and alignment of the well casing.

   Drill cuttings removed from the borehole sometimes are used as grout instead of bentonite or cement, but the effectiveness of these materials as a sealant needs careful evaluation and is not to be used for well of the US National Water-Quality Assessment Program (NAWQA). For NAWQA, bentonite, cement, or mixtures of bentonite and cement probably are the most common grout materials that will be used. Generally bentonite is recommended for grout if the well is used for water-quality sampling. However, as in the case of the underlying seal, the choice of a material depends on the purpose of the well. Detailed discussions of characteristics of annular seals and methods of placement can be found in (ASTM, 1992) and (Driscol, 1986).

The use of sealants in monitoring boreholes introduces a potential source of contamination, by 'bleeding' from the grout or bentonite into the sampling zone. Bentonite can introduce elevated sodium concentrations and fine suspended solids into groundwater. Samples from grout-contaminated wells are characterised by high pH values (usually over 10) and elevated magnesium and sulphate (derived from Portland cement). Once contaminated, it can take many years for a grout or bentonite contaminated borehole to loose all traces of contamination.

4. A surface seal is installed.

The surface seal prevents surface runoff down the annulus of the well and, in situations in which a protective casing around the well is needed, holds the protective casing in place. The depth of installation of a surface seal can range from several feet to several tens of feet below land surface. Local regulatory agencies might specify a minimum depth of installation. Because of likely desiccation of bentonite, a cement surface seal is recommended.

5. A protective casing is installed around the well at land surface.

A protective casing should be installed around the well to prevent unauthorised access to the well and to protect the well from damage. The protective casing is installed at the same time as the surface seal and should extend to below the frost line (ASTM, 1992). One design for protective casing is a steel casing with vented locking protective cover and weep hole, which permits condensation to drain out of the annular space between the protective casing and well casings (Fig. 4). (ASTM, 1992, p. 132) also calls for coarse sand or pea gravel or both to be placed in the annular space between the protective casing and the well to prevent entry of insects. A second design is a steel casing with bolted or locked manhole cover enclosing a well that is flush with the land surface.

2.3. Depth-integrated versus depth-specific sampling

Early in the selection process for groundwater-quality monitoring, it was necessary to determine whether depth-integrated or depth-specific samples were desired. A depth-integrated sample is one that is obtained when water is pumped from a well that has a long screen or from a well with an open borehole. As pumping continues water can flow into the well or open boreho1e from various depth levels (in nature possibly well separated by seals) rather than from an isolated depth level. A depth-specific sample is one that is obtained in a specific narrow depth interval from an isolated zone in a well or boreho1e.

Depth-integrated and depth-specific sampling devices are illustrated schematically in Figure 1. Depth-integrated sampling can identify the presence of a contaminant in the groundwater system but cannot determine the actual depth or *in situ* concentration of the contaminated zone. The concentrations obtained from a depth-integrated sample are normally dependent on the length of the screened interval, the depth of the pump intake, and the rate or time-period of pumping. Even under very controlled conditions of pumping and sampling it is generally not possib1e to deduce the concentration distribution in the formation. Therefore, depth-integrated sampling is usually the preferred approach for detailed groundwater-quality monitoring. However, the depth-integrated approach may be appropriate in situations where one simply desires, with minimum drilling effort, to determine whether or not contamination exists at a particular monitoring site. It is often the most appropriate technique for evaluations of water quality for public water supply wells.

Depth profiles are usually an important aspect of detailed groundwater quality investigations since contaminant concentrations in bedded deposits can vary markedly in the vertical direction and, in some situations, the entire zone of contamination may occupy only a small part of the total aquifer thickness. This zone could go undetected, or could mistakenly be assumed to represent conditions over the entire aquifer depth, if vertical profiles were not available. When depth-specific sampling is performed, the water sample is drawn from a narrow interval in the borehole in a manner that minimises mixing of water from different depth zones. If this is accomplished, the concentrations in the sample at the moment of sampling will represent the concentrations in the formation at the depth of sampling. When this sampling approach is used, it is usually necessary to do depth-specific sampling at several depths at each sampling location in order to determine the overall conditions of groundwater quality at the location (Graham, 1991).

2.4. Concepts of Multilevel Installations

There are three designs that can be used for permanent depth-specific sampling systems (Fig. 1). These are (1) multiple-borehole piezometer nests; (2) multiple-level, single borehole packer sampling; and (3) multiple-level, single borehole piezometer.

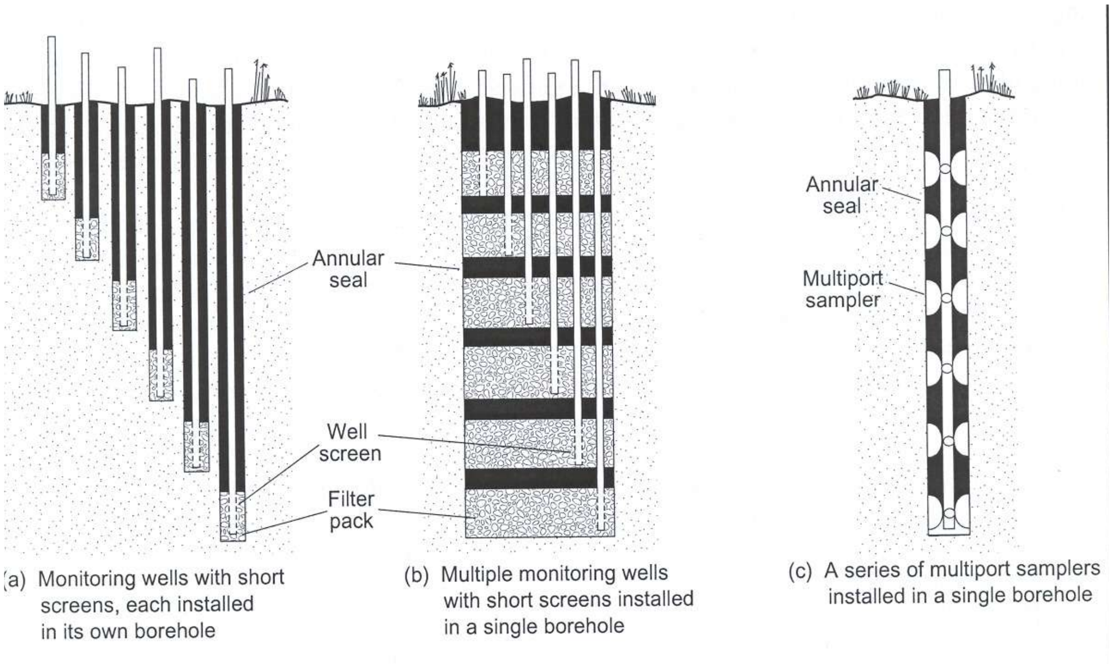


Figure 1: graphical display of 3 different possibilities of depth-specific sampling sites.

The number of nested piezometers than can be placed in one borehole is limited by the borehole size and the size of the tubing (and any couplings) used. Installation, in theory, is similar to that described above for a single piezometer, apart from the need to set separate piezometers into the borehole.
Completion of more than one sampling interval within the same borehole provides a number of challenges for the contractor and competent professional responsible for their design and installation.

2.5. Well Development

Following installation most boreholes require developing in order to remove fluids added during drilling, to clean out silt and clay collected in the borehole and to correct damage caused by the drilling process. The primary objective of bore hole development should be to recreate as far as possible the natural conditions surrounding the borehole so that samples which give an appropriate representation of water quality in the surrounding formation can be readily collected.

Borehole development (and cleaning for maintenance purposes) is often an overlooked aspect of monitoring borehole construction, primarily due to the time and cost involved in achieving full development. A balance has to be achieved between the objective of fully developing or cleaning out a borehole and the objective of attaining an appropriate sample of groundwater (or leachate).

The text in the following section is largely paraphrased from Section 7 of (Aller et al., 1989), which provides a comprehensive review of monitoring borehole development.
Three primary factors influence the process of borehole development.

- **Type of geological strata**: In well-consolidated rocks such as granites and limestones, few fines are released from the rock matrix so that borehole development can be relatively easily achieved. However, fine materials may form part of the rock matrix, be present in fractures or in weathered sections of the rock.

  In consolidated formations such as mudstones, siltstones and fine-grained rocks such as chalk, clay and silt particles may be readily freed from the formation into the borehole.

  In unconsolidated formations, such as sands, gravels, silts and clays, the structure of the formation immediately around the borehole may have altered during drilling and fine-grained particles are readily released from the formation in varying proportions.
- **Design and completion of the borehole**: In clean, well-sorted sands and gravels, monitoring boreholes can be completed relatively easily using an appropriately sized screen with no filter pack.

  In fine-grained unconsolidated formations, monitoring boreholes are normally completed using a screen and sand filter. Development of these, particularly at depth can be problematical and very slow. Difficulties are compounded where unconsolidated material is stratified and the screened section straddles coarse and fine-grained materials.

  Filters packs should be at last 50mm thick - i.e. a borehole should be at least 100mm larger than the installed screen.
  - **Drilling technique**: Air rotary rigs will leave fine particles on borehole walls and within fissures adjacent to the borehole. Development procedures should be aimed at removing these fines.

Where casing has been driven or augers used the interface between the casing and the surrounding formation becomes smeared with fine particulates, which must be removed during development.
If drilling fluids, such as mud, are used, the accumulated 'mudcake' must be removed during development. Other fluids or additives, which are added during drilling, need also to be removed as efficiently as possible by the development process.

2.6. Local Hydrogeology

2.6.1. Geology

The major geologic formations in the study area are the Mercia Mudstone, the Sherwood Sandstone aquifer and the underlying Permian stratigraphy. The outcrops of the formations are shown in Figure 2.

The Sherwood Sandstone Group (formally the Bunter Sandstone) comprises a thick sequence of red, brown and more rarely greenish-grey sandstones of fine to medium grain size with thin layers or lenses of red mudstone and siltstone. South of the study area the Sherwood Sandstone comprises of two well distinctive lithological units, namely the Nottinghamshire Castle Formation (formerly the Bunter Pebble Beds) and the Lenton Sandstone Formation (formerly the Lower Mottled Sandstones). These units are traceable northwards into the study area but are indistinguishable due to diminishing pebble content. These rounded quartzite pebbles are common in the middle and upper parts of the sandstone but they are increasingly rare and smaller in the Doncaster area.

The Sherwood Sandstone is interpreted as a sequence of mainly fluvial sediments deposited along the western margin of the intra-continental Southern North Sea Basin. The Sherwood Sandstone forms rock-head in most western and central parts, but much of it is concealed beneath Quarternary deposits. Farther east, where it dips beneath the Mercia Mudstone, the total thickness increases northwards from about 275m to over 400m (Fig. 3).

In the Doncaster area, fine-grained red sandstone is the dominant feature. However, small quartzite pebbles and rolled mudstone fragments were observed frequently (Gaunt, 1994). Some thicker mudstone layers (few meters) were observed in the north of Doncaster. The existing cores from the area can be summarised as follows. Approximately the lowest 40m of Sherwood Sandstone are characterised by an abundance of thin argillaceous layers and an absence of quartzite pebbles. The sandstone in the lower part of the formation is mainly fine to medium grained, generally thin bedded and locally laminated. The argillaceous layers and laminae are mainly dark red, but few are greyish green. They range from mudstone to, less commonly siltstone. Most are less than 0.5m thick but a few found in the North of Doncaster were up to 2m thick (Gaunt, 1994).

The middle part of the Sherwood Sandstone, from about 40m above the base to 200m, is characterised by fewer argillaceous layers. The sandstone in this sequence is almost entirely red and much of it is medium grained and well sorted. The argillaceous layers have the same characteristics as those in the lower strata, but occur less frequently. Rolled argillaceous fragments are, in contrast, more abundant, occurring both widely scattered and locally concentrated into thin 'marl conglomerate' layers. The largest pebbles recorded are 50mm across but most are well under half this size (Gaunt, 1994).

The upper part of the Sherwood Sandstone, less than 100m thick in the south, is poorly known due to the paucity of cored boreholes and absence of shafts through it. Generally, the appearance is very similar to the lower layers, showing some

argillaceous layers and rolled argillaceous fragments as well as rarely noted fine pebbles. The most obvious variation of the upper part of the Sherwood Sandstone is its greyish colour (Gaunt, 1994).
The sandstone comprises dominantly quartz and feldspar with a cement of calcite, dolomite, haematite and other ferric oxide minerals (Smedley and Trafford, 1999). In a study near Mansfield, the sandstone was found to be carbonate-free down to about 9m below ground (Kinniburgh et al., 1999).

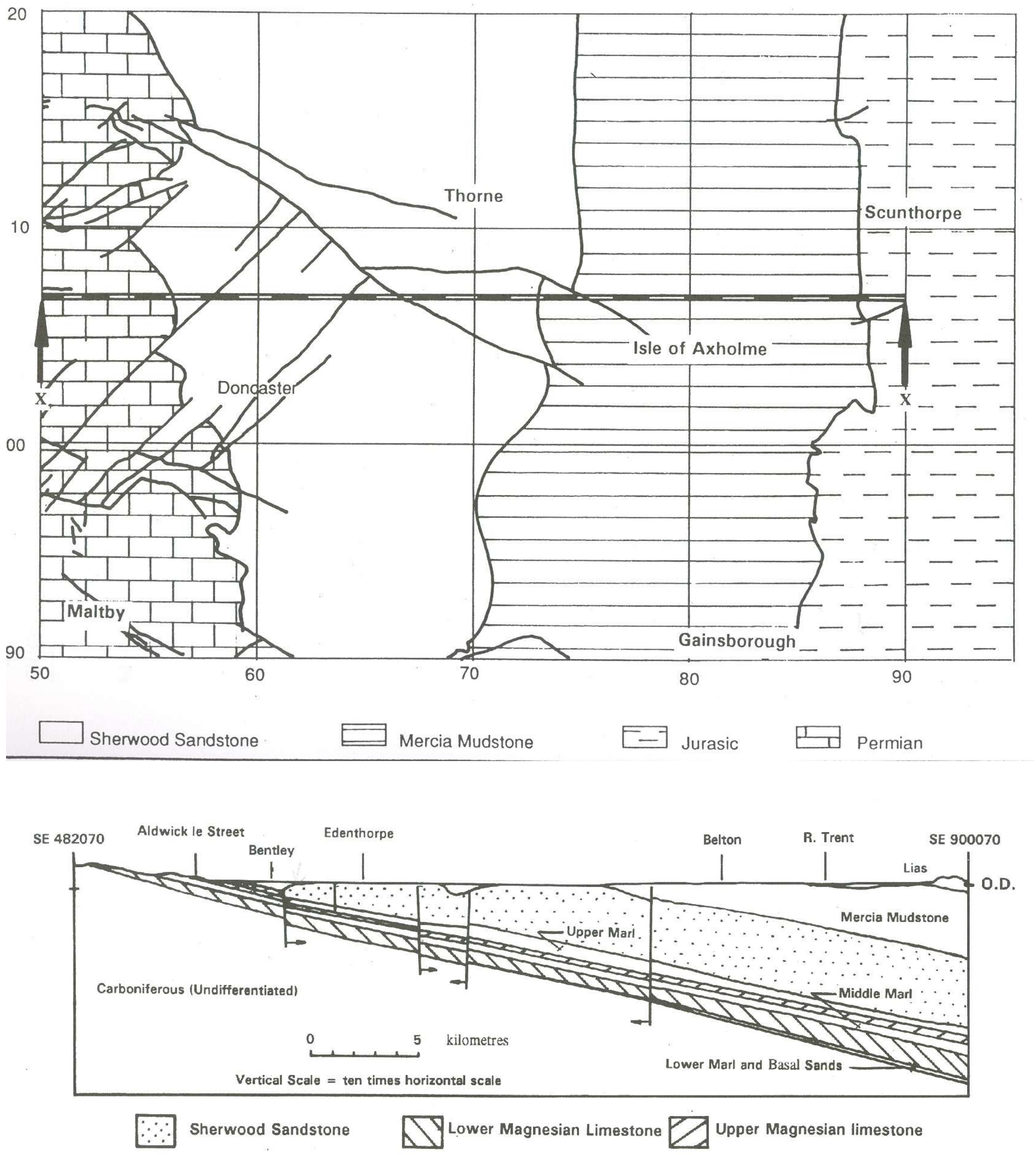


Figure 2: The map on top shows the major Geology of the area around Doncaster. The lower figure shows a cross cut as indicated in the upper map (a vertical exaggeration is applied to show the layers more clearly) from Brown and Rushton (1993).

2.6.2. Structural Geology

The stratigraphy of the sequence dips consistently to the east at between 1-3°. This uniform dip is the result of tectonic activity in the late Jurassic period, approximately 170 million years ago. After the tectonic phases, subaerial and submarine erosion

exposed the lower stratigraphies in an east to west sequence resulting in a north to south outcrop orientation (Brown and Rushton, 1993).
Large scale and extensive faulting of the geological units, including the Sherwood Sandstone sequence, is illustrated in Figure 2 (top map). The Sherwood Sandstone matrix is brittle due to the highly cemented and consolidated nature of the deposits (Brown and Rushton, 1993).

2.6.3. Drift Geology

The drift geology of the area has been rigorously examined and discussed by (Brown and Rushton, 1993). The Sherwood Sandstone is overlain by drift deposits of the Ipswichian, Devensian and Flandrian Quarternary stages. These deposits are widely spread over the area and complex in nature. Deposits range from clay tills and glacial channel deposits, to glacial and fluvioglacial sands and gravels with more recent lacustrine deposits, blown sands and peat. The Quarternary drift lithology is listed in Table 3.

Table 3: Quarternary Drift lithology. Asterisks indicate low permeability layers.

Stage	**Lithological Division**
Flandrian	Alluvium*, Peat*, Blown Sand
Devensian	First Terrace (25-Foot Drift Upper Sand) 25-Foot Sand (Marginal Sand) 25-Foot silt and Clay* Glacial Sand and Gravel, Head*
Ipswichian	Older River Gravel
Older Glacial Stage	Glacial Sand and Gravel, Boulder Clay*

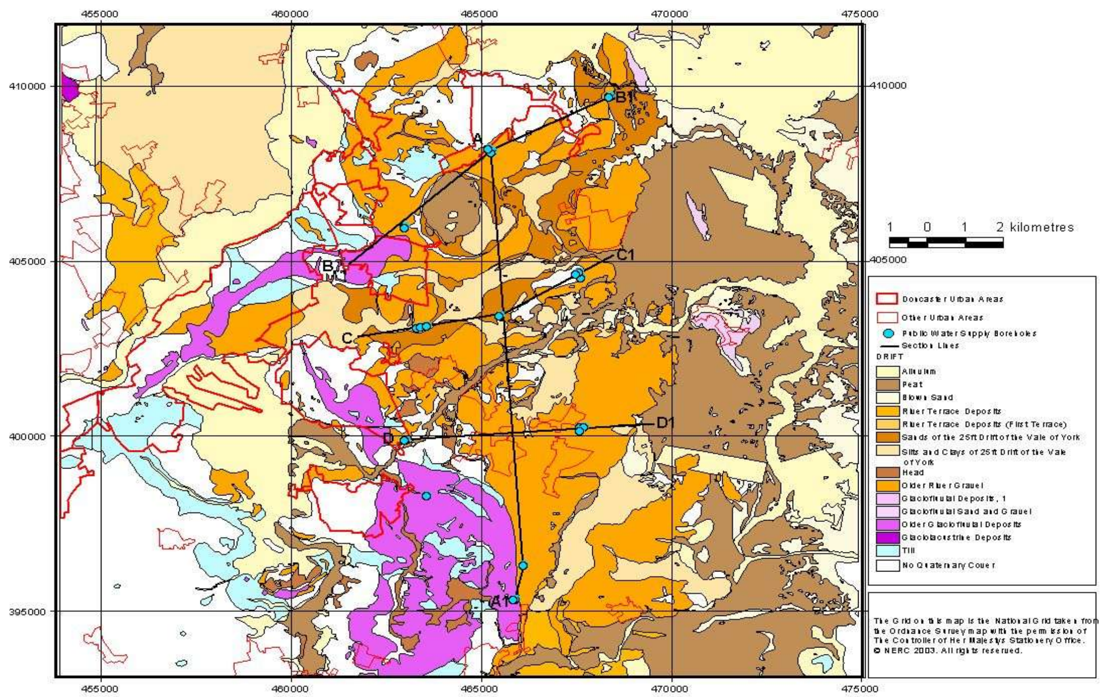


Figure 3: Drift Geology of the area around Doncaster from Morris et al. (2003).

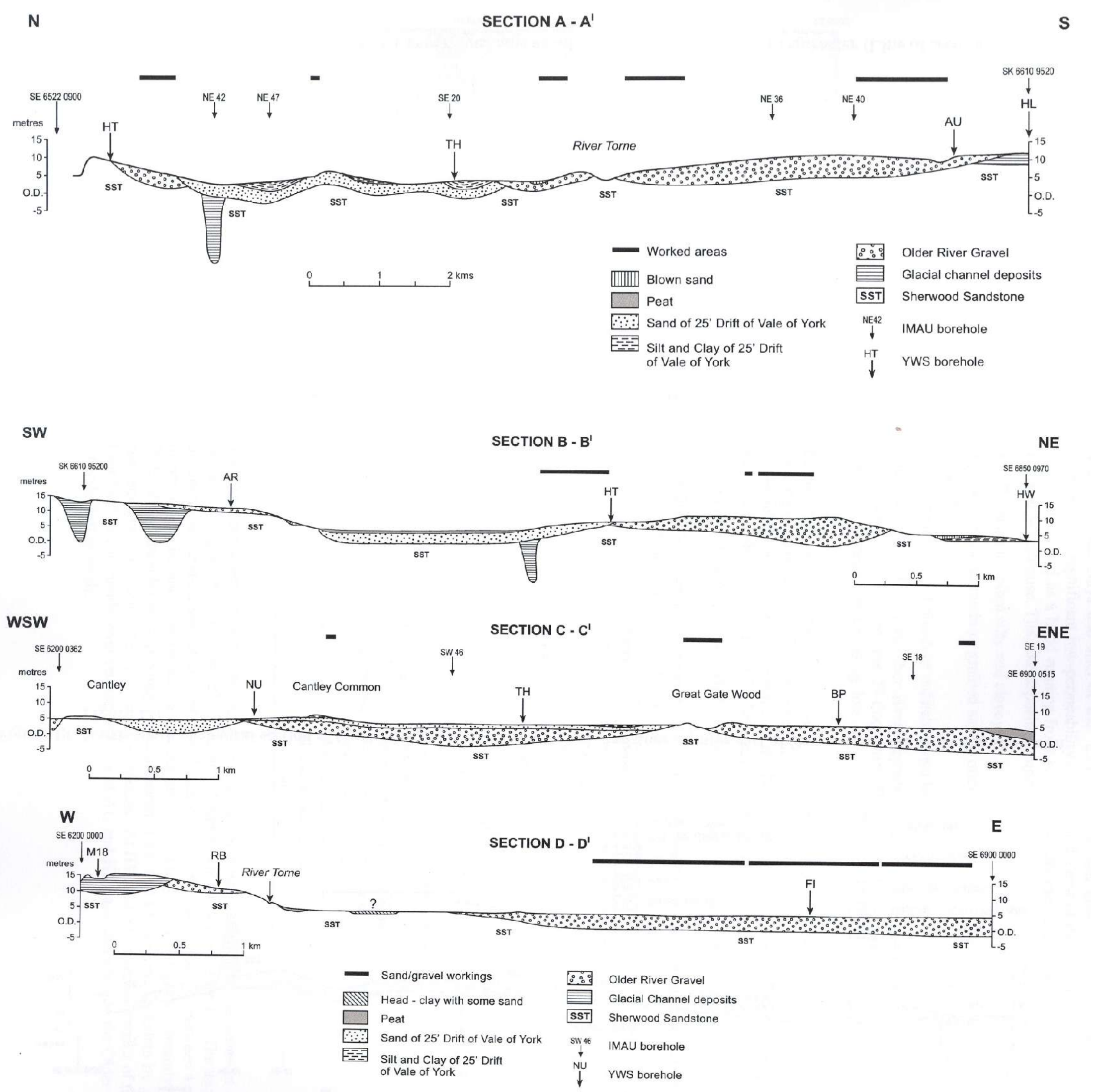


Figure 4: Cross-cuts through local geology as indicated in Figure 3 from Morris et al. (2003).

Figure 3 shows how variable and how important it is to understand the Drift Geology in this area both for finding suitable locations for the multilevel sites and for the interpretation of the results. Figure 4 shows one North-South and 3 East-West cross-sections through the top 30-40m of the drift (see figure 3). It can be seen that the glacial channels are quite important features scraping deep into the Sherwood Sandstone and therefore clearly affect groundwater flow.

3. Multilevel Sites

In this project, we are mainly interested in assessing urban recharge quality and quantity into the Sherwood Sandstone in Doncaster. Therefore, we are focusing on the sandstone layers rather than the Quarternary Drift.

3.1. Selection of Sites

Following the general recommendations listed in chapter 1, we defined and prioritised site criteria to meet the requirements of this project. All criteria are listed in Table 4.

Table 4: Siting criteria for Multilevels

#	Criterion	Comments	Priority
1	Public/utility-owned land	facilitates initial permission and continued access	1
2	Down-gradient of, or surrounded by urban area (housing or industrial)	Ideally of similar general land use e.g all residential, all industrial	1
3	Location safe and easy for subsequent sampling	Needs to be unobtrusive to avoid vandalism and quiet to make sampling safe and secure for field staff and equipment over sampling periods	1
4	On outcrop Sherwood Sandstone or where Quaternary cover is thin and/or likely to be permeable	Makes system simpler to model and sites easier to compare with each other	1
5	Sufficiently down dip to sample significant aquifer thickness (60m+)	Not likely to be a problem on River Don right bank, in Central Doncaster and eastern suburbs	2
8	Depth to water <6mbgl	So that peristaltic pump can be used	2
9	Close to abstraction borehole so that 'mixed sample' comparison possible	May provide quality check and conclusion on high flow layers	2
6	Close to sewer network with high density of recorded sewer damage	Maximises likely pollution source term	2
7	Easy disposal of drilling return fluids	For good neighbourliness, especially if EA discharge consent not being sought	2

During the first inspection of possible drilling sites in May 2003 we found 12 possible sites where drilling would generally be possible (Fig. 5). However, quite a few of these sites were found to be located on the rather deep glacial channels and therefore are unsuitable for our purposes (A1, D1, D3, D5, D7). Further, we were informed that any work on the Town Fields (site D2) would be subject to strong public pressure against it. This would mean, that permission for site access, if it would be finally given, could take quite a while. Generally, we found the best match with our criteria in the Bessacarr area (B1–B4). However, this suburb is far younger than the city centre. Therefore, we decided to drill one borehole on Sandall Beat Play Fields owned by Doncaster Metropolitan Borough Council (DMBC). We hope to see the impact of urban recharge from the old centre of Doncaster in this multilevel. The other 4 sites were decided to be in Bessacarr, namely on the play fields of McAuley Catholic Highschool, on Bolton Hill Play Fields and on Haslam Park, the latter two owned by DMBC. Since there is only little known about medium scale (tenth of meters) variability in the Sherwood Sandstone we use the opportunity of this project to drill 2 sites at a distance of about 80 metres (both on Haslam Park). Haslam Park was chosen for this reason because it is very secure for drilling and sampling.

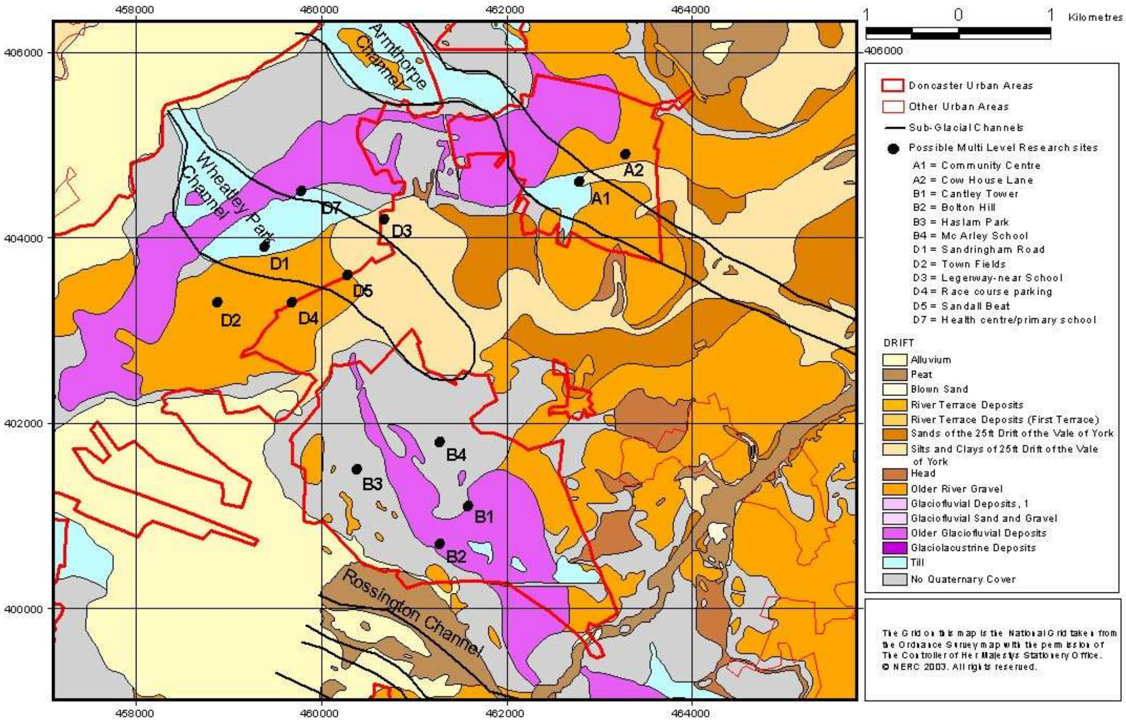


Figure 5: Locations possible sites before applying citing criteria.

3.2. Drilling and Testing Boreholes

3.2.1. Introduction

As we are going to sample mainly groundwater chemical and isotopic parameters and micro-organisms rather than organic compounds we decided to use air-flush drilling technique. Simpler techniques are not possible because we expected the sandstone to be too hard. Air-flush technique is very often used to drill water wells because it is quite inexpensive. We decided to add a permanent casing through the unsaturated zone to prevent the soft, sandy top layers from collapsing into the hole. Within the saturated zone, an open hole was to be drilled down to 60m or down to the underlying Permian Marl sediments. After reaching full depth, the hole was cleaned for 1 hour by flushing it with air. Furthermore, we wanted to take core samples at selected sites and depths to compare them with groundwater samples.
Site permissions and drilling consents were given by the landowners and the Environment Agency.

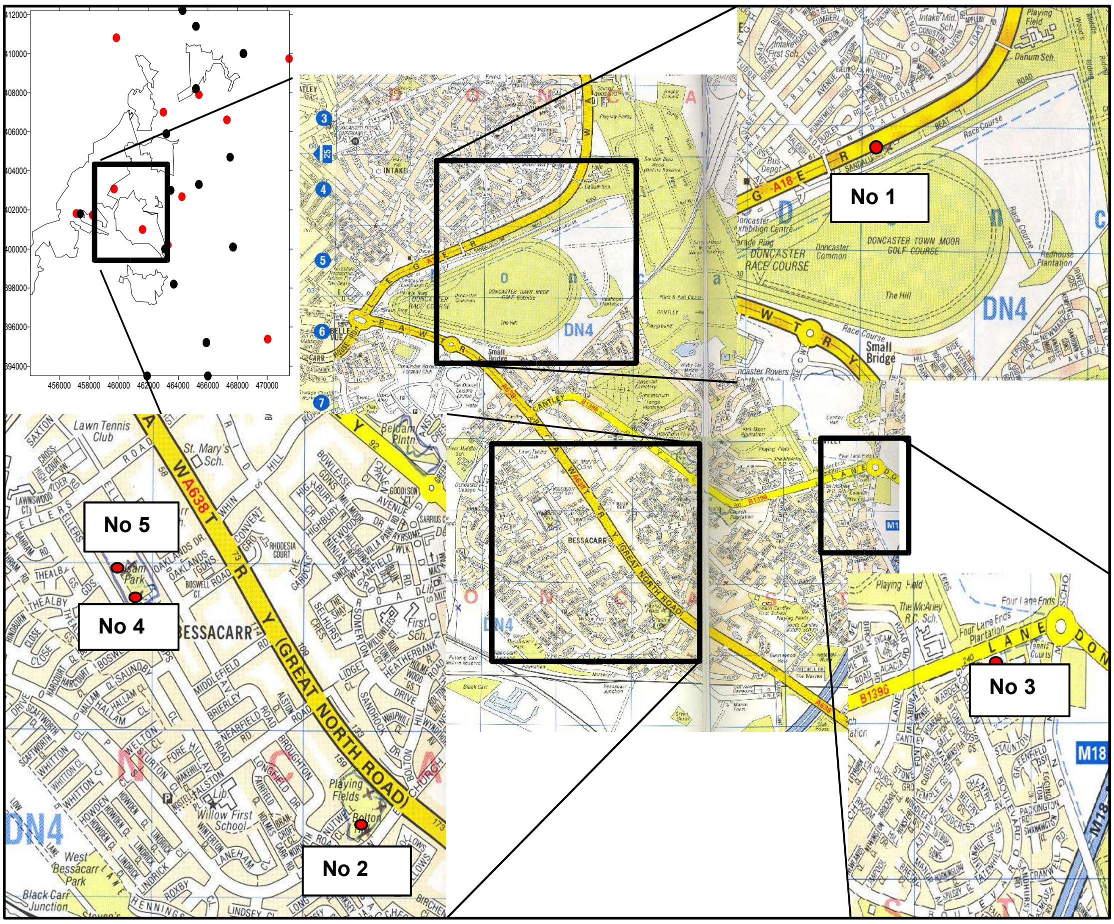


Figure 6: Locations of multilevel sites as shown on the A-Z map of Doncaster. The top left map shows urban area of Doncaster indicated with a black line and the groundwater monitoring network from the EA (black points) and from this project (red points).

3.2.2. Drilling

Drilling started on Monday 01/09/2003 on Sandall Beat site near Doncaster Race Course. After penetrating through some glacial clay and gravel layers red sandstone was hit at a depth of about 6m below ground. After drilling through a few meters of hard sandstone, the water-baring layer was reached at a depth of approximately 13m where the permanent casing was inserted and cemented in. The water level then rose up to about 2.5m below ground, indicating confined conditions. This was a big surprise because confined conditions are only expected below the poorly conductive Quarternary drift layers. However, these layers only reach to a depth of about 6m. Therefore, there must be badly conductive layers in the sandstone preventing groundwater to enter the upper layer. Drilling was continued using a $5^7/_8$” hammer. After penetrating through about 2 meters of hard sandstone, the hammer went through a few meters of soft sand before hitting hard stone again in a depth of about 18m. After that, the drillers observed the hole to cave in slightly. They tested by stopping one hour and observing 1.2m of sand falling into the hole. As the hole was expected to reach the underlying Marl before 60m and as too much sand was coming up we decided to drill to the final depth of 36.7m. After removing the bit the borehole collapsed to a plumbed depth of about 15m. Hence, the sandstone seems to be unconsolidated to larger depths than only a few meters. This hole was left until the end of the drilling session because a temporary casing had to be manufactured to drill into the existing hole to cover the collapsing layers.

We changed our drilling strategy and always used a small diameter hammer ($4^3/_4$") to penetrate through the top part of the saturated zone where collapsing was a possibility. However, the other 4 boreholes were found to be consolidated enough to prevent collapsing. After reaching the final depth, the boreholes were flushed with pressured air to remove remaining drilling debris.

3.2.3. Borehole Logs

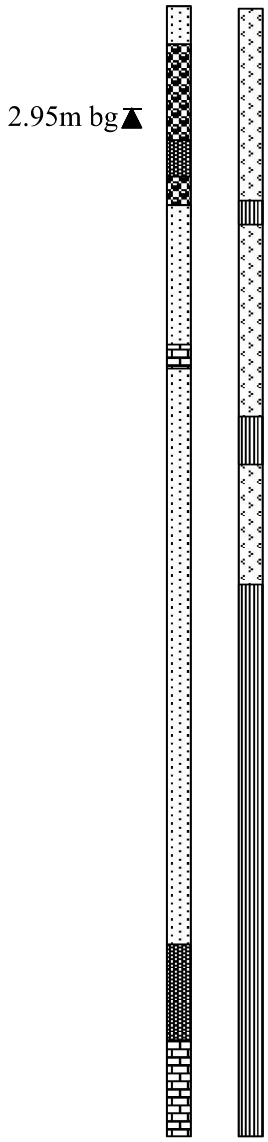
The planned open hole geophysical logging was cancelled because

- the holes were not stable enough to ensure the probes to be entered and removed safely
- of the additional costs arising due to the collapsed borehole.

Instead of geophysical logs, precise drilling logs were taken during drilling sampling drilling debris, thus recording whether the hammer bit is hammering or not indicating hard and soft layers within the sandstone. The subsequent installation of multilevels was based on this information rather than on geophysical logs.

<u>1. Sandall Beat Play Fields</u>

The left log shows the geologic lithology, the right log depicts the hammering action of the bit indicating the competence of the rock. Depths are given in metres below ground (mbg).



0-0.3 very fine sand
0.3-2 loamy sand
2-3 sandy gravel
3-3.5 coarser gravel (3.2m very wet)
3.5-4.5 fine gravel
4.5-5 grey clay
5-6 hard gravel and clay

6-9 very fine reddish sand, proceeding slowly (very hard)

12 small bits of limestone, no water yet
hammering to 13m
13.1 water hit
13-15 hard

15-18 no hammering, fine sand coming up, hole caving in a little

18-21 hard again

21-24 hard

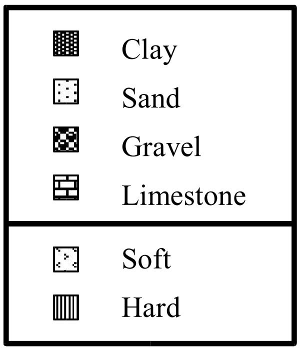
1h break: 1.2m additional sand

24-27 hard

27-30 hard

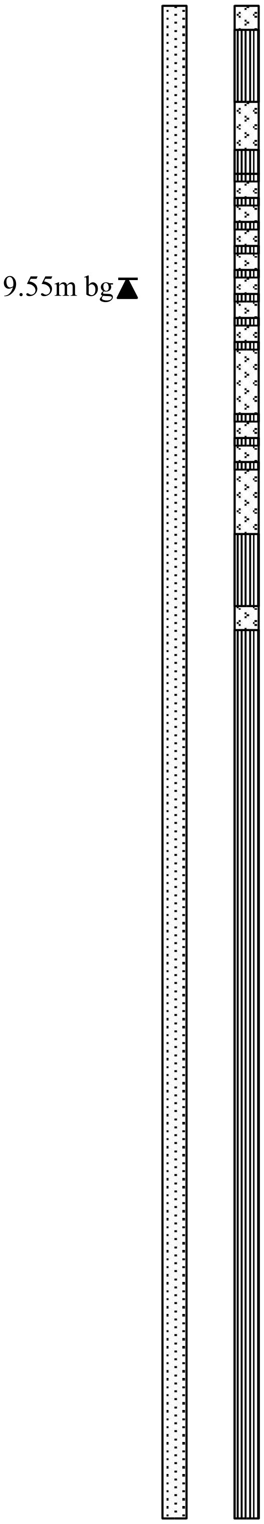
30-34 sand, clay and limestone

34-36 marl and limestone bits coming up



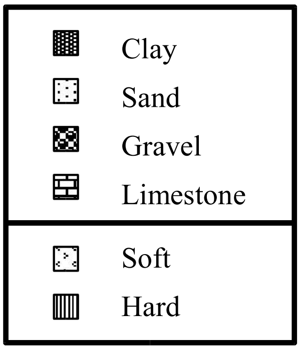
2. Bolton Hill Play Field

The left log shows the geologic lithology, the right log depicts the hammering action of the bit indicating the competence of the rock. Depths are given in metres below ground (mbg).



0-0.5 very fine sand with round stones
0.5-3 hard sand (probably sandstone)
sand getting wet after about 1.5m, water at 3m
4.4 yellow sandstone (more competent)

5 red dry sandstone
5.4-6 hard
6-6.5 hard/soft alternatively
6.5-6.8 soft
6.8-7.1 hard
7.1-8.6 hard/soft alternatively
9-9.1 hard 9.1-9.4 soft 9.4-10.1 hard
10.1-10.5 soft 10.5-10.8 hard
10.8-11.6 soft 11.6-12.8 hard (no water yet)
13.2-14.0 soft



14-17.6 hard/soft alternatively, 15.2 water hit, water level dipped at 9.55m bg

17.6-19.2 core (core barrel empty)

19.2-21.6 hard

21.6-22.0 soft

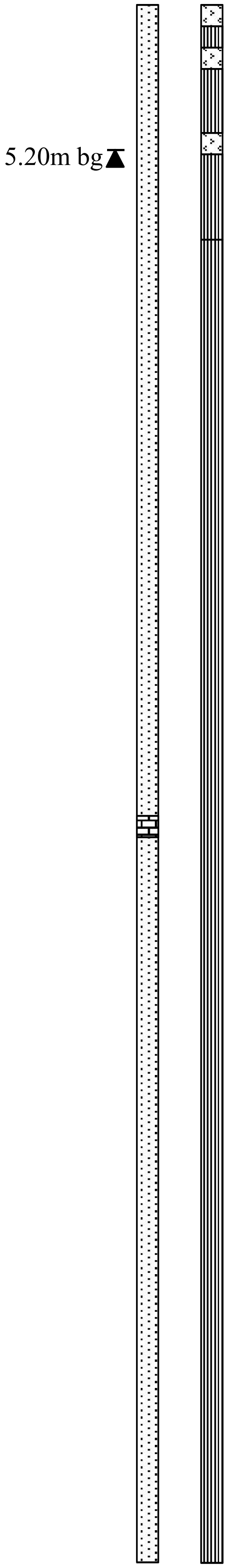
22.0-25.0 hard

25.0-26.0 core (core barrel empty)

26-52 hard, lot of water coming up

3. McAuley High School

The left log shows the geologic lithology, the right log depicts the hammering action of the bit indicating the competence of the rock. Depths are given in metres below ground (mbg).



0-0.4 very fine sand with round pebbles
0.4-1.5 hard sand (hammering)
1.5-2.2 soft
2.2-5.6 hard

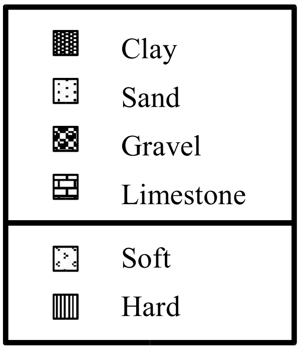
5.6-6.8 soft (no water yet)

6.8-9.6 hard, 9.6 water hit, water level at 5.20 mbg

9.6-12.8 hard

12.8-30.8 hard
Driller comment : harder than Bolton Hill site

medium size red sand



30.8 few marl bits coming up

30.8-35 hard
35-36 softer but still hammering

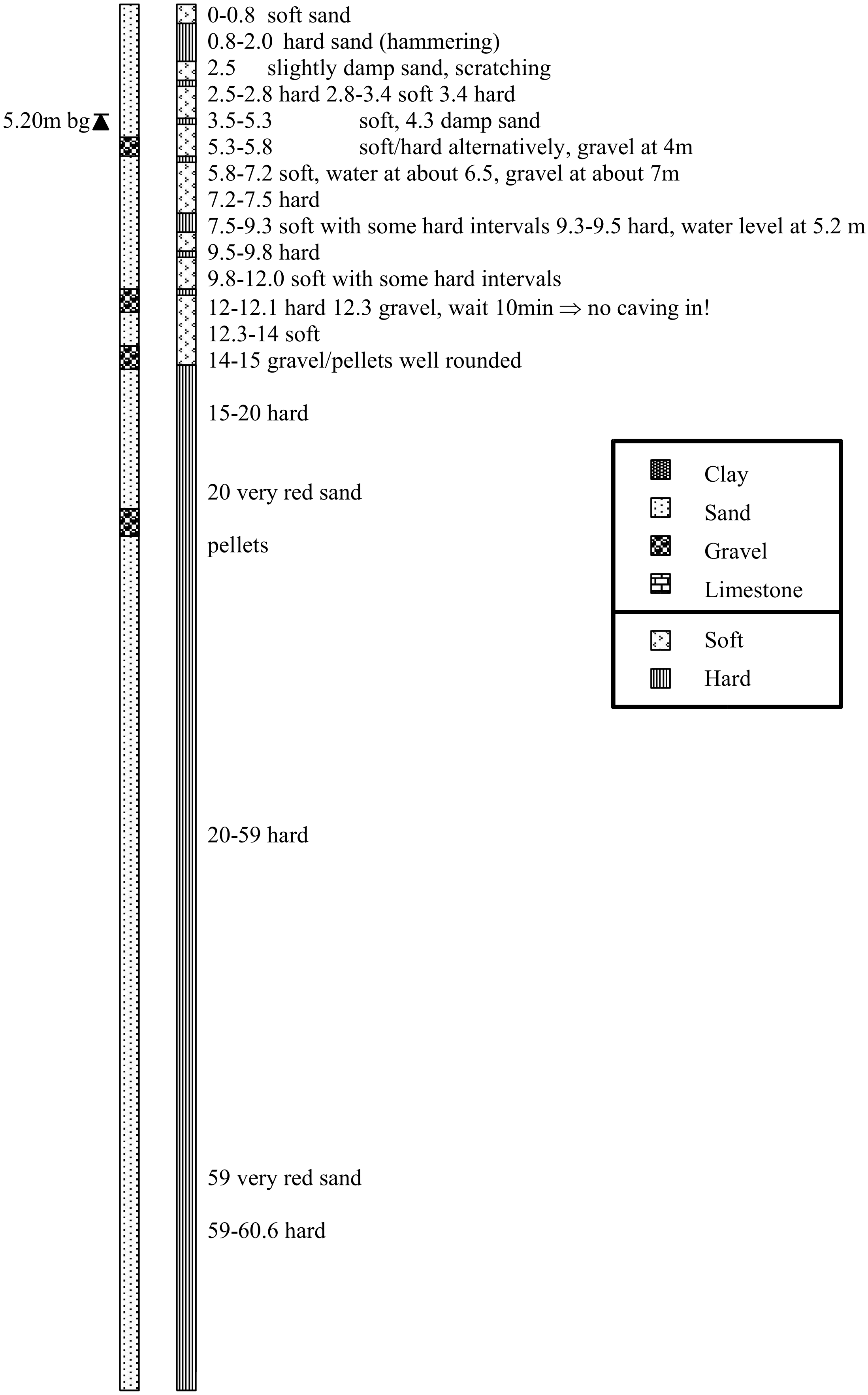
37.5 very red sand coming up

37.5-60.6 hard

medium size red sand

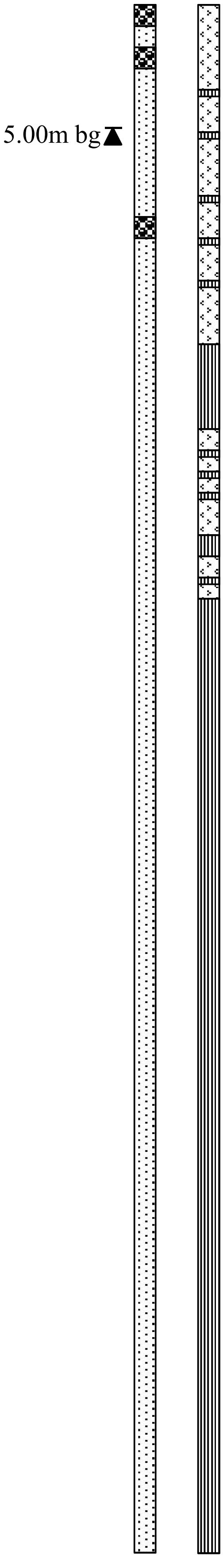
4. Haslam Park 1

The left log shows the geologic lithology, the right log depicts the hammering action of the bit indicating the competence of the rock. Depths are given in metres below ground (mbg).



5. Haslam Park 2

The left log shows the geologic lithology, the right log depicts the hammering action of the bit indicating the competence of the rock. Depths are given in metres below ground (mbg).



0-1.6 soft with gravel
1.6-2.8 soft sand
2.8-3.3 soft sand, small band of pebbles
3.3 hard
3.3-5.6 soft
5.6-6.2 hard
6.2-6.8 soft (no water yet)
6.8-7.8 hard
7.8 sand getting wet, some pebbles coming up
7.8-9.5 hard, water hit
9.5-10.4 hard
10.44-11.90 core recovered

11.9-15-7 hard

15.7-16.7 hard but quick proceeding
16.02-16.60 core recovered
16.7-18.8 soft/hard alternatively

19.6-21.2 hard
21.2-21.9 soft/hard alternatively

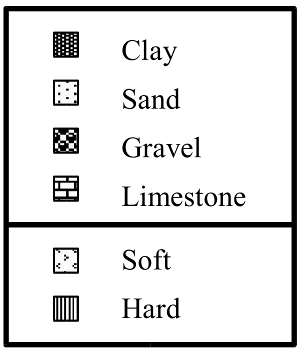
medium size reddish sand

21.9-29.1 hard

29.04-30.50 core recovered

45.6 very red sand

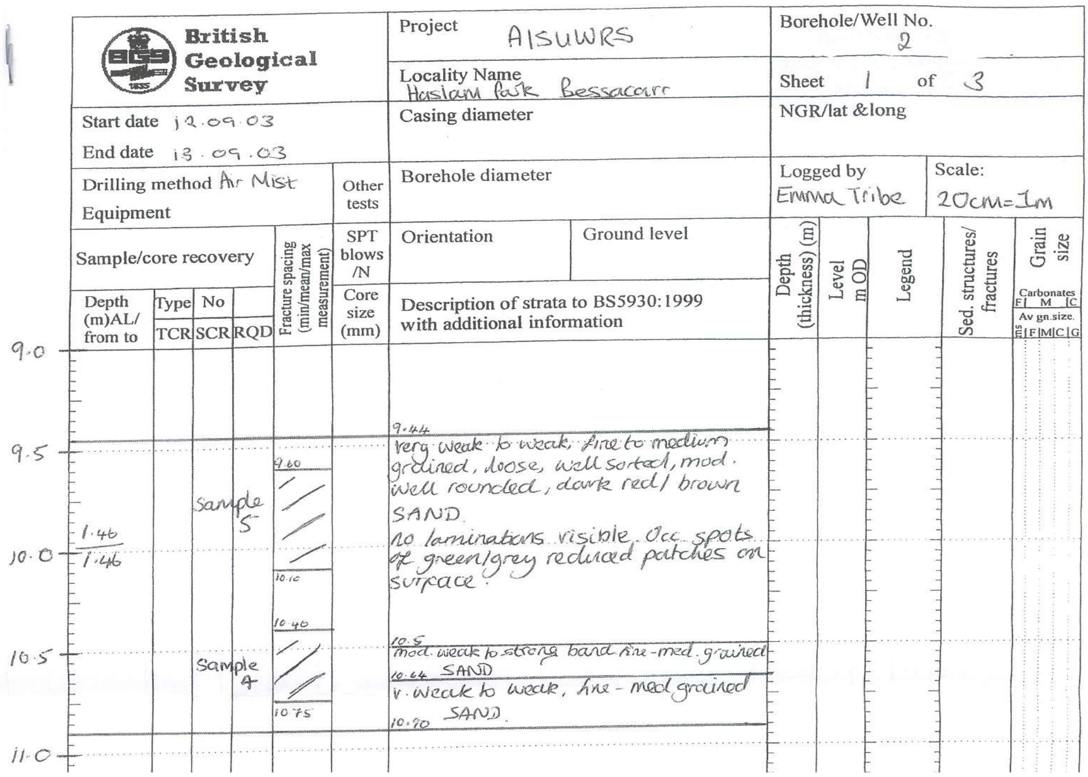
30.5-60.6 hard



3.2.4. Core Samples (Haslam Park 2)

Core samples were attempted to be withdrawn on Bolton Hill unsuccessfully. The major reasons for taking core samples were (a) to get a more detailed view of the sandstone sequence and (b) to obtain hydrochemical samples from pore water. These samples will be compared the measurements to be analysed during the one-year sampling campaign.

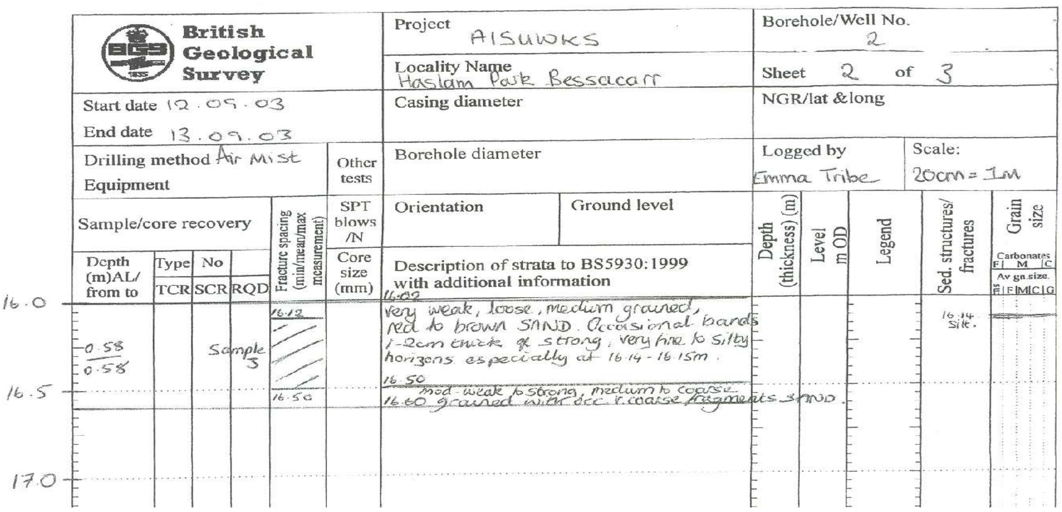
Core withdrawal was tried again on Haslam Park 2 site by adding a small amount of mist and reducing air pressure on the core barrel. This led to 3 very interesting cores from different depths. The cores were analysed both physically and chemically by the British Geological Survey. The reports of all 3 cores are displayed below (Fig. 7 to 9).



British Geological Survey
Project: AISUWRS
Borehole/Well No.: 2
Locality Name: Haslam Park Bessacarr
Sheet 1 of 3
Start date: 12.09.03
End date: 13.09.03
Casing diameter
NGR/lat &long
Drilling method: Air Mist
Equipment
Other tests
Borehole diameter
Logged by: Emma Tribe
Scale: 20cm=1m
Sample/core recovery | Fracture spacing (min/mean/max measurement) | SPT blows /N | Orientation | Ground level | Depth (thickness) (m) | Level m OD | Legend | Sed. structures/ fractures | Grain size
Depth (m)AL/ from to | Type TCR | No SCR | RQD | Core size (mm) | Description of strata to BS5930:1999 with additional information

9.0
9.44 very weak to weak, fine to medium grained, loose, well sorted, mod. well rounded, dark red/brown SAND. no laminations visible. Occ. spots of green/grey reduced patches on surface.
9.5
9.60 – 10.16: Sample 5; 1.46 / 1.46
10.0
10.40 – 10.75: Sample 4
10.5 mod. weak to strong band fine-med. grained SAND
10.64 v. weak to weak, fine - med grained SAND.
10.90
11.0

Figure 7: report of first core from Haslam Park 2 site. The core was withdrawn from 9.44 to 10.2 mbg.



British Geological Survey
Project: AISUWKS
Borehole/Well No.: 2
Locality Name: Haslam Park Bessacarr
Sheet 2 of 3
Start date: 12.09.03
End date: 13.09.03
Casing diameter
NGR/lat &long
Drilling method: Air Mist
Equipment
Other tests
Borehole diameter
Logged by: Emma Tribe
Scale: 20cm = 1m
Sample/core recovery | Fracture spacing (min/mean/max measurement) | SPT blows /N | Orientation | Ground level | Depth (thickness) (m) | Level m OD | Legend | Sed. structures/ fractures | Grain size
Depth (m)AL/ from to | Type TCR | No SCR | RQD | Core size (mm) | Description of strata to BS5930:1999 with additional information

16.0
16.02 very weak, loose, medium grained, red to brown SAND. Occasional bands 1-2cm thick of strong, very fine to silty horizons especially at 16.14 - 16.15m.
16.12 – 16.50: Sample 3; 0.58 / 0.58
16.14 silt.
16.5
16.50 mod. weak to strong, medium to coarse grained with occ. v. coarse fragments SAND.
16.60
17.0

Figure 8: report of second core from Haslam Park 2 site. The core was withdrawn from 16.02 to 16.60 mbg.

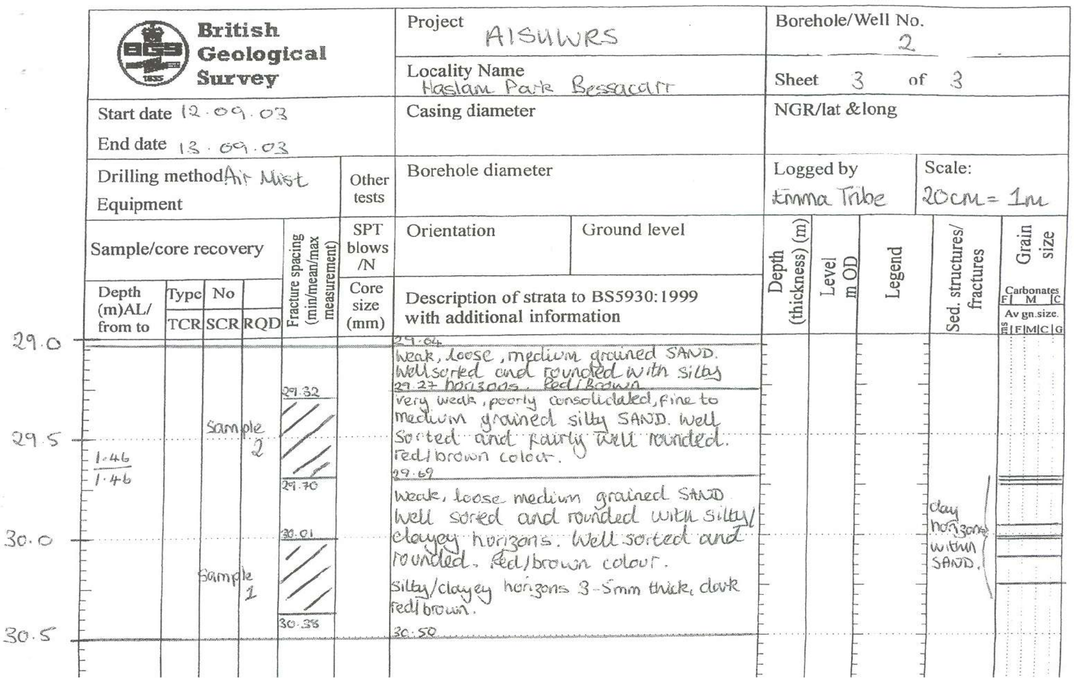

British Geological Survey
Project AISUWRS
Borehole/Well No. 2
Locality Name Haslam Park Bessacarr
Sheet 3 of 3
Start date 12.09.03
End date 13.09.03
Casing diameter
NGR/lat &long
Drilling method Air Mist
Equipment
Other tests
Borehole diameter
Logged by Emma Tribe
Scale: 20cm = 1m
Sample/core recovery
Fracture spacing (min/mean/max measurement)
SPT blows /N
Orientation
Ground level
Depth (m)AL/ from to
Type TCR
No SCR
RQD
Core size (mm)
Description of strata to BS5930:1999 with additional information
Depth (thickness) (m)
Level m OD
Legend
Sed. structures/ fractures
Grain size
Carbonates F M C
Av gn.size F M C G
29.0
29.5
30.0
30.5
1.46
1.46
Sample 2
Sample 1
29.32
29.70
30.01
30.35
29.04
Weak, loose, medium grained SAND. Well sorted and rounded with silty horizons. Red/Brown
29.27
Very weak, poorly consolidated, fine to medium grained silty SAND. Well sorted and fairly well rounded. Red/brown colour.
29.69
Weak, loose medium grained SAND well sorted and rounded with silty/clayey horizons. Well sorted and rounded. Red/brown colour.
Silty/clayey horizons 3-5mm thick, dark red/brown.
30.50
clay horizons within SAND.

Figure 9: report of third core from Haslam Park 2 site. The core was withdrawn from 29.04 to 30.50 mbg.

It was found that all samples including the one from 30m below ground are uncemented. Generally, the samples consist of medium size sand and contain various silty horizons and mud pellets.

3.2.5. Pumping Tests

After completing the boreholes and removing the rig, short pumping tests were applied on all sites except Sandall Beat (Site No 1). We decided to apply short tests because:

1. we wanted to prevent groundwater exchange from one level to another aquifer level
2. we did not want to run generators over night because 3 of the 4 sites are near housing areas
3. the effort of applying a full pumping test would not have been justified because the only additional information obtained would be the storage coefficient

Furthermore, the pumping test was useful to clean the boreholes before installing the multilevel equipment.

To monitor the groundwater levels we applied the automated loggers (Diver® by Van Essen Instruments) to be used for continuous groundwater monitoring. The results and interpretations are shown in figures 10-13. The top plots show the drawdowns measured with the diver, where the diver results were corrected using barometric measurements. As the divers only measure pressures a series of hand measurements were taken to translate pressures into groundwater levels and to check the consistency of the diver measurements. The lower plots show the analysis of the results using Jacob's method. The transmissivities obtained are of the order of 3-15 m^2/h (70-360 m^2/d) are well within the values documented for this region (Brown and Rushton, 1993). They reflect the drilling observations that Bolton Hill is the softest of these 4 sites.

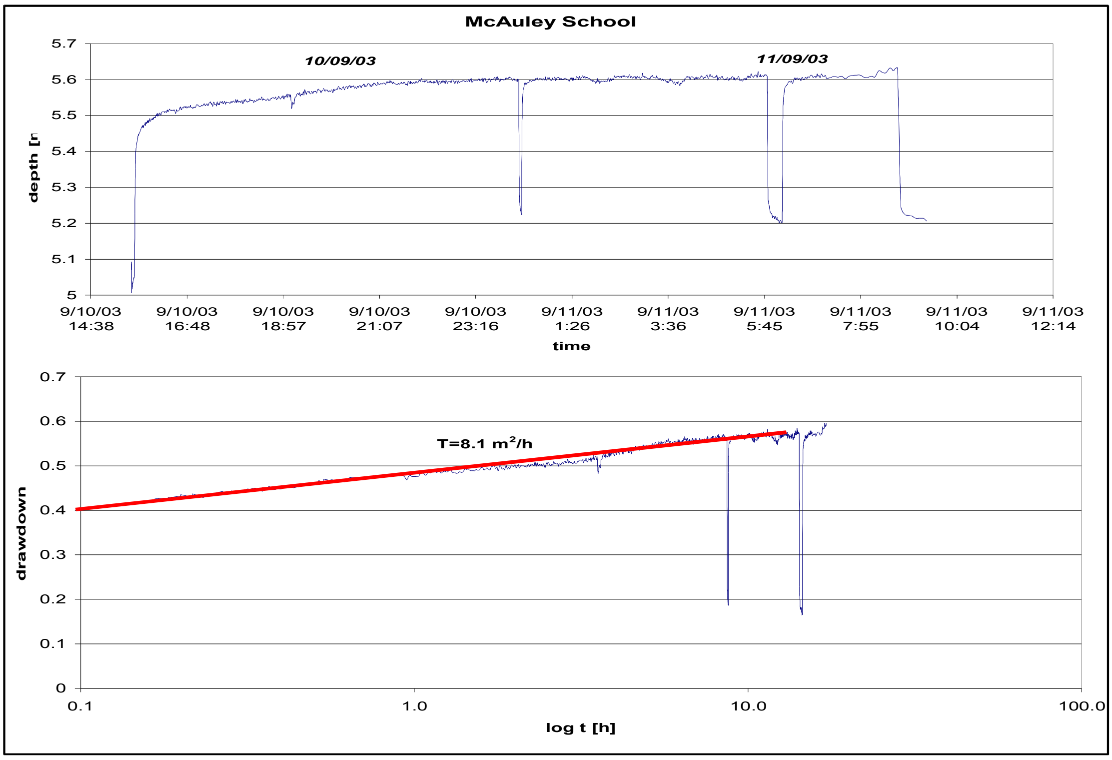


Figure 10: Pumping test on Bolton Hill Play Fields. The top plot shows groundwater levels measured by automatic loggers. The bottom plot shows the interpretation using Jacob's method. The red lines indicate the fit to the data and T means the transmissivity of the aquifer. After a first irregularity the drawdown behaved quite regular leading to a transmissivity of about 14 m^2/h.

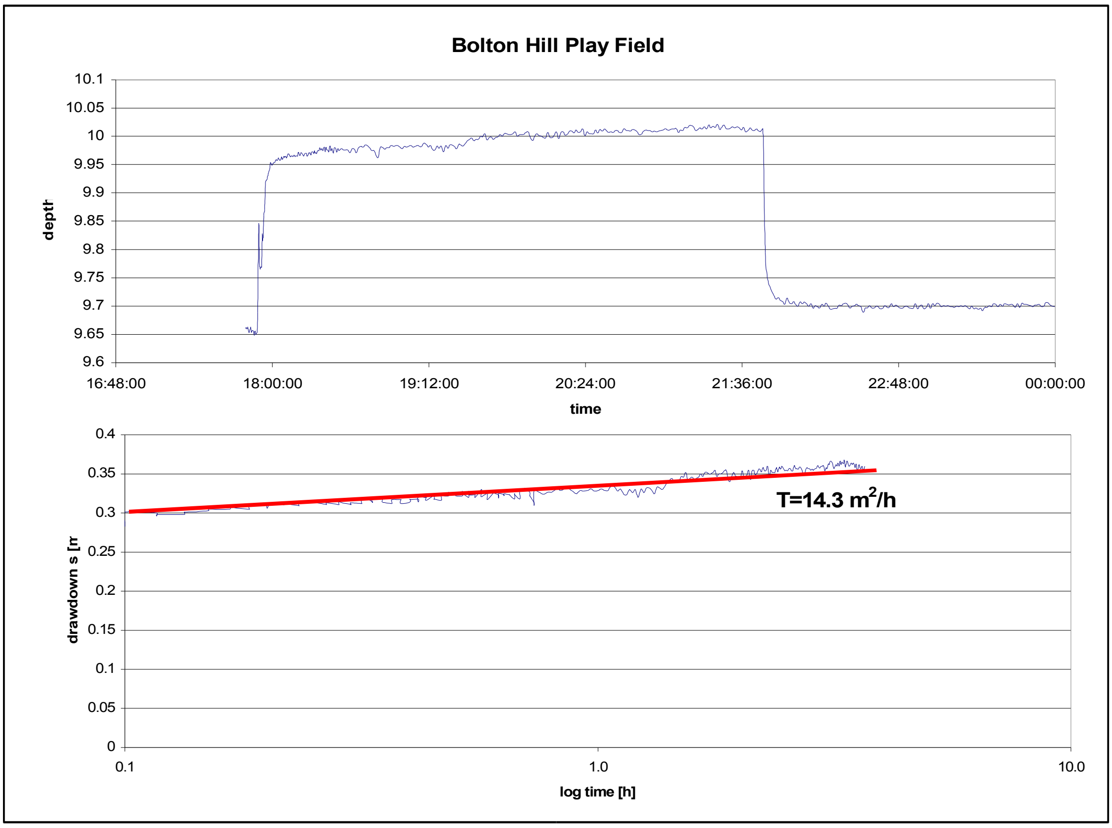


Figure 11: Pumping test on Mc Auley School. The top plot shows groundwater levels measured by automatic loggers. The bottom plot shows the interpretation using Jacob's method. The red lines indicate the fit to the data and T means the transmissivity of the aquifer. After a first irregularity the drawdown behaved quite regular leading to a transmissivity of about 8 m^2/h.

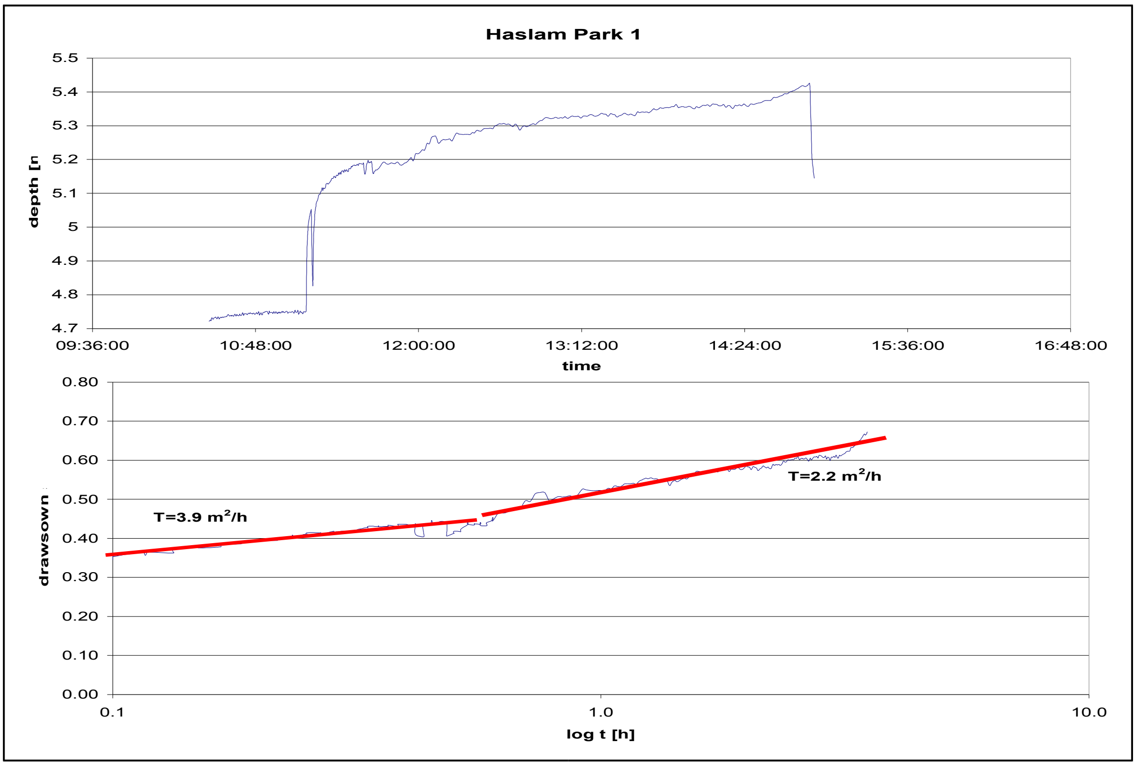


Figure 12: Pumping test on Haslam Park 1. The top plot shows groundwater levels measured by automatic loggers. The bottom plot shows the interpretation using Jacob's method. The red lines indicate the fit to the data and T means the transmissivity of the aquifer. After a first irregularity the drawdown behaved quite regular leading to a transmissivity of about 3 m^2/h.

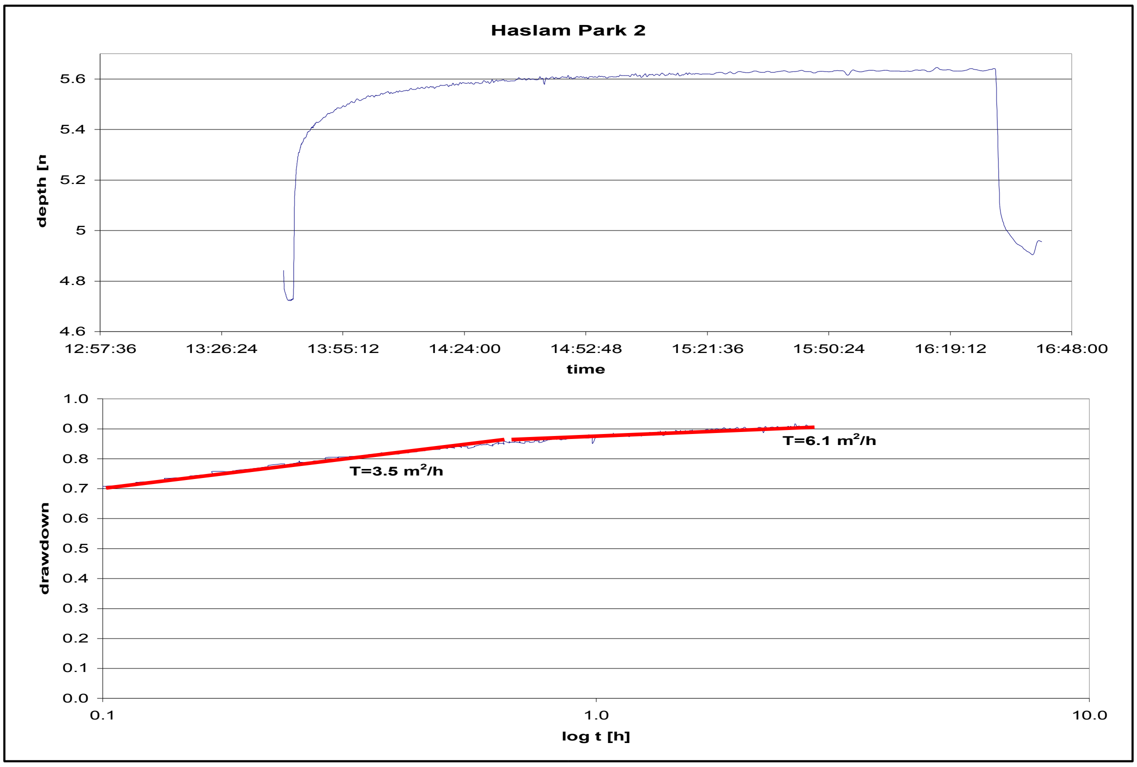


Figure 13: Pumping test on Haslam Park 2. The top plot shows groundwater levels measured by automatic loggers. The bottom plot shows the interpretation using Jacob's method. The red lines indicate the fit to the data and T means the transmissivity of the aquifer. After a first irregularity the drawdown behaved quite regular leading to a transmissivity of about 6 m^2/h.

3.3. Construction and Installation

3.3.1. Construction Materials

3.3.1.1. Bentonite Seals

Experience gained from previous work by the Robens Centre that involved the installation of 5 bundled multilevel piezometers in Nottingham and Birmingham (Taylor et al., 2003). One hole was installed without seals, all others with up to 1m thick bentonite seals. This led to a major point of discussion. Therefore, we decided to install at least 1.5m of bentonite seal between each sample port. We used MIKOLIT 300 with a swelling of about 100% in fresh water and a hydraulic conductivity after swelling of $<10^{-11}$ m/s which is about 6-7 orders of magnitude smaller than the formation conductivity.

3.3.1.2. Filter Sand

In the former project, the addition of the filter sand was very slow and in one case the added sand with an average diameter of about 250µm jammed most of the open hole (R. Taylor personal communication). This hole had to be abandoned. Therefore, we decided to use coarser sand with an average diameter of about 1mm that settles faster inside the hole. Additionally, we wanted a minimal distance to the sampling screen of 1.5m to prevent the seals to negatively influence hydrochemistry samples.

3.3.1.3. Pipes

We used 22mm (OD) HDPE pipes as small sampling tubes and threaded 42mm (OD) PVC pipes as support pipe. The PVC pipes are not optimal but they had to be chosen because HDPE pipes are usually delivered on a coil (in one piece). This would lead to problems when the pipes are pushed down the open hole. With a threaded PVC pipe in the centre, the pipe assembly can be introduced into the hole without any problems and a regular empty space is left behind were the filling material can be added.
The pipes were prepared before installation to enable groundwater sampling. We therefore drilled holes between 20 and 50cm from the pipe bottom and covered them with a stainless steel mesh (mesh size: 50 µm). The 20cm dead volume at the bottom enables solid material passing the mesh to settle inside the pipe without obstructing the sampling interval.

3.3.1.4. Well Heading

After the installation of multilevels a lockable well heading was installed that:

- enables easy access to the hole for sampling reasons
- secures the installation from vandalism
- enables adding and attaching the divers
- is flush with ground to enable grass cutting

3.3.1.5. Sampling Pumps and Pipes

To prevent cross-contamination between the levels we decided to add sampling pipes into each level that is not occupied by a diver. As we wanted to enable both hand pumping and, when possible, using a peristaltic pump we used WATERRA tubing. We added low flow (LF) tubes (13mm OD) into the HDPE pipes and standard (STD) tubing (16mmOD) into the PVC pipes. These pipes were added for the well development (see section 3.4) and not been removed since.

3.3.2. Multilevel Design

We changed the design from former experience to adapt the multilevel piezometers to the requirements of this project (Fig. 14). As we are mainly interested in urban recharge, we limited the depth of boreholes to a maximum of 60m below ground. Considering the thickness of clay seal of at least 1.5m and the safety distance of the sampling interval from the seals (2.5m) a maximum number of 7-8 levels is possible. We therefore decided to install 7 levels to allow thicker seals to be installed.
As we intend to monitor groundwater levels, temperature and conductivity online by adding automated divers into the lowest and the upper most level these two levels needed to have an internal diameter of at least 1 inch (25.7 mm). We therefore decided to use 42mm PVC pipes with an internal diameter of 35mm for these levels. For the other levels we used HDPE pipes with an internal diameter of 21mm to:

- enable Low Flow Waterra pumps to be used
- make sure to place all pipes around the centre pipe (including the PVC pipe for the shallow level)
- assure enough annular space to add sand and bentonite

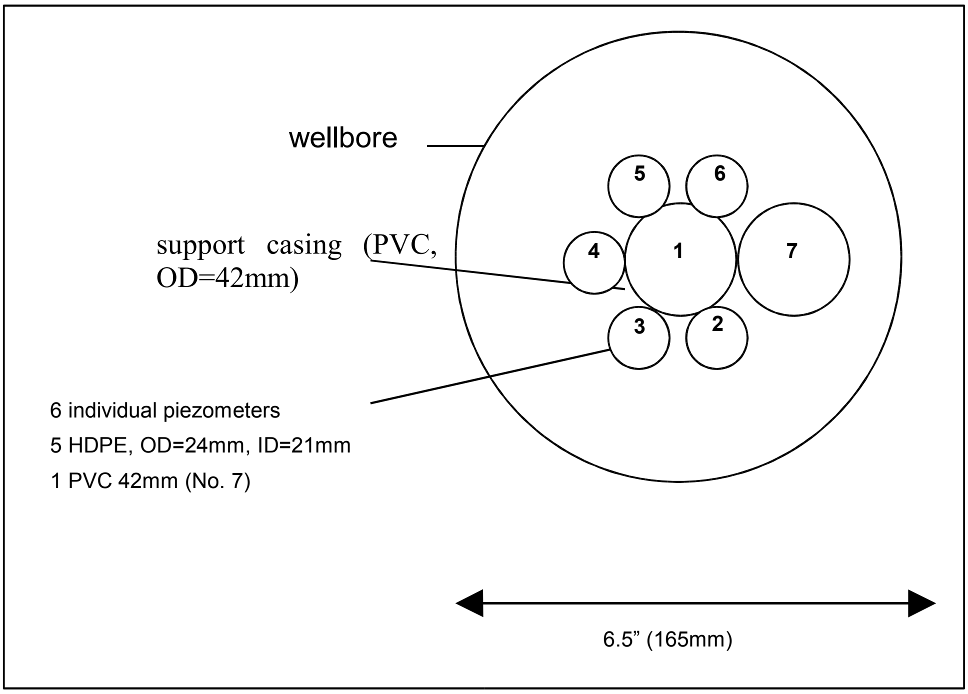


Figure 14: Design of multilevel sampling assembly.

3.3.3. Installation

The pipes were installed right after the pumping test to prevent cross flow within the open hole. The HDPE pipes were attached to the centre PVC pipe using cable ties and caps were added at the end of each pipe to prevent water entering from the bottom. At the bottom of the centre tube centralisers were added to guarantee the pipe to stay in the centre of the open hole (Fig. 15). Each level was then attached while the assembly was pushed down the hole. Figure 15 shows a picture taken during installation.

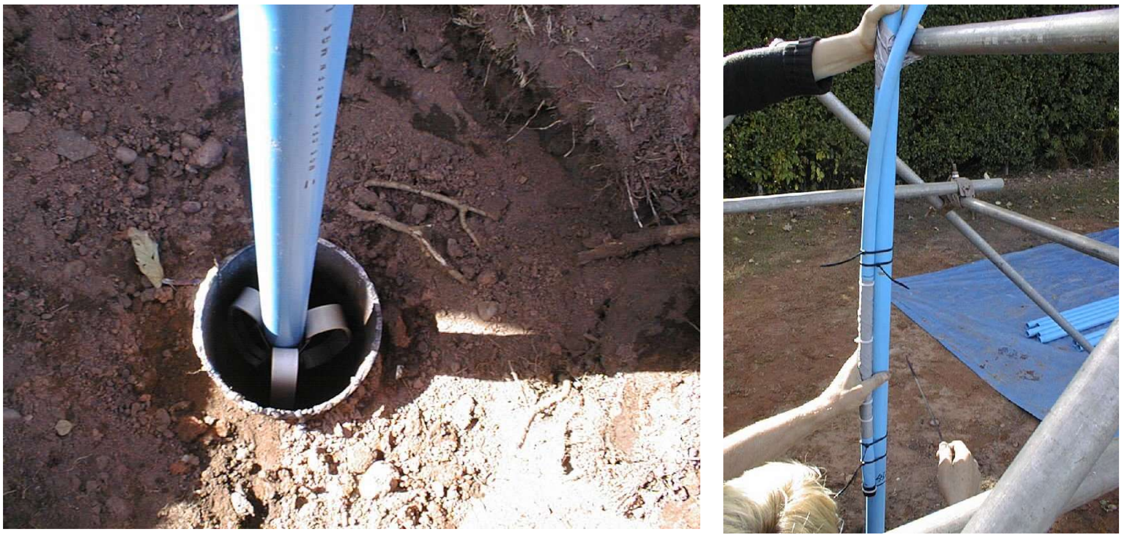


Figure 15: The left picture shows the distance holder keeping the centre pipe in the centre of the hole. The right picture shows a HDPE sampling pipe including screen and how it is attached to the centre pipe.

Figure 16: Installation of pipe assembly on Sandall Beat site where the installation was applied through temporary steel casing.

On the Sandall Beat site the installation of the multilevel assembly was more complicated because the pipes had to be added while pulling up the temporary casing to prevent the hole to collapse. This procedure needed the drilling rig to be on site to pull up the casing (Fig. 16).

After the pipes were in, sand and bentonite was added in small portions through a funnel and plumbed the depth continuously (Fig. 17). This enabled a good control of the sand and clay levels. After the last level was installed we added sand to about 3 meters below ground (above the standing water level). Thereon a 2m bentonite seal was added to prevent contamination from the top (through the well heading). Since the bentonite is not inside the water, water was added to let the clay swell properly. Finally, sand was added to finish the hole.

Figure 17: The picture shows Owen Baines waiting for the bentonite to reach the bottom of the hole.

The last step entailed cutting the pipes and closing the pipes with caps. Then the manholes were cemented in.

The resulting 5 multilevel sampling sites are equipped as described in Figure 15.

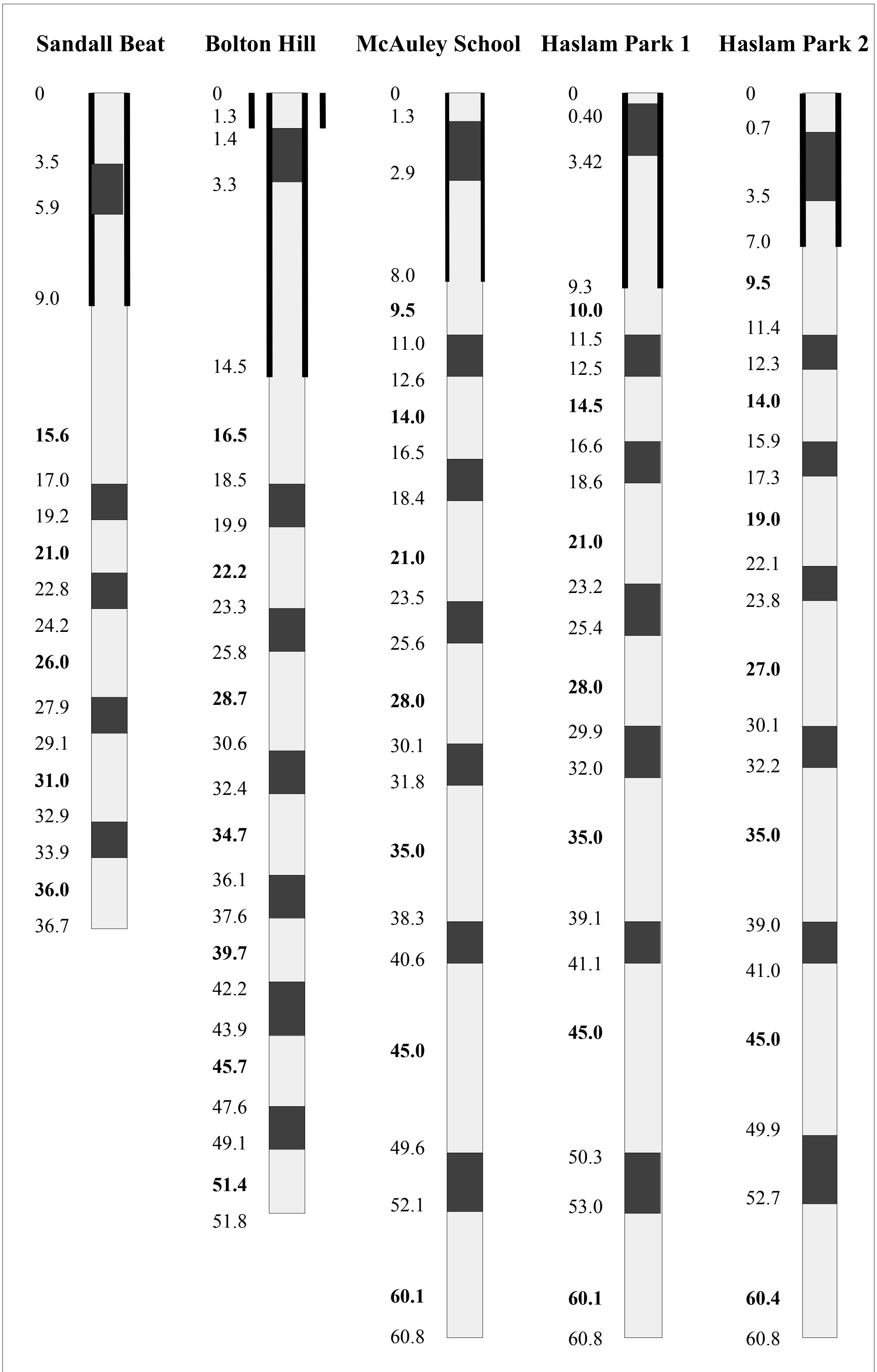


Figure 18: Installation of the sampling intervals of each multilevel peizometer (in meters below ground level). Fat black lines indicate the permanent steel casing. Dark areas show the seals with corresponding depth measures on the left. The bold numbers indicate the depths of the centres of the 30cm wide sampling ports.

3.4. Well Development

To sample micro-organisms in groundwater entailed removing all possible sources of micro-biological contamination during installation (e.g. by dirty hands touching pipes). Furthermore, the water inside the sampling intervals most likely contained a chemical signature of the added clay because the bentonite pellets were dropping through the open hole and because the seal were not active until a few hours after installation (after swelling). Therefore, we had to develop the multilevel installation by adding bleach and satisfactory purging each level.
We calculated the pipe volume and added an estimated volume of 15L of water for the sampling interval (from seal to seal). We then added this amount of bleached water (50mg/l free chlorine residual) into the pipes and let it disinfect for at least 15 minutes. Then we withdrew at least 3 times the added volume and continuously checked the Electric conductivity and water temperature. It was found that a constant level was reached after about 2 volumes. Therefore, we believe to be on the safe side when withdrawing 3 volumes or more (Fig. 19).

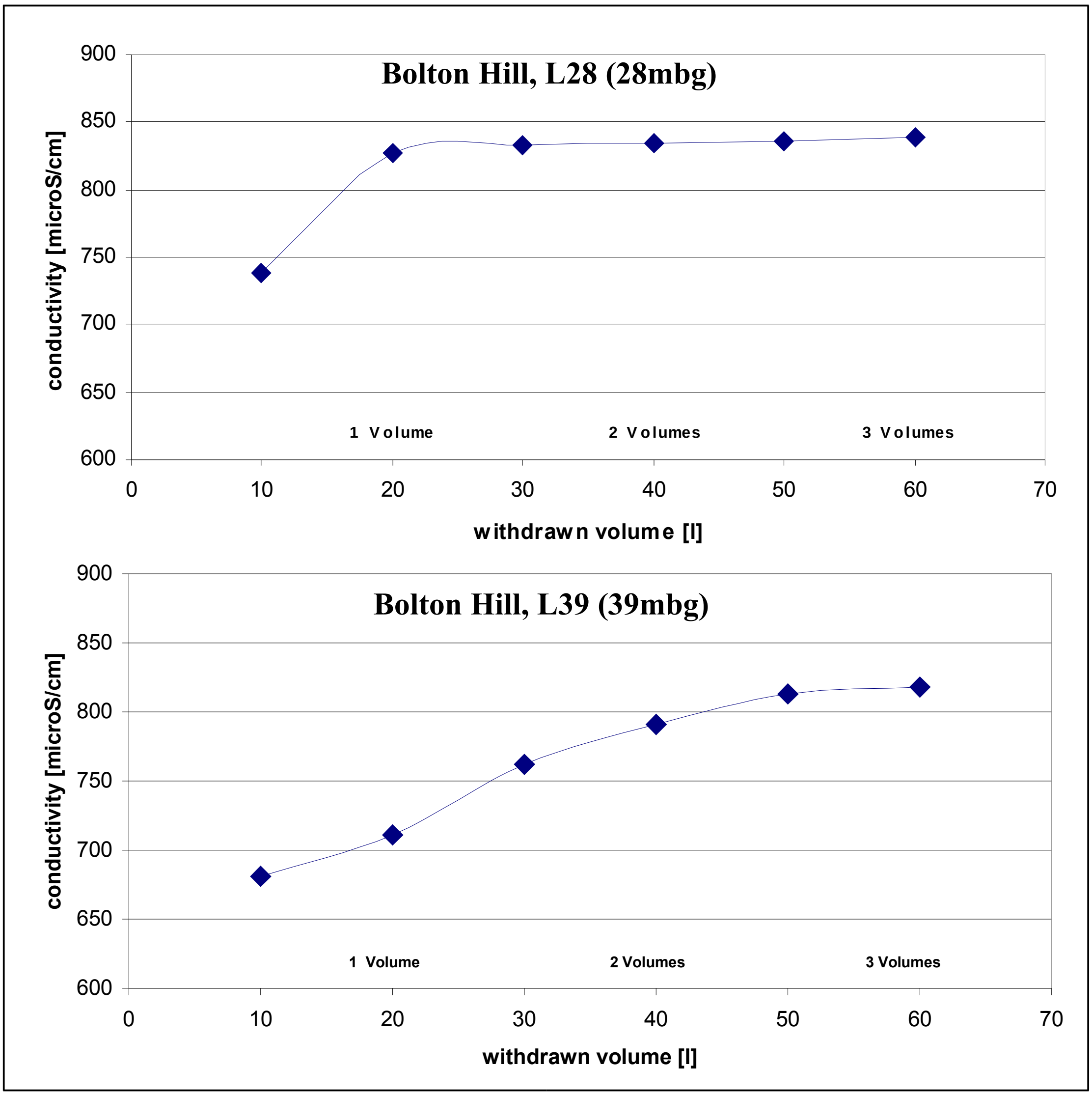


Figure 19: 2 examples of evolution of electric conductivity of withdrawn water during well development.

4. Conclusions

The 5 multilevel sampling sites are successfully installed and cleaned and they were sampled for the first time in November 2003. As the first results obtained show quite clear differences between different levels we are confident that the seals really prevent vertical flux between the levels. Results from the first multilevel sampling campaign show considerable differences in conductivity, Eh and dissolved oxygen with depth indicating that the construction was successful. However, we plan to test the seals both hydraulically and with tracers. These tests will be done at the end of the one-year sampling time because we do not want to affect any of the samples.

It was mentioned that one borehole collapsed leading to additional costs. However, we were able to rescue the hole and installed one level in the collapsing zone. Therefore, we believe that this hole could be one of the most interesting because the collapsing soft zone is expected to have a high hydraulic conductivity. This, in turn, would lead to rapid transport of contaminants in this zone.

Generally, the observations made during drilling that the aquifer is not entirely unconfined, but more likely semi-confined, was never reported before in this region and therefore was quite surprising. This is probably due to the fact that often mud-drilling technique is applied. Furthermore, neighbours reported that perched water levels, as we observed it on Bolton Hill, seem to be quite common features in the area. Both a semi-confined aquifer and perched water levels imply that groundwater recharge cannot reach the aquifer directly in these areas but reach the groundwater table retarded. This finding will certainly have a large impact on the modelling approaches to be applied in this project.

The construction of the multilevel piezometers enables online measurement of groundwater levels, temperature and conductivity at the top most and the lowest level with a high temporal resolution. We expect to obtain important information about groundwater recharge in our study area.

We are confident that the multilevel array entails a new picture of regional groundwater flow dynamics (both horizontally and vertically) and, therefore, will add important and unique knowledge to the project.

5. Acknowledgements

A huge thanks to Dr. Richard Taylor from University College London and Owen Baines from University of Bradford for their great support before, during and after installation of the multilevels.

We would like to thanks our partners from the BGS, namely Ilka Neumann, Brian Morris and Collin Cheney for their technical support before and during the drilling of the boreholes.

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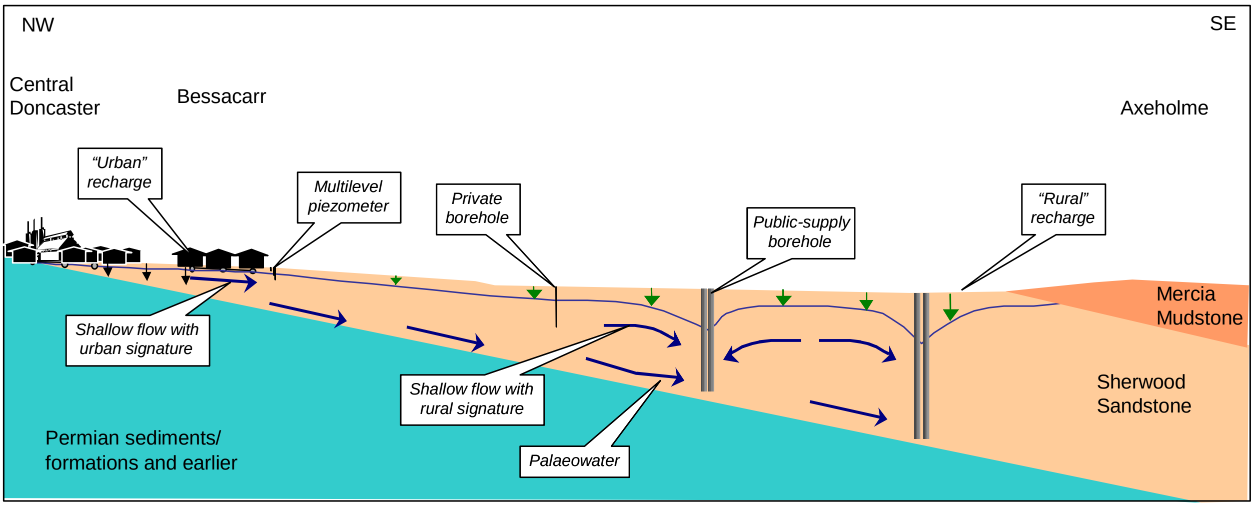
AISUWRS Work-package 4: Water quality of the Doncaster aquifer

Groundwater Systems and Water Quality Programme

Commissioned Report CR/04/026N



BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/04/026N

AISUWRS Work-package 4: Water quality of the Doncaster aquifer

M E Stuart, E J Whitehead and B L Morris

Key words

Urban groundwater, Sherwood Sandstone aquifer, urban recharge

Front cover

Conceptual model of influences on water quality in the Doncaster aquifer

Bibliographical reference

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Foreword

This report is the fourth in the UK series of the project "Assessing and Improving the Sustainability of Urban Water Resources and Systems" (AISUWRS) and is the result of collaborative work by the UK partners, the British Geological Survey and the Robens Centre for Public and Environmental Health of the University of Surrey. This 3-year urban water research project is partly funded by the European Community. It aims to develop an innovative modelling system of the urban water infrastructure which can inform decision support systems for cities that depend on underlying or nearby aquifers for their water supply.

Acknowledgements

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- Yorkshire Water plc, and in particular Meryl Knapp, for provision of water quality data from public supply boreholes;
- The Environment Agency of England and Wales for permission to use Agency public domain datasets;
- Colleagues Debbie Allen, Daniel Lapworth and Barry Townsend from BGS and Drs Joerg Rueedi and Aidan Cronin from the Robens Centre for collection of samples and field measurements.

Contents

FIGURES

TABLES

Summary

This interim report comprises the fourth in the UK series of the project "Assessing and Improving the Sustainability of Urban Water Resources and Systems" (AISUWRS). Doncaster is one of the three European urban areas being studied in this European Community 5th Framework Programme-Shared Cost Research Technological Development and Demonstration project. It comprises part of Deliverable D10 for project Work Package 4. The report assesses groundwater quality in the Triassic Sherwood Sandstone aquifer supplying the case study town of Doncaster, England. Available data from stakeholders, principally Yorkshire Water, and from the project's tripartite sampling programme have been collated and analysed. An understanding of the characteristics of groundwater from both the upper and middle/lower parts of the aquifer is emerging and has informed the conceptual model of evolution of water quality. In this part of the Nottinghamshire-South Yorkshire Sherwood Sandstone outcrop, recharge processes are complicated by the presence of variable Quaternary superficial deposits, which appear to control both the ease with which recharge can occur and the hydrochemical characteristics of the resultant groundwater.

The data suggest that this complexity manifests itself in a degree of lateral variability of geochemical trends that is at least as great as that occurring with depth. The implication is that the degree to which the underlying saturated aquifer is affected by the contaminant load depends at least as much on local recharge conditions as the magnitude of the loading itself.

At this interim stage of the field programme, the study has succeeded in initial hydrochemical characterisation of the principal constituents of the groundwater circulating in the mains water supply to the study focus area, the wastewater in its sewer system, the underlying and surrounding shallow aquifer and the deeper aquifer. Assessment of the urban recharge indicators of chloride, sulphate, boron and zinc has shown that these are likely to be only partially successful in Doncaster, for the following reasons:

- the wastewater effluent load is relatively dilute
- pollution from other human activities (agriculture, mining) is present within the same catchments, generating similar contaminant types and loading profiles
- important relatively persistent contaminants found in urban wastewater such as sulphate and chloride also occur naturally and variably in the aquifer.

Further work will be needed to unravel this complex system sufficiently to inform the urban water models that are being developed, linked and operated as the principal task of the AISUWRS project.

1 Introduction

1.1 BACKGROUND

This report is the result of collaborative work by the British Geological Survey and the Robens Centre for Public and Environmental Health of the University of Surrey, who are the UK partners of the AISUWRS project. The 3-year urban water research project is partly funded by the European Community 5th Framework Programme for Shared Cost Research, Technological Development and Demonstration. The 5th Framework Programme was conceived to help solve problems and respond to major socio-economic challenges that the European Union is facing. Its objectives combine technological, industrial, economic, social and cultural aspects.

The project is one of a number of European research projects on integrated urban water management that are grouped as the CityNet cluster. The AISUWRS project aims to develop innovative new modelling techniques and a pilot decision support system (DSS) for cities that depend on underlying or nearby aquifers for their water supply. The objective is to assess and improve the sustainability of urban water resources and systems with the help of computer tools.

The project aims to use case studies of Doncaster in England, Rastatt in Germany, Ljubljana in Slovenia and Mt Gambier in Australia to test and develop an integrated suite of models for urban water-management purposes. As the case studies cover diverse hydrogeological and water-management settings, successful application of the models to these situations will be a test of the system's robustness for wider use in the many other cities in Europe and elsewhere that depend on local groundwater for public and private water supply.

1.2 OBJECTIVES OF THIS REPORT

The AISUWRS project is divided into three Work Areas (WAs) and 14 Work-Packages (WPs). This report is part of Deliverable D10 for the Doncaster part of WP4, Field Investigations. The objectives of this part of the work are to:

- evaluate groundwater-quality data collected during the first year of the project
- develop a conceptual model of the flow system
- determine if different elements of the flow system can be characterised by their chemical compositions
- characterise the chemical composition of shallow recharge beneath the city.

2 Groundwater-quality data

2.1 INTRODUCTION

The data presented in this report were obtained from a number of sources. Yorkshire Water (YW) and the Environment Agency (EA) kindly provided raw water quality data. Additional monitoring is a key fieldwork component of the case study. A network that the AISUWRS team are sampling has been progressively established during the first year of the project:

(i) a number of privately owned boreholes in the Doncaster area

(ii) wastewater from the sewerage system.

(iii) five multi-level research boreholes drilled and installed in the project's focus area, which is the district of Bessacarr-Cantley.

The first set of data from this tripartite monitoring network is included in this report. The locations of the YW and project sampling points are shown in Figure 2.1.

2.2 PUBLIC SUPPLY BOREHOLES

YW operate 11 public-supply sites which form the Doncaster wellfield to the east of the town. The locations of these pumping stations are shown in Figure 2.1 and are labelled using the site-codes employed in Tables 2.2 to 2.4.

At each site there are two, or more commonly three, large diameter boreholes. These typically penetrate either close to the base or into the lowest third of the Triassic Sherwood Sandstone aquifer (with depths of 120 to 241 m). They are open hole or screened over the majority of their depths. A summary of borehole construction details for the sites in the central area and northern part of the wellfield is provided in Table 2.1; a fuller version forms Table 9 of Morris et al. (2003).

YW analyse raw water for a wide range of determinands (Table 2.2). Data were requested from YW for all these determinands for the last five years, except those where the dataset is small, in which case the whole set was requested.

2.3 ENVIRONMENT AGENCY MONITORING NETWORK

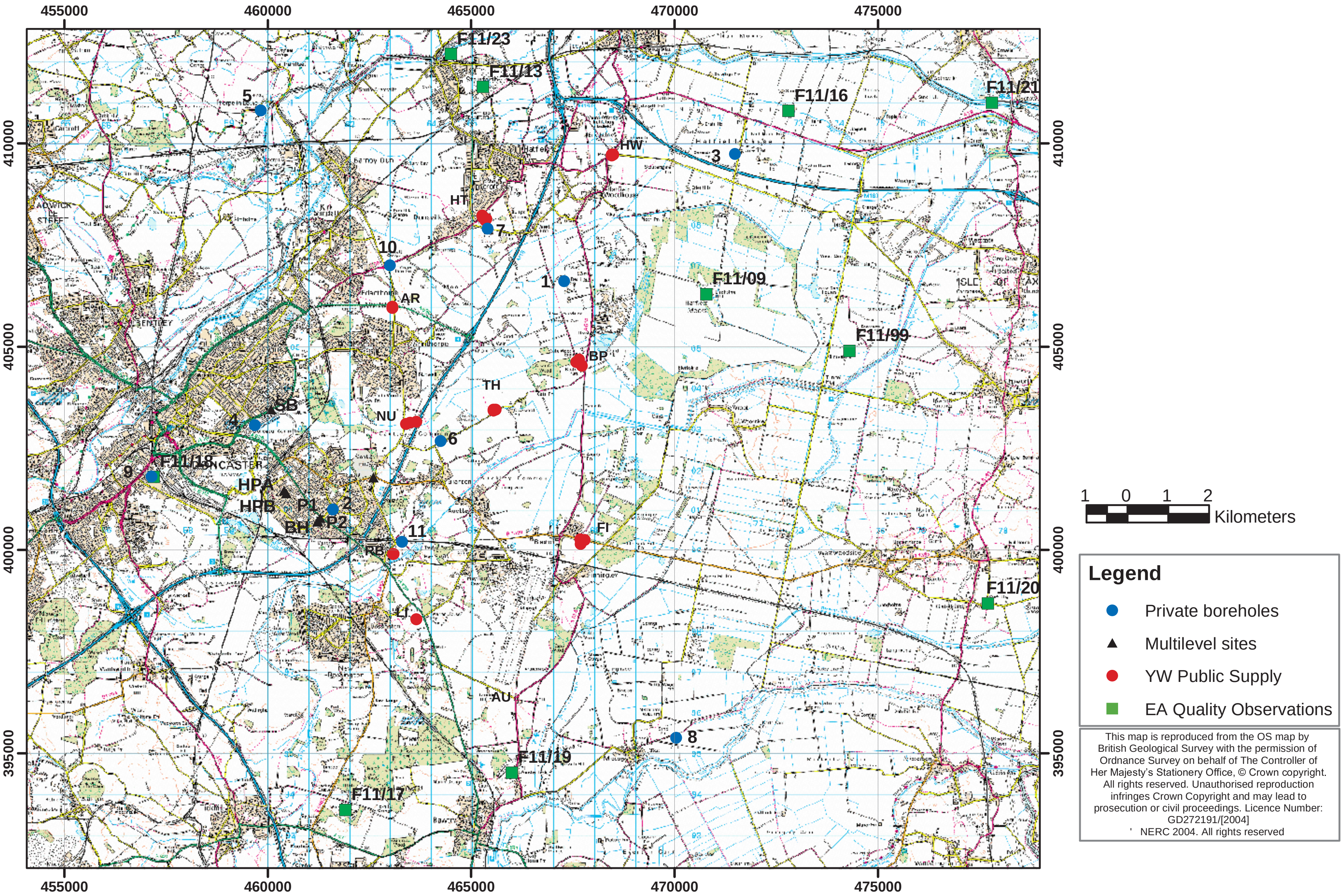
The EA maintains a database of groundwater quality. In the Doncaster area the majority of these data are supplied by YW from its public supply boreholes. Other sites are described in Table 2.3 and locations are shown in Figure 2.1. These are a mixture of farm and industrial boreholes ranging from almost entirely rural to periurban. There are no data in the database for over half these sites, and only 3 have any analyses for organic constituents. These are distant from the focus area or are otherwise unrepresentative (see 4.3.2) and inspection of the data indicates that their relevance to this project is marginal.

2.4 PRIVATE BOREHOLES

Unfortunately existing urban borehole/well sites are practically absent in Doncaster. Several privately owned boreholes in the general area are being sampled in order to provide additional regional chemistry information (Table 2.4). These sites were chosen by the following criteria:

(i) they are relatively shallow boreholes with short uppermost plain casing lengths

Figure 2.1 Locations of public supply boreholes, EA groundwater quality monitoring network, private boreholes sampled and multi-level sites (labels from Tables 2.2 to 2.4).



(ii) construction details and geological logs were mostly available

(iii) Quaternary superficial cover at the sites is generally thin (Table 2.4).

Two sampling rounds were undertaken, in June and November 2003 and the network is scheduled to be reviewed before further sampling visits.

Table 2.1 Construction details for public water supply boreholes

Site	BH no	Construction date	Drilled depth (m)	Present depth (m)	Casing (mbgl)	Open hole diameter (mm)
AR	**1**	**1964**	**176**	**176**	**30**	**375**
	2	**1967**	**168**	**168**	**30**	**375**
	3	**1967**	**168**	**168**	**30**	**375**
BP	**1**	**1969**	**231**	**176**	**30**	**375**
	2	**1974**	**137**	**137**	**30**	**375**
	3	**1974**	**137**	**137**	**36**	**375**
FI	1	1955	184	148	38	914 then 838
	2	1955	1856	139	38.4	914 then 838
	3	1955	1856	138	37.6	914 then 838
HT	1	1927	137	135	31.1	600
	2	1931	137	137	36	750
HW	1	1965	241	241	30?	375
	2	1969	180	180	30?	375
	3	1969	180	180	34	375
LI	1	1964	167	160	40	600
	2	1980	120	120	59	600
NU	**2**	**1927**	**152**	**152**	**33**	**825**
	3	**1980**	**120**	**120**	**45**	**600**
	4	**1980**	**120**	**120**	**45**	**600**
RB	**1**	**1933?**	**147**	**147**	**27**	**825**
	2	**1952?**	**145**	**148**	**27**	**825**
TH	**1**	**1934**	**155**	**159**	**32.9**	**600**
	2	**1934**	**182**	**182**	**31.1**	**750**
	3	**1980**	**121**	**121**	**45**	**825**

Boreholes in proximity to or supplying Bessacarr-Cantley study area given in **bold.**

Table 2.2 Summary of determinand classes and data/metadata for Yorkshire Water raw water analyses for the Doncaster wellfield

Determinand class	Approx. no. in class	Example	No. of analyses per well since 1980[1]
Taste and appearance	7	Colour, odour, taste	400 – 600
Temperature and pH	3	pH, temperature, turbidity	600 – 800
Major and minor inorganic constituents	22	Alkalinity	100 – 120
		Calcium, chloride, phosphate, sulphate	60 – 120
		Aluminium	60 – 80
		Boron	1 – 5
		Iron, manganese	400 – 600
		Nitrate	900 – 1100
		Nitrite	300 – 500
Trace heavy metals	8	Cadmium, lead, mercury, silver, zinc	10 – 40
Halogenated solvents	9	Trichloroethene, trihalomethanes	1 – 25
Petroleum hydrocarbons	4	MTBE, oil and grease, PAH	1 – 25[2]
Phenols	11	Chlorophenols, phenols	1 – 5
Pesticides[3]	90	Atrazine, bentazone, isoproturon, MCPP	3 – 15
Other potentially toxic parameters	10	Arsenic, selenium, cyanide, fluoride, bromate, radioactivity	1 – 5
Microbiological	15	Total and faecal coliforms	150 per year
		Cryptosporidium, enterovirus, rotavirus	<25
Surfactants	1		1
Total organic carbon	1		40-100
Total all determinands	**181**		

[1] 11sites. [2]Generally 1 – 5; extra sampling at HW due to fuel leak incident in catchment [3] since June 2000

Table 2.3 Environment Agency groundwater-quality monitoring sites (excluding YW sites)

GWCN Code	Name of site	B/H depth (m)	Easting	Northing	Inorganic data available	Organic data available	Most recent data
F11/09	Lindholme Hall	61	470780	406290			
F11/13	Hatfield Main Colliery	85	465290	411390	✓	✓	2001
F11/15	W.M. Darley, Thorne Brewery	137	468700	413400	✓		1986
F11/16	Redhouse Farm, Thorne	46	472800	410800			
F11/17	Yorkshire Bottle Co. Ltd, Bawtry	43	461910	393610	✓	✓	2001
F11/18	Peglers Ltd., Balby	30	457200	401800	✓		1992
F11/19	G.R. Stein Refractories Ltd	27	466000	394530			
F11/20	N.E. Pilkington Ltd , Graizelound	91	477700	398690	✓	✓	2001
F11/21	F.M.S. Farm Products	137	477800	411000			
F11/22	Eastoft Hall Borehole	146	480450	416330			
F11/23	Newfarm Chickens	31	464500	412200			
F11/98	Mill Lane, Crowle	107	478600	413300			
F11/99	Ninevah Farm		474300	404900			

Table 2.4 Private boreholes sampled for the AISUWRS project

Site no.	Site name	NGR	Depth (m)	Solid casing depth (m)	Drift thickness (m)
1	Beech Tree Nurseries	SE 6728 0661	30.5	17.7	up to 11*
2	Cantley Water Tower	SE 616 010	65.5	21.3	7.9
3	Crowtree Farm	SE 7148 0974	31.7	17.7	14.9
4	Doncaster Racecourse	SE 5968 0307	41.1	Not known	3.7
5	Elmstone Farm	SE 5983 1081	50.0	19.5	16.0 **
6	Gatewood Grange Farm	SE 6425 0268	76.2	Not known	7.8
7	Lings Farm	SE 6537 0791	12.0	Not known	Not known
8	Misson Quarry	SK 7004 9538	76.2	24.4	4.9
9	Peglers	SE 5714 0181	30.5	5.2	4.9
10	Sandall Common Farm	SE 630 070	63.4	17.4	4.6
11	Warning Tongue Borehole	SE 633 002	63.4	18.3	13.4

* drift/sandstone boundary poorly defined ** this value probably includes weathered sandstone

2.5 MULTI-LEVEL PIEZOMETERS

Five multi-level samplers were installed for the AISUWRS project in order to obtain depth profiles of urban groundwater chemistry (Table 2.5). At each site, a large diameter borehole was drilled and a number of piezometers were installed at different depths (Rueedi and Cronin, 2003). Most of the boreholes were drilled with air flush, however some mist was used at Haslam Park B. The piezometers are lined with plain casing throughout most of their length, with just 0.3 m interval of slotted casing used at the base of each. Bentonite seals hydraulically separate the piezometers from each other. Thus, samples of groundwater pumped from piezometers are known to originate from specific narrow depth intervals.

Two of the sampling sites (Haslam Park 1 and Haslam Park 2) were installed about 80 m apart, so that medium-scale variability in geology and hydrochemistry of the Sherwood Sandstone could be assessed. Two additional piezometers (P1 and P2, see Table 2.5) were installed in hand-augered holes to investigate very shallow groundwater, which appears to be perched upon low-permeability horizons within the Sherwood Sandstone.

Table 2.5 Multi-level samplers installed for the AISUWRS project

Site name	**NGR**	**Approx. ground elevation at site (m AOD)**	**Piezometers installed at depths (mbgl)**	**Estimated drift thickness (m)**
Sandall Beat (SB)	SE 6008 0345	9	16, 21, 26, 31, 36	6
Haslam Park 1 (HP1)	SE 6045 0139	9	10, 14, 21, 28, 35, 45, 60	0
Haslam Park 2 (HP2)	SE 6040 0146	9	10, 14, 19, 27, 35, 45, 60	1.6
McAuley High School (MHS)	SE 6259 0178	11	9, 14, 21, 28, 36, 45, 60	0.4
Bolton Hill (BH)	SE 6123 0070	5	16, 22, 28, 34, 39, 45, 51	0
P1 Bolton Hill	SE 6122 0070	5	3.15	0
P2 Bolton Hill	SE 6128 0079	5	1.30	0.5

The first round of sampling was undertaken in November 2003 and these data have been used for this report. Regular sampling of the multi-level piezometers will continue approximately every 3 months until late summer 2004.

2.6 SAMPLE COLLECTION AND ANALYSIS

2.6.1 Collection

For private-supply boreholes with in-situ pumps samples were collected directly from the pump outlet/sample tap after running the pump for a few minutes. For multi-level samplers and boreholes without pumps, samples were collected using either dedicated Waterra inertial pumps, or portable Whale® pumps connected in series or a suction-lift pump.

Hydrochemical samples were filtered through 0.45 µm cellulose nitrate membranes and collected in pairs in HDPE bottles, one being acidified to 1% with concentrated Aristar® nitric acid.

2.6.2 Field measurements

Dissolved oxygen (DO), redox potential (Eh), temperature and specific electrical conductivity (SEC) were measured during sample collection using a flow-through cell connected directly to the sample tap. Bicarbonate was determined by digital titrator.

2.6.3 Laboratory analysis

Measurements were made at BGS Wallingford. Cations, phosphorus and sulphate were determined on acidified sample splits by inductively-coupled plasma optical emission spectroscopy. On the unacidified splits, nitrogen species and chloride were measured by automated colorimetry, and bromide and fluoride by ion chromatography.

Results were reported using the normal limit of detection (LOD), which is derived from calculating the standard deviation (σ) of blanks about the mean blank value. The 6σ limit gives >99% confidence that the result can be distinguished from the blank and encompasses day-to-day variations in instrument noise. For the low concentrations of boron and phosphorus found, using this limit meant that a significant number were below the detection limit. For these determinands, data were also reported using the 3σ limit, which gives an increased number of quantifiable data, but is less statistically secure and also can mean that the limit of detection varies from day-to-day.

3 Development of conceptual model

3.1 GEOLOGICAL/GEOCHEMICAL SETTING: PREVIOUS STUDIES

3.1.1 Geological setting

Figure 3.1 indicates the regional geological setting in sketch section (from Morris et al 2003)

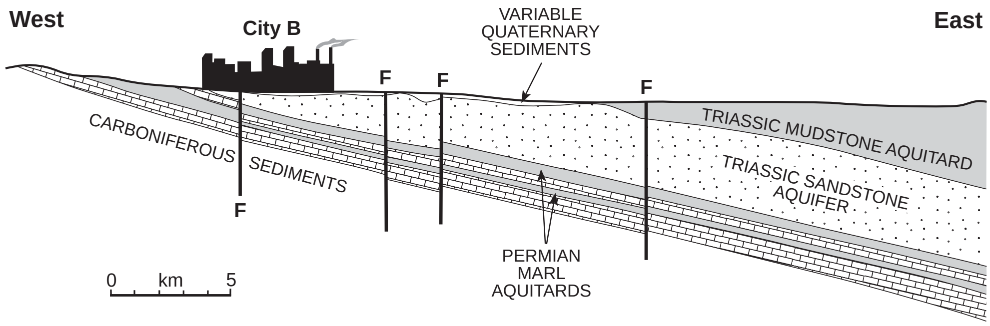


Figure 3.1 Sketch cross-section through the Doncaster aquifer

Key features of the aquifer's petrology are drawn from the regional memoir (Gaunt 1993) which describes the Sherwood Sandstone as mainly composed of quartz grains, with detrital and overgrowth silicate minerals. There are abundant clay and marl horizons and the sandstone is micaceous in parts. The red colouring is due to iron oxide present as sand coatings and in argillaceous fractions. The sandstone is poorly cemented and unconsolidated near the surface, but in parts contains a calcite cement. This cement may be gypsiferous in places and dolomite is an important accessory mineral.

3.1.2 Geochemical setting

The regional hydrogeochemical setting has been described by Smedley et al. (1993) who point out that unlike further south in Nottinghamshire, the Sherwood Sandstone Group west of the confining beds of the Mercia Mudstone Group is variably covered by Quaternary superficial deposits. Some of these deposits are semi-permeable or impermeable and produce additional locally confining conditions. Using regional reconnaissance sampling of well discharges, these authors observed that groundwater shows a distinct chemical evolution from west to east. The resultant regional hydrochemical setting has been interpreted as partly a response to anthropogenic contamination sources in the outcrop/subcrop area and partly a result of rock-water interaction, especially down-dip where the groundwater, confined beneath the Mercia Mudstone, comprises older water.

The evolution of groundwater chemistry is attributed to the strong influence of reactions with calcite and dolomite cements. In the unconfined aquifer, carbonate reaction is dominated by congruent dissolution of dolomite. There will also be progressive dissolution of gypsum, where present. Reaction with silicate minerals has a relatively minor effect compared with carbonate processes.

Previous more geographically extensive studies by Smedley et al. (1993) and Smedley and Brewerton (1997) provide a regional geochemical context to the outcrop/subcrop area between Doncaster and the Mercia Mudstone margin, which is the area the present project is exclusively concerned with.

Smedley and Brewerton (1997) in a study of the Sherwood Sandstone in the East Midlands region found that groundwater from boreholes in the unconfined aquifer show clear stratification with depth, revealing variations in the influence of pollution. In south

Yorkshire, concentrations of chloride, sulphate and nitrate are high at shallow depth and pumped groundwater appeared to be similar. Depth sampling showed that groundwater is often reducing at depth, with low nitrate, chloride and sulphate and containing a component of palaeowater with characteristically light stable-isotopic composition. This indicates that even in the unconfined aquifer, old pristine groundwater may be present at depth. Locally, Smedley et al. (1993) observed this effect at site BP, to the east of the present study area and tentatively concluded that agriculture and minor mine drainage influence were the sources of relatively high nitrate, sulphate and chloride contents in some of the public supply boreholes sampled. The patchy nature of the results was ascribed to:

(i) local confinement and protection by low permeability superficial deposits; porewater evidence showed groundwater in places to be anaerobic

(ii) depth stratification; decreasing redox potential and increasing residence time with depth was observed and palaeowater with depleted $\delta^{18}O$ and $\delta^{2}H$ and enriched $\delta^{13}C$ values was identifiable from depth sampling in BP

In their regional study, Smedley and Brewerton (1997) found nitrate to be distributed similarly to sulphate and potassium and also ascribed the distribution to diffuse pollution as a result of modern agricultural practice. Contamination of the semi-confined sources was shown to be less significant.

3.2 CONCEPTUALISATION OF FLOW SYSTEM

Figure 3.2 is a conceptualisation of the flow system as it has evolved in modern times. In the Sherwood Sandstone outcrop area east of present-day Doncaster and west of the Mercia Mudstone margin, it seems likely that pre-1900 flow patterns were both shallow and localised. The slightly elevated land below the present town and eastern suburbs is partly composed of Quaternary superficial deposits and groundwater recharge entering the subsurface is likely to have flowed only a limited distance eastwards to discharge to the River Torne, associated watercourses and wetlands on the eastern margin of the outcrop/subcrop zone. Until the turn of the 19th century this latter area was a wide fenland-type wetland, much of it less than 3 m above sea level and with eastward drainage constrained by higher land of the low Mercia Mudstone scarp of the Isle of Axholme. Unlike the main Sherwood Sandstone outcrop extending 60km to the south in Nottinghamshire there is negligible topography east of Doncaster to provide a head difference to drive down-dip flow beneath the Mercia Mudstone. In these circumstances palaeowaters would be expected in the aquifer both in the deeper aquifer at outcrop and close to the confined zone margin, which is what is observed (Smedley et al., 1993).

Post 1900, first mine dewatering then public supply, mineral washing and agricultural boreholes came into operation, and it is likely that the shallow flow cycles of lateral discharge to the wetlands west of the Isle of Axholme have become replaced by a progressively stronger vertical leakage component. In the last quarter of the 20th century, other groundwater uses have declined so that currently withdrawals for public supply, from the Doncaster wellfield, predominate. The late 20th century has therefore seen the development of a composite cone of depression, in effect replacing much lateral shallow drainage with downward leakage.

Today there is broadly radial flow towards this water-level depression, with the direction of groundwater flow from central Doncaster and Bessacarr broadly eastwards and south-eastwards towards a trough whose axis trends NNE-SSW from east of Hatfield through Finningley towards Austerfield.

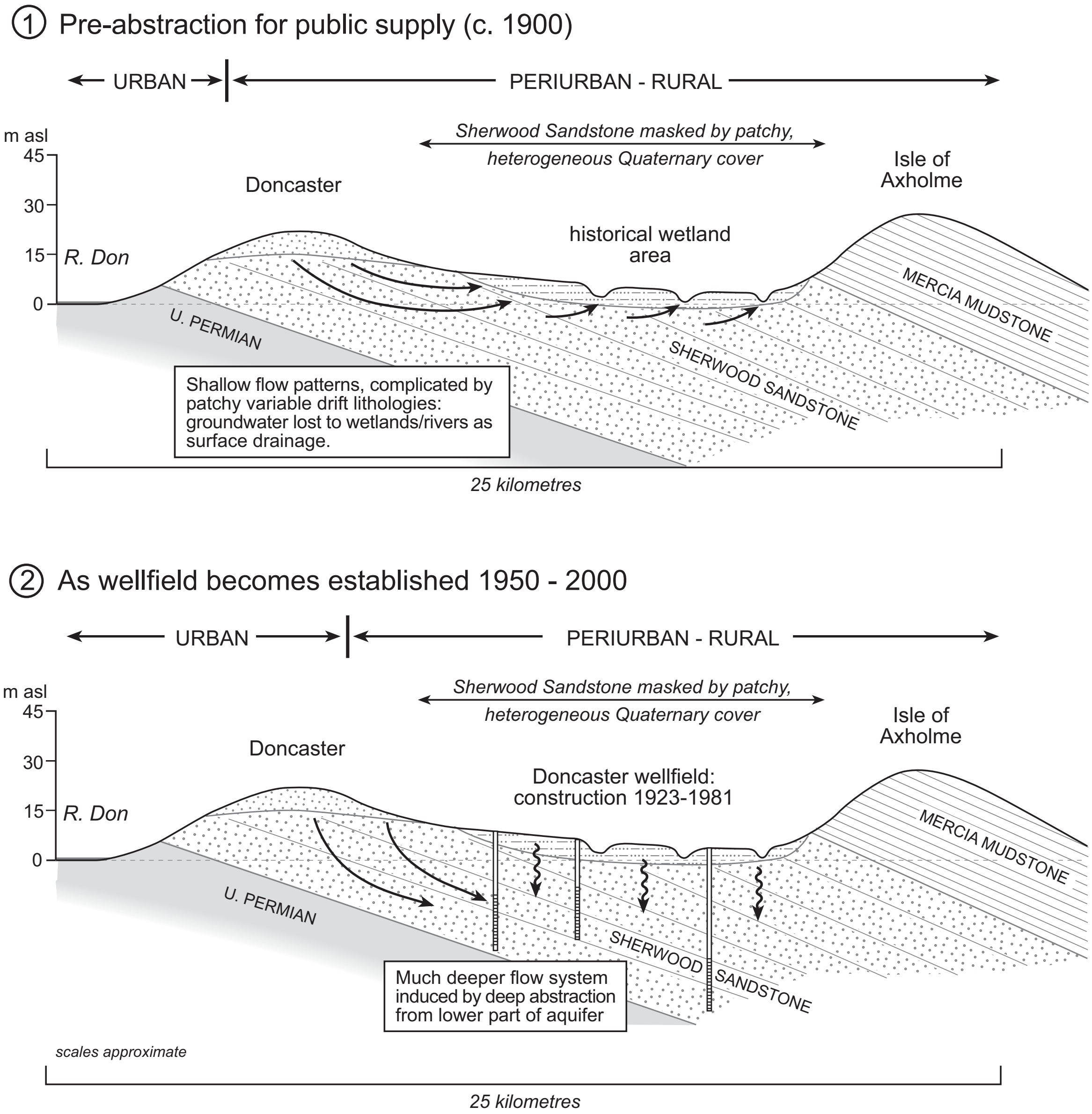


Figure 3.2 Influence of modern groundwater abstraction on groundwater flow

The pumping stations AR, NU, TH, NU and RB, which are located on the eastern margin of Doncaster and suburbs are therefore regarded as representative of local groundwater. These boreholes draw from the middle and lower part of the Sherwood Sandstone but are probably influenced by local effects on recharge, both urban and agricultural. A historic mine drainage/spoil influence is also likely from the presence of the former Markham Main coalmine at Armthorpe.

3.2.1 Local factors increasing flow system complexity

There are various lithological and sedimentary features that add complexity to local flow patterns. These are outlined below:

(i) The uppermost, weathered zone of the Sherwood Sandstone in the Doncaster area is unconsolidated or poorly consolidated; an observation verified during the drilling and construction of the multi-level research boreholes. This weathering makes the boundary between locally-derived superficial and bedrock deposits difficult to identify in many boreholes.

(ii) The Sherwood Sandstone contains mudstone and mud-pellet conglomerate horizons, particularly at the top of the sequence and towards the east of the area, some of which appear to be persistent along the strike. Interpretations of pumping-test data have shown that such fine sediments can act as a semi-confining layer (Allen et al., 1997), or at least impede vertical flow components. The effects of these horizons in a dipping sequence are not documented but one result of abstraction-induced downward flows may be to focus lateral groundwater flow downdip through the more permeable sandstone horizons rather than vertically through a given aquifer section.

(iii) Quaternary superficial deposits overlying the Sherwood Sandstone over much of the study area can be laterally and vertically variable, with lithologies ranging from gravels to lacustrine clays. Locally some deep buried channels are also present (as described in Morris et al., 2003). Consequently, permeabilities can be widely variable and the less permeable silts and clays may both impede vertical recharge and cause local confinement of groundwater.

3.2.2 Factors affecting water quality

Some minor solute inputs may occur from non-local sources. For instance, recharging rainfall will historically have contained chloride, and also contributed other halogens. Modern rainfall also contributes sulphate and nitrate (Table 3.1).

Table 3.1 Rainfall quality at Jenny Hurn monitoring site (48163986) for 2001 (Precipitation - weighted mean provided by AEAT)

SEC (µS/cm)	Concentration (mg/l)							
	SO_4	NO_3	NH_4	Na	Mg	Ca	Cl	K
30.3	2.8	2.3	0.98	0.90	0.15	0.41	2.1	0.08

The ease with which local recharge can occur also affects physicochemical parameters that influence groundwater inorganic content. For instance, under unconfined conditions, particularly at shallow depths where active recharge is taking place, groundwaters are oxidising with high dissolved oxygen (DO_2) content and redox potential (Eh). Where groundwaters are confined by the Mercia Mudstone, or locally by impermeable drift, conditions become reducing. This is marked by notably lower Eh readings and nitrate concentration. Although beyond this project's area of interest, the same effect has been noted by Smedley et al. (*op.cit*) further east in the Mercia Mudstone-confined zone, where the onset of reducing conditions beyond a redox boundary also leads to increased concentrations of iron and manganese and to a reduction in uranium concentration. These trends are reportedly less clearly defined in south Yorkshire than further south in the East Midlands as a result of local confinement (Smedley and Brewerton, 1997).

3.3 CONCEPTUALISATION OF WATER QUALITY SETTING

Figure 3.3. presents a simple conceptual model of the influences on water quality in the study area and includes the following elements:

- recharge with an urban signature enters the aquifer beneath central Doncaster and Bessacarr
- to the east of Doncaster, recharge occurs in a rural environment and agricultural chemicals especially fertilisers provide different sources of contamination, although there is overlap with the contaminant constituents of urban origin
- the characteristic ‘signatures’ of contaminated urban and rural recharge will be gradually diluted by mixing (through dispersion and diffusion) with older waters in the aquifer. Chemical processes such as denitrification and adsorption will also attenuate some contaminants
- the major public-supply sites abstract water that is a mixture of younger, contaminated shallow water and older uncontaminated (but still mineralised) water from greater depth.

3.4 POTENTIAL INDICATORS OF URBAN CONTAMINATION

Table 3.2 lists a number of potential indicators of pollution and their possible sources. After discussion the UK project partners chose a subset of these commonly encountered urban recharge indicators: chloride, sulphate, boron and zinc. *E. coli* and other faecal contamination indicator are discussed in a separate report describing the results of microbiological determinations (Rueedi et al., 2004).

Table 3.2 Possible contamination indicators

Determinand type	Determinand	Source	Activity type	Comment
Major ions	Nitrate	Fertilisers Sewage	Rural Urban	Not conservative in reducing conditions
	Chloride	Sewage Road salt Mine drainage	Urban Transport network Mining	
	Sulphate	Sewage Mine drainage	Urban Mining	
	Phosphate	Sewage Fertilisers	Urban Rural	Limited mobility in groundwater
	Potassium	Sewage Fertilisers	Urban Rural	Attenuated in soil zone
Minor ions	Aluminium			
	Iron & manganese	Low redox	Natural/urban	High natural concentrations in areas of aquifer
	Fluoride	Toothpaste	Natural/urban	
	Boron	Detergents	Urban	
		Mine drainage Metal working/processing	Mining Industrial	
Trace metals	Cadmium	Metallurgy, pigments	Industrial	Very limited data available
	Mercury	Batteries/landfill	Industrial	
	Zinc	Metal working/ landfill	Industrial	
Organics	Surfactants	Domestic and industrial cleaning	Urban	Very limited data available
	Solvents	Metal working, paints	Industrial	
	Hydrocarbons	Fuel, heating oil	Urban, industrial	
	Phenols	Timber preservatives		
	Pesticides	Agricultural herbicides, fungicides and growth regulators	Rural	Potentially wide range of determinands - analysis very expensive
		Amenity herbicides	Urban and transport network	
		Rodenticides, mothproofers	Urban/industrial	
		Timber preservatives		
Microbes	**Faecal Coliforms**	Urban wastewater	Urban	
	Clostridium			
	Viruses			

Determinands in bold selected for this study; note that pristine groundwater may also contain some or all of the above determinands as natural constituents.

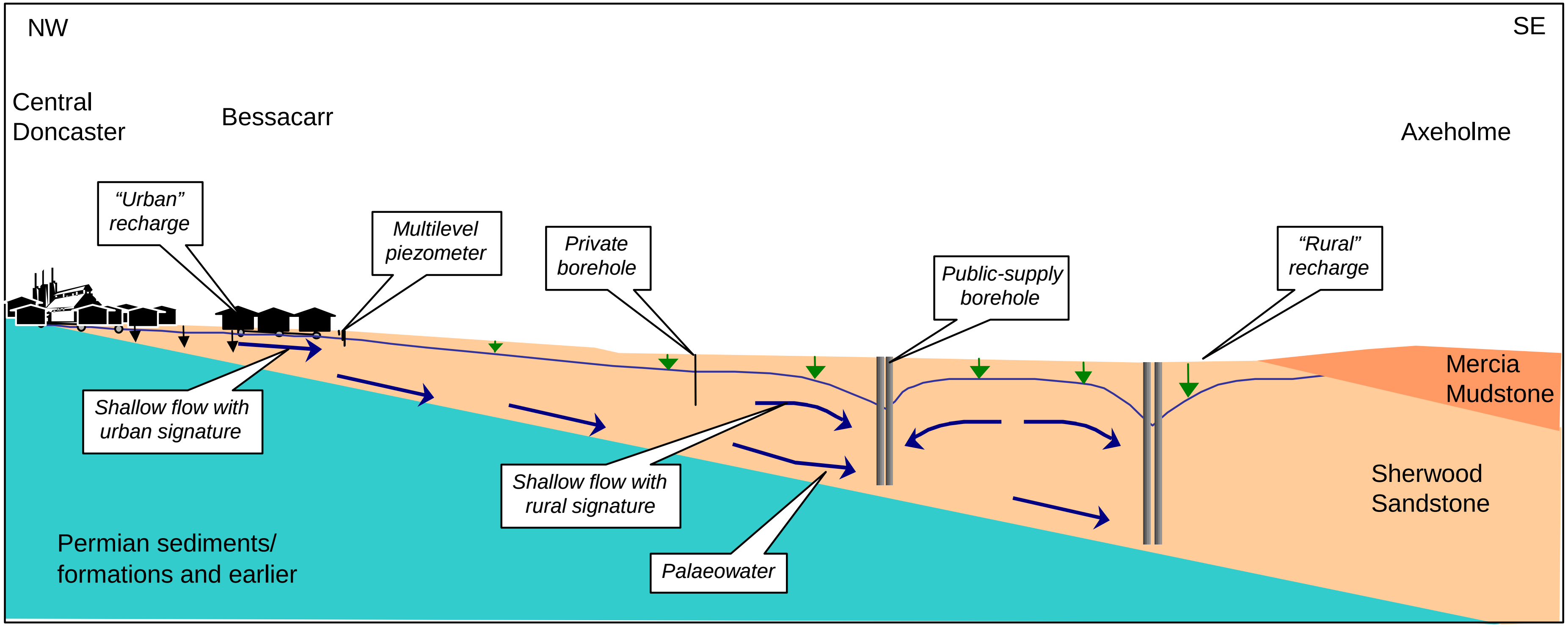


Figure 3.3 Schematic diagram illustrating the main features of the conceptual model

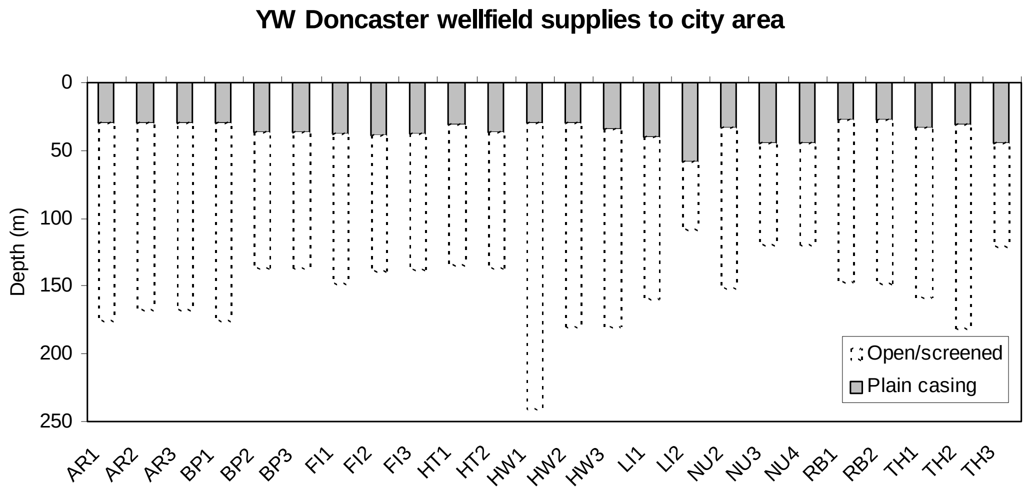
4 Inorganic monitoring results and discussion

4.1 RAW WATER DATA FROM PUBLIC SUPPLY BOREHOLES

4.1.1 Major ion chemistry

Raw water quality data from YW public supply boreholes are summarised in Tables 4.1 and 4.2. YW analyse for SEC, iron, manganese and nitrate in raw water much more frequently than for other major ions, so the data summaries in Table 4.1 are for a variable number of analyses. For the determinands shown in Table 4.2, the majority of the results are less than the detection limit, so no mean value has been calculated.

Of the sites considered in this report, these boreholes are likely to be yielding water with the least urban influence. Not only are the catchments, as delineated by the EA, in areas that are predominantly rural but also they are generally deeper than the other boreholes sampled. Nevertheless, these public supply boreholes are all open or screened over much of their depth and this design will draw in a mixture of water from different depths in the aquifer (Figure 4.1). Buckley and Talbot (1993) estimated that at HT2 about 40% of water moving to the pump was higher-conductivity water from the upper aquifer. So although boreholes at the same site may be of different depths this will not necessarily impact on the quality.



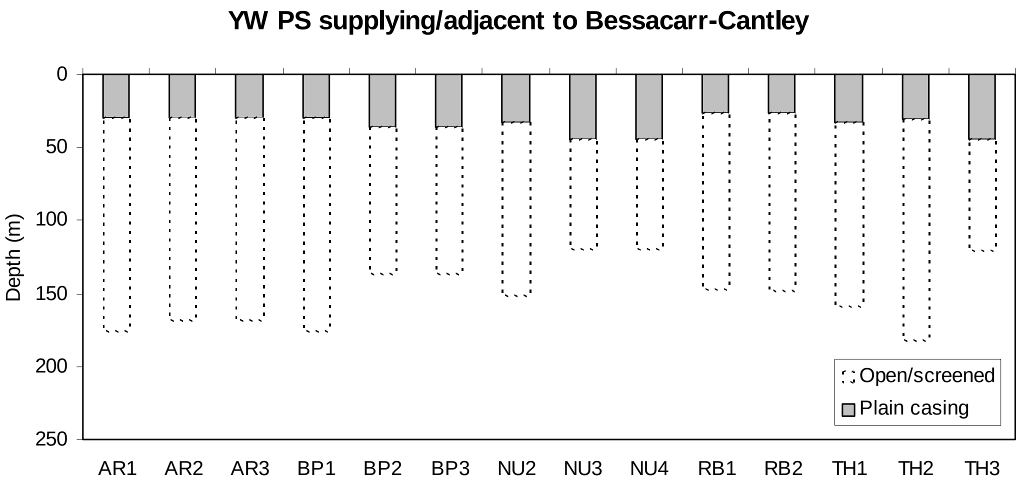


Figure 4.1 Designs of YW Doncaster wellfield supplies to the city area; in the vicinity of the study area, the boreholes tap the aquifer variously from 27-180m depth

Table 4.1 Range and mean concentrations of major and minor ions in raw and treated water from Yorkshire Water public supply boreholes since 1999

Site	BH	Depth (m)	SEC (µS/cm)			Na (mg/l)			K (mg/l)			Ca (mg/l)			Mg (mg/l)		
			Max	Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av
AR raw	1	176	537	259	401	-	-	14.1	-	-	2.4	-	-	40.3	-	-	17.9
	2	168	536	327	484	-	-	11.8	-	-	2.4	-	-	32.9	-	-	16.5
	3	168	563	369	478	-	-	14.6	-	-	2.9	-	-	45.4	-	-	20.1
BP raw	1	180	413	373	396	12.3	11.7	12.0	2.7	2.6	2.6	51.4	49.3	50.4	21.3	20.1	20.8
	2	137	598	365	365	14.4	12.3	13.2	2.4	1.9	2.2	53.5	50.6	51.9	21.2	20.0	20.6
	3	137	437	364	409	10.8	10.0	10.4	2.7	2.4	2.5	53.4	50.2	51.3	24.8	23.2	23.8
FI raw	1	148	445	298	357	12.8	11.4	11.9	2.2	2.2	2.1	44.4	41.1	42.6	17.2	15.4	16.3
	2	139	554	339	362	8.4	6.8	7.8	2.0	1.7	1.9	45.2	43.4	44.4	20.2	18.5	19.7
	3	138	565	337	430	13.9	7.6	12.3	2.3	1.8	2.1	51.7	45.7	49.9	23.1	18.6	21.9
HT raw	2	137	659	377	510	18.7	10.8	14.4	4.4	3.2	3.7	102	50.7	64.7	27.5	8.5	23.7
HW raw	3	180	533	364	431	14.9	11.0	12.7	3.5	2.9	3.2	55.8	49.2	51.3	22.9	19.7	21.3
LI raw	1	167	681	358	460	14.6	14.0	14.3	2.4	2.4	2.4	53.8	52.3	52.3	23.9	21.9	22.8
	2	120	571	305	361	12.1	9.5	10.9	2.1	1.7	1.9	44.4	36.7	40.9	19.3	16.2	18.1
NU raw	2	152	773	366	588	21.8	18.9	20.2	3.3	2.7	3.0	67.7	66.0	66.6	25.7	24.4	25.2
	3	152	1160	483	571	24.2	22.0	22.9	2.9	2.7	2.8	72.5	68.0	69.9	25.2	24.3	24.9
	4	120	865	408	528	23.4	19.1	20.5	3.0	2.6	2.8	67.3	52.0	55.7	25.1	22.5	23.8
RB raw	1	147	693	332	543	31.5	21.9	25.7	4.2	2.8	3.2	68.7	47.4	54.7	31.0	24.0	27.1
	2	145	884	350	586	57.6	13.8	32.6	3.7	2.7	3.1	65.9	38.2	55.8	33.2	21.3	27.9
TH raw	1	155	496	314	399	18.5	8.7	13.1	2.9	2.2	2.6	53.4	51.9	52.7	23.8	20.1	22.1
	2	180	737	358	428	18.5	8.1	10.0	2.9	2.2	2.7	58.9	51.3	53.8	25.5	19.9	22.5
	3	120	732	408	430	9.1	8.2	8.6	2.8	2.3	2.5	58.4	52.7	54.7	25.4	22.6	24.2
Nutwell final	-	-	607	359	456	17.9	10.9	14.9	2.9	2.3	2.7	63.0	49.5	54.4	26.9	21.5	23.0

Boreholes in proximity to or supplying Bessacarr-Cantley study area **bolded.** Max and min values not quoted where there is only one value

Table 4.1 continued

Site	BH	HCO_3 (mg/l)			Cl (mg/l)			NO_3-N (mg/l)			SO_4 (mg/l)			Fe (µg/l) §			Mn (µg/l)		
		Max	Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av	Max	Min	Av
AR raw	1	-	-	79	-	-	31.3	14.2	5.6	11.5	-	-	48.6	31	<7	8	113	<1.5	6.8
	2	-	-	104	-	-	19.9	14.4	8.3	12.6	-	-	31.0	20	<7	7	1.0	<1.5	0.9
	3	-	-	_644*_	-	-	29.9	19.5	8.8	14.4	-	-	42.0	22	<7	7	59	<1.5	2.3
BP raw	1	236	230	233	18.8	17.8	18.4	0.65	0.12	0.25	18.4	17.7	18.1	657	55	394	183	147	166
	2	233	204	216	28.8	25.5	27.0	8.4	<0.13	0.37	30.7	26.1	28.8	728	23	309	265	84	181
	3	253	244	250	16.8	14.5	15.8	8.5	0.12	0.42	25.3	23.6	24.3	832	279	494	133	17	121
FI raw	1	164	128	151	28.4	18.7	25.2	5.9	0.34	2.3	45.2	30.2	33.9	158	7	37	37	13	27
	2	230	203	215	19.7	18.8	19.3	7.6	0.15	0.46	8.5	7.5	8.1	1760	10	95	161	2.4	23
	3	202	176	193	28.9	19.0	25.9	8.3	0.34	5.0	34.3	8.2	27.3	476	12	75	54.1	4.0	21
HT raw	2	177	148	163	43.7	30.2	37.1	13.2	3.3	7.1	87.3	37.2	75.0	311	<7	12	23	<1.5	3.1
HW raw	3	152	135	148	36.2	28.9	31.5	9.9	5.8	8.2	70.9	40.4	47.0	96	<7	7	45	6.0	20
LI raw	1	138	136	137	34.6	32.3	33.1	11.8	5.6	10.4	66.3	37.2	60.5	145	<7	11	14.1	2.0	9.2
	2	135	122	131	25.5	18.5	23.1	11.4	1.9	7.7	40.4	22.7	33.3	706	<7	11	188	2.0	13
NU raw	2	223	193	204	84.3	62.5	71.0	8.95	4.7	5.8	38.2	29.7	34.2	862	10	71	167	32	113
	3	210	210	210	58.6	53.7	55.5	12.9	8.3	9.1	54.8	50.0	51.9	328	<7	49	138	49	78
	4	203	162	173	53.1	50.5	52.2	13.3	3.8	8.7	50.0	27.0	33.8	803	<7	31	462	5.0	60
RB raw	1	191	135	150	78.1	53.6	64.3	11.0	6.6	8.1	82.9	52.7	68.3	121	<7	10	66	1.7	6.7
	2	182	129	153	140	37.9	75.2	10.3	2.0	8.2	97.4	39.2	70.0	6300	<7	109	155	2.0	8.9
TH raw	1	210	170	195	51.8	20.7	31.6	9.3	0.1	2.0	38.2	24.5	30.3	416	<7	38	178	1	70
	2	231	170	211	52.8	20.6	25.5	10.6	0.1	2.0	63.3	21.8	35.6	364	<7	25	187	8.0	87
	3	246	218	237	25.7	19.4	21.5	8.5	1.6	2.1	49.1	19.8	25.7	856	<7	16	94	4.1	83
Nutwell final	-	240	180	211	41.0	25.9	34.1	10.1	0.49	4.26	45.5	27.1	36.4	48.0	<7	7	11.4	<1.5	1.2

* Data in *italics* apparently anomalous and not used.

§ It is not known if samples for Fe and Mn are filtered at the Yorkshire Water laboratory. If not the sporadic very high concentrations may be particulate in origin and therefore spurious.

Table 4.2 Maximum concentrations of infrequently analysed determinands in raw water from Yorkshire Water public supply boreholes since 1970

Site	As (µg/l)	Sb (µg/l)	F (µg/l)	Pb (µg/l)	Zn (µg/l)	B (µg/l)	PO_4 (µg/l)
AR	6.4	2.1	500	45	30	50	130
BP	-	<1	80	<5	20	<50	<10
FI	5	<1	100	20	220	<50	60
HT	5.2	1.7	50	18	70	<50	60
HW	2.0	<1	125	<5	20	<50	40
LI	6.1	<1	80	<5	70	<50	40
NU	7.3	1.3	220	13	160	<50	10
RB	<5	<1	120	25	80	<50	110
TH	1.0	<1	120	16	100	<50	30

The data show a pattern consistent with the earlier studies referred to in the previous section where the west of the aquifer is characterised by its higher chloride, sodium and possibly sulphate concentration (chloride concentrations >30 mg/l are found in all boreholes at RB, HT and NU, and some at AR, LI and TH). One interpretation is that this may be due to a higher content of modern water in the western aquifer, which is thinner due to post-depositional tilting and erosion. To the southeast water contains a higher concentration of bicarbonate, and this interpretation would derive the bicarbonate presumably from a longer residence time in the full-thickness aquifer (bicarbonate concentrations of >200 mg/l are found in all boreholes at BP, and in at least one at FI, NU, and TH). AR, NU and LI are in a similar setting to RB and HW, and BP to FI (Figure 4.2).

There is limited evidence of local reducing conditions with iron and manganese detections and variable concentrations of nitrate in water from FI, NU and TH. This is consistent with the results from some of the multi-level piezometers as described in Section 4.4. The highest and most consistent concentrations of both iron and manganese are found at BP together with generally low nitrate concentrations.

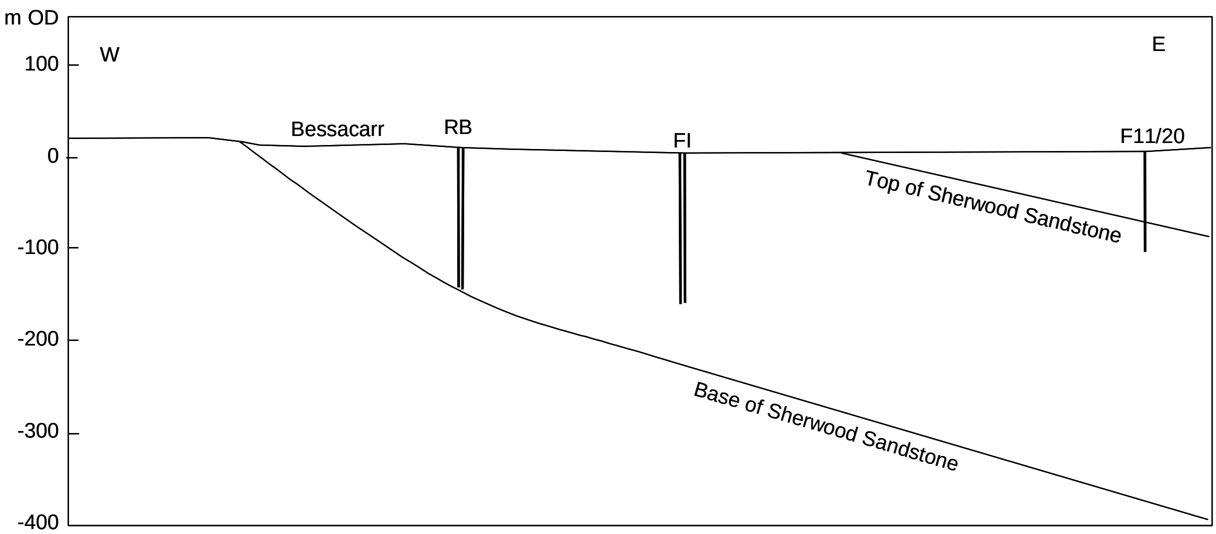


Figure 4.2 Sketch cross-section of central part of the aquifer showing examples from western PS sites where aquifer thickness is reduced by post-depositional tilting and eastern sites tapping full thickness aquifer (250m+)

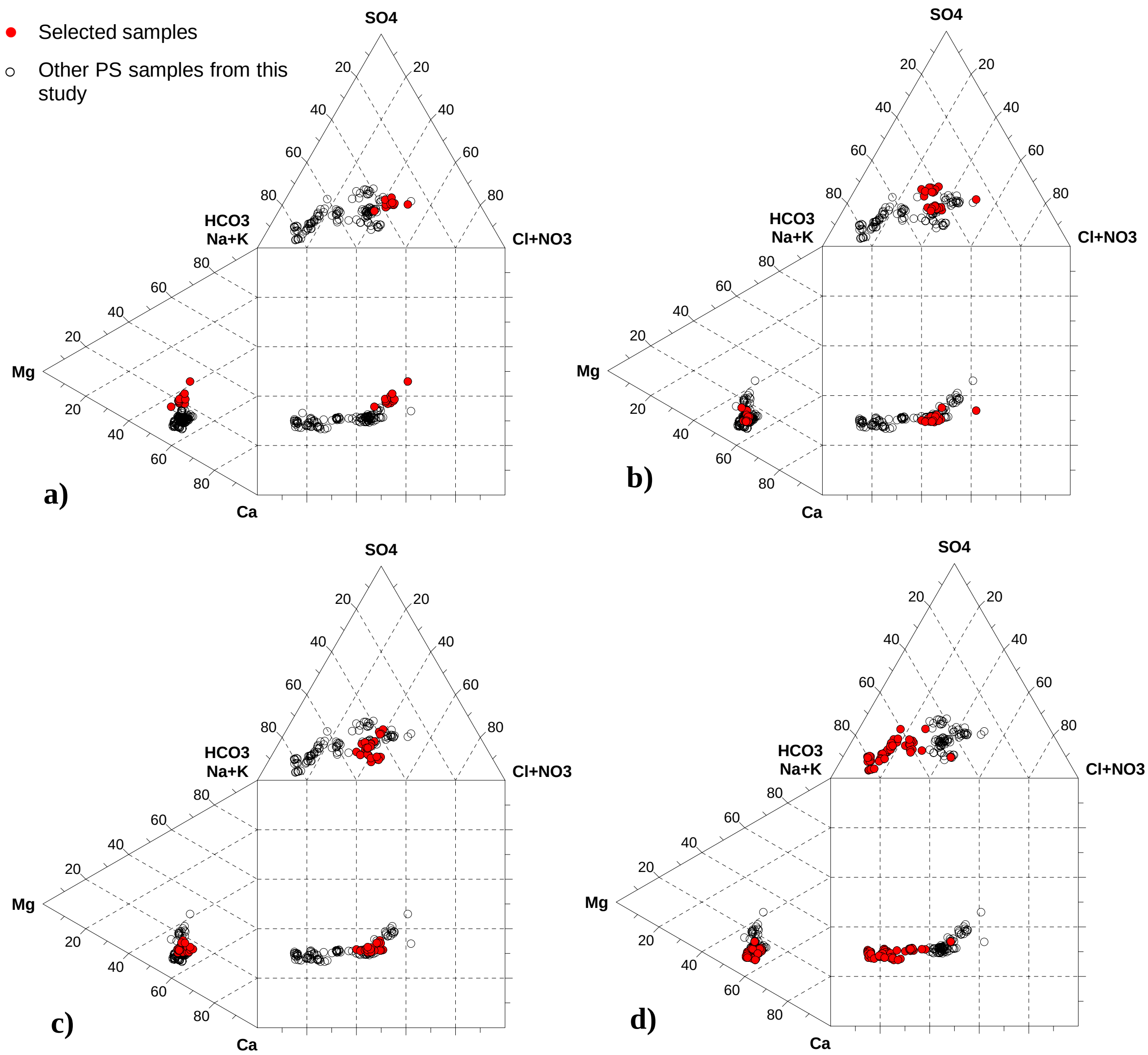


Figure 4.3 **Durov plots showing geochemical evolution of water from Yorkshire Water public supply boreholes a) RB; b) AR, HT, HW; c) LI, NU; d) BP, FI, TH**

Major-ion chemistry is summarised as Durov plots in Figure 4.3. While individual boreholes have a range of qualities, these plots show the water at RB as an end member of the distribution with the highest proportion of sodium, chloride and nitrate (Figure 4.3a) and the more reducing semi-confined water at BR, TH and FI at the other extreme dominated by calcium and bicarbonate (Figure 4.3d).

Although the 9 pumping stations that supply the city all abstract from the middle and lower Sherwood Sandstone aquifer, and are of the same general calcium-magnesium-bicarbonate-sulphate facies, the internal variability of water quality from the different pumping stations, as evidenced in Figure 4.3 and Table 4.1 is quite striking. It is clearly impractical to characterise as a single simple water type the 20 km strike section of outcrop Sherwood Sandstone aquifer that this wellfield taps. This observation has prompted a closer inspection (which is ongoing as part of the field programme) of the supply strategy to the Bessacarr-Cantley study area, with two objectives:

(i) To characterise more closely groundwater in the immediate vicinity of the study area, in part to assess whether it is already subject to urban recharge influence and in part to provide a baseline with which to compare the impact of contaminants in urban-derived recharge.

(ii) To identify which pumping stations provide the groundwater to the water mains pipe network of the study area and in which proportions, in order to provide a 'mains standard average water quality' for the UVQ model and subsequently as a source term for solute transport modelling.

4.1.2 Treated water supplied to the Bessacarr-Cantley study area

The six Demand Management Areas (DMAs) in the study area receive a combined supply from AR, BP, NU, and TH pumping stations, blended at Nutwell Water Treatment Works. Data for these sites is highlighted in Table 4.1. The blend of these four raw waters will vary with time according to operational conditions. The water is treated for manganese removal, blended to manage nitrate, then put into supply after precautionary disinfection and plumbo-solvency control stages. The resultant treated water blend is shown as an entry at the bottom of Table 4.1.This represents the typical water quality in the study area's mains supply and is a UVQ source term. Exceptionally, from November 2000, for about four months during the rehabilitation of the trunk main from Nutwell, the DMAs were supplied in approximately equal proportions with water from RB and FI.

The boreholes supplying Bessacarr-Cantley tap an aquifer with a saturated thickness of 104-222m which, depending on location, represents all or part of the middle and lower aquifer. The typical depth range for abstraction from screened or open-hole sections is approximately 32-150 mbgl. These boreholes at the four pumping stations supplying the water treatment works and RB are all located in the vicinity of the study area, with AR, NU and RB on the western side of the wellfield closest to Doncaster. Their locations and the key supply role to the study area of four of these five sites make them the most likely to be impacted by urban recharge effects. These five pumping stations will therefore become the main water supply reference points for further work in the AISUWRS field programme (Work Package 4).

4.1.3 Contaminants and potential urban indicators

The distribution of nitrate, which is widely and frequently analysed for regulatory purposes, is probably controlled by surface inputs and redox conditions in the aquifer. Previous studies (section 3.1.2) have shown that there is both local confinement by low-permeability deposits and decreasing redox potential with depth and that nitrate is absent or has low concentration where iron and manganese are significant. This may indicate either an element of denitrification (although there is little dissolved organic matter in the aquifer to drive this process) or the source water may predate pollution.

At several pumping station sites, e.g. FI and historically at HT, individual boreholes produce water with very different nitrate concentrations and sometimes large fluctuations. This may be due to one or more of the following explanations:

- land use in the individual borehole catchments of a pumping station is different. At HT, when two boreholes were operating, the catchment for borehole 1 extended under agricultural land whereas that for borehole 2 was predominantly under the village
- there are operational reasons, such as the borehole pumps are set at, and draw from, different depths
- there are interconnections between the boreholes in the aquifer
- there is a local redox boundary that can be reached by different pumping regimes.

Overall this suggests that the presence or absence of nitrate may not be a reliable delineator of contamination and especially of a particular provenance such as urban-derived recharge.

Sulphate concentration is variable over the wellfield. The highest concentrations are found in HT and RB (up to 75 mg/l) and the lowest in FI, TH and BP (generally 20 – 30 mg/l, but as low as 8 mg/l), but all sites show internal variation. This is greatest at LI and FI. It is not obviously related to Fe and Mn. Depth samples from BP1 (Smedley et al., 1993), show that sulphate is lowest in the profile from 60 – 90 mbgl, and Fe the highest from 62 – 108 mbgl. Chloride is high in NU and RB, and in the range 30 – 50 mg/l elsewhere. At BP1, HT2 and HT4 in 1993, downhole sampling showed that Cl decreased rapidly in the upper 50 m and was lowest at the base of the borehole (Smedley et al., 1993).

The less frequently analysed parameters are more difficult to interpret. Phosphate is present at low concentrations in groundwater from all boreholes except BP at 10 – 40 µg/l. Isolated higher concentrations (up to 130 µg/l) have been found at AR, RB, HT and FI. Phosphate can be derived from fertiliser applications to agricultural land and from urban wastewater (about 30 mg/l PO_4 in study area), but its ready adsorption to soil particles and other organic material is a strong attenuating factor.

Concentrations of fluoride are variable but are highest in groundwater from AR and NU. Arsenic and antimony are only occasionally detected above concentrations of <7 and <2 µg/l respectively. The highest concentrations of As and Sb were found at AR, HT and NU, and As was also found at LI. These elements appear to be present at higher concentrations in the western part of the aquifer. Boron has been infrequently analysed for. This was detected only once at a concentration close to the YW detection limit of 50 µg/l.

Smedley and Brewerton (1997) found little evidence of contamination by trace metals and the datasets from these production wells confirm this observation. Almost all analyses for Cd, Cu and Hg are below the limits of detection. Data for Pb and Zn are included in Table 4.2. Pb concentrations are highest at AR and RB. Zn is very variable and is highest in FI and NU.

The background concentrations of a range of anthropogenic organic compounds are very low with no evidence of significant urban impact on quality. There are a very few positive detections of trihalomethanes. These were all in groundwater from boreholes sampled during a two-day period in 1990 and may therefore be a laboratory artefact. There have been isolated detections of hydrocarbons at BP, oil and grease at RB, and phenols at NT. HW has been out of supply for some time as a precaution against a leaking underground storage tank problem at an adjacent fuel-filling station. Polyaromatic hydrocarbons, hexachlorobenzene, 2,4,6-trichlorophenol and ionic surfactants have never been detected.

Low concentrations of pesticides have been widely detected across the wellfield. The results can be considered to fall into four groups:

- triazine herbicides particularly at HT, but also at HW and FI – predominantly atrazine, which is presently still authorised for weed control in maize and orchards, but was previously used for road verges, railway lines and open areas until 1993
- agricultural pesticides at TH
- limited individual detections at AR and LI
- multiple detections of both agricultural and amenity pesticides at BP, NU and RB.

These results suggest that pesticides are probably present in the modern component of abstracted water from these boreholes. There is some evidence that these are related to catchment land use since significant detections of atrazine occurred in partly urban HT and RB and of purely agricultural compounds in BP, TH and NU which are more rural.

4.2 PRIVATE SUPPLIES AND ENVIRONMENT AGENCY MONITORING

4.2.1 Major-ion chemistry

The 11 private wells being monitored are located on the eastern and central zones of the Sherwood Sandstone outcrop. Major-ion chemistry for private supplies in the project monitoring network is summarised in Table 4.3. All of these boreholes apart from Cantley Water Tower and Warning Tongue Lane have higher electrical conductivities than the public supply boreholes in the vicinity, indicating a higher dissolved solids content. The distribution of major ion constituents appears unrelated to geographical position. In these boreholes the major ion constituents of the study area subset lie in the calcium-bicarbonate-sulphate hydrochemical type, within which they are as variable as the deeper aquifer waters sampled by the YW public supply boreholes (Figure 4.4). While anion chemistry is rather more variable, with higher proportions of sulphate and chloride than the deeper public-supply boreholes, a number of these wells, although rural, show possible local effects likely to be unrelated to urban recharge.

Reducing conditions are apparent at the rural sites of Beech Tree Nurseries and Elmstone Farm, as indicated by elevated Fe, Mn and sulphate and low nitrate. This is likely to be due to local confinement of the groundwater by superficial deposits or by low-permeability layers within the sandstone. The highest concentrations of Fe are found at Beech Tree Nurseries (22500 and 21100 µg/l). The redox status of groundwater from the rural site of Crowtree Farm is unclear as one set of data indicates oxidising conditions and the other reducing conditions.

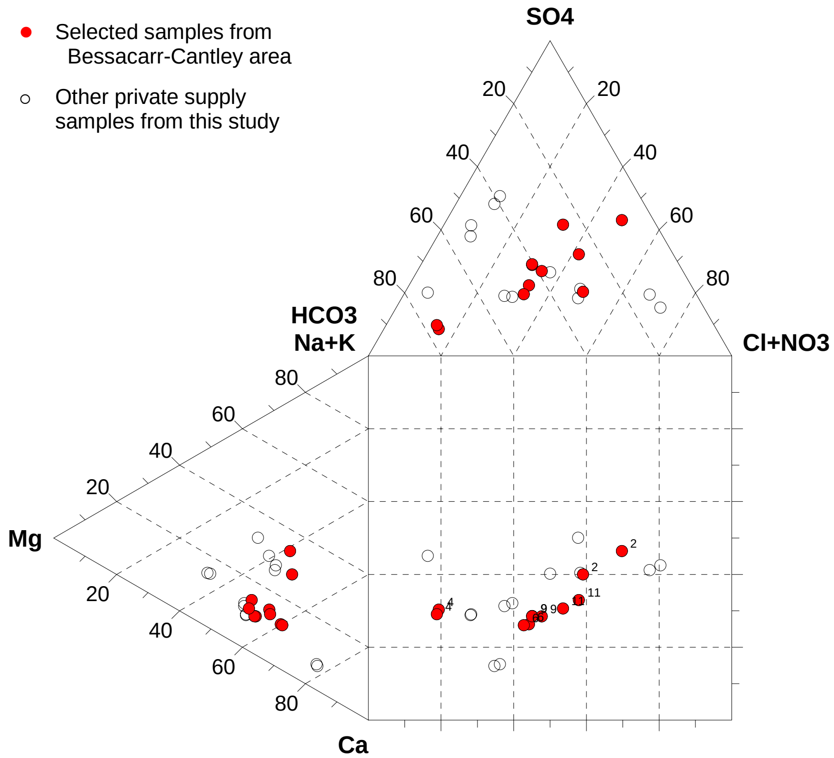


Figure 4.4 Durov plot showing composition of private supplies

Table 4.3 Mean quality data for private supplies and observation boreholes for June and November 2003

Site	Depth (m)	SEC (μS/cm)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	NO_3-N (mg/l)	SO_4 (mg/l)	Fe (μg/l)	Mn (μg/l)	Zn (μg/l)	B (μg/l)	Si (μg/l)	Sr (μg/l)	Br (μg/l)
1. Beech Tree Nurseries	30.5	981	13.7	2.1	148	19.7	238	34.2	0.05	2289	21800	270	260	<80	8400	100	750
2. Cantley Water Tower	65.5	362	24.5	6.2	36.7	12.3	55.2	46.2	5.20	55.8	30	40	30	<80	6230	40	<30
3. Crowtree Farm	31.7	800	63.8	16.1	71.3	42.4	292	111.5	<0.06	89.2	630	40	10	150	2950	690	30
4. Doncaster Racecourse	41.1	379	11.1	1.4	40.9	14.5	163	16.6	0.16	15.3	200	80	10	<80	5690	30	<30
5. Elmstone Farm	50.0	1463	36.9	3.2	186	86.0	542	46.2	<0.06	323	730	1330	10	80	7170	680	170
6. Gatewood Grange Farm	76.2	696	18.7	2.2	85.5	24.3	203	46.2	8.76	71.8	50	340	10	<80	6010	40	40
7. Lings Farm	12.0	902	13.5	31.5	64.4	58.2	191	42.0	23.00	104	40	20	20	80	6120	220	90
8. Misson Quarry	76.2	1147	31.1	5.1	122	60.8	397	81.8	10.63	112	30	390	20	<80	5570	90	550
9. Peglers	30.5	801	16.6	4.8	87.1	36.0	207	42.3	12.95	113	20	10	30	80	5460	210	60
10. Sandall Common Farm	63.4	2930	147	9.8	213	89.6	201	538.5	18.75	205	10	30	10	100	7430	120	670
11. Warning Tongue Lane	63.4	198	10.1	5.3	47.5	22.0	76.8	29.9	6.74	91.1	40	20	320	<80	5260	40	40

Elevated concentrations of Sr are observed at Crowtree Farm (966 µg/l in the more reducing sample taken in Nov 2003) and Elmstone Farm (average concentration 680 µg/l). This may be indicative of longer residence time in the aquifer.

The concentrations of K in groundwater from the research site at Lings Farm are anomalously high (32 mg/l). One possibility is that this could be derived from tracing experiments carried out in other boreholes on the site, although details of this are not known and bromide concentrations (around 0.1mg/l) at this site are similar to others in the area. Monitoring at this site and several others in the network that are rural, relatively distant from the Bessacarr-Cantley study area, and may be displaying very local effects, are likely to be discontinued and the resources released for other analyses.

Based on these observations, it is recommended that for future monitoring five of the sites most remote from, or least representative of, the study area conditions be excluded from the monitoring network (Beech Tree Nurseries, Crowtree Farm, Elmstone Farm, Lings Farm and Misson Quarry).

4.2.2 Contaminants and potential urban indicators

Some sites in the aerobic parts of the aquifer contain very high concentrations of nitrate-N (23.0 mg/l at Lings Farm and 18.8 mg/l at Sandall Common Farm), but this is not ubiquitous; Doncaster Racecourse has a surprisingly low nitrate content considering its location immediately down-gradient of older districts of Doncaster and apparently shallow depth. As noted above, very high concentrations of potassium are found in Lings Farm and Sandall Common Farm.

Beech Tree Nurseries and Warning Tongue Lane contain high concentrations of zinc (260 and 320 µg/l respectively). This should be compared with the low zinc concentrations noted in the Bessacarr-Cantley wastewater samples to date (70-100 µg/l; see Table 4.6). The rural nature of the Beech Tree Nurseries and the fact that concentrations in excess of 100 µg/l are recorded for several of the YW public supply boreholes (FI, NU, TH; see Table 4.2) implies that naturally occurring zinc concentrations in groundwater can be of the same magnitude or higher than those in potential urban recharge. It is concluded that zinc will not prove to be a useful urban recharge indicator for this case-study setting.

Boron was detected close to the limit of detection at Crowtree Farm, Elmstone Farm, Lings Farm, Peglers and Sandall Common Farm in at least one of the replicates. This limit varied from 50 to 100 µg/l for the different sample batches and an average limit of 80 has been applied to these samples. Given that boron appears to be present at about 500 µg/l in local wastewater and is regarded as a relatively conservative contaminant, further effort is merited to establish whether it will be of real use as an indicator in this study.

Sandall Common Farm borehole also has a very high conductivity and elevated bromide (670 µg/l) and is thought to be influenced by drainage from Markham Main Colliery. Smedley and Brewerton (1993) similarly interpreted the salinity and high concentrations of bromide in the NU public supply borehole as indicative of coalmine drainage from this former mine, whose workings were located to the northwest and up-gradient of the pumping station. Beech Tree Nursery and Misson Quarry also contain elevated concentrations of bromide (750 and 550 µg/l respectively).

Pesticides were not analysed in this project but a study of shallow private boreholes in the vicinity of the Doncaster wellfield showed that the majority contained detectable pesticide concentrations (Gooddy et al., in press). The borehole samples were all in the rural part of the wellfield or on the margins of the suburban area. The particular compounds detected were all consistent with the local land use:

- boreholes close to the railway line near RB contained high concentrations of atrazine (up to a maximum of 4.2 µg/l) plus propazine and terbutryn
- a borehole on a golf course contained benazolin, dicamba, MCPA, 2,4-D and atrazine, pesticides which can be used on turf and amenity grass
- boreholes on farms in agricultural production contained agricultural pesticides such as mecoprop, isoproturon, clopyralid and bentazone, although not necessarily those used in recent years around the site.

Apart from Peglers, none of the Environment Agency water quality monitoring sites is close to the Bessacarr study area. Analytical results from these unconfined-zone sites reveal various water-quality problems:

- groundwater from Hatfield Main (F11/13) has very high chloride concentration and may be impacted by mine drainage
- Yorkshire Bottle Co groundwater (F11/17) appears to have high trace metal concentrations (Cd, Cu, Ni, Pb and Zn), detectable polyaromatic hydrocarbons (anthracene, fluorene and phenanthrene) and nitrate. It seems unlikely that this represents a rural site
- Thorne Brewery groundwater (F11/15) has high conductivity and alkalinity.

Sulphate concentrations are high (180-280 mg/l) at all these sites. No boron analyses are available for these EA monitoring sites. These wells, which are presumably monitored for regulatory rather than regional assessment purposes, show localised effects unrelated to the objectives of this project and will not be considered further.

4.3 MULTI-LEVEL PIEZOMETERS

4.3.1 Major ions in pumped water

The major-ion profiles from the November 2003 sampling visit have been plotted in Figure 4.5 and the data summarised in Table 4.4. This is the first set of data collected from the piezometers and drilling effects may still be influencing the results.

The profiles for Na and K are similar at all the sites except McAuley High School (MHS), which has higher concentrations of Na near the top of the profile (Figure 4.5). Bicarbonate concentrations are also similar with the highest concentrations in all at about 20 m depth. At Haslam Park (HP1, HP2) it increases again in the lower part of the profile. Ca and Mg follow bicarbonate in a more muted profile. Dissolved oxygen and Eh measurements which are not shown show that the groundwater is predominantly oxidising. Iron and manganese suggestive of a transitional chemistry towards reducing conditions occur in some horizons, e.g. top of Haslam Park, 14m-depth zone at MHS.

Durov plots for the multi-level piezometer results are shown in Figure 4.6. These show a similar pattern to the private and public supply boreholes results, with some samples having major ion chemistry similar to the private boreholes where conditions are reducing (Figure 4.4), although nitrate concentrations are high. The shallower samples from P1, P2 and MHS9 (i.e. the 9 m deep piezometer at MHS) have a distinctly different composition, containing relatively more sodium and chloride.

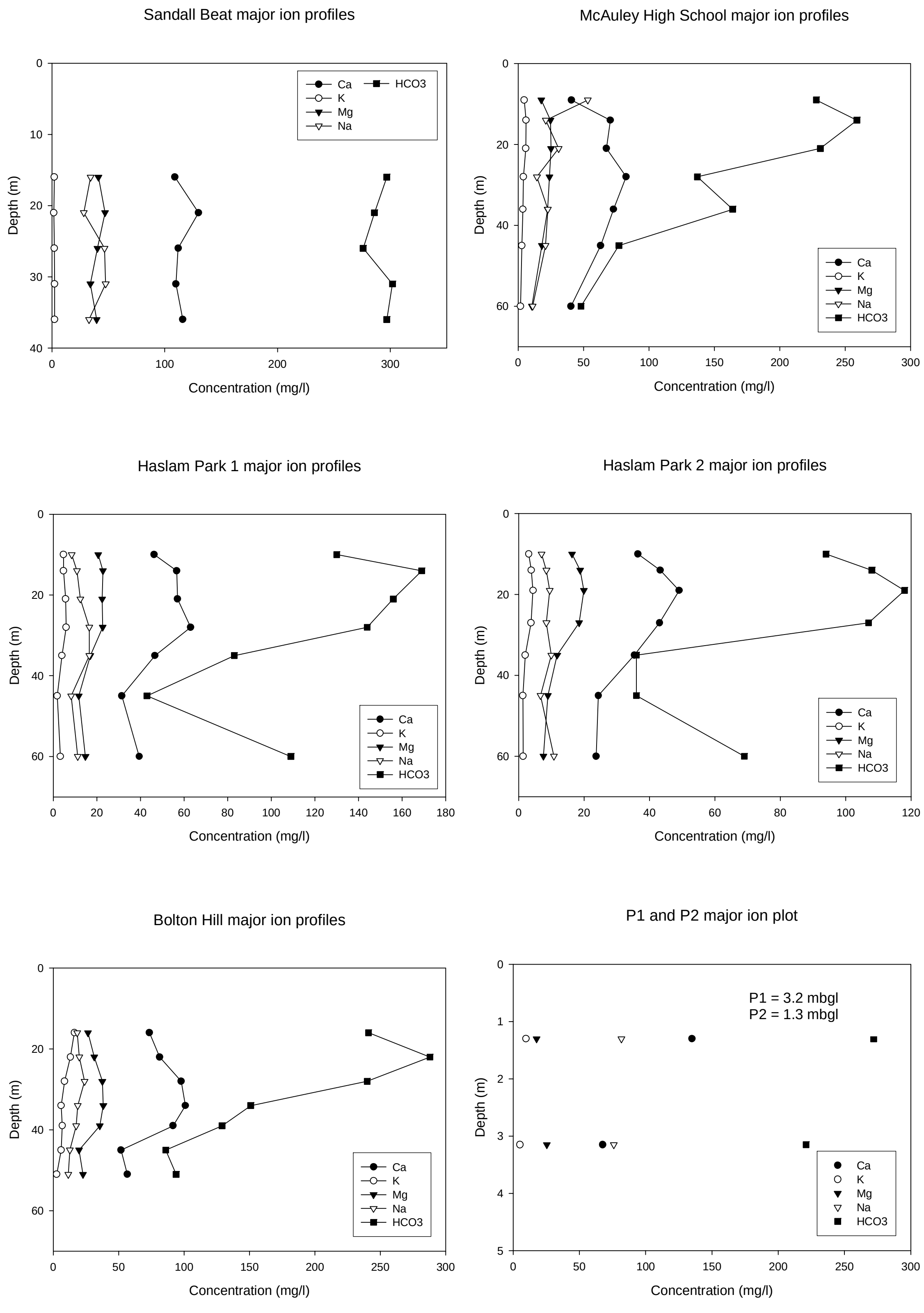


Figure 4.5 Major-ion chemistry profiles, except indicators, for multi-level piezometers for November 03

Table 4.4 Data for multi-level sampling sites, November 2003

Site	Depth (m)	SEC (μ/cm)	Concentration (mg/l)								Concentration (μg/l)			
			Na	K	Ca	Mg	HCO_3	Cl	TON	SO_4	Fe	Mn	Zn	B
Sandall Beat (SB)	16	948	34.3	2.2	109	41.2	297	75.5	13.1	131	8	686	13	<100
	21	704	28.3	1.7	130	47.1	286	73.8	12.7	134	< 5	521	16	<80
	26	1061	46.7	2.2	112	40.4	276	73.8	12.4	140	24	469	10	<100
	31	1061	47.7	2.3	110	34.2	302	39.5	7.82	165	6	288	10	<100
	36	814	32.9	2.4	116	39.7	297	61.4	10.4	149	30	299	12	<100
Haslam Park 1 (HP1)	10	480	8.5	4.7	46.3	20.6	130	26.4	4.26	52.8	649	18	10	<100
	14	567	10.9	4.7	56.6	22.8	169	32.5	5.47	59.7	< 5	4	6	123
	21	567	12.5	5.7	57	22.4	156	32.5	5.94	70.8	7	3	6	137
	28	571	16.6	5.9	63	22.7	144	38.4	10.4	80.7	< 5	3	7	137
	35	643	16.6	4	46.7	17	83	24.3	11.0	76.7	22	3	6	<100
	45	484	8.2	1.8	31.5	11.7	43	20.2	13.9	29.4	88	3	4	<100
	60	335	11.3	3.3	39.5	14.8	109	19.2	6.50	36.7	520	8	6	<100
Haslam Park 2 (HP2)	10	406	7	3.1	36.5	16.3	94	10.8	10.9	41.3	697	33	7	<80
	14	406	8.5	3.9	43.3	18.8	108	16.8	9.68	59.4	<5	15	6	100
	19	433	9.5	4.4	49.1	19.9	118	20	8.66	66.7	6	10	8	<80
	27	470	8.5	3.8	43.1	18.5	107	16.4	9.70	57	30	9	13	<80
	35	458	10	2	35.4	11.8	36	29.2	10.4	49.5	133	13	13	<80
	45	392	6.7	1.3	24.4	8.95	36	17.4	9.49	23.3	206	7	5	<80
	60	265	10.8	1.4	23.7	7.56	69	12.1	7.65	11.5	162	11	5	<80
McAuley High School (MHS)	9	597	53.2	4.7	40.8	17.8	228	19.6	6.87	35.9	29	9	7	100
	14	647	21.2	6	70.5	24.7	259	18.7	4.44	50.4	271	14	11	<80
	21	636	31	5.9	67.5	25.2	231	13.5	8.61	66.5	10	13	9	<80
	28	717	14.4	4	82.6	23.9	137	15	11.7	153	< 5	20	9	<80
	36	717	22.7	3.7	72.9	22.6	164	19	7.31	130	9	12	9	<80
	45	698	20.9	2.9	63.1	18.2	77	25.3	17.7	107	11	16	7	95
	60	623	11.1	1.9	40.4	10.5	48	33.3	11.3	36.4	46	8	7	<80
Bolton Hill (BH)	16	529	18.4	16.2	73.5	26.6	241	27.7	3.95	90.9	71	7	9	88
	22	802	20	13.2	81.3	31.3	288	29.5	5.37	88.4	15	8	9	<80
	28	691	23.9	8.7	97.9	37.5	240	63.4	6.70	144	14	7	10	<80
	34	500	18.7	6	101	38.3	151	113	4.82	156	37	4	10	<80
	39	917	17.5	7	91.6	35.7	129	103	5.61	142	< 5	8	8	<80
	45	567	12.8	6.1	51.9	19.8	86	41.7	8.17	77	6	7	6	<80
	51	604	11.5	2.6	56.6	22.7	94	45.8	9.86	76.3	46	3	8	86
Piezo 1 (P1)	3.15	1110	76	5.2	67.6	25.5	221	95.7	13.9	64.5	102	3	12	103
Piezo 2 (P2)	1.3	911	81.7	9.7	135	17.7	272	184	2.28	84.4	6200	1290	16	91

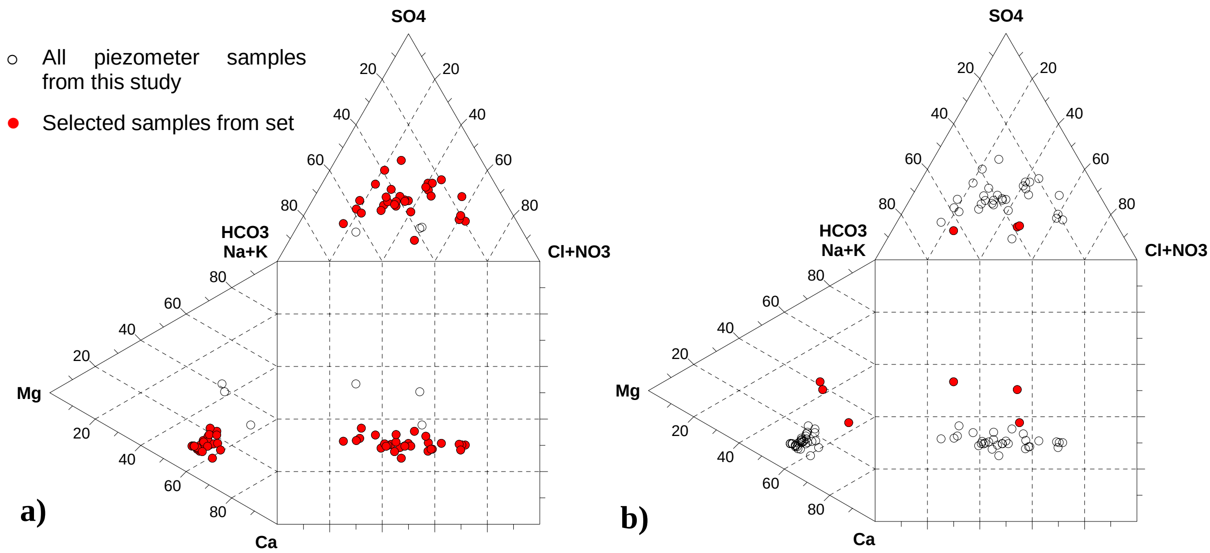


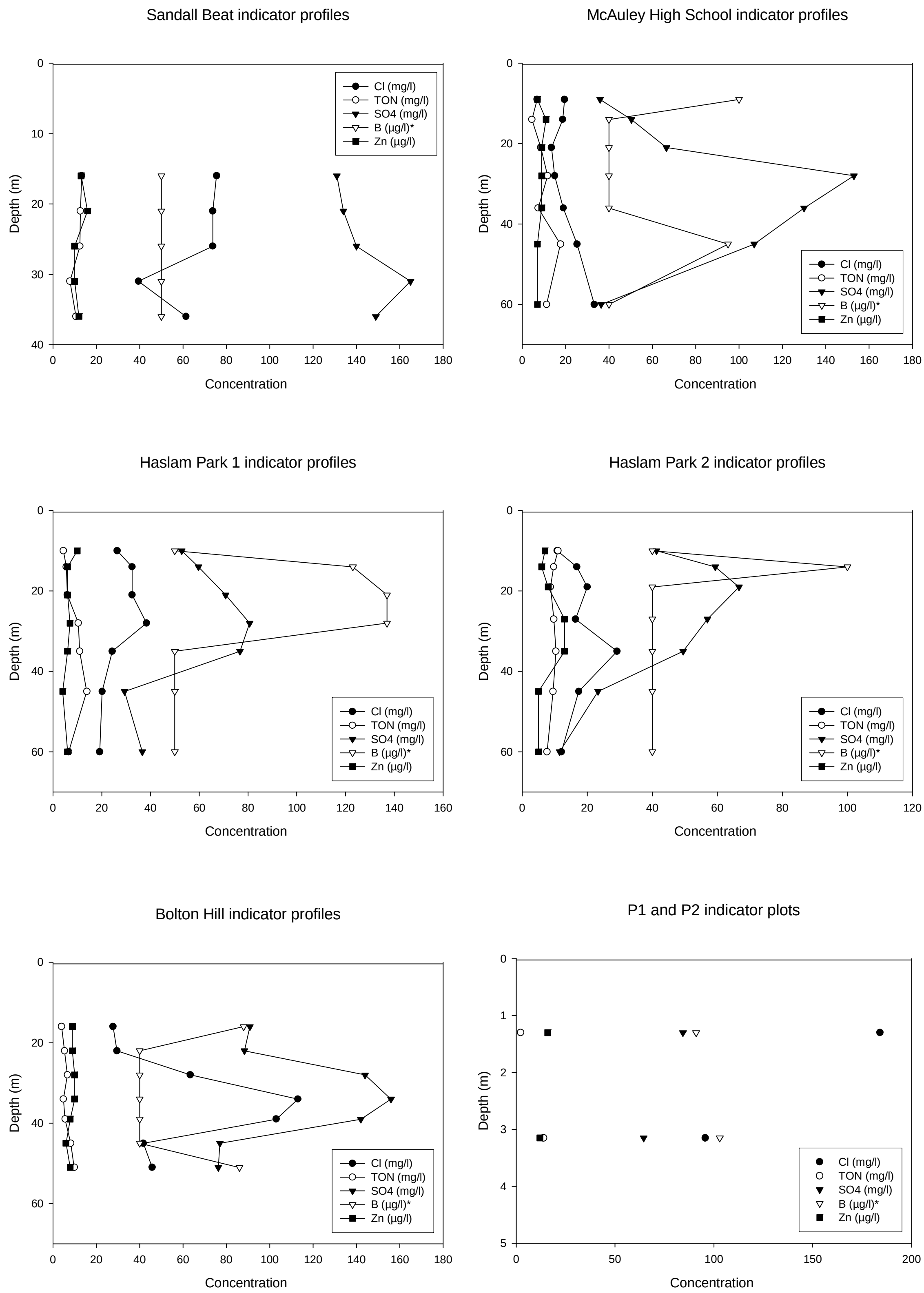
Figure 4.6 Durov plots for piezometers: a) shows the deeper samples; b) the results for P1, P2 and MHS9

4.3.2 Indicator parameters

Profiles of the indicator parameters are shown in Figure 4.7. Chloride profiles show little significant change with depth at the Sandall Beat, Haslam Park 2 and McAuley High School sites. At Bolton Hill, a peak is observed between about 30 and 40 mbgl, where concentrations rise from about 30 to 40 mg/l to over 100 mg/l and at Haslam Park 1 there is a smaller peak at about 30 m. These both coincide with elevated sulphate levels. High chloride concentrations were also observed in Sandall Beat, P1 (95.7 mg/l) and P2 (184 mg/l). These high concentrations at shallow depths are somewhat higher than the wastewater chloride concentration recorded in Table 4.3 and may be related to mine drainage, parkland fertiliser inputs or road salting.

Sulphate is one of the most variable parameters with depth, with a peak at about 30 m below ground level in BH, HP1 and MHS and a peak at about 20 m in the HP2 profile. These peaks tend to be about double the concentration observed in the shallower and deeper sample ports. The profile at SB is more subdued although the sulphate concentration is slightly elevated in the 31-mbgl sample zone. The consistent depth at which these high sulphate concentrations are observed in the multi-levels has no obvious explanation since the regional dip means that there is only minimal overlap of strata between the sites (apart from the Haslam Park dual multi-levels).

The nitrate profile from Sandall Beat shows high concentrations near the surface (12 to 13 mg/l between 16 and 26 mbgl) and an overall trend of diminishing concentrations with depth. Nitrate concentrations remain relatively stable with depth in Haslam Park B. However, at Haslam Park 1, McAuley High School and Bolton Hill the nitrate concentration increases with depth; in Haslam Park 1 the water contains 4.2 mg/l NO_3-N at 10 mbgl, rising to 13.9 mg/l at 45 mbgl. Nitrate-N (NO_3-N) concentrations exceed 17 mg/l at 45 mbgl at McAuley High School.



*Boron concentrations of <limit of detection (LOD) are represented as 50% of LOD. This may exaggerate differences between detected and not detected concentrations

Figure 4.7 Indicator profiles for multi-level piezometers for November 03.

Data for the other potential indicators is inconclusive. Boron concentrations were mainly below or very close to the normal detection limit (100 µg/l). The results for boron were recalculated using a less conservative limit of detection (LOD), which gave more positive detections but an LOD which varied for each group of ten samples analysed and ranged from 50 µg/l for some private supplies to 100 µg/l for some samples from the multi-levels. The highest profile concentrations were in the upper part of the Haslam Park profiles and in P1. All profiles except Sandall Beat contained at least one positive detection of boron. The detection limits achieved for these samples are probably too high to discriminate urban-derived boron from background reliably even in the piezometers where evidence for infiltration of urban water is the most likely. A lower detection limit would be desirable for future samples. Zinc concentrations are in the range 70 to 160 µg/l with the highest concentrations in the upper levels in Sandall Beat and at mid-depth in Haslam Park 1.

4.3.3 Porewaters from core samples

Results for the analysis of the porewaters extracted from the multi-level piezometer at Haslam Park 2 during drilling are shown in Table 4.5. A sample of the drilling water that was spiked with LiCl is also included. The results for Li clearly demonstrate that the upper three samples have been invaded by drilling water. The major cations may have exchanged with Li making interpretation even more difficult and the results should therefore be considered as unreliable.

For the two remaining samples, from the core from 29.04 to 30.50 mbgl, the results can be compared to those obtained for pumped water from the 27 and 35 m samplers shown in Table 4.5. This comparison shows that for all analytes except nitrate and Zn the porewater data are 2 to 3 times higher. This may suggest that the multi-level samplers are not yet at equilibrium with porewater concentrations.

Table 4.5 Quality of extracted porewater and spiked drilling water for Haslam Park 2 cores

Mid-depth (m)	Concentration (mg/l)								(µg/l)				
	Na	K	Ca	Mg	HCO_3	Cl	TON	SO_4	Fe	Mn	Zn	B	Li
9.85	13.1	6.4	95	41.3	119	259	19.6	41.5	<5	6	17	200	15700
10.58	17.4	6.7	80.8	39.9	123	232	13.6	57.1	<5	2	13	200	11200
16.31	17.3	7.4	70.3	28	119	163	6.305	67.4	<5	<2	12	300	9390
29.51	23.1	8.7	73.7	24.1	97.6	88.5	13.9	95.1	<5	5	14	300	<4
30.20	21.9	7.4	71.3	23.2	99.1	71.5	13.4	97.5	10	<2	12	300	<4
Drilling water	40.9	4.3	43.5	13.1		1200	5.6	90.6	10	6	49	<100	227000

4.4 WASTEWATERS

Three wastewater samples were collected from sewers serving Bessacarr (Table 4.5) as part of the monitoring programme. Wastewater contains higher concentrations of Cl (60 – 80 mg/l), B (400 –600 µg/l), K (16–25 mg/l) and PO_4 (28000-33000 µg/l) than are seen in groundwater, as well of course as Na and very high ammonium concentrations. There will also be a high organic nitrogen loading but this was not measured. Other analysed inorganic constituents appear to be in the same general range as local groundwater.

Sulphate concentrations are also relatively high (80 – 100 mg/l). The analytical technique used (ICP-AES) measures total sulphur, which is reported as sulphate as this is the dominant S species in most natural waters. However in wastewater sulphur is likely to be present in reduced forms as well as sulphate.

Zinc is present at about 80 µg/l, copper at about 4 µg/l, and lithium at about 17 µg/l. Other trace metals are mainly below the limit of detection.

Two of these samples were also analysed for a limited range of organic compounds. Both samples contained concentrations of 1–5 µg/l of the haloforms chloroform and tribromomethane, presumably by-products of water chlorination, and one had 0.8 µg/l of tetrachloroethene. Both samples contained similar concentrations (0.1–0.2 µg/l) of the polyaromatic hydrocarbons acenaphthene, fluorene, naphthalene and phenanthrene. Phenol and methyl phenol were detected in both samples at 50–200 µg/l and sub µg/l traces of a range of other phenols were also detected. No BTEX were found in either sample.

Table 4.6 Data for wastewater sampling sites, November 2003

Site	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	NH_4-N (mg/l)	NO_2-N (mg/l)	TON (mg/l)	Cl (mg/l)	SO_4 (mg/l)
Everingham Road	91.5	25.1	50.1	23.6	79.6	0.005	< 0.06	83.5	84.4
Warning Tongue Lane	119	18.7	49.3	23.4	40.4	0.007	< 0.06	69.9	102
Burnham Close	87.5	16.8	53.4	23.7	32.6	0.012	< 0.06	61.6	80.5

Site	§ PO_4 (µg/l)	Fe (µg/l)	Mn (µg/l)	Zn (µg/l)	Si (µg/l)	Sr (µg/l)	B (µg/l)	Cu (µg/l)	Li (µg/l)
Everingham Road	33400	26	15	69	5930	103	500	39	16
Warning Tongue Lane	31800	67	15	99	8600	98.8	400	57	19
Burnham Close	28100	110	17	76	7350	103	600	37	17

§ BGS data reported as total P assumed to be PO_4

4.5 RAW WATER QUALITY COMPARED TO DRINKING WATER STANDARDS

The European Directive on the quality of water intended for human consumption (98/83/EC) defines the maximum admissible concentration (MAC) in drinking water for a wide range of parameters. These limits refer, of course, to water at the point of supply (i.e. post-treatment). However it is useful to compare raw water quality to these limits in order to investigate whether anthropogenic inputs will mean a requirement for increased water treatment in the future.

While nitrate (NO_3-N) concentrations are typically low in raw water from Yorkshire Water public-supply boreholes, the mean values from boreholes AR1 and AR2 are in excess of the drinking water standard (MAC=11.3 mg/l), while that at LI1 is approaching the MAC. Water from these higher-nitrate boreholes is blended with low-nitrate water from other boreholes prior to supply.

Nitrate-N concentrations exceeded the MAC at three of the private supplies sampled (Peglers, Sandall Common Farm and Lings Farm), and the concentration in the Misson Quarry sample is close to the limit. The concentration of 29.6 mg/l in the June 2003 sample from Lings Farm is more than double the MAC, while the November 2003 sample contained 16.2 mg/l. As the

Lings Farm borehole is the shallowest of the private supplies sampled, the water is likely to be younger than at other sites. The findings from the multi-level samplers (Section 4.4) show increasing nitrate concentrations with depth at three of the sites, and the MAC is exceeded at depths of 45 mbgl at two of these sites.

Nitrite (NO_2-N) concentrations at Gatewood Grange Farm and in two depth intervals in the piezometers at Sandall Beat multi-level site exceed the limit of 0.03 mgN/l. Ammonium concentrations are typically low, however the first (June 2003) sample from Beech Tree Nurseries contained 0.57 mg/l, above the drinking water standard of 0.39 mgN/l, although the November 2003 sample contained 0.48 mg/l.

For the major ions, sulphate is generally well below the MAC of 250 mg/l, except the values of 300 and 345 mg/l measured at Elmstone Farm. Magnesium is found in excess of the drinking water standard (50 mg/l) at four of the private supplies (Elmstone Farm, Lings Farm, Misson Quarry and Sandall Common Farm). Potassium concentrations exceed those acceptable in drinking waters at Crowtree Farm, Lings Farm, and in the 16 and 22 m deep piezometers at Bolton Hill. High chloride ion concentrations were observed in the samples from Sandall Common Farm (637 and 440 mg/l in Aug and Nov 2003 respectively).

These results indicate that nitrogen from both urban and non-agricultural sources may be making a significant contribution to nitrate concentrations in groundwater in the Doncaster area and this could cause problems for public water supplies in the future.

5 Evaluation of findings

5.1 INDICATOR PARAMETERS

The results from potential indicator parameters identified in Section 3.4 are summarised in Table 5.1.

CHLORIDE:

(i) Chloride in wastewaters so far sampled is on average about twice that in local deep groundwater and that in mains water supplied to the study area, and about 60% more than that found in shallow groundwater in the vicinity.

(ii) a corollary of this observation is that on the basis of results so far there is not a strong contrast in chloride content between shallow and deep groundwater in the vicinity of the study area.

(iii) however there is significant overlap of maxima in both shallow and deep local groundwater, with public supply boreholes, monitored private boreholes away from the study area and multi-levels in Bessacarr-Cantley all revealing similar chloride concentrations to those found in autumn-sampled wastewater. Careful interpretation of results on a site-by-site basis is therefore indicated.

(iv) several of the private monitored private boreholes have high chloride contents, for local point-source reasons. This can potentially distort the shallow aquifer characterisation; in fact pumped water from those wells which are local to the study area, both urban and rural, typically have chloride content <50mg/l, not dissimilar to the mean of that encountered in the multi-levels.

(v) from the initial results of multi-level sampling, chloride seems to be indicating quality stratification.

These initial results indicate that chloride shows potential to act as an urban recharge indicator, although care is required in interpretation given the multiple potential sources in the urban environment (e.g. wastewater, road de-icing runoff, landfill leachate and industrial use of sodium hypochlorite), the overlap with naturally-occurring chloride content in the receptor aquifer and rural sources (from fertiliser) further afield.

SULPHATE

(i) Sulphate concentrations in wastewaters sampled to date are also on average higher than those in local deep groundwater, typically more than twice as high, but like chloride there is overlap in maximum values.

(ii) this difference is much less marked in shallow groundwaters in the vicinity, where sulphate is typically of the same order as that in the wastewater.

(iii) unlike the chloride trend, waters from the upper part of the aquifer in the vicinity of the study area seem to have markedly higher sulphate content compared with deeper waters.

(iv) initial results from the multi-levels indicate that these shallow aquifer sulphate concentrations can vary widely, both with depth and from site to site and again depth stratification can be observed.

(v) as with chloride, some high sulphate results from the rural private well network need to be disregarded as local effects and not of urban recharge interest.

Table 5.1 Ranges and mean concentrations of potential urban recharge indicators

Indicator	Concentration												
	Groundwater								Inputs			Urban outputs	
	PS boreholes vicinity of study area		Private boreholes		ML Piezometers & P1, P2 (0-30 mbgl)		ML Piezometers (30-60 mbgl)		Precip-itation	WTW Supplied water**		Waste water	
	Mean•	Range	Mean*	Range*	Mean	Range	Mean	Range	Mean	Mean	Range	Mean	Range
Chloride (mg/l)	39	15-85	50	17-112	44	10-184	40	12-113	2.1	34	26-41	72	60-85
Sulphate (mg/l)	39	18-97	128	15-323	84	37-153	84	11-165	2.8	36	27-46	90	80-100
Boron (µg/l)	-	<50-50	-	<80-150	-	<80-140	-	<80-100	-	-	-	500	400-600
Ortho-phosphate§ (µg/l)	14‡	5-130‡	-	100-500	-	300-600	-	300-600	-	620	<63-950	31000	28000-33000
Zinc (µg/l)	-	<6-230	66	10-320	10	6-16	7	4-16	-	-	-	81	69-99
Potassium (mg/l)	2.6	1.9-2.9	7.8	1.4-32	5.8	1.7-16.2	3.2	1.3-7	0.08	2.7	2.3-2.9	20.2	17-25

The mean is not shown where the majority of the analyses are below the limit of detection

* Excluding Sandall Common Farm (local point source pollution from mine drainage suspected)

** Blended water supplied to study area from Nutwell water treatment works; mix of AR, BP, NU, TH,

• For illustrative purposes only, averages of individual well means were used for this complex dataset

§ BGS data for total P assumed to be PO_4

‡ Data period 4/1979-4/1990 inclusive; no later analyses available

Its value as an urban recharge indicator in Bessacarr-Cantley is not yet established. While the results show both stratification with higher concentrations in the shallow aquifer, it is quite possible that the sulphate may, at least in part, be of formation origin, from gypsiferous horizons within the Sherwood Sandstone. If so, the likelihood that gypsum is naturally present in some horizons may constrain its interpretative value, as it could easily mask or mimic the influence of wastewater recharge, especially as the wastewater/groundwater concentration ratio is not particularly high. Sulphate may also be derived from the use of ammonium sulphate fertilisers.

BORON

(i) Although only sporadically measured, the few results available indicate low natural boron concentrations in groundwater from the Sherwood Sandstone, irrespective of depth. Results are almost universally less than current YW detection limits of 50-100 µg/l.

(ii) in contrast boron concentrations in wastewater so far sampled, at about 500 µg/l are at least 5 times greater.

(iii) initial values from the multi-levels are at or below minimum detection limits, and no stratification is observed.

In contrast to initial results from the case-study city of Rastatt, boron has proved so far to be a disappointing indicator. The detection limit of 80 to 100 µg/l which was obtained for the laboratory runs containing these samples was too high to discriminate small variations, but even if this were improved for future samples, these would be in the 0-100 µg/l range, implying that even if a pattern were detected, dilution/attenuation effects appear to be significant.

ZINC

(i) Zinc concentrations in the wastewaters sampled so far are low at 100 µg/l or less

(ii) this is well within the range for the relatively few analyses available for the deeper aquifer, but tends to be several times greater than that found in local private wells

(iii) nevertheless, the multi-level initial results reveal only very low concentrations of less than 20 µg/l in the aquifer down to 60m depth.

Zinc does not look promising as an urban recharge indicator at this stage.

OTHER INDICATORS

Based on the above observations, it is proposed to assess whether another indicator could be introduced, replacing zinc and boron. Possible candidates include potassium, dissolved organic carbon (DOC) or dissolved organic nitrogen. An organic compound possibility might be the relatively persistent and soluble fuel additive MTBE (methyl tertiary butyl ether), although little is known about its background concentrations in UK aquifers.

5.2 OVERALL MAJOR-ION CHEMISTRY

Figures 5.1 to 5.3 gather together key results from YW pumping stations and the monitoring network for comparative purposes. These show that:

(i) Local public supply boreholes can have quite variable major anion constituents that for parameters like TON and Cl seem to be related more to catchment activities than to the borehole depth (Figure 5.1). Thus TON, certainly with a high proportion of anthropogenic origin, is significantly higher in the deep AR borehole array than it is in the rather shallower TH boreholes, and these in turn have a similar TON to the shallower Cantley Water Tower borehole. There is a suggestion that a shallower screen/openhole top depth tends to result in higher TON, and this would be consistent with influence of infiltration of modern recharge influenced by catchment activities.

(ii) Sulphate concentrations do not seem to fit in with depth-related, screen setting or rural/urban catchment patterns and this may imply a formation control at work, perhaps related to relative occurrence of local gypsiferous horizons.

(iii) Major ion character for both shallow and deeper pumped aquifer waters is similar in type and variability (Figure 5.2). Groundwaters from RB and the nearby Cantley Water Tower are very similar in type, although the former is 145-147m deep and the latter only 65m deep. Similarly, at the other end of the data array, the low nitrate public supplies at BP and TH are similar to Doncaster Racecourse, despite the former being much deeper than the latter (120-180 m compared with 41 m deep).

(iv) Nevertheless, some shallow waters do have a higher solute content, as indicated by the SEC measurements in Figure 5.3.

(v) wastewaters monitored in the detailed study area have higher concentrations of major ion constituents than groundwaters in the same general area, but not conspicuously so (Figure 5.3). Using SEC as an indicator of total dissolved solids, groundwater mineralization can range from less than half to more than 80% that of wastewater.

(vi) the character of the wastewater solute load is only moderately distinctive from nearby groundwater. For instance, while wastewater chloride concentrations appear to be about twice those in the nearby aquifer, sulphate concentrations are about twice those in the deeper aquifer but in the same general range for the shallow zone of the aquifer. The wastewaters have a much higher relative content of PO_4, Na and K than the groundwaters, and this appears to be rapidly attenuated during infiltration, possibly by and/or ion-exchange.

(vii) the presence of aerobic/anaerobic features in different aquifer locations may provide a surrogate indicator of the relative ease or otherwise with which urban recharge can occur.

5.3 RE-EVALUATION OF THE CONCEPTUAL MODEL

Although the water-quality data reviewed and collected for the AISUWRS project to date do not yet give a clear or consistent picture of the flow systems and hydrogeochemical processes occurring in the Sherwood Sandstone aquifer in the Doncaster area, a number of characteristics have emerged. The conceptual model clearly needs some revision; this will be undertaken in the final report on the fieldwork programme once all the data have been collected.

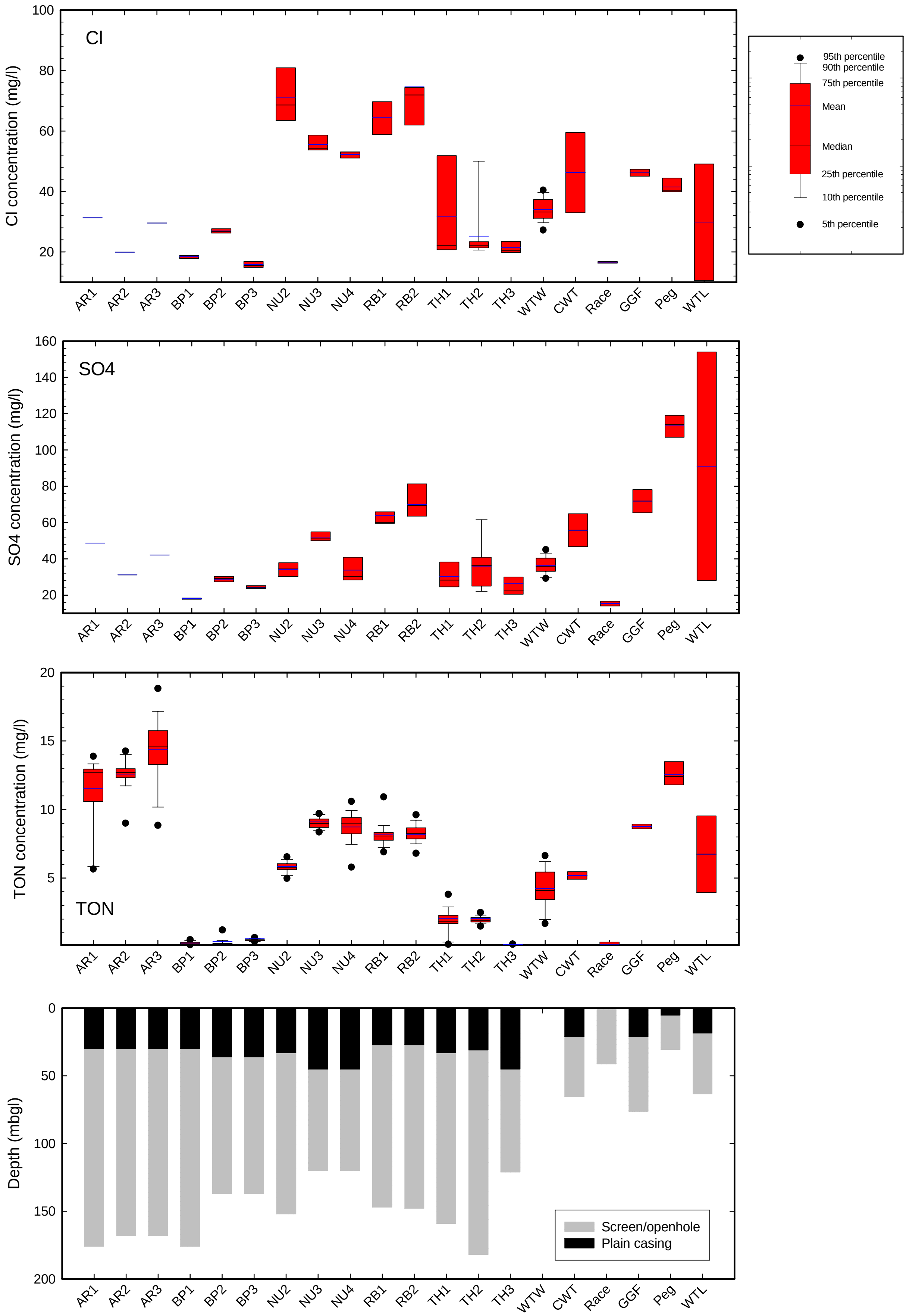


Figure 5.1 **Comparison of key major constituents TON, SO4 and Cl for public supply and private boreholes in the general vicinity of Bessacarr-Cantley**

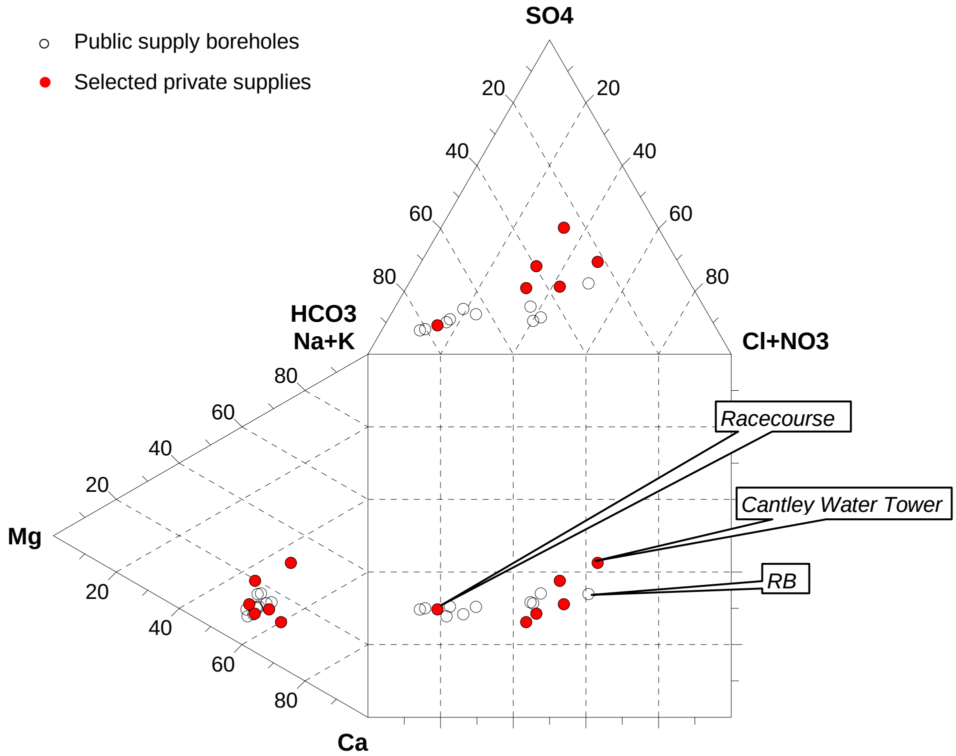


Figure 5.2 **Durov plot of average water quality in public supply boreholes and private supplies for the Bessacarr-Cantley study area.**

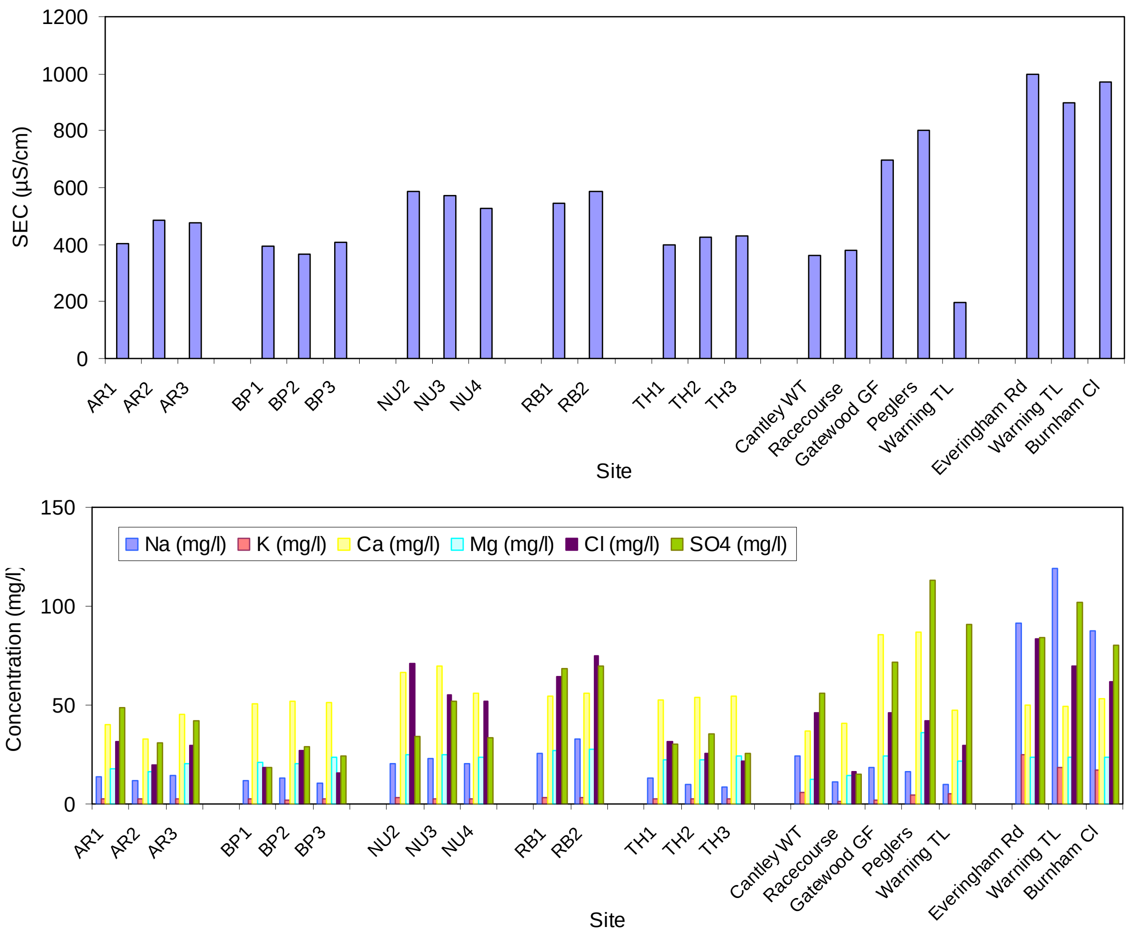


Figure 5.3 **Comparison of electrical conductivity (SEC) and major constituents in public supply boreholes, private supplies and wastewater, Bessacarr-Cantley area.**

6 Conclusions and recommendations

The main conclusions and recommendations from this phase of the programme are:

(i) A developing programme of local groundwater monitoring has complemented an array of water quality data mainly derived from operational public water supply boreholes in the Doncaster wellfield operated by the project stakeholder Yorkshire Water.

(ii) This monitoring array includes a set of local private supplies chosen to try to characterise the shallow Sherwood Sandstone east of Doncaster, and a local array for the focus area of the study (Bessacarr-Cantley district) comprising multilevel research boreholes and wastewater sampling sites.

(iii) Data from the public supply boreholes and from the monitoring network have been evaluated in order to develop and then validate a conceptual model of the flow system and its likely effect on groundwater quality in the urban and periurban area.

(iv) This conceptual model recognises that the Sherwood Sandstone east of Doncaster, as an intensively exploited unconfined aquifer with urban, rural, industrial, agricultural and mining activities at the land surface, is a complex system. The presence of variable Quaternary superficial deposits across the aquifer outcrop/subcrop adds to this complexity.

(v) Initial interpretation suggests that there is significant variability both laterally across the aquifer system and with depth. No spatial pattern to the variability indicated by the datasets has yet been discerned.

(vi) Initial wastewater sampling results indicate that while sewered waters have higher concentrations of major ion constituents than groundwaters in the same general area, the difference is not conspicuous, and the resulting effluent would be regarded as dilute in comparison with the groundwater receptor.

(vii) These relatively small differences, for instance in chloride and sulphate indicator concentrations between wastewaters and the parent groundwater forming the supply to the study area will constrain their interpretative use in mass balance calculations later in the project.

(viii) Consideration of the analytical results from the monitoring network indicate that a mid-term review of the monitoring strategy is required in order to concentrate effort on understanding processes in the Triassic aquifer in the immediate neighbourhood of the study area. This would imply some revision of the sampling programme, a closer focus on the 5 YW pumping stations either supplying the study area or located in its vicinity, and further inspection of data to assess whether an additional recharge indicator such as potassium, dissolved organic carbon or dissolved organic nitrogen can be identified to replace one or other from the present selection.

(ix) The current minimum detection limits for boron do not permit discrimination of small variations in concentrations below 100µg/l; analysis by ICP-MS needs to be considered if B is to continue to be viewed as an urban recharge indicator.

(x) Work continues to determine whether different elements of the flow system can be characterised by their chemical compositions, thereby allowing shallow recharge beneath the city to be characterised chemically.

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APPENDIX 3A INPUT FIELD WORKSHEETS WITH DATA QUALITY ASSESSMENT FOR EACH MODEL

UVQ data: Doncaster case-study

Category	Sub-category	Field	Short (db) name	Units	Description	Type	Priority rating	Data Class	Other model origin?	Source of information
UVQ Physical desc.	Unit Block	Number of unit blocks within the cluster	Amount	no.		number	High	A	-	OS cover/DMBC-PD landuse database
		Average unit block occupancy (equivalent persons)	Occupancy	persons		number	High	B	-	DMBC estimate by interview?
		Average block size	Size	m^2		number	High	A	-	OS cover/DMBC-PD landuse database
		Average garden area	Garden	m^2		number	High	B	-	OS cover/DMBC-PD landuse database
		Average roof area	Roof	m^2		number	High	B	-	OS cover/DMBC-PD landuse database
		Average paved area	Paved	m^2		number	High	C	-	OS cover/DMBC-PD landuse database
		Average % of garden irrigated	Garden_irrig	%		number	Low	C	-	DMBC estimate by interview?
	Cluster	Land use	Land_use	n/a		text	High	A	-	OS cover/DMBC-PD landuse database
		Cluster area	Area	ha		number	High	A	-	OS cover/DMBC-PD landuse database
		Road area within the cluster	Road	ha		number	High	A	-	OS cover/DMBC-PD landuse database
		Public open space area within the cluster	Public_space	ha		number	High	A	-	OS cover/DMBC-PD landuse database
		% public open space irrigated	Public_sp_irrig	%		number	Low	B	-	DMBC estimate by interview?
		Stormwater output flows into cluster number?	#_StormW_out	number		number	High for calibration	C	-	Data not identified yet as available
		Wastewater output flows into cluster number?	#_WasteW_out	number		number	High for calibration	C	-	Data not identified yet as available
UVQ measured data	Unit block	Kitchen use per person		L/c/d		number	High	C	-	Data not identified yet as available
		Bathroom use per person		L/c/d		number	High	C	-	Data not identified yet as available
		Laundry use per person		L/c/d		number	High	C	-	Data not identified yet as available
		Toilet use per person		L/c/d		number	High	C	-	Data not identified yet as available
		External water usage	Outdoor_use	kL/hh/y		number	High	C	-	Data not identified yet as available

	Cluster	Leakage rate of water supply system	Leakage	%	Long term average rate	number	Med	B	pipeline leakage model?	YWS estimates/leakage control zone field data
		Proportion of wastewater flow exfiltrating	%_WasteW_exfil	%	Long term average rate	number		C	-	Data not identified yet as available
UVQ Calibration parameters	Unit block	Roof area maximum initial loss		mm			Calibration parameter	C	-	Data not identified yet as available
		Effective roof area		%		number	Calibration parameter	C	-	Data not identified yet as available
		Paved area maximum initial loss		mm		number	Calibration parameter	C	-	Data not identified yet as available
		Effective paved area		%		number	Calibration parameter	C	-	Data not identified yet as available
		Garden trigger-to-irrigate		number		number	Calibration parameter	C	-	Data not identified yet as available
	Unit block & Cluster	Percent area of pervious store 1		%		number	Calibration parameter	C	-	Data not identified yet as available
		Capacity of pervious store 1		mm		number	Calibration parameter	C	-	Data not identified yet as available
		Capacity of pervious store 2		mm		number	Calibration parameter	C	-	Data not identified yet as available
		Baseflow index		number		number	Calibration parameter	C	-	Data not identified yet as available
		Base flow recession constant		number		number	Calibration parameter	C	-	Data not identified yet as available
		Infiltration index		number		number	Calibration parameter	C	-	Data not identified yet as available
		Infiltration store recession constant		number		number	Calibration parameter	C	-	Data not identified yet as available
	Cluster	Road area maximum initial loss		mm		number	Calibration parameter	C	-	Data not identified yet as available
		Effective road area		%		number	Calibration parameter	C	-	Data not identified yet as available
		Proportion of stormwater entering wastewater system as inflow (100% if combined system)	%_StormW_infil	%	Long term average rate	number	Calibration parameter	B	-	YWS estimate by interview +pipe network shp files
		Percent of wastewater flow as overflow (dry weather)		%		number	Calibration parameter	C	-	Data not identified yet as available
		Capacity of wastewater drainage system (wet weather overflow)		kL		number	Calibration parameter	C	-	Data not identified yet as available
		Public open space trigger-to-irrigate		number		number	Calibration parameter	C	-	Data not identified yet as available

This is data used to determine calibraiton parameter values	Cluster/Catchment	Water supply (to irrigation??)	Water_supply		Continuous record, preferably daily time step	number	Calibration parameter	C	-	Data not identified yet as available
		Wastewater flows	WasteW_flow		Continuous record, preferably daily time step	number	Calibration parameter	C	-	Data not identified yet as available
		Stormwater (surface runoff) flows	StormW_flow		Continuous record, preferably daily time step	number	Calibration parameter	C	-	Data not identified yet as available
UVQ Alternative management options	Rainwater tanks	Tank volume	Tank_V	m3		number	For scenario analysis	C	-	Data not identified yet as available
		Up-take of tanks	%_Uptake	%		number	For scenario analysis	C	-	Data not identified yet as available
		First flush volume	1st_Flush	mm		number	For scenario analysis	C	-	Data not identified yet as available
		First flush destination	??	n/a	currently no choice, must be the wastewater system via the onsite wwtp if there is one present within the unit block	text	For scenario analysis	C	-	Data not identified yet as available
		Water use points	Use_Point		Toilet, garden, laundry, kitchen, bathroom.	text	For scenario analysis	C	-	Data not identified yet as available
		Back up supply source	Backup		Potable water, treated wastewater, treated stormwater	text	For scenario analysis	C	-	Data not identified yet as available
		Back supply control level	Backup_Control_Level		Fraction of tank volume	number	For scenario analysis	C	-	Data not identified yet as available
	Direct greywater use	Greywater Source	GreyW_Source		Kitchen, bath, shower	text	For scenario analysis	C	-	Data not identified yet as available
		Up-take	%_Uptake	%		number	For scenario analysis	C	-	Data not identified yet as available
		Treated water reuse point	Re-use_Point		Sub-surface irrigation	text	For scenario analysis	C	-	Data not identified yet as available
	Unit block wastewater	Tank volume	Tank_V	m^3		number	For scenario analysis	C	-	Data not identified yet as available

		Up-take of tanks	%_Uptake	%		number	For scenario analysis	C	-	Data not identified yet as available
		Wastewater Source	WasteW_Source		Kitchen, bath, shower, toilet	text	For scenario analysis	C	-	Data not identified yet as available
		Utilised for?	Use		Garden and/or toilet	text	For scenario analysis	C	-	Data not identified yet as available
		Overflow directed to	Overflow_to		Sewer or stormwater	text	For scenario analysis	C	-	Data not identified yet as available
	Cluster scale wastewater treatment	Storage capacity	Storage_Cap	m^3		number	For scenario analysis	C	-	Data not identified yet as available
		Utilised for?	Use		Toilet and/or garden and/or public open space irrigation	text	For scenario analysis	C	-	Data not identified yet as available
		Treat wastewater from upstream clusters?	Treat_fr_Upstream	Yes/No		Yes/No	For scenario analysis	C	-	Data not identified yet as available
		Overflow connection	Overflow_connection		Sewer, stormwater drain	text	For scenario analysis	C	-	Data not identified yet as available
		Exposed surface		m^2	for evaporation calculation		For scenario analysis	C	-	Data not identified yet as available
	Cluster scale stormwater treatment (Wetlands, infiltration basin)	Storage capacity	Storage_Cap	m^3		number	For scenario analysis	C	-	Data not identified yet as available
		Utilised for?	Use		Toilet and/or garden and/or public open space irrigation?	text	For scenario analysis	C	-	Data not identified yet as available
		Treat stormwater from upstream clusters?	Treat_fr_Upstream	Yes/No		Yes/No	For scenario analysis	C	-	Data not identified yet as available
		Stormwater source	Source		Roads, unit blocks	text	For scenario analysis	C	-	Data not identified yet as available
		Exposed surface	Exp_Surface	m^2	for evaporation calculation	number	For scenario analysis	C	-	Data not identified yet as available
		First flush volume	First_flush	m2		number	For scenario analysis	C	-	Data not identified yet as available
		First flush destination	??	n/a	currently no chioce in destination - must be the cluster wastewater outflow system	text	For scenario analysis	C	-	Data not identified yet as available
	Catchment scale	Storage capacity	Storage_Cap	m^3		number	For scenario analysis	C	-	Data not identified yet as available

		Utilised for?	Use		Toilet and/or garden and/or public open space irrigation	text	For scenario analysis	C	-	Data not identified yet as available
		Overflow connection	Overflow_connection		Sewer, stormwater drain	text	For scenario analysis	C	-	Data not identified yet as available
		Exposed surface		m^2	for evaporation calculation		For scenario analysis	C	-	Data not identified yet as available
	Catchment scale stormwater treatment	Storage capacity	Storage_Cap	m^3		number	For scenario analysis	C	-	Data not identified yet as available
		Utilised for?	Use		Toilet and/or garden and/or public open space irrigation	text	For scenario analysis	C	-	Data not identified yet as available
		Exposed surface	Exp_Surface	m^2	for evaporation calculation	number	For scenario analysis	C	-	Data not identified yet as available
		First flush volume	First_flush	m2		number	For scenario analysis	C	-	Data not identified yet as available
		First flush destination	??	n/a	currently no chioce in destination - must be the cluster stormwater outflow system	text	For scenario analysis	C	-	Data not identified yet as available
UVQ contaminant data (for each modelled contaminant)	Residential sources	Water supply	Water_Supply	mg/l		number	High	A	-	YWS water supply data
		Bore water	Bore_Water	mg/l		number		N/App	-	Not applicable to this case-study
		Precipitation	Precip	mg/l		number	High	B	-	AEAT regional network on website
		Rainwater tank	Rain_Tank	mg/l		number	For scenario analysis/ calibration	C	-	Data not identified yet as available
		Roof first flush		mg/l			For scenario analysis/ calibration	C	-	Data not identified yet as available
		Kitchen greywater	Kitchen_Grey	mg/person/day		number	High	C	-	Data not identified yet as available
		Bathroom greywater	Bathrm_Grey	mg/person/day		number	High	C	-	Data not identified yet as available

		Laundry greywater	Laundry_Grey	mg/person/day		number	High	C	-	Data not identified yet as available
		Toilet wastewater	WC_WasteW	mg/person/day		number	High	C	-	Data not identified yet as available
		Roof stormwater runoff	Roof_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Road stormwater runoff	Road_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Paved area stormwater runoff	Paved_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Pervious soil runoff	Perv_Soil_Runoff	mg/l		number	High	C	-	Data not identified yet as available
		Fertiliser application	Fertiliser_app	mg/cluster/day		number	High	C	-	Data not identified yet as available
		Evaporation all sources		mg/l			Med	C	-	Data not identified yet as available
	Commercial sources	Water supply	Water_Supply	mg/l		number	High	A	-	YWS water supply data
		Bore water	Bore_Water	mg/l		number		N/App	-	Not applicable to this case-study
		Precipitation	Precip	mg/l		number	High	B	-	AEAT regional network on website
		Roof stormwater runoff	Roof_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Road stormwater runoff	Road_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Paved area stormwater runoff	Paved_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Pervious soil runoff	Perv_Soil_Runoff	mg/l		number	High	C	-	Data not identified yet as available
		Other point source application	Fertiliser_app	mg/cluster/day		number	High	A	-	Fertiliser rec ords, Doncaster racecourse
		Evaporation all sources		mg/l			Med	C	-	Data not identified yet as available
	Industrial sources	Water supply	Water_Supply	mg/l		number	High	A	-	YWS water supply data
		Bore water	Bore_Water	mg/l		number		N/App	-	Not applicable to this case-study
		Precipitation	Precip	mg/l		number	High	B	-	AEAT regional network on website
		Roof stormwater runoff	Roof_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Road stormwater runoff	Road_StormW	mg/l		number	High	C	-	Data not identified yet as available

		Paved area stormwater runoff	Paved_StormW	mg/l		number	High	C	-	Data not identified yet as available
		Pervious soil runoff	Perv_Soil_Run off	mg/l		number	High	C	-	Data not identified yet as available
		Other point source application	Fertiliser_app	mg/cluster/da y		number	High	C	-	Data not identified yet as available
	Public open space sources	Water supply	Water_Supply	mg/l		number	High	A	-	YWS water supply data
		Bore water	Bore_Water	mg/l		number		N/App	-	Not applicable to this case-study
		Precipitation	Precip	mg/l		number	High	B	-	AEAT regional network on website
		Rainwater tank	Rain_Tank	mg/l		number	For scenario analysis/ calibration	C	-	Data not identified yet as available
		Pervious soil runoff	Perv_Soil_Run off	mg/l		number	High	C	-	Data not identified yet as available
		Fertiliser application	Fertiliser_app	mg/cluster/da y		number	High	C		Coleby et al 1996; DMBC records
	Contaminant balance calibration	Greywater	Greywater	mg/l		number	For scenario analysis/ calibration			
		Central WWTP	Central_WWTP	mg/l		number	For scenario analysis/ calibration	B	-	YWS WWTP records (sparse);field measurements
		Septic tank treated sewage	Treated_Septic _Tank	mg/l		number	For scenario analysis /calibration	N/App	-	Not applicable to this case-study
		Commercial Rainwater tank	Rain_Tank	mg/l		number	For scenario analysis /calibration	N/App	-	Not applicable to this case-study
		Commercial total wastewater discharge	Total_WasteW _Q	mg/l		number	For scenario analysis /calibration	N/App	-	Not applicable to this case-study
		Industrail Rainwater tank	Rain_Tank	mg/l		number	For scenario analysis /calibration	N/App	-	Not applicable to this case-study
		Industrial total wastewater discharge	Total_WasteW _Q	mg/l		number	For calibration	N/App	-	Not applicable to this case-study
		Cluster stormwater store		mg/l		number	For scenario analysis /calibration	N/App	-	Not applicable to this case-study
		Cluster wastewater store		mg/l		number	For scenario analysis /calibration	N/App	-	Not applicable to this case-study

	Performance characteristics	Raintanks		% removal		number	For scenario analysis	N/App	-	Not applicable to this case-study
		On site Wastewater treatment		% removal		number	For scenario analysis	B	-	YWS WWTP performance statistics
		Cluster Stormwater treatment		% removal		number	For scenario analysis	N/App	-	Not applicable to this case-study
		Cluster Wastewater treatment		% removal		number	For scenario analysis	N/App	-	Not applicable to this case-study
		Estate Stormwater treatment		% removal		number	For scenario analysis	N/App	-	Not applicable to this case-study
		Estate Wastewater treatment		% removal		number	For scenario analysis	N/App	-	Not applicable to this case-study

Key:

DMBC-PD Doncaster Metropol.District Council Planning Dept

YWS Yorkshire Water Services databases

Priority rating

To be assigned by modelling development partners CSIRO and UniKarl.

High; key parameter which needs city case-study-specific value, without which the validity of/confidence in the resultant model would be compromised

Low; secondary importance, where it would be useful to have case-study specific value, but generic, assumed or approximate value could be employed

Data Class

Usually assigned by the casestudy field teams, based on their local knowledge of data available.

Class A; We have site specific/field values eg water levels, aquifer node hydraulic conductivity, pipe material class. Values would be sourced from available data and additional project field studies.

Class B; site specific values unavailable but approximations can be found from national, regional or company statistics eg sewer leakage or pipe failure rates, indoor water use. Values drawn from available data; field studies to generate these data beyond scope/resources of this project

Class C; neither site-specific nor local-context values available eg every parameter not covered by Class A or Class B. Values are working approximations/experimental/empirical/guestimates obtained from technical literature searches, studies in analogous situations, lab studies, project colleagues.

Other model origin?

To be assigned by modelling development partners CSIRO and UniKarl.

Column to help the case-study city modellers keep track of data as it cascades as output from one model to input to another, and for QA; marks the source of the data as they come from another model

e.g leakage rate and x,y coord of pipe in the unsat flow model gets supplied by output from the pipe leakage model and does not have to be generated independently for the unsat. flow model

Source of information

Can be completed by any project partner and intended to help all teams fill in data gaps of the Class C type.

e.g. a partner may have measured field data on a specialist parameter from previous research study, or be aware of technical values from literature that others might not know where to look for, or that are reported in another language.

Pipeline Leakage Model: Doncaster case-study

Category	Sub-category	Field	Short (db) name	Units	Description	Type	Priority rating	Data Class	Other model origin ?	Source of information
Pipe leakage: inputs	Sewer pipes	Unique ID of each pipe asset	ID			text	High	A	-	YWS wastewater database: YWS reference
		X co-ordinate of node	X			number	High	A	-	YWS wastewater database: coordinates
		Y co-ordinate of node	Y			number	High	A	-	YWS wastewater database: coordinates
		Internal diameter	Int. D	mm		number	High	A	-	YWS wastewater database: current diameter
		Shape	Shape			text	Low	A	-	YWS wastewater database: current diameter/current height + material
		Length of asset (node to node)	Length	m		number	High	A	-	YWS wastewater database: start & end node GID
		Date of installation	Installed	date		text	High	A	-	YWS wastewater database: date of construction
		Material	Material		Vitreous clay, concrete, brick, mild steel, CI, AC	text	High	A	-	YWS wastewater database: material
		Joint type in asset	Joint_type		Cement-mortar, rubber-ring, welded	text	High	N/Av	-	Not available in YWS wastewater database
		Length between joints	L_b/w_joints	m	Length of each pipe element	number	High	A	-	YWS wastewater database: measured length
		Slope	Slope			number	High	A	-	Not available in YWS wastewater database
		Flow direction	Flow_dir			text	Low	A	-	YWS wastewater database (unconfirmed)
		Bedding soil type	Bed_soil		Sand, crushed rock, clay	text	Low	A	-	YWS wastewater database: bedding protection
		Soil type in area	Area_soil		Sand, clay, loam	text	Low	A	-	YWS wastewater database: excavation material
		Asset burial depth , upstream	Burial_depth_US	m	from surface to pipe invert, US	number	High	A		These values can be calculated from DS_Invert_Depth, US_Invert_Depth and Pipe_Length
		Asset burial depth , downstream	Burial_depth_DS	m	from surface to pipe invert, DS	number	High	A	-	These values can be calculated from DS_Invert_Depth, US_Invert_Depth and Pipe_Length
		Groundwater level at asset location	G/w_level	m	Depth from surface to water table	number	High	A	Sat. flow model in part	Surface elevn from dig.elevn map - gw elevn from satflow model

		Defect database from CCTV condition reports (EN 13508 or equivalent)	CCTV_defect_db			object	High	A	-	YWS wastewater CCTV statistics: (unconfirmed)
	Stormwater pipes	Unique ID of each pipe asset	ID			text	High	A	-	YWS wastewater database: YWS reference
		X co-ordinate of node	X			number	High	A	-	YWS wastewater database: coordinates
		Y co-ordinate of node	Y			number	High	A	-	YWS wastewater database: coordinates
		Internal diameter	Int_diam	mm		number	High	A	-	YWS wastewater database: current diameter
		Shape	Shape			text	Low	A	-	YWS wastewater database: current diam/current height + material
		Length of asset (node to node)	Length	m		number	High	A	-	YWS wastewater database: start & end node GID
		Date of installation	Installed	date		text	High	A	-	YWS wastewater database: date of construction
		Material	Material		Vitreous clay, concrete, brick, mild steel, CI, AC	text	High	A	-	YWS wastewater database: material
		Joint type in asset	Joint_type		Cement-mortar, rubber-ring, welded	text	High	N/Av	-	Not available in YWS wastewater database
		Length between joints	L_b/w_joints	m	Length of each pipe element	number	High	A	-	YWS wastewater database: measured length
		Slope	Slope			number	High	A	-	Not available in YWS wastewater database
		Flow direction	Flow_dir			text	Low	A	-	YWS wastewater database (unconfirmed)
		Bedding soil type	Bed_soil		Sand, crushed rock, clay	text	Low	A	-	YWS wastewater database: bedding protection
		Soil type in area	Area_soil		Sand, clay, loam	text	Low	A	-	YWS wastewater database: excavation material
		Asset burial depth , upstream	Burial_depth_US	m	from surface to pipe invert, US	number	High	A		These values can be calculated from DS_Invert_Depth, US_Invert_Depth and Pipe_Length
		Asset burial depth , downstream	Burial_depth_DS	m	from surface to pipe invert, DS	number	High	A	-	These values can be calculated from DS_Invert_Depth, US_Invert_Depth and Pipe_Length
		Groundwater level at asset location	G/w_level	m	Depth from surface to water table	number	High	A	Sat flow model in part	Surface elevn from dig.elevn map - gw elevn from satflow model
		Defect database from CCTV condition reports (EN 13508 or equivalent)	CCTV_defect_db			object	High	A	-	YWS wastewater CCTV statistics: (unconfirmed)

	Water supply pipes	Unique ID of each pipe asset	ID			text	High	A	-	YWS water distrbn database: YWS reference code
		X co-ordinate of node	X			number	High	A	-	YWS water distrbn database: (unconfirmed)
		Y co-ordinate of node	Y			number	High	A	-	YWS water distrbn database: (unconfirmed)
		Internal diameter	Int_diam	mm		number	High	A	-	YWS water distrbn database: nominal diameter
		Length of asset (node to node)	Length	m		number	High	A	-	YWS water distrbn database: (unconfirmed)
		Date of installation	Installed	date		text	High	A	-	YWS water distrbn database: date pipe laid
		Material	Material		Vitreous clay, concrete, brick, mild steel, CI, AC	text	High	A	-	YWS water distrbn database: material type
		Joint type in asset	Joint_type		Cement-mortar, rubber-ring, welded	text	High	A	-	YWS water distrbn database: joint type
		Length between joints	L_b/w_joints	m	Length of each pipe element	number	High	A	-	YWS water distrbn database: (unconfirmed)
		Flow direction	Flow_dir			text	High	A	-	YWS water distrbn database: (unconfirmed)
		Bedding soil type	Bed_soil		Sand, crushed rock, clay	text	High	N/Av; see comment	-	We could use information from Sewer/Stormwater data base by matching X, Y coordinates
		Soil type in area	Area_soil		Sand, clay, loam	text	High	N/Av; see comment	-	We could use information from Sewer/Stormwater data base by matching X, Y coordinates
		Asset burial depth	Burial_depth	m	from surface to pipe invert	number	High	N/Av	-	YWS water distrbn database: not available
		Operating pressure	Op_pressure	MPa or m head		number	High	B	-	YWS water distrbn database: standing specs
		District Leakage data	CCTV_defect_db	L/hr	from night flow analysis (litres/hour)	object	High	B	-	YWS DMZ statistics
		Profile of pipes in the night flow monitoring district	Night_flow_profile			object	High	B	-	YWS DMZ statistics
		Area classification	Area_class		Road in CBD, Suburban strip shopping, Arterial Road, Inner suburban street, Outer suburban street, road, footpath, verge	text	High	A	-	DMBC-PD landuse database/GIS
		Recorded failures	Failures			number	High	B	-	YWS unaccounted-for water tests (unconfirmed)
		Failure (n) date	date	date	n is the failure number, date as yyyymmdd	date/time	Low	B	-	YWS unaccounted-for water tests (unconfirmed)

		Failure (n) reported time	time	hhmm	24hr time	date/time	Low	B	-	YWS unaccounted-for water tests (unconfirmed)
		Failure (n) duration	duration	hhmm		date/time	Low	B	-	YWS unaccounted-for water tests (unconfirmed)
		Failure (n) type	type		failure description - broken back (BB), longitudinal split (LS), blown section (BS), perforation (P), joint leak (JL), tapping band (TB), ferrule (F), gibault/repair clamp (G), other (O)	text	High	B	-	YWS unaccounted-for water tests (unconfirmed)
Pipe leakage: outputs	Wastewater	Exfiltration	Exfil	L/day	exfiltration as small medium and large point sources from each pipe	number		N/App: model output		N/App: model output
		X co-ordinate	X			number		N/App: model output		N/App: model output
		Y co-ordinate	Y			number		N/App: model output		N/App: model output
	Stormwater	Exfiltration	Exfil	L/day	exfiltration as small medium and large point sources from each pipe	number		N/App: model output		N/App: model output
		X co-ordinate	X			number		N/App: model output		N/App: model output
		Y co-ordinate	Y			number		N/App: model output		N/App: model output
	Water supply pipes	Leakage	Leakage	L/day	exfiltration as small medium and large point sources from each pipe	number		N/App: model output		N/App: model output
		X co-ordinate	Y			number		N/App: model output		N/App: model output
		Y co-ordinate	Y			number		N/App: model output		N/App: model output

KEY

N/Av	Site-specific values needed but no data available & generic (Class C) values inapplicable
N/App: model output	Not applicable because this is output from the model

Unsat. Flow mode (Provisional) : Doncaster case-study

Category	Sub-category	Field	Short (db) name	Units	Description	Type	Priority rating	Data Class	Other model origin?	Source of information
UFM: inputs	regional data	surface elevation	surf_elev	m	spatially distributed	*number*	High	A		OS cover/CEH digital elevn model
		groundwater table	gw_table	m	spatially distributed	*number*	High	A	sat flow model	Sat.flow model output using EA OW network
		profile distribution	prof_dist	special	Shape-File	*polygon*	High	A	-	NSRI-NV map unit
	unsaturated zone profiles	profile ID	prof_id			*number*	identification	A	-	NSRI-NV dominant soil
		thickness variability	prof_var_id		ID for possible thicknesses of each profiles	*number*	High	A	-	NSRI-HD U & L depth layers summed
	horizons of each profile	horizon ID	hor_id			*number*	identification	A	-	NSRI-HD layer designation
		thickness of each horizon	hor_thick	m		*number*	High	A	-	NSRI-HD U & L depth of layer
		soil type of each horizon	hor_soil		common denomination, term or grain size composition	*text*	High	A	-	NSRI-NV brief descrpn
	soil properties of each soil type	grain size distribution	grain	special	array of grain sizes and percentages, if available	*record*	Low	A	-	NSRI-HD Texture (e.g. sandy silt loam)
		saturated K	k_sat	m/s	if available, instead estimated from 'grain' or 'hor_soil'	*number*	High	A	-	NSRI-HD calc.satd.hyd.cond.
		porosity	por		if available, instead estimated from 'grain' or 'hor_soil'	*number*	High	A	-	NSRI-HD calc total pore space
		retention parameter α	ret_alpha	1/cm	if available, instead estimated from 'grain' or 'hor_soil'	*number*	High	A	-	NSRI-HD calc Van Genuchten ?m?
		retention parameter n	ret_n		if available, instead estimated from 'grain' or 'hor_soil'	*number*	High	A	-	NSRI-HD calc Van Genuchten n
	topsoil	specific infiltration rate	ts_inf	mm/d	spatially distributed, possibly transient	*number*	High	B?	-	To be estimated from soil data (e.g. sat K ?)
	pipe leakage	leakage ID	leak_id			*number*	identification	B?	pipeline leakage model?	Not identified yet as available
		x-cooridnate	leak_x	m		*number*	Low	A	pipeline leakage model?	YWS pipe network shp files

		y-cooridnate	leak_y	m		*number*	Low	A	pipeline leakage model?	YWS pipe network shp files
		z-coordinate	leak_elev	m		*number*	Low	A	pipeline leakage model?	YWS pipe network shp files
		leakage rate	leak_inf	l/h	exfiltration calculated by pipe leakage, possibly transient	*number*	High	B or C	pipeline leakage model?	YWS estimates/leakage control zone field data
		leakage area	leak_area	m^2	from pipe leakage, possibly transient	*number*	High	B or C	pipeline leakage model?	attribs to YWS pipe network shp files
UFM: outputs	unsaturated flow	effective water content	wc_eff		for each profile with respective thicknesses, possibly transient	number	-	N/App: model output		N/App: model output
		effective water residence time	t_eff	h	for each profile with respective thicknesses, possibly transient	number	-	N/App: model output		N/App: model output
	recharge	recharge rates	rech	mm/d	for each profile with respective thicknesses, transient	*number*	-	N/App: model output		N/App: model output
		affected area	rech_area	m^2	for each profile with respective thicknesses, transient	*number*	-	N/App: model output		N/App: model output

Key:

NSRI-NV	Natl.Soil Res.Inst.Natmap Vector dataset
NSRI-HD	Natl/Soil Res.Inst. HorizonData database
YWS	Yorkshire Water Services databases
Soil horizon In England & Wales	NSRI 'soil layer' term
N/App: model output	Not applicable because this is output from the model

Unsat. Transport model (provisional): Doncaster case-study

Category	Subcategory	Field	Short (db) name	Units	Description	Type	Priority rating	Data Class	Other model origin?	Source of information
Input data (WP8)	Leak	X co-ordinate	X					A	pipeline leakage model?	YWS pipe network shp files
(for each leak)		Y co-ordinate	Y					A	pipeline leakage model?	YWS pipe network shp files
		leakage rate	Leakage	L/day	Expressed as steady state leakage rate for series and stormwater pipes.			B or C	pipeline leakage model?	YWS estimates/leakage control zone field data
	Soil	Soil type	Soil_type					A	-	NSRI-NV brief descrpn
		Saturated K	K_{sat}		K of least permeable layer above the water table			A	-	NSRI-HD calc.satd.hyd.cond.
		Effective porosity	n_{eff}					A	-	NSRI-HD calc total pore space
		Approx. Depth to water table	water_tab_depth					A		Surface elevn from dig.elevn map - gw elevn from satflow model
		Temp range of soil at depth of invert	T_range		Assumed to be mean annual temp.			C	-	Estimate from mean annual air or gw temp
Output data	Water flux	Water flux at water table	Flux	L/day	Generally same as leakage rate		-	N/App: model output		N/App: model output
(for each leak)		X co-ordinate	X		Same as for pipe leakage		-	N/App: model output		N/App: model output
		Y co-ordinate	Y		Same as for pipe leakage		-	N/App: model output		N/App: model output
		Solute concentration	Solute conc.		Estimate conc. Of each specified contaminant reching the water table. Reflects relative risk, rather than expected numerical value of mean concentrations.		-	N/App: model output		N/App: model output

Sat. flow model: Doncaster case-study

Category	Subcategory	Field	Short (db) name	Units	Description	Type	Priority rating	Data Class	Other model origin?	Source of information
Subsurface Point Information Sources	Boreholes	X-Coordinate	X	m	Gauss-Krüger	number	High	A	-	Data on geological setup of area available from EA model
		Y-Coordinate	Y	m	Gauss-Krüger	number	High	A	-	Data on geological setup of area available from EA model
		Top ground surface	Z-0	m [a.m.s.l.]		number	High	A	-	Data on geological setup of area available from EA model
		Bottom hydrogeologic layer 1	Z-1	m [a.m.s.l.]		number	High	A	-	Data on geological setup of area available from EA model
		Bottom hydrogeologic layer n	Z-n	m [a.m.s.l.]	"n" different fields are necessary according to the number of layers to be considered	number	High	A	-	Data on geological setup of area available from EA model
		Maximum depth reached	Z-max	m [a.m.s.l.]		number	High	A	-	Data on geological setup of area available from EA model
	Observation Wells	Well ID	Well_ID	[-]		*number*	High	A	-	Assigned by project modeller
		X-Coordinate	X	m	Gauss-Krüger	number	High	A	-	Report
		Y-Coordinate	Y	m	Gauss-Krüger	number	High	A	-	Report
		Top ground surface	Z-0	m [a.m.s.l.]		number	High	A	-	Data with EA, possibly Robens
		Bottom hydrogeologic layer 1	Z-1	m [a.m.s.l.]		number	High	A	-	Data on geological setup of area available from EA model
		Bottom hydrogeologic layer n	Z-n	m [a.m.s.l.]	"n" different fields are necessary according to the number of layers to be considered	number	High	A	-	Data on geological setup of area available from EA model
		Maximum depth reached	Z-max	m [a.m.s.l.]		number	High	A	-	Report
		Top of screen	Z-screen-top	m [a.m.s.l.]		number	Low	B	-	Not identified so far
		Bottom of screen	Z-screen-bottom	m [a.m.s.l.]		number	Low	B	-	Not identified so far

		Beginning of piezometric level time series	Time-Series-Start	dd/mm/yy		*date*	Low	A	-	Report
		End of piezometric level time series	Time-Series-End	dd/mm/yy		*date*	Low	A	-	Report
		Piezometric level time series	Piezo_level_record	special	record consisting of date + piez. level	record	High	A	-	Data with EA, possibly Robens
		Observation well still in operation	Well_status	[-]		*logic*	Low	A	-	Data with EA, possibly Robens
		Pumping test data available ?	P_test_availability	[-]		*logic*	Low	A	-	possibly with EA or water utilities and AP manual
		Hydraulic Conductivity	Hydr_Cond	[m/s]		*number*	High	A	-	Data on aquifer properties available from EA model & AP manual
		Transmissivity	Transmissivity	[m²/s]		*number*	High	A	-	Data on aquifer properties available from EA model & AP manual
		Effective Porosity	Eff_Por	[-]		*number*	Low	A	-	Data on aquifer properties available from EA model & AP manual
	Production/Injection Wells	Well ID	Well_ID	[-]		*number*	High	A	-	Assigned by project modeller
		X-Coordinate	X	m	Gauss-Krüger	number	High	A	-	Location of abstraction available from EA model
		Y-Coordinate	Y	m	Gauss-Krüger	number	High	A	-	Location of abstraction available from EA model
		Top ground surface	Z-0	m [a.m.s.l.]		number	High	A	-	Will be taken from EA model
		Bottom hydrogeologic layer 1	Z-1	m [a.m.s.l.]		number	High	A	-	Data on geological setup of area available from EA model
		Bottom hydrogeologic layer n	Z-n	m [a.m.s.l.]	"n" different fields are necessary acc.to the no. layers to consider	number	High	A	-	Data on geological setup of area available from EA model
		Maximum depth reached	Z-max	m [a.m.s.l.]		number	High	A	-	Will be taken from EA model
		Top of screen	Z-screen-top	m [a.m.s.l.]		number	High	A	-	With us or water utilities
		Bottom of screen	Z-screen-bottom	m [a.m.s.l.]		number	High	A	-	With us or water utilities
		Beginning of piezometric level time series				*date*	Low	A	-	Data with EA, possibly Robens
		End of piezometric level time series				*date*	Low	A	-	Data with EA, possibly Robens
		Piezometric level time series	Piezo_level_record	special	Continuous record consisting of date + piezometric level	record	Low	A	-	Data with EA, possibly Robens

		Well still in operation	Well_status	[-]		Logic	High	A	-	Report
		Abstraction(-)/Injectionrate(+)	Well_abstraction	m³/d		*number*	High	A	-	Report
		Pumping test data available ?	P_test_availability	[-]		Logic	Low	A	-	possibly with EA or water utilities and AP manual
		Hydraulic Conductivity	Hydr_Cond	[m/s]		*number*	High	A	-	Data on aquifer properties available from EA model & AP manual
		Transmissivity	Transmissivity	[m²/s]		*number*	High	A	-	Data on aquifer properties available from EA model & AP manual
		Effective Porosity	Eff_Por	[-]		*number*	Low	A	-	Data on aquifer properties available from EA model & AP manual
Area Informations	Recharge	Recharge rate per cell	Recharge	[mm/d]	effective recharge rate combining natural/anthropogenic sources	*number*	High	A	Unsat. Flow model	Recharge available from EA model
	Surface Water Bodies	River Location	River_Loc	special	Shape-File	*polygon*	High	A	-	Topo maps
		River water level measuring points X-coord	RWLMP_X	m	Gauss-Krüger	*number*	Low	C	-	static levels could be assumed, if no time series data is available
		River water level measuring points Y-coord	RWLMP_Y	m	Gauss-Krüger	*number*	Low	C	-	static levels could be assumed, if no time series data is available
		River water level time series		special	Continuous record consisting of date + water level	record	Low	C	-	static levels could be assumed, if no time series data is available
		River bed colmation coefficient	R_bed_colmation	m/d²		*number*	High	A	-	applies to FeFlow, in Modflow that is the river conductance. Data available from EA model
		Lake Location	Lake_Loc	special	Shape-File	*polygon*	High	A	-	Topo maps
		Lake water level measuring points X-coord	LWLMP_X	m	Gauss-Krüger	*number*	Low	C	-	static levels could be assumed, if no time series data is available
		Lake water level measuring points Y-coord	LWLMP_Y	m	Gauss-Krüger	*number*	Low	C	-	static levels could be assumed, if no time series data is available
		Lake water level time series		special	Continuous record; date + water level	record	Low	C	-	static levels could be assumed, if no time series data is available
		Flow entering model area		m3/d		*number*	High	A	-	Will be taken from EA model
		Flow leaving model area		m3/d		*number*	High	A	-	Will be taken from EA model

KEY:
New fields, added because generic model will need them.

sat. transport model: Doncaster case-study

Category	Subcategory	Field	Short (db) name	Units	Description	Type	Priority rating	Data Class	Other model origin?	Source of information
Mesured Concentrations	Observation + Production Wells	Well ID		[-]	More Information can be found in the flow model	*Number*	High	A		Assigned by project modeller
		Chloride		mg/l	Key parameter, should be modelled	*Number*	High	A		EA and water utilities
		Boron		mg/l	Key parameter, should be modelled	*Number*	High	A		EA and water utilities
		E.Coli		MPU	Key parameter, should be modelled	*Number*	Low	A		EA and water utilities
		Nitrate		mg/l	Key parameter, should be modelled	*Number*	High	A		EA and water utilities
		Site specific marker species		ng/l	Key parameter, should be modelled	*Number*	Low	A		EA and water utilities
		Na		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		K		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		Ca		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		Mg		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		SO42-		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		HCO3-		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		CO2		mg/l	General control parameter	*Number*	Low	A		EA and water utilities
		pH-Value		[-]	General control parameter	*Number*	Low	A		EA and water utilities
		Spec. Electrical Conductivity		µS/cm	General control parameter	*Number*	Low	A		EA and water utilities
		Temperature		°C	General control parameter	*Number*	Low	A		EA and water utilities
		Redox		mV	General control parameter	*Number*	High	A		EA and water utilities
		Oxygen		mg/l	General control parameter	*Number*	High	A		EA and water utilities
	Surface Water Quality Observation Points	Obs_Point ID		[-]	More Information can be found in the flow model	*Number*	High	A		Assigned by project modeller

		Chloride		mg/l	Key parameter, should be modelled	*Number*	High	A		EA ?
		Boron		mg/l	Key parameter, should be modelled	*Number*	High	A		EA ?
		E.Coli		MPU	Key parameter, should be modelled	*Number*	Low	A		EA ?
		Nitrate		mg/l	Key parameter, should be modelled	*Number*	High	A		EA ?
		Site specific marker species		ng/l	Key parameter, should be modelled	*Number*	Low	A		EA ?
		Na		mg/l	General control parameter	*Number*	Low	A		EA ?
		K		mg/l	General control parameter	*Number*	Low	A		EA ?
		Ca		mg/l	General control parameter	*Number*	Low	A		EA ?
		Mg		mg/l	General control parameter	*Number*	Low	A		EA ?
		SO42-		mg/l	General control parameter	*Number*	Low	A		EA ?
		HCO3-		mg/l	General control parameter	*Number*	Low	A		EA ?
		CO2		mg/l	General control parameter	*Number*	Low	A		EA ?
		pH-Value		[-]	General control parameter	*Number*	Low	A		EA ?
		Spec. Electrical Conductivity		µS/cm	General control parameter	*Number*	Low	A		EA ?
		Temperature		°C	General control parameter	*Number*	Low	A		EA ?
		Redox		mV	General control parameter	*Number*	High	A		EA ?
		Oxygen		mg/l	General control parameter	*Number*	High	A		EA ?
Material Parameters	Sorption-coefficients	Boron	Sorpt_Boron	[-]	With respect to differemt aquifer materials	*Number*	Low	C		Literature
		Site specific marker species	Sorpt_Marker	[-]	With respect to differemt aquifer materials	*Number*	Low	C		Literature
	Decay rates	E.Coli	Decay_Coli	[1/s]	With respect to differemt aquifer materials	*Number*	Low	C		Literature
		Nitrate				*Number*	Low	C		Literature

		Site specific marker species	Decay_Marker	[1/s]	With respect to differemt aquifer materials	*Number*	Low	C		Literature
Concentration Input	Areal Recharge Concentrations	Chloride	Cl_Input_Conc	[mg/l]	Concentration of the cell-wise recharge flux for the saturated flow model	*Number*	High	A		CEH data collection
		Boron	B_Input_Conc	[mg/l]	Concentration of the cell-wise recharge flux for the saturated flow model	*Number*	High	A		CEH data collection
		E.Coli	E.Coli_Input_Number	1/l	Concentration of the cell-wise recharge flux for the saturated flow model	*Number*	Low	A		CEH data collection
		Nitrate	NO3_Input_Conc.	[mg/l]	Concentration of the cell-wise recharge flux for the saturated flow model	*Number*	High	A		CEH data collection
		Site specific marker species	Marker_Input_Conc	[mg/l]	Concentration of the cell-wise recharge flux for the saturated flow model	*Number*	Low	A		CEH data collection
	Additional Point Sorces	Chloride	Cl_Input_Conc	[mg/l]		*Number*	High	C		EA ?
	(Landiflls, Spillages etc)	Boron	B_Input_Conc	[mg/l]		*Number*	High	C		EA ?
		E.Coli	E.Coli_Input_Number	1/l		*Number*	Low	C		EA ?
		Nitrate	NO3_Input_Conc.	[mg/l]		*Number*	High	C		EA ?
		Site specific marker species	Marker_Input_Conc	[mg/l]		*Number*	Low	C		EA ?
	Dispersion and Advection	Chloride		[m]	Advection accounted for by simulation of gw flow velocity. Dispersion; spreading of solutes based on deviations of actual vel. from mean gw vel	*Number*	Low	C		Possibly from literature
		Boron		[m]		*Number*	Low	C		Possibly from literature
		E.Coli		[m]		*Number*	Low	C		Possibly from literature
		Nitrate		[m]		*Number*	Low	C		Possibly from literature

		Site specific marker species		[m]		*Number*	Low	C		Possibly from literature
		Na		[m]		*Number*	Low	C		Possibly from literature
		K		[m]		*Number*	Low	C		Possibly from literature
		Ca		[m]		*Number*	Low	C		Possibly from literature
		Mg		[m]		*Number*	Low	C		Possibly from literature
		SO42-		[m]		*Number*	Low	C		Possibly from literature
		HCO3-		[m]		*Number*	Low	C		Possibly from literature
	Molecular diffusion			[m]	refers to spreading of solutes driven by concn gradients	*Number*	Low	C		Possibly from literature

KEY:
New fields, added because generic model will need them.

APPENDIX 3B: NON SITE-SPECIFIC MODELLING PARAMETER VALUES TO FIND BY LITERATURE SEARCH

Model	Gen. Field	Parameter	Typical units	Pre-search Comments	Value found	Reference	Searcher's Comments
UVQ	Per capita domestic water use	Kitchen Bathroom Laundry Toilet External (carwash, gardening etc)	l/p/day l/p/day l/p/day l/p/day l/p/day	Preferred usage zone: UK> W.Europe> N. America >1st World. Urban /suburban values preferred	See table C below	EA website. Scottish pcc study. 23/07/01 A Methodology for surveying Domestic Water Consumption. K. Edwards and L. Martin 9/10/95	The paper has a lot more detail than requested, includesdiurnal water use / weekly use day/night figures/ per household income etc.
	Domestic solute concns; majors & minors	kitchen greywater, bathroom greywater, laundry greywater, toilet greywater	mg/l mg/l mg/l mg/l		See table B below.	Environment Agency website. 'Reuse firmly on the UK Agenda' 11/03/99	
	Non-Domestic solute concns; majors & minors	Road & paved surface runoff	mg/l		See paper	Character and dispersal of Motorway Run-off Water E.G Bellinger, Dr A.D. Jones and J. Tinker	Paper shows storm data/ pollution loading vs time after storm. De-icing salt application, peak monthly concentrations of major ions/ effect of water on streams/ changes of major ions in groundwater. Mostly Major ions.
					See paper	Experimental assessment of soil and groundwater contamination from two old infiltraion systems for road run-off in Switzerland. P.S Mikkelson etc 1996	Mostly metals are considered, vertical profiles.
					See paper	Impact of road run-off on receiving streams in eastern England. K. Perdikaki and C.F. Mason Sep 1998	Cd, Zn, Pb conc changes in streams.
		Roof runoff	mg/l			Ragab paper talks about amount of water not chemical analysis.	= rainfall?
		Rainfall	mg/l				EJW has values for major ion concns in rainfall

		Urban/domestic fertilizer usage	mg/l		Domestic mostly Growmore as 7%N/ 7%P_2O_4/7%K_2O Sportsfields etc double strength growmore.	FMA	Spoke to FMA who said values for usage not available.
PLM	Mains water leakage rates	Leakage part of unaccounted-for water	l/d/km (others used)	Look for YW value only eg at OFWAT, EA DM journal	295Ml/d	EA Demand Management Bulletin and Yorkshire water website	
	Sewer leakage rates	From foulwater or combined sewers	l/d/km (others used)	Compile any UK or European data	Munich exfiltration rate 5% of the total sewer flow. Nottingham figures indicate sewage leakage of 1.5 – 2% of base flow	A review of the effects of sewer leakage on groundwater quality. J.H. Reynolds and M.H. Barrett. March 2003.	Leakage depends heavily on Sewer Construction/ age. 'No published research …on extent of sewage exfiltration in the UK.'
	Storm-water leakage rates	From pipes or open channels	l/d/km (others used)				No ideas where to find a value.
STM	Sorption coefficients	MES to advise from potential lindicators list	-				

Table 2. Analytical data comparison of wastewaters (mean results)

Wastewater type	BOD mg/l	COD mg/l	Turb NTU	NH_3 mg/l	pH	P mg/l
Typical shower water	209	494	45	0.1	7.7	0.05
Typical bath water	103	286	33	0.1	7.5	0.05
Synthetic greywater	140	257	97	-	7.8	0.05
Boxworth greywater	110	256	14	-	7.5	-
Cranfield greywater	33	40	20	1.1	7.5	0.4
Linacre College grey	80	146	59	10	7.6	-
Sewage effluent	30	75	2	10	7.5	7

Table 3. Composition of water use. (from Edwards and Martin, 1995).

Water Use	SODCON data Nov 92-Oct 93 (%)	Water Facts 1992 (%)
Toilets	33	32
Dishwashers	1	-
Luxury Appliances	-	1
Washing Machines	21	12
Showers	4	17
Baths	13	
Kitchen sinks	16	-
Wash hand basins	9	-
Outside taps / External use	3	3
Miscellaneous	-	35

APPENDIX 3C PIPE INFRASTRUCTURE NETWORK ANALYSIS

Specimen mains water supply worksheet; there are similar spreadsheet compilations for foul water, storm water and combined sewer pipe networks

Assets	Total Number	Total Length (km)	Type	No.	Len.	Size, mm	No.	Len.	Age , yrs	No.	Len.	Soil type	No.	Len.
Part Asset Network	917	77.17	Cast Iron	746	65.02	0 Not Recorded	8	0.180	0-25			Reactive		
												Non-Reac		
									>25-50			Reactive		
												Non-Reac		
									>50-100	8	0.1800	Reactive		
												Non-Reac	8	0.18
									>100			Reactive		
												Non-Reac		
						<50	17	0.332	0-25			Reactive		
												Non-Reac		
									>25-50	17	0.3320	Reactive		
												Non-Reac	17	0.332
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						50-225	628	54.270	0-25			Reactive		
												Non-Reac		
									>25-50	625	54.2500	Reactive	5	0.0608
												Non-Reac	637	54.19
									>50-100	3	0.0193	Reactive		
												Non-Reac	3	0.0193
									>100			Reactive		
												Non-Reac		
						>225-350	35	3.589	0-25	1	0.0030	Reactive		
												Non-Reac	1	0.003
									>25-50	34	3.5860	Reactive	2	0.009
												Non-Reac	34	3.577
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						>350	58	6.230	0-25	39	4.0000	Reactive		
												Non-Reac	39	4
									>25-50	19	2.2300	Reactive	2	0.02
												Non-Reac	18	2.2
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
			Ductile Iron	171	12.15	0 Not Recorded	6	0.015	0-25			Reactive		
												Non-Reac		
									>25-50	6	0.0153	Reactive		
												Non-Reac	6	0.0153
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						50-225	148	12.950	0-25	31	1.6900	Reactive		
												Non-Reac	31	1.69
									>25-50	117	11.2627	Reactive		
												Non-Reac	117	11.267
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						>225-350	2	0.026	0-25	1	0.0038	Reactive		
												Non-Reac	1	0.0038
									>25-50	1	0.1120	Reactive		
												Non-Reac	1	0.112
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						>350	15	0.260	0-25	14	0.1693	Reactive		
												Non-Reac	14	0.1693
									>25-50	1	0.0922	Reactive		
												Non-Reac	1	0.0922
									>50-100			Reactive		
												Non-Reac		

Continued on following page

Assets	Total Number	Total Length (km)	Type	No.	Len.	Size, mm	No.	Len.	Age , yrs	No.	Len.	Soil type	No.	Len.
Part Asset Network	917	77.17	**Cast Iron**	746	65.02	0 Not Recorded	8	0.180	0-25			Reactive		
												Non-Reac		
									>25-50			Reactive		
												Non-Reac		
									>50-100	8	0.1800	Reactive		
												Non-Reac	8	0.18
									>100			Reactive		
												Non-Reac		
						<50	17	0.332	0-25			Reactive		
												Non-Reac		
									>25-50	17	0.3320	Reactive		
												Non-Reac	17	0.332
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						50-225	628	54.270	0-25			Reactive		
												Non-Reac		
									>25-50	625	54.2500	Reactive	5	0.0608
												Non-Reac	637	54.19
									>50-100	3	0.0193	Reactive		
												Non-Reac	3	0.0193
									>100			Reactive		
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						>225-350	35	3.589	0-25	1	0.0030	Reactive		
												Non-Reac	1	0.003
									>25-50	34	3.5860	Reactive	2	0.009
												Non-Reac	34	3.577
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						>350	58	6.230	0-25	39	4.0000	Reactive		
												Non-Reac	39	4
									>25-50	19	2.2300	Reactive	2	0.02
												Non-Reac	18	2.2
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
			Ductile Iron	171	12.15	0 Not Recorded	6	0.015	0-25			Reactive		
												Non-Reac		
									>25-50	6	0.0153	Reactive		
												Non-Reac	6	0.0153
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						50-225	148	12.950	0-25	31	1.6900	Reactive		
												Non-Reac	31	1.69
									>25-50	117	11.2627	Reactive		
												Non-Reac	117	11.267
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						>225-350	2	0.026	0-25	1	0.0038	Reactive		
												Non-Reac	1	0.0038
									>25-50	1	0.1120	Reactive		
												Non-Reac	1	0.112
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		
												Non-Reac		
						>350	15	0.260	0-25	14	0.1693	Reactive		
												Non-Reac	14	0.1693
									>25-50	1	0.0922	Reactive		
												Non-Reac	1	0.0922
									>50-100			Reactive		
												Non-Reac		
									>100			Reactive		

Continued on following page

MildSteel (Gal. Steel?)	2	0.111	0 Not Recorded	2	0.111	0-25			Reactive		
									Non-Reac		
						>25-50			Reactive		
									Non-Reac		
						>50-100	2	0.1110	Reactive		
									Non-Reac	2	0.111
						>100			Reactive		
									Non-Reac		
			50-225			0-25			Reactive		
									Non-Reac		
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>225-350			0-25			Reactive		
									Non-Reac		
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>350			0-25			Reactive		
									Non-Reac		
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
PVC, PE	211	13.97	0 Not Recorded	1	0.092	0-25	1	0.0920	Reactive		
									Non-Reac	1	0.092
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			< 50	1	0.241	0-25	1	0.2410	Reactive		
									Non-Reac	1	0.241
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>=50-225	207	13.600	0-25	134	7.7480	Reactive	4	0.4133
									Non-Reac	131	7.33
						>25-50	73	5.8500	Reactive	3	0.031
									Non-Reac	74	5.824
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>=225-<350	2	0.036	0-25	1	0.0118	Reactive		
									Non-Reac	1	0.0118
						>25-50	1	0.0248	Reactive		
									Non-Reac	1	0.0248
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>=350			0-25			Reactive		
									Non-Reac		
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
Other (Asbestos Cement)	7	0.51	50-225	7	0.510	0-25			Reactive		
									Non-Reac		
						>25-50	6	0.2880	Reactive		
									Non-Reac	6	0.288
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>225-350			0-25			Reactive		
									Non-Reac		
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
			>350	1	0.223	0-25	1	0.2230	Reactive		
									Non-Reac	1	0.223
						>25-50			Reactive		
									Non-Reac		
						>50-100			Reactive		
									Non-Reac		
						>100			Reactive		
									Non-Reac		
		91.761			92.665			92.5352			92.5306

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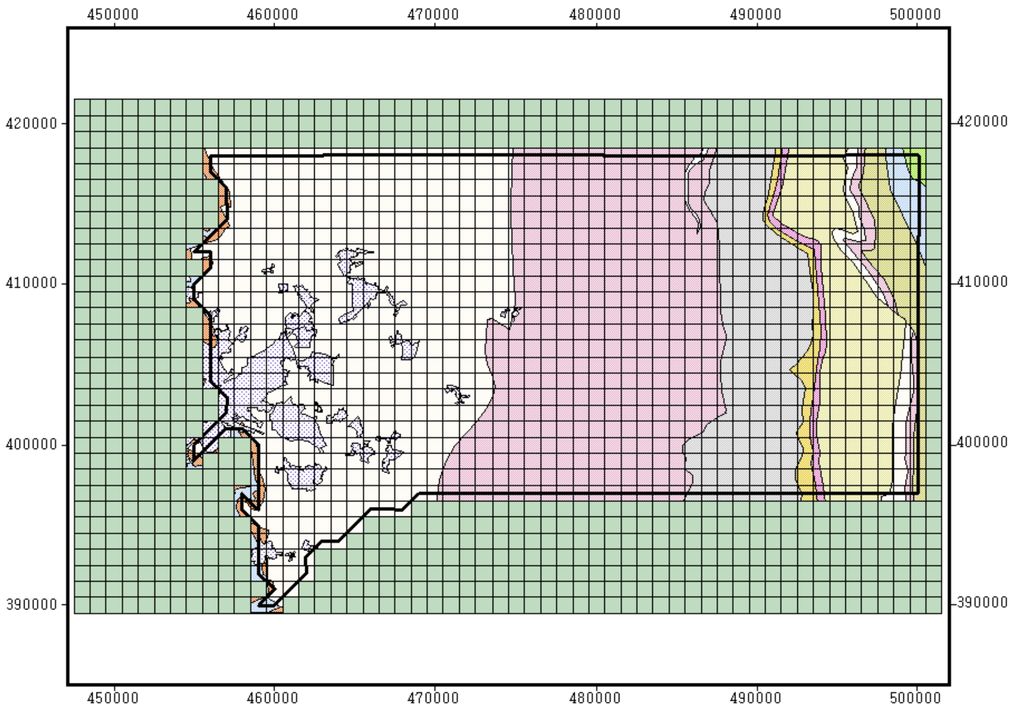
Translation of the Doncaster Groundwater Model into the MODFLOW code

Groundwater Systems and Water Quality Programme

Commissioned Report CR/03/258N



BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT CR/03/258N

Translation of the Doncaster Groundwater Model into the MODFLOW code

I Neumann and A Hughes

Key words

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The regional Doncaster model area.

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Contents

TABLES

1 Introduction

This report documents the translation of the Doncaster groundwater model, originally developed by the University of Birmingham, into a MODFLOW code (McDonald and Harbaugh, 1988) to be used within the AISUWRS (Assessing and Improving Sustainability of Urban Water Resources and Systems) project (Morris et al., 2003).

The Doncaster model (hereafter referred to as the original model) was established in 1993 by I.T. Brown and K.R. Rushton from the University of Birmingham (Brown and Rushton, 1993). It was extended and slightly modified in 1997 by M. Shepley of the Environment Agency (Shepley, 2000). The original model is regarded as a well-calibrated regional groundwater model, which adequately represents the aquifer conditions in the Doncaster area. It was therefore selected as the basis of the groundwater model to be used within the AISUWRS project. A translation of the original model code into MODFLOW code was deemed necessary in order to simulate both solute transport and groundwater flow. It also provides flexibility to change model input parameters for scenario modelling without recourse to the Environment Agency. A major aim of the AISUWRS project is to simulate various urban water resources management options. The regional MODFLOW model will form the basis for a future sub-regional model, focused on Bessacarr, a suburb of Doncaster, which is the centre of investigations within the AISUWRS project.

The report is written in six sections. Section one presents set up and discretization of both models. Section two describes the representation of aquifer parameters, while section three comments on the representation of external and internal boundaries. Section four discusses initial conditions and section five summarises the discretization of time in both models. The output of the Modflow model and the comparison with the original model outputs is given in section six.

This report details only the conversion of the original model into a MODFLOW equivalent. No detailed description of the original model itself is presented, as this is outside the scope of this report. For an in depth description of the conceptual model behind the original numerical model, the methods used to derive aquifer parameters, the way recharge values were established, etc. the reader is referred to Brown and Rushton (1993) and Shepley (2000).

2 Aquifer parameters, boundaries and recharge

2.1 MODEL SET UP AND DISCRETIZATION

The original model is a two dimensional (2-D) model, representing the groundwater flow conditions within the Sherwood Sandstone aquifer. The low permeability strata above the Sherwood Sandstone are not represented explicitly in the model. The model domain is discretized by a 1km by 1km grid, using a mesh-centred approach. However, model parameters are not always assigned to nodes, but also to areas between nodes. For example, transmissivity values are assigned between nodes, while storage coefficients are assigned to nodes (Figure 1).

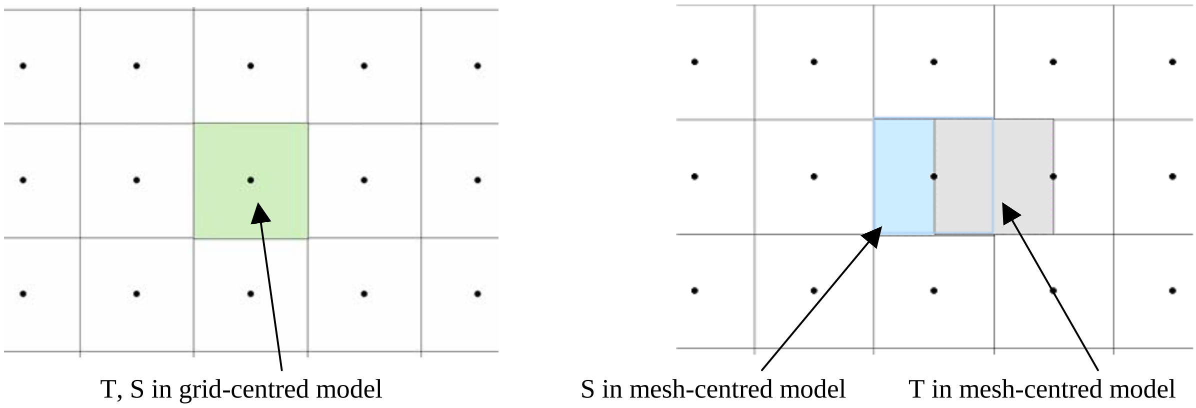

Figure 1 Differences in the assignment of parameters (T = Transmissivity, S = Storativity) in the mesh-centred original model, compared to the block-centred MODFLOW model.

In line with the original model, the MODFLOW equivalent is a 2-D model, using one layer to represent the Sherwood Sandstone aquifer. The model area in the MODFLOW model coincides with the groundwater units 1 and 2 as specified in Shepley (2000) (Figure 2). The model domain has been discretized using a block-centred grid of 1km by 1km. As the original model is nodal based, the block-centred grid covers a model area slightly larger by half a cell size all round compared to the original model area (Figure 4). The grid has been geo-referenced and cell centres coincide with the nodes of the original model (Figure 4). The block-centred approach forces all model parameters to be assigned to grid cells, with cells representing a 1km x 1km area around the nodes of the original model (Figure 1).

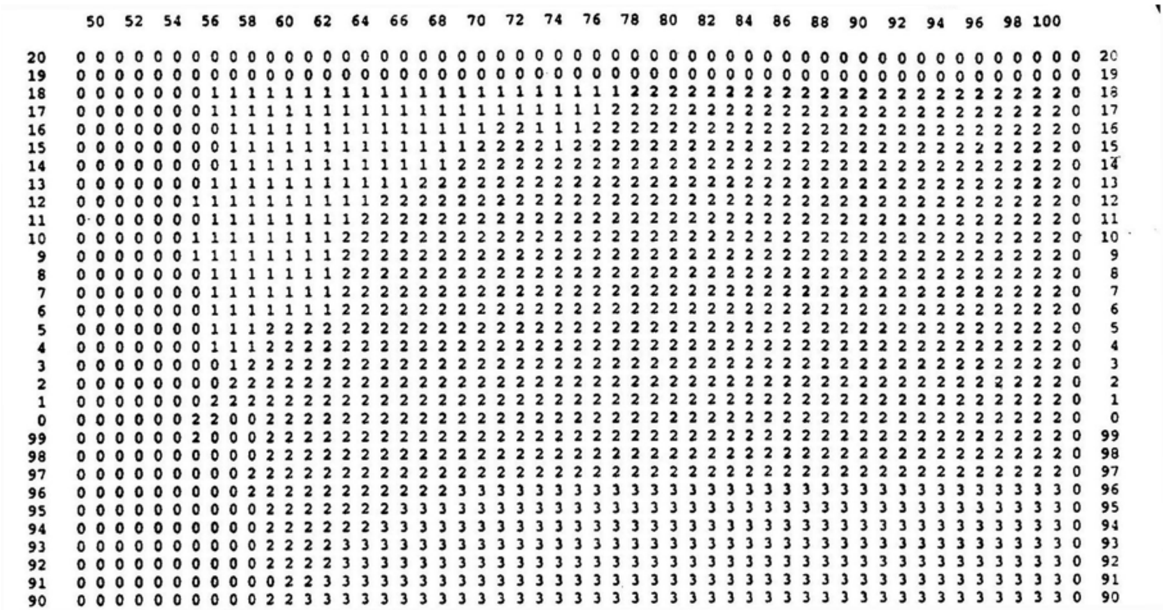

Figure 2 Node by node map of groundwater units 1 and 2 as specified in Shepley (2000). The eastings and northings are given along the margins.

2.2 AQUIFER PARAMETERS

2.2.1 Transmissivities

The original 2-D model allows for flow through the thickness of the aquifer by the specification of transmissivity rather than hydraulic conductivity and aquifer thickness. Transmissivities do not vary with changes in groundwater head. Transmissivities used in the original model are reproduced in Appendix 2.

The same approach has been followed in the MODFLOW model. However, Groundwater Vistas ©, the user-interface used to create the MODFLOW model, does not allow for direct input of transmissivities, but for aquifer thickness and hydraulic conductivities. By specifying the aquifer as strictly confined, it is ensured that the MODFLOW model uses the product of aquifer thickness and hydraulic conductivity, i.e. transmissivity directly to calculate flow through the aquifer.

The hydraulic conductivity throughout the model is 1/100 of the transmissivities used in the original model. The aquifer thickness is a constant of 100 m. The resulting transmissivities used in the MODFLOW model, which are identical to the original model, are presented in Figure 5. However, due to the mesh-centred approach used in the original model, compared to the block-centred approach used in the MODFLOW code, the area location for the same transmissivity is different by half a cell width between the two models. The MODFLOW model assigns transmissivities to areas 500 m further to the west compared to the original model (Figure 1).

2.2.2 Aquifer storage

The original model specifies the release of water within the confined part of the aquifer by the confined storage coefficient, using a value of 0.0005. Within the unconfined part of the aquifer the water release from storage is specified using a specific yield of 15% where the free water surface is within the Sherwood Sandstone, and 25%, where the free water surface is within the Quaternary sands and gravels. Storage coefficients used in the original model are presented in Appendix 2.

The same storage coefficients have been used in the MODFLOW model, and are presented in Figure 6. Even though the aquifer is specified in the numerical model as fully confined (constant transmissivity and storativity throughout model run), storage coefficients of 15% and 25% respectively have been assigned to represent the water release from storage in the unconfined part of the aquifer.

2.3 BOUNDARY CONDITIONS

2.3.1 Model boundaries

Boundary conditions of the original model have been copied to the MODFLOW model in the case of the western, northern and eastern boundary of the model domain. However, the southern boundary of the original model was set to approximate the southern boundary of the Hatfield groundwater unit. It does not coincide with the actual numerical model boundary, which is the southern boundary of the Notts-Doncaster model (Figure 7). The Notts-Doncaster model is a full model of the Doncaster and Nottingham aquifer, with the model extending as far south as Nottingham. Hence, any flows across the notional southern boundary in the original model are calculated using the full Notts-Doncaster aquifer model. Appendix 2 provides details on the flow across boundaries as applied in the original model.

The southern boundary of the MODFLOW model is the same as the notional southern boundary of the original model, i.e. the southern extent of the Hatfield groundwater unit. The data provided to the BGS by the Environment Agency only included the Doncaster part of the Notts-Doncaster model. Hence, the full Notts-Doncaster model could not be built to simulate the flows over the notional southern model boundary, i.e. the flows between the Hatfield groundwater unit and those further south. Details on the flows across the southern notional boundary were not made available either, to permit the set up of a southern flow boundary. This obliged the authors to use water balance figures from the original model to infer the flows across the boundary. Doing so, the amount and direction of flows could be established, but not the detailed distribution of flow along the southern boundary. The provision of the required data would have been useful, but in the event, the problem has been resolved by approximating the time variant flows along the boundary by evenly distributing the flows to the area mostly affected by abstraction. Flows are represented mathematically using wells.

Figure 8 presents the boundary conditions of the MODFLOW model.

2.3.2 Rivers and drainages

Rivers and drainage channels have been simulated in the original model in similar ways. River or drainage channel cells are contributing or draining water from the aquifer, depending on the head gradient between the river/drainage channels and the aquifer. If the aquifer head drops below the riverbed elevation, a limiting flux is applied. For details on the calculation of river leakage to and from the aquifer see Brown and Rushton (1993). Data input includes the stream bed level, the stream surface elevation and the river coefficient for each river/drainage channel node on the outcrop of the aquifer. The data are reproduced in Appendix 2.

The mathematical representation of river leakage in the original model is similar to the mathematical code within the MODFLOW river package. Hence, river cells can be used to represent the River Torne and drainage channels in the MODFLOW model. The river stage equals thereby the stream surface elevation of the original model, the river bottom elevation equals the stream bed level, while the riverbed conductance equals the river coefficient of the original model. Table 1 gives details of the input data.

Table 1 Details of river package input data in the MODFLOW model

I	J	Hydr. cond.[m/d]	River bottom elevation [mAOD]	Stage of river [mAOD]	Length [m]	Width [m]	Thickness [m]	Nodes
31	13	0.0003	10.5	11.5	1000	1000	1	River Torne
30	12	0.0003	11.6	12.6	1000	1000	1	River Torne
30	13	0.0003	10	11	1000	1000	1	River Torne
30	14	0.0003	9.5	10.5	1000	1000	1	River Torne
29	14	0.0003	9	10	1000	1000	1	River Torne
28	14	0.0003	8.5	9.5	1000	1000	1	River Torne
27	14	0.0003	8	9	1000	1000	1	River Torne
26	14	0.0003	7.5	8.5	1000	1000	1	River Torne
25	14	0.0003	7	8	1000	1000	1	River Torne
25	13	0.0003	6.3	7.3	1000	1000	1	River Torne
24	13	0.00005	5.6	6.6	1000	1000	1	River Torne
23	13	0.00005	5	6	1000	1000	1	River Torne
23	14	0.0005	4.6	5.6	1000	1000	1	River Torne
23	15	0.0005	4.3	5.3	1000	1000	1	River Torne
22	16	0.001	4	5	1000	1000	1	River Torne
21	17	0.0012	3.6	4.6	1000	1000	1	River Torne
20	18	0.0008	3.2	4.2	1000	1000	1	River Torne
20	19	0.0008	2.8	3.8	1000	1000	1	River Torne
11	20	0.00001	2	3	1000	1000	1	Drainage channels
11	21	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
11	22	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
12	21	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
12	22	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
12	23	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
13	23	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
13	24	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
14	21	0.0006	-0.5	0.5	1000	1000	1	Drainage channels
15	17	0.001	-0.5	0.5	1000	1000	1	Drainage channels
15	18	0.001	-0.5	0.5	1000	1000	1	Drainage channels
15	20	0.0005	1	2	1000	1000	1	Drainage channels
16	20	0.0008	1	2	1000	1000	1	Drainage channels
17	19	0.0008	-0.5	0.5	1000	1000	1	Drainage channels
17	20	0.0008	-0.5	0.5	1000	1000	1	Drainage channels
13	22	0.00001	-0.5	0.5	1000	1000	1	Drainage channels
18	21	0.0002	-0.5	0.5	1000	1000	1	Drainage channels
18	22	0.0002	-0.5	0.5	1000	1000	1	Drainage channels
18	23	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
18	24	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
18	25	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
19	20	0.0006	-0.5	0.5	1000	1000	1	Drainage channels
19	21	0.0006	-0.5	0.5	1000	1000	1	Drainage channels
19	22	0.0005	-0.5	0.5	1000	1000	1	Drainage channels
19	23	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
19	24	0.00045	3	4	1000	1000	1	Drainage channels
19	25	0.00045	-0.5	0.5	1000	1000	1	Drainage channels
20	20	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
20	21	0.00055	-0.5	0.5	1000	1000	1	Drainage channels
20	23	0.0005	-0.5	0.5	1000	1000	1	Drainage channels
20	24	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
20	25	0.0004	-0.5	0.5	1000	1000	1	Drainage channels
21	19	0.0007	-0.5	0.5	1000	1000	1	Drainage channels
21	20	0.0007	-0.5	0.5	1000	1000	1	Drainage channels
21	21	0.0007	-0.5	0.5	1000	1000	1	Drainage channels
21	22	0.00045	-0.5	0.5	1000	1000	1	Drainage channels
21	23	0.00045	-0.5	0.5	1000	1000	1	Drainage channels

2.3.3 Leakage through the overlying stratum

The mathematical representation of vertical leakage through an overlying stratum, which includes the Quaternary cover as well as the Mercia Mudstone, is similar to that of the rivers and drainage channels in the original model, although no limited flux is applied. As with the rivers and drainage channels, the original model calculates leakage by the specification of the head gradient between aquifer and overlying stratum, the vertical permeability of the stratum and its thickness. The original input parameters are given in Appendix 2. Some data describing the Quaternary deposits are however conflicting. So are Quaternary deposits assigned to areas, where their thickness is specified as being zero (Figure 9). This apparently is a result of rounding up or down of the original input data; e.g. drift thicknesses were provided as whole numbers of the original thickness, divided by 10, for easier print-out. This led to zero values being assigned to thicknesses smaller than 10 m. The actual thicknesses are not known and could only be established, if the input data provided were the actual data rather than rounded figures.

Leakage through the overlying stratum is best represented in MODFLOW using a General Head Boundary. Thereby the river stage equals the head in the stratum of the original model; the riverbed conductivity equals the stratum permeability and the thickness of the riverbed equals the stratum thickness of the original model. Zero drift thickness in the original input data was adjusted to a 1 m drift thickness in the MODFLOW model. Whether this represents the actual thickness used in the original model will remain uncertain, until the original, un-rounded input data are made available. Figure 10 to Figure 12 represent the input parameters for the MODFLOW model.

2.3.4 Abstraction

The abstraction data used in the original model were not made available to the BGS. Hence, actual abstraction data were sourced from Yorkshire Water for the years 1970 to 1997. Other private abstraction data were sourced from Brown and Rushton (1993) for the years 1970 to 1993. However, no data were available for those abstractions for the years 1994 to 1997. Also no data were available for abstractions added to the model in 1993 following the model update (Shepley, 2000). The original model represented 98% of the total abstraction explicitly (i.e. all abstraction > 0.2Ml/d). The remaining 2% of abstractions were represented implicitly by distributing them evenly over the existing abstractions. As a result, the abstraction data used in the MODFLOW model do differ slightly from the data used in the original model (Figure 14).

2.3.5 Recharge

Recharge to the original model is divided into precipitation recharge and recharge due to urban leakage. Precipitation recharge is applied where the drift cover is thin or absent, while the urban leakage is applied to waste districts (see Brown and Rushton (1993), Table 9, p. 52), which overlap permeable drift or Sherwood Sandstone outcrop. Precipitation recharge is calculated on a daily basis and summarised to provide monthly values, which are input to the model as a specified flow for each nodal point. For details on the procedure of estimation of precipitation and urban leakage see Brown and Rushton (1993).

The recharge input has been translated into MODFLOW using the recharge package. The urban leakage and the precipitation recharge have been combined to give one recharge input value to the model. Due to the fact that the MODFLOW model area is slightly larger by half a cell width due to the mesh centred approach compared to the original model, recharge for boundary cells had to be adjusted according to their cell area outside the original model area, in order to obtain the same recharge input as the original model. Figure 13 presents the distribution of urban leakage in the original and MODFLOW model.

2.4 INITIAL CONDITIONS

Initial conditions for the simulation of the original model are included by enforcing inflows and outflows, which represent the conditions prior to 1970 (Brown and Rushton, 1993). Data on these specified flows were not made available to BGS.

Initial conditions for the MODFLOW model are based on abstractions and cross boundary flows of 1970. Recharge input is based on the average of the years 1970 to 1997. These input values were used for a pre 1970 model run. The pre 1970 model was thereby run for 80 years to ensure that a stable pattern of heads and flows was produced. These then served as the initial conditions for the actual historical model run from 1970 to 1997. The pre 1970 model was run repeatedly, until the resulting heads were similar to the original model heads in 1970 (Figure 3). This was achieved by repeatedly lowering the pre 1970 abstraction rate.

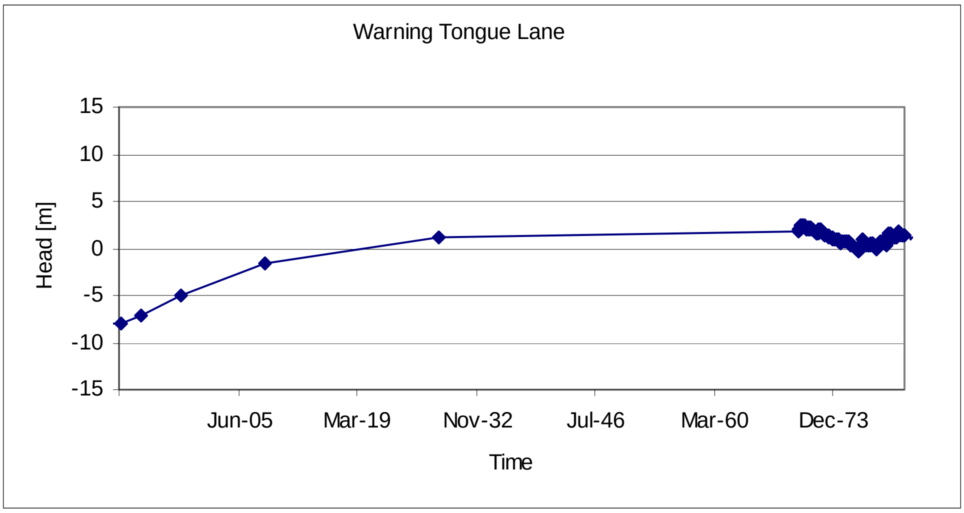

Figure 3 The pre 1970 model was run over 80 years to achieve stable heads and flows, which were similar to the conditions in 1970.

2.5 STRESS PERIODS AND TIME STEPPING

The original model simulates the period from 1970 to 1997 using monthly stress periods with time steps of two-week duration. Time variant boundary conditions are implemented by changing values annually. The notional southern boundary is not the numerical boundary and hence changes in flow correspond to the stress periods used for the model run, i.e. monthly periods. Precipitation recharge is input to the model on a monthly basis.

The MODFLOW model simulates the same period of time using monthly stress periods, which are in turn divided into four time steps, using a time step multiplier of 1.2. Time variant boundary conditions are implemented using yearly stress periods, including the southern boundary. Abstraction data changes on a yearly basis, while recharge is applied using monthly stress periods.

3 Model outputs and comparison with original model

A post-processing program is used to create ASCII files from MODFLOW output to produce time series output. Excel spreadsheets are then used to display the data and compare them with the original model output. The following time series outputs are produced for comparison with the original model data:

- Groundwater heads at observation boreholes
- Abstraction data over time
- Change in storage over time
- Total leakage between aquifer and overlying stratum, including rivers and drainage channels

3.1 WATER BALANCE

WATER LOST AND GAINED THROUGH WELLS

Figure 14 illustrates the abstraction data taken from the MODFLOW and original model output. Abstraction data is thereby all water lost or gained in the model through wells. That includes besides the borehole abstractions, the flow across the northern boundary and the southern boundary. Positive abstraction (flow into the model) reflects mainly the gain over the southern boundary, while water is lost from the aquifer, from flows to the northern boundary and abstraction.

There is good overall agreement between both models, however differences in abstraction can be observed between the MODFLOW and original model in some years (Figure 14). These changes relate to the differences in borehole abstraction values used in both models, while the amount of flow across the northern boundaries are identical in both models. The southern boundary flows are identical in both models in terms of amount of flow. However in the MODFLOW model, where the southern boundary represents the numerical boundary, flows change on an annual basis. The southern boundary flows in the original model meanwhile are not input to the model in form of a boundary condition and change monthly according to the monthly stress periods used in the model.

RECHARGE

Figure 15 shows a comparison between the MODFLOW model and original model recharge data. The recharge is thereby the sum of precipitation recharge and urban leakage. Both models are in good agreement. Urban leakage is input as a constant and accounts for 6.27Ml/d of the total recharge in both models.

LEAKAGE FROM/TO RIVERS AND OVERLYING STRATUM

Figure 16 shows the modelled leakage between rivers/overlying stratum and the aquifer. Both models produce similar results. Slight differences are due to differences in groundwater head, which determine the head gradient between river/overlying stratum and aquifer and which in turn determine the leakage rate. Differences in groundwater heads are discussed in detail in section 3.2. However, differences might also be introduced by possible differences in the thickness of the drift cover in both models (see section 2.3.3). The input data available to BGS specified zero thicknesses for some drift cells, as a result of rounding up or down of the original thicknesses to whole numbers. This was translated into MODFLOW using a 1m thickness instead (Figure 12). The thickness of the drift cover influences its conductance, which in turns influences the amount of leakage from/to the aquifer. Drift thickness could be revised, if the original data were made available.

CHANGE IN STORAGE

Figure 17 demonstrates the change in storage over time for both model runs. The storage change for the original model is the sum of the unconfined and confined storage. The data are in good agreement overall. Slight differences are likely to be the result of different abstraction rates in both models.

3.2 GROUNDWATER HYDROGRAPHS

A full set of groundwater hydrographs comparing MODFLOW modelled output with original model data are found in Appendix 1.

Data from all of the observation boreholes used in the original model have been compared to the MODFLOW model results. The locations of the observation boreholes within the study area are shown in Figure 18. Where possible, sets of hydrographs (original model vs. MODFLOW model) represent the same location within the modelled aquifer, i.e. the grid cell reference in the MODFLOW model corresponds to the nodal point in the original model used to represent the observation well. Several observation boreholes however, have nodal references equivalent to half nodal spacing in the original model (Table 2), which corresponds to grid cell boundaries rather than grid cells in the MODFLOW model. In those cases the nearest grid cell had to be selected in the MODFLOW model to represent the same observation borehole. Table 2 lists the nodal reference of observation boreholes of the original model and the MODFLOW model reference for comparison.

Table 2 Model observation borehole locations

Observation borehole	**Original Model (Column/Row)**	**MODFLOW model (Column/Row)**
Armthorpe	16/17	16/17
Bank End	24/22	24/22
Bessaccarr	12.5/21	13/21
Blaxton	22/21	22/21
Boston Park E33	21/18	21/18
Boston Park E33A	21/17	21/17
Branton Tubewell	17/21	17/21
Brier, Holme Carr	21/11.5	21/11
Cantley Towers	15/21	15/21
Cherry Tree	24.5/12	24/12
Cochwood Farm	19/18.5	19/18
Ellerholme Farm	23/18.5	23/18
Four Acres	16.5/19.5	16/19
Glentworth	22/12	22/12
Harworth	14/30	14/30
Holme House Farm	19/16	19/16
Holmewood Grange	18.5/16.5	19/17
Huggin Carr Farm	20.5/16.5	20/16
Lowgate Balne	12/4	13/4
Marshalls Quarry	19/14	19/14
Mill Hill Quarry	20/13	20/13
Partridge Hill	18.5/26	18/26
Pighill Thorne	23/6	23/6
Ponyfield	19/25	19/25
Sandall Beat	14/18	14/18
Sandall Common	16/15	16/15
Sparrington Farm	20/17	20/17
Stainforth Haggs	17/12	17/12
Stone Hill Farm	22/13	22/13
Swinnow Wood	16/28.5	16/28
Sykehouse	16/5	16/5
Thorninghurst Farm	20/7	20/7
Torne Bridge	21/18.5	21/18
Tudworth Hall	22/11	22/11
Tyrham Hall Motel	21/17	21/17
Warning Tongue Lane	17/22	17/22
Woodhouse Grange	21/15	21/15
Pincheon Green	18.5/4.5	18/4

The majority of the groundwater hydrographs show a very good agreement between the original model and the MODFLOW model. Both produce similar groundwater heads as well as the same water level trends over time.

However, some discrepancies exist for a small number of observation boreholes:

- Some hydrographs display differences in groundwater levels in the first few years of the model run (e.g. Cherry Tree, Armthorpe). This is the result of the initial conditions used in the MODFLOW model and original model respectively. The details of how initial conditions were implemented in the original model are unknown and are likely to differ from the initial conditions used in the MODFLOW model (see section 2.4). Identical initial conditions would most likely result in the same groundwater levels in those first few years of the historical model run.
- Boreholes close to the southern boundary exhibit discrepancies (Swinnow Wood, Ponyfield, Bank End). This is due to the fact, that the southern boundary condition is different in both models (see section 2.3.1). The southern boundary of the MODFLOW model is only a notional boundary in the original model. The numerical southern boundary of the original model is the southern boundary of the full Notts-Doncaster model. If the flows across this notional southern boundary could be obtained in terms of amount and location, hydrographs of both models should be the same. However, only the total amount of the flow across the southern boundary was available to BGS, so the location of the flows along the southern boundary had to be approximated.
- Slight differences between hydrographs are due to the different discretization used in both models. This results in some hydrographs representing the time variant head in a grid cell whose location is not identical to the area used in the original model to illustrate the same observation borehole (Table 2).
- The fact that the same transmissivities in both models are assigned to areas 500 m apart, due to different assignments of parameters in mesh-centred compared to grid-centred codes (see section 2.2.1), might influence hydrographs of boreholes which are situated at the border of two transmissivity zones.
- Some observation boreholes are close to abstraction points. As the abstraction input values are not identical in both models (see section 2.3.4) this leads to differences in hydrographs in some cases (Pighill Thorne, Brier Home Carr).

4 Conclusions and recommendations

A MODFLOW model has been built on the basis of the Doncaster model developed by Brown and Rushton (1993) and Shepley (2000). It has been developed to be used within the AISUWRS project. A translation into the MODFLOW code was necessary, in order to facilitate both solute transport modelling and groundwater flow simulations and to allow flexibility in changing input parameters in order to carry out scenario modelling. This regional MODFLOW model is a step, which the project team will use as the basis for a future sub regional model focused on the Doncaster suburb of Bessacarr.

A comparison of model results from the original model and the MODFLOW model led to the following observations:

- The overall agreement between the MODFLOW model and the original model is good, both for hydrographs of observation boreholes and for the water balance of the models.
- The original model domain is discretized using a mesh-centred approach, while the MODFLOW code uses a grid-centred approach. This leads to a model area slightly larger by half a cell width all round compared to the original model domain. Due to the different discretization, observation borehole nodal references used in the original model to produce hydrographs are in some cases not identical to the grid cells used in the MODFLOW model.
- Differences exist in the amount of abstraction from boreholes in both models, as an unavoidable consequence of limited data being made available.
- Differences exist in the numerical representation of the southern boundary of the model area. The southern boundary of the MODFLOW model is only a notional boundary in the original model. The southern boundary of the original model is the southern boundary of the full Notts-Doncaster model. Flows over the notional southern boundary were not supplied to BGS and had to be inferred using water balance figures of the original model. This permitted the correct assignment of the total flow amount, but the location of the flows along the boundary unavoidably had to be inferred.
- Differences may exist between both models in the thickness of the drift cover, which is used to infer a leakage rate to and from the overlying stratum and the aquifer. Original input was supplied with rounded values, which led to the assignment of zero thickness for some drift cells. The actual drift thicknesses for those cells are unknown and were approximated in the MODFLOW model to 1m.

To resolve some of the differences in both models, the following would be required:

- Update with the original abstraction input data, in order to apply the same borehole abstractions in both models.
- Update with the original, un-rounded model parameter input data, to establish the actual thickness of the drift cover in areas where rounding errors led to the assignment of zero values in the data set provided to BGS.
- Obtain data to model flows across the southern boundary more accurately. Either the flows over the southern boundary would be required or data of the Notts-Doncaster

model are needed to establish the flows over the notional southern boundary by running the full Notts-Doncaster model.

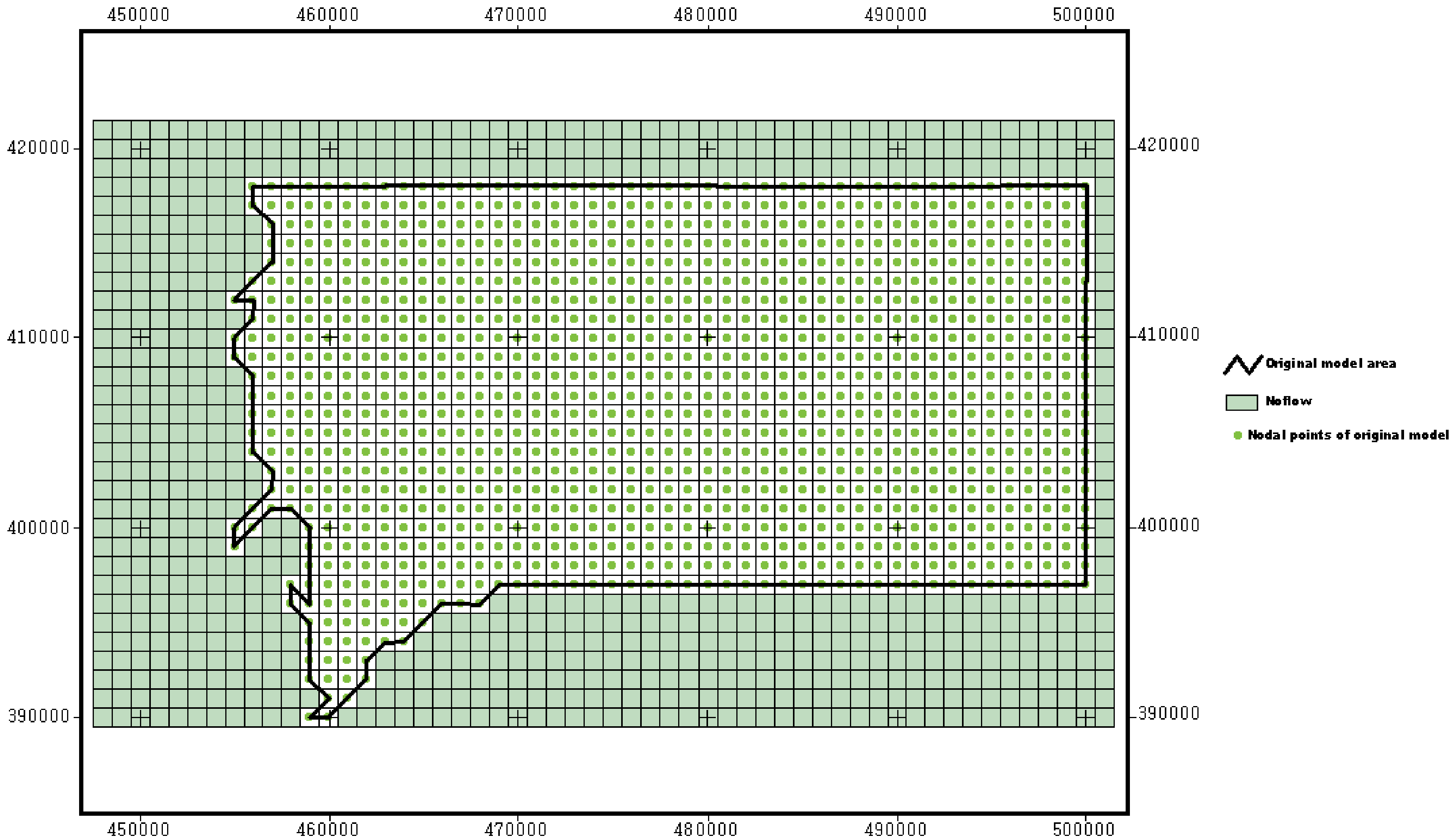

Figure 4 The block-centred grid of the MODFLOW model, overlain by the nodal based original model

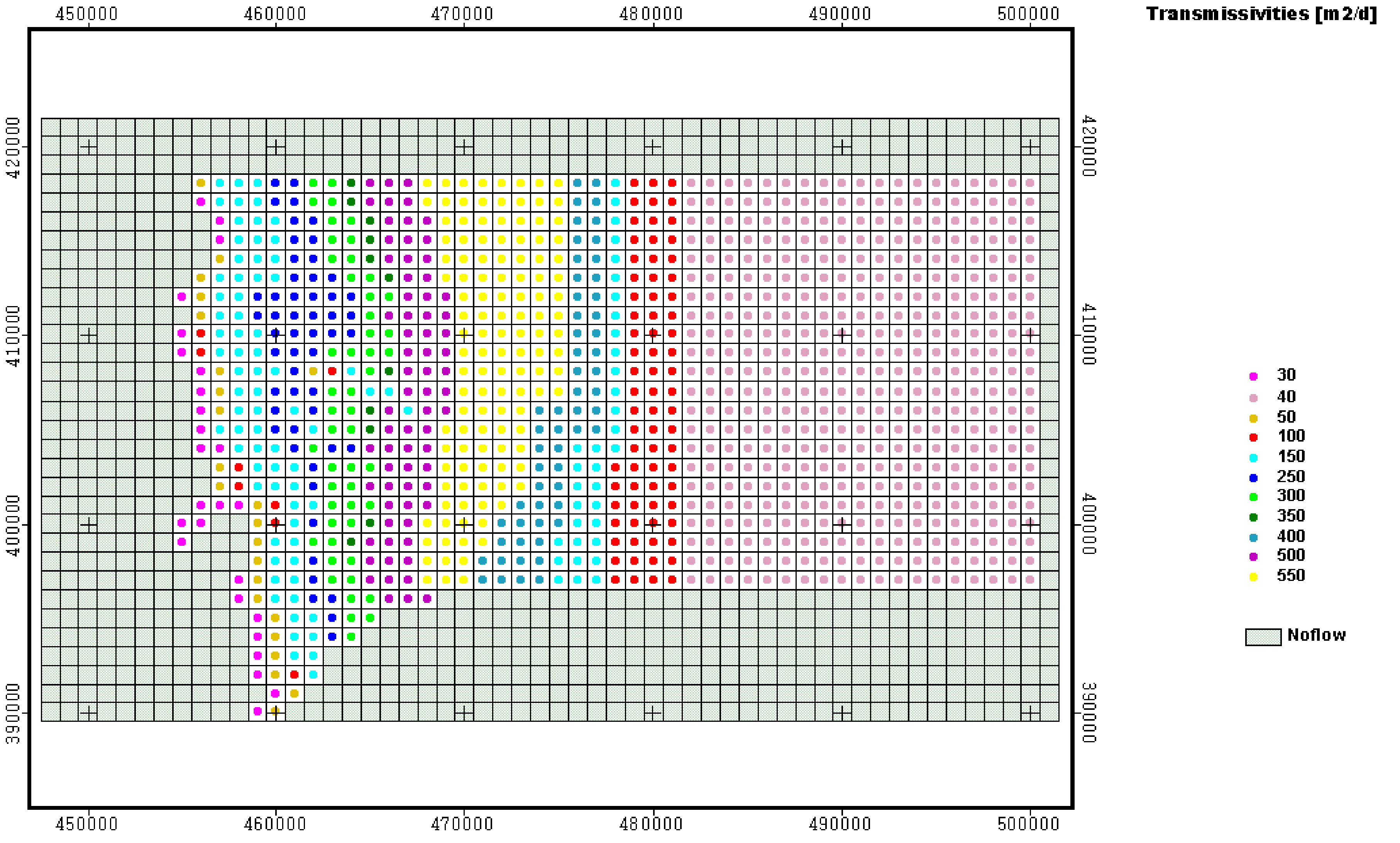

Figure 5 Distribution of transmissivities within the MODFLOW model

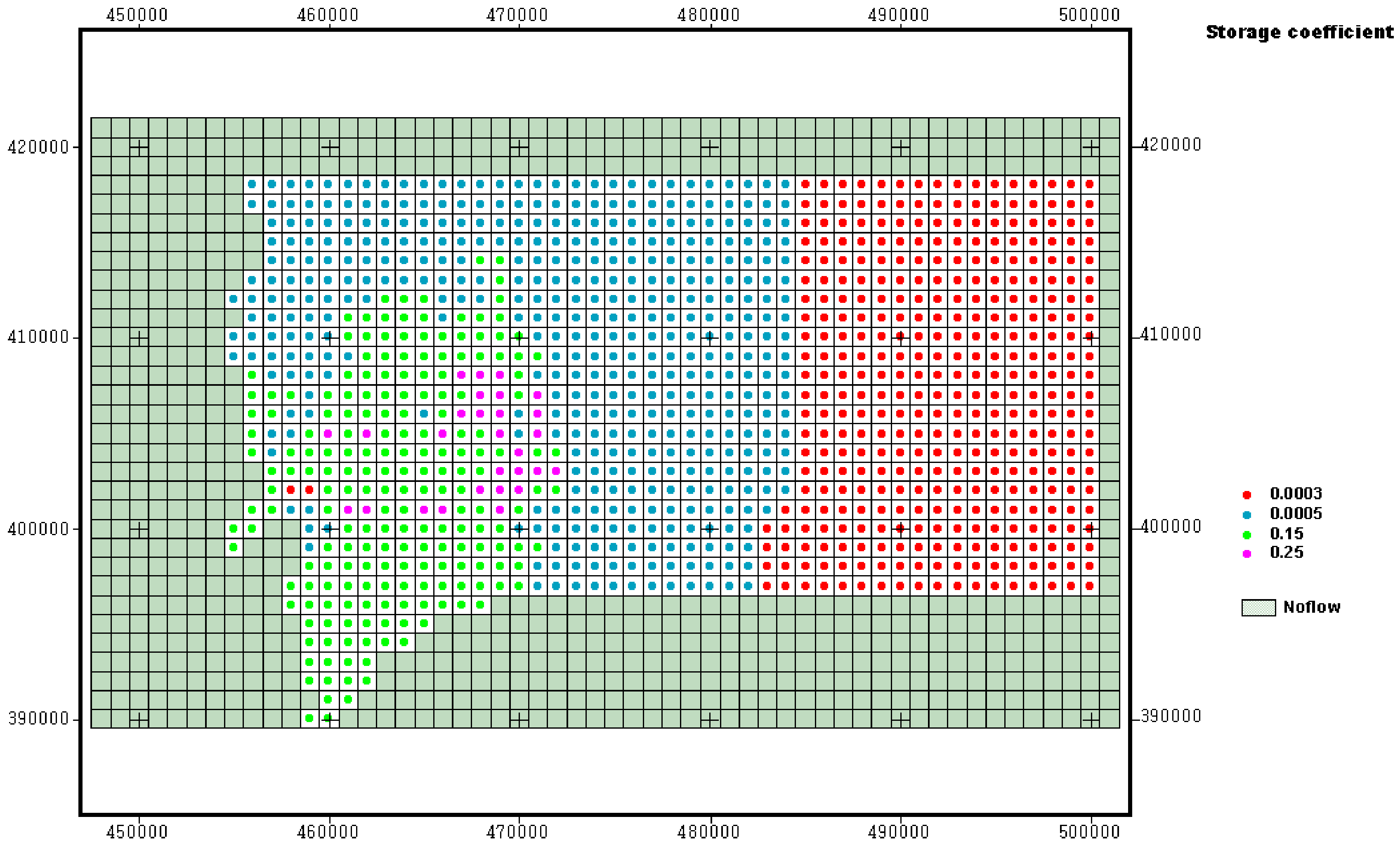

Figure 6 Distribution of storage coefficients within the MODFLOW model

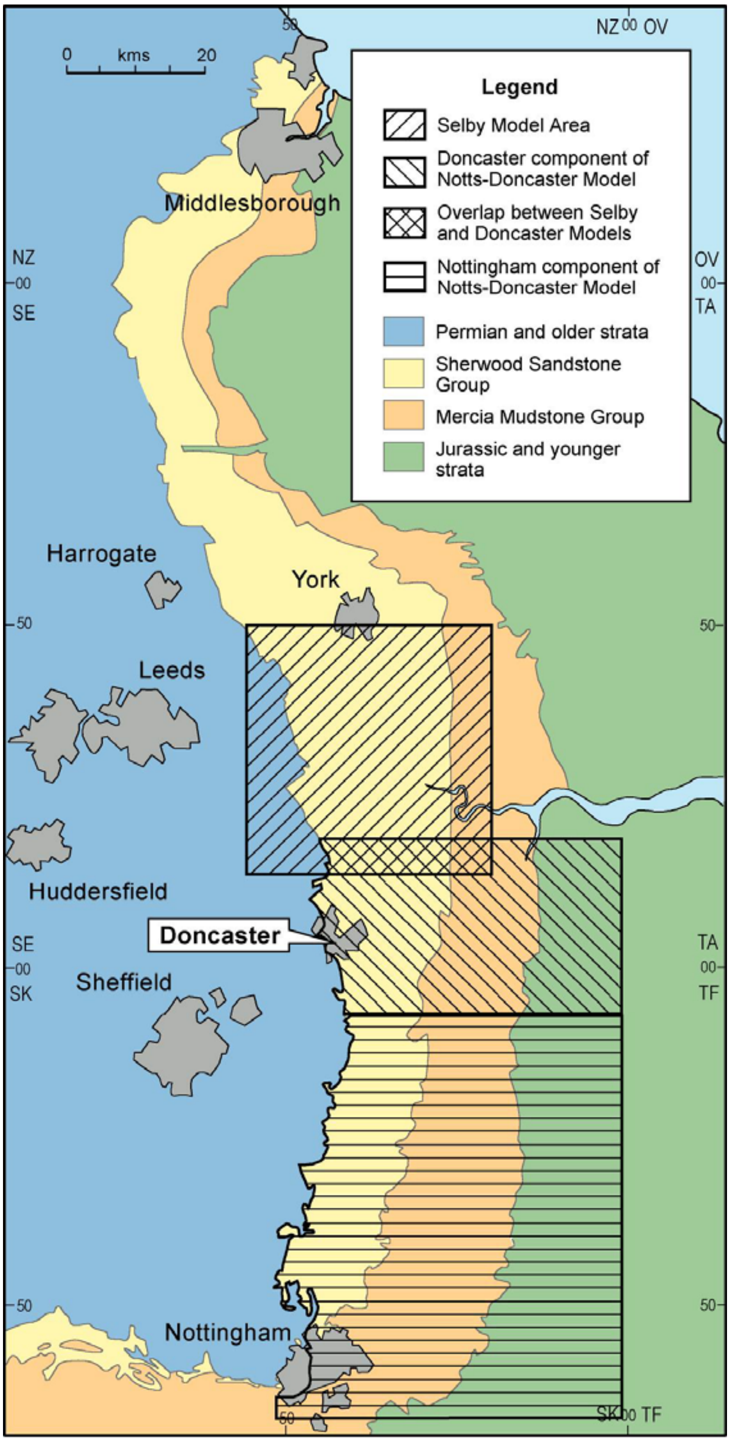

Figure 7 Extent of the Notts-Doncaster model

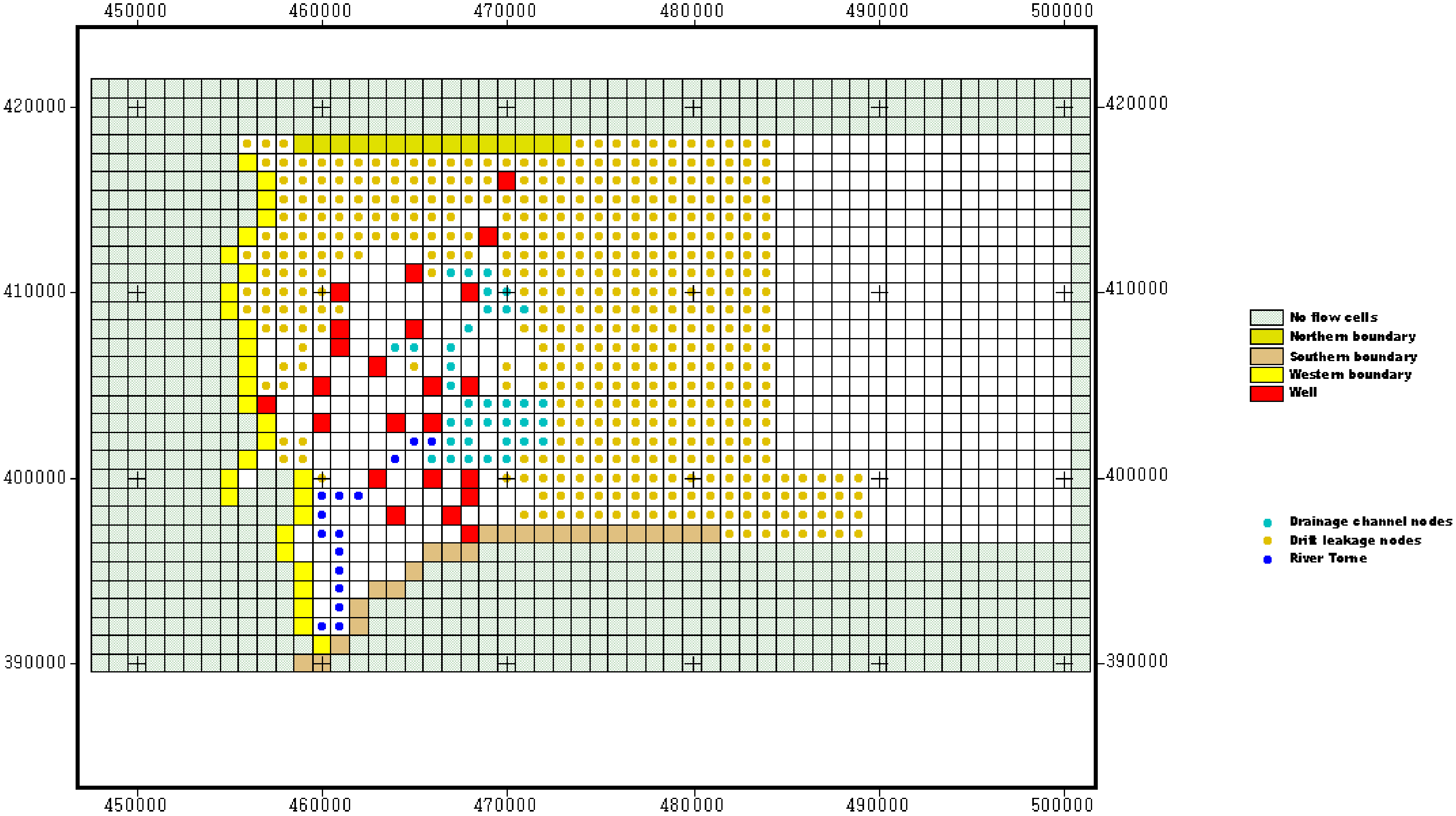

Figure 8 Boundary conditions of the MODFLOW model.

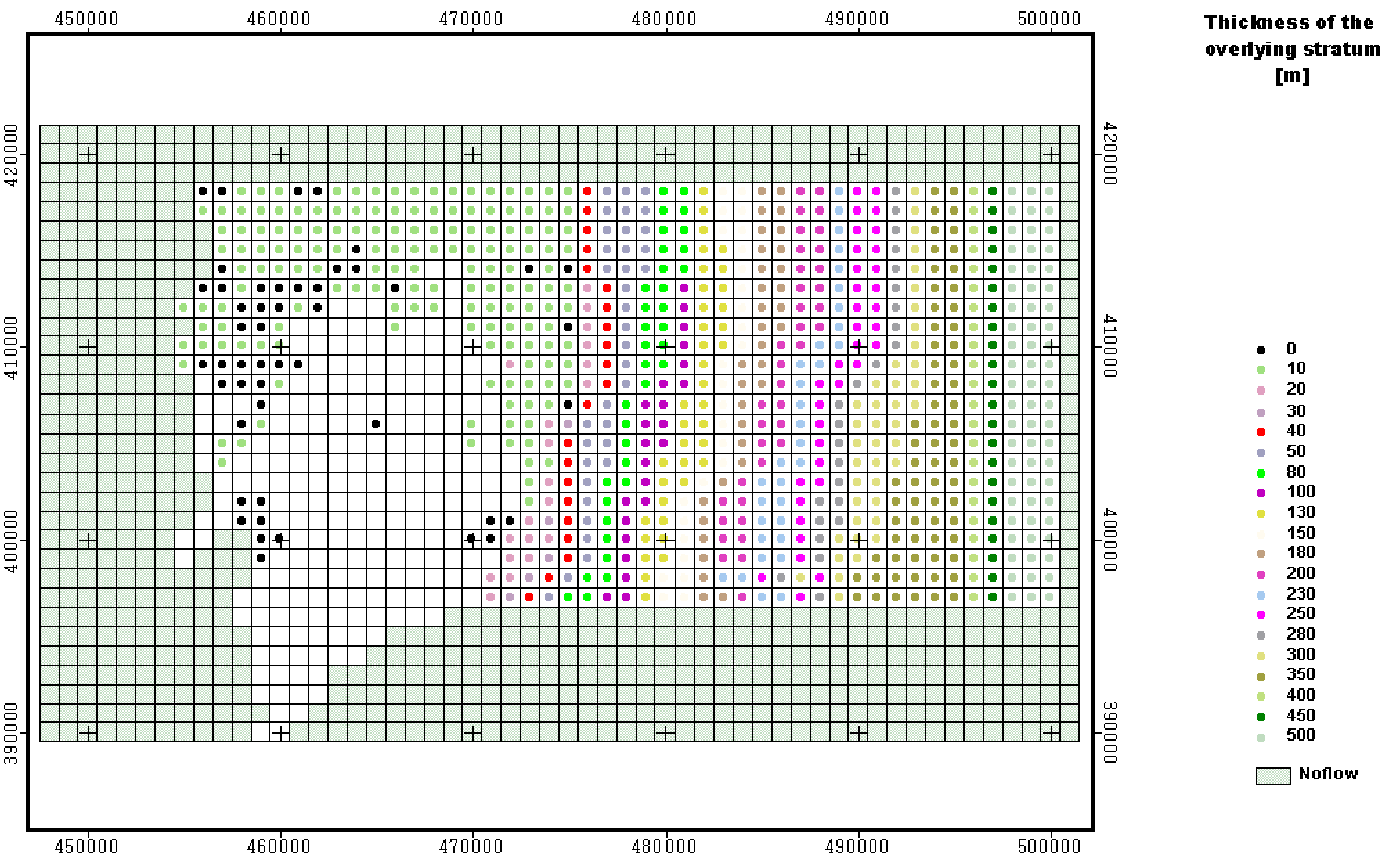

Figure 9 Distribution of the thickness of the overlying stratum (drift deposits and Mercia Mudstone) in the original model.

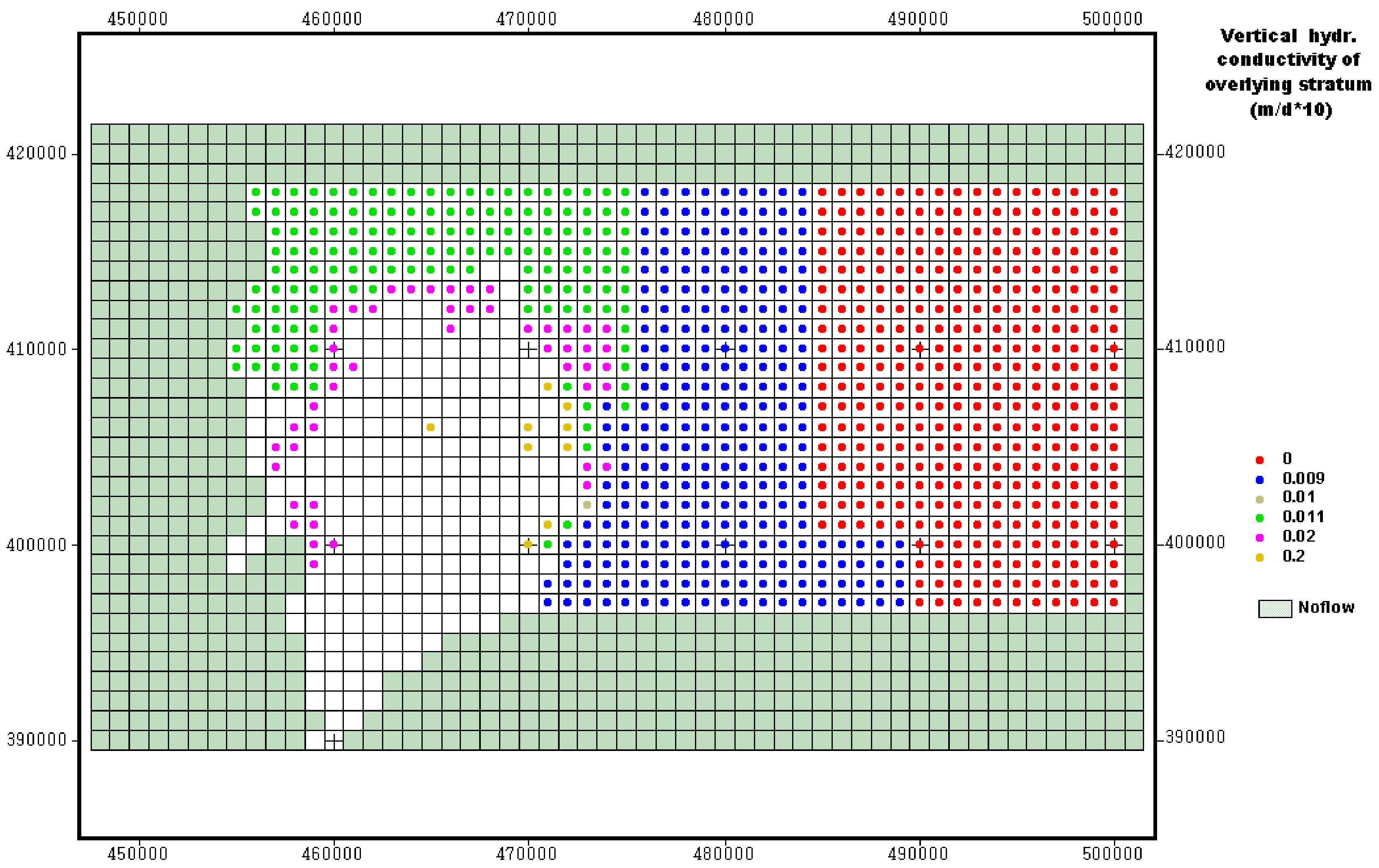

Figure 10 Distribution of vertical hydraulic conductivities in the overlying stratum in the MODFLOW model

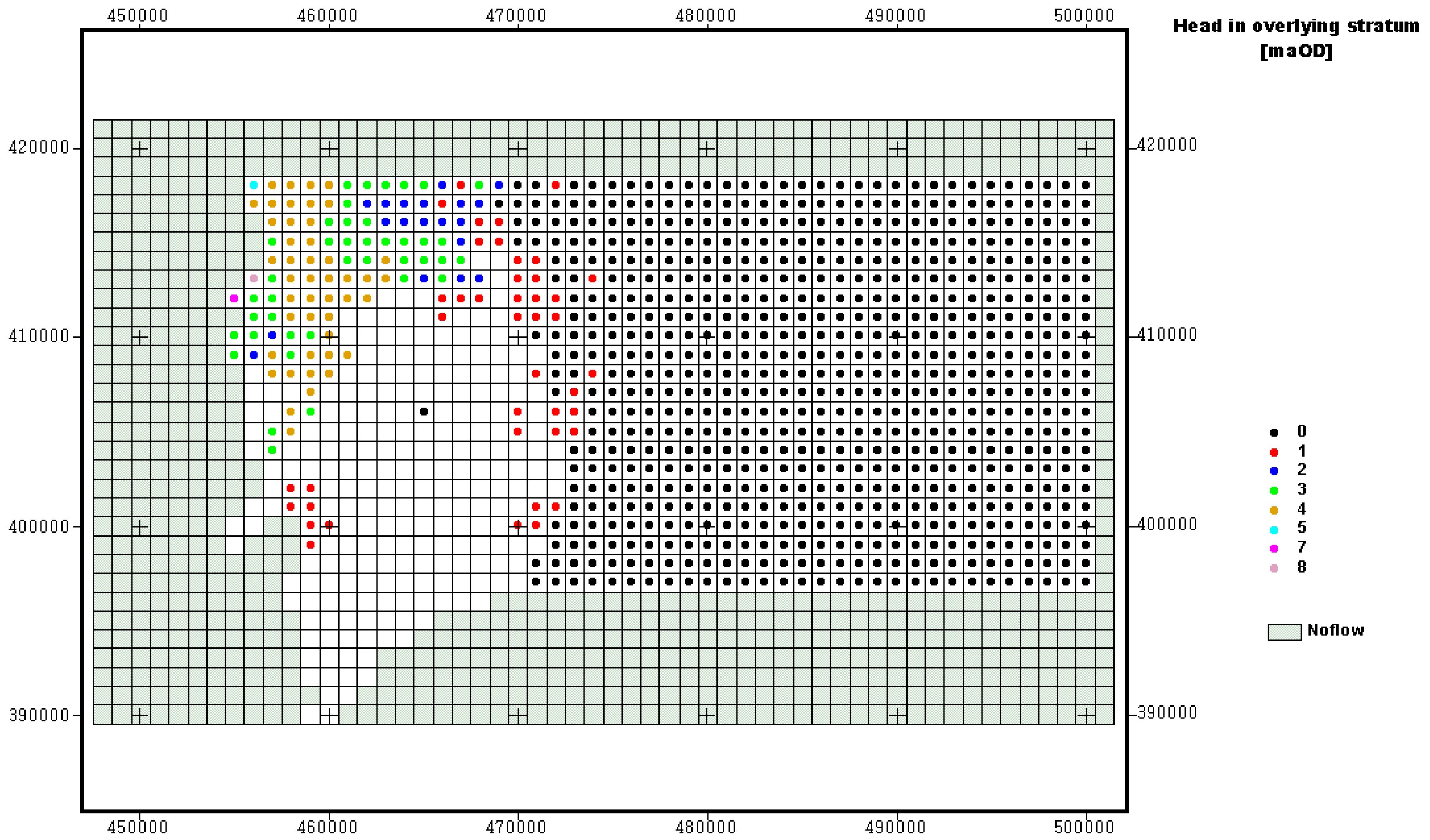

Figure 11 Distribution of hydraulic head in the drift deposits in the MODFLOW model

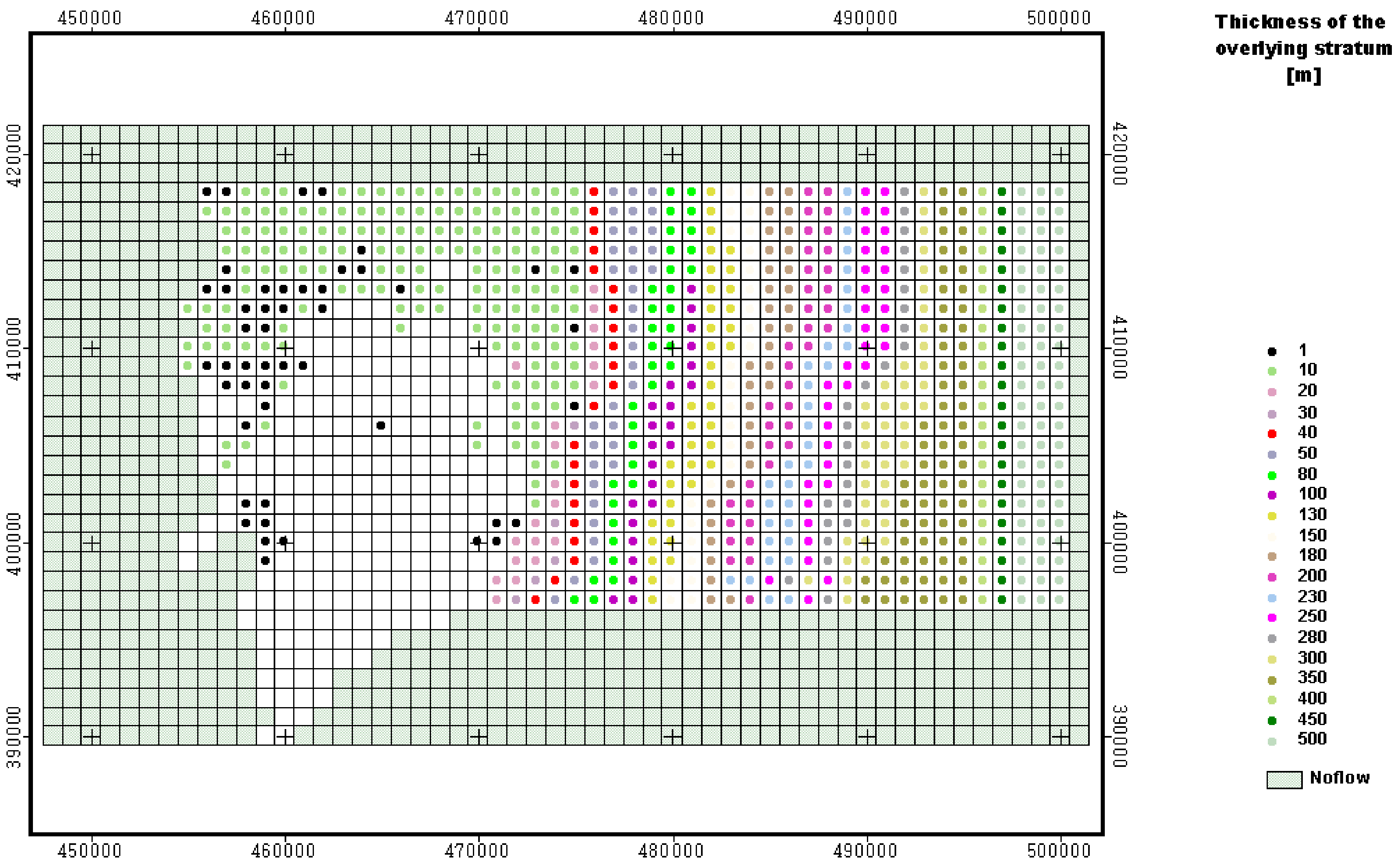

Figure 12 Distribution of thickness of overlying stratum (drift deposits and Mercia Mudstone) in the MODFLOW model

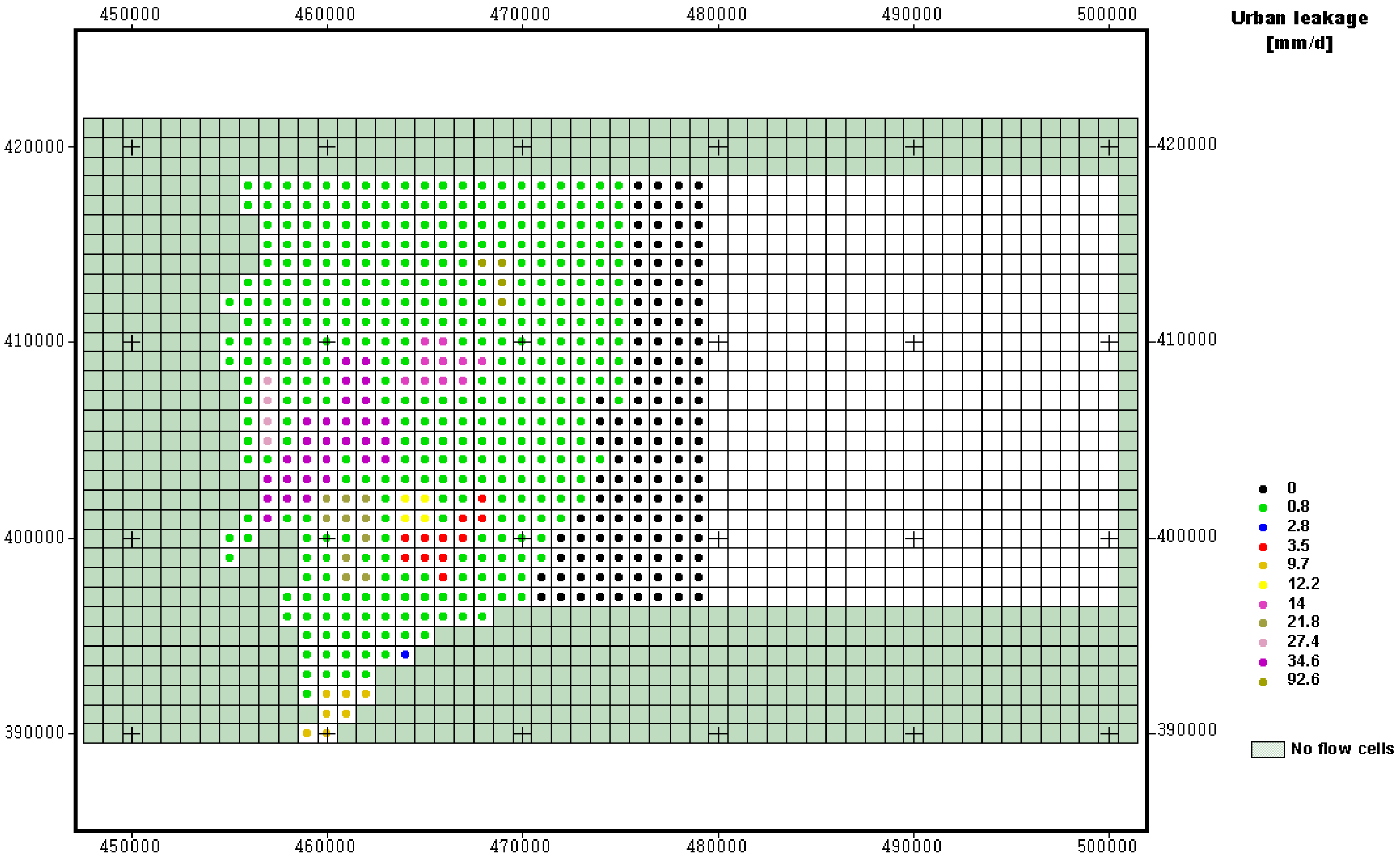

Figure 13 Distribution of urban leakage in the MODFLOW model

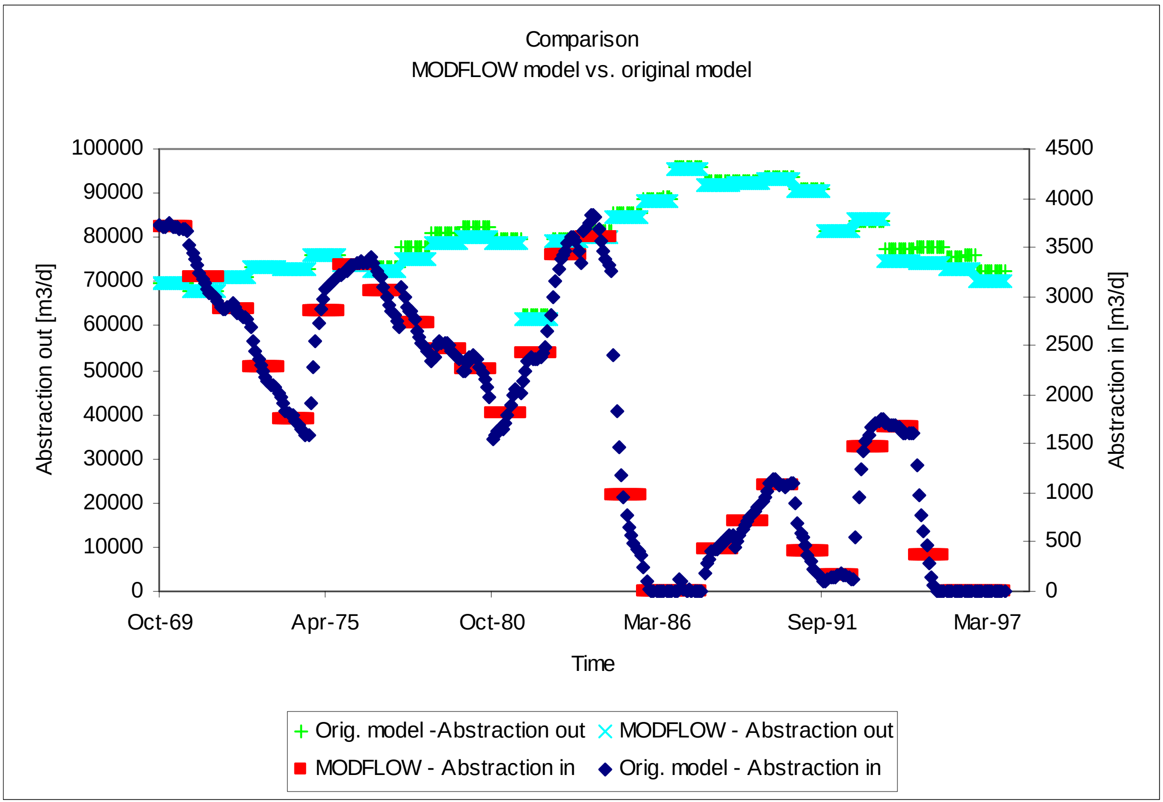

Figure 14 Comparison of abstraction volumes in the MODFLOW and original model

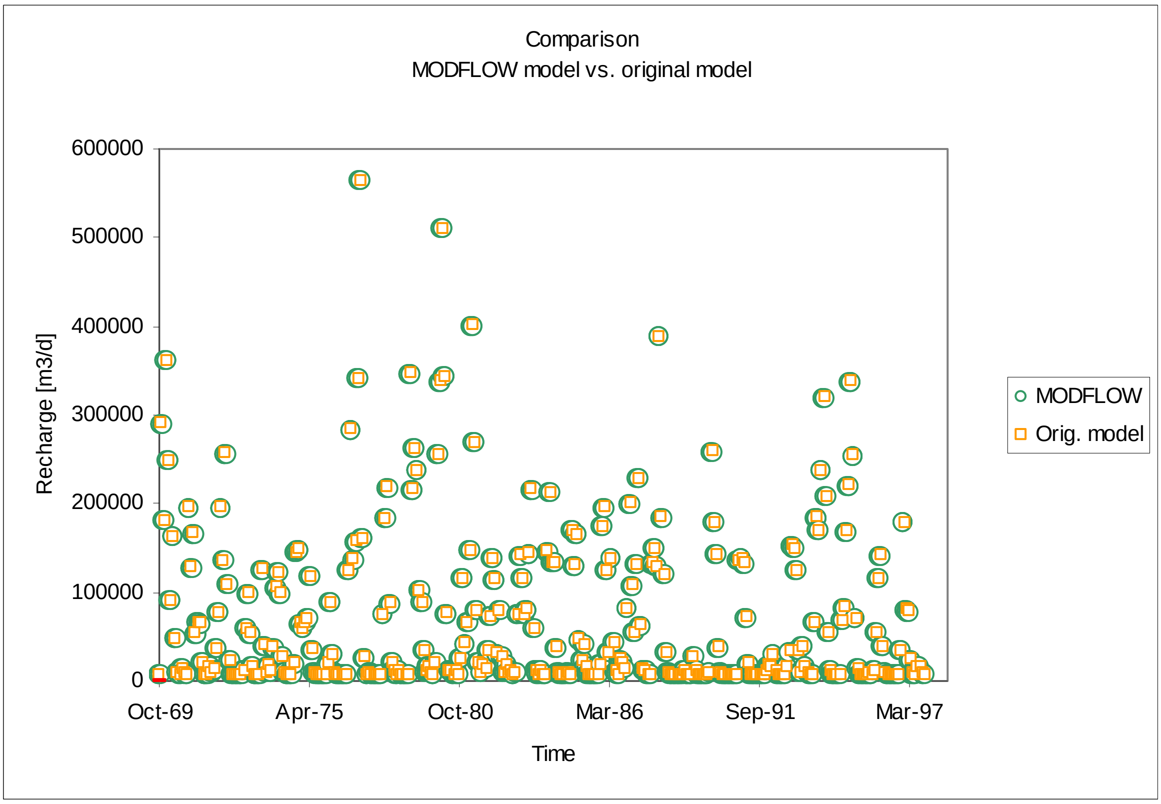

Figure 15 Comparison of recharge volumes in the MODFLOW and original model

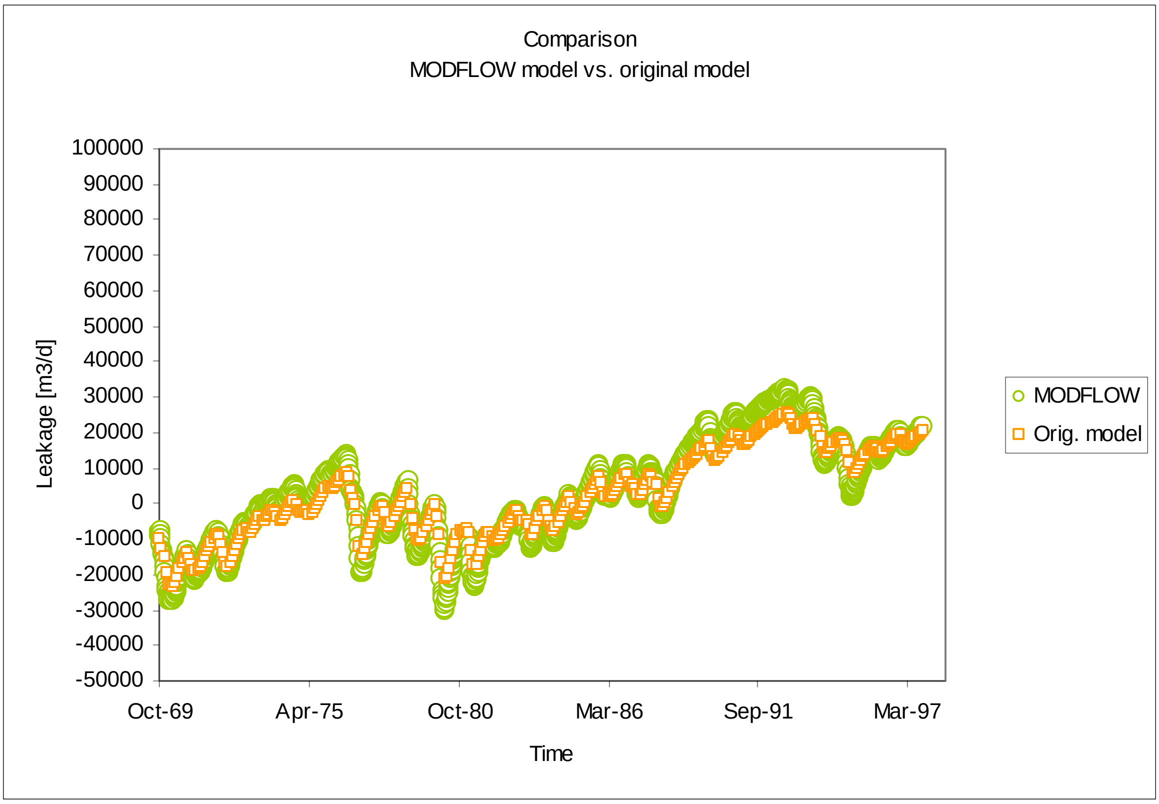

Figure 16 Comparison of leakage from/to rivers and overlying stratum in the MODFLOW and original model

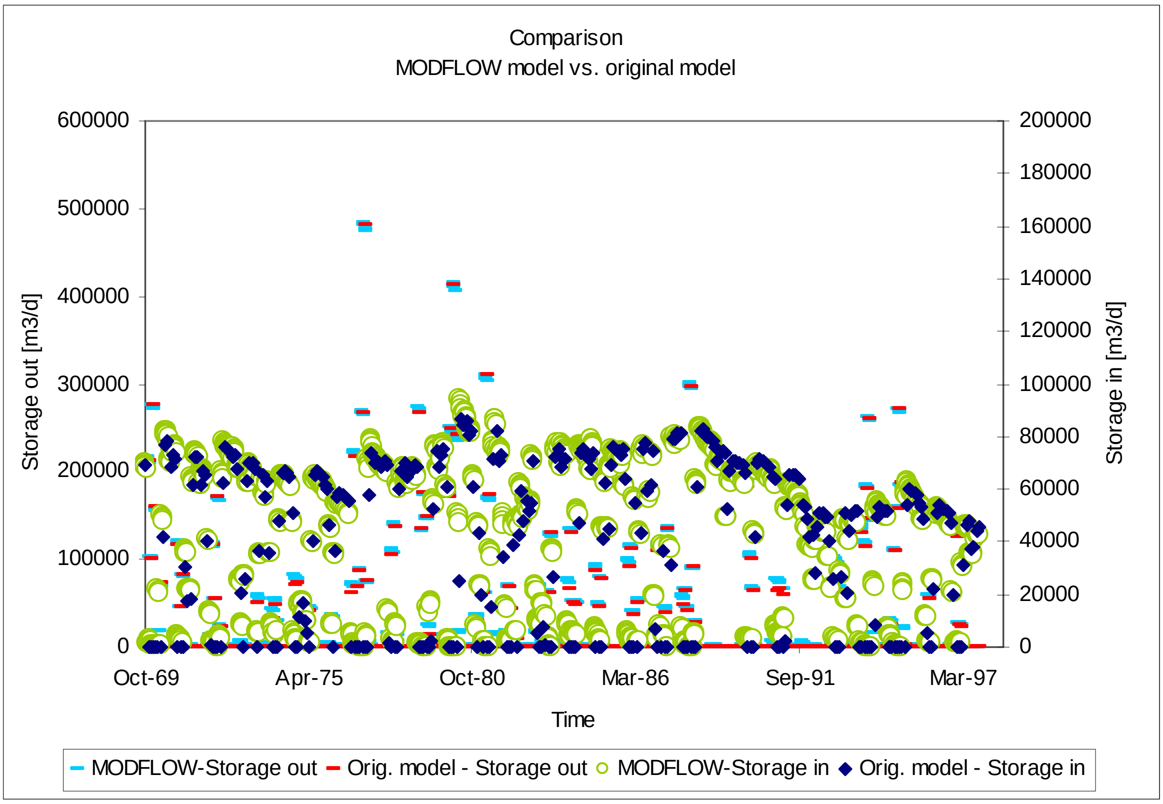

Figure 17 Comparison of change in storage in the MODFLOW and original model

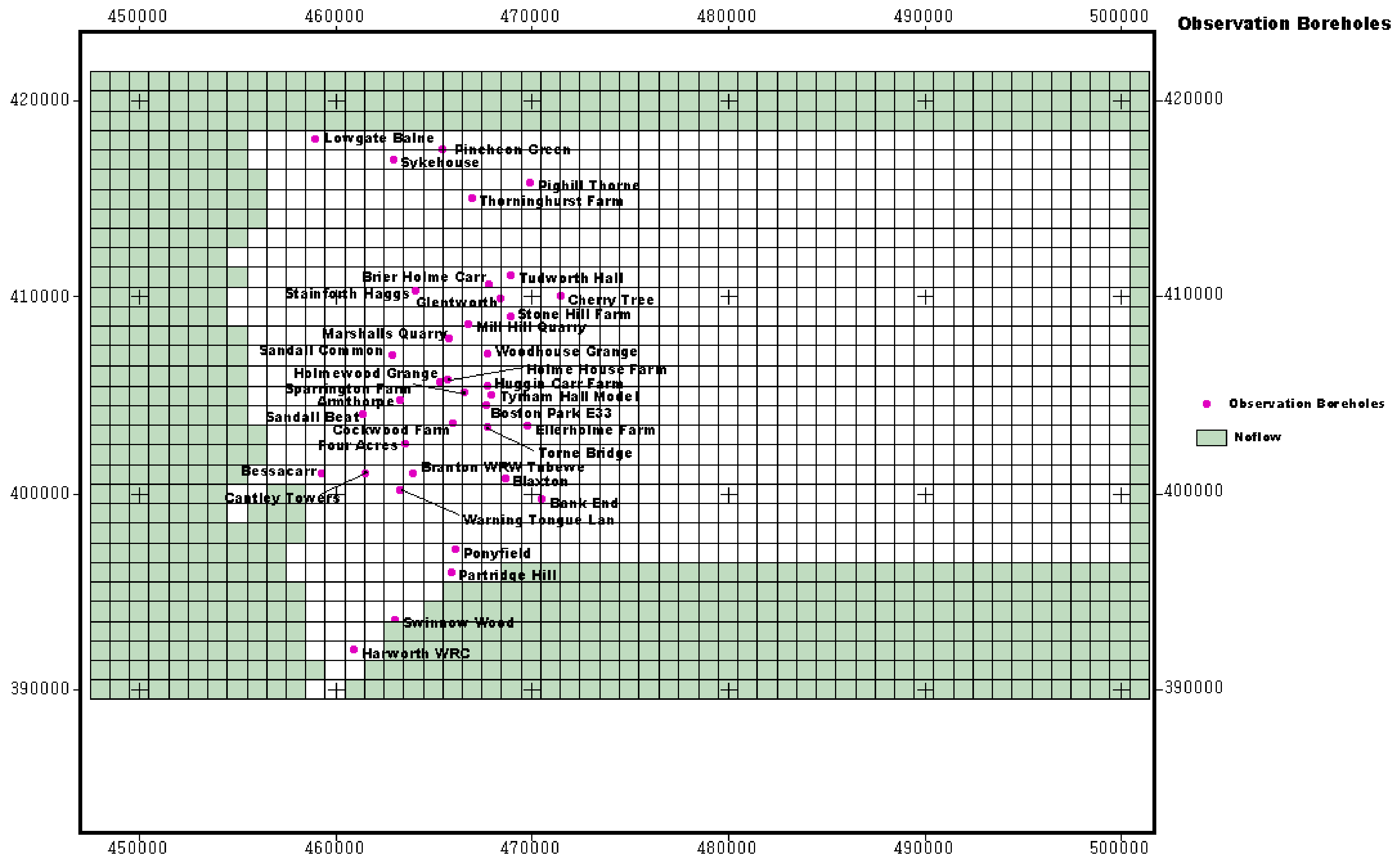

Figure 18 Position of observation boreholes

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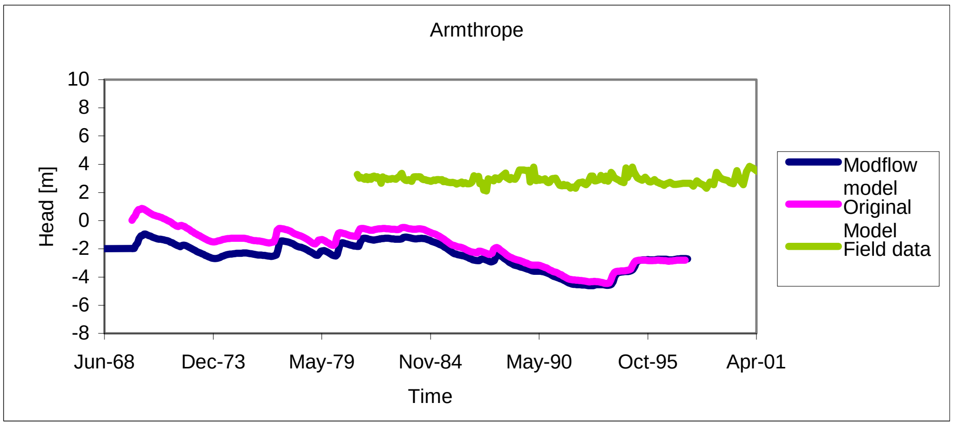
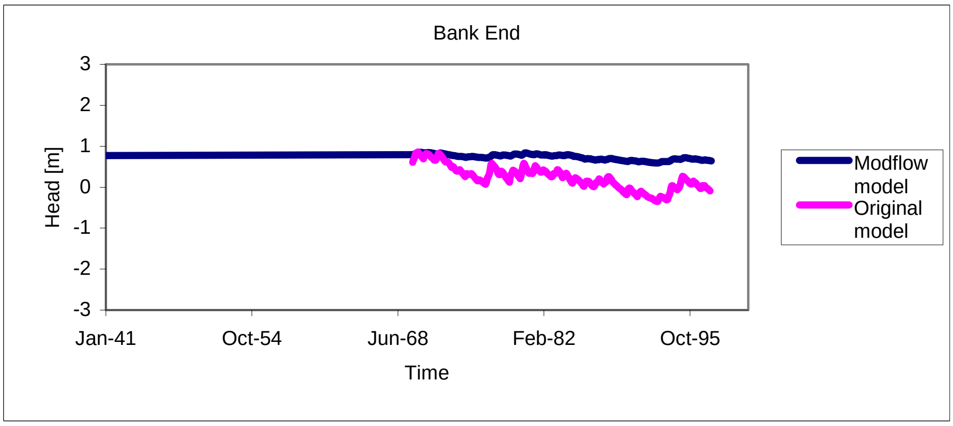
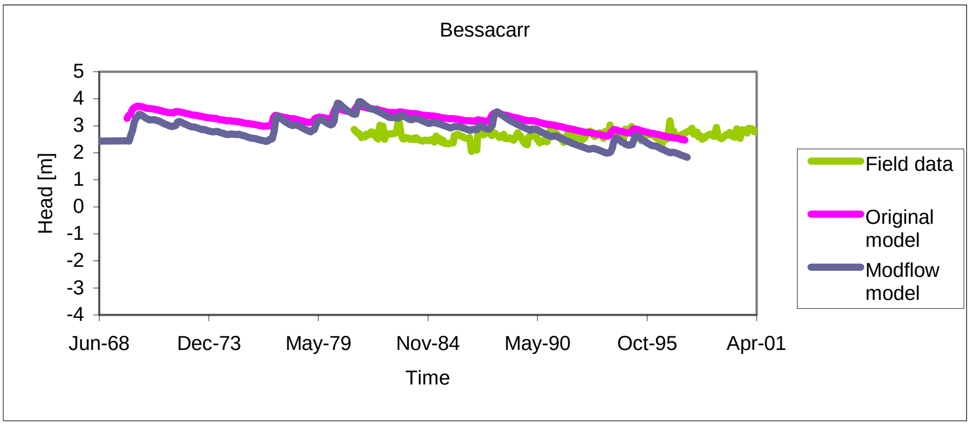
MORRIS, B.L., STUART, M.E. AND CRONIN, A.A. 2003. Assessing and Improving Sustainability of Urban Water Resources and Systems. AISUWRS Work package 1. Background study. *British Geological Survey Commissioned Report*, CR/03/052C.

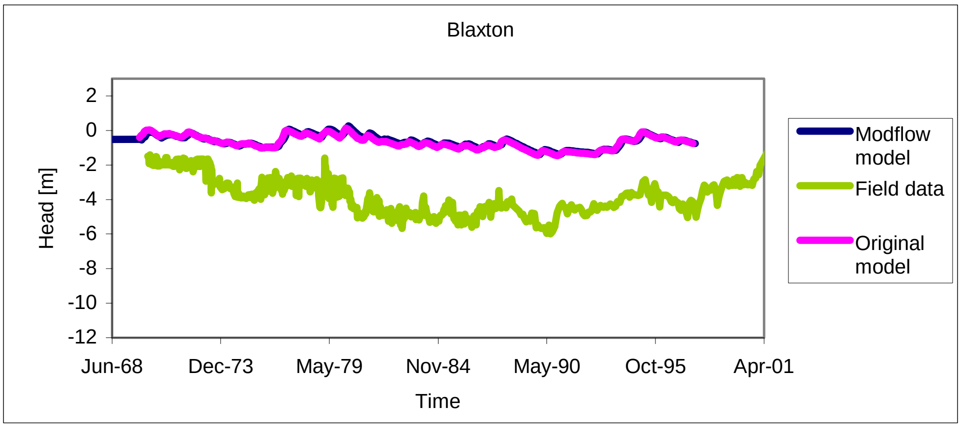
SHEPLEY, M.G. 2000 Notts-Doncaster Sherwood Sandstone Model – 1998 Update. Version 2. Environment Agency, Internal Report

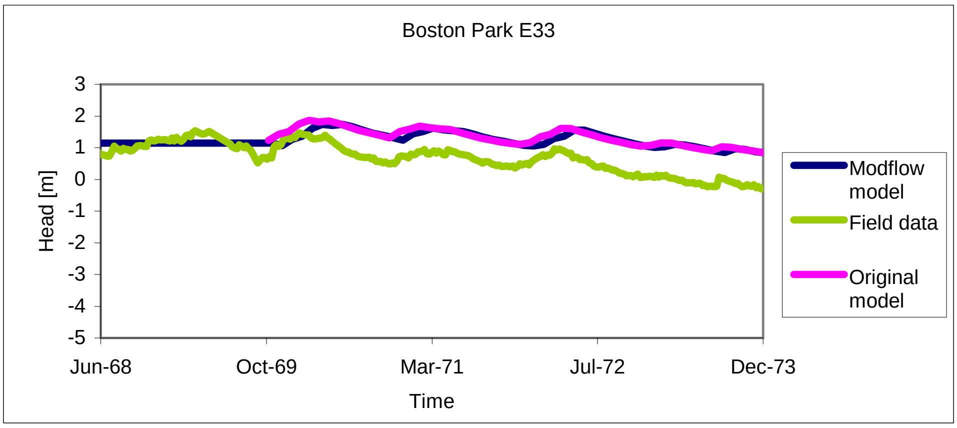
Appendix 1 Comparison of groundwater hydrographs from both models

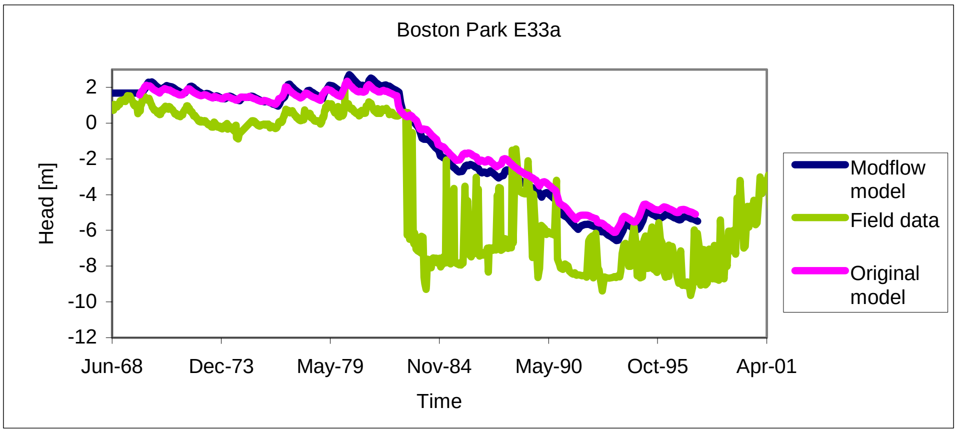

Armthrope
Head [m]
10
8
6
4
2
0
-2
-4
-6
-8
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original Model
Field data

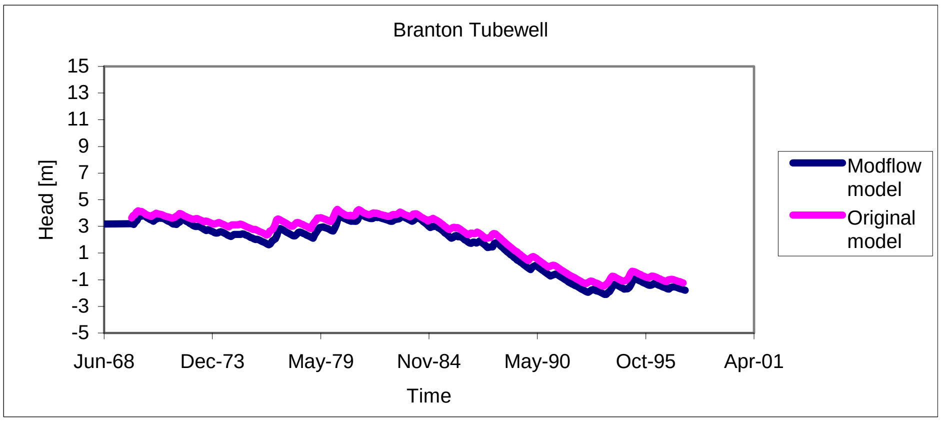

Bank End
Head [m]
3
2
1
0
-1
-2
-3
Jan-41
Oct-54
Jun-68
Feb-82
Oct-95
Time
Modflow model
Original model

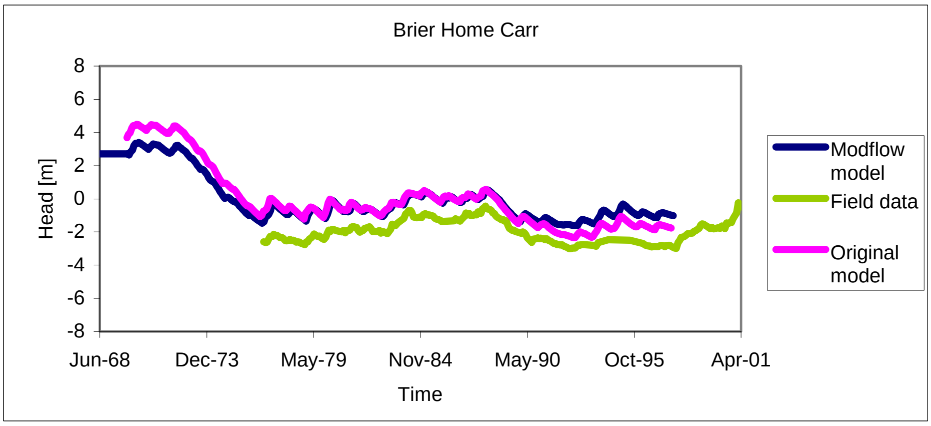

Bessacarr
Head [m]
5
4
3
2
1
0
-1
-2
-3
-4
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Field data
Original model
Modflow model

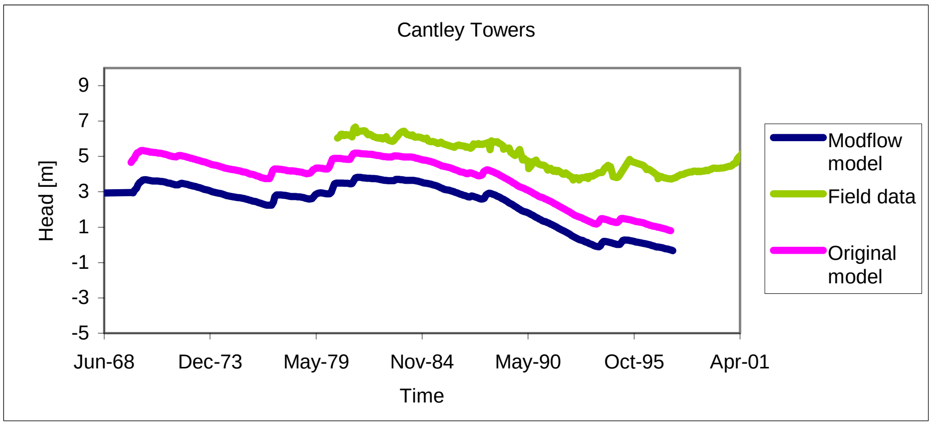

Blaxton
Head [m]
2
0
-2
-4
-6
-8
-10
-12
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

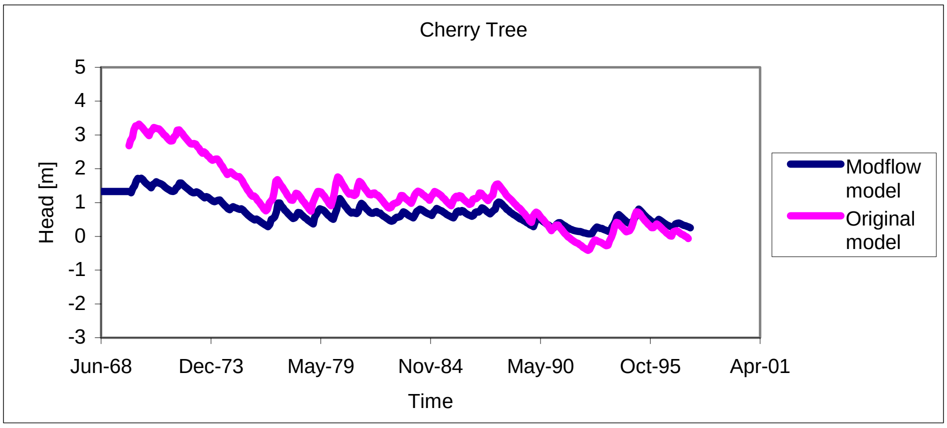

Boston Park E33
Head [m]
3
2
1
0
-1
-2
-3
-4
-5
Jun-68
Oct-69
Mar-71
Jul-72
Dec-73
Time
Modflow model
Field data
Original model

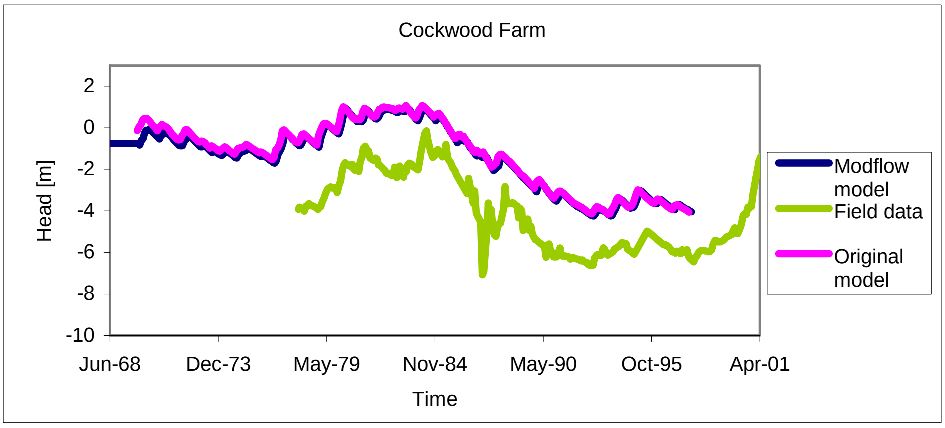

Boston Park E33a
Head [m]
2
0
-2
-4
-6
-8
-10
-12
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

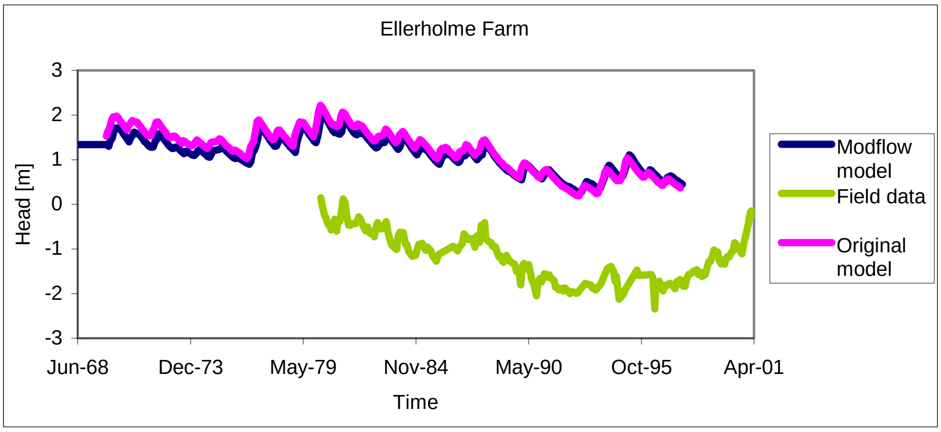

Branton Tubewell
15
13
11
9
7
5
3
1
-1
-3
-5
Head [m]
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

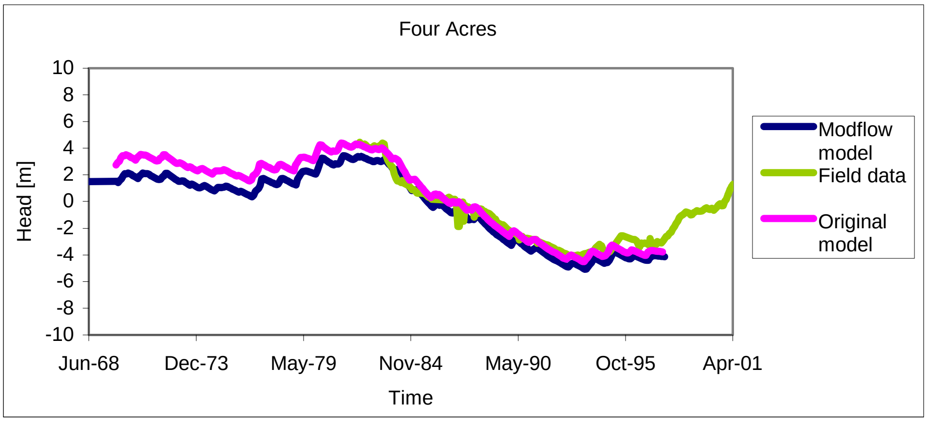

Brier Home Carr
8
6
4
2
0
-2
-4
-6
-8
Head [m]
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model


Cantley Towers
9
7
5
3
1
-1
-3
-5
Head [m]
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

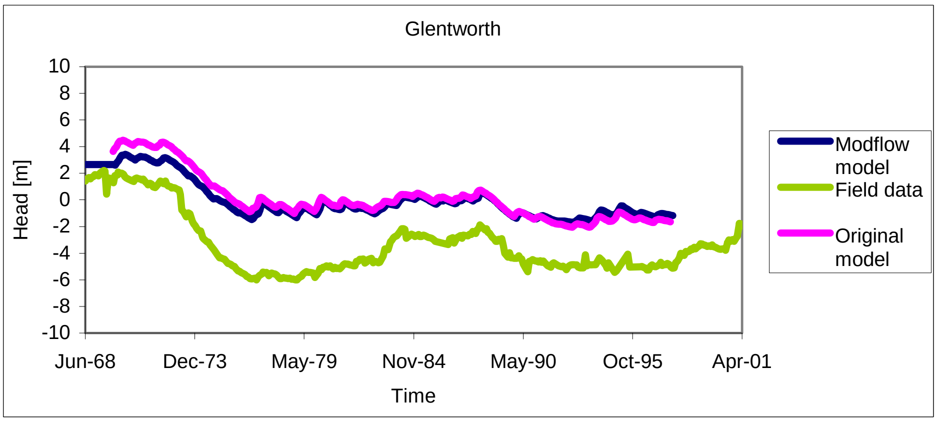

Cherry Tree
5
4
3
2
1
0
-1
-2
-3
Head [m]
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model


Cockwood Farm
2
0
-2
-4
-6
-8
-10
Head [m]
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

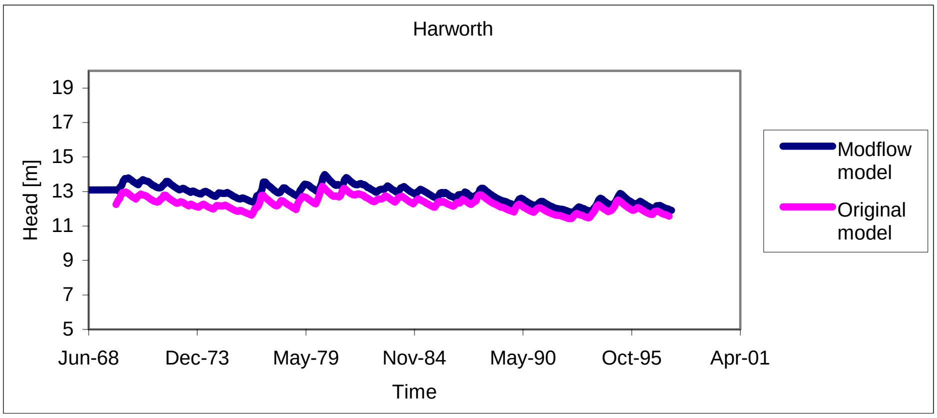

Ellerholme Farm
3
2
1
0
-1
-2
-3
Head [m]
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model



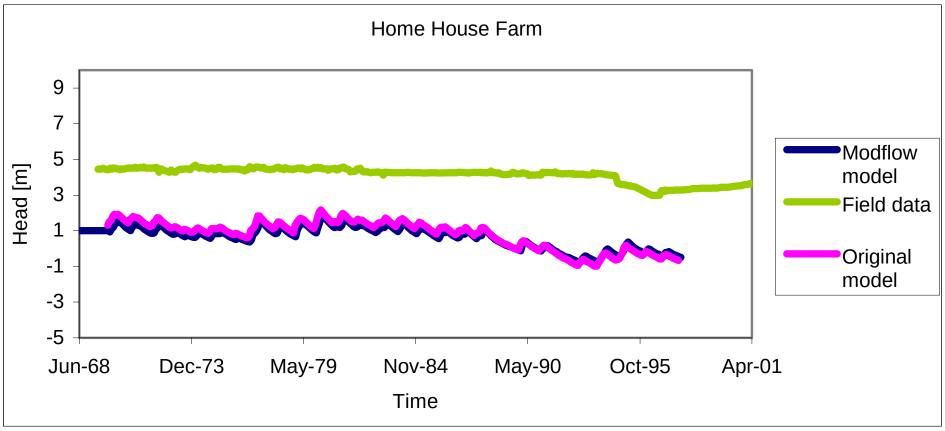
Four Acres
Head [m]
10
8
6
4
2
0
-2
-4
-6
-8
-10
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

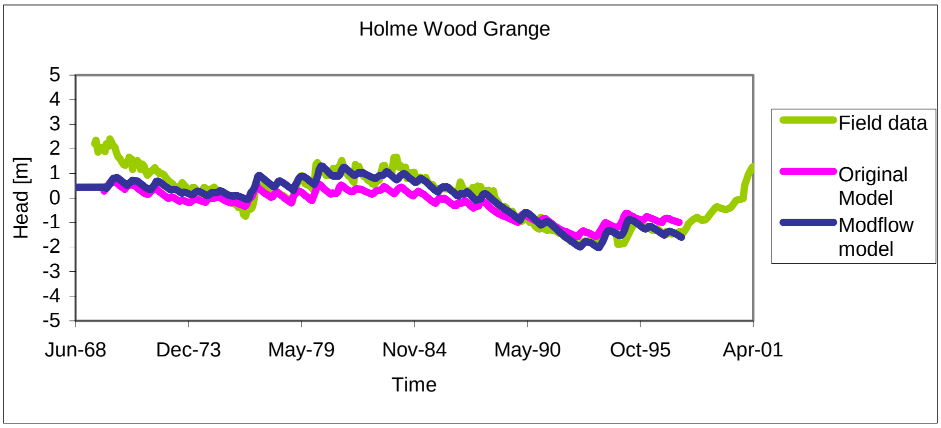


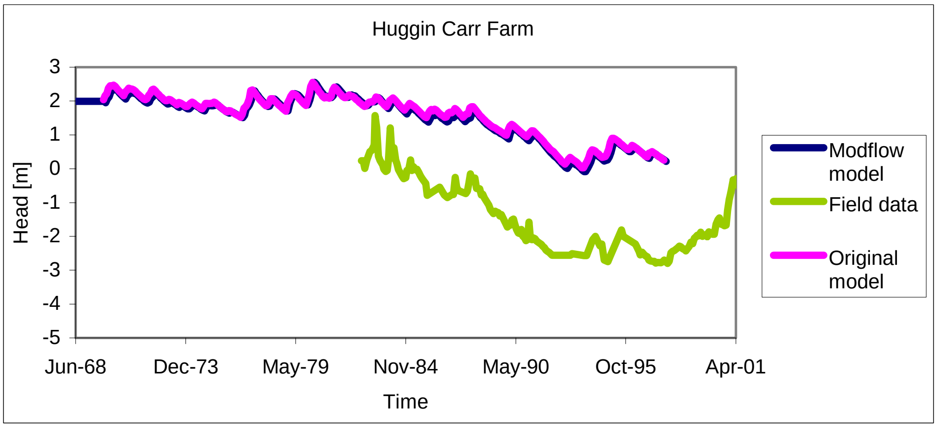
Glentworth
Head [m]
10
8
6
4
2
0
-2
-4
-6
-8
-10
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

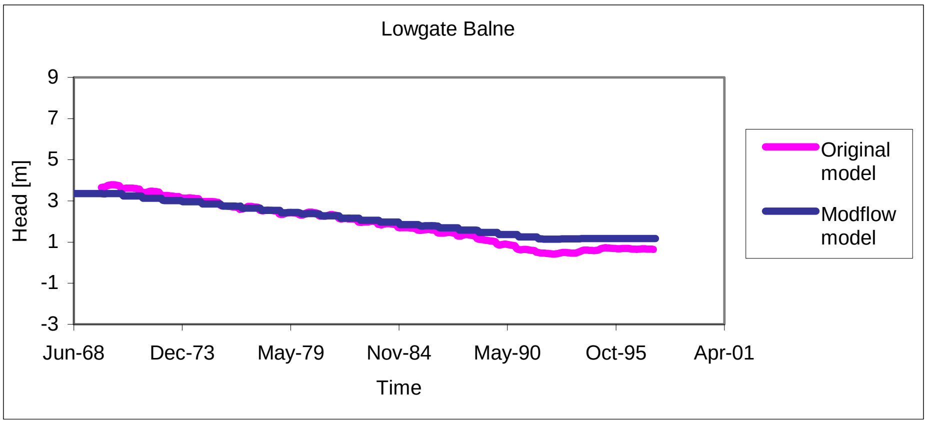


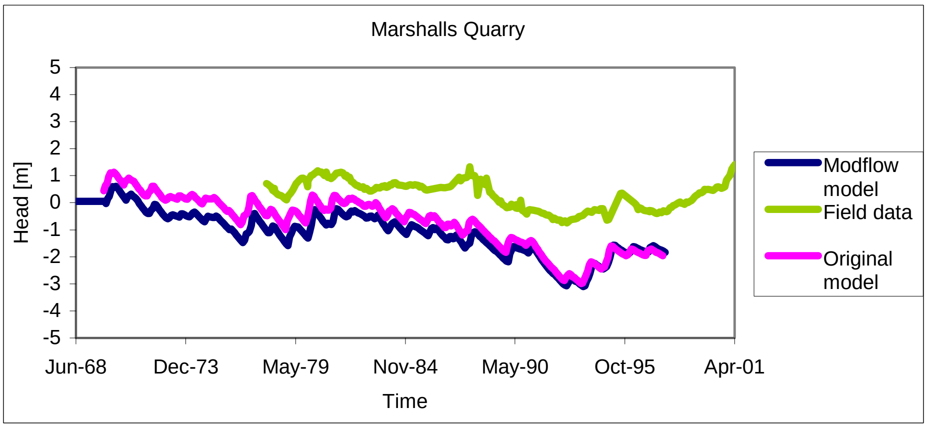
Harworth
Head [m]
19
17
15
13
11
9
7
5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

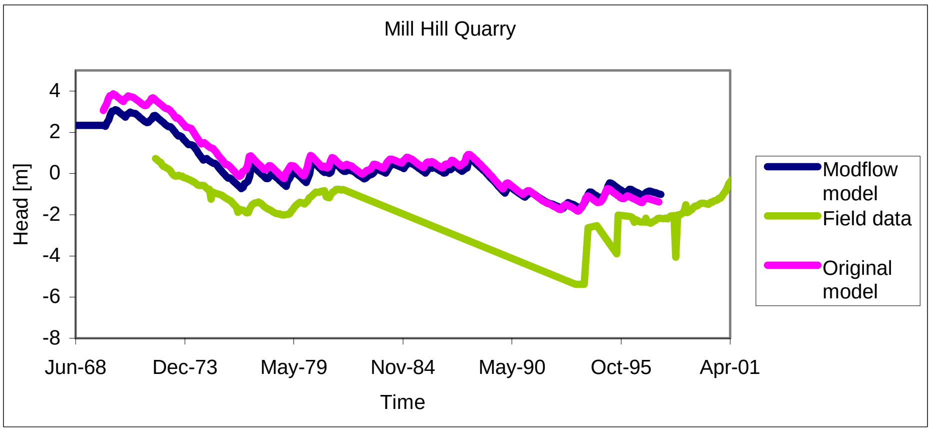

Home House Farm
Head [m]
9
7
5
3
1
-1
-3
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

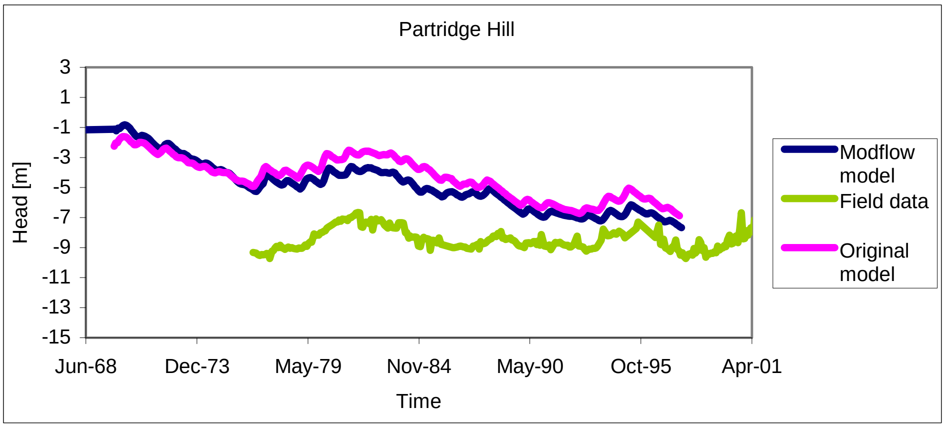

Holme Wood Grange
Head [m]
5
4
3
2
1
0
-1
-2
-3
-4
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Field data
Original Model
Modflow model

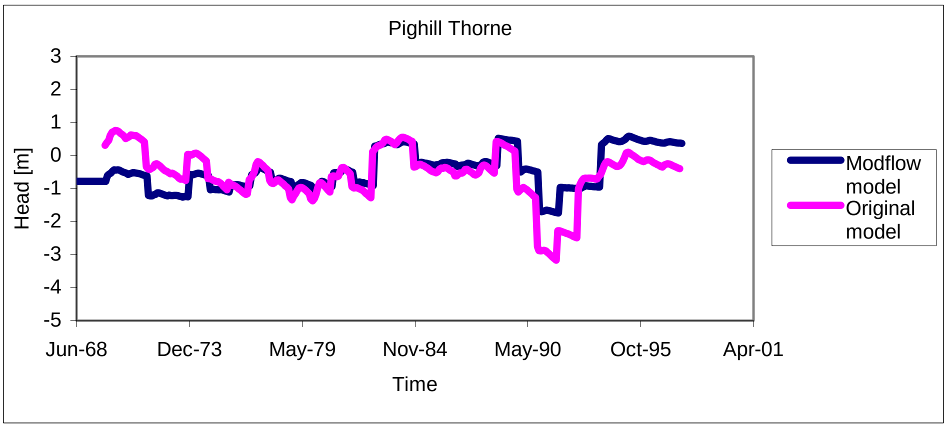

Huggin Carr Farm
Head [m]
3
2
1
0
-1
-2
-3
-4
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

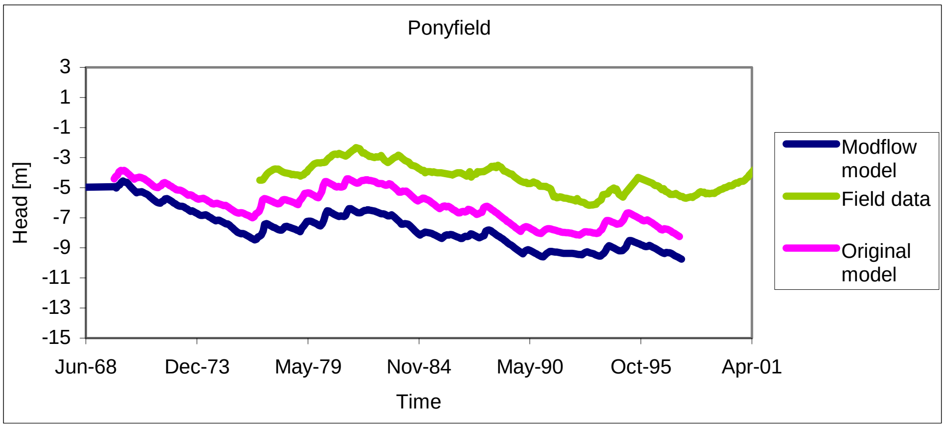

Lowgate Balne
Head [m]
9
7
5
3
1
-1
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Original model
Modflow model

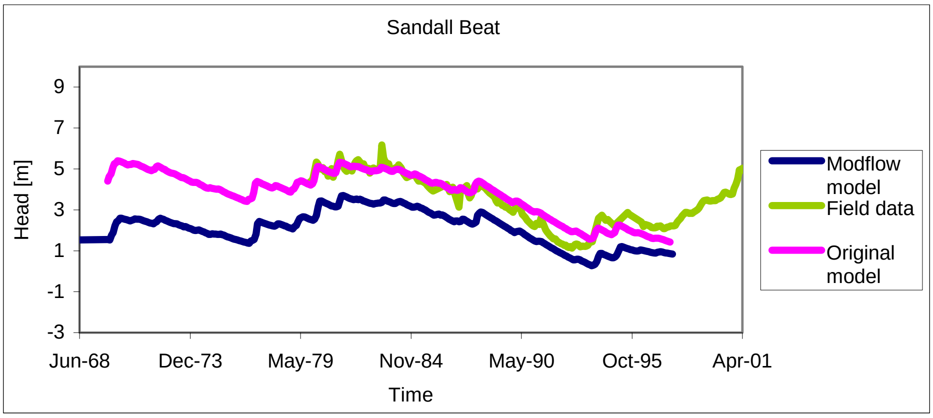

Marshalls Quarry
Head [m]
5
4
3
2
1
0
-1
-2
-3
-4
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

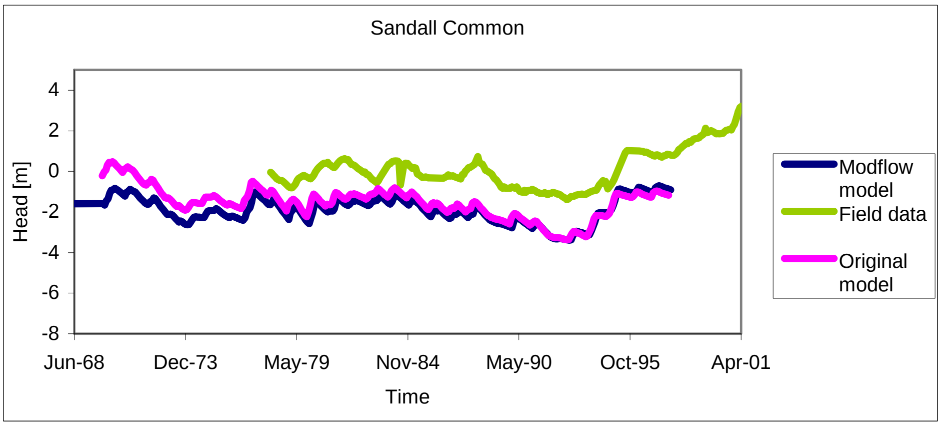

Mill Hill Quarry
Head [m]
4
2
0
-2
-4
-6
-8
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

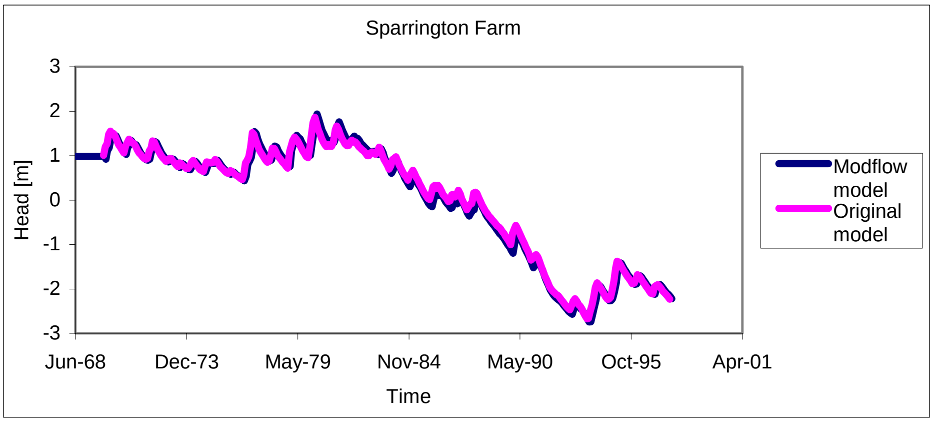

Partridge Hill
Head [m]
3
1
-1
-3
-5
-7
-9
-11
-13
-15
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

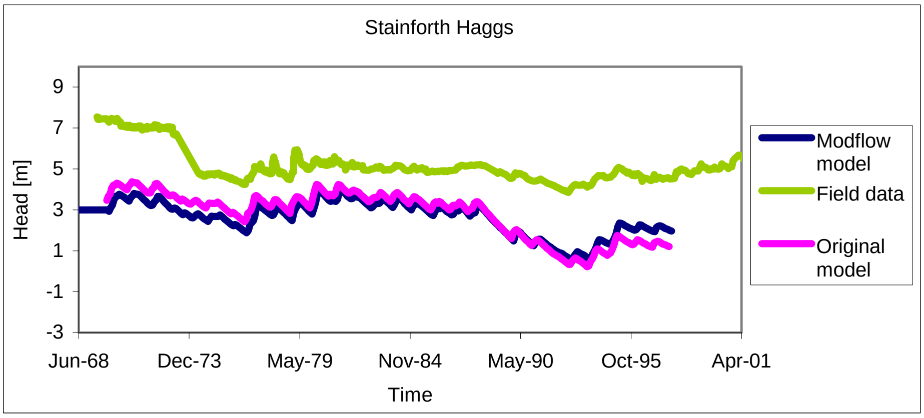

Pighill Thorne
Head [m]
3
2
1
0
-1
-2
-3
-4
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

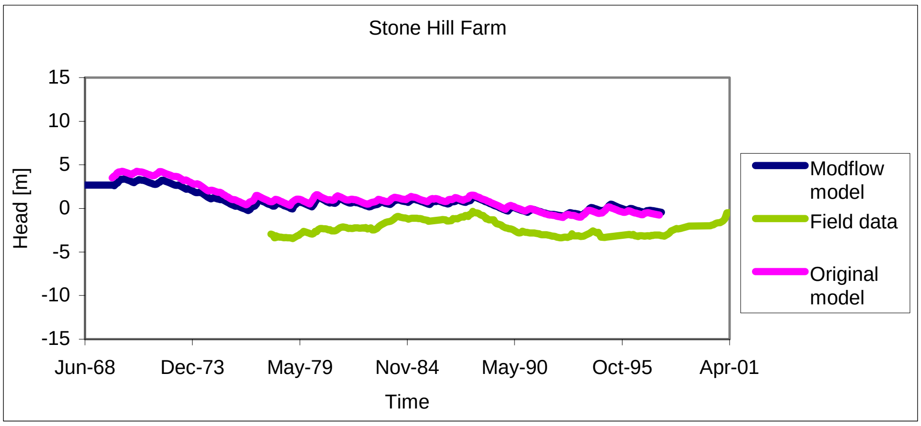

Ponyfield
Head [m]
3
1
-1
-3
-5
-7
-9
-11
-13
-15
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

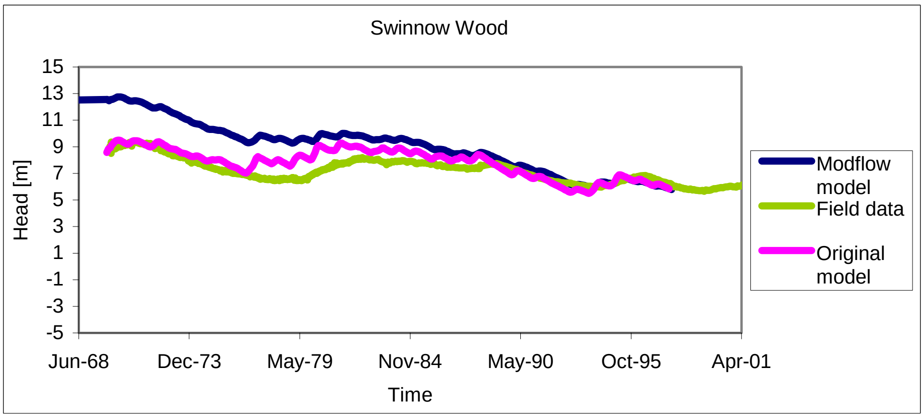

Sandall Beat
Head [m]
9
7
5
3
1
-1
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

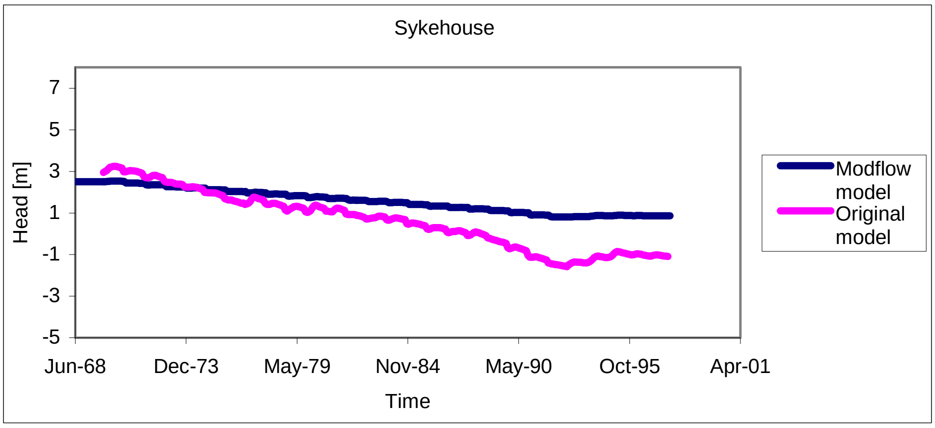

Sandall Common
Head [m]
4
2
0
-2
-4
-6
-8
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

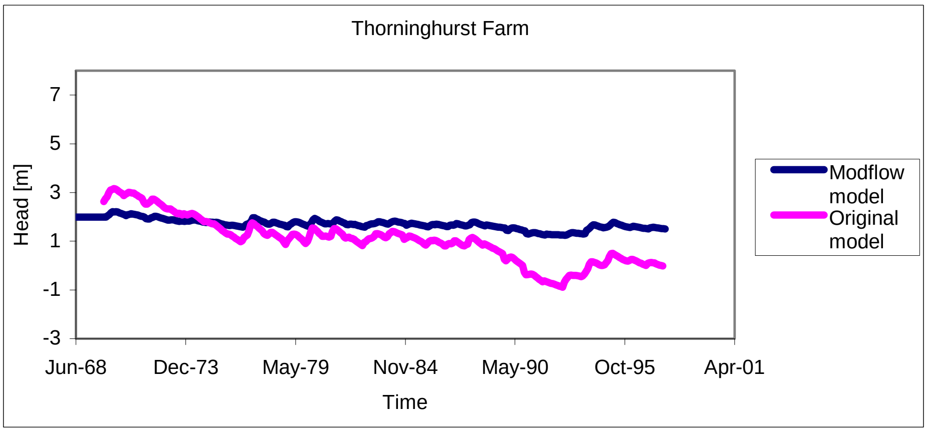

Sparrington Farm
Head [m]
3
2
1
0
-1
-2
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

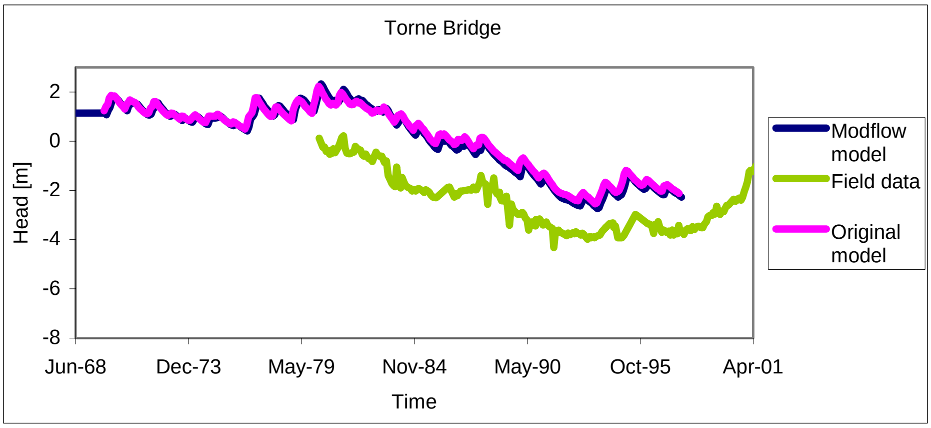

Stainforth Haggs
Head [m]
9
7
5
3
1
-1
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

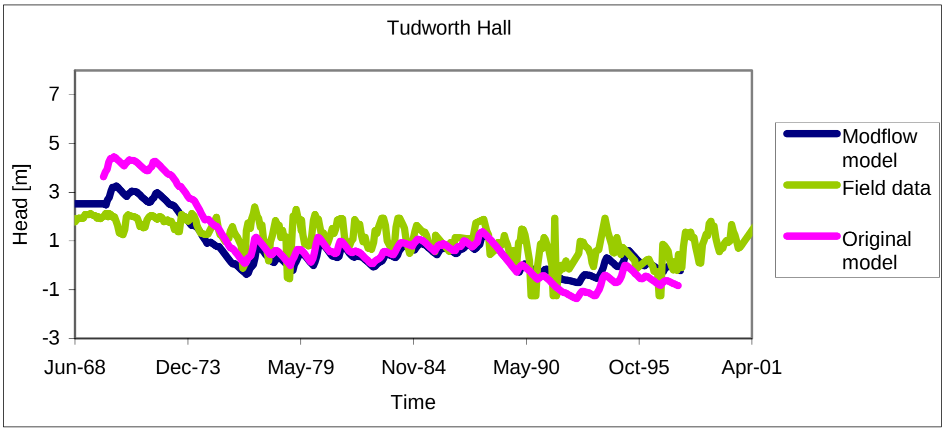

Stone Hill Farm
Head [m]
15
10
5
0
-5
-10
-15
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

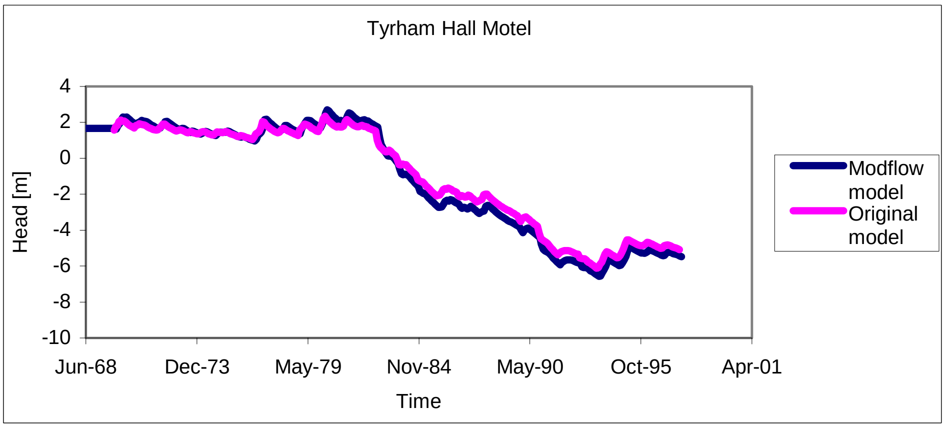

Swinnow Wood
Head [m]
15
13
11
9
7
5
3
1
-1
-3
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model

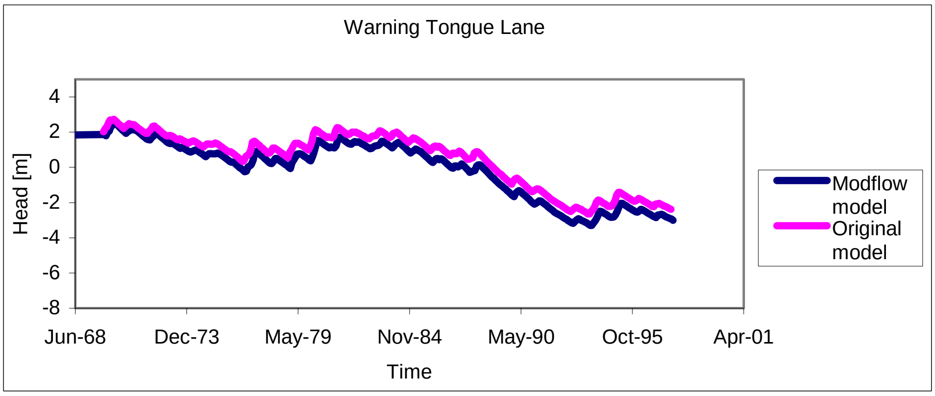

Sykehouse
Head [m]
7
5
3
1
-1
-3
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

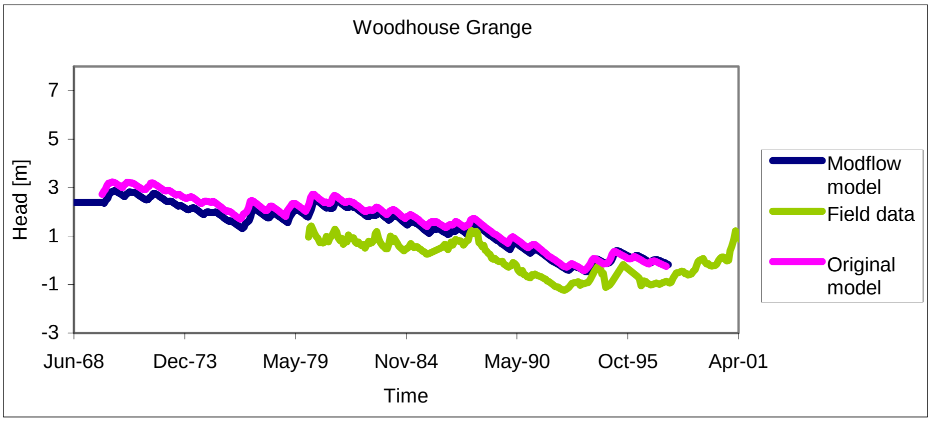

Thorninghurst Farm
Head [m]
7
5
3
1
-1
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

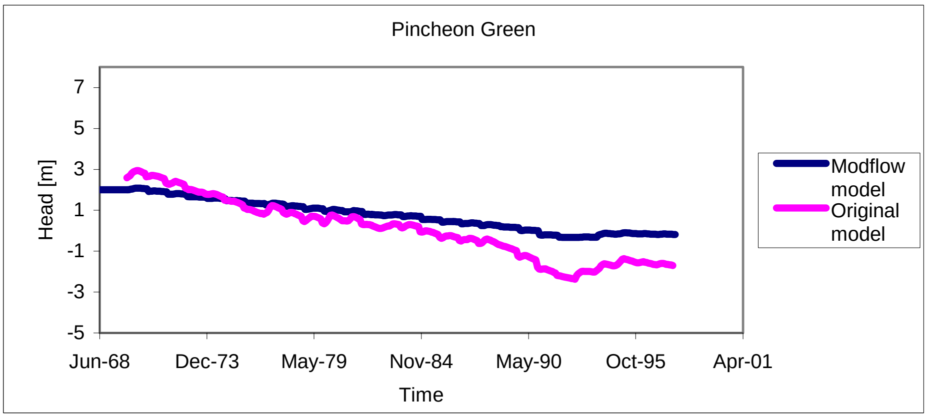

Torne Bridge
Head [m]
2
0
-2
-4
-6
-8
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model


Tudworth Hall
Head [m]
7
5
3
1
-1
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model


Tyrham Hall Motel
Head [m]
4
2
0
-2
-4
-6
-8
-10
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model


Warning Tongue Lane
Head [m]
4
2
0
-2
-4
-6
-8
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model


Woodhouse Grange
Head [m]
7
5
3
1
-1
-3
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Field data
Original model


Pincheon Green
Head [m]
7
5
3
1
-1
-3
-5
Jun-68
Dec-73
May-79
Nov-84
May-90
Oct-95
Apr-01
Time
Modflow model
Original model

Appendix 2 Input data to original model

Storage coefficient (*1000)

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
4	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	-99	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	-99	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	-99	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	150	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	150	150	150	1	1	1	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	150	150	150	150	150	1	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	-99	-99	-99	-99	-99	-99	-99	150	1	1	1	1	150	150	150	150	150	150	250	250	250	150	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	-99	-99	-99	-99	-99	-99	-99	150	150	150	1	150	150	150	150	150	150	150	150	250	250	150	250	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	-99	-99	-99	-99	-99	-99	-99	150	150	1	1	150	150	150	150	150	1	150	250	250	250	1	250	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	-99	-99	-99	-99	-99	-99	-99	150	1	1	150	250	150	250	150	150	150	250	150	150	250	1	250	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	-99	-99	-99	-99	-99	-99	-99	150	1	150	150	150	150	150	150	150	150	150	150	150	150	250	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	250	250	250	250	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	-99	-99	-99	-99	-99	-99	-99	-99	150	0	0	150	150	150	150	150	150	150	150	250	250	250	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	-99	-99	-99	-99	-99	-99	-99	150	150	1	1	150	250	250	150	150	250	250	150	150	250	150	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	-99	-99	-99	-99	-99	-99	150	150	-99	-99	1	1	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	-99	-99	-99	-99	-99	-99	150	-99	-99	-99	1	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	150	150	150	150	150	150	150	150	150	150	150	150	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Transmissivity (m2/d/10)

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
4	-99	-99	-99	-99	-99	-99	-99	5	15	15	15	25	25	30	30	35	50	50	50	55	55	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5	-99	-99	-99	-99	-99	-99	-99	3	15	15	15	25	25	30	30	35	50	50	50	55	55	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
6	-99	-99	-99	-99	-99	-99	-99	-99	3	15	15	15	25	25	30	30	35	50	50	50	55	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
7	-99	-99	-99	-99	-99	-99	-99	-99	3	15	15	15	25	25	30	30	35	50	50	50	55	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
8	-99	-99	-99	-99	-99	-99	-99	-99	5	15	15	15	25	25	30	30	35	50	50	50	55	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
9	-99	-99	-99	-99	-99	-99	-99	5	15	15	15	15	25	25	25	30	30	35	50	50	55	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
10	-99	-99	-99	-99	-99	-99	3	5	15	15	25	25	25	25	25	25	30	30	50	50	50	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
11	-99	-99	-99	-99	-99	-99	-99	5	15	15	25	25	25	25	25	25	30	50	50	50	50	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
12	-99	-99	-99	-99	-99	-99	3	10	15	15	15	25	25	25	25	25	30	30	50	50	50	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
13	-99	-99	-99	-99	-99	-99	3	10	15	15	15	25	25	25	30	30	30	30	50	50	50	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
14	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	15	25	5	10	15	30	35	50	50	50	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
15	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	25	25	30	30	15	15	50	50	50	55	55	55	55	55	55	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
16	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	15	25	30	30	35	50	15	50	50	55	55	55	55	40	40	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17	-99	-99	-99	-99	-99	-99	-99	3	15	15	15	25	25	15	30	30	35	50	50	50	55	55	55	55	55	40	40	40	40	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
18	-99	-99	-99	-99	-99	-99	-99	3	3	15	15	15	25	30	25	25	50	50	50	50	55	55	55	55	55	40	40	15	15	15	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19	-99	-99	-99	-99	-99	-99	-99	-99	5	10	15	15	15	25	30	30	30	50	50	50	55	55	55	55	55	40	40	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
20	-99	-99	-99	-99	-99	-99	-99	-99	5	10	15	15	15	25	30	30	50	50	50	50	55	55	55	55	55	40	40	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
21	-99	-99	-99	-99	-99	-99	-99	3	3	3	5	10	15	15	30	30	30	50	50	50	55	55	55	55	40	40	40	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
22	-99	-99	-99	-99	-99	-99	3	3	-99	-99	5	10	15	25	30	30	35	50	50	55	55	55	55	40	40	40	40	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
23	-99	-99	-99	-99	-99	-99	3	-99	-99	-99	5	15	15	30	30	35	50	50	50	55	55	55	55	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
24	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	5	15	15	25	30	30	50	50	50	55	55	55	40	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
25	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	30	30	50	50	50	55	55	55	40	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
26	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	25	30	30	50	50	50	55	55	40	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
27	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	30	30	50	50	50	55	55	55	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
28	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	30	30	50	50	50	55	55	55	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
29	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	30	30	50	50	50	55	55	55	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
30	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	10	15	15	25	30	35	50	50	55	55	40	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
31	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	15	15	25	30	35	50	50	55	55	40	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
32	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	3	5	10	15	15	25	30	35	50	50	55	55	40	40	40	40	15	15	15	10	10	10	10	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Head in overlying stratum for leakage nodes (mAOD)

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
4	-99	-99	-99	-99	-99	-99	-99	5	4	4	4	4	3	3	3	3	3	2	1	3	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	-99	-99	-99	-99	-99	-99	-99	4	4	4	4	4	3	2	2	2	2	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	-99	-99	-99	-99	-99	-99	-99	-99	4	4	4	3	3	3	2	2	2	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	-99	-99	-99	-99	-99	-99	-99	-99	3	4	4	3	3	3	3	3	3	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	-99	-99	-99	-99	-99	-99	-99	-99	4	4	4	4	3	3	4	3	3	3	3	-88	-88	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	-99	-99	-99	-99	-99	-99	-99	8	3	4	4	4	4	4	4	3	2	3	2	2	-88	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	-99	-99	-99	-99	-99	-99	7	3	3	4	4	4	4	4	-88	-88	-88	1	1	1	-88	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	-99	-99	-99	-99	-99	-99	-99	3	3	4	4	4	-88	-88	-88	-88	-88	1	-88	-88	-88	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	-99	-99	-99	-99	-99	-99	3	3	2	3	3	4	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	-99	-99	-99	-99	-99	-99	3	2	4	3	4	4	4	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	-99	-99	-99	-99	-99	-99	-99	-88	4	4	4	4	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	4	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	-99	-99	-99	-99	-99	-99	-99	-88	-88	4	3	-88	-88	-88	-88	-88	0	-88	-88	-88	-88	1	-88	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	-99	-99	-99	-99	-99	-99	-99	-88	3	4	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	-88	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	-99	-99	-99	-99	-99	-99	-99	-88	3	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	-99	-99	-99	-99	-99	-99	-99	-99	-88	1	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	-99	-99	-99	-99	-99	-99	-99	-88	-88	1	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	-99	-99	-99	-99	-99	-99	-88	-88	-99	-99	1	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	-99	-99	-99	-99	-99	-99	-88	-99	-99	-99	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
32	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

Thickness of overlying stratum (m/10)

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
4	-99	-99	-99	-99	-99	-99	-99	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
5	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6	-99	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	-99	-99	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
8	-99	-99	-99	-99	-99	-99	-99	-99	0	1	1	1	1	1	0	0	1	1	1	-88	-88	1	1	1
9	-99	-99	-99	-99	-99	-99	-99	0	0	1	0	0	0	0	1	1	1	0	1	1	-88	1	1	1
10	-99	-99	-99	-99	-99	-99	1	1	1	0	0	0	1	0	-88	-88	-88	1	1	1	-88	1	1	1
11	-99	-99	-99	-99	-99	-99	-99	1	1	0	0	1	-88	-88	-88	-88	-88	1	-88	-88	-88	1	1	1
12	-99	-99	-99	-99	-99	-99	1	1	1	1	1	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	1
13	-99	-99	-99	-99	-99	-99	1	0	0	0	0	0	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2
14	-99	-99	-99	-99	-99	-99	-99	-88	0	0	0	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	1
15	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1
16	-99	-99	-99	-99	-99	-99	-99	-88	-88	0	1	-88	-88	-88	-88	-88	0	-88	-88	-88	-88	1	-88	1
17	-99	-99	-99	-99	-99	-99	-99	-88	1	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	-88	1
18	-99	-99	-99	-99	-99	-99	-99	-88	1	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88
19	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88
20	-99	-99	-99	-99	-99	-99	-99	-99	-88	0	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88
21	-99	-99	-99	-99	-99	-99	-99	-88	-88	0	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0
22	-99	-99	-99	-99	-99	-99	-88	-88	-99	-99	0	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	0	0	2
23	-99	-99	-99	-99	-99	-99	-88	-99	-99	-99	0	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2
24	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2	2
25	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2	3
26	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2	3
27	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	2
28	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	2
29	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	2
30	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2	3
31	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	2	2
32	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	1	1

	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
4	1	1	1	4	5	5	5	8	8	13	15	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
5	1	1	1	4	5	5	5	8	8	13	15	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
6	1	1	1	4	5	5	5	8	8	13	15	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
7	1	1	1	4	5	5	5	8	8	13	13	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
8	0	1	0	4	5	5	5	8	8	13	13	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
9	1	1	1	2	4	5	8	8	10	13	13	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
10	1	1	1	2	4	5	8	8	10	13	13	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
11	1	1	0	2	4	5	8	8	10	13	13	15	18	18	20	20	23	25	25	28	30	35	35	40	45	50	50	50
12	1	1	1	2	4	5	8	8	10	13	13	15	18	20	20	23	23	25	25	28	30	35	35	40	45	50	50	50
13	1	1	1	2	4	5	8	8	10	13	15	18	18	20	23	23	25	25	28	30	30	35	35	40	45	50	50	50
14	1	1	1	2	4	5	8	10	10	13	15	18	18	20	23	25	25	28	30	30	30	35	35	40	45	50	50	50
15	1	1	0	4	5	8	10	10	13	13	15	18	20	20	23	25	28	30	30	30	30	35	35	40	45	50	50	50
16	1	2	3	5	5	8	10	10	13	13	15	18	20	20	23	25	28	30	30	30	35	35	35	40	45	50	50	50
17	1	2	4	5	5	8	10	10	13	13	15	18	20	20	23	25	28	30	30	30	35	35	35	40	45	50	50	50
18	1	1	4	5	5	8	10	13	13	13	15	18	20	23	23	25	28	30	30	30	35	35	35	40	45	50	50	50
19	1	2	4	5	8	8	10	13	13	15	18	20	23	23	25	25	28	30	30	35	35	35	35	40	45	50	50	50
20	1	2	4	5	8	10	10	13	15	18	20	20	23	23	25	28	28	30	30	35	35	35	35	40	45	50	50	50
21	2	3	4	5	8	10	13	13	15	18	20	20	23	23	25	28	28	30	30	35	35	35	35	40	45	50	50	50
22	2	2	4	5	8	10	13	13	15	18	20	20	23	23	25	28	30	30	30	35	35	35	35	40	45	50	50	50
23	2	3	4	5	8	10	13	13	15	18	20	20	23	23	25	28	30	30	35	35	35	35	35	40	45	50	50	50
24	3	4	5	8	8	10	13	15	15	18	23	23	25	28	30	25	30	35	35	35	35	35	35	40	45	50	50	50
25	4	5	8	8	10	10	13	15	15	18	18	20	23	23	25	28	30	35	35	35	35	35	35	40	45	50	50	50
26	4	5	8	8	10	10	13	15	15	18	18	20	23	23	25	28	30	35	35	35	35	35	35	40	45	50	50	50
27	4	5	8	8	10	10	13	15	15	18	18	20	23	23	25	28	30	35	35	35	35	35	35	40	45	50	50	50
28	4	5	8	8	10	10	13	15	15	18	18	20	23	25	25	28	30	35	35	35	35	35	35	40	45	50	50	50
29	4	5	8	8	10	10	13	15	15	18	18	20	23	25	25	28	30	35	35	35	35	35	35	40	45	50	50	50
30	3	5	8	10	13	13	15	15	18	18	20	23	25	25	25	28	30	30	35	35	35	35	35	40	45	50	50	50
31	3	5	10	13	13	13	15	18	18	20	23	23	25	25	28	28	30	30	30	35	35	35	35	40	45	50	50	50
32	3	5	10	13	13	13	15	18	18	20	23	25	25	25	28	28	30	30	30	35	35	35	35	40	45	50	50	50

Leakage - Vertical hydraullic conductivity (m/d*100)

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
4	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
5	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
6	-99	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
7	-99	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
8	-99	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	11	11	11	11	11	11	11	-88	-88	11	11	11	11	11	11
9	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	11	11	11	20	20	20	20	20	20	-88	11	11	11	11	11	11
10	-99	-99	-99	-99	-99	-99	11	11	11	11	11	20	20	20	-88	-88	-88	20	20	20	-88	11	11	11	11	11	11
11	-99	-99	-99	-99	-99	-99	-99	11	11	11	11	20	-88	-88	-88	-88	-88	20	-88	-88	-88	20	20	20	20	20	11
12	-99	-99	-99	-99	-99	-99	11	11	11	11	11	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	20	20	20	11
13	-99	-99	-99	-99	-99	-99	11	11	11	11	11	20	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	20	20	11
14	-99	-99	-99	-99	-99	-99	-99	-88	11	11	11	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	200	11	20	20	11
15	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	200	11	9	11
16	-99	-99	-99	-99	-99	-99	-99	-88	-88	20	20	-88	-88	-88	-88	-88	200	-88	-88	-88	-88	200	-88	200	11	9	9
17	-99	-99	-99	-99	-99	-99	-99	-88	20	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	200	-88	200	11	9	9
18	-99	-99	-99	-99	-99	-99	-99	-88	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	20	9
19	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	9	9
20	-99	-99	-99	-99	-99	-99	-99	-99	-88	20	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	10	9	9
21	-99	-99	-99	-99	-99	-99	-99	-88	-88	20	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	200	11	9	9	9
22	-99	-99	-99	-99	-99	-99	-88	-88	-99	-99	20	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	200	11	9	9	9	9
23	-99	-99	-99	-99	-99	-99	-88	-99	-99	-99	20	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9
24	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9	9
25	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9	9
26	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9	9
27	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	9	9	9	9
28	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	9	9	9	9
29	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	20	9	9	9	9
30	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9	9
31	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9	9
32	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	-88	9	9	9	9	9

	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
4	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
23	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
24	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
25	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
26	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
27	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
28	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
29	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
30	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
31	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0
32	9	9	9	9	9	9	9	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0

Cross boundary flows Ml/d

(abstract from water balance)

Time	Northern boundary flow	Western boundary flow	Southern boundary flow
69-70	0.000	0.010	3.704
70-71	-0.240	0.010	3.189
71-72	-0.430	0.010	2.857
72-73	-0.670	0.010	2.264
73-74	-0.850	0.010	1.748
74-75	-1.040	0.010	2.851
75-76	-1.280	0.010	3.310
76-77	-1.520	0.010	3.042
77-78	-1.700	0.010	2.713
78-79	-1.950	0.010	2.454
79-80	-2.120	0.010	2.256
80-81	-2.320	0.010	1.801
81-82	-2.550	0.010	2.410
82-83	-2.790	0.010	3.402
83-84	-2.980	0.010	3.603
84-85	-3.220	0.010	0.963
85-86	-3.400	0.010	-0.148
86-87	-3.590	0.010	-0.016
87-88	-3.830	0.010	0.427
88-89	-4.070	0.010	0.712
89-90	-4.250	0.010	1.080
90-91	-4.500	0.010	0.393
91-92	-4.750	0.010	0.144
92-93	-4.750	0.010	1.467
93-94	-4.750	0.010	1.653
94-95	-4.750	0.010	0.353
95-96	-4.750	0.010	-0.428
96-97	-4.750	0.010	-0.671

Nodal outflows (Ml/d) -ve implies flow out of model domain to the north

GRID	REF	I	J	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
590	180	12	4	0.00	-0.01	-0.02	-0.03	-0.03	-0.04	-0.05	-0.06	-0.07	-0.08	-0.08	-0.09	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
600	180	13	4	0.00	-0.01	-0.02	-0.03	-0.03	-0.04	-0.05	-0.06	-0.07	-0.08	-0.08	-0.09	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
610	180	14	4	0.00	-0.02	-0.03	-0.05	-0.07	-0.08	-0.10	-0.12	-0.13	-0.15	-0.17	-0.18	-0.20	-0.22	-0.23	-0.25	-0.27	-0.28	-0.30	-0.32	-0.33	-0.35	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
620	180	15	4	0.00	-0.03	-0.07	-0.10	-0.13	-0.17	-0.20	-0.23	-0.27	-0.30	-0.33	-0.37	-0.40	-0.43	-0.47	-0.50	-0.53	-0.57	-0.60	-0.63	-0.67	-0.70	-0.74	-0.74	-0.74	-0.74	-0.74	-0.74
630	180	16	4	0.00	-0.03	-0.05	-0.08	-0.10	-0.13	-0.15	-0.18	-0.20	-0.23	-0.25	-0.28	-0.30	-0.33	-0.35	-0.38	-0.40	-0.43	-0.45	-0.48	-0.50	-0.53	-0.56	-0.56	-0.56	-0.56	-0.56	-0.56
640	180	17	4	0.00	-0.02	-0.03	-0.05	-0.07	-0.08	-0.10	-0.12	-0.13	-0.15	-0.17	-0.18	-0.20	-0.22	-0.23	-0.25	-0.27	-0.28	-0.30	-0.32	-0.33	-0.35	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
650	180	18	4	0.00	-0.02	-0.03	-0.05	-0.07	-0.08	-0.10	-0.12	-0.13	-0.15	-0.17	-0.18	-0.20	-0.22	-0.23	-0.25	-0.27	-0.28	-0.30	-0.32	-0.33	-0.35	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
660	180	19	4	0.00	-0.02	-0.03	-0.05	-0.07	-0.08	-0.10	-0.12	-0.13	-0.15	-0.17	-0.18	-0.20	-0.22	-0.23	-0.25	-0.27	-0.28	-0.30	-0.32	-0.33	-0.35	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
670	180	20	4	0.00	-0.02	-0.03	-0.05	-0.07	-0.08	-0.10	-0.12	-0.13	-0.15	-0.17	-0.18	-0.20	-0.22	-0.23	-0.25	-0.27	-0.28	-0.30	-0.32	-0.33	-0.35	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
680	180	21	4	0.00	-0.02	-0.03	-0.05	-0.07	-0.08	-0.10	-0.12	-0.13	-0.15	-0.17	-0.18	-0.20	-0.22	-0.23	-0.25	-0.27	-0.28	-0.30	-0.32	-0.33	-0.35	-0.38	-0.38	-0.38	-0.38	-0.38	-0.38
690	180	22	4	0.00	-0.01	-0.02	-0.03	-0.03	-0.04	-0.05	-0.06	-0.07	-0.08	-0.08	-0.09	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
700	180	23	4	0.00	-0.01	-0.02	-0.03	-0.03	-0.04	-0.05	-0.06	-0.07	-0.08	-0.08	-0.09	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
710	180	24	4	0.00	-0.01	-0.02	-0.03	-0.03	-0.04	-0.05	-0.06	-0.07	-0.08	-0.08	-0.09	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
720	180	25	4	0.00	-0.01	-0.02	-0.03	-0.03	-0.04	-0.05	-0.06	-0.07	-0.08	-0.08	-0.09	-0.10	-0.11	-0.12	-0.13	-0.13	-0.14	-0.15	-0.16	-0.17	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18	-0.18
730	180	26	4	0.00	0.00	-0.01	-0.01	-0.02	-0.02	-0.03	-0.03	-0.03	-0.04	-0.04	-0.05	-0.05	-0.05	-0.06	-0.06	-0.07	-0.07	-0.08	-0.08	-0.08	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09

Urban Leakage

2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
5	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
6	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
7	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
8	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	114.4	114.4	1	1	1	1	1	1	0	0	0	0
9	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	114.4	1	1	1	1	1	1	0	0	0	0
10	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	114.4	1	1	1	1	1	1	0	0	0	0
11	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
12	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	17.3	17.3	1	1	1	1	1	1	1	1	1	0	0	0	0
13	0	0	0	0	0	0	1	1	1	1	1	1	42.8	42.8	1	1	17.3	17.3	17.3	17.3	1	1	1	1	1	1	1	0	0	0	0
14	0	0	0	0	0	0	0	1	33.8	1	1	1	42.8	42.8	1	17.3	17.3	17.3	17.3	1	1	1	1	1	1	1	1	0	0	0	0
15	0	0	0	0	0	0	0	1	33.8	1	1	1	42.8	42.8	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0
16	0	0	0	0	0	0	0	1	33.8	1	42.8	42.8	42.8	42.8	42.8	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
17	0	0	0	0	0	0	0	1	33.8	1	42.8	42.8	42.8	42.8	42.8	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
18	0	0	0	0	0	0	0	1	1	42.8	42.8	42.8	1	42.8	42.8	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
19	0	0	0	0	0	0	0	0	42.8	42.8	42.8	42.8	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	42.8	42.8	42.8	26.9	26.9	26.9	1	15.1	15.1	1	1	4.3	1	1	1	1	1	0	0	0	0	0	0
21	0	0	0	0	0	0	0	1	42.8	1	1	26.9	26.9	26.9	1	15.1	15.1	1	4.3	4.3	1	1	1	1	0	0	0	0	0	0	0
22	0	0	0	0	0	0	1	1	0	0	1	1	1	26.9	1	4.3	4.3	4.3	4.3	1	1	1	1	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	1	0	0	0	1	1	26.9	1	1	4.3	4.3	4.3	1	1	1	1	1	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	1	1	26.9	26.9	1	1	1	4.3	1	1	1	1	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	3.5	3.5	1	1	1	1	1	1	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	3.5	3.5	1	1	1	1	1	1	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	1	12	12	12	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	12	12	12	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	12	12	12	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0

Stream parameterisation - see P81, 82 of Brown & Rushton				
River	I	J	River coefficient (m3/d/km)	Stream bed level (maod)
Torne	13	31	300	10.5
	12	30	300	11.6
	13	30	300	10
	14	30	300	9.5
	14	29	300	9
	14	28	300	8.5
	14	27	300	8
	14	26	300	7.5
	14	25	300	7
	13	25	300	6.3
	13	24	50	5.6
	13	23	50	5
	14	23	500	4.6
	15	23	500	4.3
	16	22	1000	4
	17	21	1200	3.6
	18	20	800	3.2
	19	20	800	2.8
Doncaster Drainage	20	11	10	2
Channels	21	11	10	-0.5
	22	11	10	-0.5
	21	12	10	-0.5
	22	12	10	-0.5
	23	12	10	-0.5
	23	13	10	-0.5
	24	13	10	-0.5
	21	14	600	-0.5
	17	15	1000	-0.5
	18	15	1000	-0.5
	20	15	500	1
	20	16	800	1
	19	17	800	-0.5
	20	17	800	-0.5
	22	13	10	-0.5
	21	18	200	-0.5
	22	18	200	-0.5
	23	18	400	-0.5
	24	18	400	-0.5
	25	18	400	-0.5
	20	19	600	-0.5
	21	19	600	-0.5
	22	19	500	-0.5
	23	19	400	-0.5
	24	19	450	3
	25	19	450	-0.5
	20	20	400	-0.5
	21	20	550	-0.5
	23	20	500	-0.5
	24	20	400	-0.5
	25	20	400	-0.5
	19	21	700	-0.5
	20	21	700	-0.5
	21	21	700	-0.5
	22	21	450	-0.5
	23	21	450	-0.5

Water balances - EA management units - YEARLY AVERAGE BALANCES in Ml/d

See gwunits.shp for location of Hatfield and Blyth units

	Model area to north of Hatfield unit to northern boundary of model											Hatfield unit										
Time	Prec Rec	Urban Re	Unc Stora	Con Stora	Abstracti	River Torr	Drainage	North Flo	Drift	Mercia M	South Flo	Prec Rech	Urban Re	Unc Storag	Con Stora	Abstractio	River Torr	Drainage	Specified	Drift	Mercia M	CBF
69-70	12.541	1.660	-5.979	-0.037	-5.060	0.000	0.000	0.000	-1.848	-0.010	-1.269	100.032	4.610	-28.404	-0.060	-64.610	-3.121	-6.737	0.010	-6.211	-0.483	4.973
70-71	4.776	1.660	2.083	0.025	-5.280	0.000	0.000	-0.240	-1.713	-0.010	-1.298	50.518	4.610	16.913	0.034	-62.460	-2.613	-4.960	0.010	-6.053	-0.485	4.488
71-72	6.189	1.660	0.711	0.023	-5.700	0.000	0.000	-0.430	-1.298	-0.010	-1.149	60.288	4.610	7.763	0.021	-65.100	-2.090	-3.538	0.010	-5.514	-0.454	4.006
72-73	2.606	1.660	4.476	0.042	-6.060	0.000	0.000	-0.670	-0.690	-0.008	-1.359	27.649	4.610	36.136	0.252	-66.740	-0.870	-0.105	0.010	-4.194	-0.369	3.623
73-74	2.803	1.660	3.258	0.016	-4.840	0.000	0.000	-0.850	-0.375	-0.008	-1.663	29.718	4.610	31.115	0.283	-67.210	-0.238	1.708	0.010	-3.153	-0.251	3.411
74-75	4.796	1.660	1.173	0.035	-5.180	0.000	0.000	-1.040	0.124	0.000	-1.563	50.108	4.610	12.215	0.113	-69.920	-0.235	1.480	0.010	-2.617	-0.175	4.414
75-76	1.769	1.660	3.637	0.040	-4.740	0.000	0.000	-1.280	0.890	0.000	-1.974	18.208	4.610	34.769	0.065	-67.710	0.968	4.960	0.010	-1.049	-0.117	5.284
76-77	14.040	1.660	-7.680	-0.054	-4.590	0.000	0.000	-1.520	0.223	0.000	-2.077	121.920	4.610	-57.488	-0.148	-67.410	-1.318	-1.916	0.010	-3.201	-0.179	5.118
77-78	4.082	1.660	2.203	0.036	-4.530	0.000	0.000	-1.700	0.478	0.000	-2.226	43.103	4.610	21.597	0.203	-71.560	-0.614	0.331	0.010	-2.519	-0.098	4.938
78-79	10.366	1.660	-3.208	-0.008	-4.850	0.000	0.000	-1.950	0.527	0.000	-2.533	94.649	4.610	-24.421	0.020	-74.350	-1.230	-1.480	0.010	-2.723	-0.072	4.988
79-80	13.155	1.660	-5.197	-0.021	-5.150	0.000	0.000	-2.120	0.047	0.000	-2.372	113.947	4.610	-36.145	0.045	-75.290	-3.018	-4.938	0.010	-3.745	-0.098	4.628
80-81	9.585	1.660	-1.677	-0.005	-4.810	0.000	0.000	-2.320	-0.069	0.000	-2.363	84.800	4.610	-9.854	0.060	-72.480	-3.253	-4.248	0.010	-3.717	-0.093	4.164
81-82	3.419	1.660	1.942	0.035	-2.940	0.000	0.000	-2.550	0.167	0.000	-1.729	36.405	4.610	19.441	0.098	-56.790	-2.448	-2.437	0.010	-2.956	-0.072	4.139
82-83	6.547	1.660	0.475	-0.023	-3.500	0.000	0.000	-2.790	0.197	0.000	-2.562	65.708	4.610	2.824	-0.268	-73.520	-1.943	-0.613	0.010	-2.633	-0.136	5.963
83-84	4.663	1.660	1.680	0.011	-2.950	0.000	0.000	-2.980	0.268	0.000	-2.349	48.889	4.610	19.529	0.196	-75.440	-1.683	0.571	0.010	-2.533	-0.097	5.952
84-85	3.985	1.660	2.706	0.041	-3.920	0.000	0.000	-3.220	0.755	0.000	-2.005	41.788	4.610	28.798	0.160	-78.200	-0.902	2.613	0.010	-1.828	-0.018	2.968
85-86	5.171	1.660	1.203	0.013	-3.820	0.000	0.000	-3.400	1.251	0.000	-2.078	54.541	4.610	17.049	0.093	-81.390	-0.523	4.823	0.010	-1.174	0.031	1.930
86-87	6.446	1.660	1.419	0.017	-5.350	0.000	0.000	-3.590	1.517	0.000	-2.119	63.651	4.610	12.694	-0.025	-86.820	-0.688	5.596	0.010	-1.139	0.013	2.103
87-88	9.870	1.660	-2.031	-0.002	-4.820	0.000	0.000	-3.830	1.430	0.000	-2.277	81.222	4.610	-6.484	0.034	-84.060	-1.493	5.139	0.010	-1.703	0.024	2.703
88-89	0.223	1.660	6.071	0.036	-2.890	0.000	0.000	-4.070	1.963	0.000	-2.993	2.797	4.610	64.439	0.056	-85.920	0.340	9.765	0.010	0.152	0.055	3.704
89-90	4.344	1.660	2.823	0.058	-5.180	0.000	0.000	-4.250	3.009	0.000	-2.464	45.696	4.610	18.088	0.071	-84.170	0.633	10.453	0.010	0.963	0.108	3.544
90-91	3.395	1.660	3.491	0.066	-6.370	0.000	0.000	-4.500	4.009	0.004	-1.755	35.689	4.610	22.975	0.134	-79.930	1.068	11.198	0.010	1.921	0.179	2.148
91-92	0.432	1.660	4.700	0.024	-4.650	0.000	0.000	-4.750	4.660	0.010	-2.083	5.065	4.610	41.335	0.135	-71.990	2.222	12.734	0.010	3.409	0.248	2.227
92-93	4.150	1.660	1.135	-0.033	-3.490	0.000	0.000	-4.750	4.473	0.001	-3.148	43.328	4.610	4.380	0.035	-75.430	2.256	12.557	0.010	3.378	0.263	4.614
93-94	10.242	1.660	-6.561	-0.062	-1.160	0.000	0.000	-4.750	3.526	0.000	-2.896	89.870	4.610	-41.164	-0.099	-71.620	0.997	10.846	0.010	1.793	0.212	4.548
94-95	9.016	1.660	-5.274	-0.043	-0.470	0.000	0.000	-4.750	2.620	0.000	-2.763	83.323	4.610	-28.665	-0.063	-72.390	0.234	9.238	0.010	0.448	0.144	3.116
95-96	2.403	1.660	1.347	0.018	-0.440	0.000	0.000	-4.750	2.693	0.000	-2.929	25.456	4.610	24.004	0.100	-70.120	1.271	10.678	0.010	1.308	0.179	2.501
96-97	2.748	1.660	0.871	0.008	-0.450	0.000	0.000	-4.750	2.867	0.000	-2.957	29.514	4.610	14.501	0.052	-66.540	1.917	11.418	0.010	2.013	0.220	2.286
Average	5.849	1.660	0.350	0.009	-4.043	0.000	0.000	-2.779	1.132	-0.001	-2.177	55.281	4.610	7.784	0.057	-72.828	-0.585	3.398	0.010	-1.546	-0.054	3.874