Understanding water table dynamics and their influence on the buried archaeological resource in relation to aggregates extraction

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Summary

This report presents the results of hydrological monitoring and modeling of groundwater conditions at the site of Newington, in the Idle River valley, Nottinghamshire. The project arose as a result of the fact that previous work (*cf*. French 2004) assessing the impacts of aggregates extraction on groundwater systems and wetland environments, has shown that significant impacts in terms of drawdown and the compromising of the conditions necessary for the *in situ* preservation of waterlogged archaeological remains, was intimately associated with extraction.

Using a combination of geo-hydrological and GIS modeling of groundwater, alongside physico-chemical and biological studies of *in situ* burial environments, the research presented below has shown that water abstraction, as opposed to aggregates extraction, is the most significant factor influencing *in situ* preservation at Newington.

The results have demonstrated that an integrated, multi-disciplinary approach to floodplain wetlands is essential if a holistic understanding of these environments is to be generated. The research has demonstrated that long term sustainability is unlikely in this area given current water management strategies, and predicted future climate change scenarios. Recommendations for mitigation and management of the waterlogged archaeological resource of floodplain wetlands are provided, on the basis of the results obtained to date.

Acknowledgements

This work was initiated in 2004, with Dr. Gillian Wallace working as the post-doctoral researcher for the project. Her efforts at managing the implementation of the project, and controlling vandalism at the site are greatly appreciated. The geo-hydrological modeling was undertaken by Hollie Garrick and Ruth Davison of Golder Associates (Nottingham).

Tom Smith assisted with the GIS modeling and developed the models used in Figures 5.6-11 and Appendix 9. Dr. Paula Milburn undertook the palynological analysis of floodplain sequences for degradation studies. Hanson Aggregates, and in particular Ben Ayres and Dan O'Brien, have been exceptionally helpful in allowing access to the site and to data relating to the Newington extractions.

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Ian Panter helped in the initial developmental stages of this project, and gave advice as the fieldwork progressed, and after he left English Heritage Dr. Ingrid Ward, and subsequently Marcus Jecock have acted as Project Officers' for the project on behalf of English Heritage. Their help and advice has been invaluable.

John Garner (University of Hull) is thanked for his assistance in modifying and transferring images into a manageable format. Marion Brazier (also University of Hull) is thanked for her assistance with pollen preps and general laboratory work.

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1. Introduction

1.1 Background to the project

The current project arose as a result of the observation that aggregates extraction can have significant impacts on wetland environments (*cf*. French *et al*. 1999, French 2004). This research indicated that, at the site of Over in Cambridgeshire, gravel extraction resulted in a 3.5-4m lowering of the groundwater table. Extraction works undertaken by Hansons Aggregates in the Idle river valley at Newington near Bawtry (SK675943), have the potential to produce similar impacts on the groundwater table in this area.

The current project was commissioned jointly by English Heritage and the Mineral Industry Research Organisation (MIRO) in 2004. Monitoring of water levels, redox potentials and soil pH has been undertaken since February 2005 at this location. Additional research into the degradation of pollen in the floodplain sequences has been on going since March 2005. As has been noted elsewhere (Smit *et al*. 2006:14), 'archaeological baseline surveys and monitoring are…an essential precondition for the active management of archaeological sites', and it is anticipated that the current study will directly inform future management strategies in relation to aggregates extraction.

1.2 Rationale

1.2.1 Recent research has highlighted the fact that the effect of de-watering on waterlogged archaeological remains is detrimental to the survival of the resource (Welch & Thomas 1996). However, until recently (e.g. French *et al*. 1999, Heeringen *et al*. 2004), the assessment of hydrological conditions at sites of proven archaeological interest have been very site-specific in scope, and of limited duration. This situation is problematic, when it is generally accepted that the waterlogged component of the archaeological record is of considerable importance to our understanding of past human societies (e.g. Coles *et al*. 2001). In effect, organic remains provide a more holistic picture of the range of materials used by past societies, and waterlogged contexts preserve an aspect of material culture that is rare on dryland sites (e.g. Caple 1996, Coles & Coles 1996, Coles *et al.* 2001, Van de Noort & Davies 1993).

A diverse range of waterlogged archaeological sites can be found, and these often occur in widely differing environments such as raised bogs, lochs, river systems and coastal regions (*cf*. Coles 2001). As a consequence, identifying the best ways in which these sites can be preserved for the future is essential. Whilst the current project is focussed on the implications of de-watering of archaeological remains in relation to aggregates extraction, the parameters investigated will have wider applications to the understanding of buried waterlogged archaeological materials in differing burial environments (e.g. Smit *et al*. 2006).

1.2.2 Recent studies have suggested that water tables and the maintenance of waterlogged/saturated conditions are essential to the long-term survival of the archaeological and palaeoenvironmental resource (e.g. Chapman & Cheetham 2002, Corfield 1996). However, few studies have considered the specific impact and the nature of the changes to the burial environment that arise from aggregate extraction, on the waterlogged resource (*cf*. Corfield *et al*. 1996). Anecdotal observations (e.g. Pryor 2002) persistently assert that de-watering associated with extraction has caused a 'visible' drying out at sites such as the causewayed enclosure of Etton, Cambridge.

To date, studies at Etton (French & Taylor 1985) and Market Deeping, Lincolnshire (Corfield 1993, 1996) have been limited in scope in terms of the methods applied. In the case of the latter study, factors such as rainfall and farming practices were considered to have aided the production of the changes observed. Other recent studies have been undertaken by the author and colleagues at the Wetland Archaeology & Environments Centre, University of Hull, at locations such as the Knights Hospitaller's Preceptory, Beverley (Lillie & Cheetham 2002a & b), Flag Fen (Lillie & Cheetham 2002c), and Sutton Common, Yorkshire (Cheetham 2004, Van de Noort *et al*. 2001). Lillie (2007:170) has noted that one of the key limitations of site-specific studies is the lack of a more holistic understanding of the wider landscape context in which the site is located. In this context, the identification of catchment-wide hydrological parameters is fundamental to the generation of a holistic understanding of the hydrological processes that will affect the site being studied. Without this baseline data, any attempts at *in situ* preservation are fundamentally flawed. This observation forms the basis of the approaches adopted in the characterization of the Newington site.

With the exception of Sutton Common (which was studied by James Cheetham during PhD research), the studies mentioned above have been of either limited duration or of a targeted nature, and aimed at answering specific questions relating to mitigation in advance of development or other immediate impacts at the site level. More recently, French (2004) has shown that significant impacts on the burial environment can arise from the extraction process (see Chapter 2 for a detailed consideration of these impacts). Despite this limited, though important evidence, a broader range of empirical studies from differing burial environments are necessary if we are to argue for the adoption of targeted and more comprehensive mitigation strategies aimed at promoting preservation *in situ*. As such, this research represents an initial stage in the development of studies that will directly inform our understanding of the potential impacts of aggregates extraction on waterlogged burial environments.

1.2.3 Lillie (2004) highlighted the extraction site at Newington (SK675943) as a particularly valuable location for the proposed study, for the following reasons:

- Extraction of floodplain resources such as sands and gravels is a key aspect of aggregate industry activities.
- Major floodplain environments such as the Trent and the Thames, and their tributaries, are subject to on-going extraction programmes.
- The small-scale nature and the rolling programme of work at the Newington site enable the modification of methodologies and approaches with relative ease.
- Floodplain deposits with a proven palaeoenvironmental and possible archaeological potential exist at this location.
- The River Idle floodplain has, in the immediate vicinity, a proven archaeological resource located at the site of Scaftworth, near, Bawtry, where a corduroy Roman road and associated features have been studied (Van de Noort *et al*. 1997).
- Measurement of the assessment of impacts on the floodplain peat deposits during the monitoring programme will provide significant information in relation to extraction.
- The rolling extraction programme enables short-term (annual/bi-annual) monitoring to be undertaken and facilitates the rapid generation of results.

1.3 Summary

This report presents the results of twenty-six months of monitoring at the Newington site, undertaken during a phased programme of aggregates extraction. Significant insights into catchment-wide hydrological processes and site-specific impacts from aggregates extraction and water abstraction have been forthcoming from this research. These are discussed below, and the main results are considered in Chapter 5.

2. Background

2.1 Location

2.1.1 The extraction site is located *c*. 2km to the east of the town of Bawtry (Figure 2.1). Comprising *c*. 40 ha, the survey area itself is bounded by Bawtry Road to the north and the River Idle to the south, with the current extraction area occupying the northern half of the survey area. The extraction site is demarcated to the south by Slaynes Lane (as shown in Figure 2.2). In general, the topography is low-lying, ranging from between 2-3 m OD, rising to between *c*. 6-8 m OD on the northern margins of the extraction area.

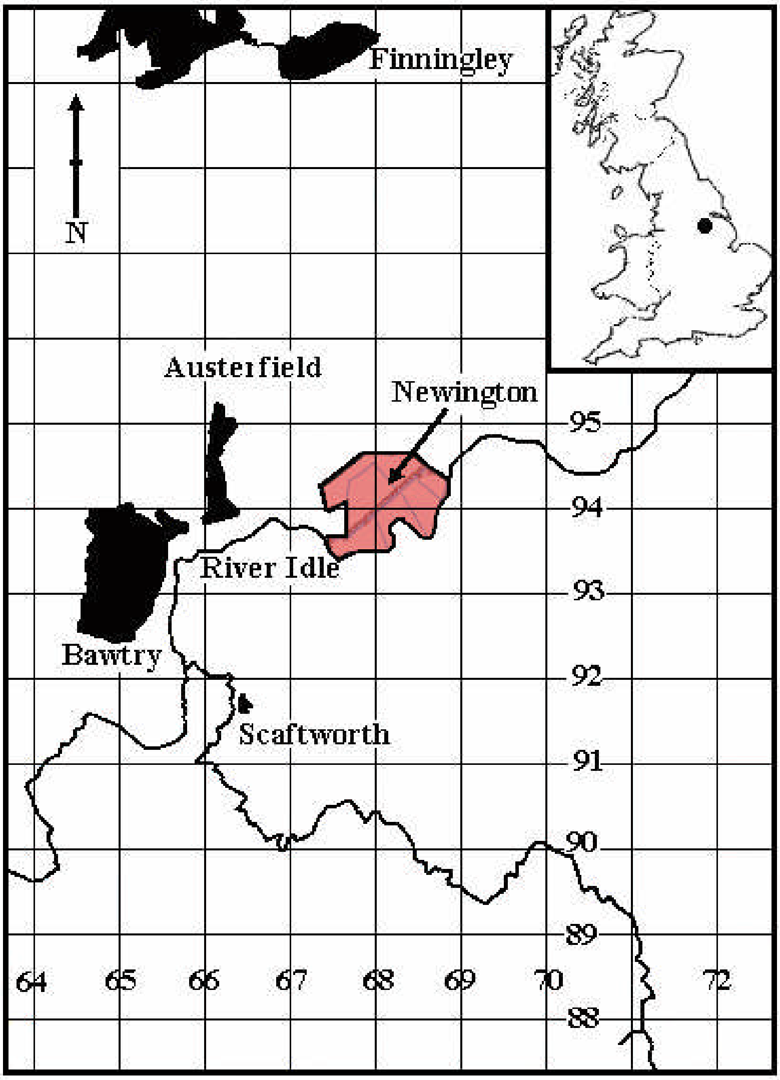

Figure 2.1: Location of the study area in relation to key urban areas and the River Idle.

The study area has been subject to intensive arable farming practices in the past, prior to the implementation of the current extraction programme.

2.2 Description of the extraction area

2.2.1 The location, geological and sedimentological setting at Newington has been outlined in detail in recent reports by Northern Archaeological Associates (NAA) (Lakin & Howard 2000) and the Wetland Archaeology & Environments Research Centre (WAERC) (Gearey *et al*. 2000).

The site is located on the northern side of the River Idle (Figure 2.1), at a point where the floodplain widens. The Idle then changes its course from its route eastwards past Bawtry, to a northwards flow past Misson towards Idle Stop (SK72109650) (Lakin & Howard 2000:3).

The river is characteristic of lowland British rivers, and is currently flowing in a single channel which reflects the low-energy environment of the river. As with the majority of the rivers in the region, the channel is currently confined by flood banks which are structured so as to facilitate the retention of any flood waters in washlands. A Site of Special Scientific Interest (SSSI) area occurs to the south-east of the extraction area (Slaynes Lane washland), and a much larger SSSI (River Idle washland) runs from Bawtry Bridge along the north side of the river, up to the south-western corner of the extraction area (*ibid*. 2000).

2.2.2 The land drainage of the area is currently controlled by the rivers Idle and Ryton Internal Drainage Board and the Environment Agency. Historically, flooding within the Idle catchment was exacerbated by high water regimes in the Trent river, into which the Idle debouches at West Stockwith. However, this drainage into the Trent system was impossible prior to the installation of pumps (Dinnin 1997, Leake 2000). Significant remedial works in the 1980's, included the re-grading of the current Idle channel and the construction of a flood relief channel to the south of Slaynes Lane. Both of these endeavours have served to reduce the impact of flooding in this reach of the Idle's course (as shown Figure 2.2).

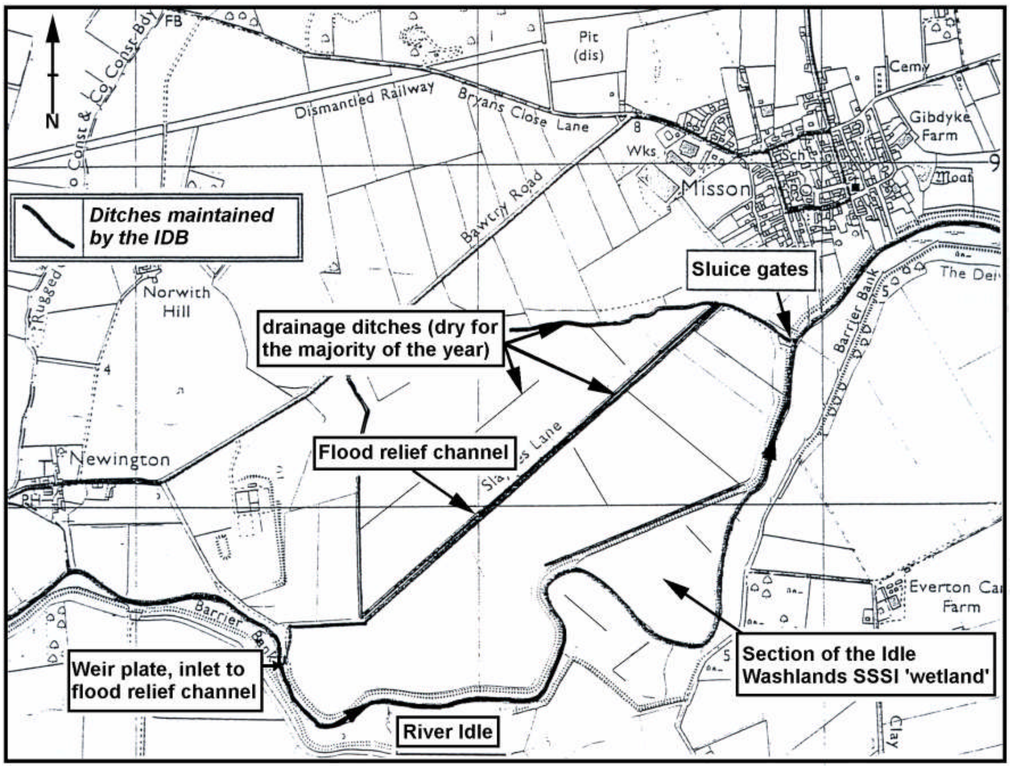

Figure 2.2: Water features in the vicinity of Newington (*after* Leake 2000, Figure 3).

2.3 Geology

2.3.1 A detailed geological summary is presented by Lakin & Howard (2000:3-6) (Figure 2.3). This work is based on data derived from the Institute of Geology Mineral Assessment Report (1979). A total of 154 boreholes from the immediate area of the extraction site have been assessed. 50 boreholes relate directly to the extraction area, and these form the basis for the mapping undertaken by Lakin & Howard (2000)

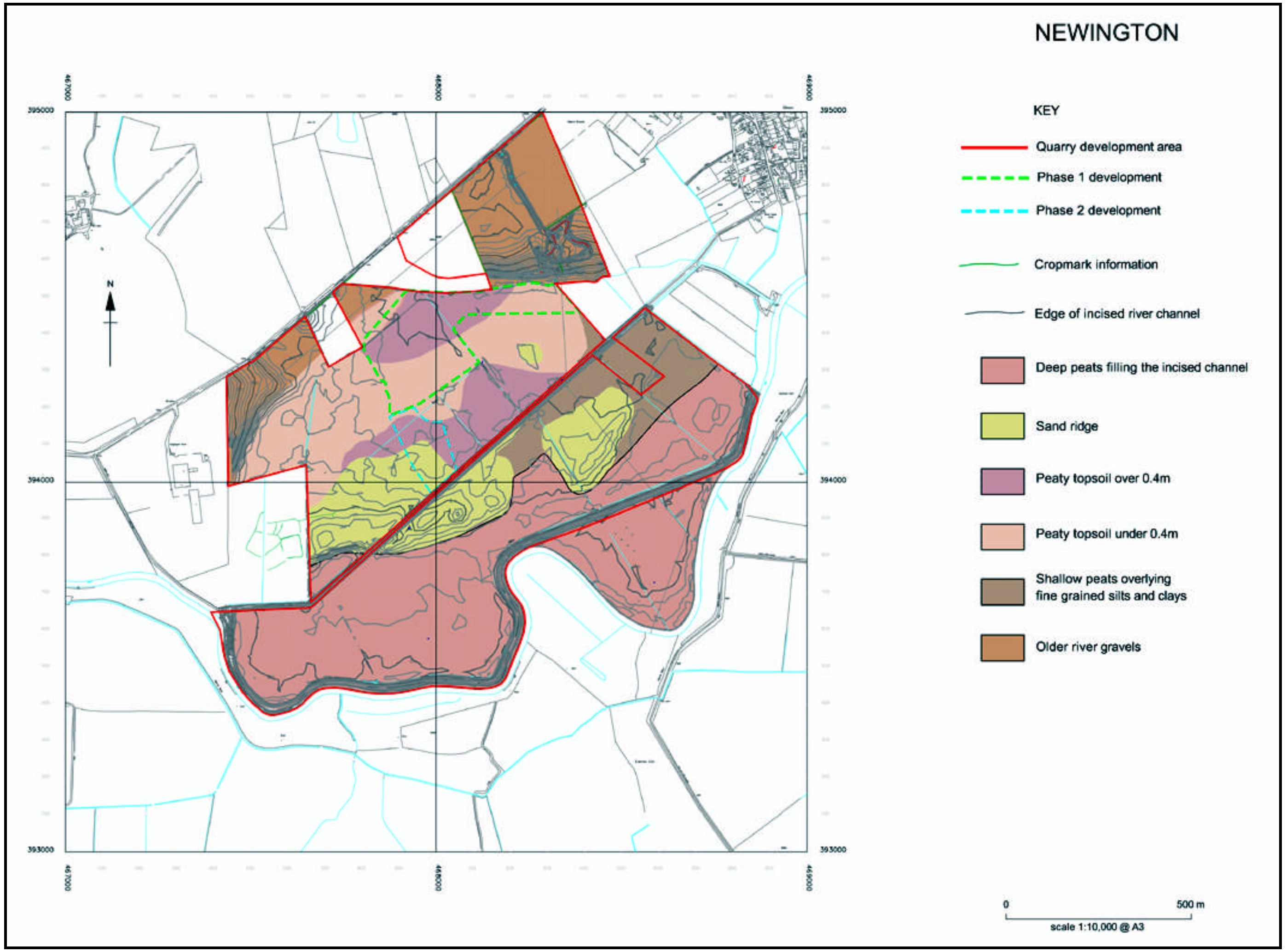

Figure 2.3: Devensian and Holocene sedimentary units associated with the Newington extraction area and adjacent floodplain (*after* Lakin and Howard 2000).

and Northern Archaeological Associates (2002) (as shown in Figure 2.3). The following represents a summary of this data, with higher resolution studies (Gearey *et al*. 2000) outlined below in Section 2.7.

2.3.2 The underlying solid geology is Triassic Sherwood (formerly Bunter) Sandstone. Superficial deposits include Ipswichian Older River Gravels and Devensian First Terrace deposits, which occur within the study area. The latter underlie the modern floodplain, and are overlain by a combination of sands (of aeolian and/or fluvial derivation), floodplain and marginal peats, and alluvial deposits.

2.3.3 Throughout the survey area, the superficial deposits include a sand ridge, located to the north of the floodplain peats, and running along Slaynes Lane, from west to east. This outcrops in a discrete area to the south of the lane on the eastern side of the survey area. Shallow peats occur on the north and eastern side of the area, with fine grained silts and clays to the west, on the northern side of the western sand ridge. The superficial deposits recorded in the area range between *c*. 0.6 m away from the floodplain to a maximum of *c*. 4 m of peat and alluvial deposits within the floodplain area. The sequences were sub-divided into three discrete units by NAA (2004:1), and comprise:

- Deep organic floodplain and river in-fill deposits
- Shallow superficial peats associated with channel margins and overbank flooding
- Sand ridge, which undulates from west-east across the northern side of the floodplain

2.3.4 The soils that overlie the area comprise four broad categories including stony organic topsoil over sandy subsoils; deep, light-textured soils over the sandy ridge; Terrace deposits; and slightly stony, peaty loams which occur at the boundary between the terrace and floodplain deposits. The final unit comprises peaty soils over the south-west corner of the site in the vicinity of the peat filled channel sequences (Lakin & Howard 2000, Royle 1999).

2.4 Early landscape development

2.4.1 Palynological studies (Gearey *et al.* 2000) at Newington have indicated the existence of floodplain sequences that span the period 13,000-2000 uncal BP, although these are spatially variable and differ in terms of their extent and timing for the onset of peat development. Recent dendrochronological assessment of oaks contained within the upper peats, away from the main channel, suggest an age range of *c*. 1136 BC and 1120 BC, with an end date of *c*. 1100 BC. These dates are wholly consistent with the palynological data from the upper sequences at the site, and broadly conform to the results of radiocarbon dating of the upper sediment units, which have ranges between *c*. 1200-400 cal BC (Gearey & Lillie 2002).

In general, the sequence of deposits recovered from extensive borehole excavation of the floodplain areas (as shown in Figure 2.4) (Gearey *et al.* 2000) indicate initial wetland development following paludification of the Devensian sands adjacent to the main channel. Subsequently, a unit of overlying silt-clay sediments with organic remains reflects the deposition of alluvium following the spread of the river beyond its earlier, discrete channel or channels, and the inundation of the wetland areas on the floodplain alongside the development of fen-carr woodlands. This sequence is characteristic of early-mid Holocene river evolution as base levels/sea levels rise towards OD after the retreat of the ice-sheets. Within the floodplain areas, the occurrence of an upper woody peat unit reflects the establishment of fen-carr communities over the study area.

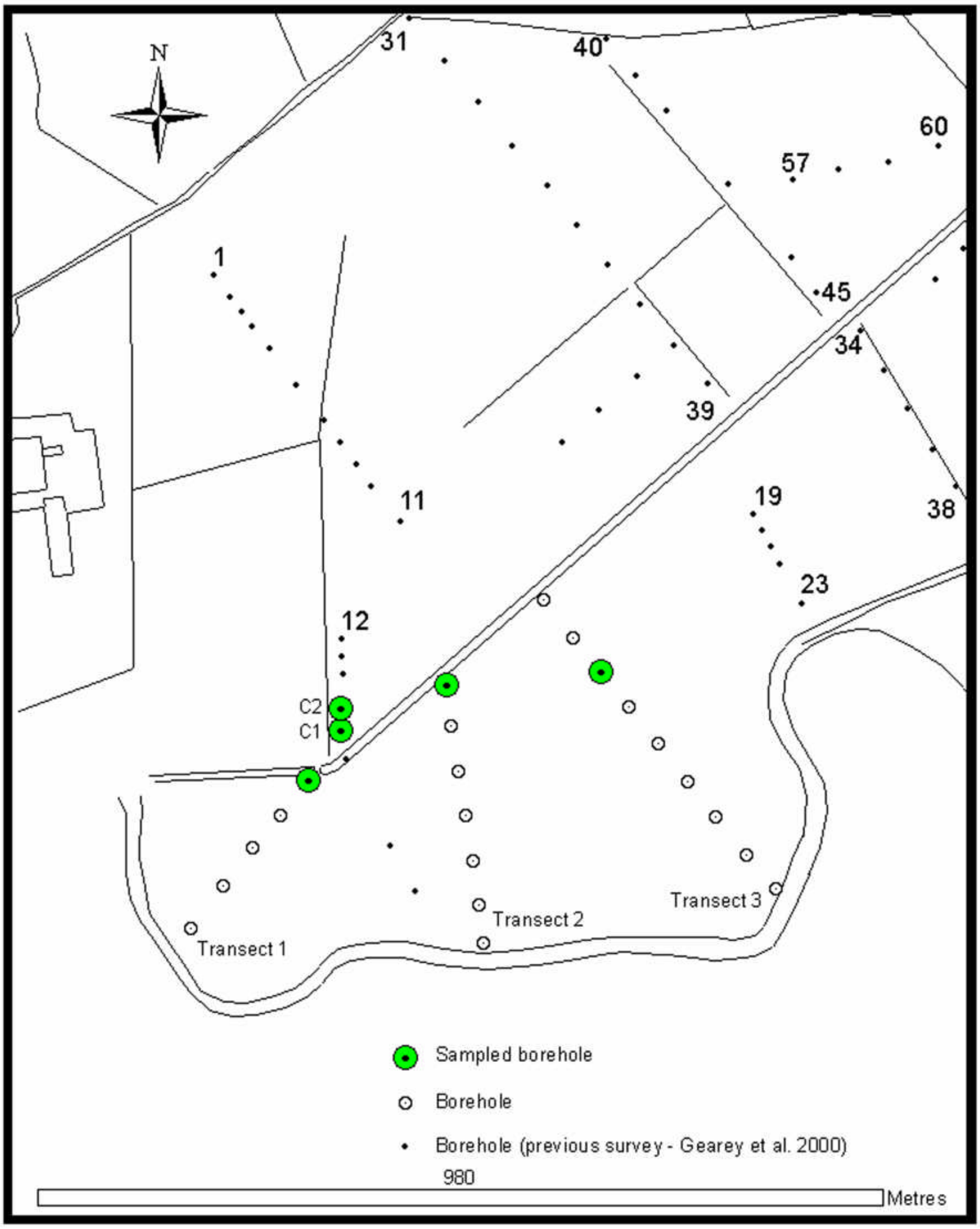

Figure 2.4: Borehole sequences excavated to assess the palaeoenvironmental potential of the Newington sequences (*after* Gearey *et al*. 2000 and Gearey and Lillie 2004).

At present no deposits that post-date the prehistoric period have been recovered from Newington.

2.5 Previous work

2.5.1 The Newington site has been subjected to detailed archaeological and palaeoenvironmental research, funded by Hanson Aggregates who currently hold the extraction licence for the area (e.g. Gearey & Lillie 2002, Gearey *et al*. 2000, Lakin & Howard 2000, NAA 2002). In addition, some background hydrological data assisted in the initial stages of the development of the hydrological models which form the basis of the current research project (Leake 2000).

2.6 Archaeology

2.6.1 Initial desk-based assessment, cartographic, aerial photographic, walk-over survey and geophysical survey work (Lakin & Howard 2000), highlighted a broad age range of archaeological material from the earlier prehistoric period through to more recent historic periods in this area. Mitigation strategies were developed subsequent to this initial work, and a number of evaluations have been undertaken as the extraction work has progressed (NAA 2002, Lakin & Howard 2000).

2.6.2 The archaeological remains in the immediate vicinity of the site include crop mark evidence of probable Romano-British date, and biogenic deposits which hold the potential for the recovery of organic remains associated with activity from the Mesolithic period onwards (NAA 2002). Recent field-walking has produced scatters of worked lithics throughout the sandy areas, with an apparent 'gap' in distribution in those areas where deeper superficial peats are in evidence. This bias may well reflect the obscuring effects of the peats, which have been dated to the later Neolithic through to Iron Age periods.

A discrete concentration of Bronze Age flint has been recovered from a buried soil in the vicinity of the extraction, indicating the presence of an activity site of this period. Overall, the general age of the flints recovered from this area appeared to span the Neolithic to Bronze Age periods (NAA 2002). However, as the earliest date for peat inception to the north of Slaynes Lane is placed in the later Neolithic, it was suggested that earlier, Mesolithic and Neolithic, activity could be anticipated on the buried land surfaces in the extraction area, as these are exposed by topsoil stripping.

Confirmation of this earlier hypothesis was provided by the discovery of a late Mesolithic-Earlier Neolithic concentration of worked flint, which was excavated in the vicinity of the extraction area (phase 3) immediately to the north of Slaynes Lane (Plate 2.1). The appearance of the material recovered suggested a later Mesolithic to Neolithic age for the assemblage (NAA pers comm.), and analysis and interpretation is on-going at the time of writing.

Plate 2.1: Close-up of late Mesolithic-Neolithic flint scatter during excavation, white tags mark location of flint finds exposed on the palaeo-landsurface (© Malcolm Lillie).

2.6.3 In the wider region of the Idle valley system, excavations have been undertaken at the Roman fort and corduroy road at Scaftworth (Van de Noort *et al*. 1997), Romano-British field systems at Blaco Hill Quarry, near Mattersey (Garton *et al*. 1995, Morris & Garton 1998) and later Medieval field banks at Tiln (Howard *et al*. 1999, Lakin & Howard 2000).

The preservation of the Roman Road at Scaftworth (Plate 2.2) has direct implications for the Newington floodplain sequences in that a proven archaeological potential exists within *c*. 3km of the study area. In terms of its preservation, the Scaftworth site was shown to be in an on-going state of compromise. In 1948, the road line was not visible in the floodplain, by 1991 a low ridge was noted running across the floodplain, and by 1995, the ridge had become pronounced due to continued desiccation of the surrounding organic matrix (Van de Noort *et al*. 1997:428).

Plate 2.2: Scaftworth Roman road, located in the floodplain of the River Idle at Bawtry. This road, the Iter V of the Antonine Itinerary is the road from *Lindum* via *Danum* to *Eburacum*, and has been identified as the most important cultural element in the landscape at Scaftworth (Van de Noort *et al*. 1997:409). © Hull University: HWP.

Earlier studies in the region have recovered Mesolithic material at Misterton Carr (Buckland & Dolby 1973), and a wider survey of the region, which included archaeological and palaeoenvironmental studies, was undertaken by the Humber Wetlands Survey (Van de Noort & Ellis 1997). This study produced evidence for human activity from the Mesolithic period onwards, which was intimately associated with the watercourses of the region. The deeply stratified organic sequences associated with the rivers of the Humber Lowlands have a significant, and proven potential in terms of the preservation of organic cultural remains and palaeonvironmental material.

2.7 Palaeoenvironmental research

2.7.1 A number of palaeoenvironmental investigations have been undertaken at Newington. The more recent of these include detailed borehole survey and palaeoenvironmental assessments (as shown in Figures 2.4 and 2.5), which were undertaken by the author and colleagues at the Wetland Archaeology & Environments Research Centre (WAERC) at the University of Hull (e.g. Gearey & Lillie 2002, Gearey *et al.* 2000).

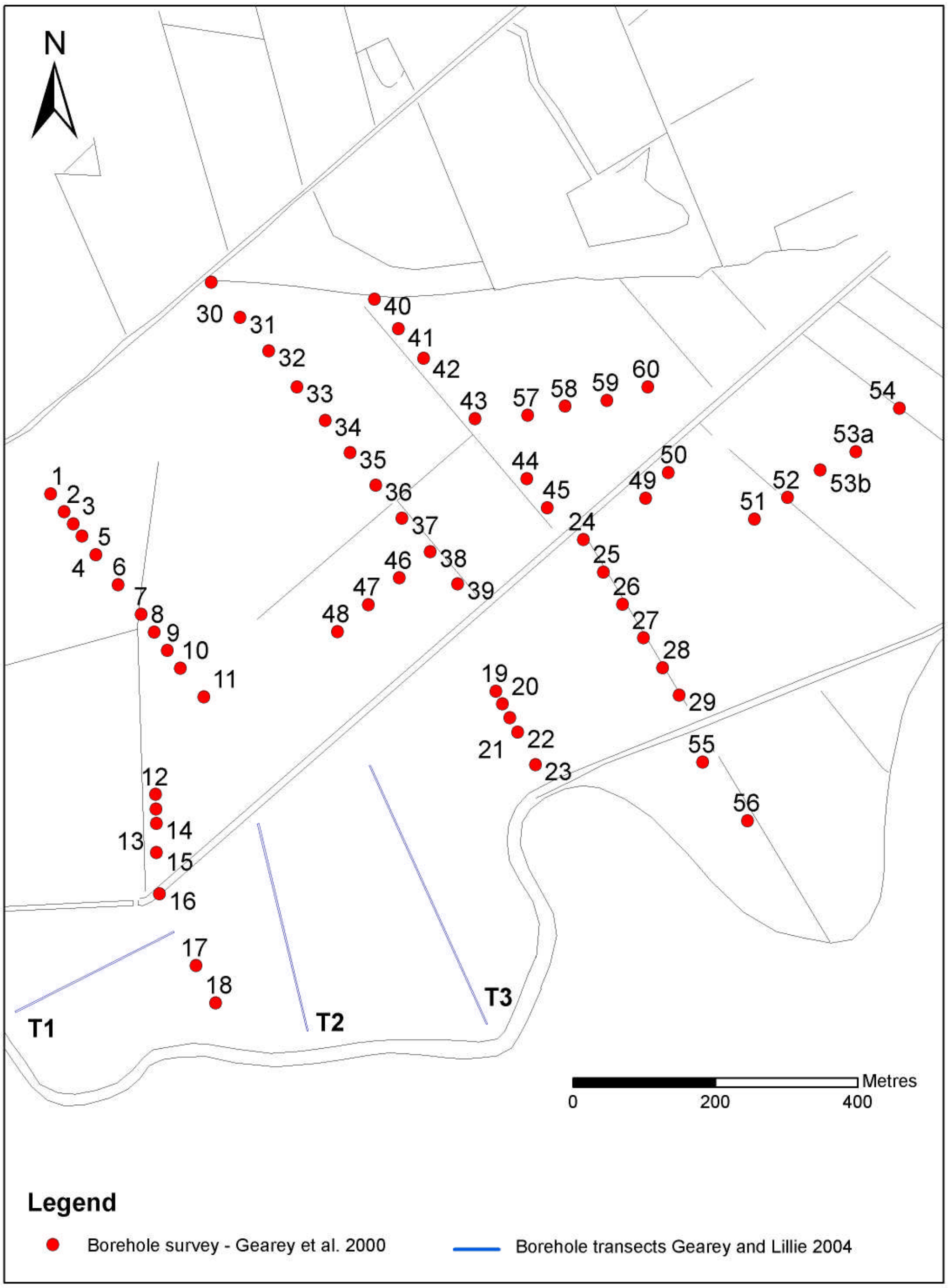

Figure 2.5: Detailed plan of borehole survey undertaken by WAERC, between 2000-2004. Certain numbered boreholes are discussed below in relation to the developmental history of the floodplains sequences.

2.7.2 Preliminary borehole studies undertaken in 2000 (Gearey *et al*. 2000) (as shown in Figure 2.4) indicated the possibility for the localised preservation of biogenic sediments dated to *c*. 13-10,000 BP (the Late Glacial), located in the south-western corner of the study area (core 14 Figure 2.5). Elsewhere in the floodplain, ages of *c*. 7-5000 BP were indicated for the development of the floodplain peats (cores 14 and 55 in Figure 2.5), with expansion and paludification into the upper areas of the floodplain margins occurring by *c*. 2-3000 years ago (cores 52 and 55 in Figure 2.5) (*ibid*. 2000).

2.7.3 Targeted assessment and radiometric dating of the depositional sequences at Newington have been undertaken by Gearey & Lillie (2002, 2004). The first of these studies analysed samples obtained during test-pitting within the proposed extraction area. Ages for wood, charcoal and peats from this area spanned the period *c*. 2860-390 cal BC.

A sample of charcoal recovered from basal silts yielded a date of 4050±50 BP (Beta-168361) which calibrates to 2860-2810 & 2690-2470 cal BC. This provided a *terminus ante quem* of the later Neolithic for the sealing of the land surface within the current extraction area at Newington. This basal date also provides a temporal marker for the subsequent development of wetland deposits in the floodplain areas to the north of the main channel and floodplain margins. The upper age of these deposits is placed at *c*. 2450±60 BP (Beta-168360 & 168364), which calibrate to 790-390 cal BC. In palynological terms, the uppermost sample in the sequence (which is discussed below), on the basis of sediment depth and accumulation rates, was considered unlikely to date much later than the mid-late Iron Age/Romano-British period.

2.7.4 Pollen analysis of the organic sediments in this area indicates that birch dominated fen is present during the earlier stages of organic sedimentation within the extraction area, i.e. away from the main floodplain area, with damp, acidic conditions indicated by the consistent presence of *Sphagnum*. It has been suggested that this initial expansion into the upper areas of the floodplain occurred sometime after the later Neolithic to Bronze Age transition at *c*. 2500 BP (Gearey *et al*. 2000). High percentages of *Alnus* and *Quercus* indicate that alder and oak were also present nearby. The former species suggests areas of open water, since this tree tends to grow with its roots in water. In addition to the tree species discussed above, hazel and lime are attested in the immediate area. Wild grass pollen, recorded in low quantities throughout the samples studied, was considered to be reflecting some local wetland grasses, but these could also be derived from grassland habitats in the wider landscape. A low peak of *Plantago lanceolata* is also recorded. This peak may be significant since ribwort plantain will not grow in woodland or wetland habitats, and as such, must reflect open, grassy and possibly anthropogenically disturbed habitats beyond the fen edge.

Towards the upper part of the depositional sequence, an increase in *Alnus* and a concomitant decrease in *Betula*, evident from 0.64 m, are thought to indicate a change in the on site vegetation from birch to alder dominance. Alder fen carr communities, as indicated by this sample, are commonly recorded from floodplain habitats in the Humber lowlands during the mid-Holocene (e.g. Kirby & Gearey 2001). The shift from birch to alder probably reflects amelioration from mesotrophic to more eutrophic conditions, but there remains insufficient data to support this observation at present.

There is very little evidence in the diagram, developed by Gearey & Lillie (2002: Figure 1), to suggest anthropogenic activity in the catchment, as total tree and shrub frequencies account for over 95 % of total land pollen. A ‘successional reversal’ of the kind outlined above is recorded in a pollen diagram from Shirley Pool in the Humberhead Levels and is dated to around 4400 BP. It is hypothesised that this is either due to the increased influence of nutrient rich surface water occurring as a result of woodland clearance, or a rise in base levels concomitant with a rise in relative sea level (Schofield 2001).

The upper levels studied by palynology suggested that the vegetation in the area was characterised by few trees, either on the sampling site or in the wider landscape. The marked reduction in the local and extra-local tree cover presumably occurred as a result of anthropogenic activity, but actual palynological evidence for this is limited in the samples studied, with pollen from the local sedge wetland forming the major source of pollen.

2.7.5 The most recent palaeoenvironmental study undertaken at Newington (Gearey & Lillie 2004) has indicated that the preservation of microfossil material is generally poor, though with some variability in evidence (*ibid*. 2004:15). The lower part of the core studied by Gearey and Lillie (core 1, Figure 2.4 above), produced an age of 8740±40 BP (Beta-191006) which calibrates to the earlier Holocene at 7950-7610 BC (*contra* Gearey *et al*. 2000), while the uppermost part of the sequence is dated to 2650±40 BP (Beta-191005) and calibrated to 850-790 BC, i.e. the later Bronze Age.

The earliest age for organic sedimentation appears to suggest that in the south-western corner of the site an isolated hollow or depression at the edge of the blown sand deposits promoted early Holocene waterlogging and the accumulation of organic sequences. Subsequently, the onset of floodplain peat development appears to be temporally divorced from this early organic sedimentation by *c*. 1-2000 years. However, this latter phase of floodplain development, in the immediate vicinity, remains undated in absolute terms.

2.7.6 Elsewhere in the Idle valley, at Tiln *c*. 10km south of Newington, Howard *et al*. (1999) recorded Late Devensian and Early Holocene minerogenic sediments - braided river sands and gravels - overlain by a palaeosol of Late Devensian age (>13,500 BP). Other organic deposits were recorded within the braided river deposits. These indicated an open, treeless, tundra landscape that was dominated by herbaceous taxa, which are typical of Late Devensian environments.

2.7.7 Dinnin (1997) has undertaken palaeoenvironmental studies of the Idle at Scaftworth, Misterton Carr, Bull Hassocks, Star Carr, Thatch Carr and West Carr. Whilst undated in absolute terms, palynological analysis of the contained deposits has indicated potential age ranges for the onset of organic sedimentation occurring from the Late Glacial at *c*. 11,000-10,200 BP (the Younger Dryas PZIII) up to *c*. AD 43-410 or later.

2.8 Hydrology and hydrogeology

2.8.1 Previous water table assessments at this location have suggested that some degree of draw down has occurred in recent years (these are outlined below). This site was determined to be of considerable holistic value to archaeologists due to the existence of Hanson's own boreholes for water table monitoring (of which there are 10 in total), and 4 Environment Agency boreholes in the immediate vicinity (*cf*. Lillie 2004). Two of these are located in the sands and gravels adjacent to the River Idle; and two deeper boreholes are situated within the Sherwood Sandstones, away from the extraction site (as shown in Figure 2.6).

Leake (2000) identified that, at that time, the groundwater flow direction on the site was to the north-west. The Environment Agency has previously identified depressed regional water tables and over-abstraction as significant issues in the region (*ibid*. 2000). As such, a degree of baseline data existed, against which the results of the current water table monitoring project can be assessed and evaluated. Leake has indicated that the nature of the near surface geology is such that the Sherwood Sandstone and all of the superficial deposits are in complete hydraulic continuity. Consequently, it could be anticipated that regional influences will also impact directly upon the superficial deposits in the immediate vicinity of the extraction site.

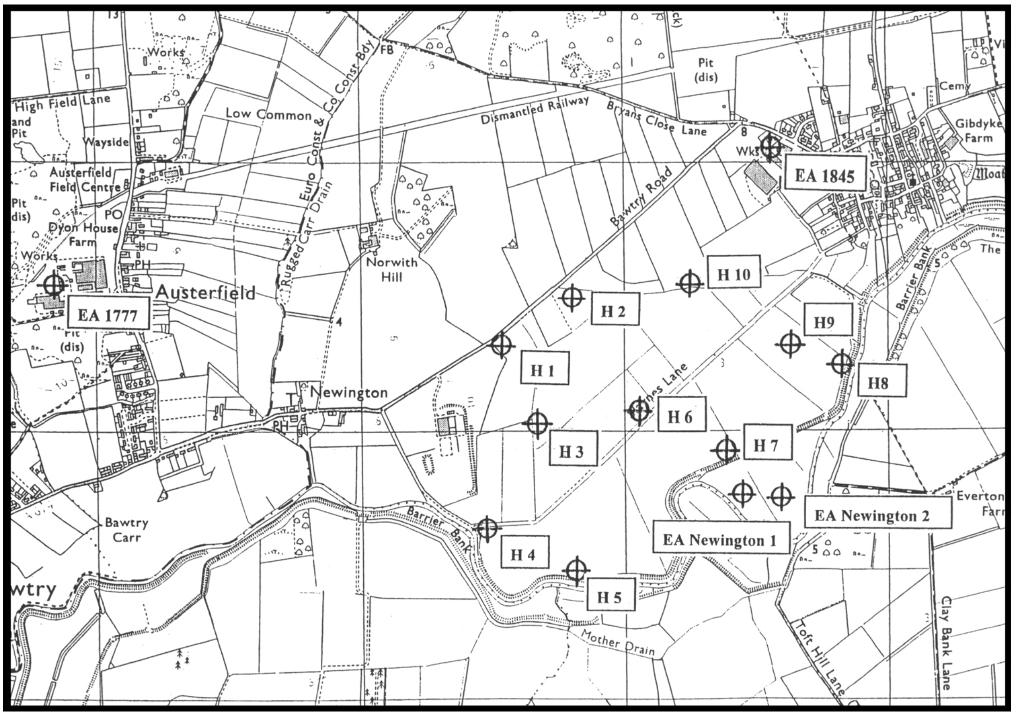

Figure 2.6: Hansons boreholes [H1-10], and Environment Agency boreholes [EA Newington 1 & 2] located in the sands and gravels adjacent to the River Idle; and two deeper boreholes [EA1777 and EA1845] situated within the Sherwood Sandstones, away from the extraction site (*after* Leake 2000, Figure 7).

As noted above, an assessment of the hydrological regimes at Newington, which are based on the Hanson dipwells and Environment Agency boreholes discussed above, has been undertaken by Leake (2000). This work demonstrated that in the extraction area to the north of Slaynes Lane, water table heights ranged from *c*. 0.5 m OD at Slaynes Lane, lowering to between -0.5 to -0.75 m OD at Bawtry Road on the northernmost side of the extraction site (as shown in Figure 2.7, below).

2.8.2 The Newington site is situated upon the Sherwood Sandstone, which has been shown to contain a major aquifer (as defined by the Environment Agency), and which is an important regional water source for public consumption (Leake 2000:15).

Leake has suggested that the groundwater regime in the immediate vicinity of the study area comprises the major aquifer, an aquifer within the sands and gravels, and the River Idle itself. As noted above (in Section 2.8.1), the interrelationship of these elements in terms of hydraulic continuity would suggest that any variability in one element may have the potential to impact upon the other two. This observation is of considerable significant when trying to assess the impact of the extraction process, as any change (or otherwise) in the hydrology of the floodplain deposits must be determined in relation to, and also isolated from, the other variables. This observation is fundamental to future mitigation strategies as change cannot be assumed *a priori* to be a consequence of any one variable (e.g. abstraction), without a considered evaluation of the impact of other factors.

2.8.2 Consideration of the dipwell data monitored by Leake between 09-07-1999 to 21-01-2000, contrasted against previous EA borehole data, shows that during this monitoring period there is a general decrease in water table levels until *c*. 05-11-1999, after which water heights re-establish themselves to previous levels. Leake (2000:19) suggests that this variability is typical for sand and gravels aquifers, and reflects seasonal variation in rainfall recharge. Such baseline data provides an essential dataset against which the proposed modelling can be tested in terms of any variability/variation resulting from the extraction activities at Newington.

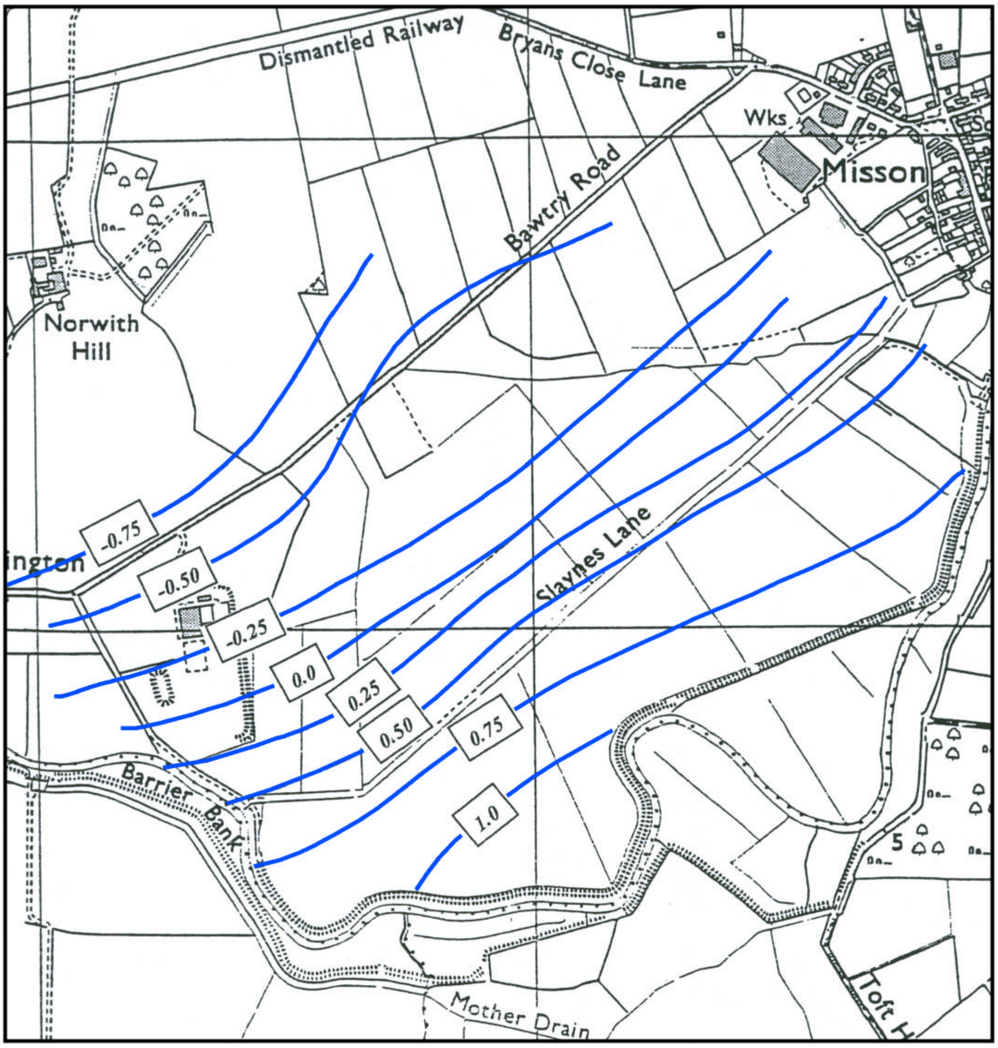

Figure 2.7: Groundwater head contours (*after* Leake 2000, Figure 12).

In addition, the data obtained from the Environment Agency boreholes located within the SSSI, alongside stage data for the adjacent River Idle, show that between March to June 1998 both data are equivalent (Leake 2000). However, after June 1998, water levels in the SSSI diverge, decreasing uniformly to *c*. 1 m below the river level by 25-10-1998. By 08-11-1998, the groundwater levels have recovered rapidly to reach equivalence with the river levels.

From the above observations, Leake (2000:19) concluded that between November and June the river and the aquifer are in hydraulic continuity. The lowered water table levels between July and October are likely to promote losses of river water to the aquifer. The rapid re-establishment of equivalence between the river and aquifer in November is likely to represent the reduction of demand from the aquifer through water abstraction towards the end of the summer. Again, this observation is fundamental to our understanding of variability in the hydrological regimes at Newington and their potential seasonal expression/influences during the proposed monitoring programme.

2.8.4 The final parameter considered by Leake (2000) relates to the wider regional hydrology as attested by the Environment Agency boreholes located at Misson (SK685495120) and the G.R.Stein refractories (SK65869448). Although these locations fail to provide any meaningful short-term/seasonal trends, during the period 1982-1998, the Misson data does indicate an overall trend of decreasing groundwater levels from *c*. -0.75 m OD to *c*. -1.5 m OD. At the G.R.Stein refractories from 1991 onwards, major short duration fluctuations are in evidence, but these data reflect the close proximity of this location to licensed groundwater abstractions.

2.8.5 On the basis of the assessment of the de-watering methodology and discharge rates, Leake (2000:34-6) has argued that the approaches adopted during the extraction process would mean that:

- the impact upon groundwater resources is minimised
- discharge of water off site will be precluded after the initial phase of the development; and as such no net loss to the groundwater system will occur as a result of the extraction proposals
- the small-scale de-watering and retention of water on site will limit any impacts on the groundwater
- after cessation of extraction and restoration, there will be no effects on groundwater resources

2.8.6 The above observations will be directly testable during from the current monitoring programme results as outlined below in chapter 5.

2.9 GIS and modelling

2.9.1 In addition to the modelling of the data generated in the Virtual ModFlow 4.0 package, all of the data generated will be transferred into a GIS package so that the data can be compared to other studies, e.g. PhD research at Sutton Common by Cheetham (2004). This aspect of the research has considerable holistic value in enabling the specific characteristics of the groundwater table to be compared in differing sedimentary environments.

2.9.2 At Sutton Common, Cheetham (2004:88, 90-182, 252-6) modelled the water table using 50 piezometers in a grid focussed over the Iron Age enclosures and their immediate surroundings. However, it should be noted that this approach would be more applicable in a constrained landscape setting where features such as palaeochannels, solution hollows and aquifers will not influence water source and/or discharge points. For the current study, the above caveats are noted, but it is considered that modelling of the shallow, near-surface water regimes in the Idle floodplain at this location may provide useful holistic data relating to catchment-wide hydrological processes.

2.9.3 As Newington has been shown to comprise a number of water sources that may be in hydraulic continuity (Leake 2000 [as shown in Section 2.8 above]), the GIS data will provide a useful background picture for comparative purposes. However, the modelling of the data generated within the ModFlow package will enable a much more robust assessment of the differing parameters affecting the water table flows in and around the extraction areas. In order to ensure that a wider landscape context is assessed, and to enable comparisons with other research e.g. that by French (2004), the piezometer grid at Newington will be extended to ensure that the maximum distance away from the extraction areas is encompassed during the monitoring programme (as shown in Section 4).

2.10 Previous research in relation to extraction activities

2.10.1 Water table monitoring in the extensively alluviated lower Great Ouse valley has recently been published by French (2004), following on from work on the pre-extraction phase at the site of Over, Cambridgeshire (French *et al*. 1999). In total, three phases of monitoring, comprising three years pre-extraction, eighteen months scaled-down pre-extraction, and two and a half years during extraction, were undertaken between November 1994 and September 2001. Interestingly, although the monitoring required an 'organic' approach, due to the limitations of the planning and extraction processes, French (2004:2) notes that this has been advantageous as the longer timeframes involved have allowed trends to be monitored over several seasonal cycles.

2.10.2 The significant observations from the above work are that:

- due to pumping, the groundwater table within the extraction area was depressed to 5 m below the modern ground surface
- pH and dissolved oxygen values increased
- downstream from, and beyond the extraction area, the groundwater table gradually dropped to approximately 2 m to 5 m below the modern ground surface
- a 'halo' effect was recorded for a distance of up to 500 m beyond the extraction area
- 'bunding' with impermeable clays slightly negated these impacts to the south of the extraction, but unconstrained conditions to the north continued the impacts of draw down
- French (2004) recommends that groundwater and water quality monitoring should be part of the archaeological brief as part of PPG16 (DoE 1990)

2.10.3 Many of the above observations will be tested during the current assessment. However, a number of caveats need to be in place before an uncritical acceptance of the above observations is undertaken. In particular, it should be noted that although the methodologies adopted are not necessarily the most viable techniques to apply when assessing groundwater tables in relation to extraction sites, they have been used by previous researchers to characterise, holistically differing types of burial environments (Caple 1993, 1996, Cheetham 2003, Lillie & Smith *in press*, Smith 2005).

2.10.4 Redox potentials have been shown to have important implications for the understanding of the burial environment (e.g. Caple 1996, Caple & Dungworth 1997, Lillie & Smith *in press*, Smith & Lillie *in press*). Redox can be used as a proxy indicator for the characterisation of the burial environment (Stumm & Morgan 1970), but it has been observed that accuracy is enhanced when *in situ* equipment is used (*cf*. Cheetham 2004:279-80). In this context, the redox potential of the groundwater recorded from dipwells is less reliable as the results obtained are generic, and not directly related to the burial environment/horizon being investigated. Similarly, measures of dissolved oxygen and pH, when recovered from dipwells, will provide only generic background data, and not data that is directly relatable to the burial environment being investigated (van Heeringen *et al*. 2004:54). Investigations at Schokland, the Netherlands (*ibid*. 2004) have indicated that the use of dipwells is problematic, not least because it is difficult to collect readings from the unsaturated zone. Oxygen is unconstrained in dipwells meaning that it has a direct influence on the oxygen content and redox potentials being measured (2004:54). Not only have these problems been encountered, but van Heeringen *et al*. (2004:54-6) have also suggested that the pH of the groundwater studied in the Netherlands indicates that greater variability occurs in groundwater, when compared to the solid phase.

2.10.5 It is acknowledged that French (2004) and French *et al*. (1999) have undertaken important research into the monitoring of water tables in extraction sites. However, the methodology of the investigation can be enhanced in order to ensure the generation of specific and targeted data which will enable a greater understanding of the dynamics of the aquifers, burial environment and water table in relation to the extraction process. French (2004:6) has noted that a complex set of variables influence the monitoring data generated at Over. These include seasonal factors, and in particular, rainfall variation, high river levels, recharge from the aquifer and irrigation. All these factors have been previously identified by Leake (2000) at Newington.

2.10.6 As such, the current research project has the benefit of hindsight in that when taking all previous archaeological, hydrological and palaeoenvironmental studies into account, the limitations inherent in previous research can be identified and mitigated against. We are currently at a point in time where our knowledge is sufficiently robust to ensure the generation of meaningful data in relation to aggregates extraction, water table dynamics, and their influences on the buried archaeological and palaeoenvironmental resource.

2.11 Reasons for and circumstances of the project (*cf*. Lillie 2004)

2.11.1 The extraction of aggregates often occurs in locations that have a proven potential for the recovery of waterlogged archaeological remains, e.g. river floodplains, their terraces and other alluviated landscapes. As such, Newington presents an ideal opportunity for research purposes.

2.11.2 In Section 1.4 the merits of the proposed research at Newington were outlined. Amongst these, the complete access to the site and its archive being offered by Hanson Aggregates ensured the success of the project. This success is also secured by the provision of the hydrological studies undertaken by Leake (2000). In addition, previous research by NAA and WAERC provide a detailed background of the sites' archaeological and palaeoenvironmental record.

2.11.3 As noted in Section 2.10.6, sufficient background studies exist to ensure that the proposed research is successful in evaluating the impacts of aggregates extraction in a holistic way that will enable detailed consideration of parameters such as water table dynamics, redox potentials and pH; and furthermore the state of preservation of the palaeoenvironmental resource. These parameters will be used to inform the methodological approaches adopted below (as shown in Chapter 4).

2.11.4 Recent work (e.g. French *et al*. 1999, French 2004, Lillie 2007, Lillie & Cheetham 2002b & c, van Heeringen *et al*. 2004) has identified those parameters that can be readily studied as part of the research programme. Chapter 4 will outline the key methodological approaches to be adopted during the study and explain the rationale behind the adoption of the approaches employed.

2.11.5 Despite the previous studies (outlined above), the potential impacts on the buried resource due to shifts in hydrological regime remains poorly studied and/or understood. This situation arises due to the limited nature of monitoring strategies that have been designed to study the geo-hydrology of what are often large-scale unconstrained landscapes, in hydrological terms. This research will ensure that different levels of information are generated in order to allow for comparisons between the current analyses and previous studies.

2.11.6 The Newington extraction site comprises phased extraction which has continued since 2004. The nature of the extraction and the occurrence of adjacent biogenic deposits, with a proven waterlogged archaeological and palaeoenvironmental record, facilitates the generation of a calibrated groundwater flow model for the area around the extraction site. This model is used to simulate current, and to assess possible future, effects of dewatering and re-injection associated with gravel extraction.

2.11.7 The combined approaches to extraction (which are outlined in detail below) include the provision of water storage areas in previously worked extraction locations. These can provide a measure of mitigation against drawdown during the extraction works. This hypothesis will be tested during the monitoring programme as this approach contrasts with that adopted during the extraction at Over, Cambridgeshire (French 2004).

In addition, the unrestricted access to areas adjacent to the extraction locations, in all directions, with a particularly important area to the south of the extraction area in the modern floodplain, is of considerable significance in respect of extraction and the subsequent modelling of water table dynamics away from the extraction area (*cf*. French 2004).

The implementation of systematic monitoring points, both adjacent to and away from the extraction areas, will significantly enhance the data generated from previous studies (i.e. French *et al*. 1999), where only limited borehole and dipwell locations were used to asses the impacts of drawdown.

3. Aims and objectives

3.1 Research design

3.1.1 Lillie (2004) noted that the current project aims to provide data relating to the effects of 'draw-down' (*cf.* French 2004), catchment-wide changes in water table dynamics and any disruptions to the burial environment concomitant with the creation of the extraction areas.

This report presents an assessment of the parameters necessary for generating hydrological models suitable to inform the Heritage sector, managers of extraction sites, and planning authorities on 'best practice' approaches to mitigation strategies in relation to the resource. It will provide a baseline for future studies of the impact of aggregates extraction in a wide range of environments in the UK and beyond. This study will also enable the quantification of the potential effects of aggregates extraction on the archaeo-environmental resource in floodplain, and associated environmental settings, and provide a methodological framework for other studies.

3.1.2 *Significance and temporal resolution*
The importance of the current research lies in the contradiction between the high archaeological and palaeoecological value of waterlogged floodplains, and related deposits, compared with our weakly developed methodologies for quantifying the impacts of aggregates extraction upon the historic resource.

Existing extraction licences are subject to mitigation at differing levels depending upon the co-operation of extraction companies and statutory authorities. Extraction is on-going, and without defined impact assessments as are proposed here, mitigation strategies can only been implemented in a reactive way until empirical data are produced that can accurately quantify the nature in which the archaeological and palaeoenvironmental resource is being compromised.

Aggregates extraction sites are managed by the developer; the long-term management plan at Newington consists of the restructuring of the landscape after extraction ceases. It can be anticipated that variations in hydrology, soil status and general nutrient parameters will occur both during and after extraction is completed. As such, future management of the excavated areas will have an effect on the status of the burial environment that will in turn have the potential to impact on any buried archaeology (*cf.* Chapman & Cheetham 2002, Lillie & Cheetham 2002c). Furthermore, differences in surface vegetation are likely to have a varied impact on any remaining archaeological/palaeoenvironmental resource arising from factors including root penetration depth (e.g. reedbeds) and contamination through impacts, such as periodic flooding of washlands and the storage of oxygenated water on-site.

The Newington landscape has been shown to have been in a state of flux due to previous water abstraction regimes (Leake 2000). Furthermore, the extraction process will remove large parts of the aquifer associated with the sands and gravels in the immediate area, and the floodplain peats to the south need to be monitored to ensure that any potential effects from drawdown can be observed and quantified. Given the longer-term changes to the landscape due to the extraction processes, it is of fundamental importance to future mitigation strategies that assessment of adjacent areas in terms of their hydrological, biological and chemical status be undertaken, and that post-extraction systems responses are quantified.

3.1.3 The results from this work will inform research in extraction areas elsewhere, both in the UK and abroad.

3.1.4 The resulting geo-hydrological models and measures of soil status will be useful and applicable to other disciplines including hydrology, ecology and nature conservation, particularly given the presence of areas of SSSI status in the immediate vicinity. As noted above (Chapter 2), these occur to the south-east of the extraction area

(Slaynes Lane washland), with a much larger SSSI (River Idle washland) running from Bawtry Bridge along the north side of the river up to the south-western corner of the extraction area (Lakin & Howard. 2000).

3.1.5 The proposed project conforms to a number of research priorities as outlined in Exploring Our Past 1998 (EoP98 - Williams 2003):

- **Primary goal A - Advancing understanding of England's archaeology**
  Programme 1: Assessing the known resource

  1.7 *Assessing and understanding specific landscapes and monuments*
  The project will enable long-term management and interpretation of landscapes with a proven archaeological potential which may be prone to aggregates extraction, and will inform broader discussion and understanding of comparative landscapes elsewhere. Particularly, this work provides better baseline information against which other similar landscapes may be assessed.

  1.8 *Analysing the national resource*
  The project enhances our understanding of the available data resource that holds the potential for understanding these landscapes. The examination of various data sources outside of the normal archaeological range (including databases held by the aggregates extractors themselves and Environment Agency abstraction data) provides information both for the Newington site, and also on the potential of available data for sites and landscapes elsewhere. This in turn will feed into the repositories of the NMR and regional repositories. Given the implications of long-term climate change scenarios, it is increasingly apparent that a solid understanding of hydrological impacts in floodplain areas is of fundamental importance if we are to determine sustainability in relation to the heritage component of floodplain wetlands.

  Programme 2: Promoting under-studied or vulnerable areas

  2.3 *Wet and waterlogged areas*
  Emphasis has been made on the continuation of the work of the English Heritage funded Humber Wetlands Project (HWP). Newington is located in the Idle floodplain, to the east of the Romano-British site of Scaftworth (Van de Noort *et al*. 1997:409-28), within the Humberhead Levels region of the HWP. The research undertaken to date has highlighted a considerable degree of archaeo-environmental potential for the areas of the floodplain investigated. However, there is a lack of resolution for the floodplain areas adjacent to the Idle floodplain, which probably reflects the limitations of current prospecting methods (*cf*. Coles & Coles 1996).

  These landscapes remain vulnerable due to changes in land use and the modification of their hydrological regimes, as a consequence of extraction/abstraction activities, irrespective of their reinstatement as wetland landscapes by the extraction companies. However, despite the above observations, *no specific reference* is made in the document entitled 'Monuments at Risk in England's Wetlands' ([MAREW] Van de Noort *et al*. 2001) to the inherent threats to the archaeological resource of alluviated lowland wetlands in the Humber region and elsewhere from aggregates extraction. This is despite their identification as locations with a proven waterlogged potential, and the quantification of *c*. 7400 monuments in these zones (Van de Noort *et al*. 2002 [and Section 2.4 below]).

  2.4 *Alluvial and colluvial zones*
  As noted above in Chapter 2, the Newington extraction site, considered here, is defined to the south by Slaynes Lane, which marks the transition from the superficial shallow peats and fine grained silts and clays to the north, to the deeper floodplain peats of the Idle floodplain to the south. Archaeological finds have previously been identified from the areas to the north of Slaynes

Lane, particularly during assessment by Northern Archaeological Associates (NAA) (see Section 2.6 above). Palaeoenvironmental potential has been confirmed both to the north and south of Slaynes Lane during assessments undertaken by the Wetland Archaeology and Environments Research Centre (WAERC), University of Hull.

Whilst the spatial boundaries of the current extraction area are defined to the north by Bawtry Road and to the south by Slaynes Lane, the proposed project area is defined by the topography to the east and west, and by the River Idle to the south of the extraction area. The northern boundary remains as defined by Bawtry Road (as shown in Figure 1). The current project area is defined as above due to the likely impacts of aggregates extraction on the hydrology of the wider area. As such, monitoring points located some distance away from the extraction area should provide insights into any 'halo effect' (*cf*. French 2004) occurring away from the defined extraction limits. Given the deeply stratified floodplain peats to the south of Slaynes Lane, and the proven palaeoenvironmental potential of this resource, quantification of impacts is of fundamental interest to this study.

2.6 *Assessing the national palaeoenvironmental resource*

The need to assess the national palaeoenvironmental resource has been recognised in EoP98. The proposed work at Newington builds partly on the previous palaeoecological work undertaken for Hanson Aggregates by Gearey & Lillie (2002). To date, the limitations of low-resolution study in floodplain environments are well established, but few studies have targeted preservation of the palaeoenvironmental resource in relation to changes in burial context resulting from aggregates extraction. The current investigation of preservation status will enhance the study of the burial environment. This is undertaken via redox potential and pH status during extraction, and by pollen studies, all of which will provide a measure of decay over time.

- **Primary goal B - Securing the conservation of England's archaeological landscape, sites and collections**

Programme 5: Survival assessment

5.2 *Agricultural damage*

Arable exploitation will have had a significant impact on the upper parts of the resource, particularly in those areas of the floodplain to the north of Slaynes Lane that are characterised by thin, superficial organic sequences.

5.4 *Monuments at risk*

The management of archaeological sites and landscapes within floodplain environments is a complex process. Whilst these landscapes fall within the legislation outlined through the planning process, many of the normal principles do not apply. This is made particularly difficult since the archaeological resource is often difficult to identify, especially where deep floodplain peats are identified, and as such, impossible to quantify. Whilst there is a clear risk to any archaeological remains through drainage, peat cutting, extraction and even reinstatement, research to date does not provide sufficient understanding of these landscapes to enable an adequate quantification of the impacts of de-watering in such contexts/landscape settings.

Programme 6: Protection and conservation

6.3 *Development of conservation theory*

The proposed project will develop further links between different users (interest groups) of the resource, particularly extraction companies, County Archaeologists and Curators, English Heritage, Natural England, and the Environment Agency (all of whom have an interest in the Newington area). The project aims to provide baseline hydrological models which will inform the future management and conservation of the potential archaeo-environmental resource of riverine/estuarine/coastal landscapes. It will also provide a benchmark against which other similar landscapes may be better understood and thereby protected.

6.5 *Advancing from PPG15 & PPG16*
The current study will inform approaches to mitigation under the auspices of the planning and policy guidance notes, particularly in relation to current approaches to *in situ* preservation strategies.

Programme 7: *Threat-led fieldwork*
7.3 *Recording significant archaeology under threat on pre-PPG16 consents*
In cases of pre-PPG16 planning permissions (notably for mineral extraction) mitigation is often dependent upon the extraction companies good will. The establishment of baseline empirical data on the impacts of the extraction process will significantly enhance our ability to argue for a more considered approach to mitigation in such situations.

- **Primary goal C - Supporting the development of research framework**
Programme 8: Research frameworks
8.2 *Regional environmental reviews*
One of the fundamental approaches of the proposed project will be to assess the palaeoenvironmental archive in a way that will assist in our understanding of the impacts on the regional and local environment in relation to extraction and the survival of the deposits.

8.4 *Assist national bodies articulation with the regional agenda*
The information generated will assist national bodies to develop national perspectives on aggregates extraction that will inform the local, regional and national agenda.

- **Primary goal D - Promoting public appreciation and enjoyment of archaeology**
Programme 10: Education
10.2 *Innovative dissemination of archaeological information for schools*
The results from the proposed project will be published in a series of formats, from complete archiving at one end of the spectrum to predictive modelling of future impacts at the other end. The latter models will be available through the Sites and Monuments Records and also via the internet. This will provide a useful and innovative resource for schools and could act as a basis for studying modern resource needs (water and aggregates), human-landscape interaction and archaeology.

Programme 11: Local archaeology and public involvement
11.3 *Local societies and interest groups access to archaeological information and expertise*
Throughout the duration of the project, there has been liaison with local interest groups, including archaeological and environmental societies in the region. This has enabled the pooling of knowledge and expertise.

Programme 14: Developing skills
14.2 *Increase awareness in other disciplines of the potential inter-action with archaeology*
The research will ensure that aggregates extractors, hydrologists and geo-hydrologists are informed of the potential impacts/interplay between the excavation of aggregates and the modification of water tables in relation to the buried archaeo-environmental resource. This data will directly inform agencies such as Natural England and the Environment Agency in their own efforts at management. In addition, it is envisaged that this research will provide a basis for highlighting archaeological concerns to those in other disciplines including geography, ecology, conservation and the wide range of disciplines with interests in these landscapes. Initial dissemination of the

interim results of the current research were presented at the World Wetlands Day conference in London, England on 1st February 2007, and at the WiP meeting held at the English Heritage offices in York on 16th February 2007.

Programme 16: Communication and dissemination

16.2 *Disseminate information on scientific techniques*
The proposed project will use and develop GIS and modelling techniques (via ModFlow). It is envisaged that, in addition to the specific outputs from the project, a series of methodological papers will be generated communicating these approaches to the wider archaeological and scientific community.

16.4 *Explore the curation of digital archaeological archives*
There will be liaison by the post-doctoral researcher with the Archaeology Data Service (ADS) throughout the proposed project to enable best-practice strategies of data curation to be completed.

16.12 *Disseminate state-of-the-art methodologies and applications*
It is envisaged that papers and documents will be produced during the lifetime of the proposed project which will outline and assess the application and usefulness of the modelling being applied and developed. In addition, these papers will include information about the usefulness of different approaches to the generation of data for use in modelling impacts from extraction and ground water impacts.

- **Primary goal E - Developing professional infrastructure and skills**

Programme 17: Methodological and technical development

17.1 *Evaluation techniques*
The development of an approach to modelling that specifically targets the impacts of extraction in relation water tables and the archaeological record is fundamental to future mitigation strategies in these environments.

17.6 *New scientific techniques for analysis*
The current project will develop new approaches to modelling-based scientific techniques for the analyses of dynamic and environmentally complex landscapes in relation to aggregates extraction.

17.8 *De-watering*
Newington and other sites around the country have suffered from de-watering activities associated with agriculture, water abstraction and aggregates extraction. The combination of these activities has compromised the integrity of the archaeo-environmental archive. Reinstatement activities, that include the raising of local water tables, has the potential to compromise the resource adjacent to extraction areas through the introduction of vegetation and the introduction of oxygen- and/or nutrient-rich water. Recent research has demonstrated that such processes, both de-watering and re-wetting, interrupt stasis in the burial environment, and thus potentially damage the buried/submerged resource (e.g. Van de Noort *et al*. 2001, Cheetham 2004).

17.9 *Mitigation strategies and in situ preservation*
The results from the proposed project will feed into future mitigation strategies, particularly through the definition of areas where *in situ* preservation is either feasible, or unfeasible, in relation to site location, projected land use and the control of water tables.

17.11 *Predictive modelling strategies*
The proposed project is aimed primarily at constructing models of the water table dynamics that result from the extraction of aggregates in order to generate predictive models of water table reaction for use in future mitigation strategies. This data will be at a higher, site-specific resolution compared with other water table monitoring projects (e.g. French *et al*. 1999, French 2004).

3.1.6 The Monuments at Risk in England's Wetlands assessment ([MAREW] Van de Noort *et al.* 2001) highlighted the archaeological importance of floodplain environments, whilst underlining the significant threat presented by agricultural activities and water abstraction. The current research will directly inform all areas of floodplain management in respect of these issues, with the specific focus being the impact of aggregates extraction on the resource.

3.1.7 *Aims*

This research was formulated with the aim of understanding water table dynamics and their influence on the buried archaeological resource in relation to aggregates extraction (*cf.* Lillie 2004). Without developing a holistic understanding of the impacts of the extraction process on the archaeology of these areas, attempts at mitigation will remain ill-informed and best practice towards *in situ* preservation will remain unclear.

The research design, as outlined above, therefore addresses the need to understand the parameters influencing the buried archaeo-environmental resource in relation to the extraction process (along with associated impacts from agriculture and water abstraction) and the possible implications of these factors in relation to mitigation and curation of the archaeological record. The main aims of the project are therefore to:

Aim 1: Define the nature of the deposits and aquifers influencing the waterlogged resource at Newington.
Aim 2: Define the impacts of pre-extraction activities such as agriculture and water abstraction on the floodplain and adjacent organic/waterlogged deposits.
Aim 3: Assess the archaeological implications which may be inferred from the impacts of de-watering upon this resource.
Aim 4: Define the nature of the burial environment over time.
Aim 5: Develop a robust modelling approach to the reconstruction of water table dynamics in relation to extraction.
Aim 6: Assess the impacts of fluctuating water tables on the resource using scientific and palaeoenvironmental techniques.
Aim 7: Develop a new method for predictive modelling of water table dynamics in relation to extraction, and also abstraction practices.
Aim 8: Provide a baseline for the development of management tools for extraction sites elsewhere and communicate this to the wider archaeological community and the general public.

Finally, in light of the recent discourse in relation to global climate change scenarios, the discussion will assess the sustainability of the heritage elements of floodplain wetlands in relation to long-term climate change and future demands on water resources. The potential for understanding the myriad impacts on wetlands will be assessed in light of the conclusions drawn below (Chapter 5).

4. Methodology

4.1 Introduction

The methods undertaken during this project have comprised a combination of water hydrology, soil chemistry, palaeoenvironmental assessment and ground water modelling using ModFlow. These techniques are outlined below.

4.2 Methods

4.2.1 *Water table monitoring (to c. 3m maximum depth)*

The generation of water table monitoring data comprised data acquisition from the Hanson boreholes (Figure 2.6), alongside abstraction data from the water abstraction boreholes in the catchment. This data was integrated into the hydrological catchment modeling as developed by Golder Associates (UK) Ltd (Section 4.25 below). Shallower water table data was recovered through the monitoring of seventy-four piezometer points established in and around the extraction area, and sunk to the base of the floodplain peats to the south of Slaynes Lane.

4.2.1.1 Piezometer construction

MGS Ltd of Bury St. Edmunds supplied the piezometers used during the project. They comprise 1 m, 2 m and 3 m long PVC tubes of 19 mm internal diameter. Attached to the buried end of the tube is a piezometer tip of 300 mm length, consisting of a perforated PVC tube containing a filter membrane designed to prevent contamination from surrounding soil (Figure 4.1). The piezometers were located within a pre-planned grid (as shown in Figure 4.2) and were cored into place using a hand auger with a 30 mm diameter screw tip obtained from Van Walt Ltd (as shown in Plates 4.1 and 4.2).

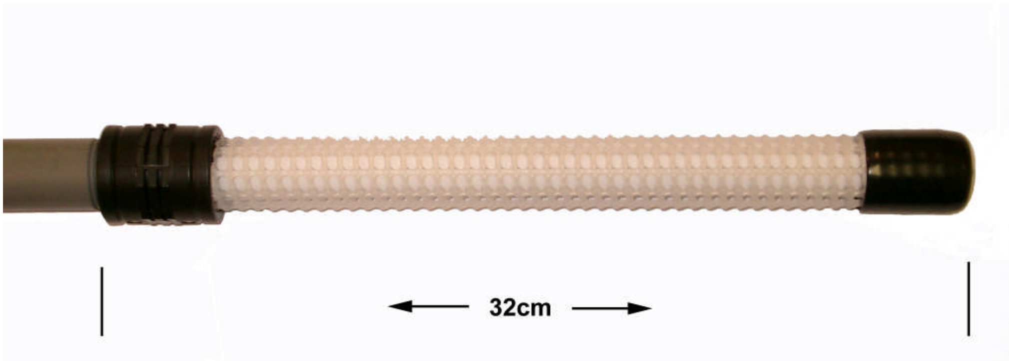

Figure 4.1: Piezometer tip: white area is a perforated PVC tube with plastic membrane lining, designed to allow water infiltration and restrict sediment contamination.

An acoustic sounder (Van Walt Ltd) measured the level of the water table. This is a device consisting of an electrical sensor at the end of a plastic tape measure. The sensor was lowered into the piezometer in order to take the readings. An audible alert sounds and an LED illuminates when the sensor meets the water surface. Readings were systematically obtained for all piezometers in the network for each visit. The results were recorded on a standard recording sheet.

4.2.1.2 Piezometer installation

Piezometers were placed both in close proximity to the extraction site and in those areas to the north, east and west where access was available. To the south of Slaynes Lane transects were established across the floodplain up to the edge of the modern course of the River Idle (as shown in Figure 4.2). The monitoring locations comprised clusters of piezometers located at depths of 1 m, 2 m and 3 m, depending upon the depth of the peat sequence. These depths were used in order to enable

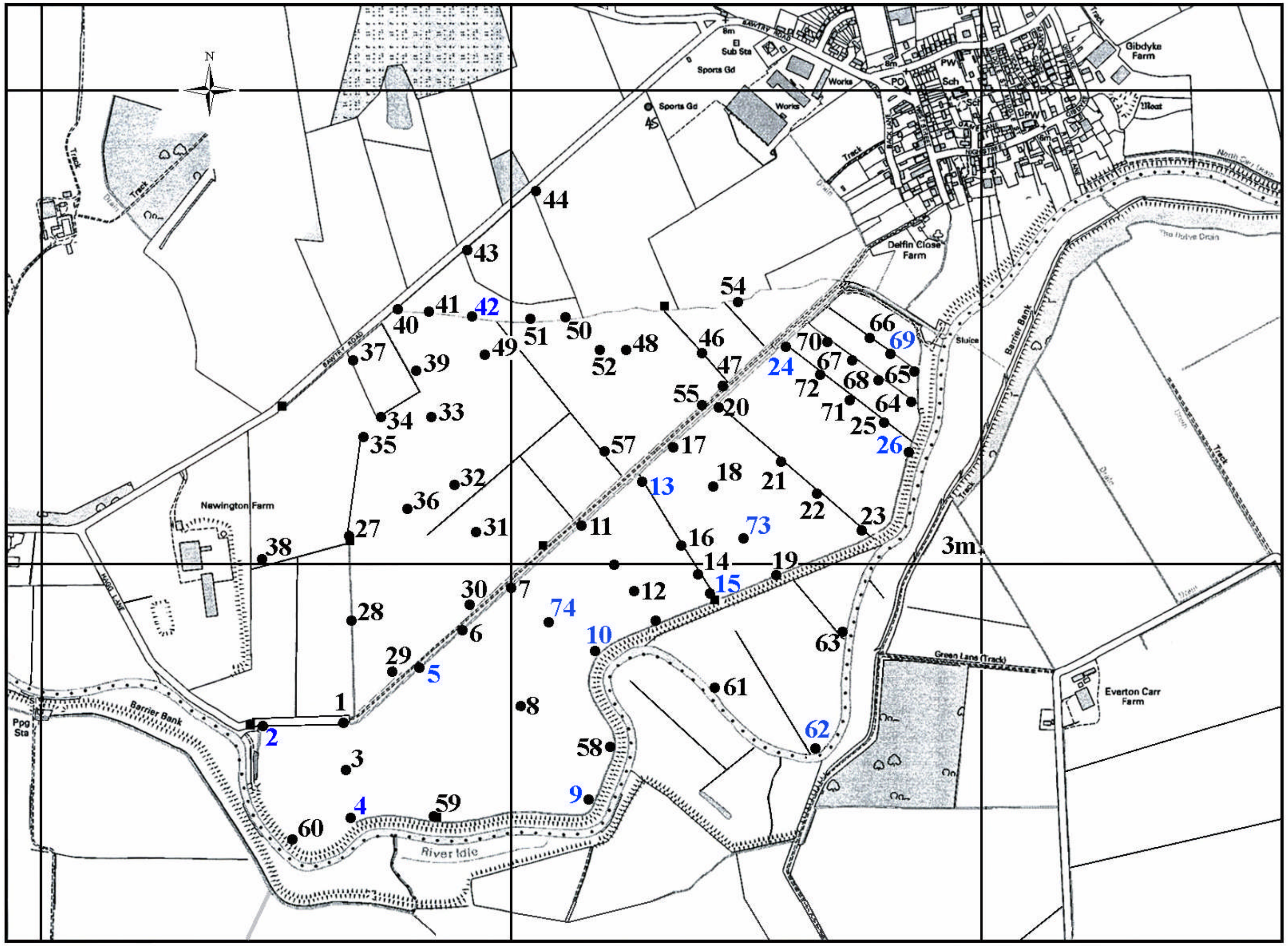

Figure 4.2: Piezometer locations at Newington. Blue numbers relate to locations where redox clusters are located in association with piezometers.

Plate 4.1: Close-up of 30mm diameter Van Walt screw tip augur used in piezometer installation (© Malcolm Lillie).

comparisons of the zone of saturation across the study area and to enable the flow of water within the vertical plane to be identified (*cf*. Cheetham 2004). In addition, the piezometer clusters enable unconfined/confined aquifer conditions to be determined in the field, as different water levels will reflect varying conditions of hydrological isolation occurring within the study area, thereby reflecting the potentiometric surface in a confined aquifer situation (*ibid*. 2004:44-5). The grid is designed to enable an assessment of water table activity, target the identification of any potential 'halo' effect (*cf*. French 2004) away from the extraction area, and enable the assessment of the re-establishment of water tables as different extraction areas are 'worked-out' and 're-instated'.

Plate 4.2: Excavation of piezometer borehole in advance of installation (© Malcolm Lillie).

All the piezometers were leveled using a Leica differential GPS. The data generated was subsequently modeled using ESRI ArcMap GIS (version 8.1) software. Accuracy using this equipment is in the region of ±0.05 m.

The principles of modeling were undertaken following those outlined by Burroughs (1986) and applied elsewhere (Chapman & Van de Noort 2001, Chapman & Cheetham 2002). Data management followed the guidelines provided by the Archaeology Data Service (Gillings & Wise 1999), including the provision of Metadata (*cf*. Wise & Miller 1997). Initial modeling in the GIS environment entailed the construction of DEM's which were compared against the available mapping of the drift deposits within the study area (*cf*. French *et al*. 1999). Kriging interpolation was used to model the preliminary hydrological data as it presents a lower RMS error (-a measure of the average error across a map) (ESRI 2007). The spherical semi-variogram produced enables the generation of smooth models that are commensurate with the anticipated water table.

4.2.1.3 Data acquisition

Piezometer monitoring was undertaken on a bi-weekly basis at the outset of the monitoring programme. The frequency of monitoring was subsequently reduced to monthly monitoring visits after the establishment of water recharge in the piezometers (*cf*. French *et al*. 1994). At Newington, stable water levels were reached after a period of two months.

4.2.1.4 Data modelling

The locations and heights of the piezometers were recorded relative to OD by means of a differential GPS. The equipment used for this was a Geotronics © System 2000 L1-RTK differential Global Positioning System (GPS).

During field monitoring the raw data generated from the piezometers were recorded in the form of measurement depth (in metres) below the ground surface. In order to produce a more accurate model and manipulate the hydrological data, these levels were subsequently corrected to OD.

The observed depths of the water table were corrected to OD by subtracting the observed depth of the water level below the ground surface from the absolute height of the top of the piezometer. Calculations were performed for each monitoring visit using an MS excel spreadsheet programme, with the results exported in ASCII text file format. These files were then incorporated into a GIS for manipulation and modeling. ArcGIS 9 from ESRI was used for the presentation of hydrological data and in the creation of location maps for all monitoring points.

ArcGIS 9 created models to represent the form of the water table in which a point shapefile was generated from X, Y and Z data from the water levels in the individual piezometers. This was then contained within a comma delimited text file that had been created previously. During this process, the shapefile was geo-referenced to the British National Grid coordinate system. The point shapefile was incorporated into ArcMap, where interpolation of the data was carried out to generate the DEM. In order to create a DEM covering the monitoring grid only, an analysis mask was used to clip the interpolated model using a polygon shapefile of the extent of the piezometer grid. Interpolation of the point data was carried out using the D-Analyst extension and tension Kriging method, using an output cell size of 5. The resultant surfaces are smooth and provide a clear view (Burrough & McDonnell 2000). Furthermore, the method of Kriging, which presents lower RMS error, will therefore give a better prediction of the interpolation (ESRI 2007).

4.2.2 *Redox potential*

Redox potential (mV) is a measure of the electron availability in the sediment, and therefore its oxidation or reduction characteristics (Corfield 2006). It can determine the oxidizing-reducing nature of the environment over a number of years without a reduction in accuracy (Veneman & Pickering 1983). The concentrations of electrons present in solutions control the redox potential reactions in the burial environment. The measurement of these electrons in a sample can determine the electrode potential that develops when incorporated into an electrochemical cell (Howard 1998). The most common measure of redox activity is Eh, the electrode potential measured against the hydrogen electrode. The unit of Eh is the volt, which is measured at specific points using permanently installed platinum electrodes and a portable voltmeter.

The standard classification used to define the redox status of soils originated from the research by Patrick & Mahapatra (1968) who assessed well-drained and waterlogged soils during studies of rice production. This research determined that values >+400 mV indicate oxidized conditions, values between +100 mV to +400 mV are indicative of moderately reducing conditions, values between –100 mV to +100 mV highlight reduced conditions and values between –300 mV to –100 mV indicate highly reduced conditions.

Numerous subsequent studies have used these standard categories in order to measure the redox potential of burial environments (Brunning *et al*. 2000, Caple 1996, 1993, Caple & Dungworth 1995, Cheetham 2004, Hogan *et al*. 2001, Lillie & Smith *in press*, Smith 2005, Smith & Lillie *in press*). It is on this basis that the same scheme will be employed in order to describe the redox results obtained from this project.

Many studies of redox potential (i.e. the soil status) have also been used in conjunction with water table conditions (via piezometers) in order to compare soil status and water tables at the intra-site level of study (Brunning *et al*. 2000, Caple & Dungworth 1997, Cheetham 2004, Corfield 1996).

It is acknowledged that the categories of redox potential described above can only serve as a generic indicator of the type of conditions occurring within a variety of different soils. This situation arises because the use of Eh creates unavoidable inaccuracies associated with the measurement of mixed potentials within the burial environment (Cheetham 2004). The inherent complexities concerning the low concentration of redox couples within oxidized environments (Bohn 1971), and the measurement of mixed potentials in water, makes thermodynamic interpretation difficult (Stumm & Morgan 1981). Nevertheless, redox potentials do provide boundary conditions, i.e. the natural limits of redox in water (Bohn 1971) and are suitable as a semi-quantitative measure of soil reduction (Ponnamperuma 1972) when taken from anoxic and aerobic environments (Caple & Dungworth 1995).

4.2.2.1 Probe construction

Construction of the redox probes used during this study follows the design presented by Faulkner and co-workers (1989) for the 'welded' type of probe. Each probe comprised a tip of 0.5 mm gauge platinum fused to a copper terminal wire; with the connection waterproofed by a sheath of shrink fit sleeving. At the opposite end of the wire, a short length of copper was exposed, where an additional band of sleeving was applied to prevent water penetrating the inside of the wiring sheath (Figure 4.3).

Hull University constructed the redox probes used during this study to a 5 % tolerance. The construction was based upon previous research undertaken at Royal Holloway Institute for Environmental Research (Hogan *et al*. 2001). The tolerance of a redox probe is dependent upon the reliability of the readings obtained when immersed in a redox buffer solution (10.211 g of potassium hydrogen phthalate in 1 litre of deionised water [previously saturated with quinhydrone] at a potential of +218 mV) (Cheetham 2004). Any probes showing readings that were ≥5 % of +218 mV were rejected.

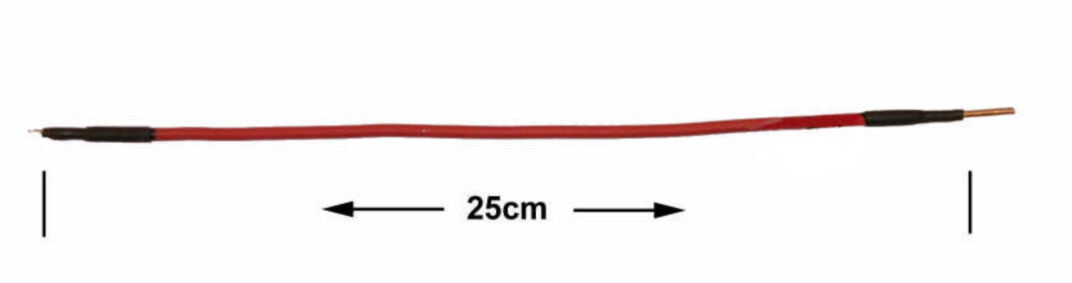

Figure 4.3: Close-up of redox probe: left terminal has 'welded' platinum wire tip, red and black = shrink-fit sleeve, right end has copper wire exposed for connection to pH\mV meter (© Malcolm Lillie).

Redox clusters were positioned throughout the monitoring grid, in locations where they did not disturb any extraction or agricultural activities during the entire monitoring programme (as shown in Figure 4.2). A small diameter auger was pushed into the sediment to create a space for the subsequent insertion of the redox probe (as shown in Plate 4.4). The probes were then inserted until a good contact was made between the platinum tip and the undisturbed soil matrix. The probes remained *in situ* for a twelve-month period in order to identify both seasonal and diurnal changes. Approximately 0.10 m of wire was left protruding above the sediment surface to enable readings to be taken from above the ground surface (as shown in Plate 4.5).

Plate 4.4: Augured holes for insertion of redox cluster, four holes were excavated to depths of 0.1m, 0.5m, 1.0m, and 2.0m depths, with four replicate probes at each depth (© Malcolm Lillie).

As noted above, probe clusters were installed at depths that mirrored two of the piezometer depths (1.0 m and 2.0 m) for comparative purposes. The upper (0.1 m and 0.5 m) redox probes were used as controls to provide an indication of redox change through the soil profile. Four probes were installed at each depth. Ten probe clusters were installed in February 2006, one probe cluster was installed in July 2006 and three probe clusters were installed in August 2006 (as shown in Figure 4.2).

Plate 4.5: Redox probes after insertion to required depths (© Malcolm Lillie).

4.2.2.2 Data acquisition

The redox probes were left for a period of two weeks in order to establish equilibrium within the burial environment before monitoring began (Caple 1996, Cheetham 2004). Redox readings were taken monthly using a portable pH/mV-meter (Wissenschaftlich-Technische Werkstatten GmbH) connected to a Silver Chloride (AgCl) double junction reference probe (BDH Gelpas) and to the *in sit*u probes by means of a clip. The reference electrode was inserted into a shallow hole previously made in the sediment surface, which was in close proximity to the redox probes. If the sediment surface was dry, a small amount of deionised water was poured into the hole prior to the insertion of the reference electrode in order to ensure a good electrical contact.

4.2.2.3 Data processing

The data from all redox probes was recorded on a pre-prepared sheet. One reading from each cluster of probes at a particular depth was disregarded from subsequent analyses, as observation of the recorded values occasionally showed the existence of an extreme value (or outlier) (Cheetham 2004). This outlier, when incorporated into the resulting analyses, would influence the mean value obtained from each cluster of probes. However, to ensure continuity throughout the results, the main outlier was always disregarded, even if it was considered to be within an acceptable limit. The rejection of such a value, which was closely associated with the mean value from a cluster, would not adversely affect the overall outcome, whereas the rejection of a true outlier would ensure greater accuracy. It is recognized that this technique may produce biased values in an instance where there are two pairs of divergent values, but this situation should not occur under normal circumstances (*ibid*. 2004).

The mean value obtained from each depth was adjusted to the Standard Hydrogen Electrode (SHE) (British Standards Institute 1990) in order to measure the redox potential (Howard 1998). This enabled comparisons to be made between values from different sampling points. Owing to the Silver Chloride (AgCl) reference electrode having a potential value of +222 mV, the equivalent numbers of mV were therefore added to each redox value obtained. In addition, each meter reading was also adjusted to pH 7 to remove pH variability between sediments. This was achieved by adding a correction factor of –59 per unit of pH for values above pH 7, or subtracting the same correction factor below pH 7 (Bohn 1971, British Standards Institute 1990). Intermediate pH unit corrections were made proportionately, i.e. for pH 6.2 a factor of 0.8 x 59 would be adjusted from the redox value.

4.2.3 *pH*

Sediment pH was measured by using a temperature compensated Sentix 21 combination electrode TFK 325/HC temperature sensor attached to a pH/mV-meter (Wissenschaftlich-Technische Werkstatten GmbH), in accordance with the manufacturers' instructions.

Sediment pH was measured monthly and in conjunction with redox monitoring, as the pH of the sediment has a direct influence upon the redox system (Cheetham 2004). The pH was obtained by taking a small sediment sample from the surface and agitating the sediment in deionised water. The pH electrode was placed into the mixture and wired to the pH/mV-meter. Readings were taken when equilibrium had been attained.

4.2.4 *Palaeoenvironmental assessment*

4.2.4.1 Borehole survey

The initial borehole survey was undertaken during the installation of the piezometer grid. Stratigraphic recording utilised the Troels-Smith (1955) method of sediment recording. pH values were obtained from the deposits in the solid state through the profile at 0.5 m intervals in order to ensure comparability between profiles. Quarterly sampling of pH values were undertaken at piezometer locations 1, 13, 15, and 25 (locations as shown in Figure 4.2) in order to assess any variation occurring/identified as a result of shifts in the hydrological balance within the deposits being studied.

Sub-sampling of cores for the assessment of organic preservation status was obtained during the piezometer installation works. Samples for palaeoenvironmental assessment, organic matter content [loss-on-ignition] and pH were obtained from significant stratigraphic horizons at critical locations throughout the extraction area as identified during the stratigraphic survey.

4.2.4.2 Pollen analysis [Dr. Paula Milburn]

Samples for pollen analysis were collected at 6 monthly intervals (March 2005, September 2005, March 2006 and September 2006), at a range of depths, from four sampling locations (located at monitoring point 1, 13, 15 and 25 - Figure 4.2). The greatest depth of organic sediment is recorded at sampling site 25 (2.50 m) followed by sampling site 1 (2.40 m), sampling site 15 (2.3 8 m) and sampling site 13 (1.30 m).

The samples were analysed throughout the project, with additional attention (higher counts), being focussed on those samples that it was judged would potentially be most sensitive to changes in preservation conditions. By increasing the level of counts for these potentially sensitive samples, it was hoped that any statistically significant changes would be more accurately identified. The samples available for pollen analysis were not entirely consistent for each site, either across the sampling runs, or across the sampling sites, placing limits on the comparability of the samples (Table 1, Appendix 1).

The value of pollen as a means of investigating degradation of biogenic sediment sequences lies in the exine layer's resistance to decay. Pollen grains are comprised of two layers, an inner cellulose layer and an outer exine layer comprised of sporopollenin (Zetzsche 1932). In essence, 'the chemistry of the coat renders them resistant to decay and wherever microbial activity is depressed, whether due to wetness, salinity, low oxygen availability or drought, there is a chance of pollen and spore survival' Moore *et al* (1991:2). However, once pollen has been deposited and become incorporated into the sedimentary environment one of 'the main causes or sources of deterioration appears to be - post-depositional *in situ* chemical changes, such as oxidation due to lowered water tables' Lowe (1982:375). As such, any changes in the burial environment at Newington can be assumed to have the potential to impact on the state of preservation on the contained pollen record.

In particular, any activity leading to increased fluctuations or overall depression of local water tables is therefore expected to have a substantial impact on the preservation of *in situ* pollen records in affected sediments. Possible impacts following the extraction of aggregates from the vicinity of the study site are considered to relate primarily to the lowering of the water table (*cf*. French 2004). As such, any changes in pollen preservation should occur most rapidly in the pollen from sediments close to the current ground surface, in areas of shallow deposits and those at the margins of deposits, where the change in water table will have the strongest effects on levels of chemical oxidation/biological activity, which may over time, result in increases in the proportions of chemically damaged grains (which include the classes corroded and degraded).

As noted by Lowe (1982:384) 'the amorphous class often increases in importance where corroded grains also become significant, and the highest percentages of amorphous pollen grains are recorded at those levels suspected to have experienced oxidation due to exposure as a result of lowered water tables'.

On this basis it was considered that marginal sediments, closest to the current ground surface, would be the first to be affected by any increase in oxidation as a result of any lowering in the water table. All of the sampling sites were located at positions around the perimeter of the application boundary. Three of the sites (1, 15 and 25) were positioned in areas of relatively deep peat. However, site 13 was located in an area of shallow peat which overlay fine grained silts and clays and it was considered that the particularly shallow deposits of organic material at this location might make it particularly sensitive to changes in hydrological conditions.

4.2.4.3 Sample preparation

Sediment samples were prepared for pollen analysis using standard procedures (Berglund & Ralska-Jasiewicsowa, 1986; Moore *et al*. 1991). Pollen was counted by linear traverses across the slide, in order to avoid any biases in pollen distribution (Brooks & Thomas 1967).

Identifications were carried out with reference to standard keys (e.g. Moore *et al*., 1991). A basic counting sum of 300 identifiable land pollen grains was employed for most samples with selected samples analysed to 1000 total land pollen and pollen of obligate aquatic plants and unidentifiable grains were excluded from the sum. Tablets of *Lycopodium clavatum*, were added during preparation to act as an exotic spike and permit the calculation of pollen concentrations (Stockmarr, 1972).

As the aim of this project was to assess changes in pollen preservation all pollen grains were assessed for deterioration during normal counting. Deterioration can occur as a result of biological activity, chemical corrosion or mechanical damage (crumpling and splitting). Various authors have suggested a range of preservation categories (Cushing 1964, Tolonen 1980, Lowe 1982, and Delcourt & Delcourt 1980). During this study pollen grains were placed in the following five categories after Delcourt & Delcourt (1980).

Normal – Well preserved grains, no indication of any degradation.

Corroded – The exine may be scored, etched, pitted or have complete perforations penetrating it, which indicates biological activity or chemical oxidation.

Degraded – The exine is generally thinned rather than locally perforated, which indicates chemical oxidation within aerial or sub aerial environments.

Crumpled – These grains show signs of mechanical damage as a result of stress during physical transport and / or compaction of grains within sediments following deposition.

Split – As for crumpled, but grains show clear breakage in addition to distortion.

Grains that were too poorly preserved to be identified were recorded as unidentifiable. The identifiability of degraded pollen grains is variable due to the impact of differential degradation on the physical characteristics of the grains (such as their shape, size, surface patterning, appearance and structure of apertures and walls).

4.2.4.3 Data Analysis

In order to determine whether the pollen preservation at the beginning of the study suggested that a usable palaeoenvironmental record was still preserved within the peat, and if so whether that record became significantly more unreliable during the course of the study, a simple screening protocol was applied to the samples, using tests proposed by Bunting and Tipping (2000; also Bunting *et al* 2001). The levels of pollen concentration and levels of indeterminate and degraded grains were considered against the failure thresholds for post-depositional biasing (Bunting and Tipping, 2000). Concentration data were also plotted against sampling site, sampled depth and sample collection time.

The results of pollen counting are only a sub-sample of the total pollen assemblage contained within the sediment, and therefore should be treated as an estimate rather than a true value. Following the method suggested by Maher (1972) for percentage data, 95 % confidence intervals were calculated for the preservation spectra for each sample, and summary diagrams were plotted using psimpoll (Bennett, 1992). The 95 % confidence interval range shown by the horizontal bar in these plots allows the analyst a clearer view of how large the difference between percentages in samples needs to be to indicate a genuine change. This plot is shown in Figure 5.35.

In order to draw out any possible patterns within the data, two further analyses were applied to the whole dataset. First, a similarity matrix was drawn up using the squared-chord distance measure of similarity between each pair of samples. This measure was chosen as it widely used in modern analogue reconstruction approaches to compare pollen assemblages (Overpeck *et al* 1987; Maher 2000; Wahr 2004). Analysis was carried out using ANALOG (Schweitzer 1994), using high thresholds of similarity (0.01 and 0.1).

Second, principal component analysis was carried out on the assemblages using expressed percentages of the preservation categories listed above. This method is one of the most widely used approaches to reducing complexity within a dataset and therefore making patterns more visible (Birks & Gordon 1985). The analysis was based on 5 variables permitting the first two axes calculated were able to explain 87 % of the innate variability within the data set. The range of scores against the axes is relatively small, showing again that the dataset is broadly similar across the site. In order to identify visually any patterns brought out by PCA analysis, several plots of the sample scores were made in which the samples were marked by symbols, showing their grouping by sample site, sample depth and sample collection date.

4.2.5 *Catchment hydrological modelling*

The original intention of the numerical modelling exercise was to model the effect of quarry de-watering at Newington upon water levels in the peat and drift deposits adjacent to the extraction areas. This model will be used both to assess the effect of de-watering upon the peats, and to consider the appropriate mitigation strategies in relation to aggregates extraction, in order to reduce any alteration in water levels in the drift caused as a result of quarry de-watering.

However, due to the nature of the software program used, ModFlow is not able to simulate groundwater heads in a perched groundwater system. As such, water levels in the peat cannot be modelled using this numerical modelling approach. Modelling has not therefore been able to fulfil the initial objective, which was to predict the effect of de-watering upon water levels in the peat deposits. Nevertheless, work has proceeded with the aim of modelling and assessing the impact of quarry de-watering on the groundwater levels in the Pleistocene sand and gravel deposits, and to provide information on the wider hydrogeological context of the system.

Ten deep groundwater boreholes were installed on site by Hanson Aggregates in 1999. These piezometers (referred to as P1 to P10), were monitored for one year prior to the planning application for the site (in 1999), and subsequently from July to October 2002, and from April 2003 to the present. Vandals destroyed point 2 between the installation period and commencement of monitoring in 2002, and points 1, 3, 4 and 9 in January 2005. The location of these monitoring points, along with the full shallow piezometer borehole grid, is shown in Figure 4.3 (below).

4.2.5.1 Approach

The first stage in the groundwater modelling exercise comprised a desk-based study to collate relevant data and develop a conceptual model of groundwater flow in the model area. The conceptual model described the conceptual understanding of the hydrogeological regime operating in the vicinity of Newington Quarry and the surrounding area. The relationships between hydrostratigraphic units, surface water and quarrying activities are described and presented schematically in Figure 4.4 (below). Within the framework of the conceptual model, the report also summarised the data available with regard to the hydraulic properties of the hydrostratigraphic units, groundwater monitoring data, groundwater abstractions and climate of the area.

The conceptual model that was developed formed the basis of the numerical modelling using ModFlow software. Initial input parameters were refined during the calibration process; first in the steady state model and then in a transient system. A transient model was developed for the period 1 January 2000 to 31 December 2004, thereby covering the development and completion of Phases 1 and 2 of the quarry working and the commencement of Phase 3.

4.2.5.2 Equations, numerical methods and software

The spatial and temporal variation of groundwater in an aquifer system with defined geometric extent is governed by a generic equation (Anderson and Woessner 1992):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} - R$$

Where h is head, K_x, K_y and K_z are the (spatially variant) components of hydraulic conductivity, S_s is the specific storage (storage per unit volume), and R is a source/sink term which includes the sum of all inputs and discharges from the system per unit time. If flow cannot occur into or out of the system at its margins or internal boundaries, R will be the sum of the recharge to, and abstractions from, the system. If flow occurs into and out of the volume of the aquifer through its lateral margins and base (e.g. through an underlying aquitard), R includes the net balance of these flows. The left hand side of the equation represents the horizontal flow through the aquifer, whilst the right hand side of the equation represents the net change in volume of water within the system with time. In order to solve this equation, it is also necessary to define boundary conditions to the system and the initial conditions at time zero.

The purpose of the modeling exercise that was undertaken at Newington was to solve the equation above for all data points within the area of interest, in order to simulate the spatial distribution of groundwater head and its variation through time. This was based upon the understanding of the inflows and outflows from the system. The equation was determined by simultaneously solving the spatial extent of the area over a period of time. It was possible to solve the problem for all locations and over the specified time period, as there were an infinite number of points. The equation was approximated numerically at a number of discrete points in a grid, covering the area of interest over a number of discrete time intervals. Head values were interpolated between these calculation points (or 'nodes') to give a distribution. A

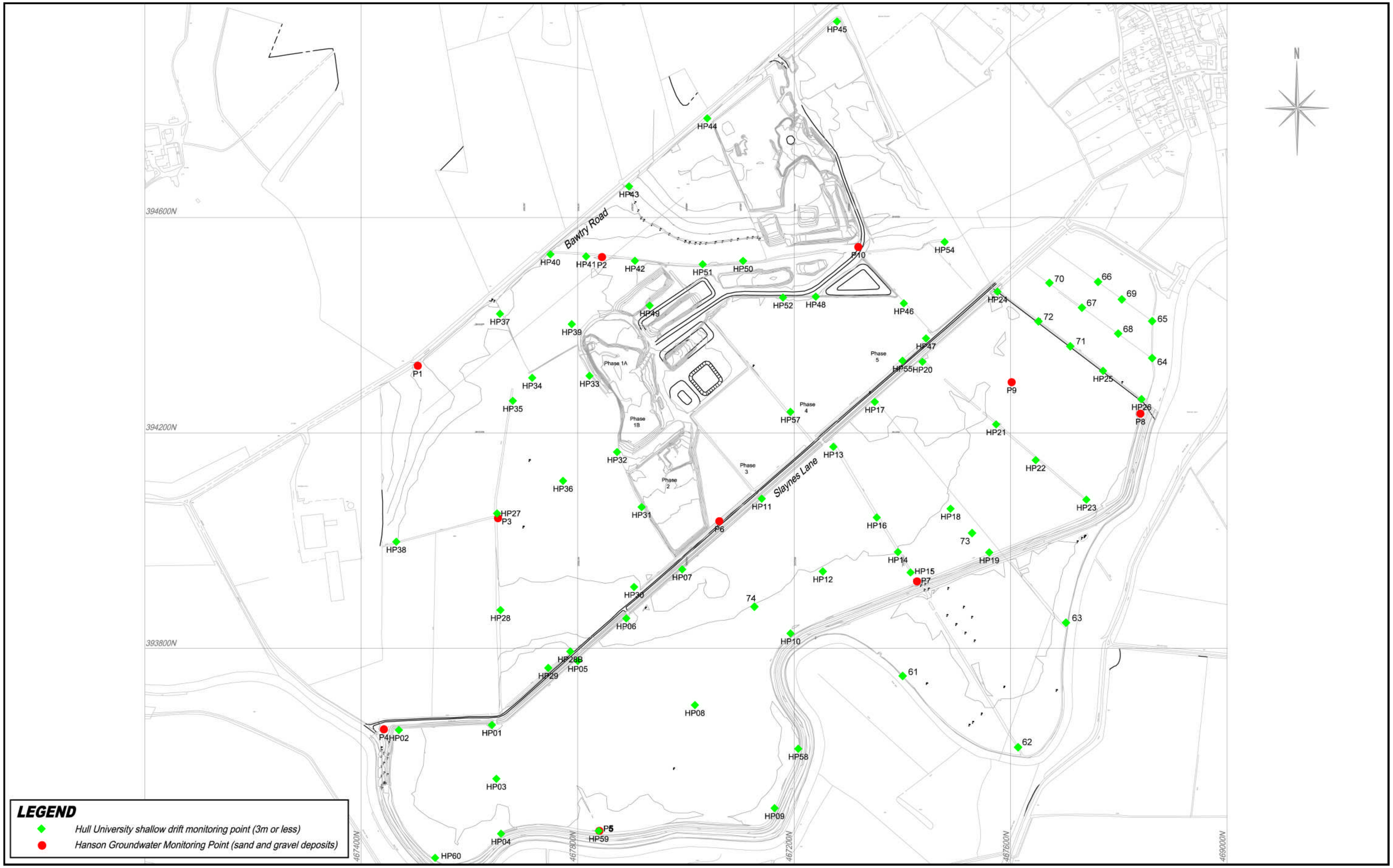

Figure 4.4: On-site monitoring locations (*after* Hanson 2007).

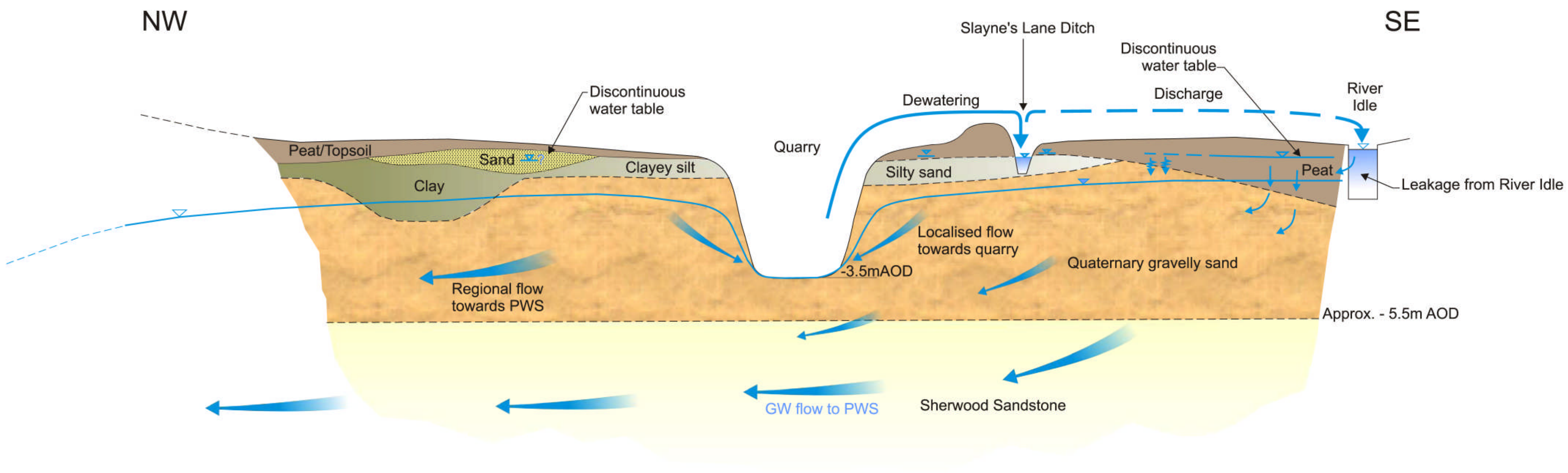

Figure 4.5: Schematic hydrogeological cross section/conceptual model (*after* Golder Associates [UK] Ltd 2005a).

number of numerical methods exist to solve the general flow equation. The method used in this study was finite difference modeling.

ModFlow is a software package which has been developed in order to solve the set of algebraic equations generated by numerically approximating the solution to the partial differential equations governing the system. The software solves the governing equation at all points in the defined grid for each time interval specified in the model. The resolution of the grid at which a solution is calculated, and the time interval, must be specified by the modeller. ModFlow includes a number of different codes for solving the modelled problem, and the user may select an appropriate ‘solver’ to this task. The WHS solver for Visual ModFlow and the pre-conditioned conjugate-gradient package (PCG2) solver were both used in the modeling process.

The software package Visual Modflow provides a pre-processor to the ModFlow code, providing a user interface where inputs can be readily defined and manipulated, and outputs assessed in visual and statistical formats.

4.2.5.3 Hydrogeological setting and conceptual model

Site operations and water movement

Newington quarry site layout is shown in Figure 4.5 (below). A site visit, which was undertaken at the commencement of the project in November 2004, provided information on the site operations at Newington quarry. At this time Phase 1 had been excavated and was flooded, Phase 2 had been excavated but continued to be de-watered, and extraction had commenced in Phase 3.

De-watering in Phase 1 commenced in September 2002. For the purposes of the hydrological modeling, it has been assumed that Phase 2 was excavated between September 2003 and September 2004, with Phase 3 commencing in September 2004. After the cessation of extraction in Phase 3, Phase 2 was infilled and excavation began in Phase 4. Excavation progressed systematically on site with the development/extraction of one phase per year.

At the time of the site visit, abstraction was occurring via a pump located in the northern part of Phase 2. This was discharging into the lagoon created from the excavation of Phase 1. Water drained by gravity from the adjacent Phase 3 into Phase 2. Water was then discharged from the lagoon in Phase 1 to the Slaynes Lane ditch (which is isolated from the adjacent river by sluice gates at both ends, which are only opened when additional flow capacity is required), and subsequently pumped into the River Idle. During this time, both the groundwater abstraction and the discharge for the purpose of quarry de-watering did not require a licence. As such, the pumping rates and the operation times were not monitored on site. The water level in the lagoon in Phase 1 was also not monitored.

A study of site surveys has allowed the development of an improved understanding of water movements at Newington. Within the limits of the functionality of the pump, pumping from the de-watered area of the site occurs either continuously, or as required depending on the rate of ingress. On the contrary, pumping from Phase 1 into Slaynes Lane ditch does not occur continuously. Only when the lagoon becomes full is the water pumped into Slaynes Lane ditch. Pumping continues until the lagoon is effectively empty, whereupon pumping ceases. The lagoon is filled and drained on a bi-weekly cycle. It takes two weeks to fill and two weeks to drain. Water is not discharged directly into Slaynes Lane ditch. Discharge from Phase 1 occurs at the northern extent of the drainage ditch to the west of the site (which is adjacent to piezometer 35 [as shown in Figure 4.2]) and drains into Slaynes Lane ditch along the drainage channel. A significant area of flooding exists around the point of discharge.

The above two paragraphs have highlighted a potential limitation in the calculation of the water that is discharged during the quarrying activities at Newington. In order to account for this discrepancy, two methods have been used to give a broad estimate of the volume of water that is currently being extracted from the quarry. The pump

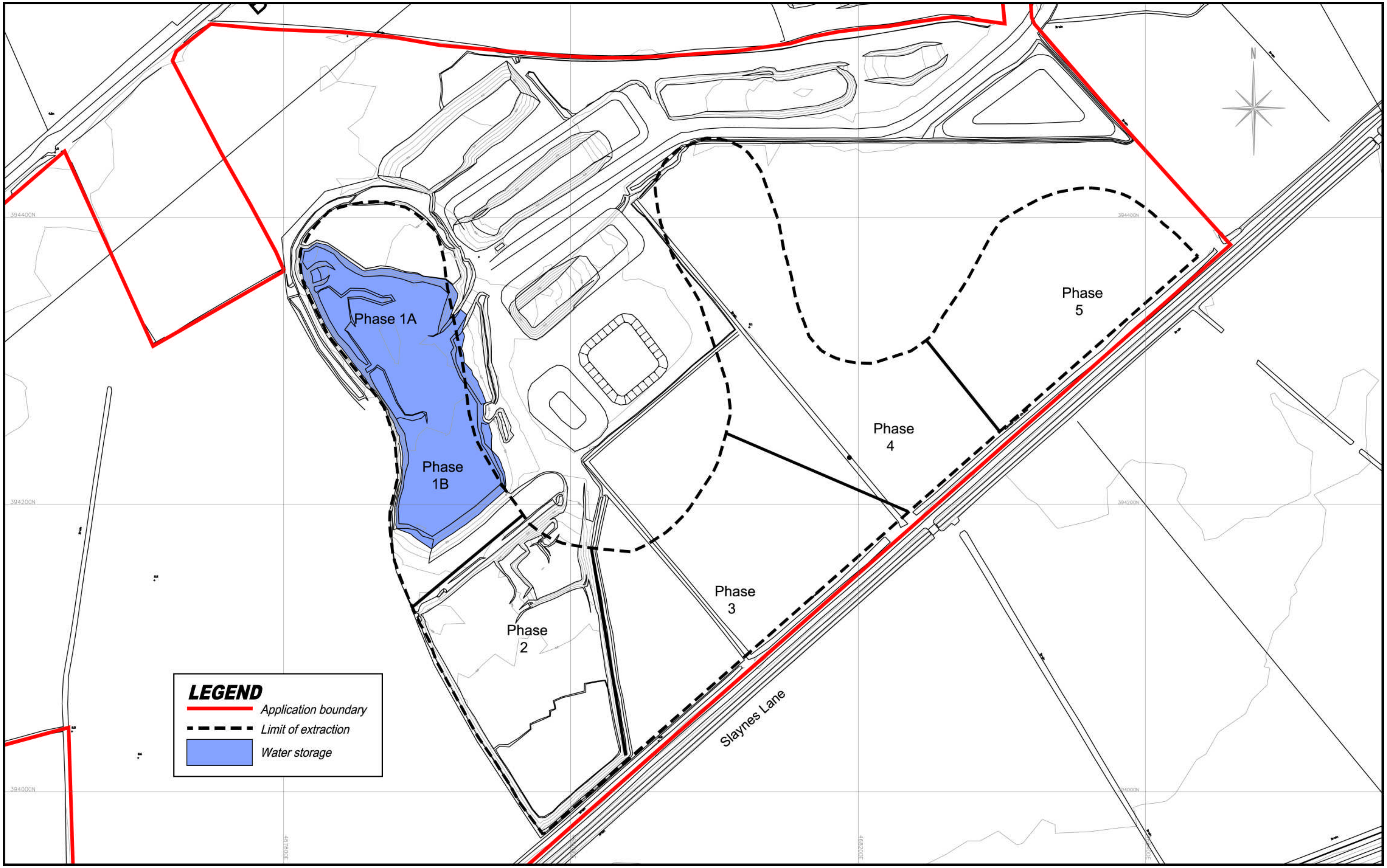

Figure 4.6: Newington quarry site layout (showing the five main phases of aggregate extraction) (*after* Golder Associates [UK] Ltd 2006).

discharging from Slaynes Lane ditch to the River Idle is a Godwin 6-inch pump. The specification for this pump indicates that, with a head difference of 10 m or less, it would be able to discharge between 80–140 l/s, depending upon the rate of operation and efficiency of the pump. Based upon an operation cycle with two weeks of continuous pump operation, followed by two weeks without pumping, this indicates an abstraction rate of 6,912–12,096 m^3/day during periods of operation (equivalent to between 1,261,440–2,207,520 m^3/year); and an average abstraction rate of 3,456–6,048 m^3/day across the year. The actual value is likely to be near the low end of this range due to the effect of pumping stoppages which are caused by malfunction of the pump, or the need for refuelling. An estimate of the volume of Phase 1, based on a flooded area of approximately 17,040 m^2 with an average depth of 4 m, indicates a volume of approximately 68,160 m^3. If this volume is filled every four weeks, the minimum annual abstraction rate will be approximately 886,080 m^3/year (-equivalent to 2,428 m^3/day). However, the actual abstraction rate will be greater than this as inflow will continue during this period whilst the lagoon is being emptied.

Anecdotal reports indicate that the water level in Slaynes Lane ditch has risen considerably since its pre-operational level in 2001. Interpretation and analysis of the ground water monitoring data for the 60 piezometers originally installed in the peat drift around the site have indicated that water levels in the vicinity of Slaynes Lane ditch and the western drainage ditch extending toward point 35 are affected by infiltration from the adjacent water courses. This indicates that a proportion of the water discharge from the site to the drainage ditches recharges to ground. Without direct monitoring of the volume of water discharged by the pump in the active phase and the pump at the point of discharge to the River Idle, the volume lost to ground cannot be constrained.

Abstractions

The largest abstraction in the southern half of the modelled area is a public water supply (PWS) which is operated by Severn Trent Water Ltd. There are also a number of significant abstractions operated by Tarmac Ltd for the purposes of mineral washing. The majority of abstractions are small scale supplies to farms for the purposes of spray irrigation and are licensed for six months of the year during the crop growing period.

In the modelled area, licensed abstractions for the purpose of general farming and domestic use range from 9,955,740 m^3/year at the Austerfield and Highfield Lane PWS, to 1,137 m^3/year at Lovershall Farm. The eight public water supplies within the model domain and abstraction of process water at Harworth Colliery constitute the largest abstractions in the model. Other abstractions licensed to remove >300,000 m^3/year are generally for the purpose of mineral washing associated with sand and gravel extraction. The modelling assumes that abstracted water is removed from the system and does not recharge to ground at any point. In the case of the public supply boreholes, this is likely to be a valid assumption. However, the utilisation rate of mineral washing and the discharge mechanism for this water is relatively poorly constrained. The location of licensed groundwater abstractions is shown in Figure 4.6 (below).

Details of the construction of wells comprising the Austerfield and Highfield Lane pumping stations were supplied by Yorkshire Water. Each pumping station has three contributing boreholes. In the case of Austerfield, these wells are all approximately 170 m deep and screened over the lower 110 m of the borehole length. At Highfield Lane, two wells are similarly approximately 170 m deep, and are screened over the lower 100 m and 135 m of their lengths respectively. The third well is 120 m deep and is screened over the lower 70 m of its length.

River stage and geometry

Modelling data has included stage data for the River Torne at Auckley (NGR 46464012) (as shown in Appendix 2). Stage data in the River Torne at this location is relatively constant between 1.7 and 2 m AOD, with an average mean daily stage over

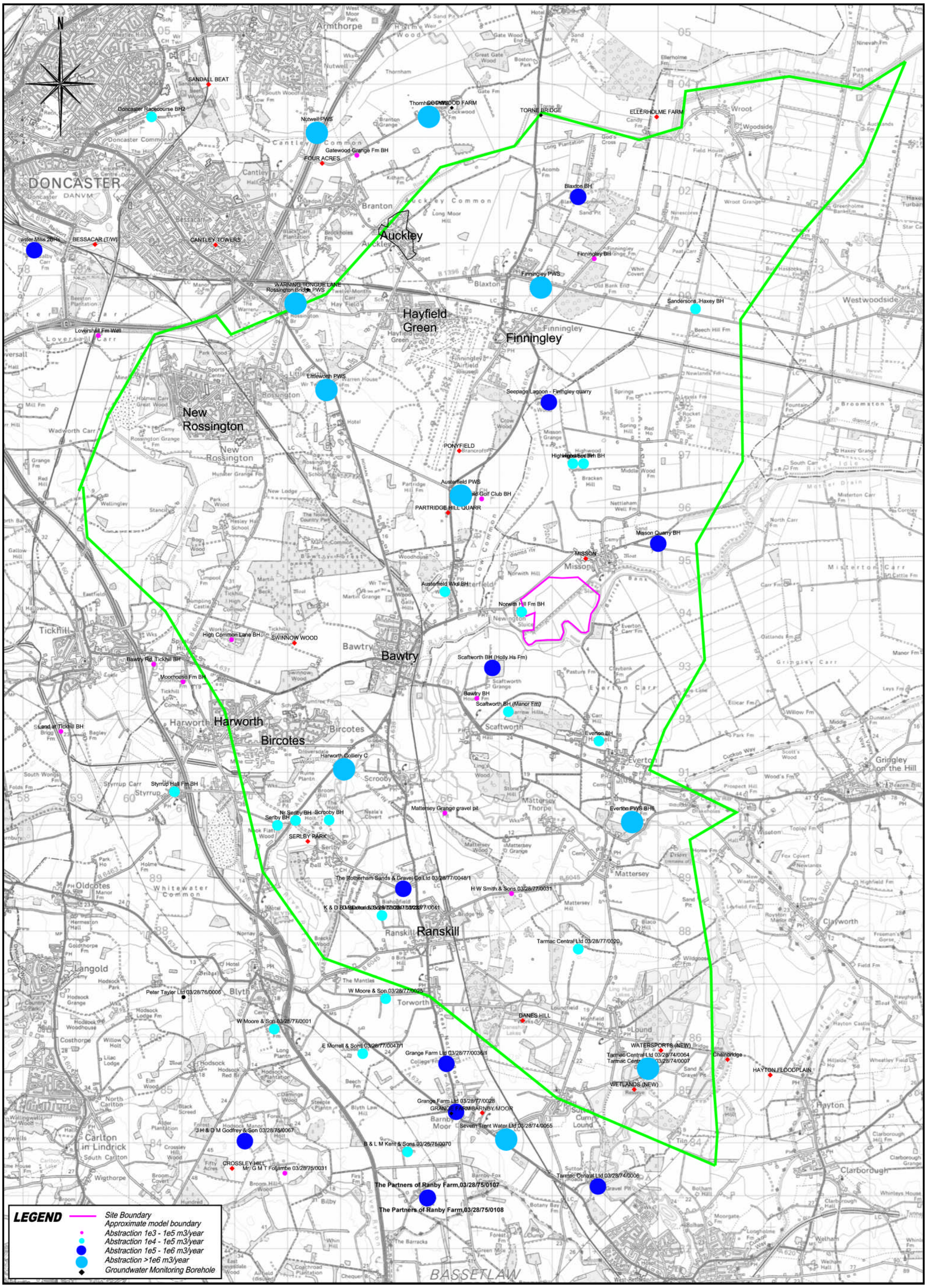

Figure 4.7: Location of licensed groundwater abstractions (*after* Golder Associates [UK] Ltd 2006).

the period 2000–2005 of 1.84 m AOD. Peaks up to 2.8 m AOD occur during storm events.

Cross-sectional profiles were obtained from the Environment Agency for three locations on the River Idle adjacent to the SSSI, south of Newington Quarry (as shown in Appendix 2). The profiles indicate that the river has a width of approximately 18 m at this point, with a bed elevation of between –0.1 and –0.9 m AOD. However, the bed elevation does not fall uniformly downstream, and is deeper in the intermediate survey point (–0.9 m AOD) than at the upstream (–0.1 m AOD) and downstream (–0.5 m AOD) points. The nature and thickness of bed sediment in the stream section remains poorly constrained.

Typical relationships between groundwater level, topography and river-aquifer interaction are such that rivers may be expected to gain in their upper reaches, where land gradients are steep and groundwater discharges in valleys from surrounding elevated areas; and lose in the floodplains of their lower reaches. In the context of the area considered in this model, the River Torne and River Idle are both low lying (less than 10 m above sea level) through much of the model area. To the east of the model domain, the land is artificially drained and the rivers are supported in some sections above the surrounding land level. In these areas, the rivers are effectively managed waterways and are used as transport channels for artificial drainage. Consequently, it is likely that they will be losing water to the surrounding environment. This scenario occurs in both rivers beyond the eastern boundary of the model. However, the River Torne appears to be artificially engineered in the eastern portion of the model domain, and the River Idle appears to remain as a natural watercourse throughout the model domain.

It should be noted however, that the relationship between the river stage and surrounding ground level suggests that the river is unlikely to receive significant natural drainage and groundwater discharge. This is supported by the observed relationship between the river stage and the groundwater level in the vicinity of Newington. In contrast, the River Ryton lies on higher ground and shows a greater fall in elevation through the modelled area. Therefore, this river is considered more likely to gain water along much of its length than the two more significant rivers. Comparison of recharge rates and licensed abstractions in the north of the model domain also indicates that a significant contribution to the regional water balance in this area must come from the loss of surface water bodies to groundwater. This supports the conceptual understanding of the relationship between these rivers and groundwater levels.

4.2.5.4 Model design

Two hydrogeological models have been created as part of this project. A steady state model has been developed with constant values for all inflows and outflows to the system, which is calibrated against the regional and on-site monitoring data for December 2004. A transient model has also been created with monthly stress periods covering the period 1st January 2000 to 31st December 2004 (-a total of 1827 days). Although the basic unit of time in the transient model is days, temporally variable inputs have been assigned on monthly time periods within the model. The methodology behind the creation of the two models is described concurrently through this section, as the main structure is common to both.

Model domain

The hydrogeological setting of the Sherwood Sandstone–Pleistocene drift system in the model domain is a complex, lithologically variable aquifer system, in which ground water resources have been heavily exploited for use by industry and for public supply. Both the Sherwood Sandstone and overlying drift contain a sequence of more permeable sand, or sand and gravel horizons, which are interspersed with horizons of silt or clay. In the Sherwood Sandstone vertical flow is inhibited by the presence of clay or mudstone horizons (BGS 1997). Thus, the aquifer thickness, which is affected by each abstraction or supply borehole, is limited to the depth of the well in question.

Mineral investigation at Newington has revealed a sequence of drift lithology, which at some locations on the site comprises clayey horizons that are present both above and below the permeable sands and gravels. This sequence of drift lithology potentially isolates them both from the peat or superficial sand deposits above, and from the sandstone below. Therefore, in response to a de-watering of the quarry area, the groundwater in adjoining units may be reduced due to the damping effect of the intervening clay horizons.

In the Sherwood Sandstone, the lack of spatial resolution in borehole data (particularly at depth) and the scale of lithological variation in comparison to the total thickness of the aquifer (-clay or mudstone horizons are often between 1 m and 5 m in thickness, compared to a total aquifer thickness of 300 m) delimits the accurate location of individual horizons. However, it is necessary for these horizons to be incorporated, wherever possible, into the hydraulic properties assigned to the aquifer unit within the model. As such, the model considers the Sherwood Sandstone as a single layer, rather than a multilayered system. It calculates a single head value for each cell, which is reported in any observation monitoring well in the cell, regardless of the well screen elevation.

In order to represent the Newington site, the drift lithology has been highlighted as a single layer, due to the complexity of the lithology. The drift lithology varies greatly across the site. The variability in thickness and depth of individual lenses or horizons is too complex to be accurately represented across the wider model area, where no data is available. As a consequence, the model considers a simplified system where the entire thickness of the drift comprises sand and gravel deposits. Although this is a simplification, the sand and gravel deposits represent the greatest constituent element of the drift cover on site, and are of most interest as a water bearing horizon.

The numerical model considers a two layer system in which the Sherwood Sandstone is overlain by sand and gravel drift deposits. These deposits may have different hydraulic and lithological properties. Outside the site area, the detail provided by modeling the effect of the drift upon ground water flow is considered to be redundant, as it does not have a significant effect upon the accuracy of prediction for the on-site groundwater head. Layer 1 (the drift) is therefore present throughout the model domain; however, outside the site area it has been assigned a constant thickness of 5 m below the ground surface. This figure is similar to the thickness of the sand and gravel deposits which are located north of the site, resulting in the base of Layer 1 lying above the water table, separate from the simulated flow system.

Limits of the model domain

The limits of the model domain are shown in Figure 4.7 (below). The model domain covers an area of approximately 190 km^2, and is centred near to the town of Bawtry. The Newington site covers an area of approximately 1.7 km^2 and is located in the centre-east of the model domain.

The model domain has been delineated based upon the natural boundaries to the system. To create a robust model it is necessary to ensure that the boundaries selected are suitably distant so as not to exert undue control on the simulated head in the area of interest. Therefore, although the River Idle may form a boundary to the localised system around Newington, the proximity of the river to the site is such that it cannot be used to define a boundary to the system. Defining a boundary under these circumstances would strongly influence the modelling outcome.

The model is bounded to the east by the Sherwood Sandstone/Mercia Mudstone geology. This boundary has been based upon the assumption that negligible flow occurs into the confined zone from the model domain. As there is no major known point of discharge from the Sherwood Sandstone once it enters the confined zone to the east, flow in this direction is likely to be limited. Regional groundwater contours (as shown in Figure 4.8, below) indicate that flow into the model domain occurs from

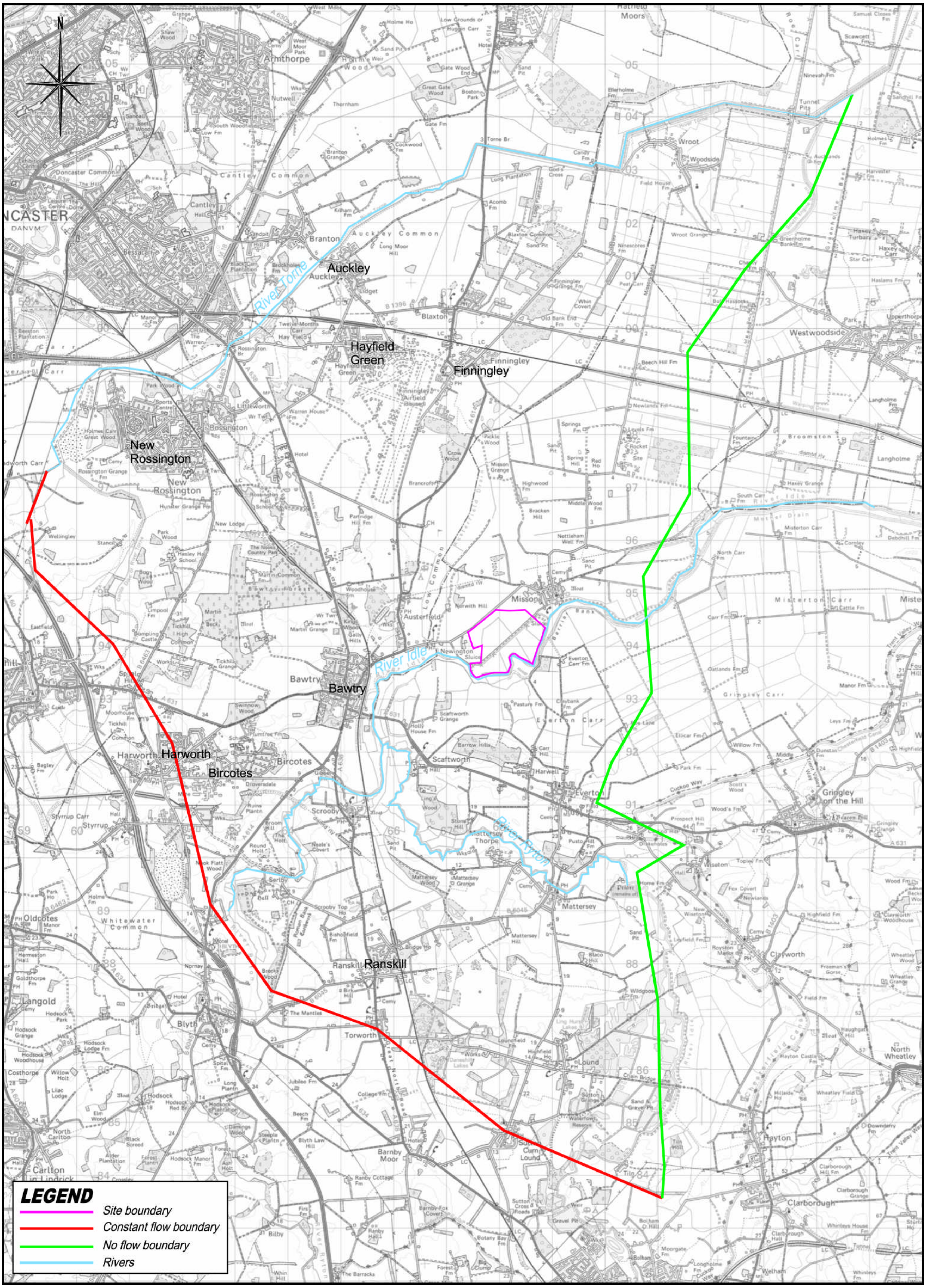

Figure 4.8: Limits of model domain (*after* Golder Associates [UK] Ltd 2006).

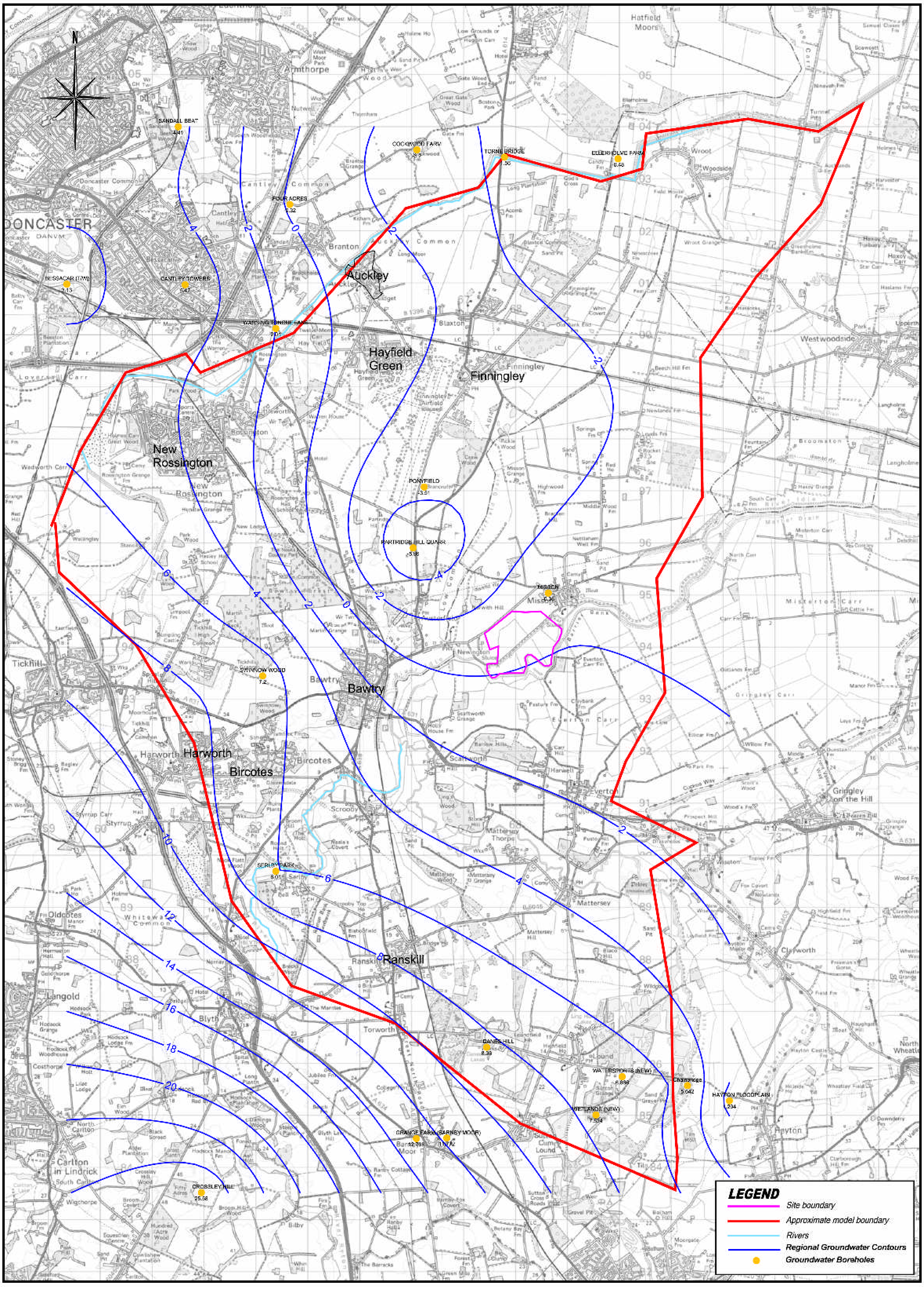

Figure 4.9: Regional groundwater contours (*after* Golder Associates [UK] Ltd 2006).

the west, but suggests that this flow is largely captured by abstraction within this area, with little apparent flow occurring east into the confined zone.

The north of the model domain is delineated by the River Torne, which rises to the west of the model area and flows north, before turning east toward its confluence with the River Trent. To the east of the model area, the River Torne is managed as part of the land drainage system, with an elevation slightly above sea level. However, in the upper reaches the River Torne forms a natural water course.

The southern and western model extent is delineated by regional groundwater head contours. This boundary follows a line of equal head elevation in the water table, so that negligible lateral flow is occurring along this boundary and flow is perpendicular to it.

Discretization of the model domain
In order to lessen the model complexity it is necessary to limit the number of nodes in the model grid where possible in order to avoid redundancy in the calculation. As discussed above, the model domain has been split into two vertical layers, one to represent the Sherwood Sandstone and one to represent the drift. The model inputs for these surfaces are discussed below.

Over the model domain, a basic horizontal grid comprising 250 m by 250 m cells has been defined. However, at Newington the grid comprises 10 m by 10 m cells in order to give high resolution predicted heads. To maintain numerical stability in the model, it is necessary that the cell length or width between two adjacent cells is <1.5 of the total length/width. As a consequence, the grid size has been increased incrementally away from the area of interest in order to ensure a gradual transition between the small and large grid discretization. The resulting grid layout and model domain is shown in Figure 4.9 (below).

4.2.5.5 Boundary conditions

A zero flow boundary condition was defined by a line of inactive cells along the eastern model boundary which represents the Sherwood Sandstone/Mercia Mudstone geology. A river boundary was defined along the northern boundary of the domain coinciding with the River Torne. The boundary was defined in two segments. The river stage at the start and end points of the boundary were defined as 3 m and 0.5 m AOD respectively; this was based upon the surrounding ground level and assuming the water level in the river was 1.5 m below the adjacent bank level. The assigned stage was confirmed by a known value at the centre point, which was based upon monitoring data for the River Torne at Auckley. The river also achieves a stage of 0 m AOD, shortly before it's confluence with the River Trent, at approximately 15 km downstream of the modelled area.

The river is assumed to be 1.5 m wide through the rising reaches and 10 m wide through the lower reaches, based upon the OS map of the area (Ordnance Survey 1:25000 scale maps, Sheets 279 & 280). Assumed values were assigned for the river bed permeability (1e-6 m/s), the river bed thickness (0.7 m) and the water depth (1.5 m), in the absence of specific values. The permeability value was based upon an assumed mixed sand and silt river bed, and is assumed to be less permeable than the underlying sandstone. These values are used to calculate a river bed conductance and leakage in ModFlow, based upon the equation:

$$C = \frac{KLW}{B}$$

Where *C* is conductance, *B* is the riverbed thickness, *K* is the hydraulic conductivity of the river bed material, *W* is the river width and *L* is the length of the reach present in the cell.

Initially, a constant head boundary at 10 m AOD was defined along the western and south-western model boundary; based upon the location of the 10 m AOD head

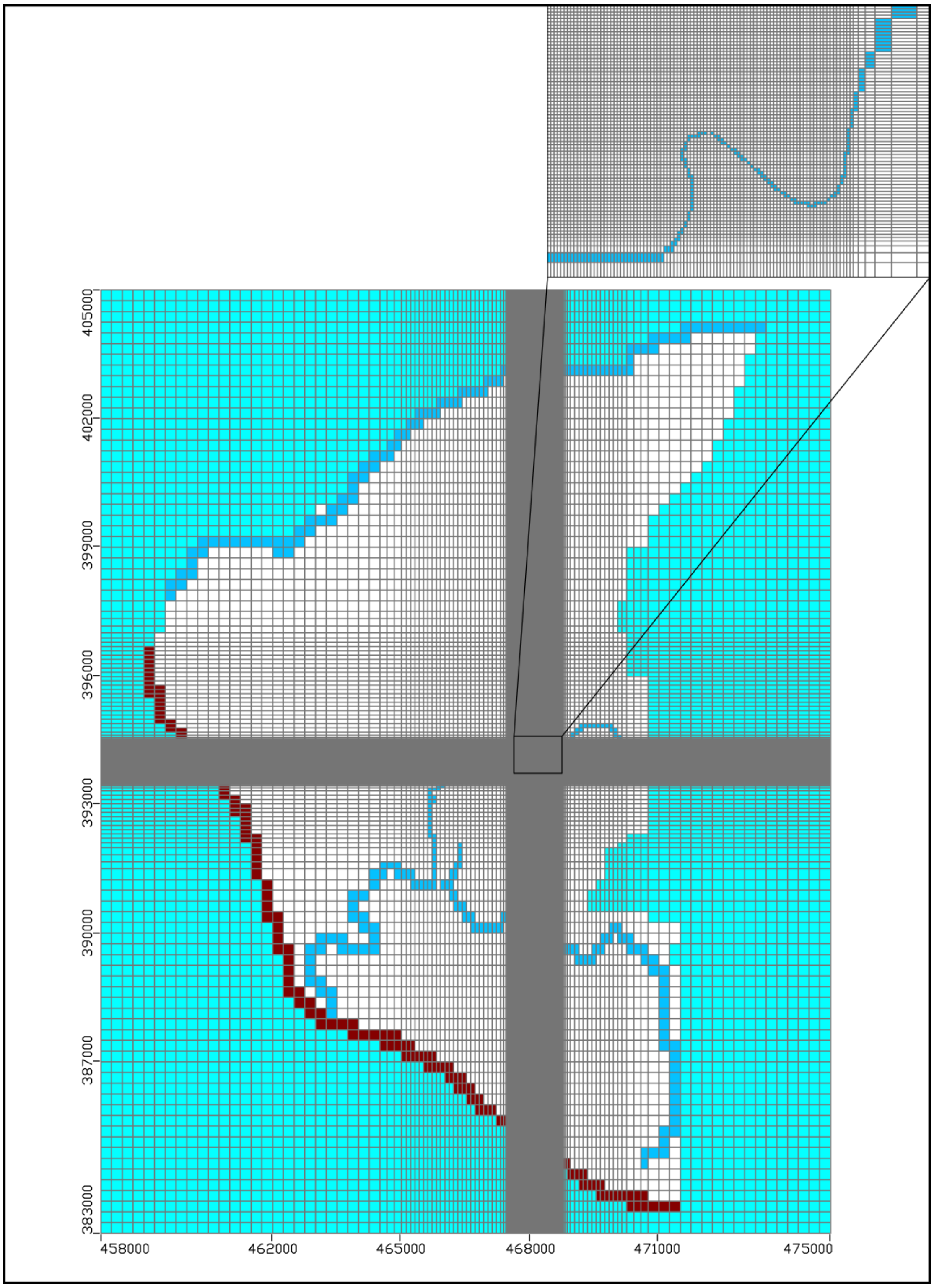

Figure 4.10: Grid layout and visual ModFlow boundaries (*after* Golder Associates [UK] Ltd 2006).

contour in the Sherwood Sandstone (Hydrogeological Map of the North East Midlands, Institute of Geological Sciences [IGS] 1981). However, the calibration process indicated that this limited the sensitivity of the system. In order to prevent this from occurring, the boundary was replaced by a constant flow boundary as the modelling process progressed.

The constant flow boundary defined along the western and south-western model boundary is described in the model as a series of injection wells located in each cell along the boundary. Initial injection rates were determined using Darcy's law, based upon the regional hydraulic gradient, the thickness of the sandstone aquifer (shown in the Regional Hydrogeology Map [IGS 1981]) and the hydraulic conductivity of the sandstone (8e-5 m/s) (as shown in Table 4.1). The total length of the boundary is approximately 20.8 km. The Sherwood Sandstone varies in thickness between approximately 40 m at the northern extent of the boundary and 235 m at the southern extent of the boundary. This methodology assumed that the total flow across the boundary could be represented as four separate segments. The segments were 40 m, 60 m, 100 m and 235 m in thickness; with each containing a series of cells belonging to one of three size categories (i.e. 10 m, 100 m, or 250 m in width). Each well was assigned an injection rate equal to the product of the regional gradient, hydraulic conductivity, cell width and aquifer thickness.

Table 4.1: Initial constant flow boundary inputs.

Segment	Initial NGR	Final NGR	Regional Hydraulic Gradient	Sandstone Thickness (m)	Sandstone Hydraulic Conductivity (m/s)	Flow 10 m Cell (m^3/d)	Flow 100 m Cell (m^3/d)	Flow 250 m Cell (m^3/d)
1	359600, 397900	361400, 392070	1.7e-3	40	8e-5	4.7	47.0	117.5
2	361400, 392700	363200, 388000	1.7e-3	60	8e-5	7.05	70.5	176.3
3	363200, 388000	367400, 385600	1.7e-3	100	8e-5	11.75	117.5	293.8
4	367400, 385600	371400, 383500	1.7e-3	235	8e-5	27.6	276.1	690.3

Initial heads were not directly supplied in the steady state model; instead these were taken from constant head cells allocated in the model. Starting heads for the transient model were generated from an amendment to the calibrated steady state model, which considered the heads without abstraction occurring in the quarry area to represent conditions at the commencement of modeling in the transient system.

Top elevation

The model surface elevation which has been defined is based upon a simplified topography of the area. The eastern half of the model domain comprises low lying, relatively flat land with an elevation between 10 m AOD and 0 m AOD. The lowest values are situated in the north-east corner of the model domain. The topography continues to decline towards the east of the model domain, where the land is predominantly flat, artificially drained and lies at sea level. The ground rises within the western half of the model domain, with an area of elevated moor land which is located approximately 35 m AOD, lying to the west of Bawtry. The River Idle and the surrounding flood plains are lower lying than the remaining land within the model domain. These floodplain areas are located at approximately 5 m below AOD.

Both within and immediately surrounding the Newington site, a detailed surface topography has been defined, which is based upon surface contours from the Ordnance Survey 1:25000 map. In the surrounding area, a Surfer grid of approximate topography was constructed. This grid was based upon spot height and contour information in order to characterise the main features of topographical variation. The primary features include the elevated area to the west of Bawtry and the River Ryton valley. The resulting surface is shown in Figure 4.10 (Layer 1) (below).

Basal elevation

The thickness of the drift deposits at Newington has been defined by mineral investigation boreholes which provide high resolution information about the nature of the drift geology. Away from the site, the difference between the drift and Sherwood Sandstone hydraulic properties is not considered to have a strong influence on the predicted heads. Therefore, an arbitrary thickness of 5 m (below ground level) has been assigned to Layer 1 away from the quarry area, which generally lies above the water table. The 5 m thickness is typical of the drift to the north of the site, which is based upon information held by the British Geological Survey (BGS) for ground investigations that were conducted in the area to the north and east of Newington. Records from 36 boreholes have indicated that the drift/Sherwood Sandstone contact occurred most commonly between 4 m and 6 m below ground level. As a consequence, over the majority of the site, the base of Layer 1 mirrors the topography shown in Figure 4.10. This is contoured using mineral investigation data which is shown in Figure 4.11 (below).

The basal elevation of the sandstone has been defined by contours which are shown on the Regional Hydrogeology Map of the area (IGS 1981). Regional data shows the base of the Sherwood Sandstone gradually declines to the east, from an elevation of approximately –20 m AOD in the west of the model domain, to an elevation of approximately –240 m AOD in the east of the model. After digitising the published contours, the basal surface was imported into ModFlow and subsequently contoured in Surfer. The resulting surface is shown in Figure 4.12 (below).

A deep coal investigation borehole (the Misson borehole) is situated approximately 1 km from the site. The base of the Sherwood Sandstone at this location was 278.9 m below ground level. Although this depth is different to the depth shown by the regional contours, the reason for this is unclear. Unfortunately, there is insufficient information available to define the base of the Sherwood Sandstone from similar data.

Hydraulic properties

Initial aquifer properties comprised the most significant parameters used in the model calibration. An initial hydraulic conductivity of 18 m/d was applied in Layer 1, which was based upon site measurement. Typical specific storage, specific yield, effective porosity and total porosity values of 2e-3, 0.2, 0.2 and 0.35 respectively, were assigned. These values were based upon typical figures from (*cf*. Fetter, 2001) for unconsolidated sand and gravel, in the absence of site specific measurements. An initial hydraulic conductivity of 5 m/d was assigned in Layer 2. This was considered the most likely value based upon the available information (Golder Associates 2005a). A specific storage of 2e-3 was considered appropriate in Layer 2 and was based upon available data. Lower specific yield, effective porosity and total porosity values of 0.15, 0.15 and 0.3 respectively, were assigned.

Based upon the available information, the hydraulic conductivity of the Sherwood Sandstone was considered to lie within the range 0.5 m/d to 10 m/d (BGS, 1997). A comparison between published data for the Doncaster area and data from within 10 km of the site itself indicates that sandstone permeability is higher locally, when compared to data in the wider context.

4.2.5.6 Sources and sinks

Abstractions

Licensed groundwater abstractions within the model domain were obtained from the Environment Agency. Records of actual abstracted volumes were supplied by Yorkshire Water for the Austerfield and Highfield Lane abstractions over the period 2000 to 2005. Details of the abstraction well construction for both pumping stations were also supplied.

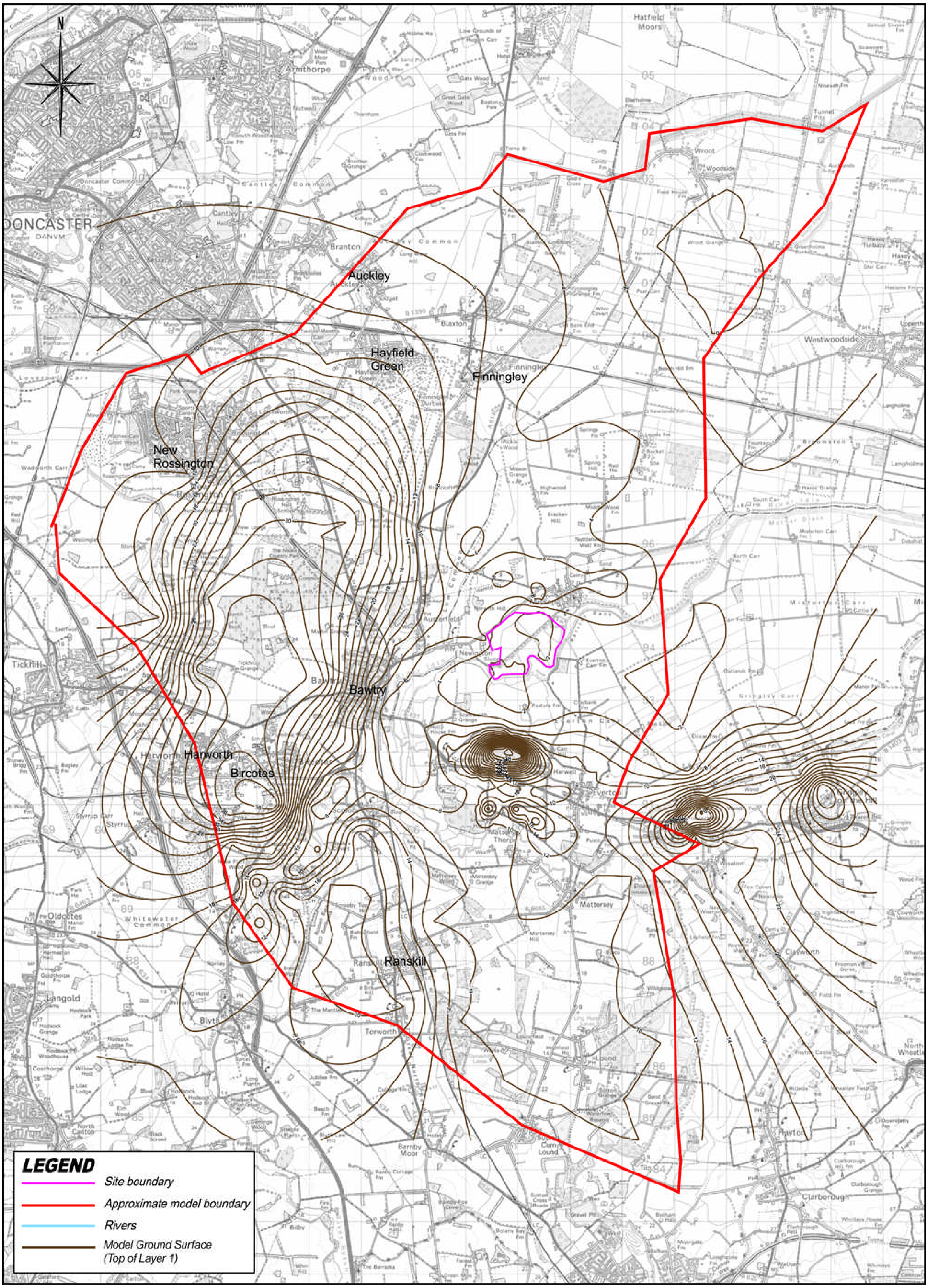

Figure 4.11: Model ground surface. (Top of layer 1) (*after* Golder Associates [UK] Ltd 2006).

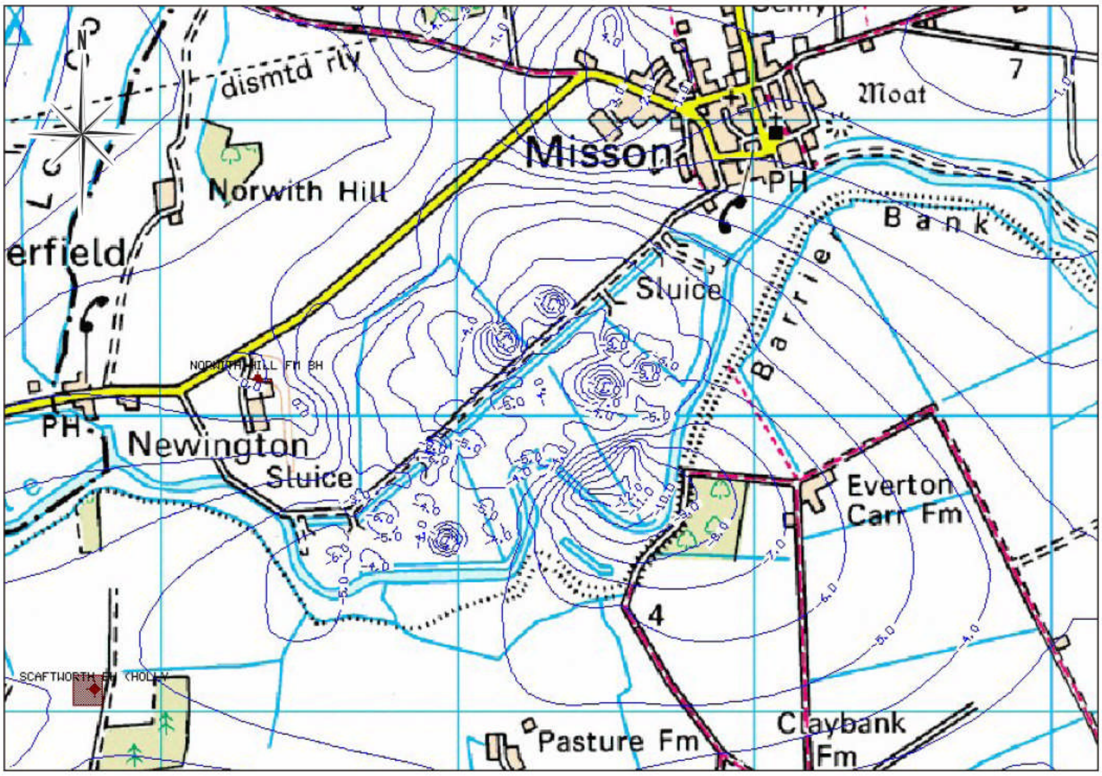

Figure 4.12: Modelled base of drift on site. (Base of layer 1) (*after* Golder Associates [UK] Ltd 2006).

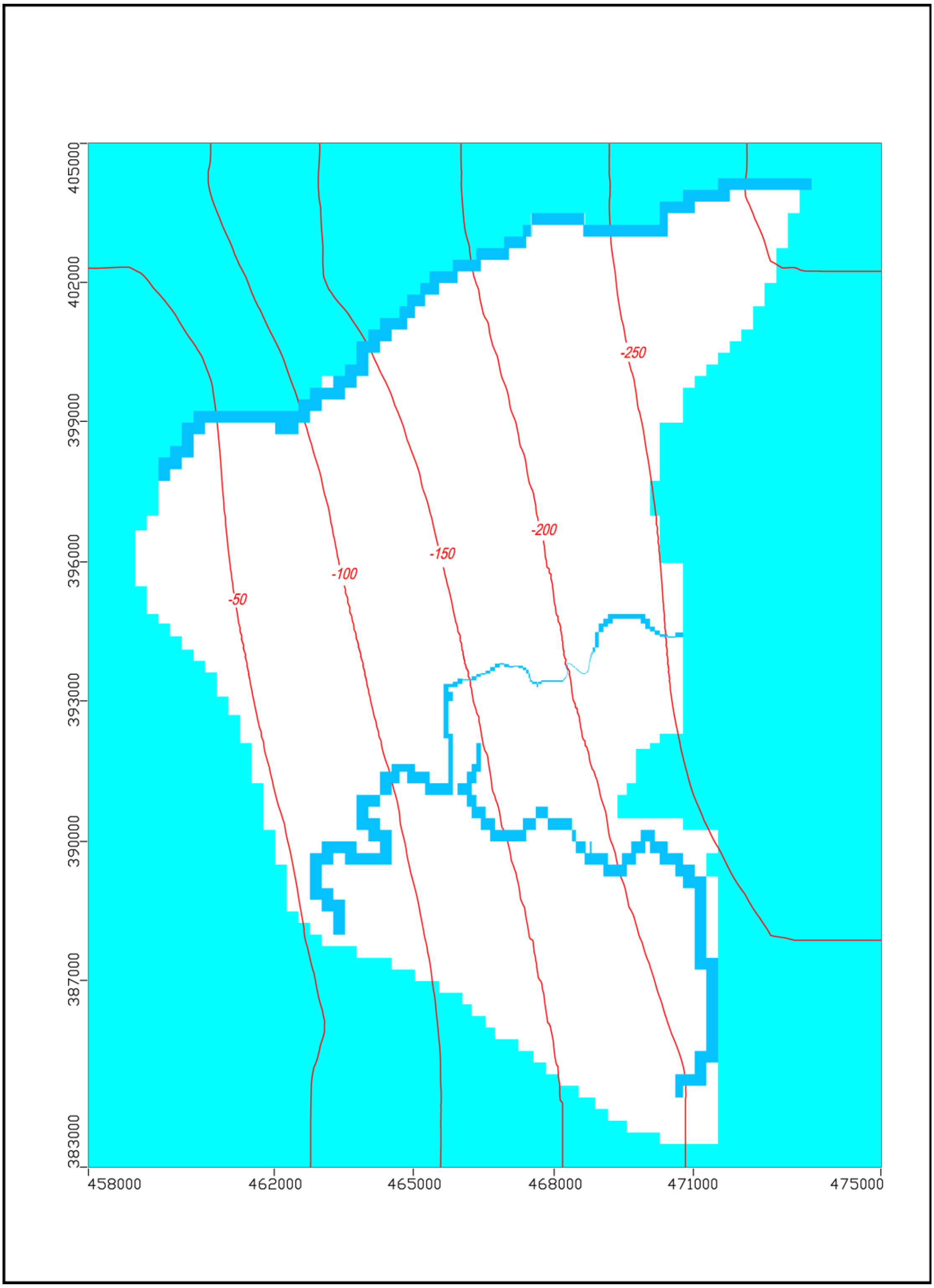

Figure 4.13: Modelled sandstone basal elevation. (Base of layer 2) (*after* Golder Associates [UK] Ltd 2006).

Comparison of returns for the Austerfield and Highfield Lane Public Water Supplies (PWS) to the licensed abstraction rate indicated an utilisation rate of approximately 80 % of the licensed volume over the period 2000 to 2005. A similar utilisation rate (0.8 of the licensed abstraction) was assumed for other abstractions in the model, as the major abstractions within the model domain are also public water supplies and are likely to operate on a similar basis. In areas where licensed abstractions were limited to certain periods of the year (i.e. six months of the year for spray irrigation), the transient model average daily rate was defined to be temporally variable and functioning over a period of six months. However, the steady state model average daily rate was calculated assuming that the licence applied over 1 year.

Internal river boundaries
In addition to the River Torne, which forms the northern boundary of the model domain, the rivers Idle and Ryton have also been defined as river boundaries which pass through the model domain. A river boundary is able to both gain water from, and lose water to the model system, depending upon the difference between the defined river stage in the river cell and the ground head calculated in that cell. The leakage rate is governed by the head difference between the river and the aquifer, and by the river bed conductance.

The river stage for the River Ryton has been based upon ground level contours and spot heights close to the river channel on the Ordnance Survey (OS) 1:25000 scale map. The methodology assumes that the river level lies approximately 1.5 m below the surrounding ground level at the scale visible on the OS map. Variations in channel width indicated on the map were used as guidelines. The river was assumed to be 1.5 m deep and 7.3 m wide in its upper reaches near Blyth, which increased to 2 m deep and 10 m wide in its lower reaches.

The river stage for the River Idle was similarly based upon contours and spot heights for the surrounding land level shown on the OS 1:25000 scale map. The River Idle stage was based upon Environment Agency monitoring data. An average stage value was applied to Newington in the steady state model. Monthly stage values were applied in the transient model by selecting values at the relevant dates to the start of each model stress period in the monitoring record. Due to the absence of data in the upper and lower reaches, the depth of the River Idle was assumed to be 2 m in the upper sections and 2.5 m in the lower sections. The width of the river ranged from 7.5 m to 20 m (based upon the river's representation on the 1:25000 scale OS map). The depth and width of the river adjacent to the site is based upon surveyed cross sections which have been supplied by the Environment Agency (as shown in Appendix 2). At this location the river is 18 m wide and approximately 2.7 m deep; although the depth is variable for a short distance past the Newington site.

In all cases, in the absence of specific information, the river bed for all river sections was initially assumed to be 0.7 m thick, with a permeability of 1e-6 m/s. Due to the uncertainty of these parameters, river bed conductance was treated as a calibration parameter during the calibration phase.

Table 4.2: Parameters Describing Internal Rivers.*

	NGR	**Width (m)**	**Water Depth (m)**	**River bed vertical permeability (m/s)**	**River Bed thickness (m)**	**Stage (m AOD)**
R. Ryton 1	46243866	7.5	1.5	1e-6	0.7	7.6
R. Ryton 2	46453912	10	2	1e-6	0.7	4
R. Ryton 3 R. Idle confluence	46573921	10	2	1e-6	0.7	3
R. Idle 1	46943842	15	2	1e-6	0.7	8.5
R. Idle 2	47093892	20	2	1e-6	0.7	6
R. Idle 3 R.	46573921	15	2	1e-6	0.7	3

Ryton confluence						
River Idle 4	46823938	**18**	**2.7**	1e-6	0.7	**2.2**
River Idle 5	47073945	20	2.5	1e-6	0.7	1.65

*The values in bold are known values. The River Ryton has been defined as 2 segments between three points; the River Idle has been defined as 4 segments between 5 points.

Recharge

In the steady state model, an initial long term average annual recharge value was assigned based upon MORECS supplied data, and an estimation of resulting infiltration using the Penman and Grindley method (Golder Associates 2005a). This calculation indicated a long term recharge of 60 mm/yr; although the recharge has been higher than this over the past 5 years. This value is particularly low. Comparison to licensed abstractions in the area indicates that it may not be sufficient to balance the abstraction rate from the aquifer. However, recharge may be higher than that estimated by the Penman and Grindley calculation if the soil is well drained. Under these circumstances the soil moisture deficit indicated in the recharge calculation cannot be achieved because the field capacity of the soil is low. Recharge was used as a calibration parameter in the model. It was assumed that the true recharge value lay between the calculated Penman and Grindley recharge and the effective rainfall (precipitation minus actual evaporation), which was calculated to be 134 mm/yr.

Recharge in the transient model was based upon the MORECS supplied monthly precipitation and evaporation data for the period 2000 to 2005. Initial monthly recharge values in mm/year were calculated using the Penman and Grindley method from the supplied data (as shown in Appendix 3). These values were then scaled to match the calibrated steady state recharge by reducing the evaporation rate by a fraction, F, until the average annual recharge was correct; thus ensuring that the temporally variable aspect of recharge was represented.

In the initial steady state model, a single recharge zone was defined across the entire model area. However, during the calibration period it became evident that some of the data would be better matched by an elevated recharge rate on the higher ground to the west of Bawtry. Higher rainfall in this area is likely as the area to the east of this ridge lies in a rain shadow. The recharge zone was defined as Zone 2, with an elevated recharge initially of 120 mm/yr (-which is double the long term average value in Zone 1).

As discussed previously, there is considerable uncertainty regarding the water movements around Newington. Many of the apparent recharge events evident in the borehole hydrograph records cannot be explained in terms of the current conceptual understanding of water movement at the site. Based upon rates of discharge and vertical heads observed in the shallow piezometers, it is probable that a proportion of the water abstracted from the void area on the site is recharging to the ground from both the drainage ditch to the west of the void area and from Slaynes Lane ditch. Additional areas of recharge were assigned in the vicinity of these ditches during the calibration phase of modeling.

Quarry de-watering

Water movements around Newington are not monitored. As a consequence, the volume of water abstracted from the quarry area cannot be accurately constrained. If a value for this parameter was assumed, it may have resulted in an unwarranted effect on the predicted groundwater heads in the site. Therefore, quarry de-watering was not represented as an active abstraction in the model. By defining the cells representing the quarry de-watered area as constant head boundary cells, with a head elevation equal to the quarry base, the model is not constrained and determines the quantity of water removed from these cells based upon the surrounding head and hydraulic properties.

The steady state model considers the scenario that by the end of 2004, abstraction is ongoing in Phase 2 and Phase 3. A cyclic abstraction is also occurring in Phase 1 as the lagoon is emptied on a bi-weekly basis. Initially, a constant head was applied across the entire area of Phase 1 and Phase 2 at the elevation indicated by the November 2004 survey. However, initial model runs indicated that this resulted in an artificial addition of water to the system as the quarry base lay above the water level within the cone of depression, which was generated by the abstraction from the lowest point in each phase. The constant head area was therefore reduced to the area of deepest excavation in each phase in order to allow the model to determine the head.

In Phase 1, a head of –2 m AOD was applied in the steady state model in order to represent the average head in this phase over a monthly period. (The head oscillates between approximately 0.5 m AOD and –4.5 m AOD at its deepest point). Initial transient modelling considered this phase to have a bi-weekly oscillating head value. However, this proved to be unstable and was replaced by a –2 m AOD head in the transient model during the post-extraction period.

In the transient model, the sequence of head changes in Phase 1 and Phase 2 is shown in Table 4.3. In each phase, the timing of the commencement and cessation of de-watering is relatively poorly constrained, even though a precise date must be assigned in the model. Although an approximate date for the development of each phase is known (as is the final depth), the interval between the commencement of excavation, the commencement of de-watering and the final de-watering elevation is poorly understood.

Table 4.3: On-site de-watering activities.

Start Date	End Date	Initial Head (m AOD)	Final Head (m AOD)
Phase 1 (A)			
01/01/2000	22/09/2002	0	0
22/09/2002	01/11/2002	0	-1
01/11/2002	01/12/2002	-1	-2
01/12/2002	01/01/2003	-2	-3
01/01/2003	01/02/2003	-3	-4
01/02/2003	01/03/2003	-4	-4.8
01/03/2003	01/10/2003	-4.8	-4.8
01/10/2003	16/10/2003	-4.8	-2
16/10/2003	01/01/2005	-2	-2

Start Date	End Date	Initial Head (m AOD)	Final Head (m AOD)
Phase 1 (B)			
01/01/2000	22/09/2002	0.2	0.2
22/09/2002	01/10/2002	0.2	-0.5
01/10/2002	01/11/2002	-0.5	-1.25
01/11/2002	01/12/2002	-1.25	-2
01/12/2002	01/01/2003	-2	-2.5
01/01/2003	01/02/2003	-2.5	-3.25
01/02/2003	01/03/2003	-3.25	-4.5
01/03/2003	01/10/2003	-4.5	-4.5
01/10/2003	16/10/2003	-4.5	-2
16/10/2003	01/01/2005	-2	-2
Phase 2			
01/01/2000	23/08/2003	0	0
23/08/2003	01/10/2003	0	-3
01/10/2003	01/08/2004	-3	-3
01/08/2004	01/09/2004	-3	-2.5
01/09/2004	01/10/2004	-2.5	-2
01/10/2004	01/11/2004	-2	-1.5
01/11/2004	01/12/2004	-1.5	-1
01/12/2004	01/01/2005	-1	-0.5
01/01/2005	01/01/2005	-0.5	-0.5
Phase 3			
01/01/2000	01/09/2004	0.4	0.4

01/09/2004	01/10/2004	0.4	-0.75
01/10/2004	01/11/2004	-0.75	-1.5
01/11/2004	01/12/2004	-1.5	-2.25
01/12/2004	01/01/2005	-2.25	-3

The timing assigned in the model has been formulated in relation to the extraction activities at the site and in response to the groundwater monitoring record. Step changes in head have been assigned in each phase between the commencement or cessation of de-watering activity and the arrival at a stable head value. Phase 1 has been represented in two parts; the first part, which was de-watered to a maximum depth of –4.8 m AOD, and the second part, which was de-watered to a depth of –4.5 m AOD. As it is not possible to de-activate the constant head boundary for only a part of the modelling period, an initial head value in each cell has been assigned a similar value to that indicated by groundwater monitoring prior to de-watering.

De-watering in Phase 3 was removed from the final transient model as it was not possible to de-activate the constant head boundary over the specified time period, prior to the commencement of de-watering in this area. The constant head in the vicinity of the newly excavated area is affected by the de-watering in Phase 2. Consequently, in order to prevent Phase 2 from affecting the model, it would be necessary to predict the effect of de-watering Phase 3 by defining the constant head value. This would directly affect the modelling outcome. Thus, attempts to model the de-watering in Phase 3 were considered to increase, rather than reduce, the model error.

4.2.5.7 Model calibration

The model has been calibrated manually by adjusting the parameters in order to achieve the optimum fit between the observed and modelled groundwater heads. Calibration focussed on the parameters with the greatest initial uncertainty and greatest sensitivity in the model. It was undertaken in two stages, with an initial calibration in the steady state (which was representative of the long term model behaviour). Calibration was firstly undertaken by incorporating average water levels into the model, whilst keeping water flows within the model realistic (i.e. the steady state model), and secondly, in response to fluctuating stresses on the system by enhancing the parameters in order to produce a real time monitoring sequence (i.e. the transient model).

Steady state model

Steady state calibration was undertaken by using the data obtained from eight Environment Agency regional groundwater boreholes which are installed in the Sherwood Sandstone, and from nine piezometers installed by Hanson Aggregates which are situated in the sand and gravel deposits. A suitable date for data calibration was selected by combining the annual range of groundwater level at the monitoring points and the spatial coverage of the monitoring record. Monitoring data for January 2005 was applied for the on-site points, as these levels were representative of the average water level. November 2004 data was applied for the regional monitoring boreholes, as November was the most appropriate date for which adequate coverage was available in the data set. Table 4.4 shows the values that were applied in the calibration.

On site monitoring wells were assigned in the model with screen elevations based upon the borehole logs. The model was allowed to select whether the wells reflect the water level in Layer 1 or Layer 2 of the model, which is based upon the screen elevation and the contoured base of Layer 1 within the vicinity of Newington. It has been assumed that all of the Environment Agency's regional monitoring boreholes are of sufficient depth to be installed in the Sherwood Sandstone, hence reflecting the water level in Layer 2.

Table 4.4: Calibration data, steady state model.

Borehole Number	Eastings	Northings	Minimum Water Level (m AOD)	Maximum Water Level (m AOD)	Calibration Head (m AOD)
On-Site Monitoring Boreholes, Calibration Head Measured 13/01/05					
1	467504.6	394324.5	-0.921	-0.021	-0.041
3	467652.8	394041.4	-0.027	1.293	1.293
4	467441.9	393649.4	0.692	1.102	1.032
5	467840.1	393470.9	0.851	2.901	1.131
6	468061.8	394035.9	-1.445	1.255	-0.495
7	468427.1	393924.2	0.475	1.24	0.575
8	468839.8	394235.6	0.641	1.131	0.826
9	468601.9	394294	0.343	0.833	0.363
10	468318.6	394545.1	-0.379	1.231	-0.159
Regional Monitoring Boreholes, Calibration Head Measured 05/11/2004					
Serlby Park	463330	389820	4.96	6.42	6.07
Misson	468540	395120	-1.53	0.61	-0.37
Partridge Hill	465960	395980	-9.73	-5.66	-6.2
Ponyfield	466170	397140	-6.17	-2.34	-3.4
Swinnow Wood	463080	393540	5.66	9.35	7.12
Danes Hill	467360	386460	7.72	9.18	8.39
Watersports (new)	469950	385900	5.811	7.491	6.89
Wetlands (new)	469450	385170	6.724	7.954	7.514

Considerable uncertainty exists regarding the water balance and flow volumes within the system. In light of this, calibration focussed upon matching the predicted groundwater head to the observed values. Approximate estimates of flow volumes were used in comparison to flow balance information generated within the model wherever possible. In particular, the flow volume that was generated by the constant head boundary was used to represent quarry de-watering. This was compared to estimates of approximate abstraction rates from the site. The flow balance generated by the model was assessed in relation to the conceptual understanding of flows within the system, in order to provide an accurate representation of the primary processes affecting it. Further consideration was made to the behaviour of the rivers in the study area. Each river was represented within the model in order to ensure that the areas of gain and loss were appropriate to the conceptual understanding of river/aquifer interaction.

Initial calibration was undertaken using recharge and aquifer hydraulic conductivity, as the aquifer system is the most sensitive to these parameters. The initial steady state model showed limited sensitivity to these factors, due to the dominating influence of the inflow through the constant head bounding the model to the west. The constant head boundary was therefore replaced with a constant flow boundary in order to allow greater sensitivity.

Calibration of recharge values indicated that a higher recharge than that previously calculated by the initial Penman and Grindley model ([58 mm/yr], as shown in Appendix 3) was required across the mode area. This suggests that well drained sandy soils in this area have lower soil moisture storage capacities than were previously assumed. Recharge in Zone 1 (the general model area) was increased to 120 mm/yr in the steady state model. Recharge in Zone 2 was assigned a value of 150 mm/yr. The elevated observed heads in the west of the model domain and the observation of a distinct ridge of elevated ground to the west of Bawtry was considered adequate, in order to support the addition of this area of higher recharge. The southern limit of the elevated recharge zone does not extend to the limit of the ridge feature, as the geology in this area consists of Boulder Clay drift which is likely to limit the recharge potential.

Calibration of hydraulic conductivity resulted in an increase in hydraulic conductivity in both layers, in order to accommodate a greater transport of water away from the western model boundary and meet the water balance required for discharge at Newington. Calibration indicated that a combination of low hydraulic conductivity and elevated original flow values assigned to the western constant flow boundary, which was situated in the southern region near to the Watersports and Wetlands monitoring locations, were resulting in elevated heads in this area. The model was amended to add a higher hydraulic conductivity zone in this area and reduce the inflow across the boundary in this location. This resulted in an improved representation of the observed data. The reduced inflow suggests that active flow is not necessarily occurring throughout the full 240 m thickness of the aquifer at this point. Therefore, it is unrealistic to use this value in calculating inflow across the boundary. An elevated hydraulic conductivity in the south of the model is consistent with published data (BGS 1997). This has previously separated the Sherwood Sandstone in the East Midlands into two sections (i.e. north and south of northing NGR 400000). It concluded that the average permeability of the Sherwood Sandstone is higher in the southern region.

The steady state calibration resulted in a hydraulic conductivity of 4e-4 m/s in Layer 1. In the three zones of conductivity in Layer 2, the northern zone was assigned a hydraulic conductivity value of 8e-5 m/s, the central zone was assigned a value of 6e-5 m/s and the southern zone was assigned a value of 1e-4 m/s. In each zone a slightly lower vertical permeability was assigned to allow for the conceptual presence of lower permeability horizons which limit vertical flow.

The initial steady state calibration was advanced until all the predicted values were within the annual range of each monitoring point, and the fit to the predicted head could not be improved by further calibration of hydraulic conductivity and recharge values. However, the initial phase of the transient calibration indicated a potentially excessive water loss through the river elements of the model. A further phase of calibration was undertaken in the steady state model in order to assess the effect of river bed conductance.

The final model calibration used a lower river bed conductivity of 1e-7 m/s, which reduced the amount of water removed from the system into the river elements, increasing the sensitivity of the model to recharge. Hydraulic conductivity and recharge were then recalibrated in the revised system to the values in the transient model described below.

Transient model

The transient model was calibrated against groundwater monitoring data for the period 2000 to 2005. Hydrographs for each monitoring point are shown in Appendix 4. Initial calibration was undertaken by varying the recharge and hydraulic conductivity values in order to assess the sensitivity of the model to these values and improve the fit to observed data.

Initial transient recharge was based upon the data supplied by MOERC. The average recharge value of 90 mm/yr over the transient period (as shown in Appendix 3) was adjusted in proportion to the increase in recharge during the steady state calibration. Calibration to the transient heads indicated a better fit with a higher recharge value in Zone 2 than that assigned in the steady state model. Recharge in Zone 2 was increased to an annual average of 174 mm/yr. An additional zone of elevated recharge (Zone 3) was also assigned in the south-east of the model. This zone reflects a large area of open water associated with the flooded gravel workings adjacent to the River Idle. The elevated recharge was assigned an annual average value of 192 mm/yr as the effects of soil moisture storage do not exist in this area. A better fit was achieved to the transient heads in the southern part of the model with a hydraulic conductivity of 2e-4 m/s.

Flow through the western boundary was also used as a calibration parameter as this is controlled by the permeability of the Sherwood Sandstone, the effective aquifer thickness and the local hydraulic gradient. Although the total aquifer thickness may be relatively well constrained, the presence of low permeability horizons in the sandstone may limit the effective thickness through which flow can occur into the modelled area. The actual flow is also dependent upon the local hydraulic gradient. However, this has only been estimated from a limited number of monitoring points, and as a consequence, may differ from the value indicated by the published groundwater contours (BGS 1981) and the values calculated by the contouring of supplied regional data (as shown in Figure 4.11). The calibrated values assigned to the western flow boundary are based upon an average hydraulic conductivity of 1e-4 m/s. Calibration indicated that the calculated inflow through the southern quadrant, formulated from a hydraulic conductivity of 1e-4 m/s and a thickness of 235 m, resulted in too much flow through this segment of the boundary. A better fit in relation to observed data was generated by using a lower flow in the southern quadrant which produced a lower hydraulic gradient and thickness across the boundary than elsewhere in the model.

Table 4.5: Calibrated constant flow boundary inputs

Segment	Initial NGR	Final NGR	Regional Hydraulic Gradient	Sandstone thickness (m)	Sandstone hydraulic conductivity (m/s)	Flow 10 m Cell (m^3/d)	Flow 100 m Cell (m^3/d)	Flow 250 m Cell (m^3/d)
1	359600 397900	361400 392070	1.7e-3	40	1e-4	5.85	58.5	146.1
2	361400 392700	363200 388000	1.7e-3	60	1e-4	8.8	88	220
3	363200 388000	367400 385600	1.7e-3	100	1e-4	14.7	147	267.5
4*	367400 385600	371400 383500	1.7e-3	-	-	-	250	250

*Assigned inflow not based on precise parameters.

As discussed above, assessment of the model sensitivity to a change in recharge values during the initial calibration stage indicated that limited sensitivity has increased recharge values. This has resulted in an increased loss from the river elements of the model and decreased the response of the groundwater head within the model to changes in recharge. The steady state and transient calibrations were revisited to consider the effect of river bed permeability/conductivity on the sensitivity of the model. Calibration indicated that where river gradients were low, the river bed conductivity was too high. The model was recalibrated with a river bed permeability of 1e-7m/s in the lower elevation river sections (i.e. the River Torne and the northern segment of the River Idle).

Although the resulting transient model produced a good fit to the overall behaviour of the system, the model poorly represented some events at Newington (as indicated by the hydrographs of the monitoring locations). In particular, a number of monitoring locations showed a late time recovery in the later part of 2004 which was not reflected in the model. The cause of this recovery is not known, as it was not found to coincide with any particular change in activity at the site. It is suggested that the recovery may be due to changing patterns of discharge at the site which would result in an increase in local recharge (i.e. the re-infiltration of the abstracted groundwater). Water is currently discharged from Phase 1 (which is flooded) to a drainage ditch on the north-west of the site. It then flows along the western site boundary and into Slaynes Lane ditch, prior to discharge within the River Idle. Anecdotal reports indicate increased water levels in Slaynes Lane ditch and flooding in the western ditch around the point of discharge. Furthermore, the piezometer measurements obtained from 1 m at points which are adjacent to the ditches indicate that recharge of abstracted groundwater is likely to be occurring from the western ditch and Slaynes Lane ditch.

Two areas of recharge were added to reflect this change in the model. It was assumed that recharge was equivalent to 10-15 % of the abstracted volume over the total length of the ditches. However, limitations in the resolution of the observed heads within the piezometers are such that it was not possible to calibrate accurately this value. The value of the additional recharge was formulated on the water movement on-site, and the available groundwater flow within the peat and shallow drift deposits.

During the final stage of calibration, the model sensitivity to changes in the storage parameters (specific storability, specific yield, and total and effective porosity) was assessed. However, these parameters did significantly affect the calibration and were left unchanged.

Calibration was not undertaken with respect to abstraction rates as these are considered to be well constrained in comparison to other parameters surrounding the site.

4.3 Summary

The above discussion has outlined the methodological approaches adopted at Newington in order to assess the impacts of aggregates extraction on the waterlogged floodplain sequences. As the catchment-based geo-hydrological element of this research has direct implications for the interpretation of the results from the monitoring of shallow piezometers, redox potentials and pollen degradation studies, this element of the research programme is presented first in the results section (Chapter 5 below), and is followed by a consideration of the shallow drift hydrology. Both of these studies form the basis of the subsequent discussions relating to the results of the *in situ* studies of redox and pollen preservation.

5. Results

5.1 Introduction

As noted above (Chapter 4), the analysis undertaken at Newington falls into broad categories relating to the catchment and site hydrology, the soil chemistry, and the preservation of organic remains. The results are structured to reflect this division, in that the work undertaken by Golder Associates forms the basis of Section 5.2, which outlines the geo-hydrology of the catchment. Section 5.3 presents the results obtained from the analysis of the shallow hydrology which relates directly to the organic floodplain sequences in and around the extraction area; whilst section 5.4 outlines the results of the pH analysis undertaken both to calibrate the redox potentials at the site, and to provide a background to the palaeoenvironmental assessment of pollen degradation. This latter element forms the basis for Section 5.5, which assesses the visible degradation of *in situ* pollen at four locations in the floodplain peats.

5.2 Geo-hydrological modeling

5.2.1 *Calibrated model* (Golder Associates)

The calibrated model can be found under NewingtonTr.vmf on the attached CD (as shown in Appendix 5). The primary parameters affected in the calibration process were recharge, hydraulic conductivity, riverbed conductance and inflow through the western boundary.

The comparisons between the observed and modelled heads in the steady state model, and as time history plots during the transient simulation, are presented in Appendix 6. Transient time history plots are the primary tool used in the model calibration as they produce a good visual fit between the two datasets. Statistical comparisons are also used to judge the outcome of the calibration exercise. The calibration aims to minimise the absolute residual mean (the mean of the difference between the observed and the modelled heads, shown as an absolute value). This indicates that the difference between the observed and the modelled datasets has been minimised. However, in cases where an offset remains, equal distribution ensured that the model did not consistently under predict or over predict heads.

Appendix 6 also shows the distribution of residuals for the calibration points in the calibrated model. Graphs present the plots of observed versus modelled values for both site and regional data. The data set for each monitoring point plots a ‘trail’ over the period of modeling. Generally, the model does not show simulated heads which are consistently above or below the predicted values across the model domain. However, the offset between the observed and the modelled values may be persistently positive or negative at any individual location.

A selection of groundwater head contours from the model history are presented in Appendix 7; and Figures 5.1 and 5.2 (below) present contour data for September 2002 and November 2003. This data is shown in conjunction with the corresponding contour plots which are based upon the observed data at the equivalent dates. It can be seen that, both on site and within the wider landscape, the model represents the flow pattern and the general head distribution of the area with relative accuracy. Calibration data for the regional groundwater monitoring wells which were installed in the sandstone indicate that the model simulates the longer time period fluctuation in groundwater head across the system. This data highlights a representative response to the main driving influences which are recharge and large scale abstraction.

Groundwater heads on site were within 0.5 m of the observed heads, with an overall absolute mean residual between 0.2 m and 0.3 m for most of the simulated period. The accuracy of model prediction remained similar throughout the period of site operation. The only exceptions to this prediction include, the isolated discrepancies which are associated with short-lived events in the monitoring record (e.g. an event in

P10 in April 2003 and in P3 in May 2003), and in the final six month period where the modelled heads did not match the gradual rise in the groundwater heads.

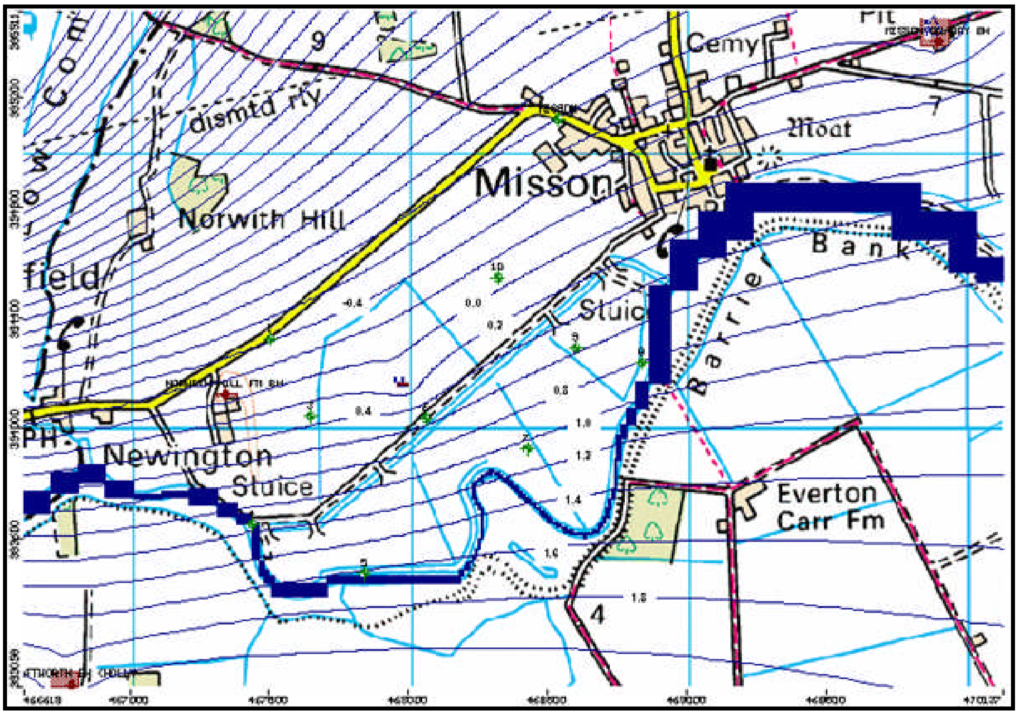

Figure 5.1: Groundwater head contours from the model history, for September 2002 (*after* Golder Associates 2006).

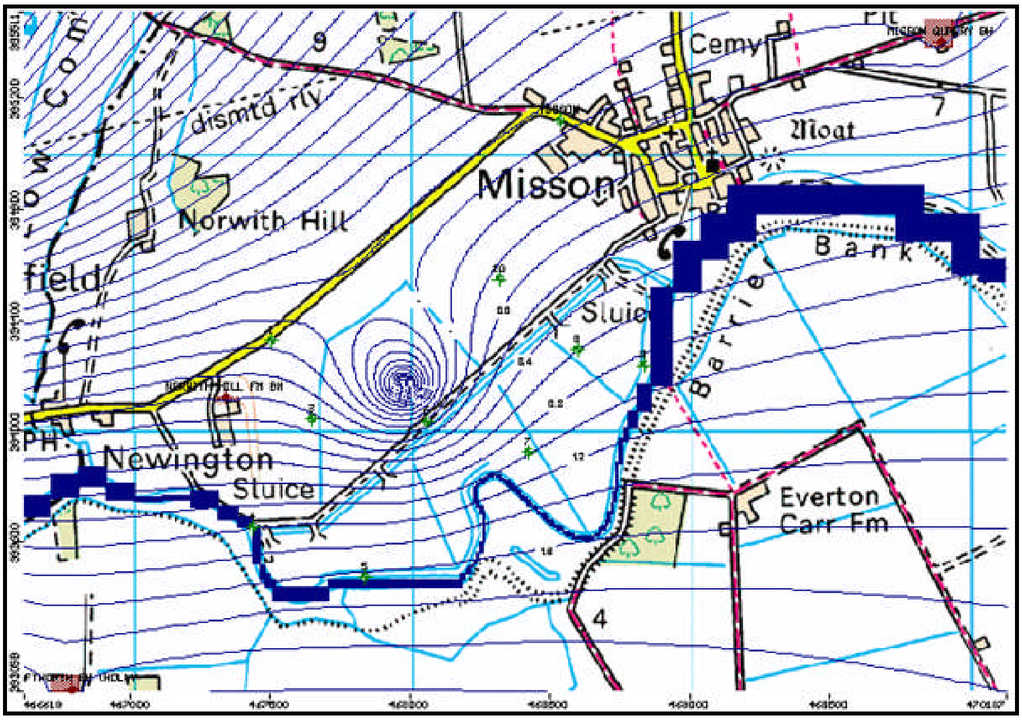

Figure 5.2: Groundwater head contours from the model history, for November 2003 (*after* Golder Associates 2006).

In plotting the observed groundwater levels for the site, the groundwater contour pattern was seen to be dominated by P6 (as shown in Figure 5.2), as this point was the only location within the de-watered area. As P6 is the closest monitoring location to the extraction area, the groundwater contours which were plotted from the observed data on site, show a reduced response to the de-watering than the modelled contours which have a higher spatial resolution.

Visual ModFlow allows the results of tracked particles of groundwater to be displayed during the model period, from either forward stated start locations at the beginning of modelled time, or from backward locations, in order to arrive at the stated end locations at the end of modelled time. Appendix 8 shows the pathlines which were taken by the modelled particles during the period of the simulation in order to arrive at the margin of the de-watered area (e.g. Figure 5.3). These paths are modelled in reverse, i.e. each particle is assumed to have arrived at the quarry at the end of modelled time. The line shows the path along which it has travelled during the simulation. The results show that de-watering has only captured the particles (representing the water) within a relatively small radius around the sump points. In close proximity of the de-watered area in Phase 2, particles drawn into the quarry at the end of the model sequence have flowed from an approximate 400 m radius over the five year period. The results also indicate that the particles downstream of Phase 2 begin to move north-west. These are subsequently captured and pulled back into the quarry when de-watering commences. The effect of quarry de-watering is demonstrated in the particle paths which are seen at approximately 150 m away from the quarry.

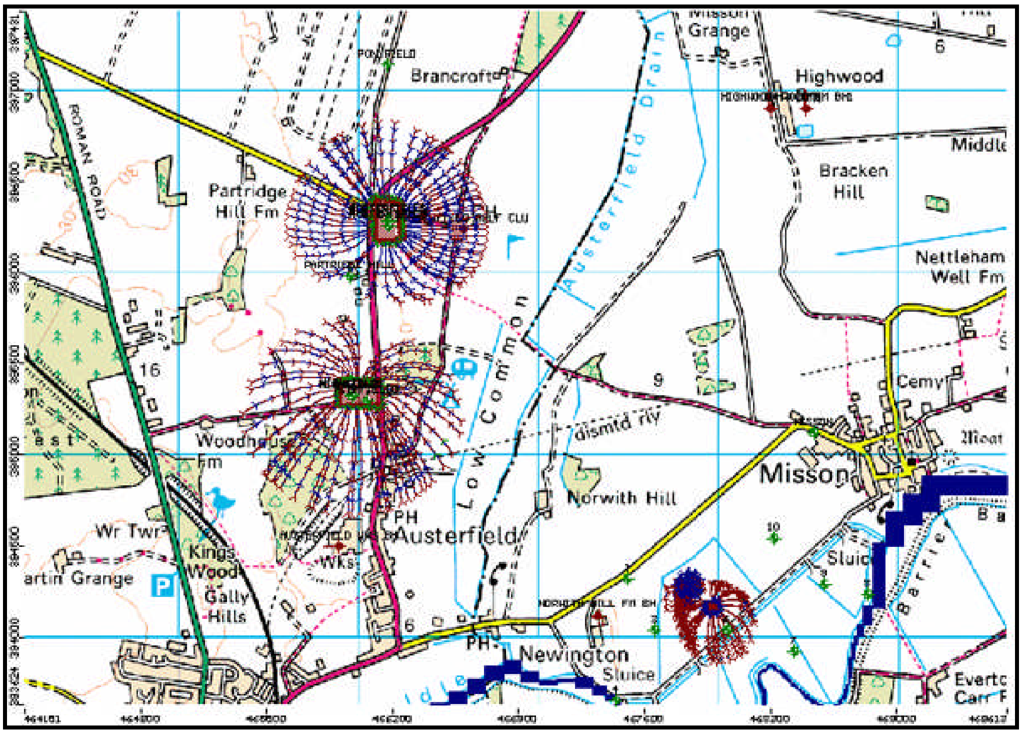

Figure 5.3: Predicted particle pathlines, backward simulation, quarry margins and abstractions.

Particle paths were also plotted around the major abstractions at Highfield Lane and Austerfield. The particles are also modelled backward from the end of modelled time. The comparative plot in Appendix 8 shows that the abstractions are influencing both the quarry and abstraction particle paths over a significantly wider area during the model simulation.

Calibration of the model was primarily focused upon comparisons between the short frequency fluctuations of site monitoring data. In the wider landscape, although the model can replicate the major processes which cause the groundwater head to fluctuate, it cannot replicate a number of points within the hydrograph. Due to the scale of the model, many of the localised effects which may be affecting these hydrographs have not been incorporated in the calibration process, as they do not affect the accuracy of prediction. Each monitoring location may also behave differently, depending upon the screen elevation and construction of the monitoring borehole. The monitoring boreholes may contain short screen sections which sample a relatively isolated segment of the Sherwood Sandstone aquifer. These screen sections do not possess the same hydraulic properties that are typical of the aquifer as a whole. They can represent a smaller body of water which is isolated by confining clay bands within the overlying aquifer. In this situation, the borehole may not measure a typical aquifer hydraulic head as local vertical gradients may be induced. The variation in aquifer lithology is too complex and too poorly defined to be accurately represented in the model. This may account for the discrepancies associated with the monitoring boreholes which do not reflect the general trend in head fluctuation described by the model.

Hydraulic conductivity is a highly variable and influential parameter in the calibration model. Typical values, which were assigned at the commencement of the modeling exercise, are based upon literature values that were derived from the borehole pumping tests. During these tests, the borehole response is sensitive to both the screen length and the number of fractures intersected across the screen length. Intersection of a significant fracture will greatly increase the yield from the borehole, and as a consequence, it will strongly influence the resulting estimated permeability. The regional hydraulic conductivity may not be accurately represented by the measurements within the individual boreholes. This is due to the localised effect of fracturing and/or the existence of low permeability horizons in the screened interval of the borehole, affecting the flow regime.

Zone budget calculations in the final steady state model indicate an average discharge of 2,273 m^3/day (equivalent to 830,320 m^3/year) from the constant head representing the quarry area. Although this figure is slightly below the estimates previously outlined in Section 4.2.5.3 (3,456 – 6,048 m^3/day and 2,428 m^3/day, respectively), it is within a similar range and is considered to be a good fit based upon the uncertainties of understanding the site water balance.

Comparison of the steady state river leakage, both in and out of the assigned segments, indicates that the River Ryton and the upper section of the River Idle are gaining river sections (i.e. water is lost from the aquifer to the river elements). In contrast, water is lost from the River Torne and the lower part of the River Idle along their length (although with a lower overall leakage rate than other interactions).

River flows from the aquifer to the River Idle (flow out) and from the River Idle to the aquifer (flow in) are shown in Appendix 6. The average net flow calculated over the period of the simulation is 1730 m^3/day (6.34e5 m^3/year) from the river to the aquifer. Mean flow in the River Idle at Mattersey is 2.46 m^3/s, (equivalent to 7.76e7 m^3/year). The River Ryton joins the River Idle between this point and the site. Although flow increases at this confluence, some loss occurs to the aquifer along this section, and to the site itself. As a consequence, the flow at Mattersey is considered to be lower than the flow in the River Idle past the site, even though it is of a similar order of magnitude. The average loss from the River Idle in this section of the model is estimated to comprise a maximum of 0.8 % of the total flow in the river, suggesting that the rate of loss predicted by the model in this area is within a reasonable limit.

5.2.2 *Modeling problems*

There are three main problems which have been identified during the calibration of the model. Throughout the calibration period, a poor fit exists between the observed and the model heads of the Sinnow Wood monitoring well. The model continues to predict lower heads at this location than those observed in monitoring. Furthermore, the observed data showed a highly damped oscillation in the head of this borehole. This was not consistent with the seasonal fluctuation which was observed in the other boreholes or with the recharge response seen in the modelled heads. It is concluded therefore, that the head which is observed at Sinnow Wood is anomalous to the regional pattern of groundwater heads. As such, the elevated heads in this area cannot be explained in terms of processes which are active on the scale and that are represented in the model. The geology map for the area around Sinnow Wood (BGS Sheet 88 for Doncaster) indicates an area of boulder clay, which possibly overlies glacial sands and gravels. Although a geological log is not available for the Sinnow Wood borehole, it is suggested that a greater thickness of drift in the area and variable drift geology, may be the causes of differential local groundwater flow behaviour.

In the south-east corner of the model, the observed versus modelled heads at the Watersport and Wetlands monitoring points show a persistent over estimation in the modelled head; and a reduced amplitude of fluctuation in the modelled heads when compared to the observed heads. Although the cause of this issue has not been identified, a good fit was obtained to the nearby Danes Hill borehole. However, no parameters could be identified which would fit both Danes Hill and the Wetlands/Watersport boreholes simultaneously. It is suggested that this problem is associated with the large groundwater abstraction operated by Tarmac, which is situated between these two wells. Although the model considers licensed abstraction rates from this borehole, actual rates were not available. As such, this does not reflect the short term changes which may significantly affect the groundwater heads in this area. The heads may also be influenced by localised affects from nearby surface water bodies and by abstractions outside the model domain. However, given the distance of these boreholes from the site, any error is unlikely to affect the accuracy of the simulation.

The calibration of the on site boreholes shows variation between points, with a better fit shown between the modelled and the observed data at certain locations. This is despite the close proximity of these boreholes and their similarity of construction. Figure 5.4 (below) shows the site monitoring data which was used in the calibration. The main phases of site operation and the water levels in the nearby Misson borehole are included for reference. Appendix 6 also displays in graphical format the modelled on site points and the calibration data as it appears in model output graphs. It is noted that the on site monitoring ceased in October 2002, which was immediately after the commencement of the development of Phase 1. Monitoring subsequently recommenced in April 2003. As a consequence, any initial effect of Phase 1 is not recorded in the monitoring record. The model solution which is presented in the results has been determined by convergence using the WHS solver in Visual ModFlow. Although this is one possible numerical solution to the governing equation, the nature of the numerical modeling produces a non-unique solution to problems, with other possible solutions if different starting conditions or solvers are applied.

Two major responses can be seen in the model output graphs for the on site piezometers: the effect of the Phase 2 de-watering in P6, which is even more pronounced into the Phase 3 extraction period (Figure 5.5), and a de-watering event which is followed by recharge in P3. In addition, a long term seasonal fluctuation is evident. The steep increases in the modelled head which is seen in all points are controlled by periods of high recharge and high water in the River Idle (which are associated with rainfall). The increases are subsequently followed by a gradual decline. A minimal response to the de-watering of Phase 2, which comprises an initial perturbation, a gradual decline and a late time recovery, is visible in most monitoring points (with the exception of P8).

Comparison between the observed and the modelled on site data indicates that some of the processes affecting water levels in the site boreholes are not represented in the model. This situation is associated with the late time rebound which is evident in all the site boreholes and in groundwater levels recorded at the nearby Misson monitoring point. Although the model is able to represent the rebound in P6, which is nearest to the abstraction area, it does not show a response at a greater distance away from the site. The conceptual understanding of the site does not include any processes which may have resulted in the site wide rebound over this period, as de-watering and quarry extraction are still ongoing at this time. It is suggested that the discrepancies are associated with a poor understanding of the water movement on

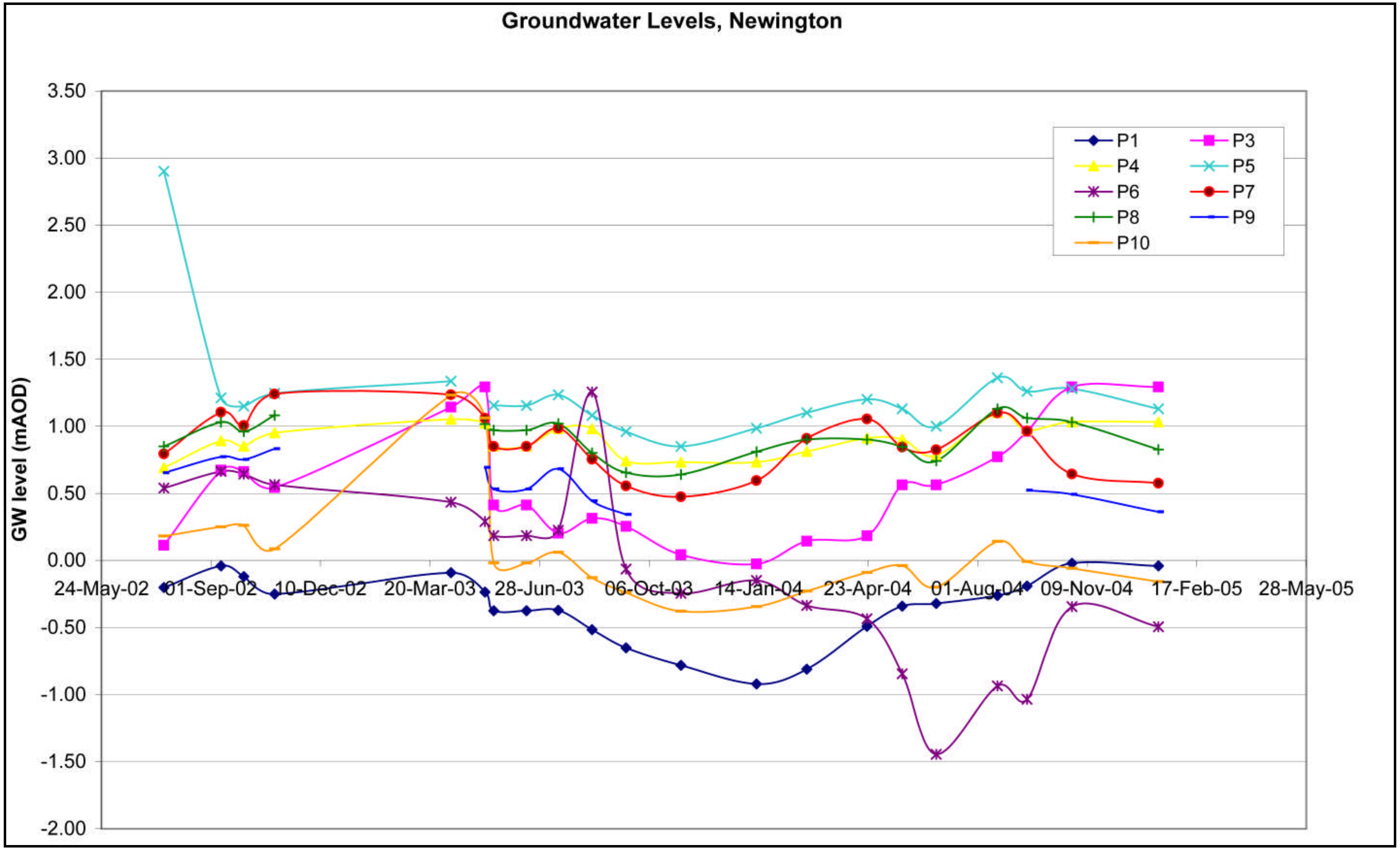

Figure 5.4: On-site monitoring data used in model calibration. The main phases of site operation and the water levels in the nearby Misson borehole are included for reference.

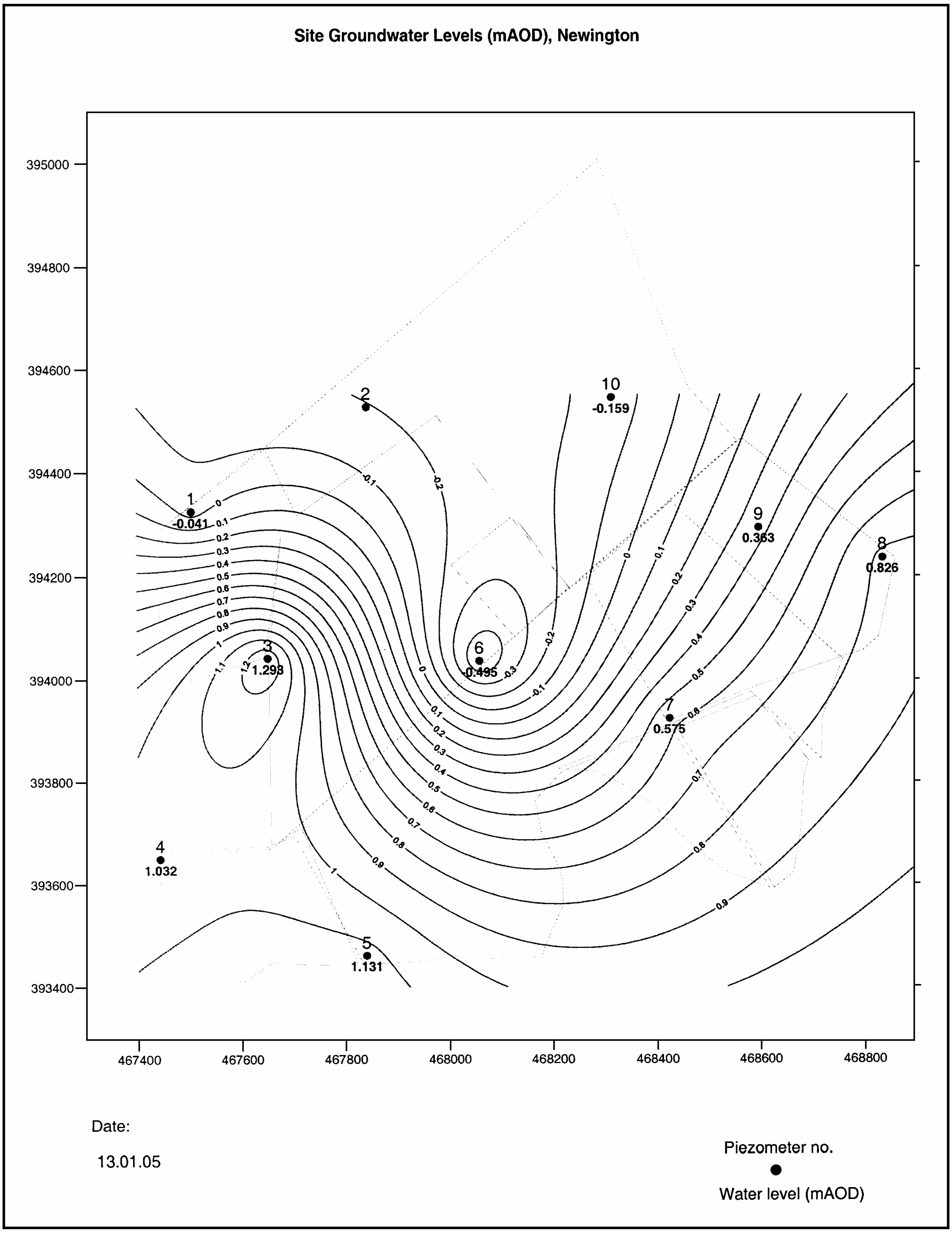

Figure 5.5: Site groundwater levels at Newington, highlighting drawdown in P6 across phases 2 and 3 of the extraction process.

the site. This is due to a lack of written records or more precise information. However, the presence of a similar rebound in the nearby Misson borehole suggests the potential of a more extensive effect. A potential cause of this may be due to the water movement which is associated with abstractions at the nearby Austerfield Works borehole or the Misson Quarry borehole. However, neither the method of discharge of extracted water, nor any changes in water usage during the model simulation period at these locations, is known.

The achievement of a good model calibration was hampered by the lack of data in certain areas. For example, the observed groundwater heads were not constrained throughout the north-east of the model, especially in the vicinity of the Finningley public water supply. Although this abstraction has a dominant effect on the modelled groundwater heads in the north-east of the model domain, due to the lack of monitoring locations in the area, the drawdown associated with this abstraction is not represented in the monitoring data.

The poor constraint on the results of the river bed conductivity induced uncertainty in the calibrated model parameters. There is a considerable interdependence between the calibrated values for river bed conductivity, recharge and aquifer hydraulic conductivity. These three parameters largely govern the water balance of the model, and the total inflows and outflows to the system. If the loss or gain from the rivers within the model domain are poorly constrained this may affect the accuracy with which other flows within the catchment can be determined.

Despite the problems discussed above, the model successfully represents the overall flows and the magnitude of response in the system. However, because the model is only a simplification of reality, some elements cannot be represented accurately. As a consequence, during the transposition of the modelled results to the observed results, complications have occurred. This is due to the uncertainty concerning the key processes involving water movement around the site.

5.2.3 *Sensitivity analysis*

The model was found to be highly sensitive to changes in hydraulic conductivity. The hydraulic conductivity strongly affects the response to the major abstractions and the drawdown around the quarry area, and the spatial distribution of head across the site. The model was also found to be relatively sensitive to changes in recharge rates following a reduction in river bed permeability.

The accuracy of the model fit to the calibration points improved following the addition of the transient fluctuations in the River Idle adjacent to the site. This indicates a degree of sensitivity of the water levels on the site to recharge from the river. However, this effect did not produce a strong fluctuation in the modelled groundwater heads. The response to the river leakage was found to be less dominant than the effect of recharge due to precipitation, upon the water levels on the site. The water levels in the model showed the greatest response to large scale nearby abstractions and changes in recharge, whilst the effect of quarry de-watering was extremely localised, showing significant drawdown only in those boreholes closest to the quarry area.

The model did not prove sensitive to changes in storage properties. Changes in river bed conductance have a significant effect on the model water balance. However, as the river leakage volume is strongly affected by other parameters in the model (permeability and recharge), it has not been possible to calibrate this value accurately. The results of the calibration have indicated that the higher values of river bed conductivity have resulted in a lack of sensitivity to the recharge. This is due to the ease with which water can potentially be lost from the model system by river leakage. River bed conductance is therefore considered to be a significant factor in the behaviour of the system in terms of the response to other driving factors; but it did not appear to have a dominant effect on head distribution across the model as a whole.

5.2.4 *Analytical approaches to model de-watering effects*

This study has focused on the development of a numerical model to assess groundwater impacts around Newington Quarry. Whilst such detailed assessment of the potential impacts are not usually undertaken for a site of this type, there are a number of analytical approaches which are routinely used to provide an estimate of the scale of impact. This can be carried out without the associated cost and site investigation implications of a full numerical model. There are four principal methods that are used to assess the rates of groundwater inflow and the subsequent drawdown of groundwater levels around a quarry site.

5.2.4.1 Adapted analytical well equations

The most common analytical well equation is the Dupuit-Forchheimer (for unconfined aquifers) or Thiem (for confined aquifers). The quarry is represented as a large 'equivalent well' which allows established radial flow analytical models to be applied (*cf*. Preene *et al*. 1997). Equations for an equivalent well in a radial flow system where the well fully penetrates the aquifer in question are presented below. These equations assume horizontal flow in the aquifer. Either a supplied flow rate is used to estimate the radius of influence of de-watering around the excavation, or a radius of influence is approximated to estimate the flow rate required in order to produce the necessary drawdown in the excavation for the commencement of dry working.

Confined conditions:

$$Q = \frac{2\pi kD\left(H - h_w\right)}{\ln\left[R_0 / R_e\right]}$$

Unconfined conditions:

$$Q = \frac{2\pi kD\left(H^2 - h^2{}_w\right)}{\ln\left[R_0 / R_e\right]}$$

Where k is the soil permeability, D is the thickness of the aquifer, H is the initial piezometric level in the aquifer and h_w is the piezometric level in the equivalent well. The equivalent radius R_e can be estimated in a rectangular system from the plan dimension a x b using the equation:

$$R_e = (a + b) / \pi$$

The radius of influence R_0 can be estimated from the empirical formula (Preene *et al*. 1997):

$$R_0 = C(H - h_w)\sqrt{(k)}$$

Where C is an empirical calibration factor and (H – h_w) is the drawdown in the equivalent well. As the site at Newington displays a permeability of 18 m/d (2.08e-3 m/s) and a C value of 3000 (which is usual if R_0 is in metres and k in m/s), a radius of influence of 152 m is calculated.

If the well does not fully penetrate the aquifer system, the flow rate from the well will be less than that from a fully penetrating well by a factor which is dependent upon the degree of penetration of the well and the geometry of the system.

This approach can be applied at Newington in order to provide an estimate of the abstraction rate required to maintain the drawdown observed in the quarry. Alternatively, if a known abstraction rate was required in order to maintain a level of drawdown in the quarry, it would be possible to calculate the radius of influence. At Newington, the aquifer is unconfined and the flow to the excavation is predominantly horizontal. Water flows in a radial manner around the excavation area. A drawdown (H-h_w) of approximately 3.5 m would be required in order to achieve a water level of -3 m AOD in Phase 2. Based upon the understanding of the relationship between the Quaternary sands and gravels, and the Sherwood Sandstones, the excavation is partially penetrating the aquifer under consideration as it is in hydraulic continuity with the groundwater in the Sherwood Sandstone.

5.2.4.2 Superposition

The principle of superposition can be used to design the de-watering of the quarry if it is de-watered by pumping from the wells or well points, if pumping tests have been undertaken, and the pattern of drawdown around a borehole which has been pumped at a controlled rate has been determined. This method calculates the cumulative effect of several well points pumping together, and allows the flow rate and drawdown pattern to be assessed. It is based upon similar equations to those described above, only with the addition of cumulative calculations. However, this approach is not required at Newington as de-watering is not being undertaken via these techniques.

5.2.4.3 Zone of contribution

If only limited hydrogeological information is available, the likely inflows to quarries are primarily estimated on a catchment infiltration basis. The groundwater catchment associated with a quarry is estimated (either from topographic features or by assuming an arbitrary zone of influence). The inflow to the quarry is assumed to be the total infiltration over the area. Unfortunately, this approach is not without its problems and can often significantly overestimate de-watering inflows. However, in the case of Newington, the lack of both topography and a distinct groundwater catchment in the vicinity of the site delimits the viability of the approach.

5.2.4.4 Numerical models

In a small number of cases numerical groundwater models have been used to model quarry de-watering events, and to assess flow rates and drawdown patterns. Due to the complexity of such methods, they are generally only used where the hydrogeology is considered to be very complex, or if the site is in a sensitive environmental setting. However, changing legislative requirements (see Chapter 6) may significantly increase the reliance on numerical modeling in this field in the future.

5.3 Shallow water table monitoring (floodplain peats)

This area of the analysis encompasses modeling of the water tables in the superficial depositional sequences around the immediate area of the extraction site. The water table modeling was undertaken on the basis of recorded water level readings obtained from the seventy four piezometer points located at Newington (Figure 4.2, above). The figures presented here are the most representative models of water table activity in the floodplain for the periods' winter 2005-7 and summer 2005-6 (additional GIS plots of February, May, August and November data 2005-7 are presented in Appendix 9).

Figure 5.6 (below) shows the data presentation format, for all three piezometer depths (1.0 m, 2.0 m, and 3.0 m), with a map drape overlay to show the location of the GIS models in relation to the floodplain sequences and topography. The vertical scale in this image is exaggerated in order to highlight areas of high and low relief in relation to the study area. The scales represent water table heights used to plot the model across the duration of the study, and are corrected to Ordnance Datum (OD). (All water level data scales in Figures 5.6-5.11 are corrected readings in mOD).

The immediate observation at this stage is the indication in the generic model that the lowest levels of the water table occur throughout the floodplain areas, and that the lowest point in the model lies directly beneath the area of the Slaynes Lane Washland SSSI to the southern part of the floodplain. The validity of this observation will be assessed through a consideration of the models presented in Figures 5.7-5.11, below.

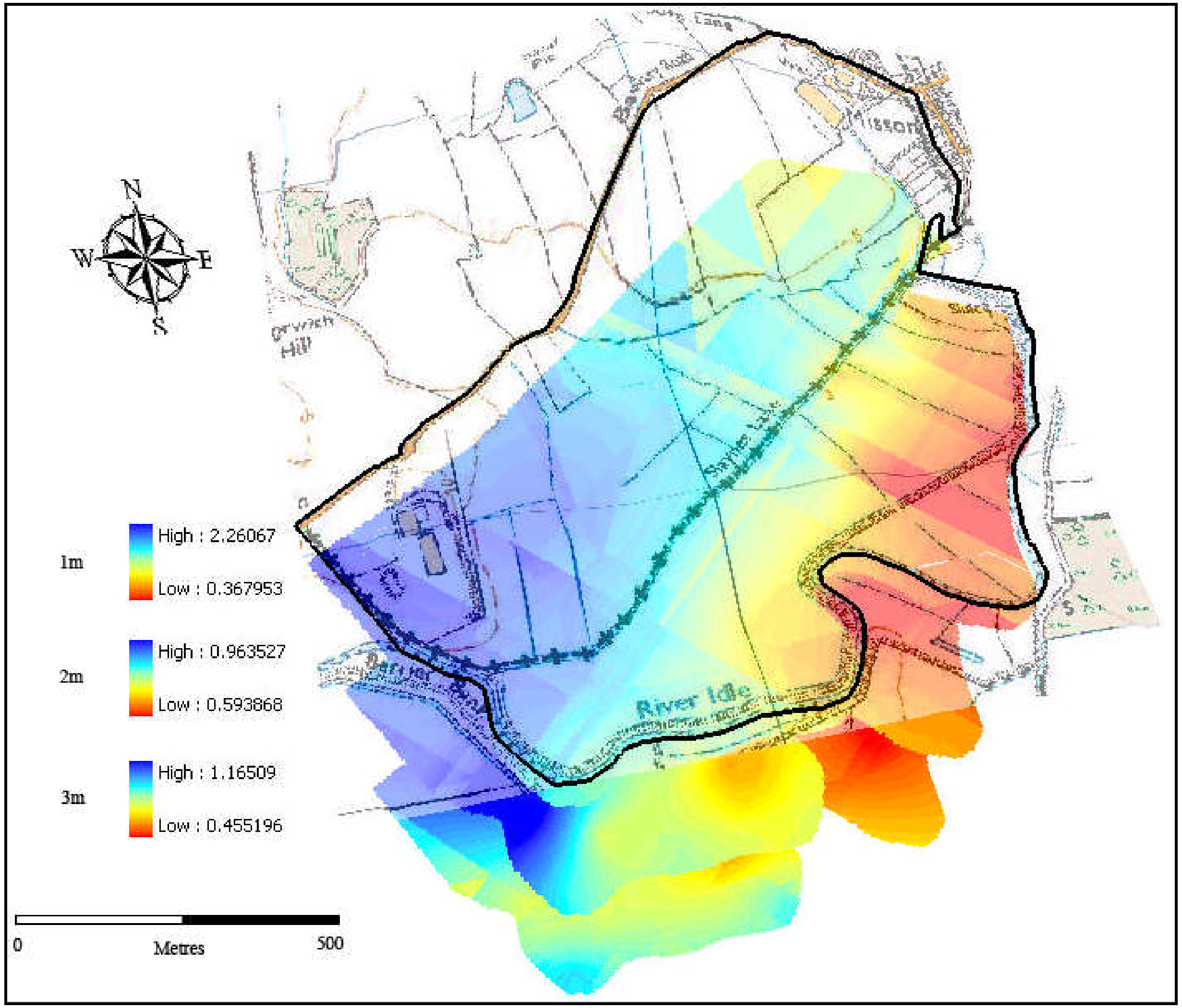

Figure 5.6: Digital elevation model (modelled in ArcGIS 9 from ESRI), showing map drape and water level data from 1.0 m, 2.0 m and 3.0 m piezometers.

As can be seen from Figure 5.7 (below), during the period when extraction was being undertaken in Phase 3 (December 2004-February 2005), the water table data recovered from the 1.0 m and 3.0 m piezometers indicates that the floodplain areas have the lowest water tables. More specifically, the area beneath the Slaynes Lane Washland SSSI, and the south-western part of the deeper floodplain peats have water levels between 0.84-0.23 m OD. The 2.0 m piezometers appear to show a depression towards the extraction area. However, as there are only limited piezometers in the immediate area of the extractions, some measure of interpolation between monitoring points may be producing an artificially low point in the model for the extraction area.

Figure 5.8 shows the summer water table data for 2005, plotted as a DEM, at a time that is equivalent to the final stages of the Phase 3 extraction, which were continued until September 2005. All of the maximum height values for each level (i.e. 1.0 m, 2.0 m and 3 m piezometers) are lower in the summer than in the previous winter months, as might be anticipated. The summer lows, however, do not exhibit any marked lowering in the 3.0 m piezometers and only *c*. 0.4 m lowering in the 2.0 m piezometers. Contrary to these results, the 1.0 m piezometers are higher in the winter than in the summer months. The 1.0 m piezometers may reflect increased pumping from the extraction areas into the Slaynes Lane ditches, which are providing a measure of recharge to the floodplain peats in the summer. In general, the winter ranges (between the maximum and minimum water levels) are greater than the summer ranges.

The winter 2005-6 water table data (Figure 5.9) are equivalent to the earlier stages of the extraction of Phase 4. The 2.0 m and 3.0 m low values are higher than in the previous summer (2005). Although the 1.0 m water lows are lower than the summer values recorded, they are in fact equivalent to the previous winter values (Figure 5.7). The winter highs are difficult to interpret when compared against the previous summer values; however, in general, they are slightly lower when compared to the previous winter (2004-5) values. Figure 5.9 primarily shows that the areas with the lowest water values are again focussed in the floodplain peats and the area beneath the Slaynes Lane Washland SSSI. The pattern that emerges highlights the presence of low water levels beneath the deeper floodplain sequences to the south. This is very consistent when compared to the previous summer water level models.

The summer 2006 water level data is equivalent to the latter stages of extraction in Phase 4 (Figure 5.10). No water table model could be generated for the 1.0 m piezometers due to a lack of water at this level. This contrasts markedly with the 2005 summer water levels model. There is a significant lowering of the basal water level data from the 2.0 m and 3.0 m piezometers to *c*. 0.3-0.4 m below the previous summer values, and *c*. 0.4-0.5 m below the previous winter (2005-6) values. Again, as with previous observations, the lowest water levels are focussed in the southern part of the floodplain, and in particular, the Slaynes Lane Washland SSSI. The summer (2006) highs are *c*. 0.4-0.5 m lower than the previous winter highs (2005-2006) and *c*. 0.4-0.6 m lower than the previous summer (2005) highs. The general pattern produced by this data highlights an overall reduction in the water budget and marked seasonal variations in the southern part of the floodplain, up until the summer of 2006.

The winter 2006-7 water table model (Figure 5.11) is equivalent to Phase 5 of the extraction, and *appears* to mark a reversal in the trends of lowered water levels in the floodplain. The winter lows are *c*. 0.6-0.8 m higher than the previous summer lows (2005), and the highs are *c*. 0.3 m higher than this. However, when compared to the winter 2004-5 and winter 2005-6 data, the surface water levels (1.0 m piezometers) are at the upper end of the scale, but lower towards the base. The 2.0 m and 3.0 m winter highs are both lower than in the previous winters. The trends are not particularly marked and will simply be reflecting rainfall variability between the three winter periods studied. The main variation appears to relate to the exceptional lowering of the summer 2006 water levels in this catchment.

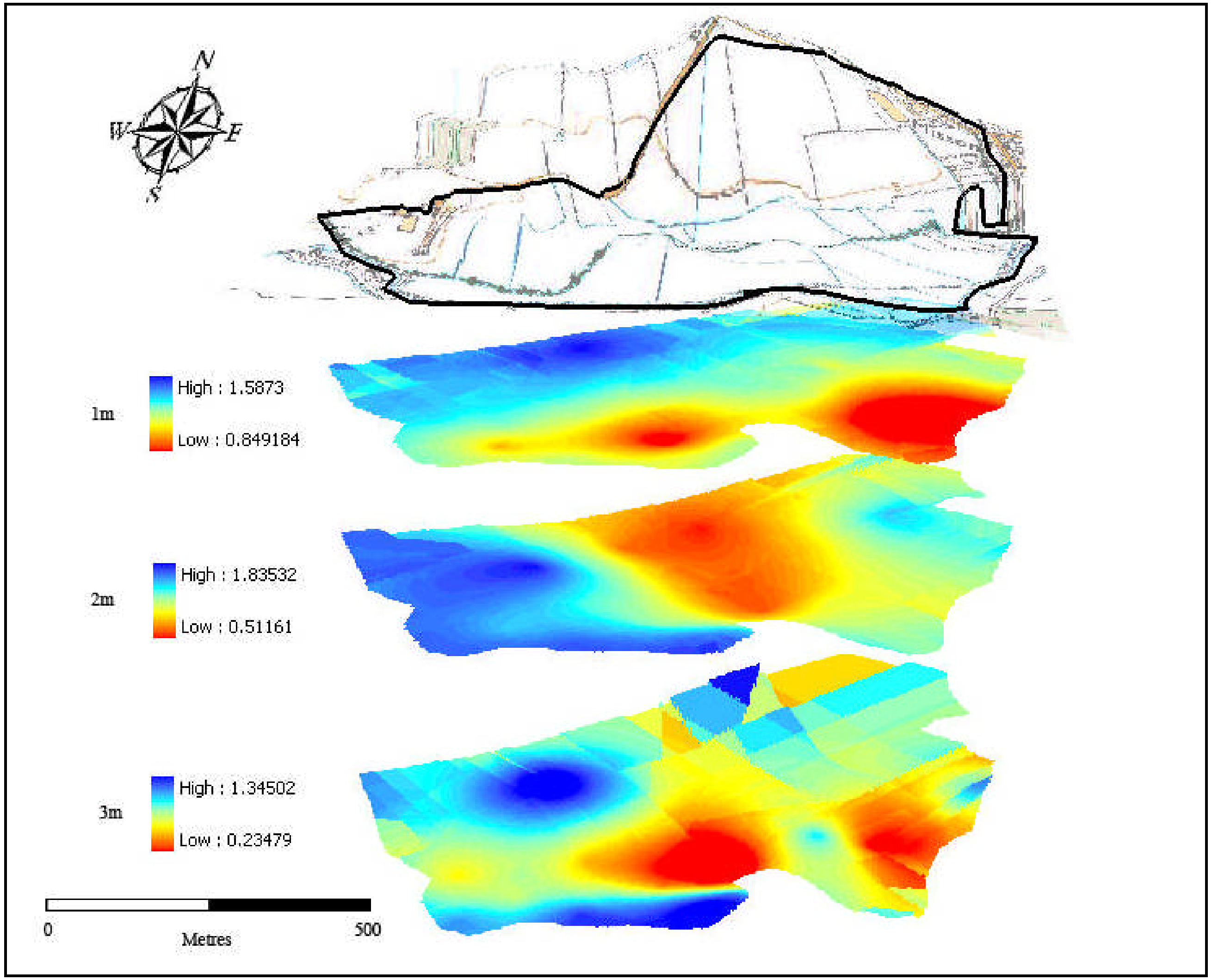

Figure 5.7: Winter water table levels from Newington (2004-5). DEM shows pooled data for the period December 2004 to February 2005.

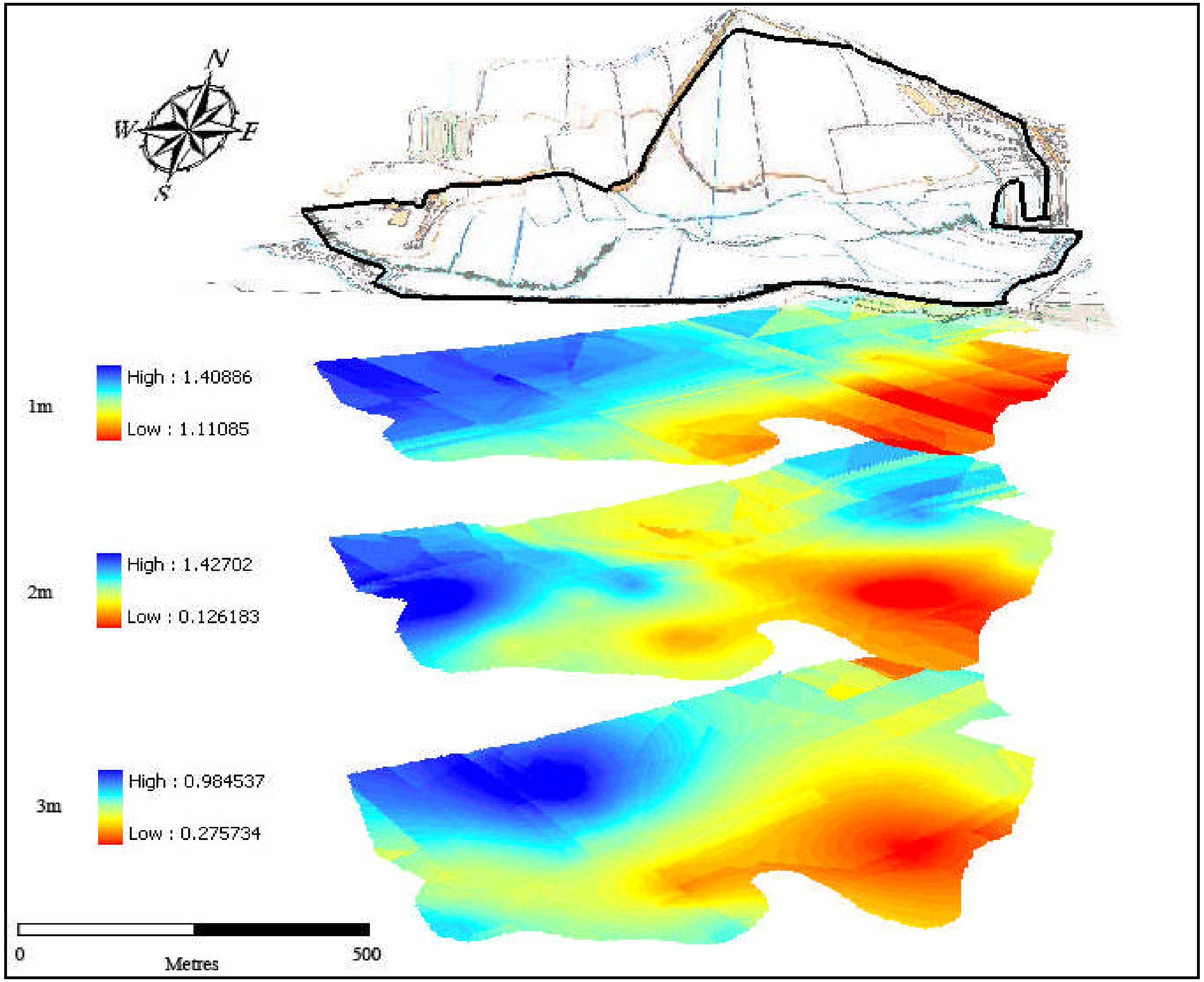

Figure 5.8: Summer water table levels from Newington (2005). DEM shows pooled data for the period June-August 2005.

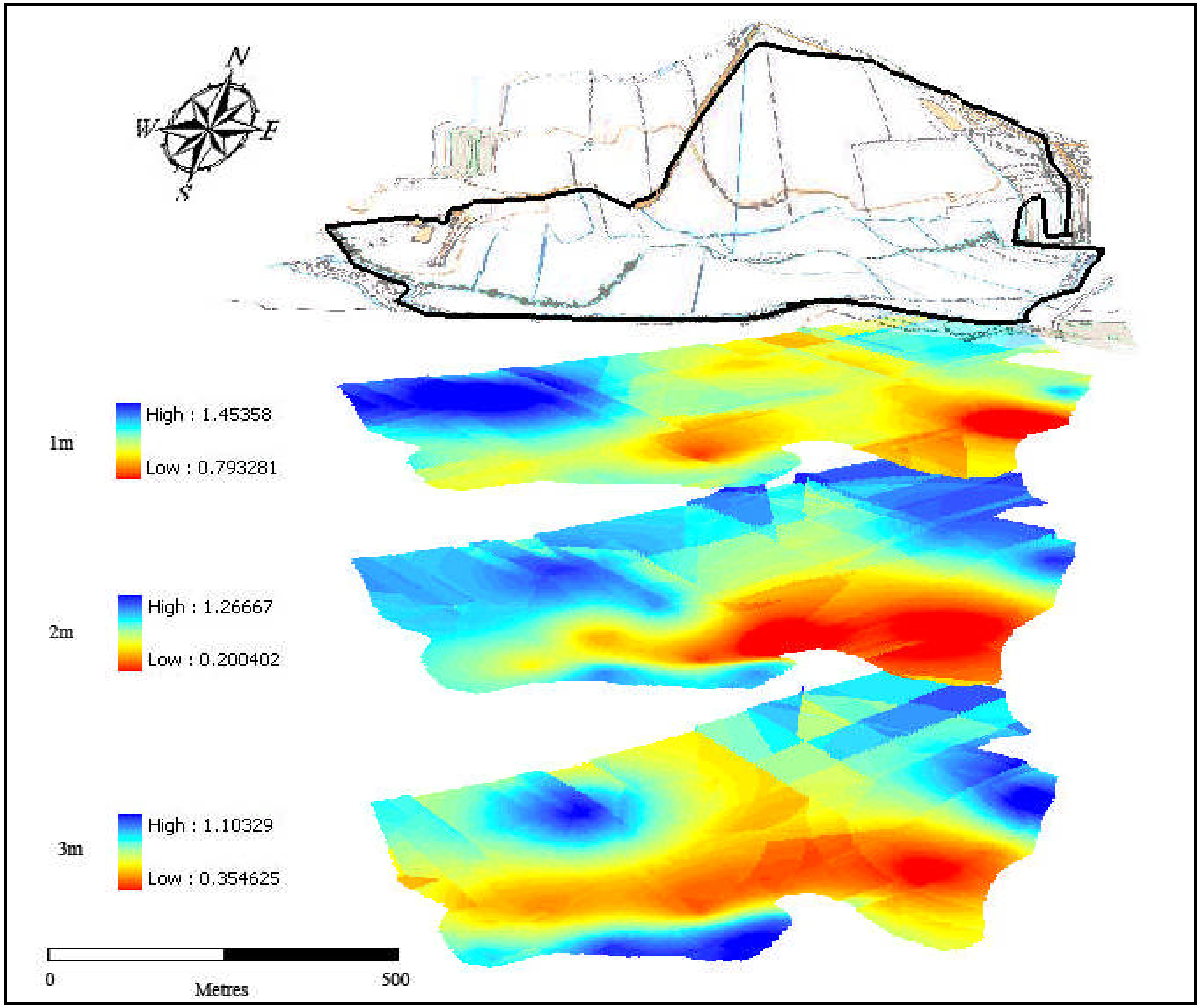

Figure 5.9: Winter water table levels from Newington (2005-6). DEM shows pooled data for the period December 2005 to February 2006.

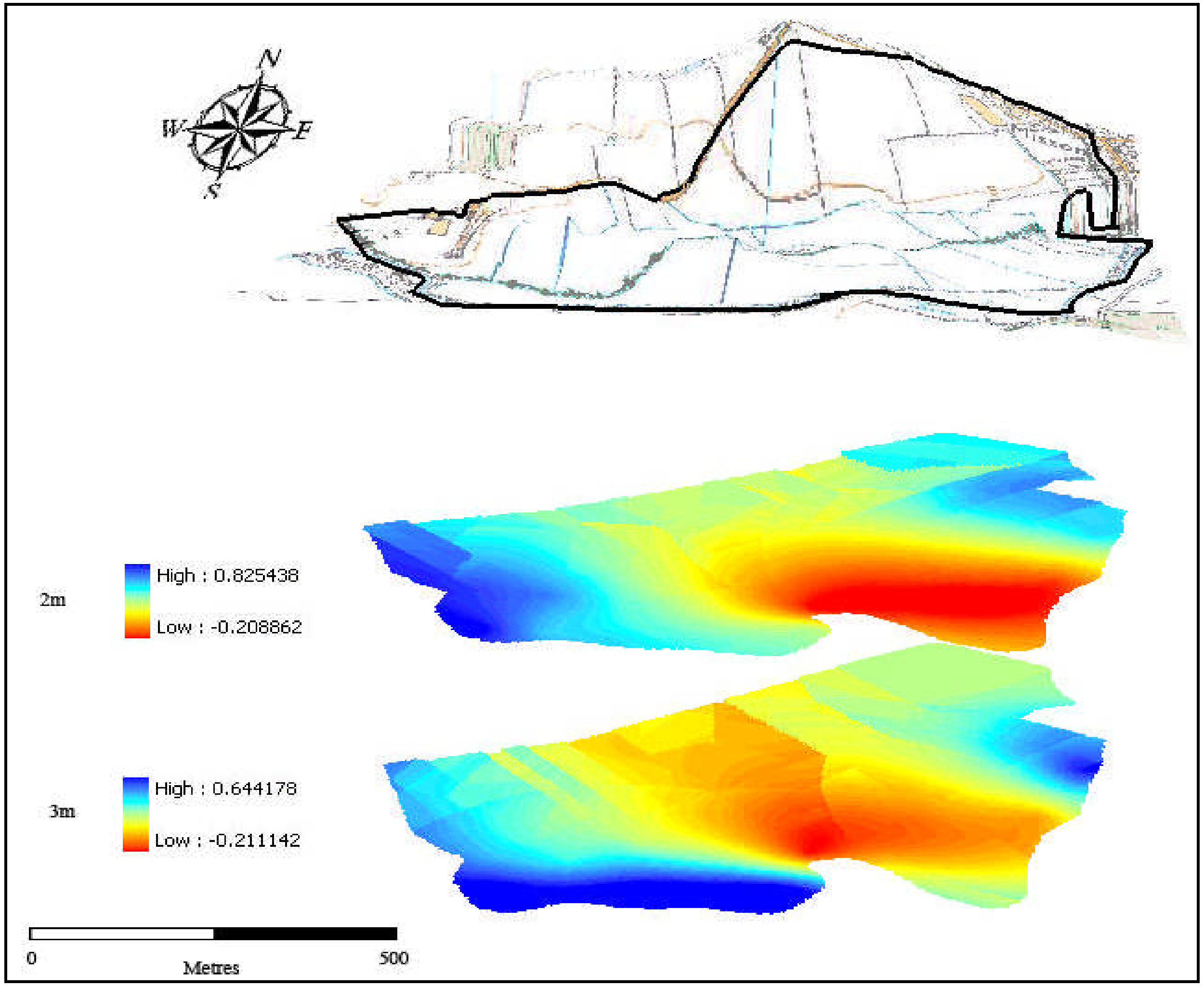

Figure 5.10: Summer water table levels from Newington (2006). DEM shows pooled data for the period June-August 2006 (note 1.0 m piezometers are too dry to facilitate the creation of DEM for this level in the summer of 2006).

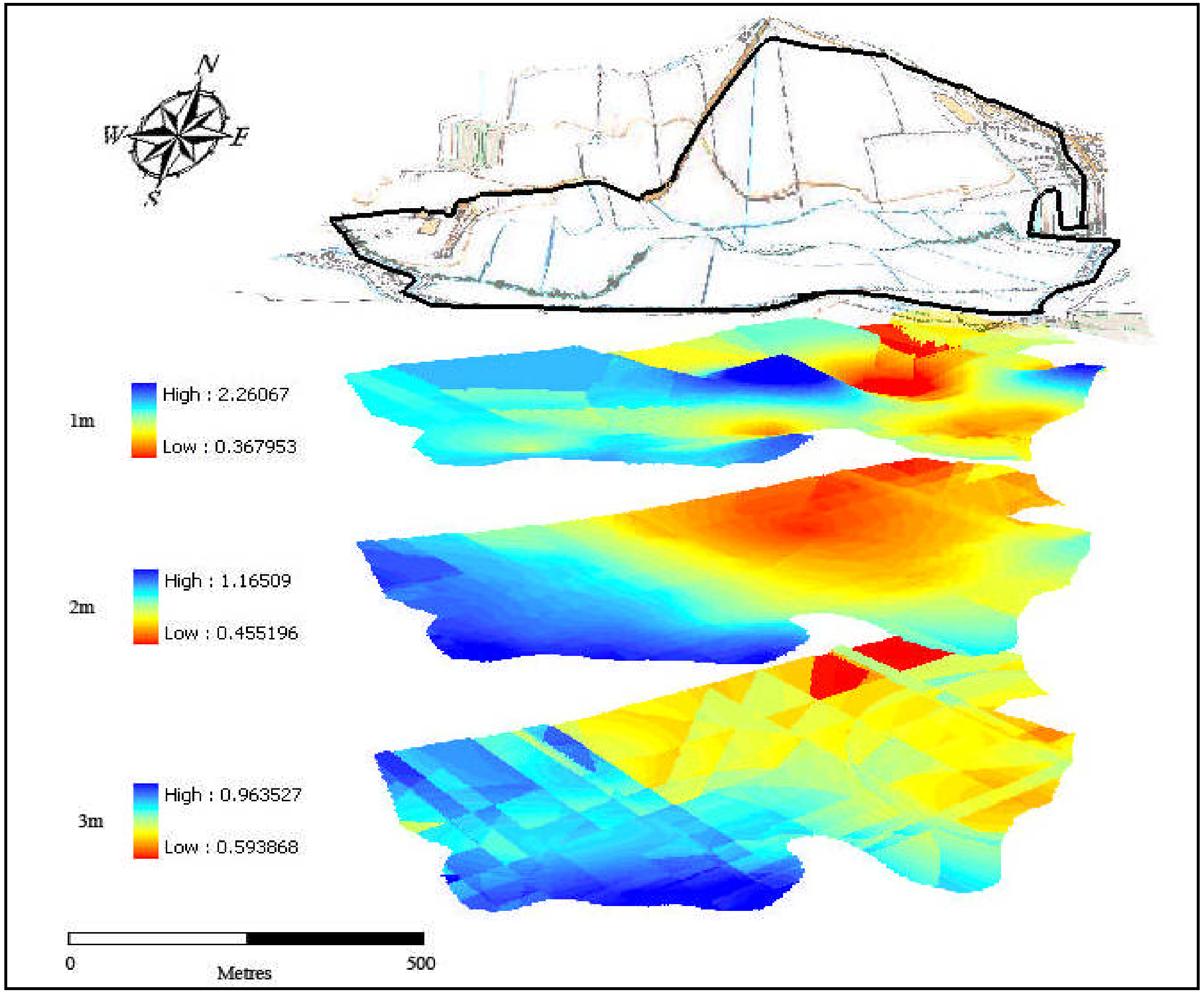

Figure 5.11: Winter water table levels from Newington (2006-7). DEM shows pooled data for the period December 2006 to February 2007.

5.4 pH analysis

The pH analysis of the floodplain peat deposits was undertaken in order to provide a background to the palaeoenvironmental assessment of pollen degradation on the site and to calibrate the redox potential values obtained from each redox cluster located on the site. Appendix 10 shows the stratigraphic loss-on-ignition (LOI) and pH values obtained from selected sampling points on the site (1, 13, 15, 23). Each sampling location was in close proximity to a piezometer point. Appendix 11 displays the surface pH values of the floodplain peats which are used in the redox calibrations.

5.4.1 *pH values adjacent to piezometer point 1*

Figure 5.12 highlights the pH values of the peat samples obtained adjacent to piezometer point 1 over the duration of the monitoring programme. The majority of the pH values fluctuate between pH 7 and pH 5 (with the exception of the pH values obtained at 2.4 m depth [pH 5-6]). The deeper peat samples highlight lower pH values which are indicative of mildly acidic conditions, whereas the superficial peats indicate more neutral conditions. It is suggested that rainfall inputs into the superficial peat deposits promote more neutral pH levels; whilst at depth the low moisture content of the peat creates slightly more acidic conditions.

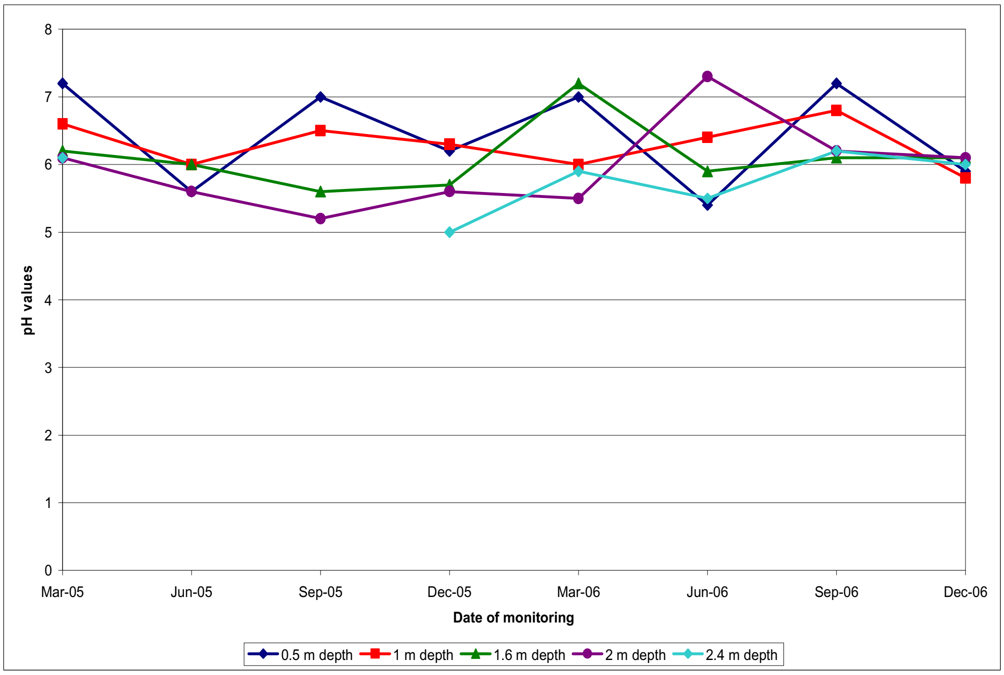

Figure 5.12: pH values of samples obtained adjacent to piezometer point 1 over the duration of monitoring.

5.4.2 *pH values adjacent to piezometer point 13*

Figure 5.13 highlights the pH values of the peat samples obtained adjacent to piezometer point 13 over the duration of monitoring. The majority of the pH values fluctuate between pH 6 and pH 4. However, there is less differentiation between the pH values of the samples obtained throughout the peat profile, when comared to point 1. Furthermore, the pH values at the three sampling depths tend to increase in acidity during the winter months, in contrast to the summer months. This may be due to the location of the sampling site which is adjacent to Slaynes Lane ditch. It is suggested that water recharge from the ditch, due to pumping activities, may infiltrate the peat deposits throughout the profile during the summer months, consequently promoting more neutral conditions. The low moisture content of the peat in the winter months reflects more acidic conditions.

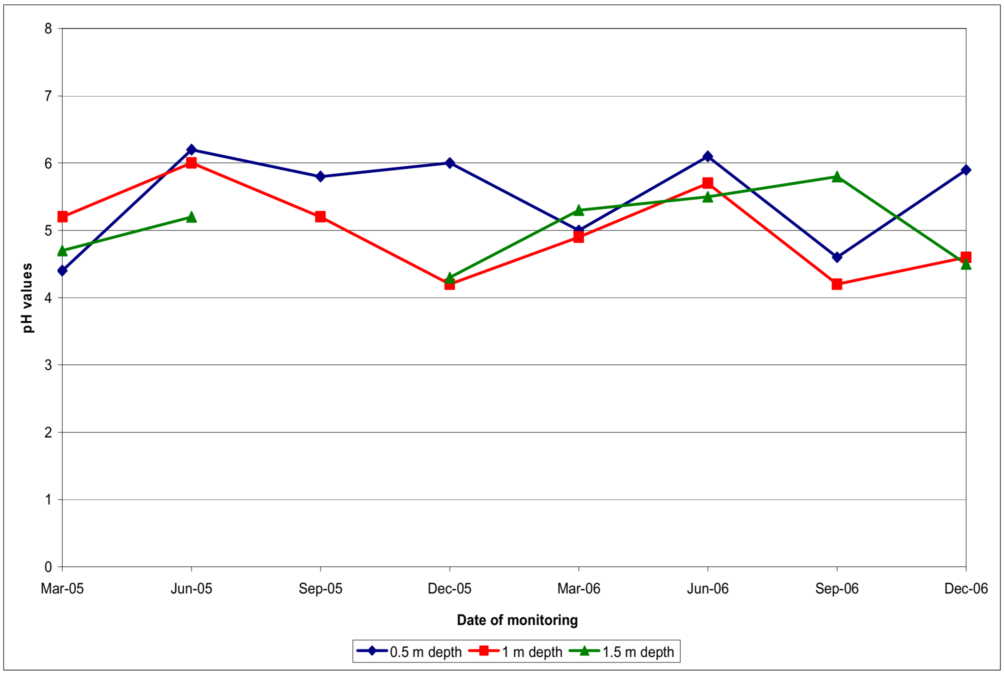

Figure 5.13: pH values of samples obtained adjacent to piezometer point 13 over the duration of monitoring.

5.4.3 *pH values adjacent to piezometer point 15*

Figure 5.14 highlights the pH values of the peat samples obtained adjacent to piezometer point 15 over the duration of the monitoring programme. The pH values obtained from the samples at 0.50 m and 1.00 m depths are slightly less acidic than the pH values obtained further down in the peat profile. This suggests that rainfall inputs into the superficial peats increases the neutrality of the sediment. At depth the low moisture content of the peat promotes slightly more acidic conditions.

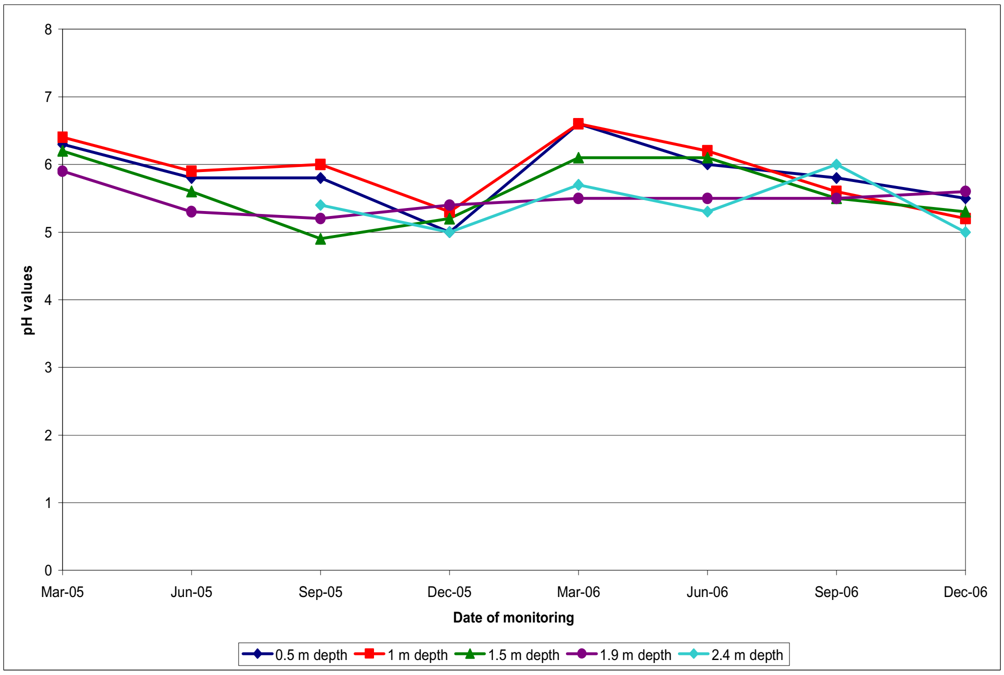

Figure 5.14: pH values of samples obtained adjacent to piezometer point 15 over the duration of monitoring.

The pH values of the peat samples at this location return to near neutral conditions during the summer months. However, during the winter months mildly acidic conditions prevail. This information reinforces the previous observation regarding the pH values adjacent to piezometer point 13, i.e. water recharges from the Slaynes Lane ditch, into its tributary ditches and consequently infiltrates the peat deposits during the summer months, which is making the peat more neutral.

5.4.4 *pH values adjacent to piezometer point 25*

Figure 5.15 shows the pH values of the peat samples obtained adjacent to piezometer point 25 over the duration of monitoring. The pH values obtained from the samples show some similarity to the values which were previously obtained adjacent to piezometer point 15. However, there is a greater separation of values between the superficial samples obtained at 0.50 m and 1.00 m depths (which are between pH 5 and pH 6) and those obtained from lower in the peat profile (which fluctuate between pH 4 and pH 5). Water recharge from the ditches surrounding the site may again be responsible for infiltrating the peat deposits during the summer months, consequently promoting more neutral conditions.

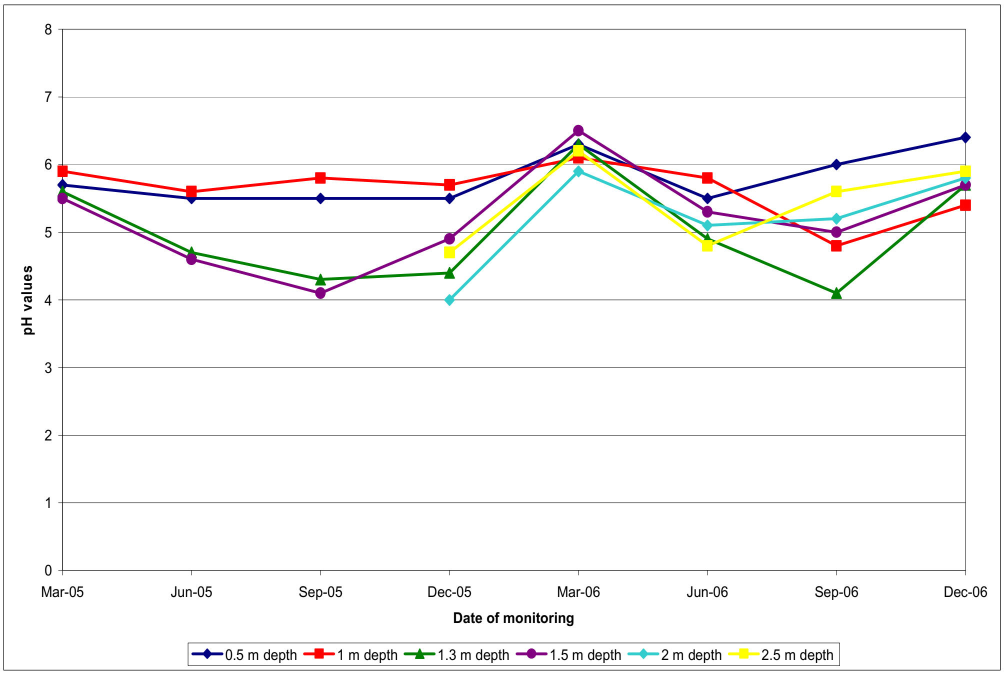

Figure 5.15: pH values of samples obtained adjacent to piezometer point 25 over the duration of monitoring.

5.5 Redox potential

At total of 14 redox clusters have been installed on site at Newington (Appendix 6, and below). Initial installation of clusters 1-10 was undertaken during February 2006; cluster 11 was installed in July 2006; and clusters 12-14 were installed in September 2006. The last three redox clusters were installed as part of a variation order commissioned by English Heritage. The primary aim of the variation order was to provide higher resolution data associated with the final phases of quarry extraction to the north of Slaynes Lane, and to assess the impacts of the anticipated recharge of water back into the floodplain peats when extraction ceases.

There are 13 redox clusters located to the south of Slaynes Lane, and 1 cluster located to the north of Slaynes Lane, in close proximity to Bawtry Road (see Figure 4.2 for the location of all redox clusters). The redox cluster near Bawtry Road (cluster 10) is situated in the superficial peaty topsoil and sand deposits close to the extraction area in order to produce baseline aerobic data to compare with the floodplain area. The data produced will help to determine the preservation status of the peat deposits and identify the oxidising-reducing nature of the environment.

The table below outlines the redox clusters and their association to adjacent piezometer points. All redox clusters were installed within *c*. 0.30 m of the piezometer points.

Table 5.1: Installation of redox clusters.

Redox cluster	Piezometer point
1	2
2	4
3	5
4	9
5	10
6	15
7	13
8	26
9	24
10	42
11	62
12	69
13	73
14	74

The results of 5 redox clusters will be discussed in this section, commencing with the basline information generated from cluster 10 (near Bawtry Road). The remaining clusters are representative of the oxidising-reducing nature of the peat deposits to the south of Slaynes Lane. The results from all the remaining clusters are tabulated and graphically shown in Appendix 6.

5.5.1 *Redox cluster 10*

Figures 5.16-5.18 present the adjusted redox values obtained from cluster 10 to the north of Slaynes Lane at 0.10 m, 0.50 m and 1.00 m depths, respectively. Due to the limited depth of the peat deposits in this location it was not possible to install the 2.00 m redox probes.

Throughout the duration of monitoring the redox potential values obtained from 0.10 m depth (Fig 5.16) fluctuate between +500 mV (which is indicative of oxidising conditions) and +200 mV (which indicates moderately reducing conditions). The standard classification used to define the redox status of soils has previously been outlined in Chapter 4 (section 4.2.2). It is suggested that these fluctuations may be associated with rainfall events, which increase the anaerobic nature of the peat by filling the voids within the peat matrix with water (through the processes of water flux and air diffusion). This is followed by the evaporation of water from the peat surface, which subsequently allows the addition of air into the void spaces left by the water.

The redox potential values obtained from 0.50 m and 1.00 m depth (Figures 5.17 and 5.18 respectively) show more stable patterns than the values obtained from 0.10 m depth. Redox values at 0.50 m depth indicate moderately reducing conditions (+200 mV), whilst values at 1.00 m depth are indicative of highly oxidising conditions (+400 mV). This situation suggests that the sandy clay deposits at 1.00 m depth are more oxidising than the deposits at 0.50 m depth, indicating that whilst water flux and air diffusion associated with rainfall inputs and evaporation is still evident at 0.50 m depth, the underlying sands do not mirror this trend, due to their lack of organic content. The sandy clays are consistent with their composition in terms of redox potentials at this location.

The stratigraphic profile of the redox potentials of the peat at this location indicates that the deposit is experiencing oxidising to moderately reducing conditions over the duration of the monitoring programme. At 1.00 m depth the underlying sands have void spaces which contain air, but are not filled by water, reflecting the general porosity of such deposits.

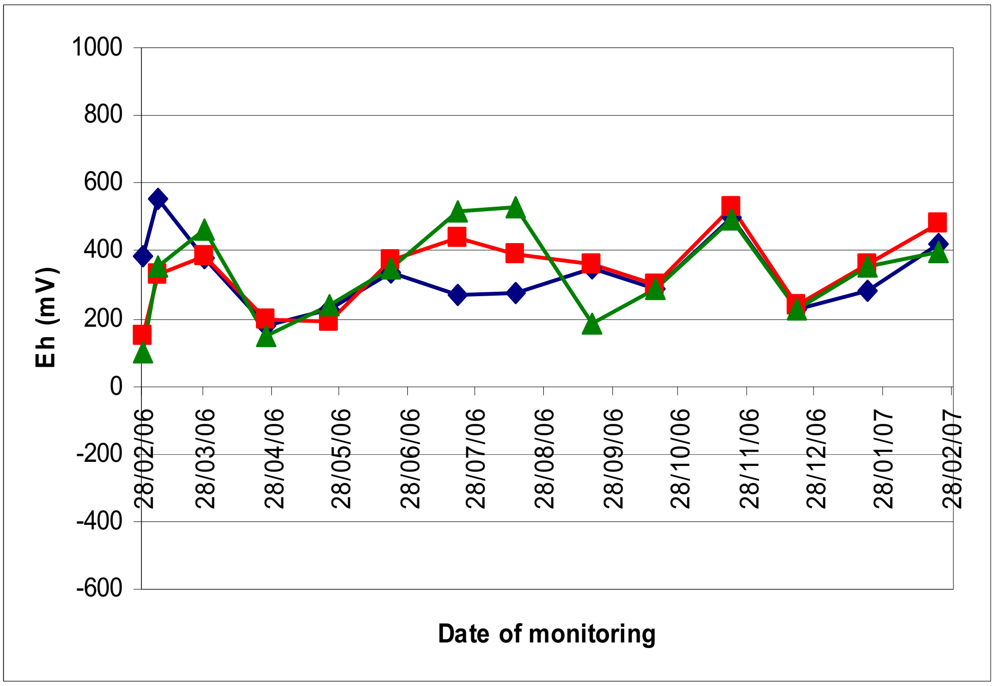

Figure 5.16: Adjusted redox potential values obtained from cluster 10 at 0.10 m depth over the duration of monitoring.

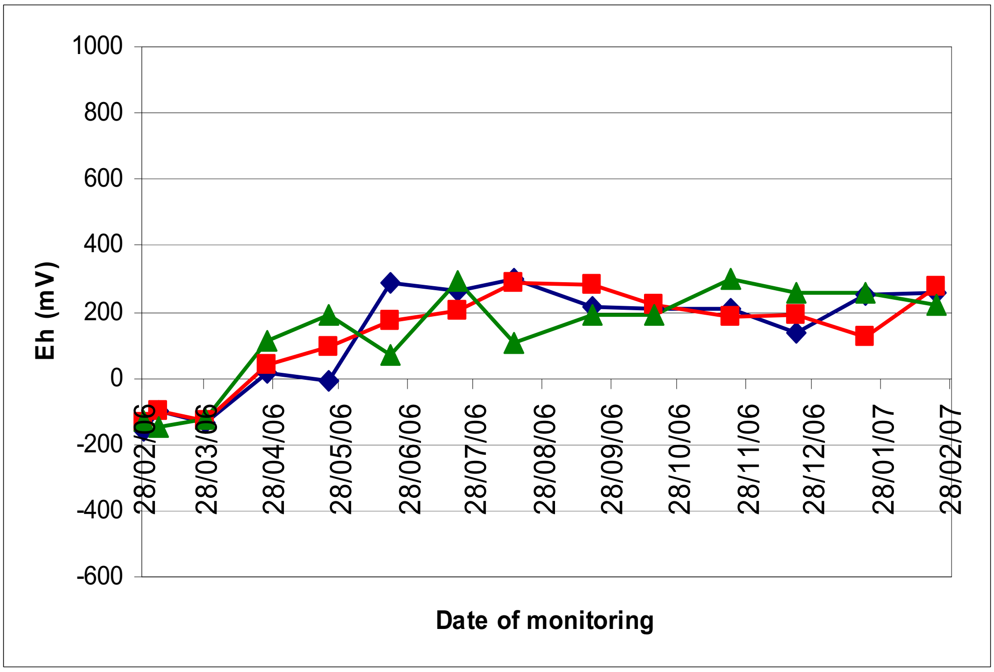

Figure 5.17: Adjusted redox potential values obtained from cluster 10 at 0.50 m depth over the duration of monitoring.

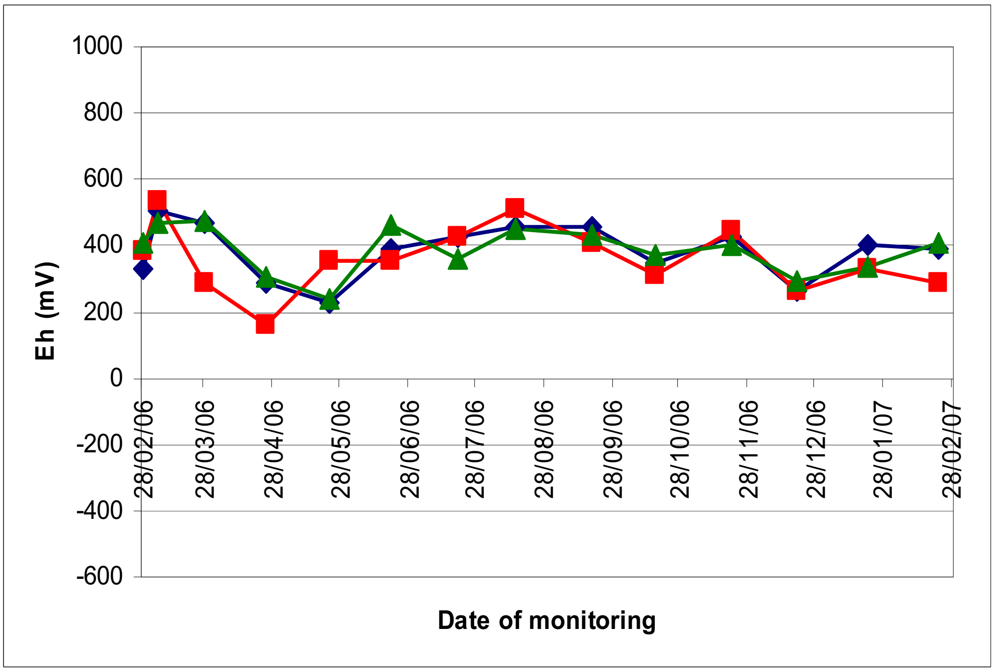

Figure 5.18: Adjusted redox potential values obtained from cluster 10 at 1.00 m depth over the duration of monitoring.

5.5.2 *Redox cluster 8*

Figures 5.19-5.22 represent the adjusted redox values obtained from cluster 8 (piezometer 26), at 0.10 m, 0.50 m, 1.00 m and 2.00 m depths, respectively. Cluster 8 is located in the south-eastern corner of the site, in the area where the deepest floodplain peat deposits are situated (Figure 4.2). The missing values for May 2006 in the four figures were associated with vandalism of the redox cluster and its associated piezometer point.

The majority of the redox values obtained at 0.10 m and 0.50 m depths (Figures 5.19 and 5.20 respectively) indicate the presence of oxidising to moderately reducing conditions. These values appear to be dependent upon the time of year. In the colder months (October to May), the majority of the redox values were between +200 mV to +300 mV, indicating the presence of moderately reduced conditions; whilst in the warmer summer months (June to September) redox values were generally between +400 mV to +600 mV, indicating the presence of oxidising conditions.

The seasonality shown at 0.50 m depth impacts upon the optimum reducing conditions necessary for the preservation of organic material, which is between –110 mV to –400 mV (Caple 1996), and implicates temperature in the process of preservation.

The increase in temperature associated with seasonal fluctuations is not as pronounced at 1.00 m and 2.00 m depths where the majority of the redox values are approximately +200 mV for the duration of the monitoring programme, indicating the presence of moderately reduced conditions. These values still indicate that even at 2.00 m depth the optimum reducing conditions necessary for the preservation of organic material are severely compromised (Caple 1996).

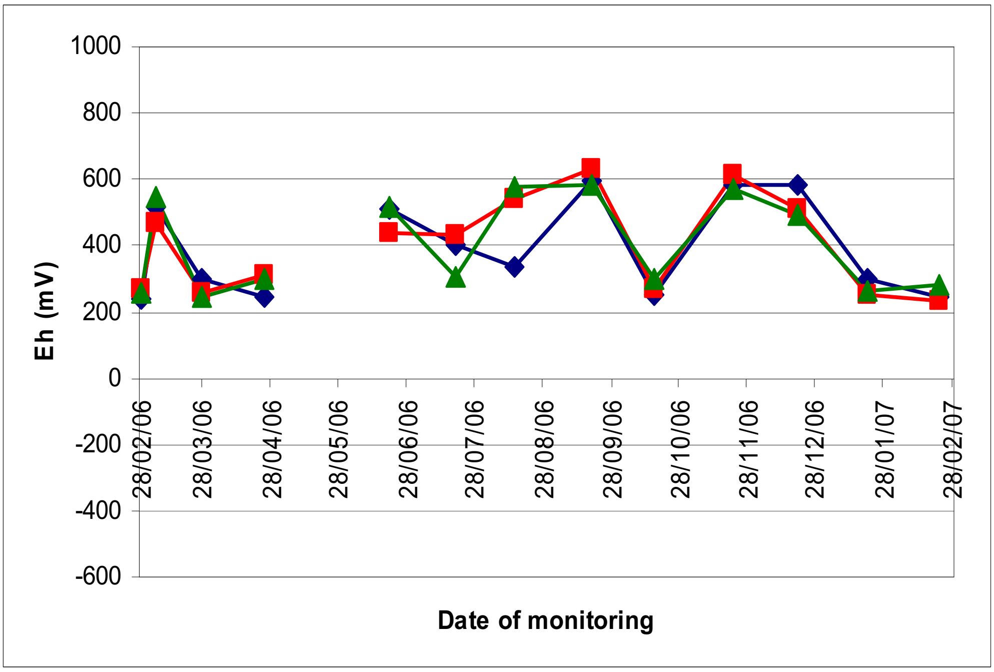

Figure 5.19: Adjusted redox potential values obtained from cluster 8 at 0.10 m depth over the duration of monitoring.

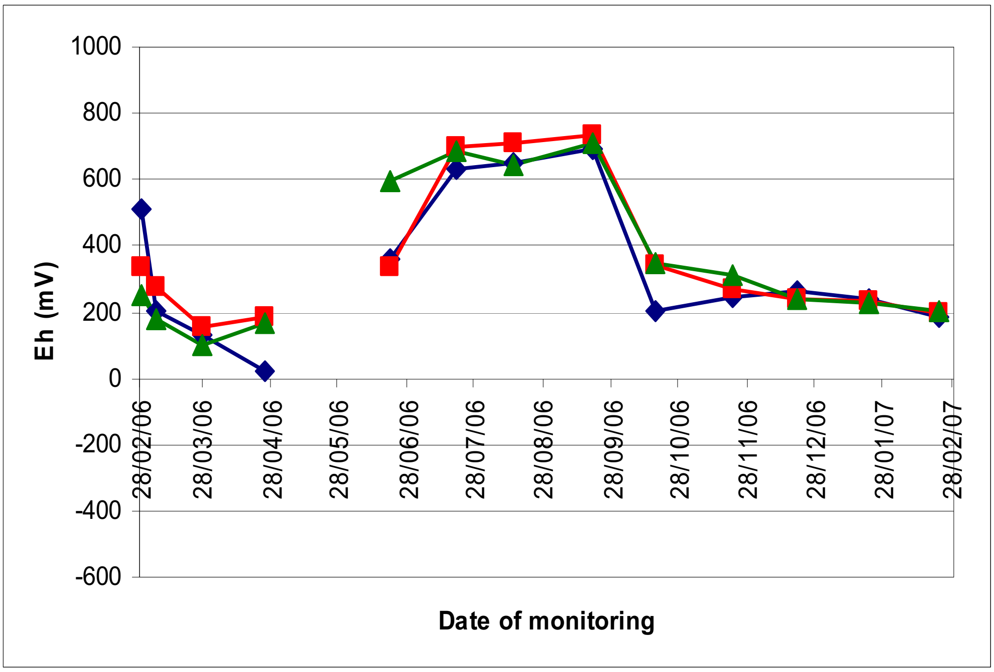

Figure 5.20: Adjusted redox potential values obtained from cluster 8 at 0.50 m depth over the duration of monitoring.

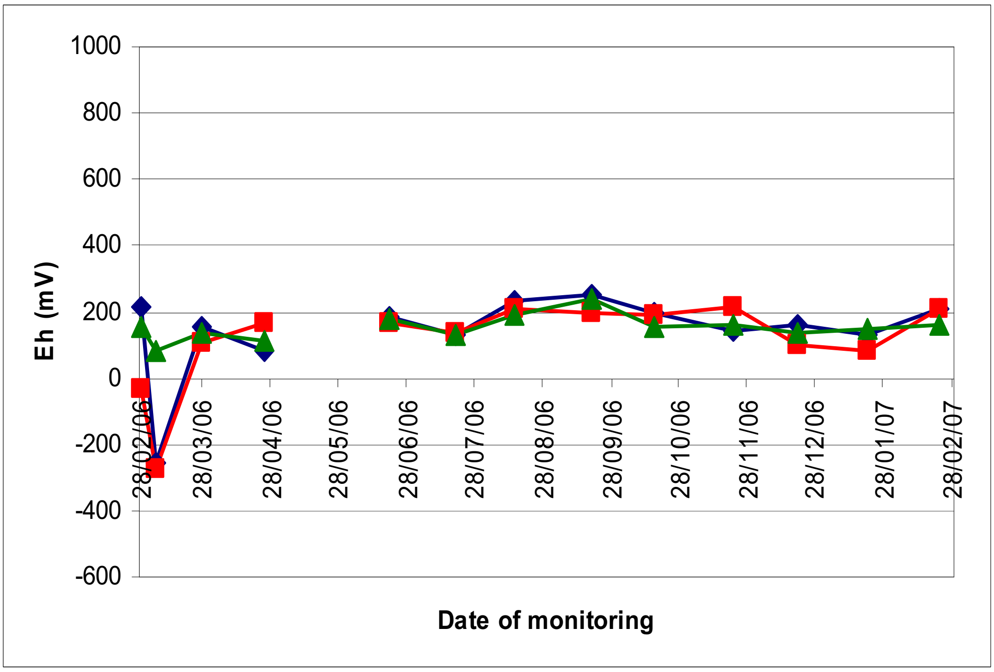

Figure 5.21: Adjusted redox potential values obtained from cluster 8 at 1.00 m depth over the duration of monitoring.

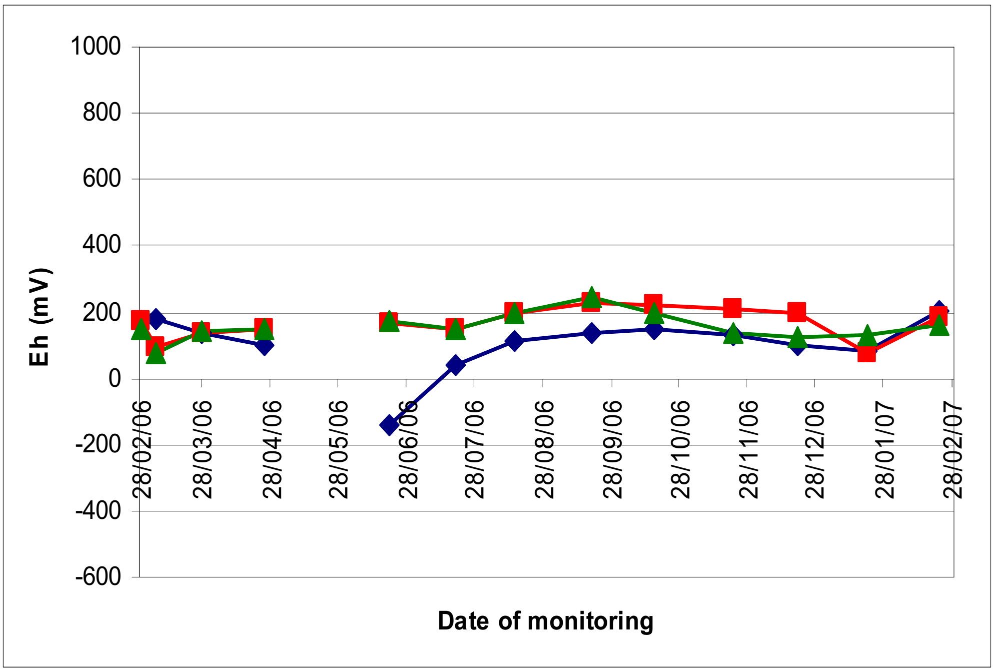

Figure 5.22: Adjusted redox potential values obtained from cluster 8 at 2.00 m depth over the duration of monitoring.

5.5.3 *Redox cluster 4*

Figures 5.23-5.26 represent the adjusted redox values obtained from cluster 4 (piezometer 9) at 0.10 m, 0.50 m, 1.00 m and 2.00 m depths, respectively. Cluster 4 is located in the south of the site (within the River Idle meander bend) in the area where the deepest floodplain peat deposits are situated (Figure 4.2).

Throughout the duration of monitoring the redox potential values obtained from 0.10 m depth (Figure 5.23) fluctuate between +600 mV (which is indicative of highly oxidising conditions) and +200 mV (which indicates moderately reducing conditions).

These results suggest that the fluctuations may be associated with rainfall events (i.e. water flux and air diffusion within the peat matrix). These rainfall events are followed by the evaporation of the water from the peat surface; and the subsequent addition of air into the void spaces left by the water.

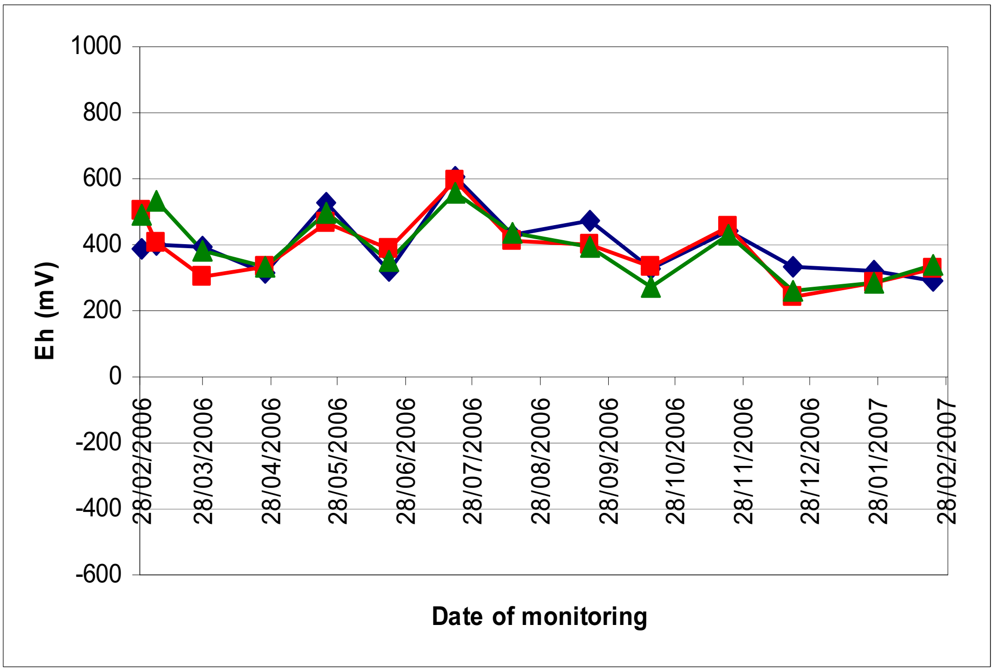

Figure 5.23: Adjusted redox potential values obtained from cluster 4 at 0.10 m depth over the duration of monitoring.

The majority of the redox potential values obtained from 0.50 m and 1.00 m depths (Figures 5.24 and 5.25 respectively) generally fluctuate seasonally. This is especially pertinent in the redox values at 1.00 m depth between June-October.

During the summer months redox values indicate highly oxidising conditions at both sampling depths (+600 mV); whilst in the winter months moderately reducing conditions prevail (+200 mV to +400 mV). These results indicate that even at a depth of 1.00 m seasonal fluctuations (in temperature and saturation) can still impact upon the preservation potential of the organic component of the floodplain peats.

The redox potential values obtained at 2.00 m depth (Figure 5.26) show great consistency through the duration of the monitoring programme; with the majority of the values between +300mV and +100 mV (indicating moderately reducing conditions). These results suggest that the void spaces between the sediment primarily contain air which promotes aerobic conditions in the peat deposits.

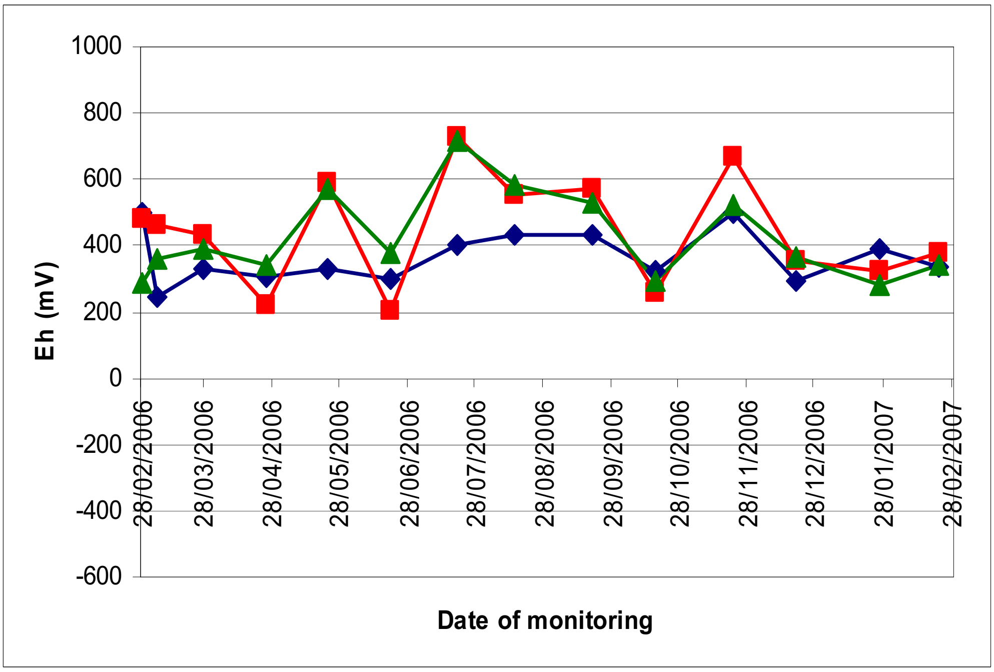

Figure 5.24: Adjusted redox potential values obtained from cluster 4 at 0.50 m depth over the duration of monitoring.

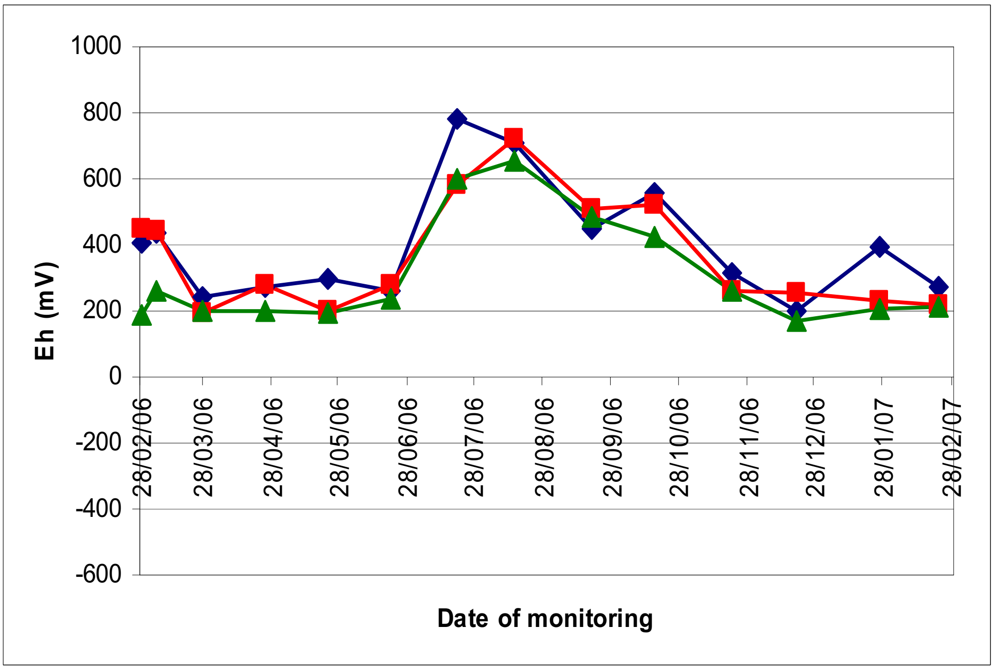

Figure 5.25: Adjusted redox potential values obtained from cluster 4 at 1.00 m depth over the duration of monitoring.

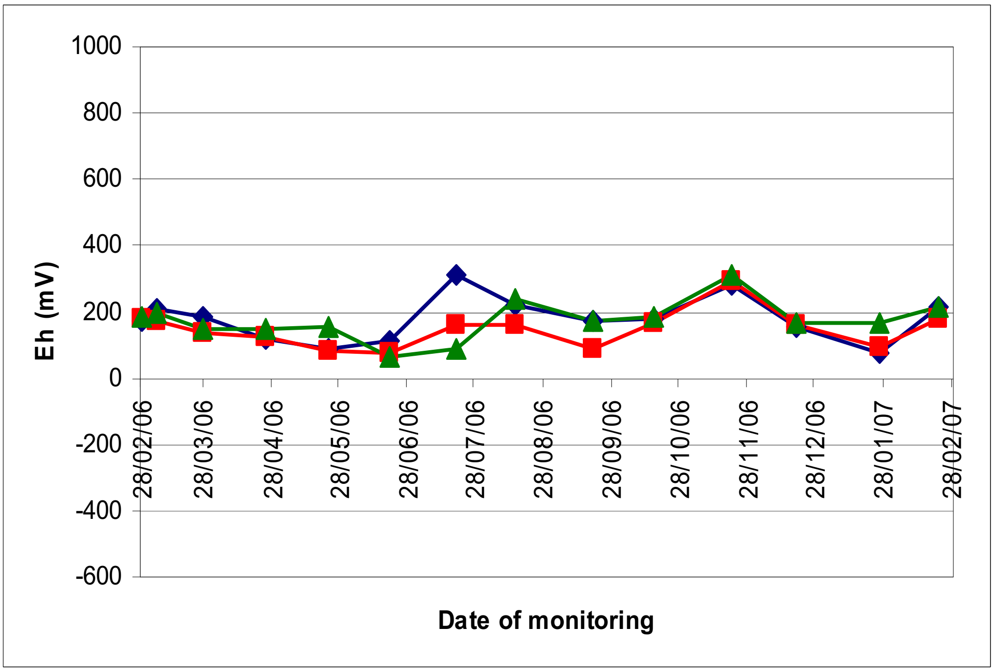

Figure 5.26: Adjusted redox potential values obtained from cluster 4 at 2.00 m depth over the duration of monitoring.

5.5.4 *Redox cluster 2*

Figures 5.27-5.30 represent the adjusted redox values obtained from cluster 2 (piezometer 4) at 0.10 m, 0.50 m, 1.00 m and 2.00 m depths, respectively. Cluster 2 is located in the south-west of the site in the area where deep floodplain peat deposits are situated (Figure 4.2).

Throughout the duration of monitoring the redox potential values obtained from 0.10 m, 0.50 m and 1.00 m depths (Figures 5.27-5.29 respectively) fluctuate between +600 mV (indicating highly oxidising conditions) and +200 mV (indicative of moderately reducing conditions). These results further substantiate the notion that the fluctuating readings may be associated with water flux and air diffusion within the peat matrix, from rainfall events.

The redox potential values obtained from 1.00 m depth indicate highly oxidising conditions (+600 mV) between April-July. This is in contrast to the majority of the redox values obtained in the other months surrounding this time period. Values during these latter periods are indicative of moderately reducing conditions (+400 mV to +200 mV). It is suggested that these values may be influenced by water flux into the peat deposits at this depth, either due to the periodic pumping of water into the Slaynes Lane ditch during quarry extraction, or to river seepage. High redox values may be associated with the influx of more oxygenated water into the peats across the period April-June 2006.

Figure 5.30 shows the 2.0 m redox potentials, which range from *c.* 0 to +300 mV, reflecting reduced to moderately reduced conditions. The higher winter redox potentials may reflect the input of oxygenated waters from river seepage, at depth, at this location. The redox potentials at 2.0 m depth mirror, albeit at more negative values, the situation occurring at 1.0 m depth. This would suggest that the cause of the April-June increase in redox potentials is resulting from the same process at both depths.

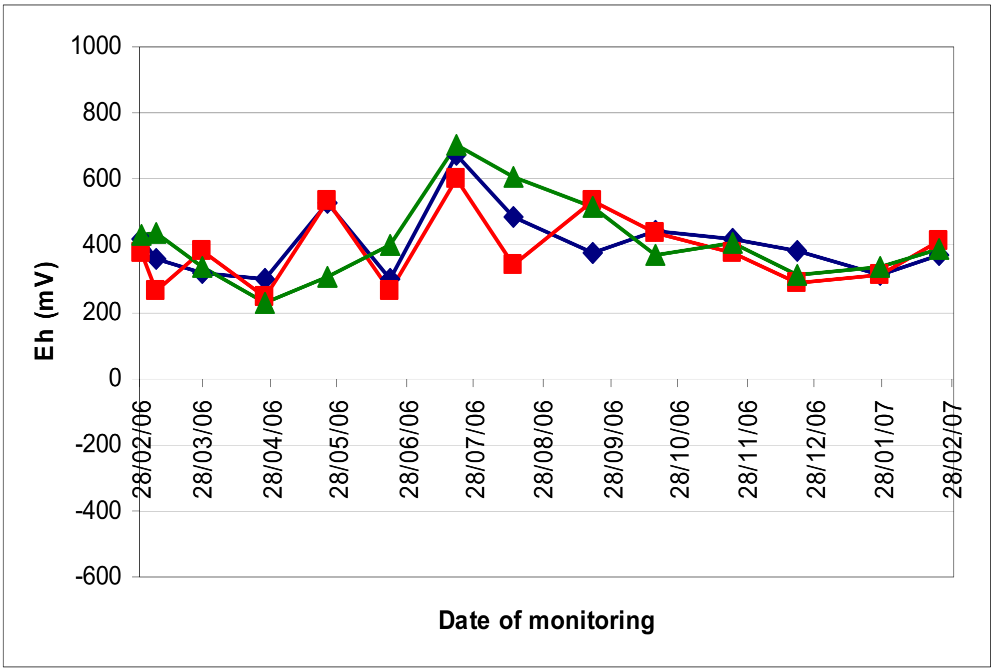

Figure 5.27: Adjusted redox potential values obtained from cluster 2 at 0.10 m depth over the duration of monitoring.

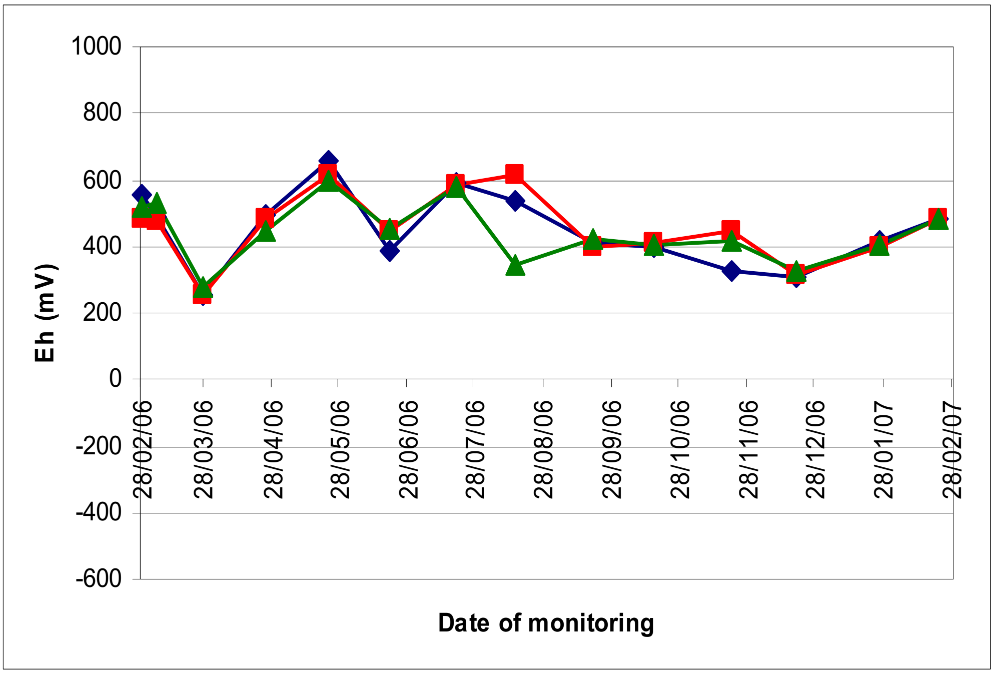

Figure 5.28: Adjusted redox potential values obtained from cluster 2 at 0.50 m depth over the duration of monitoring.

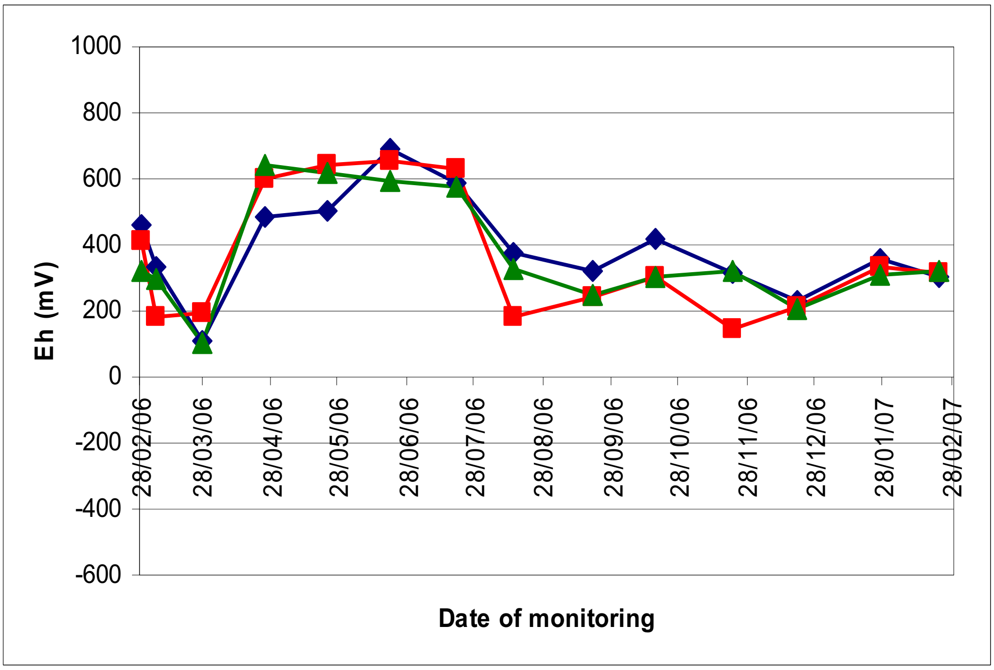

Figure 5.29: Adjusted redox potential values obtained from cluster 2 at 1.00 m depth over the duration of monitoring.

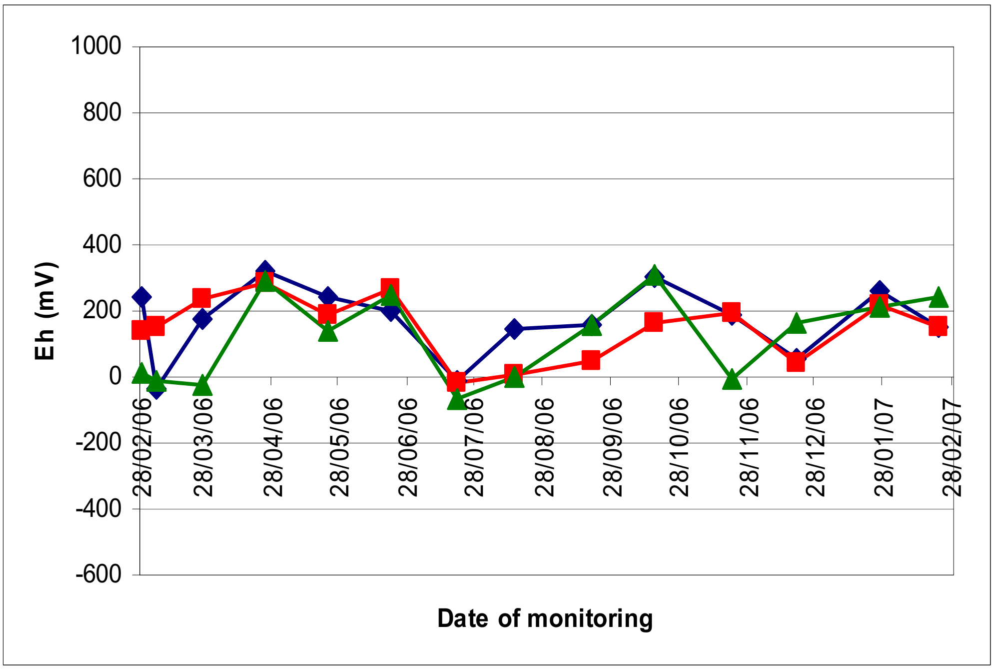

Figure 5.30: Adjusted redox potential values obtained from cluster 2 at 2.00 m depth over the duration of monitoring.

5.5.5 *Redox cluster 3*

Figures 5.31-5.34 represent the adjusted redox values obtained from cluster 3 (piezometer 5) at 0.10 m, 0.50 m, 1.00 m and 2.00 m depths, respectively. Cluster 3 is located to the south of Slaynes Lane, immediately adjacent to Slaynes Lane ditch (Figure 4.2).

Throughout the duration of monitoring the majority of the redox potential values obtained from 0.10 m depth (Figure 5.31) fluctuate between +600 mV (indicating highly oxidising conditions) and +200 mV (indicating moderately reducing conditions). These fluctuations may be associated with water flux and air diffusion within the peat matrix from rainfall events.

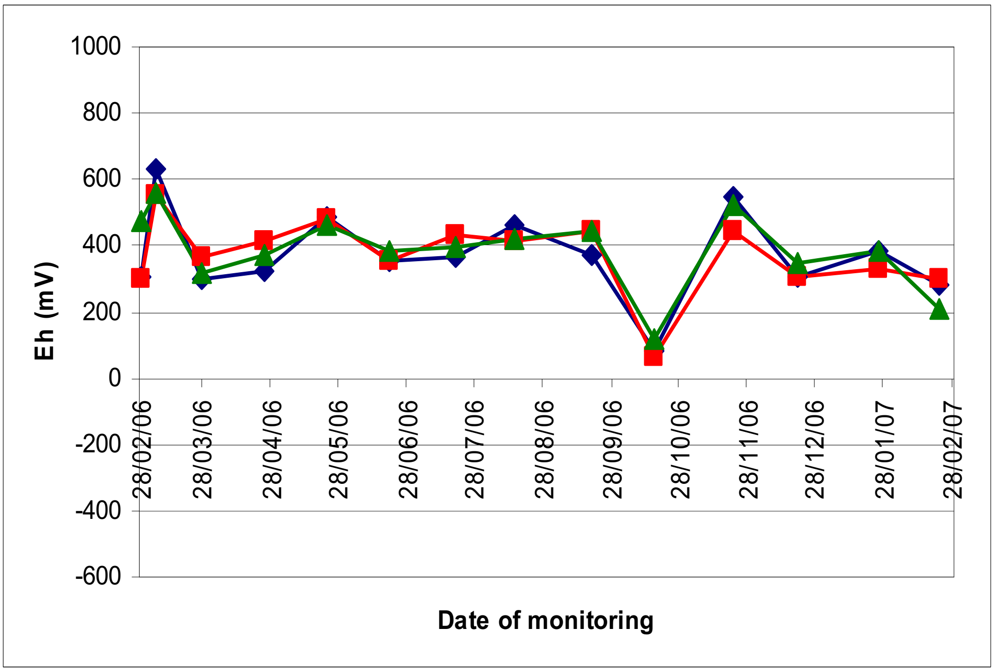

Figure 5.31: Adjusted redox potential values obtained from cluster 5 at 0.10 m depth over the duration of monitoring.

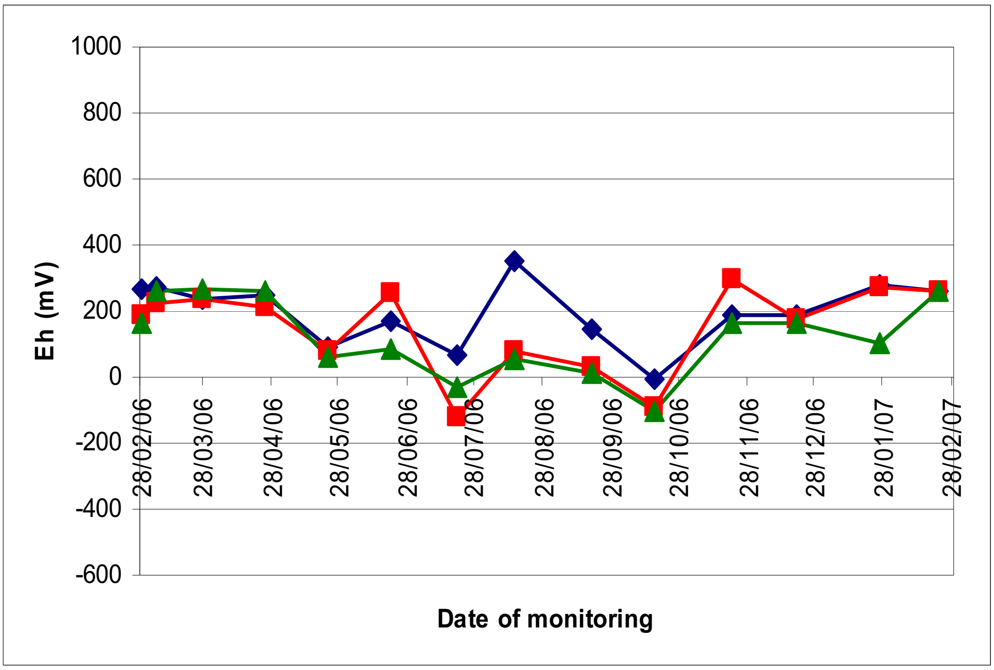

Figure 5.32: Adjusted redox potential values obtained from cluster 5 at 0.50 m depth over the duration of monitoring.

The redox potential values obtained at 0.50 m, 1.00 m and 2.00 m depths (Figures 5.32-5.34 respectively) fluctuate between +200 mV (which indicates moderately reducing conditions) and –100 mV (which is indicative of reducing conditions). The majority of the redox values at these depths display similar reducing conditions throughout the peat profile during July-October, with some variation down to -300 mV reflecting shifts to highly reducing conditions. These values are lower than those present at equivalent depths at other redox locations. In light of this information, it is suggested that the water which is being pumped from the extraction area into Slaynes Lane ditch is recharging the peat deposits which are adjacent to, and in close proximity to the ditch (as highlighted previously in Section 5.5.4). The increased reducing conditions will help promote the preservation of organic material (Caple 1996).

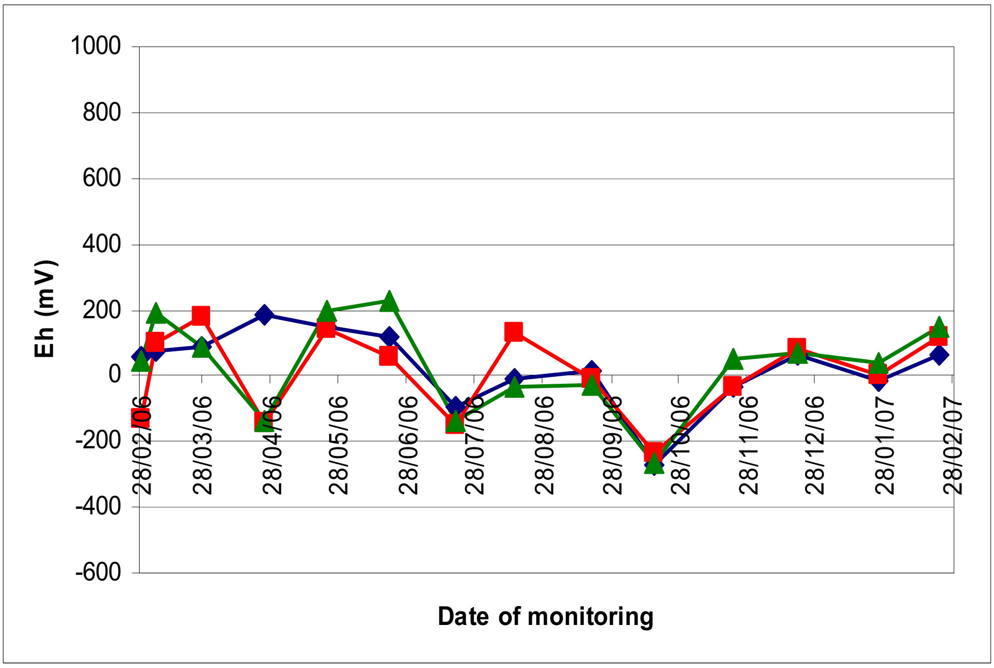

Figure 5.33: Adjusted redox potential values obtained from cluster 5 at 1.00 m depth over the duration of monitoring.

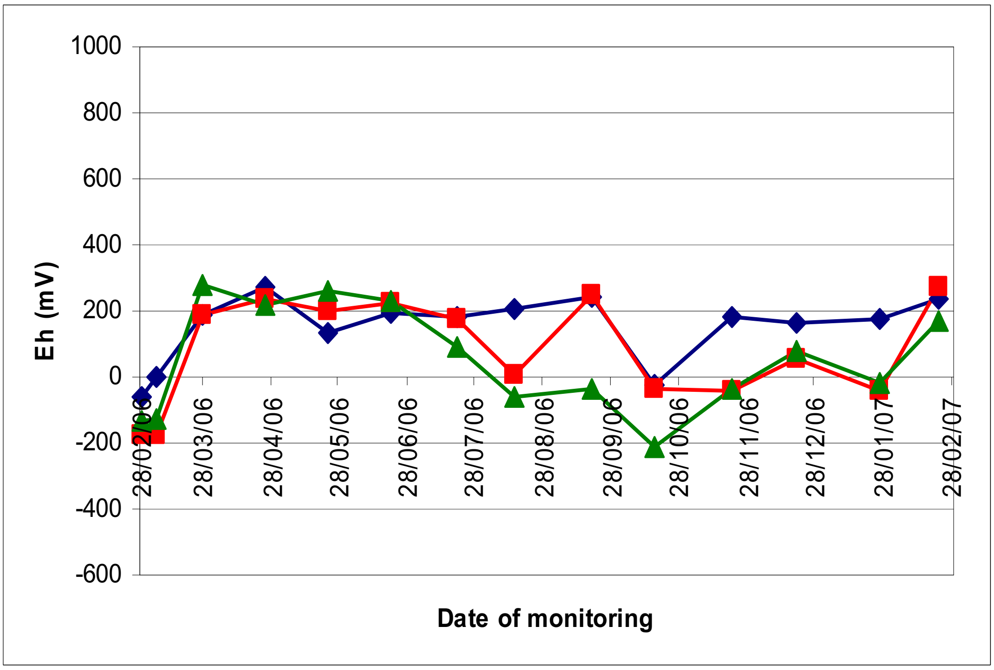

Figure 5.34: Adjusted redox potential values obtained from cluster 5 at 2.00 m depth over the duration of monitoring.

The redox clusters discussed above are considered to provide a representative sub-sample of the general picture of floodplain redox potentials as a whole (Appendix 6). The northernmost cluster (cluster 10) provides a control point against which the redox potentials in the floodplain peats can be assessed. This redox cluster suggests that saturation of the superficial peaty deposits (proven to 0.65 m depth) can result in moderately reducing conditions, probably after rainfall events (section 5.5.1), with the recorded fluctuations reflecting the periodic drying out of the superficial sequences (Figure 5.16). At 0.5 m depth (Figure 5.17) more stable conditions, which are more consistently moderately reducing, persist, but this trend is reversed at 1.0m depth, where the conditions are primarily oxidised and reflect the sandy nature of the substrate at this location.

The remaining redox clusters considered (clusters 8, 4, 2 and 3) all provide information on the anaerobic/aerobic conditions prevailing in the deeper floodplain peats to the south of Slaynes Lane. The first of these clusters (8), is located in the southeastern part of the floodplain, in an area that has been shown to exhibit fluctuating water levels (Figure 5.7-5.11). In general, saturation is associated with good conditions for *in situ* preservation (e.g. Caple 1996), with redox potentials indicative of highly reducing conditions (> -100 to -400 mV) providing the optimum burial environments for the survival of the organic part of the cultural resource (*cf*. Caple and Dungworth 1997). In light of this observation, it should be considered possible that the situation at point 8 could be compromised by the water levels recorded during the current monitoring programme.

What is immediately apparent from figures 5.19-5.22 is that the upper levels (0.10-0.50 m) reflect either oxidising or only moderately reducing conditions, and that seasonal variation is marked across the summer of 2006 at 0.5 m depth. The lower points (1.0 and 2.0 m depth) do not reflect seasonal variation, and are stable at *c*. +200 mV to *c*. 0 mV. Despite the stable conditions, the general trend of only moderately reducing conditions would suggest that even at depth, these sequences would be susceptible to reduced preservation potential given any further fluctuations in water tables.

Cluster 4 (Figures 5.23-5.5.26), again has indications of rainfall events influencing redox potentials (0.10 and 0.5 m depths), whilst the 1.0 m redox potentials again reflect seasonal trends, with summer temperatures influencing the sequences to this depth. The 2.0 m depth readings are slightly better than the 1.0 m readings, however, they are again only moderately reducing. The general pattern is not for excellent preservation conditions in the deeper floodplain sequences at Newington.

The general trends identified for redox clusters 8 and 4 are mirrored, with minor variations, in cluster 2, although oxidising conditions between April-July 2006 at both 1.0 and 2.0 m depths, could be indicating the input of oxygenated water into the peats at this depth. Interestingly, redox cluster 3, located adjacent to Slaynes Lane, appears, on the whole, to be more stable, and to be indicating better redox potentials for *in situ* preservation across the study period. This latter observation could be reflecting the consistent saturation of the deposits at this location as the Slaynes Lane ditch is kept re-charged with water from pumping and land drainage.

The overall impression obtained from the redox data is that, in general, the deeper floodplain peats do not have highly reducing environments indicative of continual saturation and good preservation environments. The areas where saturation is more permanent, i.e. adjacent to the Slaynes Lane ditch and the areas to the south-east of the floodplain are those areas where the redox potentials are slightly more positive in terms of *in situ* preservation potential. Seasonal variation is in evidence, and where this is occurring to *c*. 1.0 m depth, it suggests that in these areas the deposits are sufficiently dry and aerated to result in compromised burial conditions. Finally, there is some evidence for a trend towards better preservation environments with depth, particularly below 1.0 m, but this is dependent on saturation and location in the floodplain.

5.6 Palaeoenvironmental assessment

5.6.1 *Pollen analysis*

This section outlines the results of the analysis of pollen degradation in relation to four locations (1, 13, 15, 25 [Figure 4.2]). All sampling points are adjacent to piezometer monitoring points. Samples 1 and 13 are located on the northern side of the floodplain, close to the Slaynes Lane ditch. Samples 15 and 25 are located towards the southern side of the floodplain, in close proximity to the River Idle. This strategy is aimed at providing contrasting sequences of floodplain peat for comparative purposes. Table 1 (Appendix 13) shows the samples analysed and provide the key to the sampling codes that are used throughout the analysis.

5.6.2 *Spectra of pollen condition*

Figure 1 with 95 % confidence intervals shows variation among samples across the site, at different depths and from times of collection, but no strong relationships are apparent.

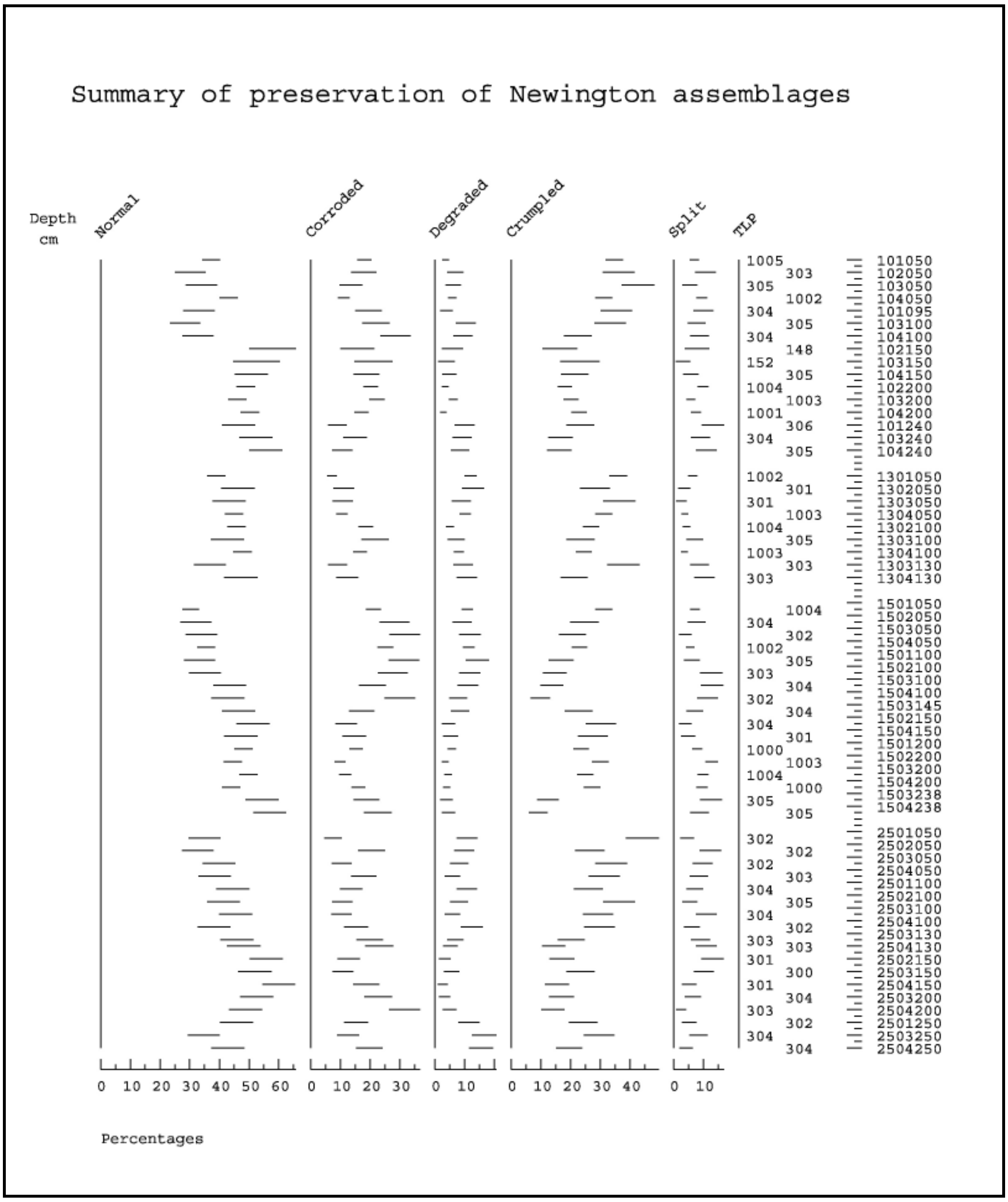

Figure 5.35: Variation among samples across the site, at different depths and from times of collection. Note: no strong relationships are apparent (95 % confidence intervals).

5.6.2.1 Sampling location 1

A total of 16 samples from depths of 0.5 m, 0.95 m, 1.0 m, 1.50 m, 2.00 m and 2.40 m were examined at this location. Counts of 1000 total land pollen (TLP), undertaken to increase the sensitivity of the analysis, were undertaken on sampling runs 1 and 4 at a depth of 0.50 m. Higher counts were carried out on these samples as it was considered that any increases in oxidation, resulting in higher levels of corroded and/or degraded pollen, occurring in response to any lowering in the water table, would be first detected in samples closest to the current ground surface. Enhanced counts of 1000 TLP were also undertaken on sampling runs 2-4 at a depth of 2.0 m. Overall pollen preservation was considered to be poor with normal pollen forming between 28 % and 56 % of the TLP. Pollen which was either crumpled or split and showed signs of mechanical damage as a result of stress during physical transport and/or compaction of grains within sediments following deposition formed between 16 % and 36 % (crumpled) and 2 % and 13 % (split) of TLP. Pollen which was chemically damaged, corroded as a result of biological activity or chemical oxidation, or degraded as a result of chemical oxidation within the aerial or sub aerial environment formed between 9 % and 28 % (corroded) and 3 % and 9 % (degraded) TLP.

5.6.2.2 Sampling location 13

A total of 9 samples from depths of 0.50 m, 1.00 m and 1.30 m were examined at this location. Counts of 1000 TLP were undertaken on sampling runs 1 and 4 at a depth of 0.50 m and on sampling runs 2 and 4 at a depth of 1.00 m. Overall pollen preservation was considered to be poor with normal pollen forming between 36 % and 48 % TLP. Mechanically damaged pollen formed between 7 % and 18 % (crumpled) and 5 % and 12 % (split) TLP, whilst chemically damaged pollen formed between 20 % and 37 % (corroded) and 2 % and 8 % (degraded) TLP.

5.6.2.3 Sampling location 15

A total of 17 samples from depths of 0.50 m, 1.00 m, 1.45 m, 1.50 m, 2.00 m and 2.38 m were examined at this location. Counts of 1000 TLP were undertaken on sampling runs 1 and 4 at a depth of 0.50 m and runs 1–4 at a depth of 2.00 m. Overall pollen preservation was considered to be poor with normal pollen forming between 30 % and 57 % TLP. Mechanically damaged pollen formed between 10 % and 28 % (crumpled) and 4 % and 11 % (split) TLP, whilst chemically damaged pollen formed between 8 % and 30 % (corroded) and 3 % and 13 % (degraded) TLP.

5.6.2.4 Sampling location 23

A total of 18 samples from depths of 0.50 m, 1.00 m, 1.30 m, 1.50 m, 2.00 m and 2.50 m were examined at this location. Overall pollen preservation was considered to be poor with normal pollen forming between 32 % and 60 % TLP. Mechanically damaged pollen formed between 7 % and 31 % (crumpled) and 3 % and 16 % (split) TLP, whilst chemically damaged pollen formed between 14 % and 44 % (corroded) and 4 % and 13 % (degraded) TLP.

Statistical analysis (presented below), has indicated that, whilst variations are recorded among samples across the site, both at different depths and in relation to the time of collection, no strong patterns emerge from either the standard or enhanced counts undertaken.

5.6.3 *Squared-chord distance similarity measures*

The similarity matrix is presented in Figure 5.36 (below). This matrix shows that all of the samples studied have a high level of similarity, with all of the samples falling below the 0.25 threshold identified by Wahl (2004). This level of similarity is considered to reflect the presence of all categories of preservation in all samples. However, no strong patterns are reflected within the plot.

5.6.4 *Principal component analysis*

Figure 5.36 shows the eigenvectors from the principle component analysis. The position of the split and degraded categories close to the origin indicate that they are

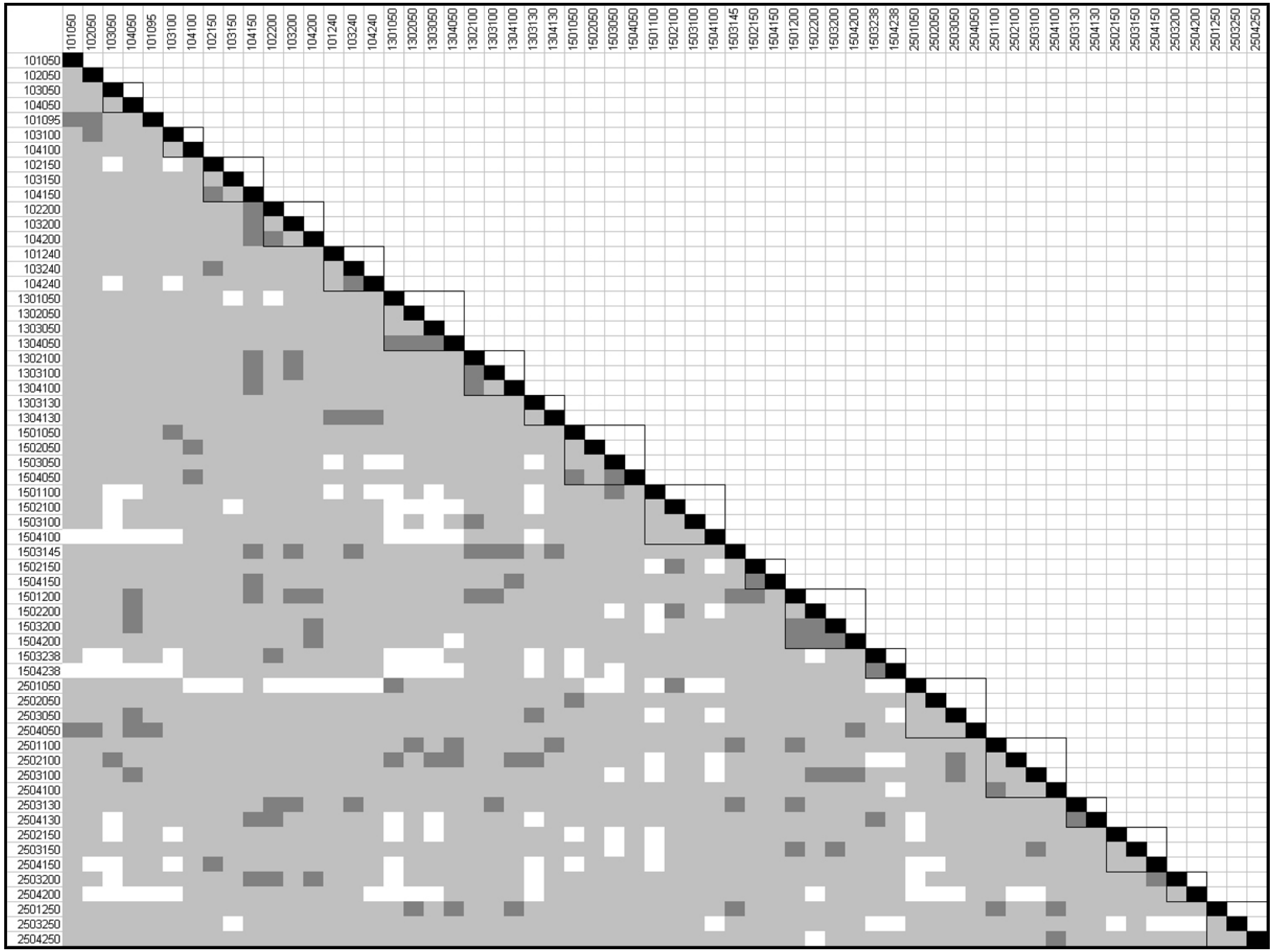

Figure 5.36: Squared-chord distance similarity matrix for Newington pollen samples.

not significant in distinguishing samples. Normal, corroded and crumpled categories are each found in different quadrants at similar distances from the origin. The arrangement of samples along axis one (eigenvalue = 0.551) is largely driven by a separation of crumpled from normal and corroded. Axis 2 (eigenvalue = 0.327) then separates the corroded and normal grains.

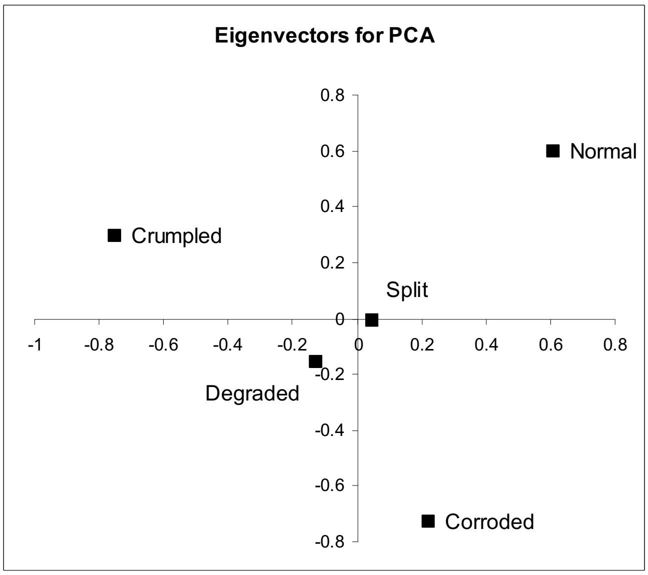

Figure 5.37: Eigenvectors from principle component analysis.

Figure 5.38, shows sorting by site. The samples show a substantial degree of overlap; however, it is noted that samples from site 13 all score above 0.2 on axis 2 suggesting that corrosion is somewhat less common in assemblages from that location.

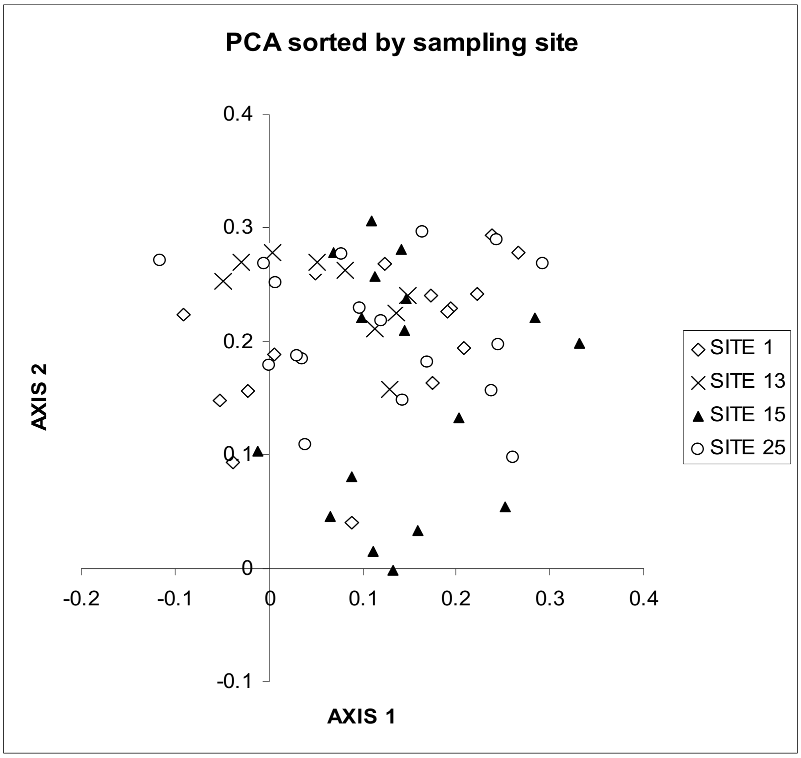

Figure 5.38: Principle component analysis sorted by site.

Figure 5.39 shows sorting by collection run. The lack of clustering suggests that there are no strong patterns over time. In order to more fully assess this observation, Figure 5.40 (below) links runs of 3 or 4 samples from the same location and depth. If there was a trend over time within the data, it would be anticipated that the lines would be roughly aligned along the direction of the trend. However, as can be seen in Figure 5.40, no directional trend is observed. The samples from site 15 at depths of 1.0 m and 0.5 m are closer to the *x*-axis than other sets, suggesting that more corrosion (oxidative damage) has occurred in this location than elsewhere in the site. However, no clear trend over time is seen.

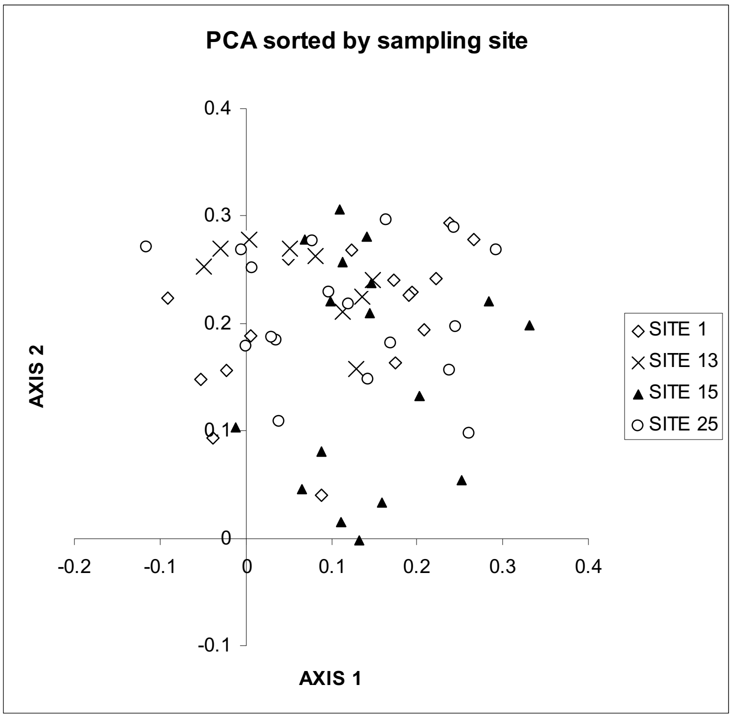

Figure 5.39: Principle component analysis sorted by sampling site.

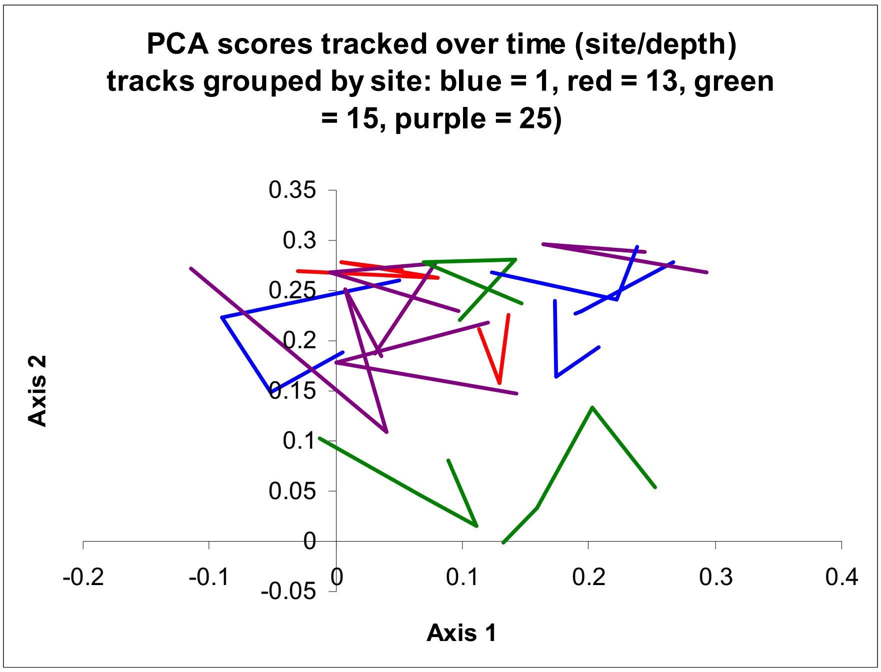

Figure 5.40: Principle component analysis scores tracked over time.

The analyses presented above indicate that, whilst variations are recorded among samples across the site, at different depths and from different times of collection, no strong patterns emerge from either the standard or enhanced counts. It is suggested that the preservation status of the pollen at Newington reflects past depositional conditions and that there have been no significant changes in the levels of damaged pollen over the course of this 18-month study.

5.6.5 *Pollen concentration data and indeterminate grains*

Data relating to pollen concentrations and levels of indeterminable grains is presented in Table 2 (Appendix 13). Figures 5.41-5.44 (below) present an analysis of concentration data in relation to the collection runs, (Figure 5.41), sampling locations (Figure 5.2), sampling depths (Figure 5.43) and sampling depths against sampling locations (Figure 5.44).

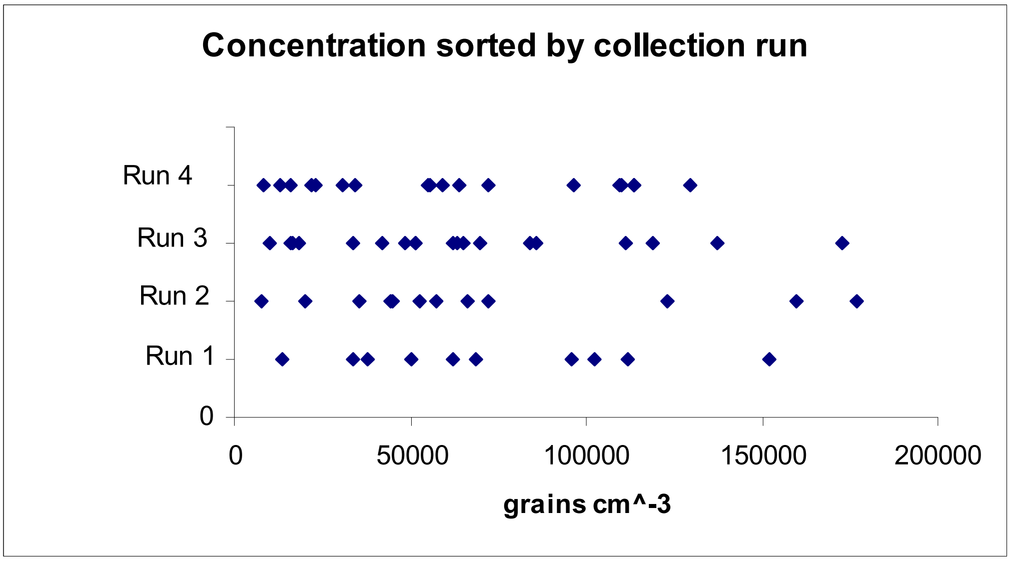

Figure 5.41: Concentration sorted by collection run.

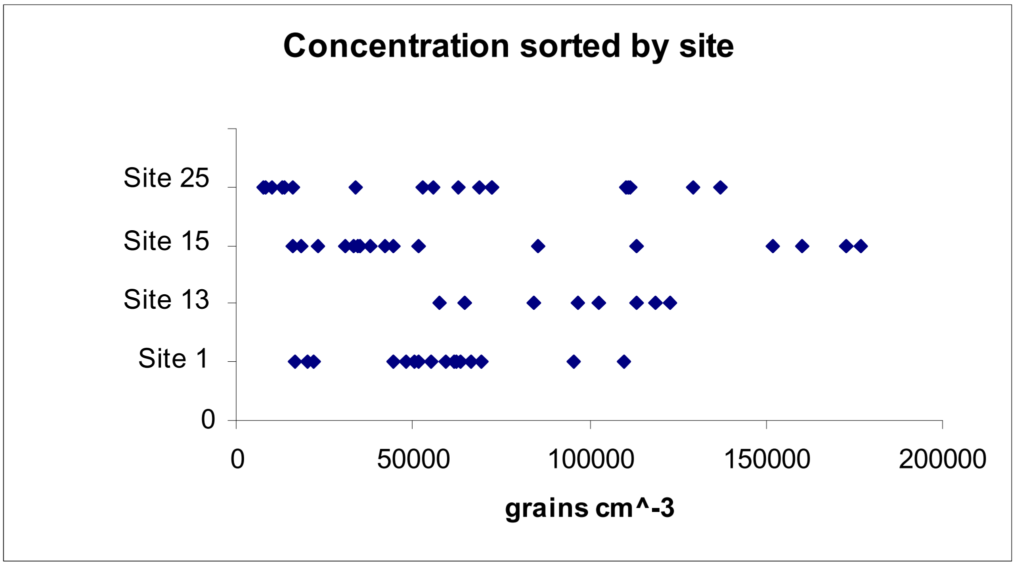

Figure 5.42: Concentration sorted by sampling locations.

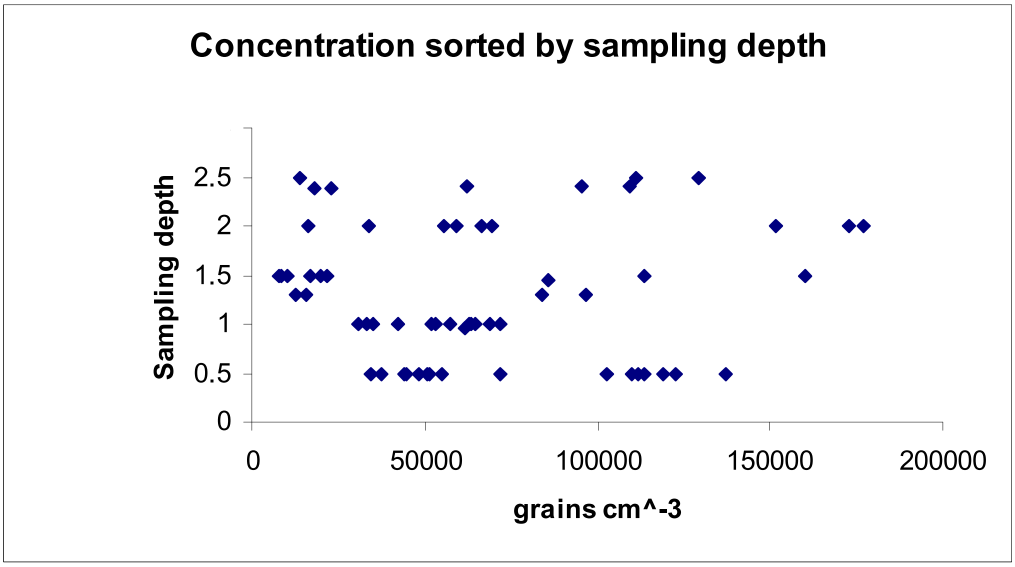

Figure 5.43: Concentration sorted by sampling depths.

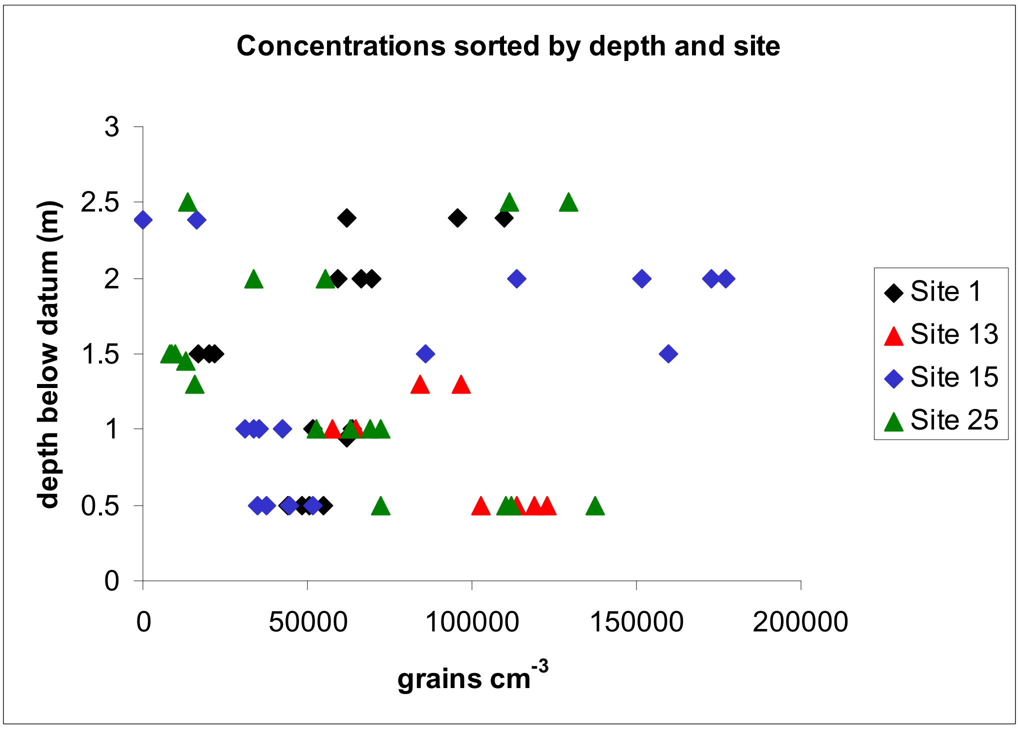

Figure 5.44: Concentration sorted by sampling depths against location.

In terms of pollen concentrations, the lowest concentration of 7974 grains/cm³ was recorded from a depth of 1.50 m at sampling location 25, and the highest of 177000 grains/cm³ was recorded from a depth of 2.00 m at sampling location 15. In general however, whilst the samples from Newington contain a broad range of pollen concentrations, no clear meaningful patterns can be identified.

In relation to the levels of indeterminate grains, these range from a low of 6 % TLP recorded at a depth of 0.50 m at sampling location 25 to a high of 28 % TLP recorded at a depth of 2.50 m at sampling location 25. It has been suggested by Hall (1981: 205) that 'high frequencies of deteriorated or indeterminable pollen grains and low total pollen concentrations in a single stratigraphic interval are strong clues suggesting that partial destruction and alteration of the pollen assemblage have occurred'.

Tipping *et al*. (1994) and Bunting & Tipping (2000) have suggested a range of criteria and thresholds that should be used to determine if a pollen sample is of an acceptable standard for analysis. They have proposed that levels of indeterminable grains of over 45 % TLP (Tipping *et al*. 1994) and 30 TLP (Bunting & Tipping, 2000) should be considered as a reason to reject a sample for analysis. They also proposed the rejection of assemblages containing <3000 grains/cm³, as this can be indicative of post-depositional biasing and the rejection of samples containing a high percentage (> 35 % TLP) of severely deteriorated (degraded) pollen grains, as high numbers of these grains indicate that the assemblage has 'been distorted by either differential pollen preservation or by mixing with older material' (Bunting & Tipping, 2001: 494).

Pollen concentration values and levels recorded for indeterminable and degraded pollen grains for the samples at Newington fall within acceptable levels and 'pass' on the basis of these criteria. However, it is noted that levels of indeterminable grains are generally high; and that in 21 out of the 60 samples examined indeterminate grains reach levels of equal to or greater than 20 % TLP, reflecting the generally poor preservation status of the pollen assemblages at these four sampling locations.

On the basis of the analysis undertaken during the 18-month study of pollen preservation at Newington, it appears that variations in the pollen concentrations at different depths at individual sampling locations and across the site as a whole are reflecting differences in the depositional environment in which the pollen was originally deposited. There is no evidence to indicate that pollen concentrations have dropped, or that levels of indeterminate and degraded pollen grains have increased over the course of the project.

The analyses presented above, indicates that although variations are recorded among samples across the site, at different depths and from times of collection, no distinct patterns have emerged. It is considered that the preservation status of the pollen at Newington reflects past depositional conditions and that there have been no significant changes in the levels of damaged pollen over the course of this study. However, in general the pollen is poorly preserved, and whilst no strong patterns were observed in the data, location 13 appears to have less corrosion of pollen grains in evidence, and location 15 (at 0.5 m and 1.0 m depths) exhibits greater levels of corrosion than elsewhere on the site. The lack of evidence for degradation during this study may simply reflect the limited duration of the analysis, and in general, the data produced forms a baseline, against which any future investigation can be compared and contrasted.

5.7 Summary

The results which have been outlined above have identified a number of issues that need to be discussed in relation to the extraction of aggregates from Newington quarry and the potential ramifications that this process has upon the preservation potential of the floodplain peat sequences to the south of Slaynes Lane. The next chapter (6) will discuss the main findings which have been identified during the results in order to answer the aims and objectives of the project (as previously identified in Chapter 3).

6. Discussion

6.1 Introduction

The interim results of this monitoring project have been presented to colleagues at a number of venues, including the PARIS 3 conference in Amsterdam (7th-9th December 2006), the World Wetlands Day conference in London (31st January - 1st February 2007), and the WiP meeting held at the English Heritage offices in York (16th February 2007). The PARIS 3 conference proceedings will see the first publication of the results of the project. These outputs form the first stage in the dissemination of the project results (EoP98: Primary goal D; 16.2, and 16.12).

This report has presented the analysis of floodplain hydrology, physico-chemical and biological parameters relating to *in situ* preservation in an organic floodplain environment. The aims of the project revolve around the assessment of the impacts of aggregates extraction on wetland environments, and the identification of any impacts associated with extraction activities (*cf*. French *et al*. 1999, French 2004).

The rationale of the project was based on the observation that de-watering is detrimental to the waterlogged heritage component of wetlands (Welch and Thomas 1996), and that, to date, work of generally limited duration and scope has been undertaken (Corfield *et al*. 1996, French *et al*. 1999, Lillie 2007, Smit *et al*. 2006, Heeringen *et al*. 2004). Of particular significance to these studies is the observation that the identification of catchment-wide hydrological parameters is fundamental to the generation of an holistic understanding of the hydrological processes that will impact on the site being studied. Without this baseline data, any attempts at *in situ* preservation are fundamentally flawed (*cf*. Lillie 2007:170).

The Newington extraction site provides an ideal location for the resolution of key limitations relating to waterlogged floodplain sequences and the lack of understanding of the impacts upon these from aggregates extraction processes. Leake (2000) has noted that water abstraction regimes in the Newington area have created a degree of flux in the groundwater regimes, and consequently any removal of aggregates adjacent to the deeper floodplain sequences could have the potential to exacerbate an already compromised hydrological context.

Of some significance in this study, is the observation that the area has two SSSI's in the immediate vicinity located to the south-east of the extraction area (Slaynes Lane washland), with a much larger SSSI (River Idle washland) running from Bawtry Bridge along the north side of the river up to the south-western corner of the extraction area. Given the recent Natural England targets for 2010, that 95 % of SSSI land needs to be in 'favourable' or 'recovering' condition (English Nature 2007), the observations presented in Section 5.3 are of considerable significance. In light of these observations in relation to the floodplain hydrology (Section 5.3), the Slaynes Lane SSSI clearly represents a site that will be in the remaining 5 %, i.e. not in 'favourable' or 'recovering' condition, and it should be anticipated that this location could be unsustainable in the longer term if current water abstraction rates continue.

The discussion below will outline the key observations of the results obtained to date (Chapter 5), and will relate these to the aims and objectives of the research as outlined above (Chapter 3). For continuity, the format of this discussion will follow the results section where possible, and will outline the hydrology, physico-chemical, and biological aspects of the study, and consider these in relation to the main research aims, and also to the research priorities as outlined in Exploring our Past 1998 (EoP98 - Williams 2003).

6.2 Geo-hydrological modeling

6.2.1 The catchment modeling (Section 5.2) has highlighted a number of significant factors relating to the groundwater table and the floodplain environments at Newington

(EoP98 Primary goal A: 1.7, 1.8, 2.3, 2.4, 2.6, Primary goal B: 5.2, 5.4, 7.3, Primary goal D; 14.2, Primary goal E: 17.1, 17.8, 17.9, 17.11). In particular, the geo-hydrological, catchment modeling, has shown that despite a number of limitations in the modeling programme (Section 4.2.5), after the development of a conceptual model, the ModFlow simulations have produced a model of sufficient resolution to suggest that water abstraction is having the biggest influence on groundwater in the catchment (Aim 5). This is due to the fact that in the modelled area, licensed abstractions for the purpose of general farming and domestic use range from 9,955,740 m^3/year at the Austerfield and Highfield Lane PWS, to 1,137 m^3/year at Lovershall Farm, and that the eight public water supplies within the model domain and abstraction of process water at Harworth Colliery constitute the largest abstractions in the model, with other abstractions licensed to remove >300,000 m^3/year being generally for the purpose of mineral washing associated with sand and gravel extraction. As the hydrogeological setting of the Sherwood Sandstone–Pleistocene drift system in the model domain is a complex, lithologically variable aquifer system, in which groundwater resources have been heavily exploited for use by industry and for public supply, when modelled, the aquifer thickness, which is affected by each abstraction or supply borehole, is limited to the depth of the well in question (Aims 1, 2 and 5; Page 24).

The numerical model, as developed, considers a two layer system in which the Sherwood Sandstone is overlain by sand and gravel drift deposits. The limits of the model domain are shown in Figure 4.7 (above), and a detailed summary of all aspects of the model development is presented in Chapter 4 (Section 4.2.5). The calibrated model (Appendix 5) has shown that primary parameters affected in the calibration process were recharge, hydraulic conductivity, riverbed conductance and inflow through the western boundary.

6.2.2 The main observation drawn from the modeling are that, H6 (Hanson borehole), which is located immediately to the south of the extraction area, has indicated that limited drawdown occurs in and around the area of aggregates extraction (Appendix 14). The overall effect of quarry de-watering is demonstrated in the particle paths which are seen at approximately 200 m away from the quarry (Section 5.2.1). However, the comparative plot (Appendix 8) has demonstrated that, overall, water abstractions in this catchment are influencing both the quarry and abstraction particle paths over a significantly wider area during the model simulation. Despite this, the results suggest that quarry de-watering at Newington is not having a significant effect on the groundwater levels in this area, and that *contra* French (2004:1), no significant 'halo' effect or marked (and sustained) lowering of the water table has resulted from the extraction of aggregates in this catchment. In fact, the main cause of lowered groundwater tables in the vicinity of Newington occurs as a direct result of water abstraction in the catchment.

A separate water table is identified within the floodplain peats at Newington. The shallow water table data (discussed below) does not show any significant influence from the quarrying activities in the immediate area of the extractions. It is noted that, whilst ModFlow has proven useful in providing a generic overview of the catchment-wide hydrological parameters in this region, the numerous limitations inherent in the modeling, the setting of the parameters, and the resolution of the models generated, effectively makes this area of the study useful as a heuristic tool for understanding the site context, but it is limited in relation to the specific hydrological conditions relating to the extraction site and the immediate area around this. It also provides the basis for the higher resolution study of the floodplain hydrology provided by the seventy-four piezometer monitoring points located at Newington (discussed below).

6.2.3 In effect, the work of Leake (2000:23) reinforces the above observations, and confirms that the groundwater table at Newington is at *c*. 1 m OD in the vicinity of the floodplain at Newington, and falls away to the north-west, towards the Austerfield PWS. This situation mirrors that indicated by the current modeling (Figure 4.9). In addition, the available borehole data indicates a general trend for water levels at between *c*. 1.4 m above to 1.0 m below OD (see Appendix 7), with the modern floodplain ground level nearest the river (piezometer point 10) placed at 2.0 m OD. Variation in Hanson borehole water level heights (Figure 5.4) reflects the variations in topography around the site. Another important observation from the current study is that the floodplain deposits have a separate water table to the catchment groundwater table identified from the Hanson boreholes.

A significant limitation in the modeling programme is the absence of data relating to the initial stages of the de-watering in relation to Phase 1-3 of the extraction programme. This hiatus in monitoring coincided with the period during which funding was being sought for the current research programme. Baseline data is therefore missing for the preliminary stages of water table impacts, thereby limiting the effectiveness of the catchment monitoring programme. A minimum period of 12 months of baseline data (to highlight seasonal trends) is normally necessary prior to extraction, if meaningful observation are to be generated in relation to impacts both during and after extraction has taken place (Lillie 2007:170).

Despite this observation, the hydrological monitoring of the floodplain peats (Figures 5.7-5.11) has shown that, in general, seasonal variation is influencing the water table levels within the peats, with the most severe summer lows indicating a reduction of water levels to -0.2 m OD (Figure 5.10). This equates to a seasonal low of *c*. 2.2 m below the modern floodplain in the vicinity of the Slaynes Lane SSSI (Aims 3, 5, 7 and 8; Page 24). This data is considered to be an accurate representation of the situation at Newington, as the catchment modeling has shown that the influences of the quarry de-watering are limited in the immediate area of the site.

6.2.4 The most significant observation from the GIS modeling is that, in general, the central floodplain area exhibits the lowest water table levels in the vicinity of the extraction site. The extraction area does not appear to influence water levels to any significant degree, and there is some evidence to suggest that some recharge occurs around the southwestern and eastern margins of the floodplain, probably as a result of seepage from the River Idle in these areas. Intriguingly, winter (2004-5) to summer (2005) lows are not dissimilar in the modeling, suggesting that the water table is maintained at a level *c*. 1.8m below the ground surface across these periods. Slight elevations occur through the winter of 2005-6, but these are not sufficient to suggest that the *in situ* context of any contained organics will be preferentially influenced by the winter highs, to any significant degree (Aims 3, 5, and 6; page 24).

The overall impression from the GIS modeling is that the higher resolution data provides a significant resource which can provide important insights into the water table reactions in the floodplain areas. However, some limitations exist in the interpolations between monitoring points, as the smoothing of the data does, on occasion, produce 'artificially' low points in the model. These are most apparent in Figure 5.7 (2 m depth) and Figure 5.11 (2 m depth). In both of these models the lows beneath the extraction areas may be reflecting some level of drawdown, but the resolution of the model in not sufficient to determine the precise causes, and the lack of corresponding values at 1 m and 3 m depths during both of these monitoring periods would suggest that discrepancies are occurring between the modeled heights. The suggestion from this is that despite the placement of seventy-four piezometer clusters around the extraction area, the GIS model resolution could be enhanced with more monitoring points in the immediate vicinity of the extraction areas.

One significant point to add to this part of the discussion is the inherent limitations imposed on hydrological modeling due to the complexity of hydrological responses in peats (Baird 1997, Beckwith *et al*. 2003a & b). These limitations are influenced by parameters such as bacteriogenic gas production (Baird & Waldron 2003), measures of horizontal and vertical hydraulic conductivity (Beckwith *et al*. 2003a & b), and time-lag errors related to the use of standpipe piezometers (Hanschke & Baird (2001). The latter situation is considered to be of limited significance to the current study as water levels are recorded at monthly intervals and are designed to provide an overview of saturated conditions in the floodplain. The complex hydrologic properties of the peats may have an influence on the modeled data, in that variability in response to wetting and drying episodes may be difficult to identify, however, the redox moniotoring points (especially at points 10, 4, and 2 - see Section 5.5 above), appear to be showing responses to rainfall events that could be cross-correlated to the recorded water levels monitored throughout the floodplain. The only parameter that is not directly assessable is the potential for bacteriogenic gas production and the development of water fronts within the peats. The latter element will be influenced by differential peat preservation, variations in sediment type, and flow rates within the peat.

6.3 pH

6.3.1 The pH data discussed in Section 5.4 demonstrates a general trend towards more acidic conditions with depth (Aims 2, 3, 4, 6 and 8; page 24). The range of recorded values extends from *c.* pH 7 to pH 4, and the data suggest that rainfall inputs into the superficial peat deposits promote more neutral pH levels. In certain locations (e.g. point 1, 13, 15 and 25); the low moisture content of the peat at depth is resulting in slightly more acidic conditions. In addition, it appears that degree of saturation and location within the floodplain is influencing the recorded pH levels at Newington, with increased saturation changing pH levels towards neutral conditions.

6.4 Redox

6.4.1 A consideration of the redox potentials obtained from the fourteen redox clusters at Newington provides some refinement of the influences that the water tables are exerting on the buried organic remains (Aims 1, 3, 4, 6, and 8; page 24). This stage of the analysis relates directly to a number of the EoP98 objectives (Primary goal A; 1.7, 1.8, 2.3, 2.4, 2.6, Primary goal B; 5.2, 5.4, 6.3, 6.5, Primary goal C; 8.2, 8.4, Primary goal D; 14.2, Primary goal E; 17.1, 17.8, 17.9, 17.11).

The general impression obtained from the redox analysis is that, overall, the conditions occurring in the floodplain environments are not sufficient to ensure the long term *in situ* preservation of material to depths of *c.* 1.8-2.0 m below the modern surface of the floodplain. Agricultural activities and drainage are having a marked effect on the superficial deposits throughout the floodplain, but low water levels are particularly marked to the south and south-east of the floodplain (Figures 5.7-5.11), indicating the potential for significant problems in relation to the buried resource, and also the Slaynes Lane SSSI.

6.4.2 The redox potentials from the northernmost monitoring point (cluster 10) suggest that rainfall events are visible in the recorded redox potentials, alongside a seasonal (summer) trend towards more positive redox potentials that is usually considered to reflect drying out of the superficial organic sequences. As might be anticipated, the aerated sands range between +200 to +500 mV at this location (i.e. moderately reduced to oxidising), depending on the season, and by inference, the level of saturation.

6.4.3 In the southern areas of the floodplain (redox points 8, 4 and 2) exhibit redox potentials that generally range between +600 mV to *c.* 0 mV, with the lowest readings recorded at 2.0 m depth in cluster 2. As the ranges reported for soil redox status are: >+400 mV indicates oxidized conditions, values between +100 mV to +400 mV are indicative of moderately reducing conditions, values between –100 mV to +100 mV highlight reduced conditions and values between –300 mV to –100 mV indicate highly reduced conditions, the general trend is for oxidising to reduced conditions. However, given that the majority of redox values lie above the +100 mV boundary, with only limited (deeply stratified) readings below this boundary, the redox values obtained are indicative of only moderately reduced to oxidised conditions throughout the floodplain sequences.

Even in areas where the watertables modeling suggests seasonally high water levels (redox points 4 and 2 to the south-west if the floodplain), the deepest monitoring points (2 m) indicate that reduced conditions only occur seasonally, and even at the most saturated point (redox point 2), the values never fall below the reduced to highly reduced boundary. This would suggest that the depositional sequences are not well-preserved to *c*. 2.0 m depth in the majority of the floodplain areas.

6.4.4 Perhaps counterintuitively, the redox point that displays the most positive conditions for *in situ* preservation is the point that is located adjacent to the Slaynes Lane ditch (point 3). The discussion above (Section 5.5) has suggested that the recharge of the ditch from pumping activities and land drainage is producing more stable saturated conditions at this location. Reduced to highly reduced conditions occur at depth, and perhaps even more unusual in this context, is the fact that across the dryer summer months, the redox potentials are not dissimilar to the winter readings, fluctuating around the reduced to highly reduced boundary.

Conditions in the floodplain are clearly compromised, and if the lowered water levels resulting from water abstraction in the catchment continue in the longer term, the *in situ* preservation conditions, which are already unsuitable, will be further reduced. The pumping of water from the extraction areas is clearly enhancing the *in situ* conditions adjacent to the mineral workings, and it appears that this situation is actually producing conditions that are not mirrored in the floodplain areas that are adjacent to the River Idle. This would imply that seepage from the river is not sufficient to produce saturated conditions in the southernmost areas of the floodplain.

6.4.5 Finally, the redox potentials have shown that periodic events, probably relating to rainfall events, are visible in the data. These are interspersed with the seasonal trends, wherein redox potentials are more positive during the dryer months of the year, and as such future studies could investigate the links between the redox potentials identified, and rainfall data for the area. This would allow for higher resolution conclusions relating to the data generated, and the causes of the trends identified from that data. In addition, through the profile pH studies would further enhance the interpretation of the impacts of any rainfall events on the floodplain redox potentials and levels of saturation.

The worrying element of these observations is that the sands at 1.0 m depth at location 10, to the north of the extraction area, have similar redox potentials to the majority of the floodplain peat sequences. This would suggest that when considered alongside floodplain water levels, conditions are such that sediment shrinkage, wastage/mineralisation and compaction could be anticipated in the upper *c*. 1.0 to 2.0 m of the floodplain peats, if sustained de-watering continues, and that even in the SSSI areas, wetland plant communities would be at the very limits of their preferred contexts in relation to groundwater saturation (Wheeler *et al.* 2004). In addition, whilst it is acknowledged that peatlands act as carbon sinks (Price *et al*. 2003), it should be remembered that the alluvial and peat sequences in lowland rivers may function in a similar fashion, so their demise is clearly not desirable.

6.5 Palaeoenvironmental assessment

6.5.1 The assessment of the condition of pollen in the burial environment forms the final part of the current study. This area of the study is aimed at attempting to determine whether any visible impacts in the preservation condition of one of the more robust elements of the palaeoenvironmental record are discernible as a result of the extraction process. This stage of the analysis relates directly to a number of the EoP98 objectives (EoP98 Primary goal A; 2.6, 5.4; Primary goal B, 7.3, Primary goal C; 8.2; Primary goal E; 17.1, 17.9, Aims 1, 2, 3, 4, 6, 7, and 8; page 24).

The assessment of pollen preservation has suggested that variation in pollen concentrations occur across the site, but that these do not display any discernible pattern. The levels of indeterminate grains do support the suggestion that partial destruction and alteration of the fossil pollen assemblage has taken place, but that in general, the degradation is not considered to be too excessive to facilitate analysis. In general, the levels of degradation in evidence suggest that differential preservation is a product of differing conditions in the burial environment, and may well relate to the time of deposition. However, it should be noted that whilst the 18-month study failed to determine on-going degradation, the compromised environments attested by the water table and redox analyses would suggest that sustainability in the longer term is questionable.

The pollen analysis has produced baseline data against which future studies can be compared. The burial environments have been shown to vary across the floodplain, producing areas with either greater or lower potentials for *in situ* preservation of the palaeoenvironmental resource. This situation is clearly very complex, and could be used to suggest that overall, the predominantly compromised condition of the floodplain sequences is primarily due to water abstraction practices, and that more targeted, higher-resolution studies of the burial environment (e.g. microbiological studies, through-the-profile temperature and pH, and pollen analysis in areas of enhanced preservation potential) would resolve a number of the outstanding issues relating to preservation at this location.

6.6 Summary

This report has shown that without catchment-wide hydrological studies, the meaning of the site-specific hydrological research (undertaken using seventy-four piezometer points) would be difficult to resolve. The identification of water abstraction as a significant influencing factor in regional groundwater tables has led to the identification of two separate water tables in the vicinity of the extraction site at Newington. Whether ModFlow is the most appropriate modeling package for the analysis has been questioned by the numerous limitations inherent in the modeling, but in general the catchment-wide overview has enabled a more holistic understanding of the hydrology to be generated.

The shallow water table modeling has facilitated an understanding of seasonality and has shown very specific detail in relation to the floodplain sequences as a whole. The fact that significant areas of the floodplain appear to be in a water deficit situation, and that the worse area on the whole underlies the Slaynes Lane SSSI, is problematic and implies that poor *in situ* preservation environments should be anticipated in this area.

This observation is reinforced by the variability in pH and redox potentials across the study area, and this data has shown that the low water tables (up to *c*. 2 m below the modern floodplain) have produced compromised burial environments to similar depths. Changes in floodplain hydrology in the future will clearly exacerbate an already compromised situation. The pollen studies mirror many of the physico-chemical results, and are suggestive of already compromised conditions that will again be further impacted upon by continued dewatering.

In effect, saturation (moisture content), de-watering and soil redox potentials combine to provide insights into the potential of the environment to allow for the long term *in situ* preservation of organic remains. The impacts from arable farming practices and (in particular) water abstractions for domestic and industrial use have all been identified as having the potential to compromise the waterlogged burial environments at Newington.

This study highlights the fact that while water abstractions have been identified as having a significant role to play in the destruction of the resource, when this is combined with the specific context of lowland floodplains (Macklin & Needham 1992), and global warming/sea level predictions (e.g. Gregory & Orlemans 1998), the problems have a more complex interrelationship.

Effectively, the research discussed above suggests that the interplay of factors such as de-watering, sediment wastage and climate change all combine to produce a scenario wherein lowland river systems in north-west Europe may already be at a point where they are compromised, and will not be able to cope with future changes in weather patterns and sea-level rise. Sustainability of the resource is unlikely without a considerable degree of remediation and management of water resources, especially if longer, hotter and dryer summers continue over the coming decades.

In real terms, the floodplain sequences are being severely compromised to the extent that, with predicted annual temperatures set to rise over the coming decades (possibly to levels of *c*. 4° C by 2100), humans will no doubt demand greater water consumption, beyond the current levels of *c*. 150 l per day/per person. In areas such as the River Idle reach considered here, this will exacerbate an already unsustainable situation. As noted by Price *et al*. (2003), drainage and removal of the acrotelm can cause surface subsidence of up to 3.7 cm y^{-1} m^{-1} of peat shortly after drainage (compression), and long term rates of up to 0.3 cm y^{-1} m^{-1} (compression and oxidation), which can decrease hydraulic conductivity by over 75 %. This observation highlights the need for a rapid and sustainable implementation of the Environment Agency's programme 'Restoring Sustainable Abstraction' (2002, 2005).

The results and discussion (above) all provide a baseline for the future development of management approaches to floodplain wetlands, and they highlight the need for a considered approach to water management in light of future global climate change scenarios. Given predicted damage/losses of archaeological sites in lowland wetlands in recent decades (Van de Noort *et al*. 2002:11), the implications of the destruction of lowland river valley wetlands is that *c*. 7,400 monuments may be at risk in these areas (however, these figures are based on extrapolated estimates of site densities that neglect to account for specifics of context, and should be treated with caution). Irrespective of the real numbers of sites at risk, the lack of long term sustainability in floodplain wetlands in terms of water use and climate change scenarios is a significant issue. This issue has resonance for heritage managers, nature conservators and the water supply companies alike, and has wide implications for the global population in general.

7. Conclusions

7.1 Introduction

The investigation of the potential impacts on floodplain wetlands from aggregates extraction, undertaken in this study, has shown that water abstraction and agricultural activities are having a greater impact on floodplain organic sequences than aggregates extraction.

The reductions in water levels at this location have clearly compromised the upper *c*. 2.0 m of the floodplain sequences (*cf*. Welch & Thomas 1996), and it has been suggested that long term survival *in situ* cannot be assumed to be certain in light of the observations presented in Chapter 5. Despite the fact that the results presented above appear to contradict those of French *et al*. (1999) and French (2004), this study is, in fact, designed to offer a new dataset which will further inform best practice approaches to aggregates extraction. The specific geomorphological and hydrological context of the Newington site is such that other study areas can be expected to exhibit differing responses to the external and internal permutations imposed upon them. In the current context water abstraction has proven to be a particularly significant factor influencing the results obtained.

It has been argued above, that when combined with factors such as land drainage for agricultural purposes, desiccation and peat shrinkage/wastage, increased floodplain under-fitness, rising sea-levels and longer hotter summers (as the global climate continues to change), we can anticipate a 'snowball effect' whereby all of these factors will combine to produce serious problems in the management of lowland river systems. Furthermore, given predictions of increased precipitation in upland areas, alongside rising sea levels, the central reaches of river systems will be put under increasing pressure. Consequently, the floodplains will not be able to cope with changes in hydrological regimes, and they will effectively retain water and inhibit drainage for longer periods. Areas of former floodplain wetlands will simply become land that holds water on its surface. The implications for managing flood risk and the archaeological record of floodplain wetlands are therefore obvious. In addition, it is still uncertain whether the hydrological, ecological and carbon storage functions of peatlands can be restored (Price *et al*. 2003), even if remediation strategies are implemented.

7.1.1 *Suggestions towards best practice guidelines*

In light of the above observations, the present study can inform future management strategies in lowland floodplain wetland systems by highlighting a number of positive approaches to their study, and offering best practice guidelines for their management. A range of these elements are outlined below:

- Despite inherent limitations in defining model parameters, catchment modeling of hydrological status is essential if the fundamental characteristics of the study area are to be generated - this data will also inform higher resolution studies (*cf*. French 2004)
- Site specific baseline data, with a minimum monitoring interval of 12 months (to ensure the identification of seasonal variability) is necessary if any impacts from extraction activities are to be identified
- High resolution water table data has been shown to provide significant information in relation to water table movements in the immediate vicinity of extraction areas, and has also proven invaluable in terms of identifying areas where the *in situ* potential of the floodplain sequences is at greatest risk
- Pumping from the quarry workings into the Slaynes lane ditch has provided a measure of recharge to the adjacent floodplain sequences
- Physico-chemical studies (e.g. pH and redox) have shown that the floodplain sequences at Newington exhibit a considerable degree of variability in terms of their depositional contexts, and have highlighted fine scale variation in relation to depth, saturation and rainfall

- Palynological studies have suggested that preservation is compromised, and that this could relate to the original depositional context (i.e. an active river channel system), although post-depositional cycles of wetting and drying will be significant in the upper *c*. 2.0 m of the floodplain sequences

The above points highlight the effectiveness of the monitoring strategies applied to study the Newington area. As significant areas of the floodplain at Newington exhibit water levels that fall outside the Environment Agency's ecohydrological guidelines for lowland wetland plant communities (Wheeler *et al.* 2004) for the majority of the year, and are sufficiently low to indicate that two-thirds of the maximum depth of floodplain peats are sufficiently compromised to reduce the potential for *in situ* preservation, management strategies need to be put in place with the utmost urgency if this location is to be sustainable by 2010.

In addition, recent research (Brunning *et al*. 2000, Lillie & Smith *in press*, Smith 2005, Smith & Lillie *in press*,) has suggested that as wetland scientists, we are still some way from fully understanding the reactions in the burial environment to sustained de-watering. In particular, on-going studies into the microbiological characteristics of wetland areas (Douterelo-Soler *forthcoming*) has shown that microbial community diversity and the ability of these communities to function as competent degraders of the organic part of the archaeological record, is heavily dependent on context, and in particular the physico-chemical status of the wetland sequences (*cf*. Corfield 2007).

As such, as advocated above in Section 6.5; the situation is very complex, and requires more targeted, higher-resolution studies of the burial environment (e.g. microbiological studies, through-the-profile temperature and pH, and pollen analysis in areas of enhanced preservation potential) in order to resolve a number of the outstanding issues relating to *in situ* preservation both at this location, and in order to provide baseline data for studies in other lowland river systems.

From a management perspective the situation is complex. We have evidence to suggest that even where saturation is removed, archaeological remains can survive for long periods above the water table (e.g. Brunning 2006). However, this will again depend on context, the nature of the microbial communities, and the specific physico-chemical character of the soil matrix containing the archaeology; all elements that are in need of further investigation (*cf*. Brunning *et al*. 2000).

The research outlined above has direct resonance to archaeologists, wetland scientists, and heritage managers, alongside the interests of the aggregates industry, nature conservationists and water resource managers such as the Internal Drainage Boards' and the Environment Agency.

7.2 Recommendations

Significant observations/recommendations, that can both inform and direct future management strategies in floodplain wetlands include:

- Water balance: the Newington catchment is in a water deficit situation, with water levels recorded at depths of up to 2.0 m below the modern floodplain surface

This situation is unsustainable from the perspective of water abstraction, nature conservation and archaeology. Positive water balances are required if long term climate change scenarios are to be managed sustainably. This situation is of direct relevance to all lowland floodplain wetlands experiencing water abstraction and that are being managed under the Environment Agency CAMS programme.

- Geo-hydrological study: the investigations of water table dynamics undertaken during this research have demonstrated that only minimal impacts have arisen from the aggregates extractions (Section 5.2.3)

Baseline data in the immediate floodplain areas would have enhanced the analyses undertaken by Leake (2000), and directly informed the mitigation strategy for this location from the perspective of the aggregates extractors. Holistic studies of this sort are of fundamental importance when developing management and extraction plans.

- High-resolution water table data: the floodplain has been shown to be the dryest part of the study area, with a particularly low area located beneath the Slaynes Lane SSSI

From the perspective of a SSSI, sustainability is unlikely, and if current water levels continue surface water retention (due to the desiccated and compacted nature of the superficial peat horizons) will mean that the water levels at this location are consistently beyond the ‘desirable’ and ‘tolerable’ water table limits outlined by Wheeler *et al*. (2004: Figure 1.4). Natural England targets for 2010, that 95 % of SSSI land needs to be in 'favourable' or 'recovering' condition (English Nature 2007), are unachievable at this location. This analysis has demonstrated the existence of ‘hot spots’ where good (and bad) conditions for *in situ* preservation can be anticipated.

- Physico-chemical and water table analysis for archaeology: this area of the research has shown that the floodplain sequences are compromised to a significant degree, and that this situation may have been in place for some time

Baseline data of this sort is of fundamental importance for archaeologists, both in terms of developing understanding of management strategies (*cf*. Brunning *et al*. 2000), and to inform heritage managers when defining mitigation to threat. Significant areas of the floodplain are compromised, some severely, and this area is not sustainable in the longer term given current management strategies. The integration of the high resolution water table data with the physico-chemical studies has shown that recharge from the Slaynes Lane ditch is producing ‘hot spots’ of enhanced preservation potential.

- Palaeoenvironmental analysis: this data has added to the overall impression that preservation is variable, and that areas of enhanced preservation potential persist, despite the negative water regimes at Newington

This data can be linked to the high resolution water table, and physico-chemical results to highlight those areas of the floodplain where the greatest potential for the recovery of archaeological remains *in situ* could be anticipated.

On the basis of this observation, the integrated, holistic overview produced by the current research can be used to predictively model those areas of lowland floodplain wetlands with high archaeological potential.

The above research has presented a multi-disciplinary approach to the study of lowland floodplain wetlands, and has assessed these in relation to aggregates extraction. The results have shown that water abstraction is the most significant variable impacting on the floodplain wetlands. In management terms, the floodplain sequences are not sustainable given current water budgets. When considered against future climate change predictions and the anticipated increases in water demand associated with longer dryer summers, the situation is in need of significant mitigation and considered management if the floodplain wetlands are to be sustainable into the future. Holistic, integrated studies such as the current project, provide baseline data for understanding these environments, and are of fundamental importance to the future management of lowland wetlands.

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