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Pollution Potential of Cemeteries: Impact of the 19th century Carter Gate Cemetery, Nottingham

J K Trick, G M Williams, D J Noy, Y Moore and S Reeder[1]

Fluid Processes and Waste Management Group
[1] Analytical and Regional Geochemistry Group

BRITISH GEOLOGICAL SURVEY

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Statement of use
This report provides an overview of the pollution potential of a 19th century cemetery and its impact on groundwater resources.

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EXECUTIVE SUMMARY

The impact of a 19th century cemetery called "Carter Gate" on groundwater in the underlying Triassic Sandstones aquifer has been determined directly by drilling three boreholes after exhumation of the graves. Pore-water in the unsaturated zone beneath the graves contains high concentrations of Calcium (Ca), Sodium (Na), Magnesium (Mg) and Potassium (K) with Sulphate (SO_4) and Chloride (Cl), in ratios which are inconsistent with the known composition of a human body and solutes released from graves. The inorganic solutes are probably derived from contaminated material deposited, or effluents discharged, above the graves. Despite this extraneous contamination, the pore-water profiles are thought to provide evidence of migration of grave derived material. Immediately below the graves a dark-coloured zone (called the "grave cut") occurs containing elevated concentrations of phosphorous, calcium, copper and zinc. The unsaturated pore-water profiles in one borehole contains peaks of Total Organic Carbon (TOC), Manganese (Mn) and Ammonium (NH_4) up to 2–3 m below the grave level. The Mn is thought to result from reductive dissolution of the Triassic Sandstones due to biodegradation of organic material leached from the graves, and is coincident with the TOC peak. The NH_4 is reported to be a major solute from graves and is thought to be retarded in its migration relative to conservative species such Na, Cl, SO_4. These are also likely to have been released from the graves but probably migrated through the unsaturated zone within a period of 20 years.

Anthropogenic organic compounds which were not available industrially when the cemetery was in use, are found in the unsaturated and saturated zones. Coliform bacteria were found at the water table but the associated concentrations of Boron (B) and Phosphorous (P) suggests that they could be from a leaking sewer. Because of time constraints, it was not possible to carry out a detailed microbiological study, but all boreholes contained microbial numbers similar to those in uncontaminated groundwater.

The study confirms that this cemetery no longer presents a source of contamination, but suggests that, by comparison with the ammonium peak, the maximum impact of inorganic solutes and volatile fatty acids on groundwater was probably minimal.

1. INTRODUCTION

In order to provide guidance on the risks to groundwater from the burial of humans or animal carcasses, the Environment Agency commissioned a study of the pollution potential of cemeteries, initially through a review of the literature. While this review was underway, a 19th century cemetery called "Carter Gate" was exposed during building development in the centre of Nottingham, and has provided an opportunity to determine directly the impact of an old cemetery on groundwater quality in the underlying Triassic Sandstones aquifer.

Jointly funded by the British Geological Survey and the Environment Agency, this investigation took place within two weeks in August 1998 when access was possible after the graves had been exhumed, and before building commenced.

The investigation entailed drilling three boreholes in the area cleared of graves, to obtain cores of the underlying strata and samples of groundwater from the aquifer. Pore-water obtained by centrifuging the cores, and groundwater samples were analysed for inorganic and, in selected samples, for organic constituents. Because of time constraints, limited microbiological characterisation was carried out only on the groundwater samples. The material immediately surrounding the skeletal remains (referred to as the "grave cut") was also collected for solid phase and pore-water analysis.

2. PREVIOUS STUDIES OF CEMETERIES

A review of the literature dealing with the pollution potential of cemeteries has recently been carried out on behalf of the Environment Agency (Young *et al.*, 1998). In general there have been very few published investigations into the hydrogeological impact of graveyards and no UK studies are known.

The composition of the human body and its fate when buried has been described by a number of researchers e.g. van Haaran (1951) and, more recently, by Forbes (1987) who quotes the elemental composition of an average human body (Table 1).

The decay of a corpse has been reported by Reed (1958) who classified four stages of decomposition - fresh, bloated, decay and dry - although the decay stage is often sub-divided to active and advanced. While the rate of decay will be affected by various factors such as temperature, depth of burial and rainfall, complete decay after burial at depth commonly occurs within twelve years.

Table 1. Composition of 70 kg adult male (after Forbes, 1978)

Element	Mass (g)	% by weight
carbon	16000	22.9
nitrogen	1800	2.57
calcium	1100	1.57
phosphorous	500	0.71
sulphur	140	0.2
potassium	140	0.2
sodium	100	0.14
chlorine	95	0.14
magnesium	19	0.03
iron	4.2	0.006
zinc	2.3	0.003
copper	0.07	0.0001
manganese	0.01	0.00001
strontium	0.32	0.00005
lead	0.12	0.00017
aluminium	0.06	0.00009
water		70-74

Polson and Marshall, (1975) reported that while body tissues begin to decompose within a few hours after death an adult body takes ten to twelve years to decay fully when buried in ordinary soil, leaving just the skeleton which comprises 10 – 20 % of the original body weight. Putrefaction occurs due to bacterial action and autolysis (the destruction of body cells by their own enzymes). Evidence is given by Corry (1978) that putrefaction occurs progressively due to the presence of a number of different organisms. The majority of these organisms are found in the intestine, and many are pathogenic and associated with water-borne diseases. Pathogenic viruses and protozoa have also been found in corpses.

Pacheco *et al*., (1991) investigating the bacteriological quality of groundwater in the vicinity of graveyards reported proteolytic and lipolytic bacteria, (which are associated with the process of decomposition), faecal streptococci, sulphate reducing clostridia and in one case salmonella in samples from three cemeteries. Dent and Knight, (1998) reported pathogenic bacteria in groundwater at a number of Australian cemeteries.

Van Haaran (1951) described a high salinity plume in shallow groundwater below a graveyard in the Netherlands (Table 2), while Knight and Dent (1995) identified a high salinity leachate plume containing elevated concentrations of chloride, nitrate, nitrite, ammonium, orthophosphate, iron, sodium, potassium and magnesium near active cemeteries in Australia. They detected elevated concentrations of these species in pore-waters from the unsaturated zone and reported slightly elevated concentrations of copper and zinc close to the graves.

Table 2. Composition of groundwater beneath a cemetery in the Netherlands

(after van Haaren 1951).

Electrical conductivity (μS cm^{-1})	2300
Chloride (mg L^{-1})	500
Sulphate (mg L^{-1})	300
Bicarbonate (mg L^{-1})	450

Apart from the human remains, an additional source of contamination arises from the use of embalming fluids to preserve corpses. Embalming originated in Egypt in about 3200 BC, but modern day embalming developed from the need to preserve bodies for anatomical dissection (Mayer, 1996). Preservatives, including saltpetre, pitch or resin, camphor, cinnamon, alcohol, arsenous oxide and mercuric chloride, have been in use since the 17th century, but current embalming practice uses formaldehyde.

3. DESCRIPTION OF THE CARTER GATE CEMETERY

3.1 Location

The cemetery covers an area of 3500 m^2, and is situated in the grounds of the Nottingham Ice Centre, to the east side of the Lace Market area in the City of Nottingham. It lies between Lower Parliament Street and Bellar Gate, National Grid Reference SK 579 398 (Figure 1).

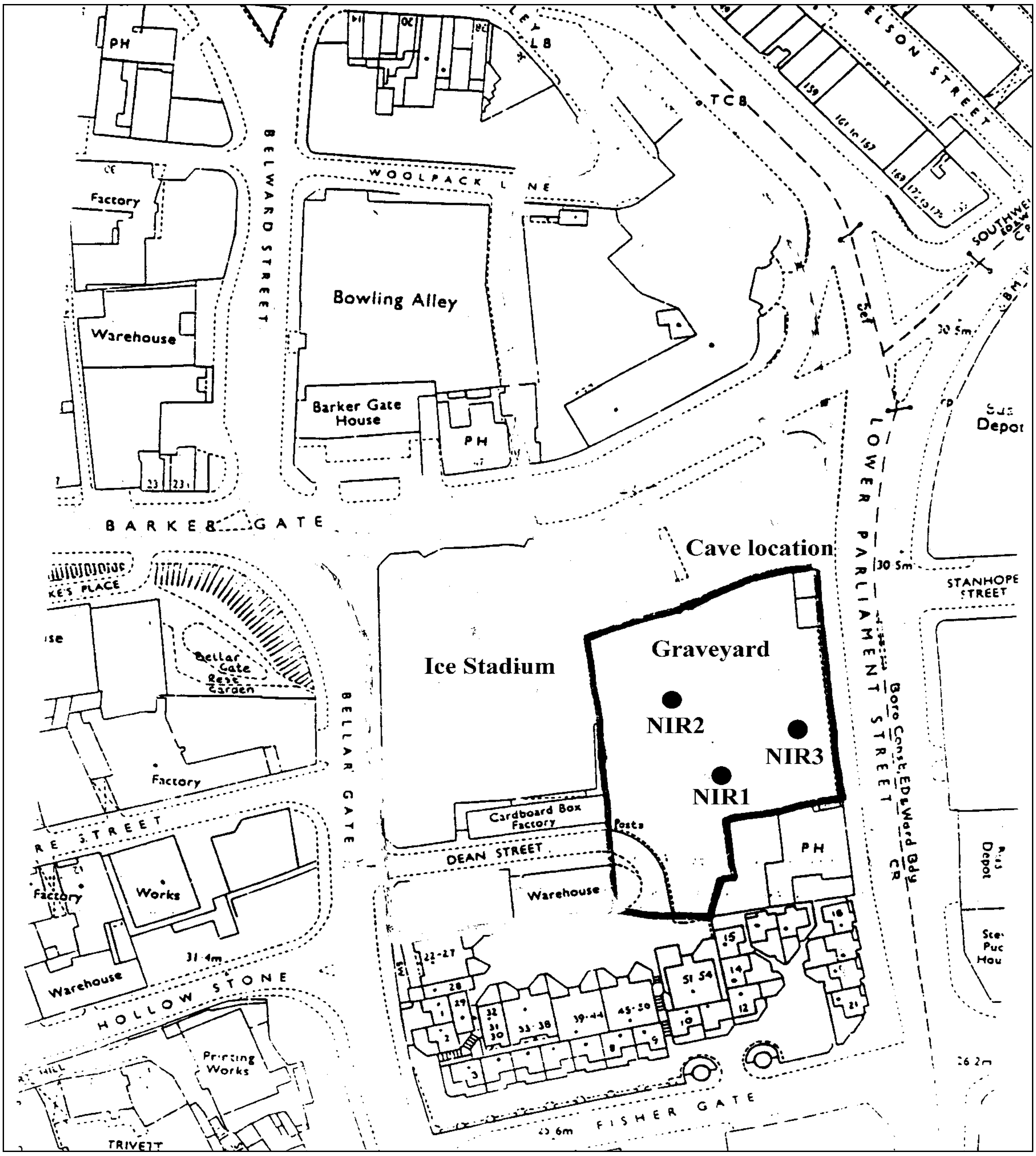

Figure 1. Location map showing position of Carter Gate Cemetery and investigation borholes.
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3.2 Historical Background

The site lies in an historically important area of the City, where remains of defences dating from an early Anglian settlement (c. AD 650-850), surround a sandstone hill later to become known as St Mary's Hill (John Samuels Archaeological Consultants, 1998). The area underwent three periods of occupation prior to the Norman Conquest, including that of the Late Saxon borough recorded in the Doomsday Book. Following the Norman Conquest, a French community developed around Nottingham Castle built by William the Conqueror in 1067 to the west of the borough. Nottingham thus became a town of two boroughs. The English borough was centred around St Mary's Church which, founded in Saxon times, was rebuilt in 1175 and again between 1375 and 1475.

In 1155 Nottingham was granted a Charter by Henry II which recognised it as an ancient borough and granted it the privilege of holding a market on Fridays and Saturdays. In 1449 Nottingham's population had risen to some 3000 and Henry VI granted the city its Great Charter. By the early 19th century many of the town houses on St Mary's Hill were replaced by factories associated with the lace trade, and the area subsequently became known as the Lace Market, which at one time, was the largest lace-making centre in the world.

Prior to 1850 most large lace manufacturers did not own their own machines and were not in reality lace makers. The Lace Market was simply used for warehousing, finishing and sales. Textiles were primarily a "cottage industry" in which workers owned or hired their machines and worked at home in living rooms and bedrooms. Later they rented "standings" in large factory premises. However, with the development of lace making machines Nottingham's lace industry expanded in the second half of the 19th century. In 1890 about 17,000 people were employed in 500 lace factories and massive ornate warehouses were built often with impressive centrally-placed entrances that resembled huge town houses.

The lace industry eventually declined after the First World War and many of the warehouses were subdivided and let to small textile firms paying minimal rents. Lack of maintenance led to very run down conditions by the 1960s. The present day Lace Market is a thriving retail, leisure and residential area although many of the original warehouses remain, some still involved in the textile industry. Industries close to the Carter Gate at the present time include Transport (Bartons Bus depot); Chemical and pharmaceutical production, (The Boots Company, Knoll Pharmaceuticals) and Energy Production (Energy Centre, Yorkshire Environmental Solutions Ltd, Eastcroft Incinerator).

Apart from St Mary's Churchyard, the parish had three supplementary burial grounds before the cholera epidemic of 1832, all situated in the Barker Gate area. The Nottingham cholera epidemic was the worst outbreak in the East Midlands with 930 cases and 330 deaths and there is a report that cholera victims were buried at Carter Gate. Walker, (1991) describes a large pit in the centre of a cemetery where uncoffined bodies were interred in heaps. However, there is some confusion over the names of the cemeteries at this time and during exhumation no evidence for mass graves was found. A fourth burial ground was established during this period outside the town limits and it is likely that this was used for the majority of cholera victims. Opened in 1813, Carter Gate was used until 1875 by which time the area had become extensively developed with back-to-back housing, leaving Carter Gate the only substantial open area within the conurbation. Some time after the cemetery closed, the grave stones were removed and the site landscaped with trees and paths (Kinsley *et al.,* 1996). In 1938 the Nottingham Ice Rink was built, and some time between 1952 and 1962 Carter Gate Cemetery was covered over and used as a car park.

4. GEOLOGY AND HYDROGEOLOGY

4.1 Geology

The geology and hydrogeology of Nottingham are described by Charsley *et al.*, (1990). Carter Gate Cemetery site lies on the Sherwood Sandstone Group of the Triassic, which is made up of the Lenton Sandstone Formation overlain by the Nottingham Castle Sandstone Formation. The latter formation is well exposed in the crag below Nottingham Castle (NGR SK 569 394) and is composed of buff to pale red brown sandstone with subordinate conglomerate, siltstone and mudstone. Situated just north of the alluvial tract of the River Trent, the site does not contain drift deposits. A variable layer of top soil (made ground) up to 1 m thick overlies unconsolidated sands which extend to about 4 m bgl and grade into harder sandstone below. The unconsolidated sands probably represent the weathered surface of the Nottingham Castle Formation.

Because of the relative ease by which the Triassic Sandstones can be excavated, there are numerous man-made caves beneath Nottingham (Owen and Walsby, 1989). Over 400 have been identified. Many date back to medieval times, and have been used for a variety of purposes including water wells, cess-pits, storage areas, hiding places, breweries, tanneries, underground passageways and bomb shelters. Several exist in the vicinity of the Carter Gate cemetery (Figure 1).

4.2 Previous Investigations at Carter Gate

Prior to the demolition and rebuilding of the Nottingham Ice Rink in 1998, geotechnical investigations and an archaeological study of the site were commissioned by Nottingham City Council.

Mini Soil Surveys (MSS) carried out geotechnical investigations in August 1996, and Allied Exploration and Geotechnics Ltd (AEG) extended these in April and May 1998. Mini Soil Surveys drilled 14 boreholes to depths of up to 4.6 m bgl to evaluate the thickness of made ground and to probe for contamination. Allied Exploration and Geotechnics Ltd excavated two trial pits and drilled three boreholes by percussion and rotary methods to intercept the water table.

The boreholes and trial pits revealed a variable thickness of made ground consisting of brown gravelly sand, the gravel containing ash, sandstone, foundry slag and brick. The Sherwood Sandstone was found to be weathered to depths of 5.5 m. Soil samples were analysed and results are given in Table 3.

Table 3. Results of soil analysis from site investigation reports.

Source	Depth (m bgl)	Analyte	Concentration mg/kg	ICRCL* Trigger Level
Mini Soil Surveys - BH1	1.0 - 1.6	Phenols	7.0	5.0
Allied Exploration and Geotechnics Ltd - BH5	0.50	Total sulphate	3574	2000
Allied Exploration and Geotechnics Ltd - BH5	0.80	Zinc	334.7	300

* ICRCL (1987)

John Samuels Archaeological Consultants undertook a desk survey and were subsequently responsible for the systematic recording and exhumation of about 1,100 graves (John Samuels Archaeological Consultants, 1999).

4.3 Hydrology and Hydrogeology

Hydrogeologically, the Sherwood Sandstone forms a major aquifer in the area and has been extensively developed for public and private water supply. Rainfall in Nottingham amounts to about 635 mm a^{-1} and actual evaporation averaged over the Trent Basin is approximately 482 mm a^{-1} (Downing *et al.,* 1970). Thus infiltration is likely to be about 153 mm a^{-1}.

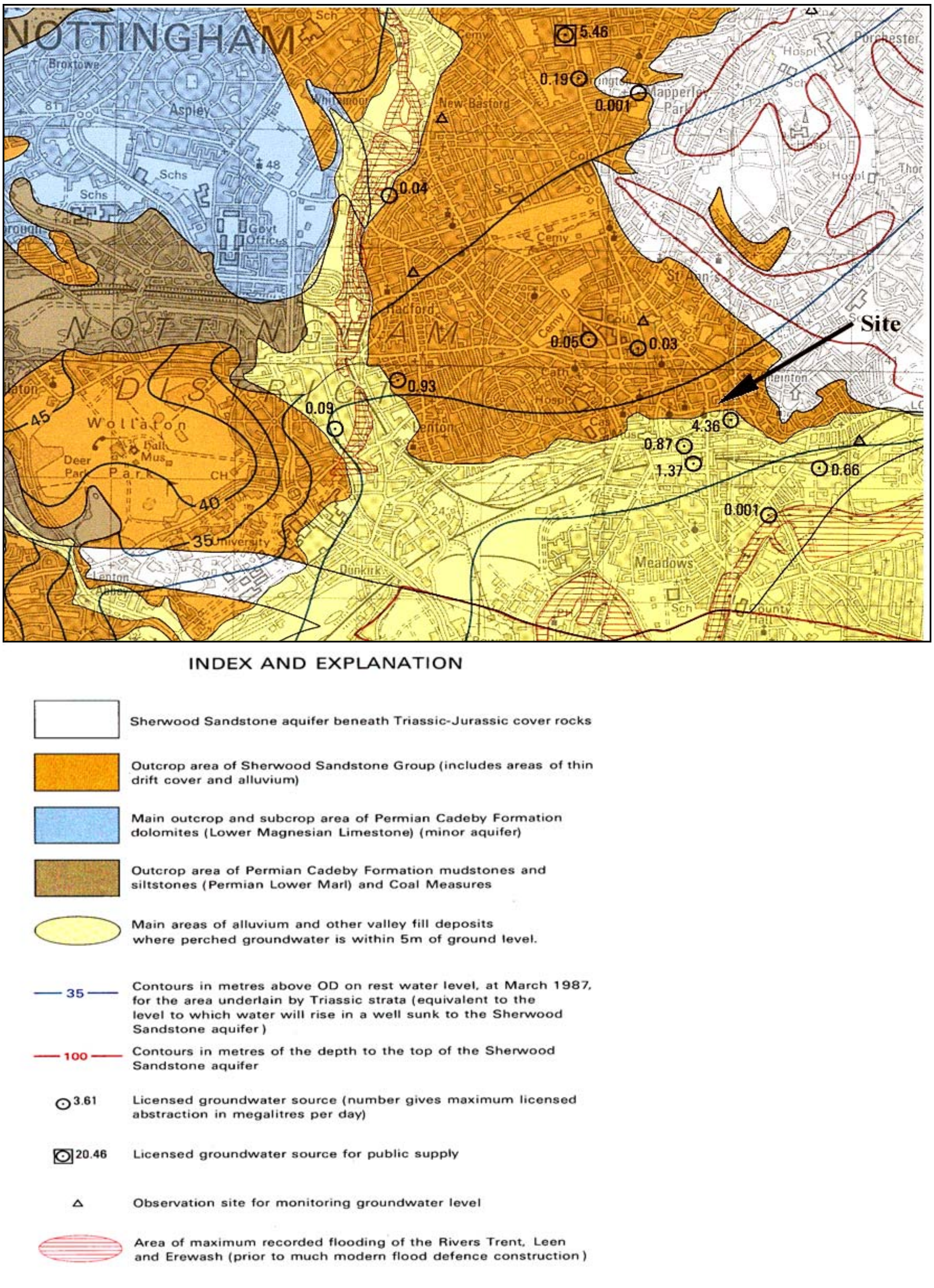

Figure 2. Geological map of Nottingham with rest water levels in m AOD (after Charsley et al 1990). © Crown Copyright. All rights reserved.

The Nottingham Groundwater Unit (Charsley op. cit.) has an estimated resource of 19 Ml/d. In 1989, licensed abstractions amounted to 22 Ml/d but actual abstractions were only 14 Ml/d. Rest water level contours within Nottingham (Figure 2) show that the water table beneath the site is around 25 m above ordnance datum (AOD) with a hydraulic gradient of

0.004 to the south-south-east. Based on a porosity of about 24% and a hydraulic conductivity of 0.5 $m.d^{-1}$ for the Triassic Sandstones (Young *et al*., 1994), this would give an average flow rate in the sandstone of about 0.008 $m.d^{-1}$ (or 3 $m.a^{-1}$). However, local pumping may have a profound effect on these rest water conditions and the rate and direction of groundwater movement could be significantly different from those suggested by the rest water contours.

Groundwater quality in the Sherwood Sandstone Group is generally good but high nitrate concentrations occur beneath Nottingham as a result of leaking sewers (Barrett *et al*., 1997).

5. SITE INVESTIGATION

5.1 Aims of the Investigation

The investigation focused on obtaining core material from the unsaturated and saturated zones beneath the graves, from which pore-water could be obtained and analysed to produce geochemical depth profiles. These, and analysis of groundwater taken directly from the boreholes, would be used to assess the degree of contamination from the cemetery. Drilling only took place after exhumation of the graves. The original intention was to obtain a background "uncontaminated" profile through the unsaturated zone outside the cemetery, but this was not possible due to access restrictions and the danger posed by man-made caves

5.2 Exhumation

Exhumation of the graves, was undertaken by John Samuels Archaeological Consultants under licence from the Ecclesiastical Faculty and the Home Office. After removing the tarmac surface, topsoil and overburden were excavated to a depth of 3 m using a hydraulic back-actor fitted with a toothless bucket. Three burials in one grave were common, and the coffins were completely degraded and the skeletons compressed. Once the grave cuts were exposed, mechanical excavation ceased and the remains removed by hand-digging and individually bagged for reburial at Wilford Cemetery, Nottingham. All the graves were recorded and mapped. The excavations were back-filled with the overburden. Samples of the material surrounding and directly below the skeletal remains (called the “grave cut”) were provided to BGS by the archaeologists.

The risk of contamination or infection from the remains was considered to be no worse than normally encountered in exhumation work (pers. comm. Forbes Marston, John Samuels Archaeological Consultants). Personal protective equipment included dust masks and latex gloves, which were worn at all times.

5.3 Drilling and Core Sampling

Three boreholes were drilled at the locations shown in Figure 1. Boreholes NIR1 and NIR3 were in areas of high grave density while borehole NIR2 was located where the grave density was relatively low. BB Drilling of Nottingham were contracted to drill and core three boreholes to obtain continuous samples to approximate 3 m below the water table. A tractor mounted rotary rig (Dando 250) with integral air compressor, was used (Plate 1). To avoid contaminating the cores during drilling, no fluids apart from air were introduced into the borehole unless unavoidable for progress. In the unconsolidated sand (to depths of between 6 and 7 m bgl), samples were collected using a 15 cm diameter dry sampler. The more consolidated sandstone below was collected in rigid plastic core liners. All core liners were sealed immediately upon collection and, each night, were transferred into cold storage at 4°C. Because of the weathered nature of the sandstone, full core recovery was not always achieved, particularly in borehole NIR2 where no samples were collected from the saturated zone.

Plate 1. Dando Drilling Rig

5.4 Groundwater Sampling and On-Site Chemical Analysis

Groundwater samples were collected on intercepting the water table and after reaching total depth in boreholes NIR1 and NIR3. Groundwater was collected using a Teflon bailer cleaned with Decon 90 and rinsed with de-ionised water between sampling to avoid cross-contamination. Temperature, pH, electrical conductivity (EC), redox potential (Eh) and dissolved oxygen concentration (DO_2) were determined on the unfiltered bulk sample using calibrated ion selective electrodes and colorimetric field techniques. Alkalinity was determined using a 25 ml filtered aliquot of sample titrated with 0.1 M H_2SO_4 to the bromocresol green end-point using a Hach portable titrator. Ammonium was determined on-site using Quantofix ammonium test sticks. Samples for laboratory determinations were filtered through 0.45 µm cellulose acetate membrane filters prior to preservation. The samples were kept in a cold box in the field and transferred each evening to cold storage. The methods of sample preservation and analysis are given in Table 4.

Blank samples were also collected. These included a sample blank, consisting of laboratory deionised water collected in the bailer, filtered and preserved in the same way as the other samples, and a deionised water blank analysed without any handling, filtration or preservation.

Table 4. Groundwater preservation and analysis scheme

Filtration	Preservation	Analysis	Method
0.45 µm	none	anions	Ion Chromatograph
0.45 µm	1% HNO_3	cations	ICP-AES; AFS
0.45 µm	0.1% 2,2-bipyridyl	reduced iron	Colorimetry
0.45 µm	1% H_2SO_4	ammonium	Flow Injection colorimetry
none	1% NaOH	reduced sulphur	Hydride Generation ICP-AES
none	none	organics	GCMS
none	fixative	total bacteria	Epifluoresence microscopy

5.5 Pore-water extraction Extraction by Centrifugation

Pore-water from cores recovered from the unsaturated and saturated zones was obtained by drainage centrifugation, a technique which has been widely applied to the extraction of pore-waters from unsaturated materials (Edmunds and Bath, 1976). The core material was crushed to approximately pea-sized fragments and transferred immediately to a previously weighed centrifuge bucket consisting of an upper sample holder above a detachable collecting cup separated by a glass-fibre filter mounted on a perforated titanium disk. The buckets were capped to prevent evaporative loss during centrifugation and balanced to a tolerance of ±0.1 g. Samples were spun at 14,000 rpm for 30 minutes at 10°C using a MSE High Speed 25 centrifuge. Pore-water was collected from the sampling cup and filtered through a 0.45 µm membrane prior to preservation for chemical analysis as in Table 4. Because of the small volumes of pore-water collected, it was not always possible to carry out a complete chemical analysis.

5.6 Moisture Contents

Moisture contents were determined by drying the core samples at 105°C to constant weight (Table 5). The gravimetric water content was converted to a volumetric water content assuming an average porosity of 0.24 and a grain density of 2,650 kg m^{-3} for the sandstone using the formula:

$$\textbf{volumetric moisture content} = \textbf{gravimetric moisture content} \ (1-\theta)\ \rho_g$$

where θ = porosity

ρ_g = grain density

Table 5. Gravimetric moisture content of core samples (% wt/wt)

NIR1 Depth m bgl	Moisture content	NIR2 Depth m bgl	Moisture content	NIR3 Depth m bgl	Moisture content	Grave cuts	Moisture content
2.61	9.93	2.59	7.94	2.75	9.89	gc1	10.2
3.30	8.04	3.35	4.95	4.60	6.97	under gc1	6.38
3.56	8.63	4.60	7.36	4.80	n/s	gc2	16.7
4.25		4.95	7.83	4.95	9.35	under gc2	15.2
4.40	9.15	5.30	8.15	5.15	10.88		
4.50	8.52	5.95	8.88	5.65	6.80		
4.60	7.87	6.25	7.52	5.95	9.31		
4.75	10.4	6.55	8.26	6.10	9.94		
6.08	6.91	8.93	6.51	6.45	8.17		
8.60	6.12			6.60	11.1		
11.6	6.21						

5.7 Chemical Analysis

Groundwater and pore-water samples were analysed for major and trace inorganic constituents. Major cations (Ca, Na, Mg, K), trace metals (Ba, Sr, Mn, Fe, Al, Co, Ni, Cu, Zn, Cr, Mo, Cd, Pb, V, Li), total P, total S, Si and B were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES). Major and trace anions (Cl, SO_4, NO_3, NO_2, Br, HPO_4) were determined by ion chromatography. pH and alkalinity were determined by automated titrimetry. Ammonium was determined by flow injection colorimetry. TOC and TIC were determined by automated combustion with non-dispersive infra-red detection. Reduced sulphur was determined by hydride generation ICP-AES. Reduced iron was determined by colorimetry. Arsenic and selenium speciation and total mercury were determined by hydride and vapour generation atomic fluorescence respectively. All chemical analysis was carried out using quality assured methods compliant with the International Standard BS EN ISO 9001: 1994. Groundwater and selected pore-water samples were analysed by GC-MS for a range of organic compounds by SAC Scientific and M-Scan Ltd operating to UKAS Standards. Samples were extracted with 2 x 10 mL of dichloromethane (DCM) after the addition of known amounts of internal standards. Each DCM extract was concentrated by rotary evaporation and dry-nitrogen blow down and a 1 μL aliquot analysed by gas chromatography-mass spectrometry (GC-MS).

A small number of solid samples, including samples from the grave cuts, were analysed for total major and trace element content by x-ray fluorescence spectrometry (XRFS).

5.8 Microbial Analysis

Bacteriological analysis for total and thermo-tolerant (faecal) coliforms was carried out on-site using an Oxfam-Delagua portable water testing kit (Robens Institute). A measured quantity of water was passed through a sterile filter to trap bacteria. The filter was placed onto a paper pad soaked in liquid growth medium, which supports coliform bacteria but inhibits others. Two filters were prepared for each sample by incubating at 44°C and 37°C for 16 to 18 hours, to allow colonies of bacteria to form.

6. RESULTS

6.1 Summary of Samples Obtained and Analyses Performed

A summary of the samples obtained and the analysis performed is given in Tables 6 and 7.

Table 6. Summary of samples obtained and analyses performed.

Borehole NIR 1			Borehole NIR 2			Borehole NIR 3		
Depth m bgl	Type	Analysis	Depth m bgl	Type	Analysis	Depth m bgl	Type	Analysis
2.61	PW	I	2.59	PW	I	2.75	PW	I
3.30	PW	I	3.35	PW	I XRF	4.60	PW	I
3.56	PW	I	4.60	PW	I	4.80	PW	I XRF
4.25	PW	I XRF	4.95	PW	I	4.95	PW	I
4.40	PW	I	5.30	PW	I	5.15	PW	I O
4.50	PW	I	5.95	PW	I	5.65	PW	I
4.60	PW	I	6.25	PW	I	5.95	PW	I
4.75	PW	I O	6.55	PW	I O	6.10	PW	I
6.58	PW	I	8.93	PW	I	6.45	PW	I
8.60	PW	I	11.00	GW	I O MB	6.60	PW	I
11.60	PW / GW	I O MB				11.0	GW	I O MB
13.77	PW	I				13.0	GW	I O MB
						14.3	PW	I
14.89	PW /GW	I O MB						
17.80	PW	I						

I = inorganic analysis; O = organic analysis; MB = microbiological analysis;
XRF = solids analysis

Table 7. Summary of analysis performed on grave cut samples.

Grave Cut 1		Grave Cut 2		Under Gave Cut 1		Under Gave Cut 2	
Type	Analysis	Type	Analysis	Type	Analysis	Type	Analysis
PW	I XRF	PW	I O XRF	PW	I	PW	I

I = inorganic analysis; O = organic analysis; XRF = solids analysis

6.2 Analysis of Grave Cuts

Results of inorganic analysis of the pore-water from Grave Cut 2 are presented in Appendix 1a. Solid analysis data for grave cuts and selected core samples are presented in Appendix 1b. Organic analysis data of the pore-water from Grave Cut 2 are presented in Table 8.
The grave cuts were visibly different from the underlying sandstone (Plate 2), being much darker in colour, and believed to be due to organic residue derived from the breakdown of body fat. Organic analysis of the solid grave cut material was not undertaken. X-Ray Fluorescence Spectrometry analyses of solid material from the two grave cut samples and on one solid sample from each borehole (Appendix 1b) show the grave cuts to contain higher concentrations of phosphorous, calcium, copper and zinc than the cores
Pore-water from the grave cuts contain elevated concentrations of Ca, Na, Mg and K with SO_4 and Cl at concentrations typically double those found in the pore-waters in cores below the grave cut (see Section 6.3). TOC was up to 13.8 mg L^{-1} and Mn was less than 0.43 mg L^{-1}. NH_4 was low at < 2.5 mg L^{-1} but 39.1 mg L^{-1} of NO_3 was present in pore-water from Grave Cut 2.

Trace element concentrations in the grave cut pore-water are similar to those in the cores with the exception of strontium, aluminium and boron, which again are typically double. Grave Cut 1 contained 103 μg L^{-1} selenium but arsenic was below the limit of detection.

Plate 2. Comparison of the material from the grave cut (right) and core material from the unsaturated zone (left) in borehole NIR1.

6.3 Pore-water Chemistry in Core Samples

6.3.1 Analytical results

The results of the inorganic analyses of the pore-water samples from boreholes NIR1, NIR2 and NIR3 are presented in Appendices 2a, 2b and 2c respectively. Organic analyses for pore-water samples is given in Table 8.

Table 8. Results of organic analysis of pore-water

Borehole/Cut		NIR1	NIR2	NIR3	Grave Cut 2
Depth	mbgl	4.75	6.55	5.15	~3
Compound					
Chlorinated hydrocarbon	µg/l	1.3	2.6	1.6	1.7
pentanoic acid	µg/l	2.3	4.8	1.2	
Branched alkane	µg/l	2.3	3.5	1.9	
Dipropylene glycol monomethyl ether	µg/l		3.6	2.6	
2-Ethylhexanol	µg/l	15	7.4	5.9	3.3
Methanol	µg/l			1.9	
2-Phenoxyethanol	µg/l		2.7		
unknown	µg/l		1.5		
unknown	µg/l	3.4			
Phthalic anhydride	µg/l	1.1	1.9		
Ester of propionic acid	µg/l		13	19	
Ester of propionic acid	µg/l		16	27	
Napthene	µg/l		3.2		
Diethyl phthalate	µg/l	2	24	9.6	
Alkyl cyclohexanediol / benzophenone	µg/l	7	20	28	1.5
Branched alkane (possibly chlorinated)	µg/l	1.9			
Alkene	µg/l	3.4	2.3		
Branched alkene	µg/l	1.5			
Dibutyl phthalate	µg/l	27	97	100	7.2
2,2-Dimethoxy-1,2-diphenylethanone	µg/l			3.3	
Dibutyl phthalate	µg/l	3	3.6	2.2	
Dihexyl phthalate	µg/l		2.2	1.5	
Dioctyl phthalate	µg/l	6.8	5	7.1	3.2

6.3.2 Inorganic components and TOC

(a). Borehole NIR1

The moisture content profile (Figure 3) suggests a perched water table at 4.40 m bgl where the moisture content approaches 33.3 % similar to the expected porosity of the sand.

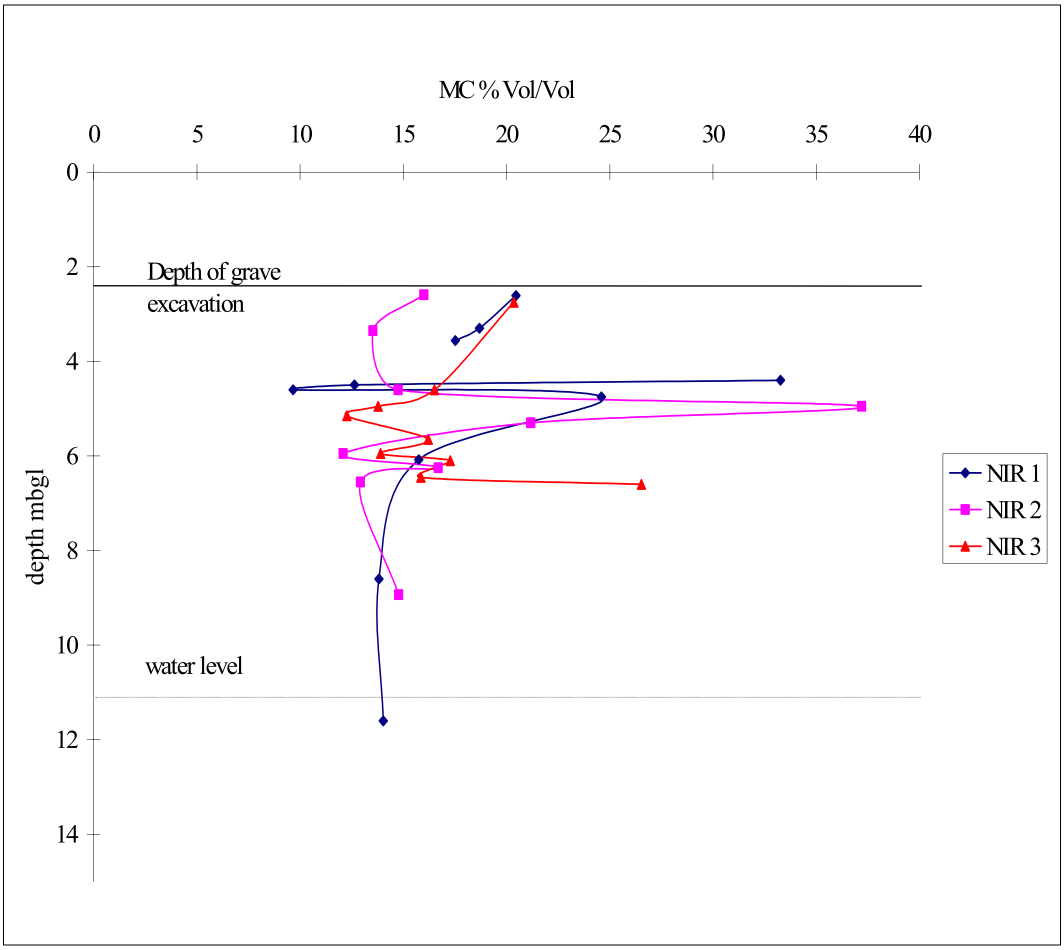

Figure 3. Volumetric moisture content in cores from boreholes

The Piper diagram for NIR1 (Figure 4) shows distinct clusters for the compositions of the unsaturated zone pore-water and the groundwater (discussed in Section 6.4), with pore-water samples centrifuged from the saturated zone (below 9.5 m bgl) clustered with an intermediate composition.

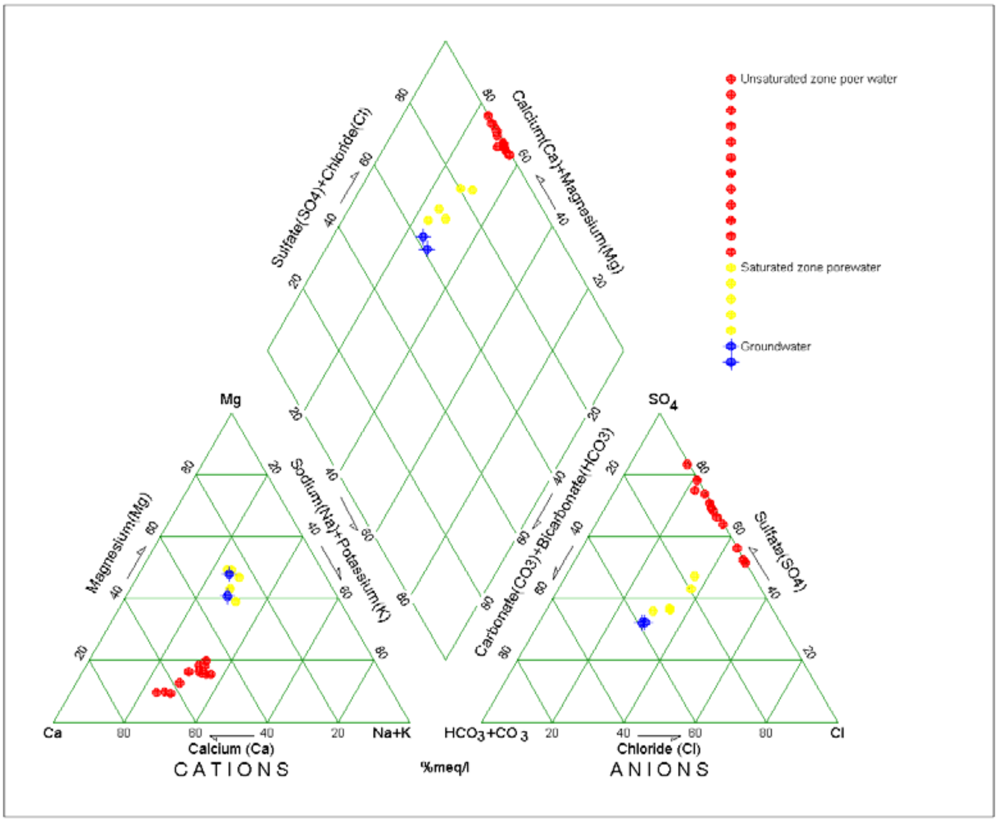

Figure 4. Piper diagram for pore-water from cores from borehole NIR1

The Stiff diagram (Figure 5) shows that the unsaturated zone is dominated by relatively high concentrations of Ca, Na, Mg and K, with SO_4 and Cl as the major anions.

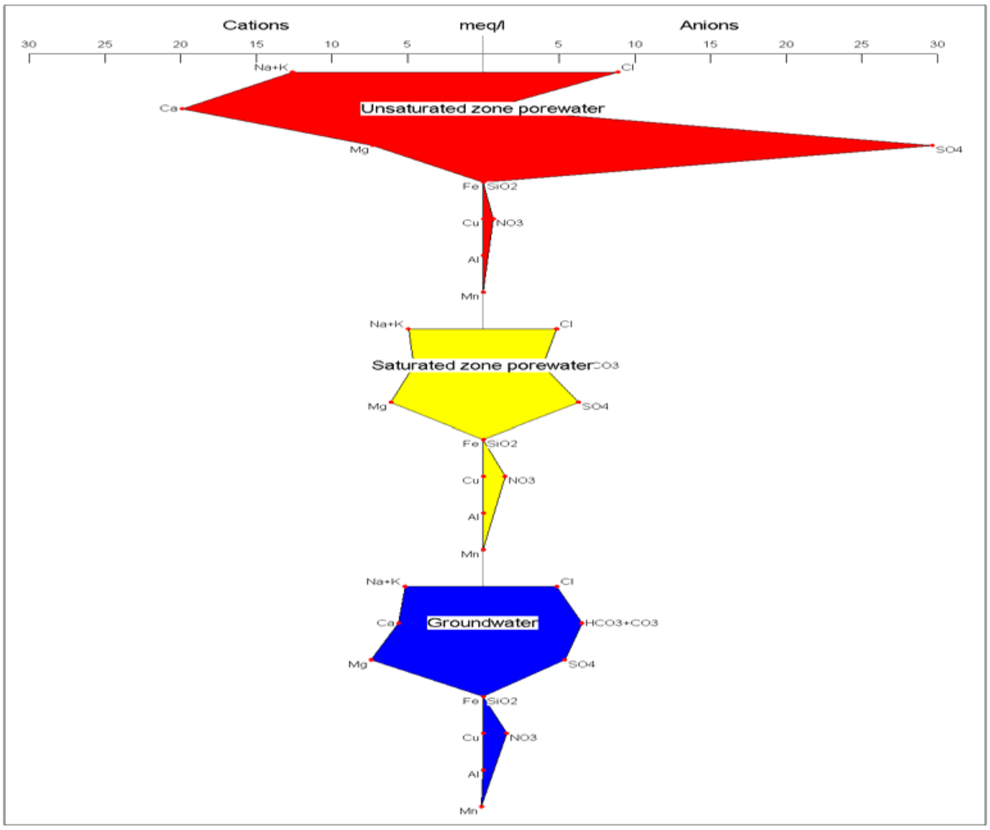

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Figure 5. Stiff plot comparing pore-water and groundwater samples

Solute profiles within the unsaturated zone are given in Figures 6 and 7. TOC peaks at 25 mgL^{-1} at a depth of 4.25 m bgl but is generally below 10 mg L^{-1}. Mn forms two peaks of 11.3 and 10.2 mg L^{-1} at 3.56 m bgl and 4.75 m bgl respectively, the latter coinciding with the TOC peak and a small NH_4 peak of 2.68 mg L^{-1} at 4.75 m bgl. Nitrate does not exceed 12.4 mg L^{-1} to a depth of 4.75 m bgl, but below 5.8 m increases to over 60 mg L^{-1} in the unsaturated zone and up to 97 mg L^{-1} in the saturated zone. Sr mirrors the Ca concentration (not shown).

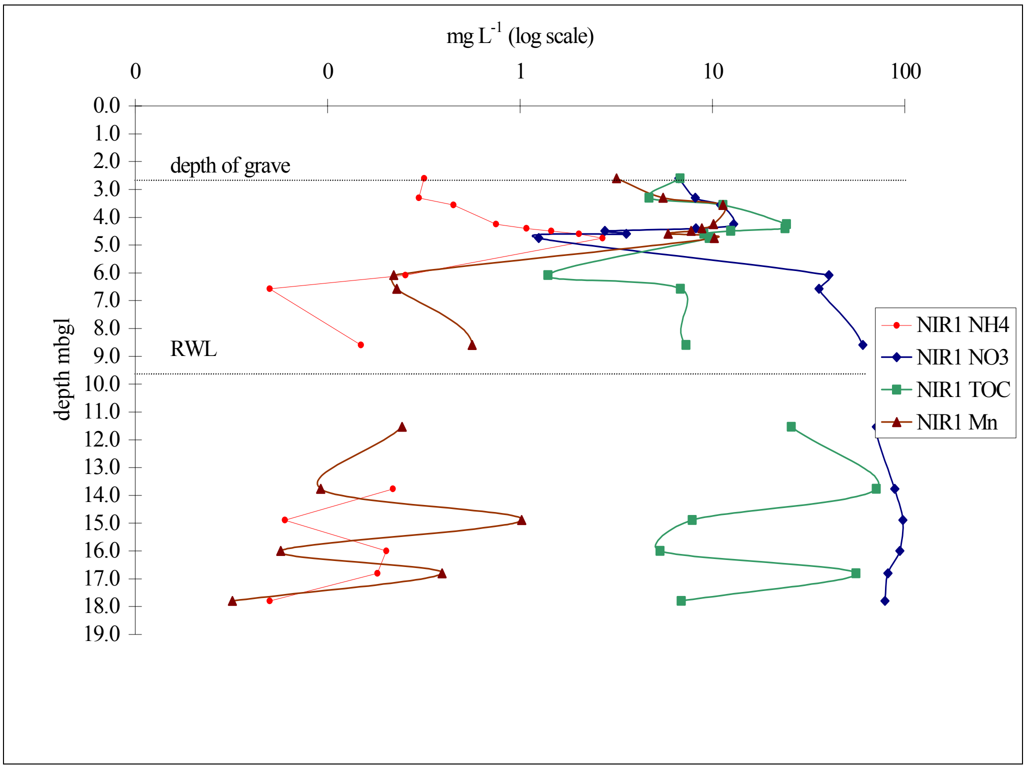

Figure 6. Pore-water profiles for NH_4, NO_3, TOC & Mn in cores from borehole NIR1

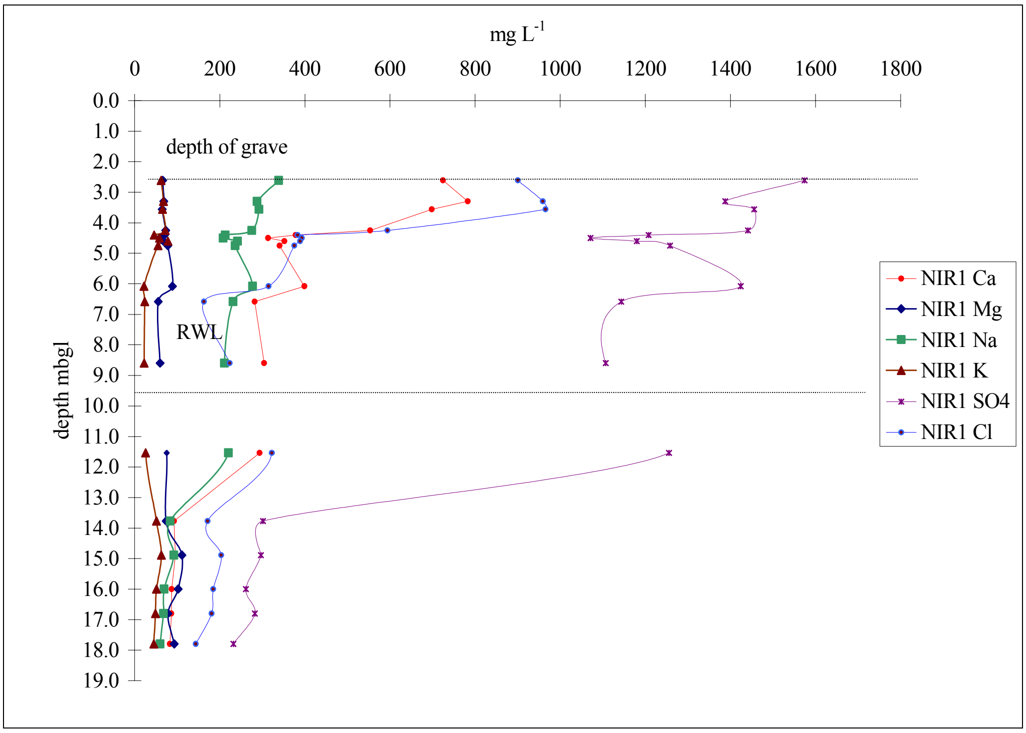

Figure 7. Pore-water profiles for Ca, Mg, Na, K, SO_4 & Cl in cores from borehole NIR1

(b). Borehole NIR2

The moisture content peaks at 38% by volume at 4.95 m bgl suggesting that there is a perched water table at this depth (Figure 3). The Piper diagram and depth profiles for borehole NIR2 show the unsaturated zone pore-water to be dominated by Na, Ca, Mg and K with SO_4 and Cl very similar to that found in borehole NIR1, but again distinctly different in character from the groundwater (Figures 8 and 9).

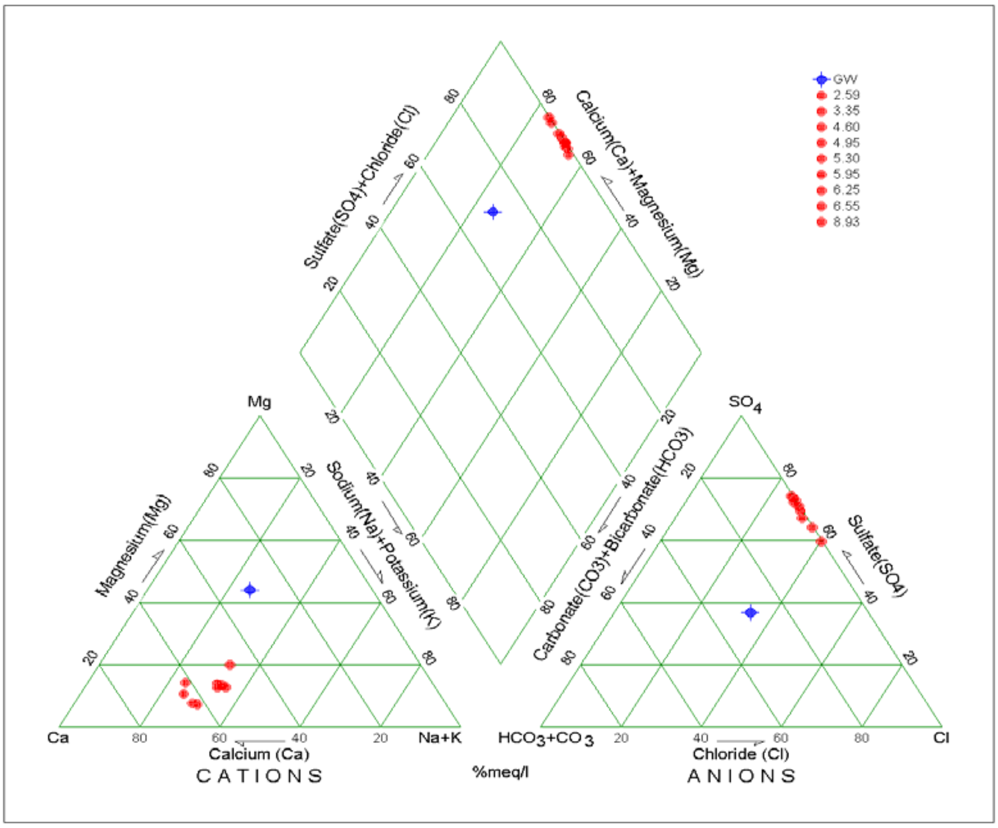

Figure 8. Piper diagram for pore-water from cores from borehole NIR2

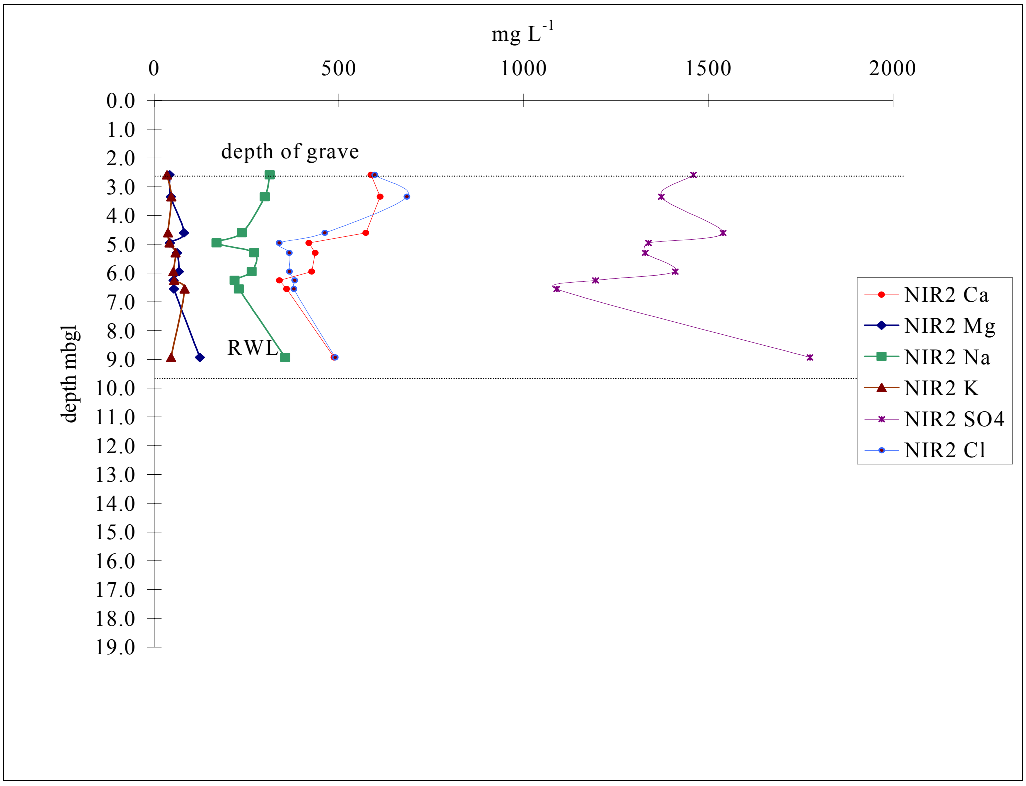

Figure 9. Pore-water profiles for Ca, Na, Mg, K, SO_4 & Cl in cores from borehole NIR2

TOC shows a peak of 17.6 mg L^{-1} at 2.59 m bgl and a second peak of 16.5 mg L^{-1} at 6.25 m bgl (Figure 10). NH_4 concentrations are low throughout the profile at <2.5 mg L^{-1} but NO_3 peaks at 38.5 mg L^{-1} at 5.3 m bgl. Mn is elevated with a peak of 13.6 mg L^{-1} at 5.95 m bgl and a smaller peak at 4.6 m bgl. Al and Si concentrations reduce slightly with depth but other trace elements (Zn, B, Fe) have no apparent trends.

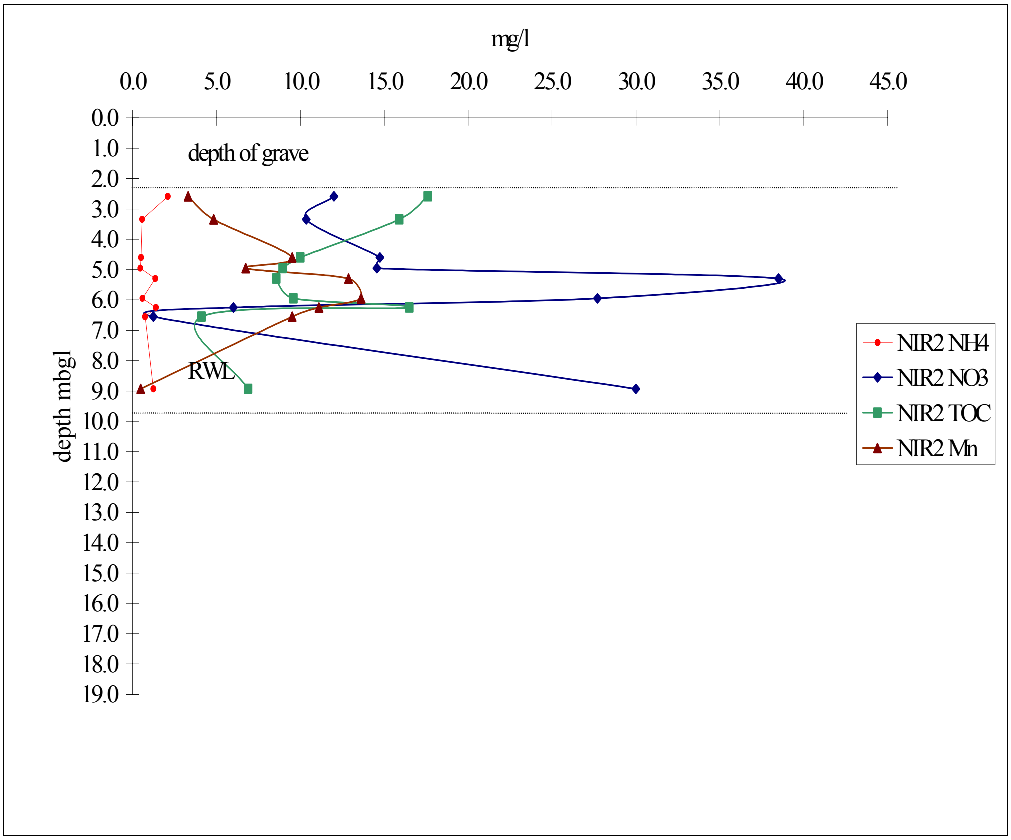

Figure 10. Pore-water profiles for NH_4, NO_3, TOC & Mn in cores from borehole NIR2

(c) Borehole NIR3

The moisture content varies between 12 - 26% by volume and probably approaches saturation (Figure 3).

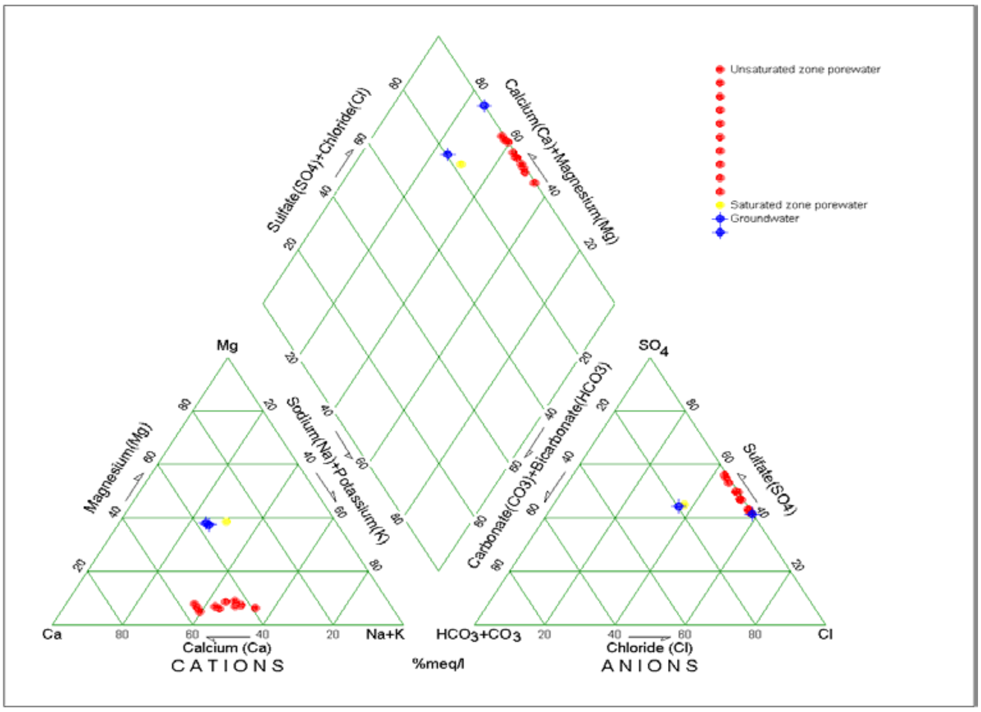

Figure 11. Piper diagram for pore-water from cores from borehole NIR3

As with the other profiles, the unsaturated zone pore-water is dominated by Na, Ca, Mg and K with SO_4 and Cl (Figures 11 and 12). TOC is low at 10 mg L^{-1} and both NH_4 and NO_3 are < 2.5 mg L^{-1}. However, NO_3 reaches 159 mg L^{-1} in the groundwater below

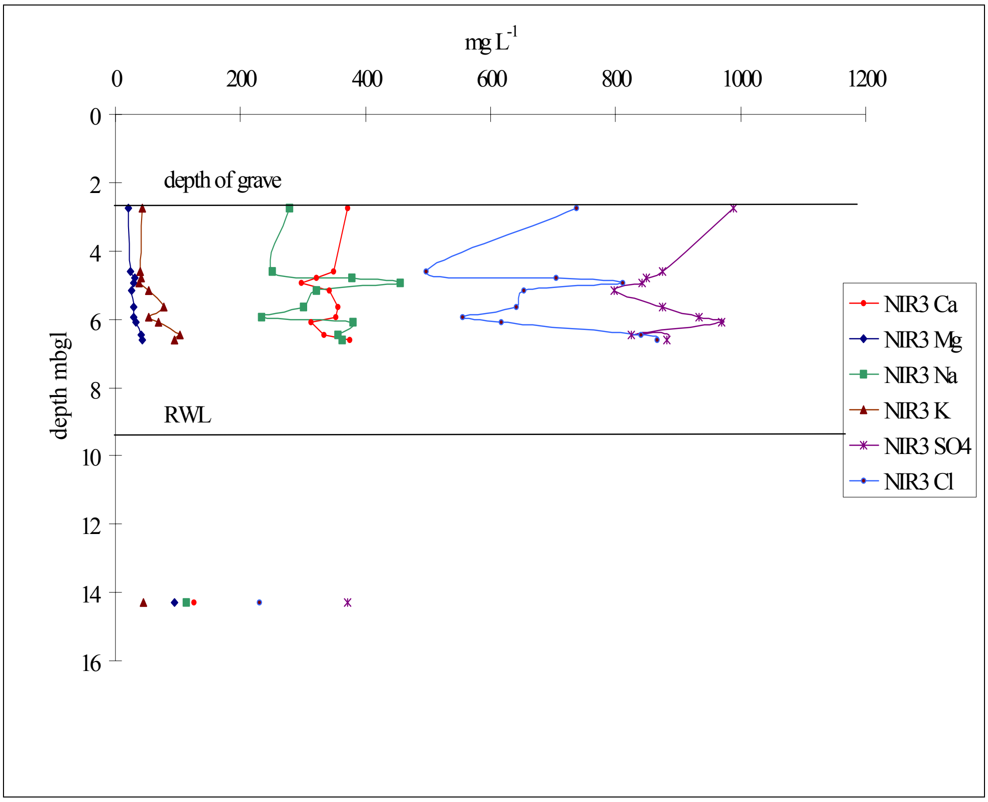

Figure 12. Pore-water profiles for Ca, Na, Mg, K, SO_4 & Cl in cores from borehole NIR3

6.3.3 Organic Constituents

Because of the low sample volume obtained, organic analysis was only carried out on selected pore-waters from the unsaturated zone (Table 8). All samples are dominated by phthalates particularly boreholes NIR2 and NIR3, however, concentrations in the grave cuts were substantially lower. Phthalates particularly the dioctyl phthalates, are common plasticisers but dibutyl phthalate is used as a textile lubricant and is impregnated into clothing as an insect repellent. Other industrial compounds include tetrachloroethane and 2-ethylhexanol used for dry cleaning and cotton strengthening respectively.

Table 8. Results of organic analysis of pore-water

Borehole/Cut		NIR1	NIR2	NIR3	Grave Cut 2
Depth	mbgl	4.75	6.55	5.15	~3
Compound					
Chlorinated hydrocarbon	µg/l	1.3	2.6	1.6	1.7
pentanoic acid	µg/l	2.3	4.8	1.2	
Branched alkane	µg/l	2.3	3.5	1.9	
Dipropylene glycol monomethyl ether	µg/l		3.6	2.6	
2-Ethylhexanol	µg/l	15	7.4	5.9	3.3
Methanol	µg/l			1.9	
2-Phenoxyethanol	µg/l		2.7		
Phthalic anhydride	µg/l	1.1	1.9		
Ester of propionic acid	µg/l		13	19	
Ester of propionic acid	µg/l		16	27	
Napthene	µg/l		3.2		
Diethyl phthalate	µg/l	2	24	9.6	
Alkyl cyclohexanediol / benzophenone	µg/l	7	20	28	1.5
Branched alkane (possibly chlorinated)	µg/l	1.9			
Alkene	µg/l	3.4	2.3		
Branched alkene	µg/l	1.5			
Dibutyl phthalate	µg/l	27	97	100	7.2
2,2-Dimethoxy-1,2-diphenylethanone	µg/l			3.3	
Dibutyl phthalate	µg/l	3	3.6	2.2	
Dihexyl phthaltae	µg/l		2.2	1.5	
Dioctyl phthalate	µg/l	6.8	5	7.1	3.2

Alkyl cyclohexanediol/benzophenone is present in all samples including the grave cut but its significance is not known. Pentanoic acid and esters of propionic acid which could be a breakdown product of body derived organics is found in some unsaturated zone samples but not in the grave cut (Vass *et al*., 1992).

6.4 Groundwater Chemistry

6.4.1 Analytical results

The results of the inorganic, and organic analyses of the groundwater samples are presented in Appendices 3a, and 3b. Results of microbiological tests are given in Table 10.

6.4.2 Major components

Major cation and anion chemistry data for groundwater samples collected from the three boreholes have been plotted on a Piper Diagram (Figure 13). The waters are calcium-magnesium and chloride-sulphate dominated with calcium values in the range 106 to 330 mg L^{-1} and magnesium in the range 90 to 205 mg L^{-1}. Calcium is also associated with carbonate ions in the groundwater. Both bulk samples from boreholes NIR1 and NIR2 and the water table sample from NIR3 (NIR3/1) correlate closely in their major cation chemistry. However, the groundwater sample from borehole NIR3/2 correlates more closely with pore-water chemistry from the same depth. Potassium concentrations are in the range 50 to 60 mg L^{-1} which are high for natural groundwater systems. Chloride and sulphate concentrations are also relatively high; values for chloride range from 172 mg L^{-1} in borehole NIR1 to 720 mg L^{-1} in borehole NIR3 and sulphate values range from 258 to 772 mg L^{-1}. Elevated nitrate concentrations occur in all boreholes, although ammonia is low. All major ions except for sodium exceed the World Health Organisation guide concentrations for substances in drinking water (WHO, 1993). While not necessarily harmful to health, these may give rise to complaints from consumers. The concentrations of nitrate in all the groundwater samples are at least double the 50 mg L^{-1} WHO Guideline Value for nitrate in drinking water.

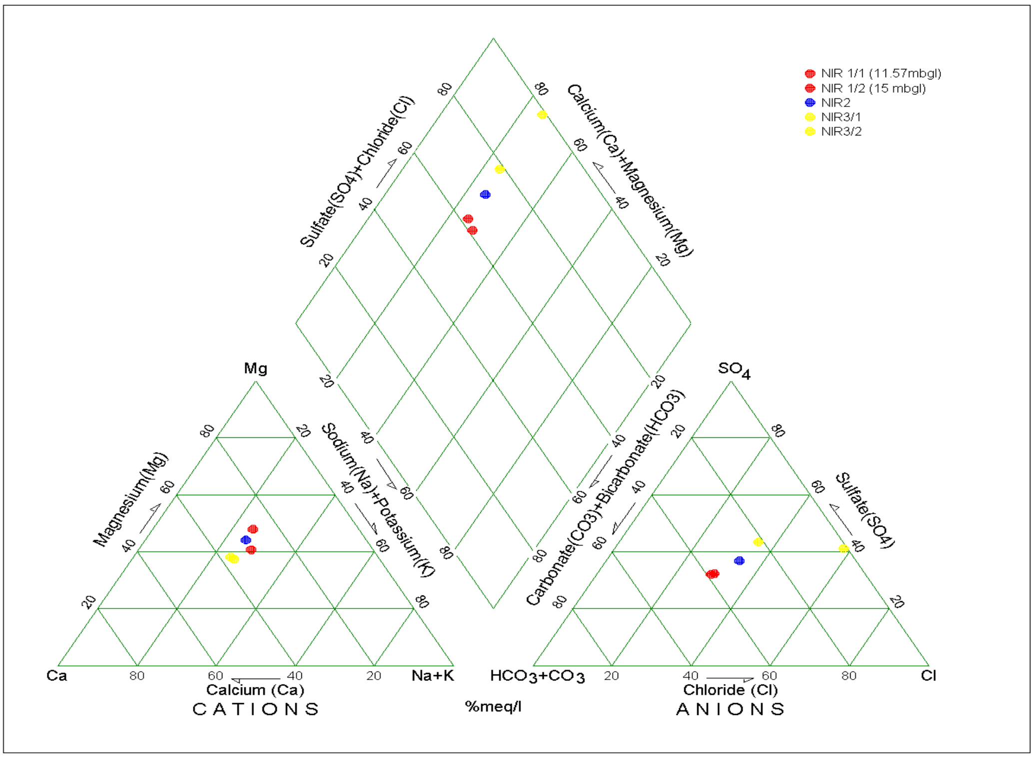

Figure 13. Piper diagram for groundwater from boreholes NIR1, NIR2 and NIR3

6.4.3 Trace Components

Most of the trace elements present in the groundwater are below the analytical limit of detection, although elevated concentrations of manganese (3.5 mg L^{-1} in NIR1), iron (9.8 mg L^{-1} in NIR3), aluminium (4.57 mg L^{-1} in NIR3), boron (0.85 mg L^{-1} in borehole NIR3), arsenic (23.9 mg L^{-1} in borehole NIR3) and selenium (6.56 mg L^{-1} in borehole NIR3) were detected. All of these values exceed WHO (1993) guide concentrations for drinking water. Trace concentrations of mercury were detected in boreholes NIR2 and 3. Total organic carbon in the groundwater is generally low (4.55 mg L^{-1} in borehole NIR2).

6.4.4 Organic compounds

A broad scan was carried out on the groundwater samples for haloforms and chlorinated solvents, PCBs as congeners, PAHs, BTEX and VFAs. Oils and toluene extractable material were also analysed (Table 9). There was no evidence of groundwater pollution by specific organic compounds. A low concentration of acetic acid at 6.3 mg L^{-1} was found in borehole NIR2, but BTEX compounds were all below the limit of detection. PAHs were also below detection limits in all samples except for acenaphthylene at 1.3 µg L^{-1} in borehole NIR1. Haloforms and chlorinated solvents were detected in some of the groundwater samples. None of the concentrations obtained exceeded WHO guide levels (WHO 1993). All of the compounds detected are thought to be used in the textile industry.

Table 9. Results of GCMS analysis of groundwater samples

Haloforms and chlorinated-solvents	units	NIR1/2	NIR2/1	NIR3/2
Carbon tetrachloride	µgL^{-1}	0.1	0.1	<0.1
Tetrachloroethylene	µgL^{-1}	0.5	0.3	<0.2
1,1,1-trichloroethane	µgL^{-1}	0.5	0.5	0.4
PAH				
Acenaphthylene	µgL^{-1}	1.300	<0.050	<0.050
Napthalene	µgL^{-1}	0.067	<0.050	<0.050
Volatile Fatty Acids				
Acetic acid	mgL^{-1}	<3.0	6.3	<3.0
Oils by GC	µgL^{-1}	22.0	<10.0	50.0
Toluene extractable	mgL^{-1}	7.0	2.0	1.0

6.5 Microbiology

Groundwater samples were analysed for total and thermo-tolerant (faecal) coliforms in the field and results are given in Table 10. Only borehole NIR2 produced a positive total coliform result of 46 colonies in 100 ml of filtered groundwater incubated at 37°C for 16 hours. All groundwater samples were analysed for total bacterial counts using epifluorescence microscopy. Results indicate average background concentrations of 1.38×10^5 bacteria mL^{-1}.

Table 10. Results of microbiological analysis on pore-water samples.

	NIR1/2	NIR2/1	NIR3/2
Total Bacteria	7.46×10^4 bacteria per ml	2.08×10^5 bacteria per ml	1.30×10^5 bacteria per ml
Total coliforms	None detected	46 counts per 100ml	None detected
Faecal coliforms	None detected	None detected	None detected

6.6 Summary of Results

The results of the investigation can be summarised as follows:-

- Analysis of the grave cut solid phase revealed elevated concentrations of P, Ca, Cu and Zn when compared to core from the unsaturated zone
- Pore-water from the grave cuts contains elevated concentrations of Ca, Na, Mg and K in conjunction with Cl and SO_4.
- The moisture contents of the unsaturated zone are around 20 % by volume in the sand immediately below the graves falling to about 15% in the consolidated sandstone below.
- Thin perched water tables may exist in each borehole between 4 – 6 m bgl where moisture contents reach up to 38% vol. /vol.
- The unsaturated zone contains relatively high concentrations of Ca, Na, Mg and K with Cl and SO_4 at near neutral pH. Highest concentrations occur immediately below the graves.
- TOC appears to form a peak below the graves in boreholes NIR1 and NIR2 but at concentrations below 25 mg L^{-1}.
- NH_4 forms a small peak of 2.68 mg L^{-1} at a depth of 4.75 m bgl in borehole NIR1 but below, NO_3 dominates the profile. NO_3 is also the dominant species of nitrogen in borehole NIR2, but both NH_4 and NO_3 are low in borehole NIR3.
- Mn appears as a peak in all profiles corresponding with peaks of TOC and NH_4.
- Anthropogenic organic compounds in the unsaturated pore-water include chlorinated hydrocarbons and phthalates.
- The composition of groundwater is significantly different from the pore-water in the unsaturated zone and contains nitrate and a range of anthropogenic organic compounds.

7. DISCUSSION

7.1 Flow in the Unsaturated Zone

The rate of flow of solutes in the unsaturated zone is related to the moisture content, infiltration rate and sorption between the solute and the aquifer minerals. For conservative species, migration rates of between 1-2 m.a^{-1} have been reported for the Sherwood Sandstone beneath a landfill site (Young *et al.*, 1994). If the cemetery closed in 1875, at this rate of migration, conservative species would be expected to have migrated through the 7 m unsaturated zone over a hundred years ago. However, if infiltration was lower or sorption significant, solutes from the graves could migrate at much slower velocities and might still be detectable in the unsaturated zone profiles. This is discussed further in Section 8.

The high moisture contents in boreholes NIR1 and NIR3 may also reflect very thin perched water tables (Figure 3). The possibility that the profile encountered is not completely due to vertical migration but could be affected by a lateral input is always a problem in interpreting vertical unsaturated zone profiles and this should be kept in mind.

Chlorinated hydrocarbons such as TCE came into widespread use in the 1930s as industrial solvents particularly in dry cleaning, and are now ubiquitous in urban aquifers. The existence in the unsaturated zone of chlorinated hydrocarbons and phthalates (which were not available when the cemetery was in use) to depths of 6.55 m bgl, in the unsaturated zone profiles indicates that solutes are moving at a rate in excess of 0.1 m a^{-1}.

7.2 Major Components in the Unsaturated Zone

The most obvious feature of the unsaturated zone pore-water is the high concentrations of inorganic constituents Ca, Na, Mg, and K together with SO_4 and Cl. If these were derived from the graves, they should by now have migrated through the unsaturated zone, and their existence suggests that they are from another source.

The ratios of major elements in the pore-water are also dissimilar from those expected from a grave. The elemental composition of a body in percent is given in Table 1. Not all these elements are leachable from a body since the bones remaining in the grave will still contain significant Ca, P and K. Carbon will contribute to insoluble and slowly degradable grave wax. Nitrogen is a dominant element in the body particularly in protein, and this degrades to produce NH_4. This, and other elements such as Na, Cl and S (as SO_4), are likely to be leached from a corpse and as a first approximation they might be expected to be present in leachate in the same ratios as they occur in a body. Vass *et al*., (1998), reported pore-water compositions in soils beneath a corpse which supports this assumption, and shows NH_4 to be by far the dominant solute. The obvious dissimilarity between this and the pore water (Figure 14) suggests that the major solutes in the unsaturated zone are not from the graves. However, the NH_4 peak in borehole NIR1 may represent leaching of the graves and this is discussed in more detail in Section 8. Vass (op. cit.) also states that volatile fatty acids representing the degradation of original organic carbon compounds, are present in the leached water at much lower concentrations than NH_4. Thus, if the concentration of NH_4 can be determined, then the expected concentration of other species in the body leachate may be estimated.

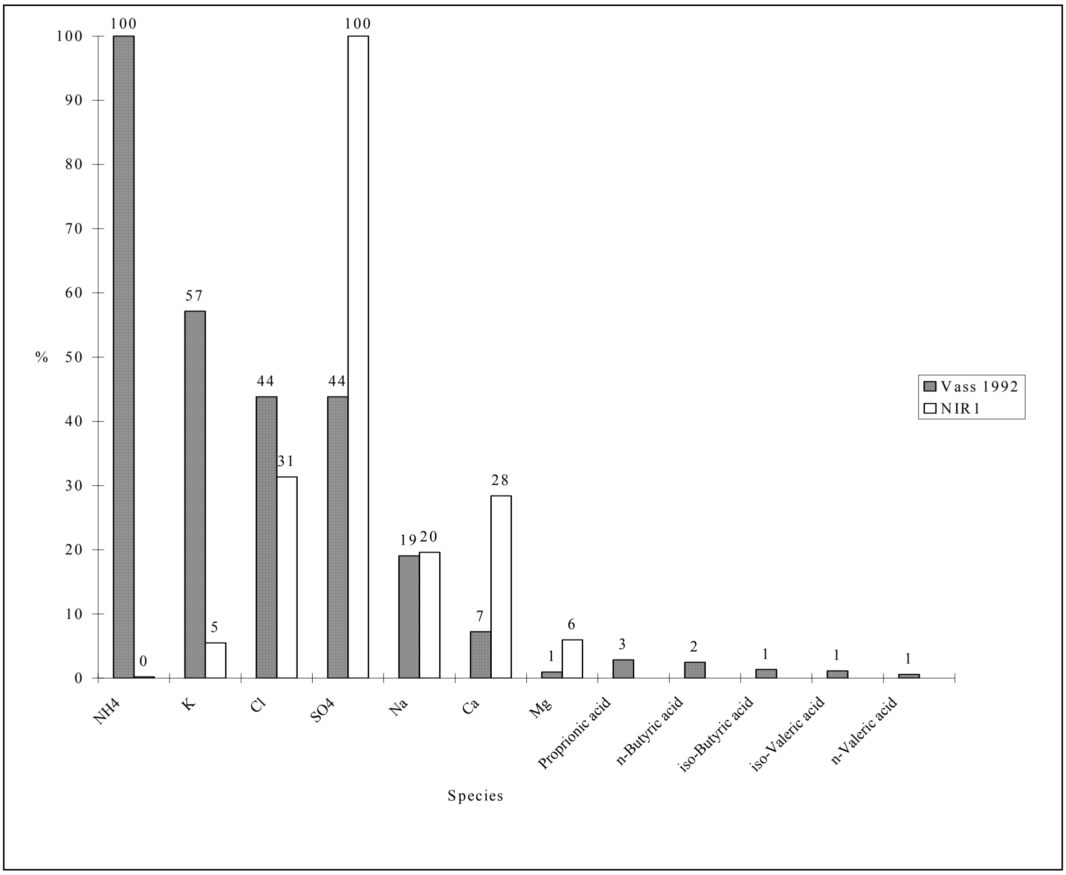

Figure 14. Solutes and VFAs released from a 75 Kg body normalised to NH_4 (after Vass 1992) compared with unsaturated zone pore-water from borehole NIR1 normalised to SO_4.

7.2.1 Geochemical modelling

Geochemical modelling using PHREEQC, (Parkhurst, 1995), was undertaken to identify dominant aqueous species in the pore-water and whether they are saturated and therefore likely to precipitate. PHREEQC (v1.6) is a computer speciation model which describes the distribution of chemical components of a system by modelling the chemical reactions occurring within it assuming that the system is at equilibrium. Each water sample analysed has been modelled.

For the grave cuts Ca is present as free ionic Ca but up to 25% exists as $CaSO_4$. Na is virtually all present as the free ion with a small amount as Na_2SO_4. Mg present at much lower concentrations exists mainly as Mg^{2+} with about 25 –30 % as $MgSO_4$. K exists as the free ion with a small proportion as K_2SO_4.

Similar relationships occur within the pore-waters from the unsaturated zones in all three boreholes and in all cases the $CaSO_4$ is under-saturated which means that it will not precipitate. This is consistent with leaching of a deposit of gypsum near the surface.

7.2.2 Source of the inorganic species

The presence of inorganic species with highest concentrations just below the graves suggest a nearby source. It is not clear whether the source is in the graves or material deposited above them. The bones remaining in the graves were reported by the archaeologists to be in a poor leached state, however, the top-soil and made ground above had already been excavated before this study took place. Previous site investigation (Mini Soil Surveys, 1996) indicated high sulphate concentrations within the top 4 m of made ground (Table 3). Lime, which was commonly placed in plague pits, was not encountered in any of the graves (pers. comm. Forbes Marsden) and there is no evidence of any other deposit in the graves. The pore-water is near neutral pH and not alkaline as would be expected if lime had been used.

An alternative source of contamination may be the chemicals used in the ice rink. However, the ice was made up of mains water only and when allowed to melt was discharged to sewer (pers. comm. Mr Norman Beck, Chief Engineer at Nottingham Ice Rink). The refrigeration system in the Ice Rink did contain a mixture of calcium chloride and ammonia in a sealed system but according to Mr Beck (who has worked at the rink for 40 years), no leaks have ever occurred and the system contents were always tankered away if replaced.

The possibility that chemicals were used in some other manufacturing process nearby or that they had been stored in caves cannot be discounted. The high concentrations of solutes in pore-water relatively near to the surface and their absence in the groundwater would however, reduce the likelihood of the source being a cave.

The source of the Ca and Mg sulphate is not clear; but it could be from plaster rubble utilising gypsum, although the Mg content is unusually high. The source of the sodium chloride may have been road salt used to de-ice the car park above the graves. In the UK most road salt comes from Triassic deposits in Cheshire and like gypsum contains little Mg.

7.2.3 Redox sensitive species

Electron acceptors which can be chemically reduced (such as O_2, NO_3, Mn^{2+}, Fe^{3+}, and SO_4) are required in the microbial oxidation of organic carbon. The order in which electron acceptors are used follows a thermodynamic sequence based on the energy released by the process (Stumm and Morgan, 1981; Table 11). Free oxygen is used initially for aerobic respiration. After this oxygen is depleted, microbes use NO_3, Mn, Fe, SO_4 and CO_2 in that order, so that a set pattern of redox zones may be found in aquifers receiving biodegradable organic materials (Williams, 1998).

The profile in borehole NIR1 shows that immediately below the grave, the pore-water contains relatively high concentrations of Mn which persist down to about 4.5m bgl. This suggests that Mn^{4+} in the solid phase has been reduced to Mn^{2+} which is much more soluble and enters solution. TOC at 18 mg L^{-1} occurs down to 4.5 m bgl, but below this level decreases along with Mn to very low concentrations. Ammonia and nitrate at this depth show an inverse relationship although the decrease in nitrate is not in stoichiometric proportion to the increase in ammonia. This may indicate the preferential denitrification of nitrate to nitrogen gas rather than reduction of nitrate to ammonia, or may reflect a pulse of ammonia rather than nitrate moving down in the profile. The inverse relationship between nitrate and ammonia in borehole NIR1 could also reflect a zone of denitrification/nitrate reduction which only occurs where there is an organic substrate and where the moisture content is high enough to sustain anaerobic decomposition.

Table 11. Sequence of redox reactions in a closed system (after Stumm and Morgan, 1981)
(Organic material is represented as a simplified form)

Aerobic respiration		
$CH_2O + O_2$	→	$CO_2 + H_2O$
Denitrification		
$CH_2O + \frac{4}{5} NO_3^- + \frac{4}{5} H^+$	→	$CO_2 + \frac{7}{5} H_2O + \frac{2}{5} N_2$
Mn(IV) reduction		
$CH_2O + 2\ MnO_2 + 4\ H^+$	→	$CO_2 + H_2O + 2\ Mn^{2+}$
Nitrate reduction		
$CH_2O + \frac{1}{2} NO_3^- + H^+$	→	$CO_2 + \frac{1}{2} H_2O + \frac{1}{2} NH_4^+$
Fe(III) reduction		
$CH_2O + 4\ Fe(OH)_3 + 8\ H^+$	→	$CO_2 + 11\ H_2O + 4\ Fe^{2+}$
Sulphate reduction		
$CH_2O + \frac{1}{2} SO_4^{2-} + \frac{1}{2} H^+$	→	$CO_2 + H_2O + \frac{1}{2} HS^-$
Methanogenesis		
$CH_2O + \frac{1}{2} CO_2$	→	$\frac{1}{2} CH_4 + CO_2$

7.3 Composition of Pore-water and Groundwater

7.3.1 Major inorganic components

Compared with the unsaturated zone pore-water the groundwater samples contain more nitrate (up to 159 mg L^{-1}), iron (9.82 mg L^{-1}) and aluminium (4.57 mg L^{-1}) which are probably derived from other sources. The Sherwood Sandstone aquifer is known to contain high concentrations of nitrate from leaking sewers in urban areas (Barrett *et al*., 1997). Boron and HPO_4 are also good indicators of sewer leakage with up to 0.85 mg L^{-1} and 10.9 mg L^{-1} respectively in borehole NIR3.

7.3.2 Trace components

There is no indication of pollution by trace elements. However, Se in the grave cut pore-water (108 μg L^{-1}) was very much higher than in the groundwater at 4 μg L^{-1} (although sample volume meant that not all pore waters could be analysed for Se, As, and Hg).

Arsenic was found in the groundwater but was below detection in the pore-water from the unsaturated zone. This could mean the bodies were not embalmed at least near where the boreholes were drilled. Enhanced concentrations of Cu and Zn were found in the solid material from the grave cuts, similar to the findings of Knight and Dent (1996) at the Botany

Bay Cemetery, Australia, close to recent graves. These elements are commonly complexed with organic compounds, which allows them to be mobilised in solution. The strontium profile in borehole NIR1 is related in concentration to Ca suggesting that they are probably derived from the same source.

7.3.3 Organics

The pore-water in the grave cuts and underlying cores contain relatively low concentrations of TOC. Pore-water, which has been characterised by GCMS (Table 8), contains trace concentrations of anthropogenic compounds that are all used in the textile industry. The area up-gradient of the cemetery has been the main area of textile manufacture in Nottingham for over one hundred years and is a likely source of these. The groundwater samples contained more anthropogenic organic compounds, again reflecting the industrial/commercial nature of the area where chemical reagents are used in quantity and have direct access to the aquifer.

7.3.4 Microbiology

Total bacteria counts were similar in number to uncontaminated groundwater and no faecal coliforms were identified. Total coliforms were detected in borehole NIR2 but at concentrations below WHO (1993) limits for drinking water. With the limited sampling it is not possible to be definitive about the source of these bacteria. However, the concentrations of B, NO_3 and PO_4 suggest that it may be from a leaking sewer. Bitton *et al.,* (1983) observed that micro-organisms are generally stable in groundwater but degrade over time, so a modern day source rather than the cemetery is favoured.

8 MODELLING SOLUTE PROFILES IN BOREHOLE NIR 1

An attempt was made to simulate the solute profiles in borehole NIR1 using analytical one-dimensional solute transport solutions as given in van Genuchten and Alves (1982).

The expected percolation rate through the unsaturated zone can be estimated knowing the average moisture content (approx. 20% by volume) and the infiltration rate (0.153 $m.a^{-1}$), assuming that flow occurs by piston displacement. Thus the depth of penetration of the annual infiltration into the sandstone gives the downward percolation rate in $m.a^{-1}$ (i.e. 0.2 m of infiltration would produce a percolation rate of 1 $m.a^{-1}$). An infiltration of 0.153 $m.a^{-1}$ will give a percolation rate of 0.76 $m.a^{-1}$. Any reduction in the infiltration rate due to local conditions e.g. trees and/or a surface covering which favours run-off would reduce this percolation rate.

The percolation rate can also be estimated from the NH_4 peak at about 4.75 m bgl in the unsaturated zone profile in borehole NIR1 if it is assumed that this represents a retarded pulse released from the graves. This assumption is tenuous at present and additional evidence in support of its origin would be preferred. Possible identification methods would include determination of stable nitrogen isotope ratios which could be compared with typical values from animal sources.

Assuming the distribution coefficient (K_d) for NH_4 in Triassic Sandstones to be in the range 1.0 – 1.5 ml g^{-1} (Higgo et al., 1999), a retardation factor can be calculated. Using a grain density of 2,650 kg m^{-3} and a moisture content (porosity) of 20%, a retardation factor of between 11.6 and 16.9 (average of 14.25) can be calculated from the following:

Retardation factor $= 1 + [(1-\theta)/\theta)]\ \rho_g.\ K_d$

where θ = effective porosity

K_d = distribution coefficient

ρ_g = grain density

The depth of the graves adjacent to borehole NIR1 are not known precisely, although they would probably have been shallower than 2.61 m bgl where bedrock was intercepted. Many of the graves exposed at the time of this investigation were at, or just above, the bedrock surface. Thus the base of the grave in borehole NIR 1 for the sake of these calculations is taken as around 2.3 m bgl.

For these calculations it was also assumed that the input pulse of NH_4 just lasted for the length of time that the cemetery was in use (from 1813 to 1875). Also, in the absence of definite information, an arbitrary small value of 0.01 m has been assigned to the dispersivity. The result (Figure 15) suggests that the NH_4 pulse is migrating with a velocity of 0.0175 m.a^{-1} and has migrated 2.45 m in 140 years. The average percolation rate of water through the unsaturated zone would then be 0.19 – 0.28 m.a^{-1} (average 0.25 m.a^{-1}).

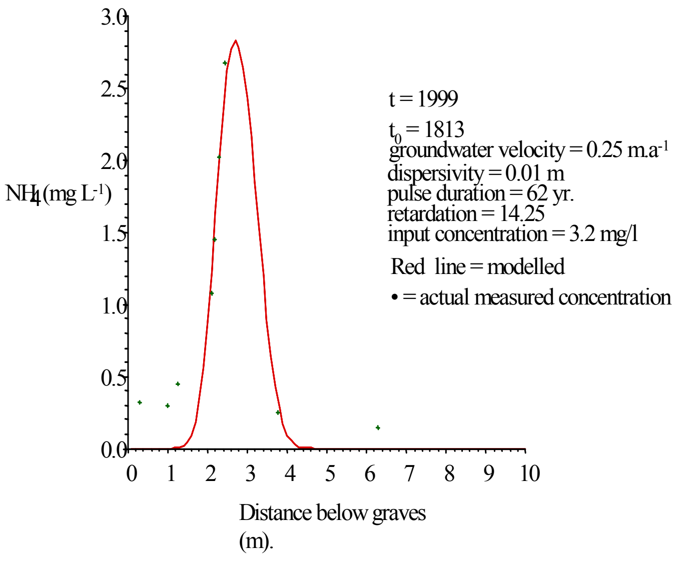

Figure 15. Model of NH_4 transport in the unsaturated zone.

Finally, it is of interest to note how quickly conservative species are removed from the system. Figure 16 shows the movement of an unretarded solute pulse. The initial pulse was arbitrarily set to a five year duration and it is seen that all solute has passed down to the water table within 50 years.

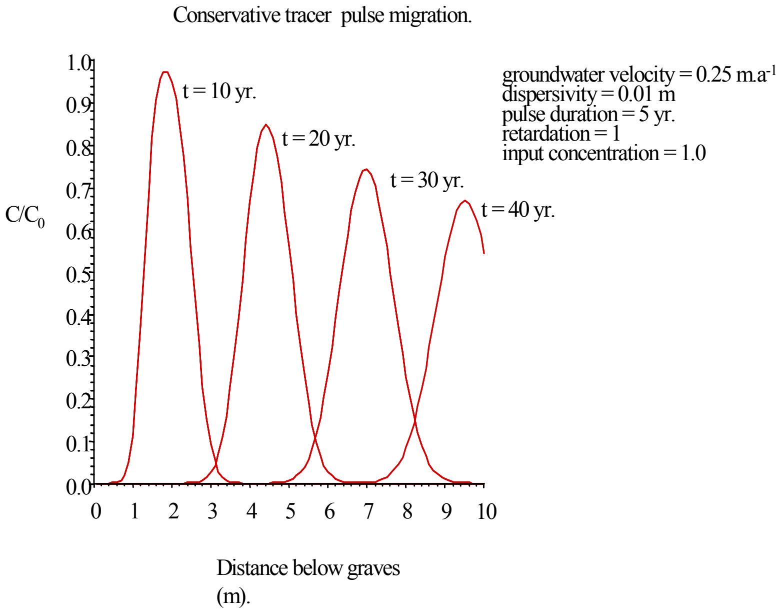

Figure 16. Model of conservative species transport in the unsaturated zone.

The calculations described here all assume that the unsaturated zone is essentially homogeneous and the infiltration rate constant. The moisture content profiles show that this is only a first approximation and that there are significant variations in both infiltration rate and soil properties which at this stage are not possible to evaluate.

9. CONCLUSIONS

The Carter Gate cemetery operated between 1813 and 1875 and contained up to 1100 graves. Drilling three boreholes after the graves had been exhumed allowed pore-water geochemical profiles in the unsaturated zone and saturated zone to be determined.

Pore-water in the unsaturated zone contains inorganic solutes, principally Ca, Na, Mg and K with SO_4 and Cl, in ratios which are inconsistent with the known composition of a body and solutes released from graves. The actual source of these solutes has not been confirmed but may relate to de-icing of the car park which once covered the graves, and/or made-ground containing gypsum waste recorded in the preliminary site investigation report, but removed before the present investigation took place.

Despite the presence of these solutes, the profiles are thought to provide evidence of migration of grave derived material. Immediately below the graves a dark coloured zone (called the “grave cut”) occurs containing elevated concentrations of phosphorous, calcium, copper and zinc. The unsaturated zone pore-water profile in borehole NIR1 contains slightly elevated concentrations of TOC, Mn and NH_4 in pore-water up to 2–3 m below the grave cut.

The Mn in the pore-water may well represent reductive dissolution of the Triassic Sandstones due to biodegradation of organic material leached from the graves and is coincident with the TOC peak. Ammonium is also a dominant solute from graves and is known to be sorbed on Triassic Sandstone (published Kd in the range 1-1.5 mL g^{-1}), giving a retardation factor of between 11.6 –16.9. This explains its occurrence in the unsaturated zone but further support that it is derived from the graves could be obtained by nitrogen isotope ratio analysis. Conservative species such Na, Cl, SO_4 potentially released from the graves would have migrated through the unsaturated zone within a period of 20 years after the cemetery closed.

Pore-water in the unsaturated and saturated zones contains anthropogenic organic compounds which were not used industrially when the cemetery was in use, and their source is probably from nearby 20th century industrial activity. Coliform bacteria were found at the water table in borehole NIR2 but the associated concentrations of boron (0.49 mg L^{-1}) and phosphorous (3.06 mg L^{-1}) suggests that it could be due to a leaking sewer. Because of time constraints, it was not possible to carry out a detailed microbiological study, but all boreholes contained microbial numbers similar to those in uncontaminated groundwater.

The study confirms that the Carter Gate Cemetery no longer presents a source of contamination, but suggests that, by comparison with the ammonium peak, the maximum impact of inorganic solutes and volatile fatty acids on groundwater in the past was probably minimal.

10. RECOMMENDATIONS FOR FURTHER WORK

10.1 Possible Approaches for Investigating the Impact of Cemeteries

For any risk assessment to be undertaken from whatever potentially polluting activity, the actual source composition of contaminants and their fate in the subsurface need to be addressed. The source term defines the range of contaminants and how their flux into the natural environment varies in terms of time and concentration. Their fate in the subsurface depends on the nature of the contaminant and the hydrogeological environment in which they are released. In order to study these aspects a combination of laboratory and controlled field experiments could be considered in conjunction with field investigations of a range of cemeteries in hydrogeologically representative situations within UK (e.g. Williams and Higgo, 1994).

10.2 The Source Term

In terms of the actual and perceived risk from cemeteries it not only the release of inorganic species (for which limits can be set knowing the composition of a human body) but rather the organic material, pathogenic organisms, viruses and other biologically harmful organic materials which could adversely affect human health if consumed in drinking water, that needs to be addressed more fully. Knowing how a body decomposes in a grave and what contaminants (organic/inorganic, micro-organisms, viruses etc.) are produced will allow the source term to be quantified. Definition of the source term is presently poor and any proposal to study it directly would not be appropriate although experiments could be contemplated using animal surrogates. A literature review of the movement of bacteria, viruses and colloids in aquifers would obviously be a starting point for developing specific advice relating to cemeteries, as would a review of genetic methods for identifying human related material leached from the graves.

10.3 The fate of Contaminants in the Subsurface

10.3.1 Controlled field experiments

The fate of the specific contaminants released from a grave can be assessed by understanding the processes controlling their movement in different hydrogeological situations. The nature of the contaminant is of fundamental importance and should be defined under the source term. However, assessing the migration of these could be carried out at least partly using surrogates. For particulate materials e.g. bacteria, or viruses, similarly shaped but inactive forms such as latex microspheres or bacteriophages could be developed as tracers (Ward *et al.,* 1997, Harrison and Higgo, 1994, Higgo *et al.*, 1993). These could be used in a series of experiments in representative unsaturated or saturated formations on which cemeteries are typically located but not necessarily at cemetery sites. The fundamental knowledge provided by these experiments would provide quantitative data for describing contaminant movement at specific sites for assessing the groundwater vulnerability.

10.3.2 Investigating existing cemeteries

The impact of existing or former cemeteries on groundwater should also be determined directly as in this study. Whether this would get public acceptance is debatable, but certainly where it is possible, investigations should be considered. Prior investigation and instrumentation of potential new cemeteries should be undertaken as a normal requirement of a potentially polluting activity, and monitoring data could be obtained in the longer term. Carter Gate represents a snap-shot in time of a fairly old cemetery and, as such, forms one end of a spectrum of sites that could be investigated. Operating cemeteries form the middle of the spectrum while recent mass war graves form the other extreme.

An alternative is to study buried animal carcasses although the extent to which this is presently practised would need to be determined. This, probably offers the most feasible avenue for future research.

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