THE UNIVERSITY OF HULL

An assessment of the potential for *in situ* preservation of buried organic archaeological remains at Sutton Common, South Yorkshire

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by

James Leslie Cheetham BSc MSc

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Summary of Thesis submitted for PhD degree

by James Leslie Cheetham

on

An assessment of the potential for *in situ* preservation of buried organic archaeological remains at Sutton Common, South Yorkshire

The research presented herein is concerned with monitoring the burial conditions of the organic archaeological remains that exist on Sutton Common, South Yorkshire.

The development of a monitoring package to enable identification of conditions conducive to long-term preservation of organic archaeological materials, in particular wood, was a key aim.

Three key disciplines were studied, namely; soil hydrology relating to water table dynamics; soil chemistry through measurement of redox potentials and assessment of microbiological activity within the soil profile.

The hydrological monitoring of Sutton Common effectively characterised the water table and its dynamics. It was shown by the creation of GIS generated surfaces that the water table was relatively shallow and followed the contours of the surface topography. A water budget for Sutton Common was calculated and this supported the evidence that the water table is significantly influenced by seasonal variation and is precipitation fed. Development of an archaeological wood model using ArcGIS has shown the interaction between this resource and the water table.

Redox monitoring highlighted diversity in the character of the burial environment across Sutton Common, although reduced conditions were predominant at depth across the majority of the site where saturated conditions exist. Seasonal variation within the burial environment, characterised by fluctuating water table heights, resulted in varying oxidised conditions. Significant data was produced during flooding of the site indicating that a considerable and lasting change in the burial environment occurred.

Microbial assessments provided baseline data concerning the microbial dynamics of the soil profile. Of significance is the strong relationship between enzyme activity and organic matter content.

Integration of these data highlights that saturated conditions are necessary for the creation of a reduced environment and therefore *in situ* preservation of buried organic archaeological remains on Sutton Common will only prevail at depth where these conditions exist.

For my Uncle Ian

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Throughout the course of this research, many people and organisations have provided valuable assistance and advice to whom I would like to pass on my gratitude. Foremost, the Carstairs Countryside Trust (CCT) and the Department of Geography at the University of Hull have provided the opportunity to undertake this work and have provided financial assistance without which this could not have been possible. English Heritage has provided support to the CCT and directly to the project without which the monitoring on Sutton Common could not have taken place. I would like to thank everyone participating in the 'Sutton Common Project' for their involvement and feedback that has been highly valued throughout this research.

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Chapter 1 Introduction

I have a deep fascination and strong connection with Sutton Common. This archaeological site has revealed many wonders to me, not only material objects, but also things on a more personal level. For example, when you excavate a piece of worked wood and are able to touch the axe facets for the first time since they were made millennia ago, you are given a direct connection to the individual who made them. You cannot help yourself but wonder who they were and what their life was like. In essence, you bring them alive and in the process realise that you are the same as them in all respects except one...time.

1.1 Introduction

This thesis will approach the issue of the *in situ* preservation of archaeology, specifically in a wetland environment where it is recognised that organic materials are often preserved in an exceptional condition (Coles & Coles, 1986). The research aims to identify an approach by which wetland archaeological sites can effectively be monitored, their dynamics identified and an accurate assessment of their condition, and that of the archaeological remains preserved within them, be made. Such an insight will help sites to be protected, either through the maintenance or the creation of suitable burial conditions.

The study site is Sutton Common, an Iron Age double enclosure located in South Yorkshire. This site has gained importance within the archaeological community in recent years as a direct result of its unique construction and setting within a former wetland landscape and the associated quality of preservation of archaeological remains identified in previous site excavations (Whiting, 1938). Sutton Common has been the subject of increasing attention following extensive damage to the site resulting from agricultural improvements that have taken place since 1980 (Parker Pearson & Sydes, 1997). The recognition that valuable archaeological information was being lost prompted the site to be taken into protective ownership by the Carstairs Countryside Trust (CCT) with the aid of agencies including English Heritage. Through this an emphasis has been made to preserve *in situ* the remaining archaeology and create a site dedicated to the conservation of wildlife through the recreation of a wetland environment.

This chapter will provide a background to the issue of *in situ* preservation and discuss the inherent importance of preserving organic archaeological remains. The role of English Heritage in promoting such an approach will be examined, along with the impact of development upon the archaeological resource and the initiatives being taken to enhance further the credibility of *in situ* preservation.

1.2 The significance of wetland archaeology

It has long been recognised that wetland environments have the potential to preserve important archaeological materials. Evidence of the activities of humans and often an uninterrupted environmental record locked within palaeoenvironmental remains can be discovered (Coles, 1995). Simply put, the continual saturation of soils and archaeological deposits excludes air, and in turn this can lesson the activity of aerobic microbial degradation and bioturbation caused by soil fauna and flora. Therefore, materials that normally degrade very quickly within what can broadly be termed a dryland environment are often present within the wetland context. A wide range of materials can be preserved in an equally wide ranging number of wet environments from peat bogs to deep urban deposits; probably the most recognised and emotive of all being human remains (Glob, 1965). In contrast to dryland sites, in a waterlogged context (such as a peat bog environment) soft tissues such as skin and hair are capable of preservation. Such discoveries provoke widespread reaction and interest.

The United Kingdom's most famous 'bog body' is that of 'Lindow man' (or 'Lindow Pete' as locals like to refer to him), discovered within the peat on Lindow Moss, Cheshire in 1984 by two peat workers. Whilst sifting through collected peat they discovered what they initially thought was a piece of wood, but it was in fact a human leg (Stead *et al.*, 1986). This prompted a search to discover the location of the find which was followed by the rapid excavation of the remainder of the body, still untouched, within the peat.

Lindow Moss itself has since gained publicity and in recent years this has helped highlight the current plight of the site. Like a large number of peatlands in the British Isles, Lindow Moss is under threat from industrial activities and in the longer term, from development. Within the last three years peat extraction has been increased significantly on the site following the purchase of the land by Croghan Peat who have instigated a change in the methods of peat extraction. Whereas previously peat was dug by hymac (a mechanical digger) and then removed by narrow gauge railway, it is now milled. The former method was relatively slow and small scale and allowed large areas to retain and develop diverse vegetation, including a significant wetland component. The latter method, in contrast, is intensive and requires that large peat fields are cleared of all vegetation thus rendering whole tracts of land barren. Indeed, the reasons for, and the method of this approach are questionable, and it is suggested that the cost of milling the raw material, transporting and processing it is considerably greater than the commercial income from the finished product. When looked at in the context of the development proposals for the site submitted to the local council by the extraction company, it is not difficult to suppose what the future is likely to hold for the Moss (Hyde & Pemberton, 2002). Unfortunately, this situation is common for many wetland sites within the British Isles where development, either urban, agricultural or industrial, impacts upon the archaeological resource, with much of the hitherto preserved archaeology becoming lost forever. The recognition of this destructive activity has directly motivated the interest and research into wetlands which it is hoped will lead to the preservation of such sites in the future (Van de Noort & Davies, 1993).

1.2.1 Archaeological wood

The major differences between dryland and wetland archaeology have already highlighted the potential for the preservation of organic materials in wet conditions. This means that materials widely used by people in the past, such as wood, leather, textiles, basketry and others, may be represented in a waterlogged context (Corfield, 1998), the most commonly encountered materials within such situations being archaeological wood (Cronyn, 2001). The archaeological importance of waterlogged wood comes from its ubiquitous use in the past as a raw material for many applications, the most common of which was as a major component in most types of structure (Brunning, 1996). Where such material exists, it can be used for accurate dating, through the application of dendrochronological techniques, to study woodworking technology from structures and the preservation of tool facets, along with the reconstruction of past climates (Brunning, 1996).

This means that archaeological wood is perceived as a valuable material worth studying and sites that exhibit it are worth identifying and often preserving. However, this is made more urgent by the fragile nature of waterlogged wood. Although in terms of archaeological significance, waterlogged wood may be 'well-preserved' as it retains its original dimensions, tool facets and carving etc., at the same time, wood scientists might categorise such material as heavily degraded (Björal & Nilsson, 2002a). On immediate excavation this material may therefore look in good condition, but the real situation is revealed as soon as drying of the object commences, with the wood irreversibly cracking, warping and shrinking at an alarming rate (Cronyn, 2001).

The reason why archaeological wood persists within a waterlogged burial environment is because the major degraders of wood are excluded due to the low-oxygen environment (Björdal *et al*, 1999). In well-aerated environments the decay of wood mainly occurs as a result of the action of fungi (Powell *et al*, 2001) and under optimal conditions this can lead to, more or less, the complete destruction of the material within a short period of time. In contrast, under waterlogged conditions, bacteria have been determined as the primary agents of decay (Blanchette *et al*, 1990; Björdal *et al,* 1999; Björdal & Nilsson, 2002). Wood degrading bacteria can be divided into three groups, these being determined by their mode of degradation; tunnelling, erosion and cavitation. Through the study of the type of degradation that pieces of archaeological wood have been subjected to, it has been determined that erosion bacteria are the main degrading organisms, these being capable of attack in low-oxygen environments (Blanchette *et al*, 1990; Björdal *et al,* 1999; Björdal & Nilsson, 2002).

The degradation of wood under true anaerobic conditions has not been unequivocally demonstrated, but the fact that bacterial degradation occurs at a slow rate relative to fungal attack (Blanchette *et al*, 1990), may explain the persistence of archaeological wood in waterlogged environments. During waterlogging, and for a period of time afterwards, bacterial degradation of the ligno-cellulose structure of wood occurs at a slow rate through the action of erosion bacteria. Under stable environmental conditions, this would ultimately lead to complete anaerobic conditions under which the final breakdown of the resilient lignin skeleton is not possible. This occurs through the consumption of oxygen and oxidised chemical species by chemical reactions and aerobic microorganisms (Caple, 1996). However, where the burial environment becomes subjected to disturbance, such as the through the lowering of the water table, the material may once again be vulnerable to bacterial degradation and where aerobic conditions are allowed to re-establish, this would rapidly lead to the ultimate removal of the material through the action of fungi. Björdal and Nilsson (2002b), demonstrate this in their study of the susceptibility of waterlogged archaeological wood to degradation by fungi. Other recent studies that confirm the dominance of erosion bacteria as the main agents of decay of waterlogged archaeological wood are Björdal *et al* (1999) and Powell *et al* (2001).

Björdal *et al* (1999) made use of light and electron microscopy techniques to study 92 samples of archaeological wood from seven separate sites and of various ages and wood species. It was found that decay was related to sample age, wood species and environmental factors, such as the amount of time taken for waterlogging to occur. For example, the presence of fungal decay on samples of structural wood indicated that the material was subjected to an oxygen rich environment prior to waterlogging, at which point fungal activity was replaced by degradation by erosion bacteria.

Powell *et al* (2001) used an active approach, whereby fresh samples of wood were buried in two contrasting burial environments at Flag Fen, a Bronze Age archaeological site, where the presence of waterlogged archaeological wood has been demonstrated. Samples were then regularly removed over a period of 550 days and analysed. This study also made use of light and electron microscopy techniques to study the mode of degradation, but also monitored environmental parameters, such as soil redox potentials, pH, the depth of the water table and soil organic matter content, in an attempt to identify the factors influencing degradation. It was found that bacterial decay occurred in samples buried at near-anaerobic conditions, whereas fungal soft-rot occurred under less anaerobic conditions. It was also identified that a combination of a high water table, low pH, anaerobic conditions and high organic matter content of the soil prolonged the preservation of the wood samples.

Although the most common techniques for the assessment of the condition and the type of degradation of archaeological wood are light and electron microscopy, many other varied techniques exist. Such methods for condition analysis include; chemical analysis, whereby the wood structure is broken down chemically and its constituent parts are quantified, and various penetration tests, such as the use of the Sibert Decay Drill, a tool that provides a trace of the resistance of wood this relating to the wood's soundness or amount of decay suffered (Panter & Spriggs, unpublished). Another more sophisticated technique is the use of Nuclear Magnetic Resonance (NMR), specifically solid-state NMR, which can provide a comprehensive analysis of the wood being studied, although this approach is often prohibitively costly when a large number of samples are required (Panter & Spriggs, unpublished).

Possibly the most effective means of analysing the condition of archaeological wood, and the amount of degradation that it has suffered, is through a combination of the described techniques. Such an approach has been carried out in a study assessing the effectiveness of proactive management of the burial environment of the Sweet Track in Somerset (Brunning *et al*, 2000). Excavated samples of the Neolithic trackway, obtained from four locations along its length within the Shapwick Heath nature reserve, were the subject of analysis of moisture content, shrinkage upon drying, light and electron microscopy and NMR. In addition to these, measurements of parameters affecting the burial environment were made, these being; the depth of the water table, soil redox potentials, water chemistry, electrical conductivity and pH. The study concluded that although the wood making up the trackway was heavily degraded, it was still 'archaeologically' well-preserved and the decay observed dated to prehistory. Also, it was determined that the management regime was effective at protecting the site from further degradation.

1.2.2 Wetland archaeological surveys

Although peat extraction destroys the archaeology preserved within it, it also provides a new opportunity to study such sites (Coles & Coles, 1986). Peat extraction within the Somerset Levels led to the discovery of a number of trackways and structures, the most famous of which is the Neolithic aged Sweet Track (see section 1.3). This early work recognised the value of a systematic and detailed survey and resulted in the creation of the Somerset Levels Project that ran from 1973 through to 1989 and published fifteen *Somerset Levels Papers* containing 130 reports. These included environmental studies and specialist reports on conservation of wooden artefacts, experimental archaeology and reports of excavations undertaken by the project (Coles, 1989). The project was formed with the support of the Department of the Environment and latterly by English Heritage. Work focused upon two main areas of the Somerset Levels; the Brue Valley and Sedgemoor, and largely involved maintaining contact with peat-cutters and surveying peat-fields, this lead to rapid and extensive identification of many valuable archaeological sites that were under imminent threat of destruction (Coles, 1989).

A similar approach was carried out in the extensive peatlands of Ireland and has identified hundreds of trackways and structures (Raftery, 1990). By the late 1980s it was clear that there was a requirement for a survey to be established, as the raised bogs of the country were potentially the richest source of archaeological material in Ireland (Bermingham, 1997, Raftery, 2002). Following five years of excavation and research on ancient trackways in the Mount Dillon complex of bogland in County Longford and County Galway, the Irish Archaeological Wetland Unit (IAWU) was formed in 1990. The unit is a joint venture between the Office of Public Works and University College Dublin and its aim is to undertake ongoing surveys of the raised bogs of Ireland that are commercially milled by the state energy company Bord na Móna and carry out rescue excavations at these sites. During seven years of the project running, the IAWU have identified 1,900 new archaeological sites in bogs where previously only 53 were known. Publication of all survey and excavation work carried out by the unit has resulted in four volumes published in the Transactions of the Irish Archaeological Wetland Unit (Raftery, 2002).

With the success of the Somerset Levels Project the archaeological potential of other wetland areas within England was recognised, resulting in English Heritage providing extensive resources and funding that has led to the setting up and running of a number of regional wetland surveys including the Fenland Survey (Hall & Coles, 1994), the North West Wetlands Survey (Cowell & Innes, 1994) and the Humber Wetlands Survey (Van de Noort & Davies 1993). A number of basic aims were identified for these surveys:

i) To identify the extent of wetlands and their development
ii) To catalogue known archaeological sites
iii) To identify areas of high archaeological potential
iv) To describe the extent and nature of threats to the archaeological resource

(Howard-Davis *et al.*, 1988; Van de Noort & Davies, 1993). The emphasis was not solely on the study, research and assessment of archaeological sites, but also took a broad approach, including the study of landscapes and detailed palaeoenvironmental programmes, in order to obtain the most thorough knowledge possible. The English Heritage funded wetland surveys have culminated in the final regional publication of the Humber Wetlands Project, the Wetland Heritage of the Lincolnshire Marsh (Ellis *et al.*, 2001), although a synopsis volume providing an overview of the Humber Wetlands Project is still to be published.

The Humber Wetlands Project started in 1992 with a desk based assessment titled Wetland Heritage (Van de Noort & Davies, 1993). This exercise reviewed the physical development of the region since the last glaciation and catalogued and described the distribution of known archaeological sites. It also provided recommendations for the future archaeological and palaeoenvironmental management of the Humber Wetlands. This culminated in the recommendation that a programme of fieldwork was required to identify and evaluate undiscovered sites and to assess the preservation of known archaeological sites (Van de Noort & Etté, 1995). The fieldwork undertaken by the Humber Wetlands Project ran between 1994 and 2000 and resulted in the publication of six 'Wetland Heritage' volumes each covering an individual region of the wider Humber Wetlands; Holderness, the Humberhead Levels, the Ancholme and lower Trent Valleys, the Vale of York, the Hull Valley and the Lincolnshire Marsh.

The English Heritage sponsored wetland surveys encompassed a great variety of wetland environments, from the peatlands of the Somerset Levels through to the foreshore environments and alluvial washlands of the Humber and extensive lowland wetlands of the Cambridgeshire Fens (Figure 1.1). All of these types of wetland environment suffer from a number of threats, both specific and widespread, which potentially impact upon the continued preservation of both archaeological materials and their palaeoenvironmental context. These threats have been recognised for many years, along with the need to assess and monitor them through the formulation of methodologies and strategies to manage the wetland archaeological resource. There has been an increasing emphasis on the need to be able to assess and understand many different parameters including the hydrological regime of a site and its archaeological contexts, soil chemical characteristics such as redox potentials, conductivity and pH, and also, (but so far to a lesser extent), soil microbiological status (Brunning, 1996; Caple & Dungworth, 1998; Corfield, 1993, 1996, 1998).

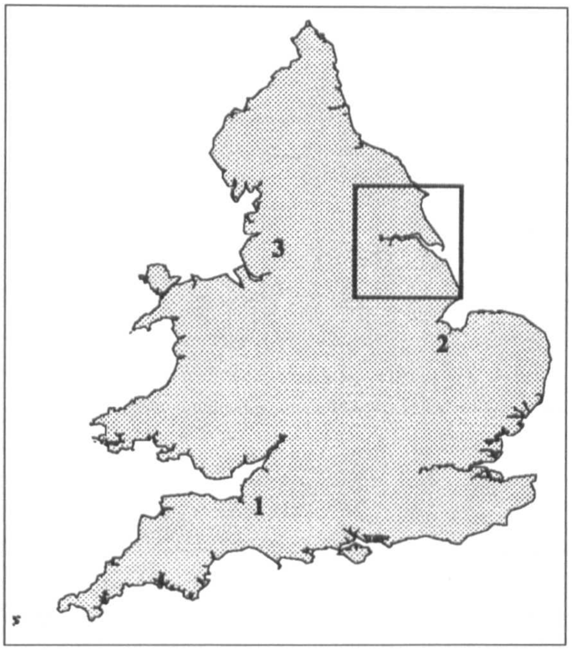


Figure 1.1 Map showing the location of the Humber Wetlands Project (square) and the Somerset Levels Project (1), Fenland Survey (2) and the North West Wetlands Survey (3). From Van de Noort & Davies (1993).

1.2.3 Threats to the wetland archaeological resource

The most widely accepted threat to wetlands and the archaeological resource that they hold is the impact of agriculture, more specifically the drainage of former wetland areas. Van de Noort & Davies (1993) detail the effects of agricultural drainage upon groundwater levels within the Humber region over the last 30 years, these showed a clear and ongoing pattern of decline directly due to increasingly intensive agricultural practices and associated drainage. Figure 1.2 shows the maximum and minimum annual groundwater levels recorded from two locations within the Humberhead Levels between the late 1960s and early 1990s (Van de Noort & Davies, 1993). The definite downward trend in groundwater levels can be easily seen. Exacerbating this situation is the intensification of farming practices over the last 30 years, and the resultant use of irrigation. This water is often obtained via abstraction from groundwater aquifers and surface rivers, and along with ongoing extraction for industrial, power generation and private use, is resulting in the constant lowering of groundwater levels (Van de Noort & Davies, 1993).

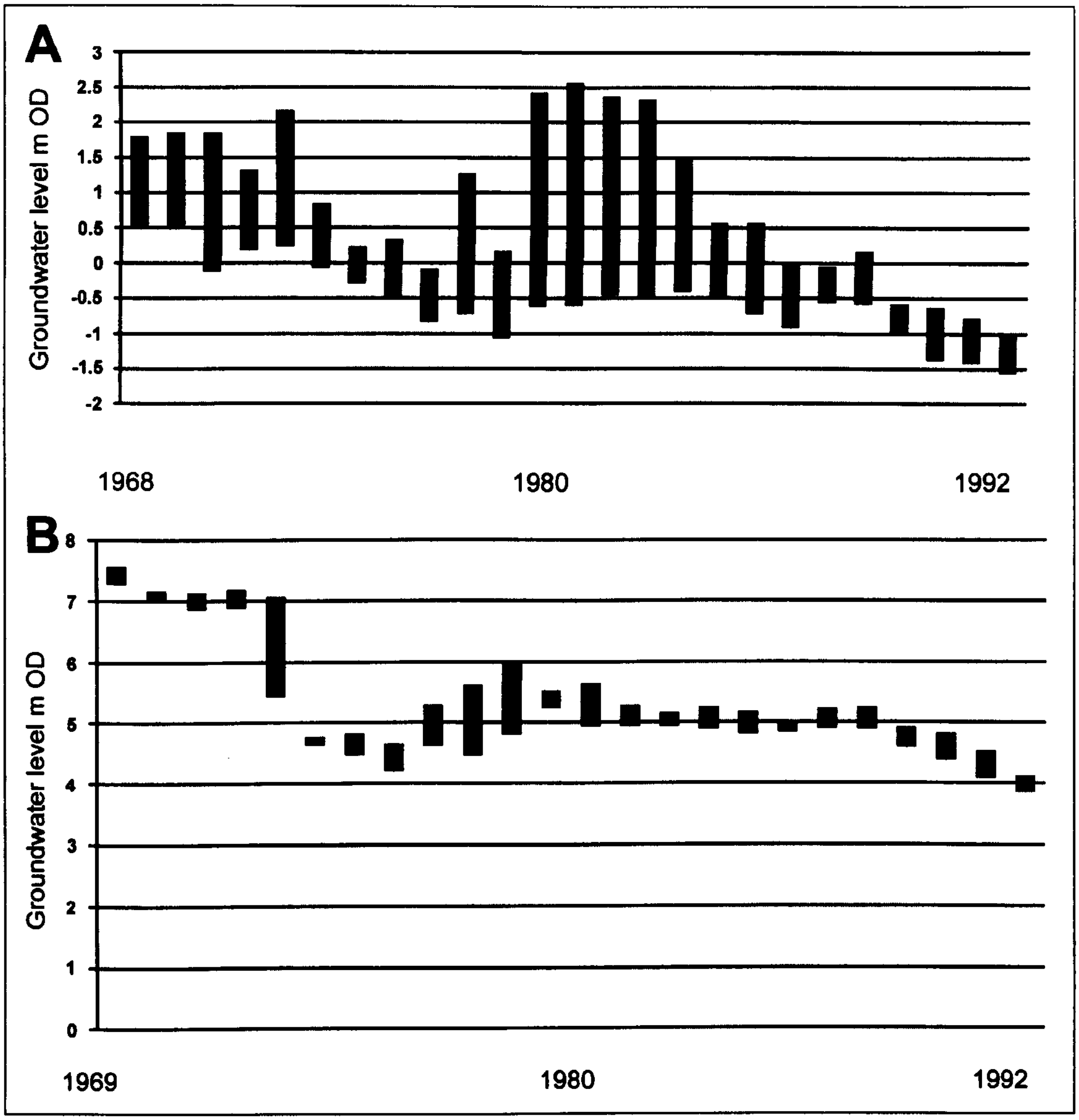


Figure 1.2 Hydrographs showing maximum and minimum groundwater levels for Cherry Tree Farm, Hatfield Chase (SE71541000) between 1968 and 1992 and Stainforth Haggs, Stainforth (SE64111029) between 1969 and 1992. From Van de Noort & Davies, 1993).

Drainage associated with extraction industries results in the physical removal of archaeological remains and can also have a potentially widespread impact upon the wider burial environment as a result of dewatering. Peat extraction has already been discussed but mineral extraction, especially that of sand and gravel, can have a wide reaching impact on water tables through the process of draw-down. These resources are invariably located in low-lying areas associated with past or present river systems (Van de Noort & Davies, 1993) and therefore during the extraction process the constant removal of groundwater to prevent flooding is required. It is this constant removal of water that results in the draw-down effect which occurs throughout the duration of the extraction process, this being months or years, especially when extensive deposits exist.

Climatic change is also becoming a more recognised threat to the archaeological resource as the long-term effects of processes such as global warming, become better understood (Chapman, 2002). Rising sea levels, changing precipitation patterns and temperatures all potentially lead to secondary effects that will impact upon the archaeological resource, especially where this is preserved in delicate burial environments such as those found in wetland deposits. Processes such as coastal erosion also represent a threat to archaeological materials. High concentrations of organic archaeological remains have been identified within the foreshore environment of estuaries around the British coastline (Fletcher *et al.*, 1999). Studies within the Humber Estuary have established that these environments are under threat from severe erosion, including peat shelves within which large quantities of wet-preserved archaeological materials exist. From documentary evidence it is clear that this process of erosion has significantly increased in recent decades as a result of changes within the flow dynamics of the Humber Estuary (Chapman *et al.*, 2001).

A detailed discussion of the threats to wetlands, management techniques and examples of management practices, can be found in the survey commissioned by English Heritage (Coles, 1995). This work clearly identifies the relationship between nature conservation and the preservation of archaeological remains within a wetland context, providing examples of the mutual benefits of raised water-levels, such as the site of the Corlea trackway in the extensive peatlands of Ireland. This project was designed to ensure the continued preservation of a section of the Corlea trackway within a surviving fragment of raised bog by means of constructing a bund around the site. Details of such techniques were collected from a wide variety of sources and presented in the publication, culminating in the presentation of archaeological applications, implications and recommendations. Although this survey was completed in 1995 (and therefore some elements of it are in need of updating), this work is as significant and applicable in the present day and will continue to be so in the future. An extensive discussion of the management of wetlands including wetland creation and restoration are presented by Mitsch & Gosselink (1993) and also in Cox *et al.* (1995).

The process of development can impinge upon wetlands and wet deposits, especially within an urban environment where surface development is ongoing from generation to generation. Again, the major threats to archaeology are through changes in hydrological dynamics. There is a significant variation in the occurrence of well-preserved archaeological remains and organic-rich deposits between urban and rural sites. Within a rural context, sites can often be naturally delimited and identified, meaning that assessment, research and management can be focused clearly upon them. Within an urban environment the situation is different as often vast quantities of archaeology are often spread over a wide area that has many differing land uses. Occupation at ancient riverside settlements such as York, can be traced back into prehistory, meaning that archaeological remains exist from a long time-span.

Within York there are archaeological deposits of 7.45 m in depth (Addyman & Hall, 1991). However, with increasing levels of development occurring and an associated expansion of the urban environment there is an obvious but unquantified impact upon the archaeological resource. This has been highlighted by recent excavations where the condition of archaeological deposits was assessed but a true understanding of the affects of development could not be made due to a lack of comparable data from prior to the development taking place (Davies *et al.*, 2001).

1.2.4 *In situ* preservation and the management of the archaeological resource

The significance of archaeological remains preserved within a wetland context or a saturated environment has already been established. A policy of *in situ* preservation now exists resulting from the introduction of the Planning and Policy Guidance note 16 (PPG16) by the Department of the Environment in 1990 (Dept. of Environment, 1990). PPG16 highlights the importance of archaeological remains as they contain information not only about the past but have the potential to increase our knowledge in the future. As these remains are a finite and non-renewable resource and are often fragile and vulnerable to damage, it is essential that they are preserved, or that the information they contain is satisfactorily recorded. This premise has become the widely accepted notion of *in situ* preservation:

> 'Where nationally important archaeological remains, whether scheduled or not, and the settings, are affected by proposed development there should be a presumption in favour of their physical preservation.' (PPG16)

This approach has been questioned in relation to wet deposits in an urban environment compared to a rural one, due to the complexities discussed previously (Kenward & Hall, 2000; Davies *et al.*, 2001). However, it has been emphasised that the dynamics of *in situ* preservation on a rural site are also very complex. For example, processes can occur across a range of scales within a single archaeological site (Van de Noort *et al.*, 2001), meaning that ultimately the issues are essentially the same.

English Heritage has been a motivating force in the development of strategies for *in situ* preservation and a source of funding for research. With the introduction of PPG16 English Heritage now favours, where possible, the preservation of the archaeological resource *in situ* and has been developing strategies based upon this principle (English Heritage, 1997, 2003). Targets within the implementation plan published by English Heritage include promoting under-studied and vulnerable areas, including wet and waterlogged areas (Primary goal A: programme 2.3). To this end, English Heritage commissioned the University of Exeter to undertake an assessment of the Monuments at Risk in England's Wetlands (MAREW) (Van de Noort *et al*, 2002) by means of a desk-based assessment using mapping sources, historical records, drainage records and accessing data on previously identified 'wetland monuments'. The main findings of the assessment are that over the previous 50 years (prior to 2001) an estimated 2950 monuments have been destroyed, and 10,450 have suffered from damage, desiccation and partial destruction. The potential for several thousand more monuments still existing intact was identified but an estimate of the numbers was not made.

Based upon the understanding that MAREW has generated and the realisation that there is a requirement to establish a framework for a coherent approach to the conservation and management of wetlands (English Heritage, 2002a) English Heritage has created a Wetlands Strategy that sets out broad objectives as well as specific initiatives based on four principles:

- Management, promoting practical mechanisms to conserve and protect the cultural heritage by developing guidance and best practice for the integration of cultural heritage and nature conservation in wetland management;
- Outreach, promoting and disseminating understanding and appreciation of the cultural heritage of wetlands by making the results of wetland research easily accessible to the general public, to landowners and managers, and to professional interests;
- Policy, promoting the cultural heritage interests of wetlands in the work of local authorities, national, international, and intergovernmental agencies;
- Research, continuing with programmes of survey and excavation as an essential pre-condition for the development of successful management practices and promoting applied research to underpin good management of wetlands and to inform future policy development.

(English Heritage, 2002b).

If this approach is to succeed then effective monitoring of archaeological sites has to be seen as an essential part of the strategy. If monitoring is not addressed, then there is no mechanism by which the 'quality' of sites, i.e. the maintenance of a suitable burial environment, can be assessed. Therefore, it must be seen that monitoring is equated with successful management practices and that English Heritage remains a driving force for continued research and development of these. However, there is definitely a basis for the creation of standard practices to enable the efficient implementation of a monitoring programme and swift generation of results. There must also be material resources available for workers who are tasked with the development of such projects, such as readily available information on the acquisition and operation of various equipment types. Studies undertaken into monitoring the burial environment have identified factors that need to be accounted for if an accurate understanding is to be achieved (Brunning *et al.*, 2000, Caple & Dungworth, 1998). These obviously include the need to account for local hydrological dynamics, but also factors such as redox potential, electrical conductivity, pH and water quality. Not all studies, including the one covered by this thesis, make use of all factors for reasons such as cost, availability of equipment and the specialist skills required to operate equipment. Added to this, it is often not obvious where the necessary equipment can be sourced, for example the *in situ* redox probes used in all recent studies have been specifically manufactured for the purpose and as such are not commercially available. A more open and easily accessible source of information, such as a website, that has the advantage of being easily updated and can be used to pool knowledge, may hold the key to widespread, successful monitoring. Such an approach would also adhere to all four of the principles set out in the English Heritage Wetland Strategy reproduced in the previous paragraph.

English Heritage, as part of its strategy has commissioned the development of a Geographical Information System (GIS) enabled wetland-archaeological resource for use by archaeological curators in the planning process (Van de Noort, & Powlesland, 2001). This approach is designed to increase awareness about wetland archaeological sites within local authorities, the majority of which have no specific policy regarding such sites. The next logical step from this is management, including effective monitoring, of these sites if their preservation is deemed necessary.

1.3 Examples of *in situ* preservation

The importance of organic archaeological remains preserved within a wet burial environment has been established previously. It is therefore useful to detail some of the ongoing *in situ* preservation projects that are taking place within the United Kingdom.

Within a rural context there are two well-known sites that have been subjected to extensive *in situ* preservation work - the Sweet Track located in the Somerset

Levels and Flag Fen in the extensive wetlands of the East Anglian Fens. The Sweet Track is the oldest known trackway structure identified within continental Europe and dates back to around 3800 BC. One of many trackways built within the Somerset Levels in prehistory, it acted as a communication route across the wetlands of the Levels and enabled the population to exploit the resources present there (Coles & Coles, 1986). The construction consists of a raised walkway supported by stakes pushed into the peat and is approximately 2 km in length.

The Sweet Track has been the subject of considerable research since the 1970s, culminating in extensive excavations of some stretches (Coles & Orme, 1984). Concern over the long-term survival of the remaining elements of the structure led to the purchase of the Shapwick Heath Nature Reserve and the instigation of re-wetting through pumping along the stretch of the trackway that runs through the reserve (ongoing since 1983). Along with this, construction of a bund was carried out in order to reduce drainage from the site (Brunning, 1999). In recent years the success of this management system has been assessed by an extensive monitoring exercise and limited excavation of the trackway for the purpose of sampling and condition analysis of the archaeological remains (Brunning *et al.*, 2000). During this exercise, ongoing monitoring of the burial environment was undertaken for 12 months for redox potentials and water levels. In addition, more specific aspects such as hydraulic conductivity measurements were recorded. Small-scale excavation placed the monitoring within the context of the depths that the trackway remains exist and enabled sampling of the wooden structure for analyses of; moisture content, shrinkage susceptibility, Scanning Electron Microscopy, wood chemistry and microbiology. It also provided a source of palaeoenvironmental material to assess the potential of the peat matrix as an ongoing source for environmental reconstruction.

This study indicated that the current hydrological regime was adequate to maintain full saturation and that the burial environment was generally favourable for the continued preservation of the archaeological remains. Significantly, the study also generated important points and questions regarding the assessment of waterlogged archaeological remains and the monitoring of such sites. These included the accurate assessment of local hydrological conditions being vital for the formulation of a successful management strategy and that the combination of variables such as redox, pH and water quality, form the most important characteristics for assessment (Brunning *et al.*, 2000).

Flag Fen is a large waterlogged prehistoric site located near Peterborough in the wetlands of the Fens, consisting of a manmade timber platform and an associated kilometre long post alignment, both dating to the Bronze Age. The site was identified in 1982 during the deepening of a drainage dyke that runs through the site; this dyke is also one of the main reasons why the site was considered to be under threat. A large proportion of the site is being excavated as the archaeological remains are drying out due to the lowering of the groundwater table by artificial drainage, to below the level of the archaeological remains (Pryor, 1992). The site is now managed by the Fenland Archaeological Trust and in 1987 it was decided that the problem of drying of the site should be mitigated against. To this end an artificial lake was constructed covering the majority of the platform and part of the post alignment, along with the construction of a museum and visitor centre. With an approximate circumference of 400 m, the lake was created by means of excavating a trench to the depth of an underlying clay unit with low permeability and installing a polythene membrane into it. This method of retaining water over the site was cost efficient and rapid and has kept the Flag Fen archaeological remains within its influence saturated (Pryor, 2001).

The site at Flag Fen, similar to other important wetland archaeological sites such as Sutton Common and the Sweet Track, has become the focus of significant and diverse research to increase knowledge into the processes and dynamics of the burial environment and the development of effective monitoring techniques (Caple & Dungworth, 1998). It has also provided an opportunity to understand the effects of engineering activity designed specifically to enhance the preservation potential of the burial environment (Pryor, 2001). Even though the projects at Flag Fen and the Sweet Track have similar aims, to protect wet preserved organic archaeological remains, and both have been established for a number of years, the two approaches are considerably different. The value of this diversity is significant as it explores potential solutions to a common problem within the archaeological community, and the re-wetting being carried out at Sutton

Common is providing the opportunity to add to this knowledge, taking into account the experiences of these two important projects. Additionally, adjacent to the Flag Fen site and in an area where the causeway exists, sewage sludge from a local sewerage plant was injected into the ground on a large scale until very recently. This provides a very real threat to the continued preservation of remains at the site, and an opportunity to understand this process so that such threats to other sites can be assessed more accurately.

Work on Flag Fen included the monitoring of the burial environment using parameters such as pH, redox potential (Eh), depth of the water table and other water quality measurements. This work was undertaken as part of a wider project into the burial environment funded by English Heritage and carried out by the University of Durham (Caple & Dungworth, 1998). Pryor (2001), states that in the region where the monitoring took place (which is fed by percolating water from the lake on the site), the Eh values indicated a strongly reducing environment, suggesting that the creation of the lake has indeed produced conditions within the burial environment that are conducive to the continued preservation of the organic archaeological remains. The lake has allowed slow percolation of water into the ground after it has stagnated; in effect the lake has acted as a buffer, or filter, and removed oxygen from the water.

Studies looking specifically into the degradation of buried wood have also taken place at Flag Fen (Powell, 1999) involving burying samples of different species of wood at two different locations and then retrieving them at time-points over an 18 month period. By studying the retrieved wood samples at high resolution, using techniques such as Scanning Electron and Light Microscopy, an insight into the degradation process of wood was made within the context of specific burial conditions over a long period of time (3 years) since monitoring began. The study showed that in certain areas of Flag Fen, significant degradation of wood could occur in a short period of time and that this was dependant upon the conditions within the burial environment. The overall conclusion was that an increase in the water table around the Flag Fen area would limit all types of microbial decay of archaeological timbers in the future (Powell *et al.*, 2001).

The Sweet Track and Flag Fen are two well-known and highly studied archaeological sites that have been the subject of considerable monitoring and mitigation over the past few decades. However, the English Heritage sponsored wetland surveys identified numerous sites that either demonstrated the presence of well-preserved and archaeologically important remains, or had a high potential for these to exist. Furthermore, nearly all these sites were deemed to either be beyond saving or required urgent action in order to prevent total destruction of the wet-preserved archaeological resource. Taking the example of the Humber Wetlands Project, nine sites were identified through excavation assessments as containing wet-preserved, organic archaeological remains. Significant sites included Skipsea-38 (West Furze) where despite excavations undertaken on the site in 1880 being left open for several years, the site still showed good preservation of some materials but required hydrological management to ensure its protection (Van de Noort *et al.*, 1995). In the Humberhead Levels the Roman bridge at Rossington (Rossington-10) and the Roman road at Scaftworth (Scaftworth-5) were shown to contain well-preserved remains that were threatened by desiccation and were in urgent need of management (Van de Noort, 1997). In the Lincolnshire Marsh a significant site under threat was that of Butterbump (Willoughby-13), consisting of a barrow cemetery in the middle of which exists a small wetland. Contained within this wetland were wet-preserved organic archaeological remains, suggesting that the site may hold further important and well-preserved archaeological remains (Van de Noort & Ellis, 2001). Other significant archaeological sites identified in the foreshore environment within the Vale of York at Melton and North Ferriby (Van de Noort & Ellis, 1999), are threatened not so much by a lack of saturation but by the physical destruction of the archaeological contexts resulting from erosion. All of these sites have the potential to benefit from accurate monitoring of the burial environment, either through initial assessment of the burial conditions leading to an assessment of preservation potential, or through ongoing monitoring after the initiation of site management aimed at securing *in situ* preservation.

1.4 Aims and objectives of the thesis

This research project, studying methods of, and carrying out, monitoring of the burial environment on Sutton Common, resulted from the recommendations made following archaeological assessment of the site undertaken in 1999 (Van de Noort & Chapman, 1999). These recommendations state that "the experimental and pioneering nature of re-wetting of an archaeological site in order to achieve enhanced *in situ* preservation should be recognised. In view of this, any re-wetting programme should be accompanied by a programme of monitoring of the groundwater hydrology and its effect on the archaeological deposits. This would enable the reversal of the re-wetting programme if this was found to have adverse effects on the burial environment, while the obtained information is of significant academic importance." (Van de Noort & Chapman, 1999: p82-83)

The core of the research presented herein, is the monitoring of burial conditions of the organic archaeological resource that exists on Sutton Common. This encompasses the gathering, presentation and interpretation of monitoring data obtained during the fieldwork phase, along with laboratory data generated by microbiological assessment and additional, complementary sources of data.

The aims of this thesis fall broadly into two categories. There are those that directly relate to the conditions that exist within the burial environment on Sutton Common and those that relate to the methodological approach taken and the development of techniques for the effective monitoring of the burial environment. This second point relates to the generation of baseline data concerning the dynamics of the burial environment and the development of a multidisciplinary approach to monitoring, to ensure the accurate assessment of wetland archaeological sites. More specifically the aims of the research are -

1. To develop a monitoring package that can effectively and accurately identify conditions that are conducive to the long-term preservation of organic archaeological materials, specifically wood.
2. To understand in detail the burial dynamics of Sutton Common
3. To identify the changes within the burial environment on Sutton Common that occurred as a consequence of activities aimed at raising the water

table and assess whether these increased the potential for *in situ* preservation

Achieving the above aims could have a significant influence upon the effective monitoring of sites such as those that have been discussed earlier in this chapter. The information gained from the extensive monitoring programme that has been undertaken on Sutton Common will provide comparable data for other sites that have been subjected to similar monitoring, especially in the future if similar techniques are applied.

The development of a well documented and demonstrably effective monitoring approach should make the accurate monitoring of sensitive archaeological sites more accessible in the future, therefore encouraging more monitoring of these sites to take place. This would lead to more archaeological remains being preserved *in situ* rather than having to be preserved on record, as often occurs for those sites that are at threat, or even worse, left to deteriorate in the ground. In addition to this, known, important archaeological sites that are currently physically preserved can easily be the subject of targeted monitoring to ensure that burial conditions are indeed suitable for preservation and remain so into the future.

Future archaeological surveys, of any scale, could also include a component of monitoring, whereas this has not necessarily been the case for previous surveys. This would encourage the monitoring component to be included in the initial stages of fieldwork, from the proposal stage onwards ensuring that costs would be accommodated for and funding made available.

Overall, this thesis sets out to demonstrate that the monitoring of the burial environment, using effective and multidisciplinary methods, can yield accurate results and provide an unprecedented insight into the burial conditions of wet-preserved archaeological remains. It shows that where this is an issue, especially regarding *in situ* preservation, such an approach can be cost effective and be can used as an effective tool for site management.

1.5 Structure of the thesis

The structure of this thesis reflects a positivist approach with a layout of introduction, methods, presentation of results, interpretation and conclusion.

This chapter introduces the value of wet-preserved, organic archaeological remains along with the concepts and issues surrounding *in situ* preservation. Examples of wetland archaeological sites are discussed and information on previous monitoring work is presented. Finally, the aims and objectives of the research are stated.

Chapter 2 provides a background to Sutton Common, including the physical setting of the site and the archaeological structures that are present, along with a history of the investigations that have taken place. Details of the current 'Sutton Common Project' are presented including details of the drainage-mitigation work that has been carried out.

Chapter 3 will present detailed information on the techniques and methodological approaches used during the course of the research and the ways in which the data has been presented.

Chapter 4 is an intermediate results chapter where physical and environmental details of sampling locations are presented. This chapter is separate from the other results chapters in order to provide clear reference.

Chapter 5 presents the results of the hydrological monitoring that has taken place on Sutton Common in the form of GIS generated surfaces representing the water table. Also presented in this chapter are results derived from integrating the hydrological representations and additional spatial data for archaeological wood identified during excavations. Additional observations and measurements on the hydrological characteristics of the deposits on Sutton Common are also presented. Chapters 6 and 7 present the results obtained during the monitoring of soil redox potentials and microbiological assessment of soil profile samples respectively. Results are presented within the context of previous published research.

Chapter 8 provides an overview of the work that has been carried out and presents the significant findings of the monitoring programme. Discussion includes the integration of the findings derived from the individual approaches for hydrological, soil redox and microbiological techniques followed by a critical assessment of these methods. Detailed recommendations for the individual techniques are presented and the final sections of the chapter include separate discussion of the impact of the re-wetting and flooding on the site.

Chapter 9 presents an overview of the main findings of the research along with a reflection on the original aims. General recommendations arising from this research are presented along with a legacy section where details are presented of the contribution that this work has made to the field of archaeology.

1.6 Summary

This chapter has introduced the issue of *in situ* preservation of organic archaeological remains through discussion of the importance of such materials. The need for an effective means to assess conditions within the burial environment is presented as a consequence of ever-changing threats to this archaeological resource. The efforts at recognising and addressing this problem through the extensive wetland archaeological survey that have taken place during the latter part of the 20th century are presented as has the wetland strategy developed as a result of these by English Heritage.

Examples of successful management of wetland archaeological sites are given and the potential number of additional sites highlighted by examples identified during the course of the Humber Wetlands Project. The aims and objectives of this piece of work have been stated and an outline of how this thesis is structured is given. The following chapter will provide details of the study site, Sutton Common, its environmental setting, the archaeology present and a history of archaeological investigations on the site. Details of the 'Sutton Common Project' are given, including details of the drainage mitigation strategy that has been undertaken with the aim of raising the water table across the site.

Chapter 2 The study area

2.1 Introduction

The existence of the earthwork enclosures on Sutton Common has been widely known within the archaeological community for almost 150 years. Until relatively recently the site was extremely wet in character and seemingly always had been. The site has been cited as evidence for the activity of fugitives (Allcroft, 1908), the Roman invasion of Britain (cited by Whiting, 1938) and possible ceremonial functions (Parker Pearson & Sydes, 1997). Sutton Common has now been extensively drained and this plus agricultural improvement on the site has had a significant impact. Although Sutton Common is recognised as an important site in terms of its archaeological status, the archaeological remains present on the site are under a very real threat from further degradation.

This chapter will introduce the study site; provide a description of the archaeological remains and an account of changes that have occurred on the site and its environment. Details of the previous excavations and examples of the type of preserved organic archaeological materials will also be presented. The events that led to the site being taken into the protective ownership by the Carstairs Countryside Trust (CCT) will be detailed along with the aspirations of the current 'Sutton Common Project', headed by CCT.

2.2 Sutton Common, its archaeology and changing environment

Sutton Common has been recognised as a unique archaeological site in the context of its type of construction within a wetland environment in England, although to date, its actual function is not definitively known (Van de Noort & Chapman, 2001). As such, it has attracted great interest and has been the subject of many investigations describing both its archaeological and environmental background.

2.2.1 Environmental background

Sutton Common is located approximately 10 km north of Doncaster, South Yorkshire, near the town of Askern. The site lies close to the foot of a ridge of the

Upper Magnesian Limestone located to the west of the silts and clays of the pro-glacial Lake Humber (Gaunt, 1994). The site lies within the Humberhead Levels, a flat, low-lying region to the southwest of the upper reaches of the Humber estuary, bounded by the River Aire to the north, the River Trent to the East and to the south and west by the higher ground of the Pennines (Figure 2.1). Ellis (1997) provides a detailed synopsis of the characteristics of the Humberhead Levels. This area, approximately 620 km^2, lies at no more than 5 m OD, the characteristics of which are mainly due to the geological conditions resulting from the last glacial period and subsequent sea-level rise, and secondly, from the extensive modification of the area by human activity.

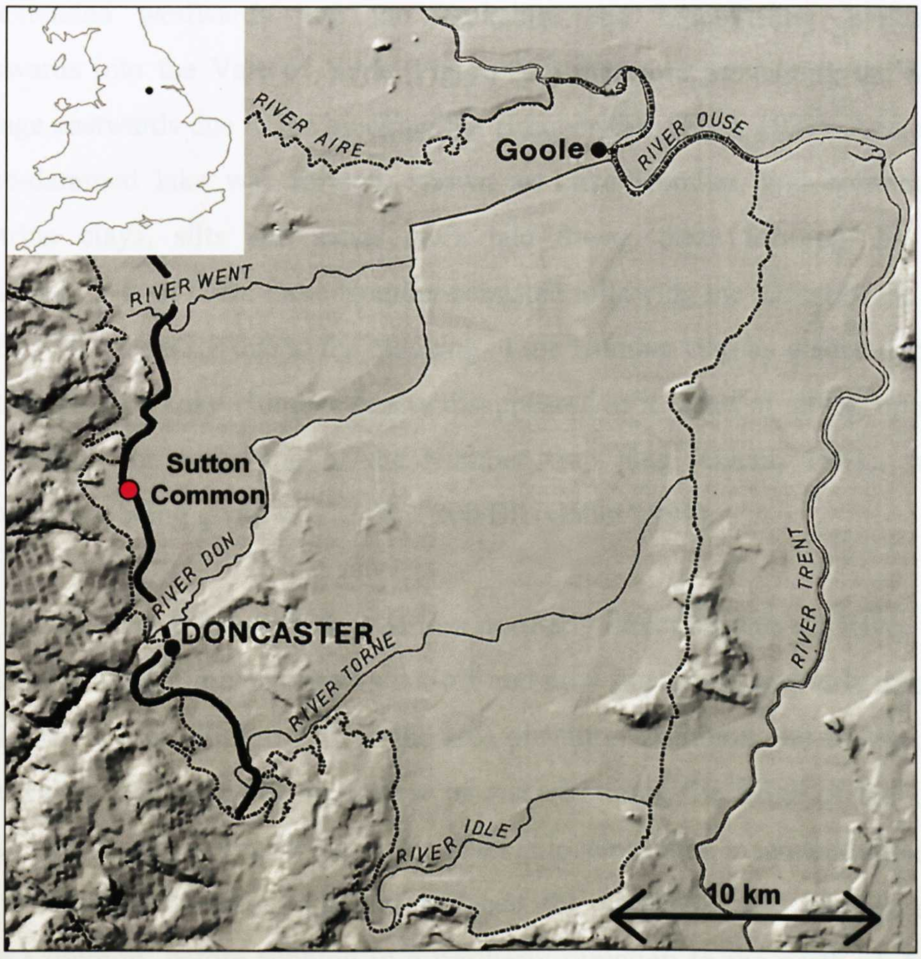


Figure 2.1 DEM of the Humberhead Levels with relief, drainage, solid geology and the location of Sutton Common. Thick line shows boundary between Upper Magnesian Limestone and Upper Permian Marl. From Ellis (1997).

Four main rivers drain the Humberhead Levels; the Don and Went drain north to the Ouse, and the Torne and Idle east to the Trent, although the present day pattern is different from that in the past. For example, parts of the lower Don have been the subject of diversion and straightening as has the Torne. In addition to modifications to the natural watercourses, an extensive network of artificial drains exist, installed over the past three centuries, including waterways such as the Aire and Calder Navigation.

The on-site deposits are dominated by the presence of surface peats relating to the former course of the Hampole Beck. Lillie (1997), citing the work of Gaunt (1976), describes the presence of an irregular peat-filled channel incising the 25-Foot Drift that flowed through the archaeological enclosures located on Sutton Common. At around 18,000 years BP, during the late Devensian Period, glacial ice extended westwards into the Yorkshire and Lincolnshire Wolds and southwards into the Vale of York (Figure 2.2) therefore preventing the natural drainage eastwards due to ice blocking the Humber Gap (Ellis, 1997). As a result, an ice-dammed lake was formed, known as Lake Humber, and consequently lacustrine clays, silts and sands were laid down, these forming the afore mentioned 25-Foot Drift. Lake Humber persisted following the retreat of the ice at about 13,000 years BP due to the blocking of the Humber Gap by glacial deposits. It is thought that Lake Humber finally disappeared as a result of silting up rather than through the breaching of the Humber Gap plug (Gaunt, 1981), with a minimum age being given as 11,100 ± 200 BP (Gaunt 1994).

The Hampole Beck formerly flowed in a northerly direction into the River Went but at some time in prehistory was cut-off and now flows in a southerly direction into the River Don (Figure 2.3). In the area of Sutton Common, the course of the palaeo-Beck runs from the southwest of Askern, along the ridge of the Upper Magnesian Limestone (upon which the town is located) then meanders initially in a north easterly direction, passing between the archaeological enclosures on Sutton Common, before running in a northerly direction to the north of Askern (Head *et al.*, 1997). The onset of peat formation within the palaeochannel of the Hampole Beck is placed sometime after *c.* 5320-3990 cal BC (Lillie, 1997).

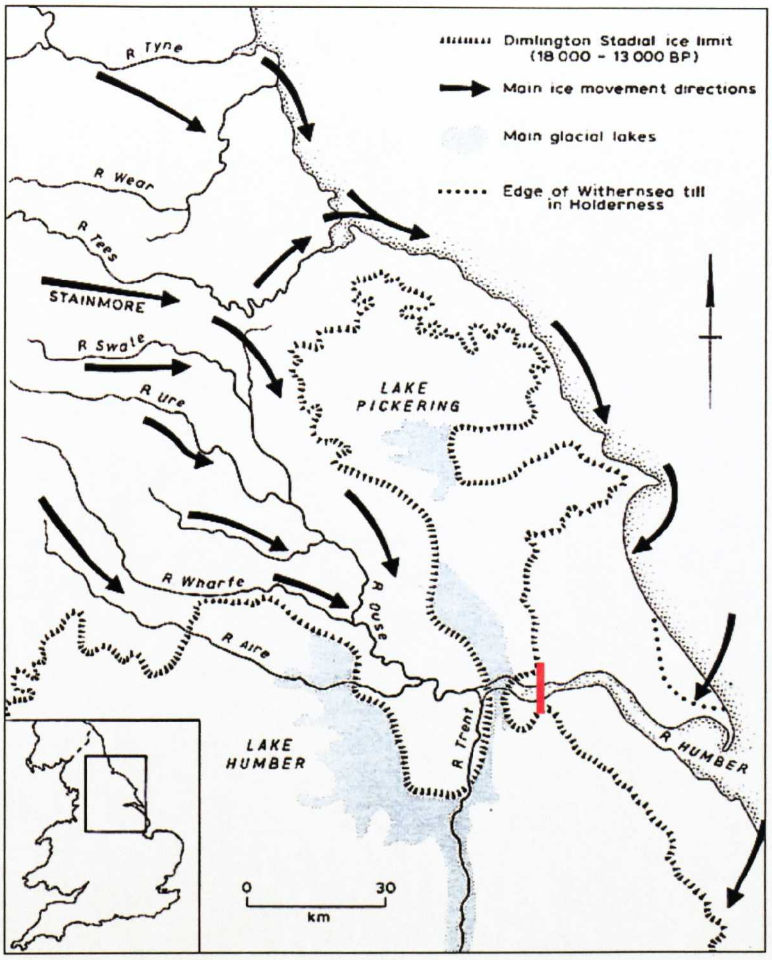


Figure 2.2 The location of the proglacial Lake Humber during the time of the Dimlington Stadial. From Catt (1990). The red line shows the approximate location of the Humber Gap.

Sutton Common itself lies within a field of irregular shape and is demarcated by drainage ditches, sections of which form part of the main drainage conduit from a greater area of agricultural land to the west, these being the Thistle Goit and Haywood drains (Figure 2.4). To the southeast lies the SSSI of Shirley Pool with an area of trees bordering the site; these continue along the eastern edge running northwards as Shirley Wood, an area that is characteristically very wet. The area to the north of Sutton Common is named Rushy Moor and although subject to land improvements, is again wet in character.

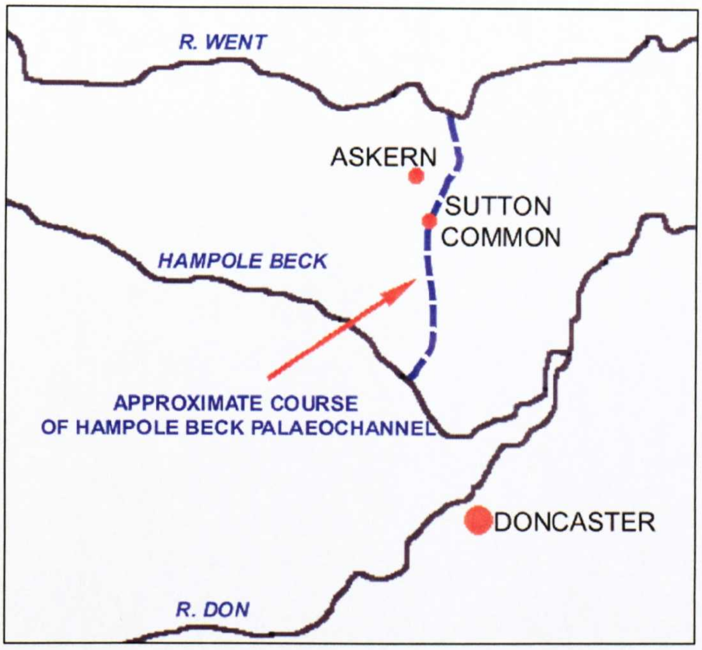


Figure 2.3 Map showing the course of the Hampole Beck palaeochannel in relation to the current drainage network in the Sutton Common region.

From literary sources, Parker Pearson and Sydes (1997) describe the common being enclosed at around 1850. Enclosure divides were by means of shallow ditches of less than 1 m deep and these along with some shallow, clay field drains, served to assist in the removal of surface water (Geomorphological Services Ltd. 1990). Despite this, early literary sources describe the site as still being very wet in nature and that the site remained as wetland pasture until 1979 when the larger of the two archaeological enclosures was bulldozed and subsequently ploughed. Parker Pearson & Sydes (1997) describe this event as occurring in 1980; however aerial photography clearly shows that the field within which the bulldozed enclosure is situated had been ploughed by September 1979. Just prior to this, running from 1977, extensive drainage of the area resulted in a significant drop in the level of the general water table. This work has been titled the 'Thistle Goit Scheme' as it resulted in the redirection of surface water away from the SSSI at Shirley Wood and into the Thistle Goit Drain (Geomorphological Services Ltd, 1990). As part of this scheme, pumping capacity within the system was increased, several open drains were deepened, including the Stream Dike/Thistle Goit Drain itself and the Haywood and Coalit Drain immediately bordering Sutton Common and included the construction of a new drain, the Rushy Moor Cross Drain.

Significantly, this scheme also included the installation of under-field drains crossing the earthworks of the archaeological enclosures in an east-west orientation.

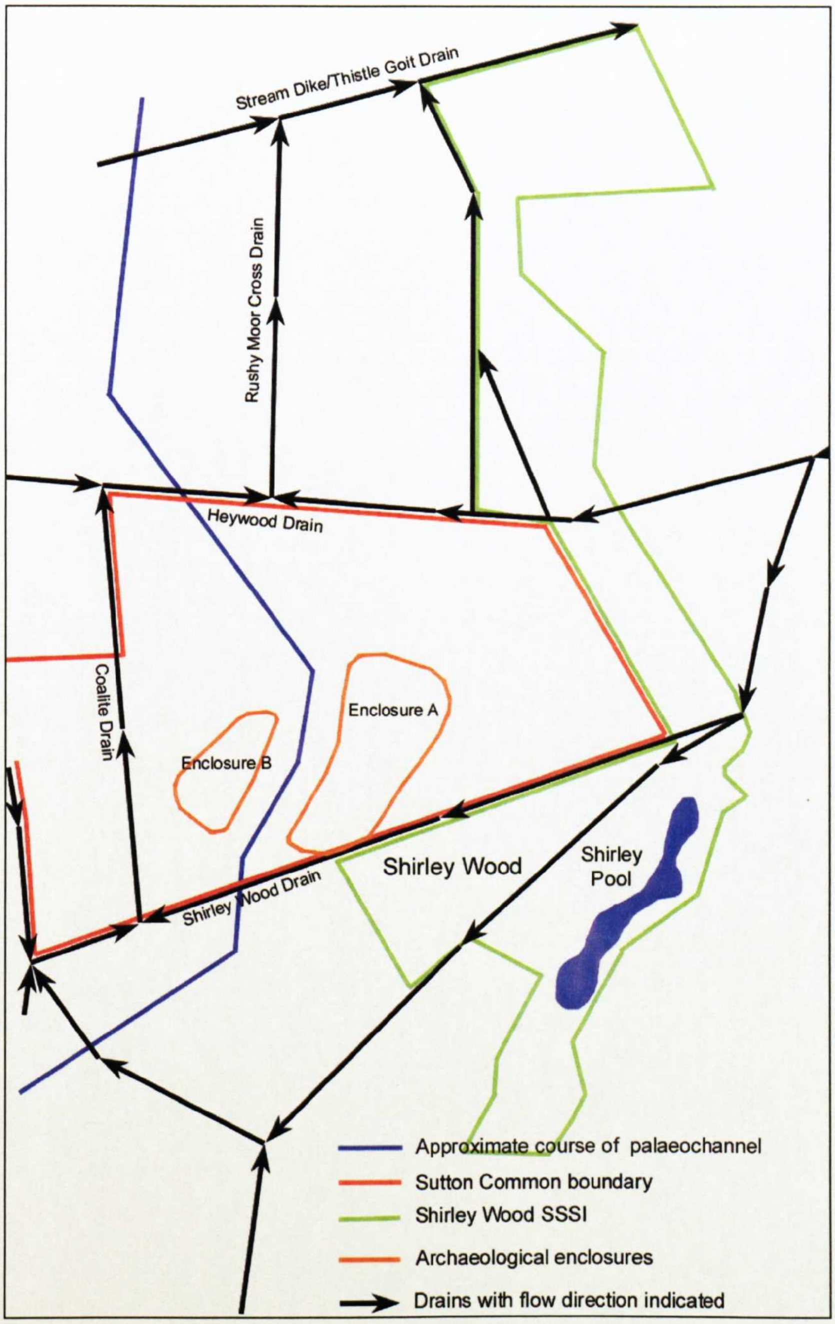


Figure 2.4 Map showing the surface drainage network of Sutton Common and the immediate area. After Geomorphological Services Ltd. (1990).

2.2.2 Archaeological background

Archaeological sites within the enclosed area of Sutton Common have been identified in four areas and are described by Parker Pearson and Sydes (1997). They consist of two enclosures and two raised areas upon which evidence of human activity has been identified. Enclosure A is located on the largest and highest area of ground (4.5 – 5.6 m ASL). Enclosure B is located to the west of A on the opposite side of the palaeochannel of the Hampole Beck (refer to Figure 2.5). A further two smaller sites are located on areas of raised topography to the north of Enclosures A and B, with activity on one being dated to the Mesolithic or early Neolithic (Head *et al.*, 1997).

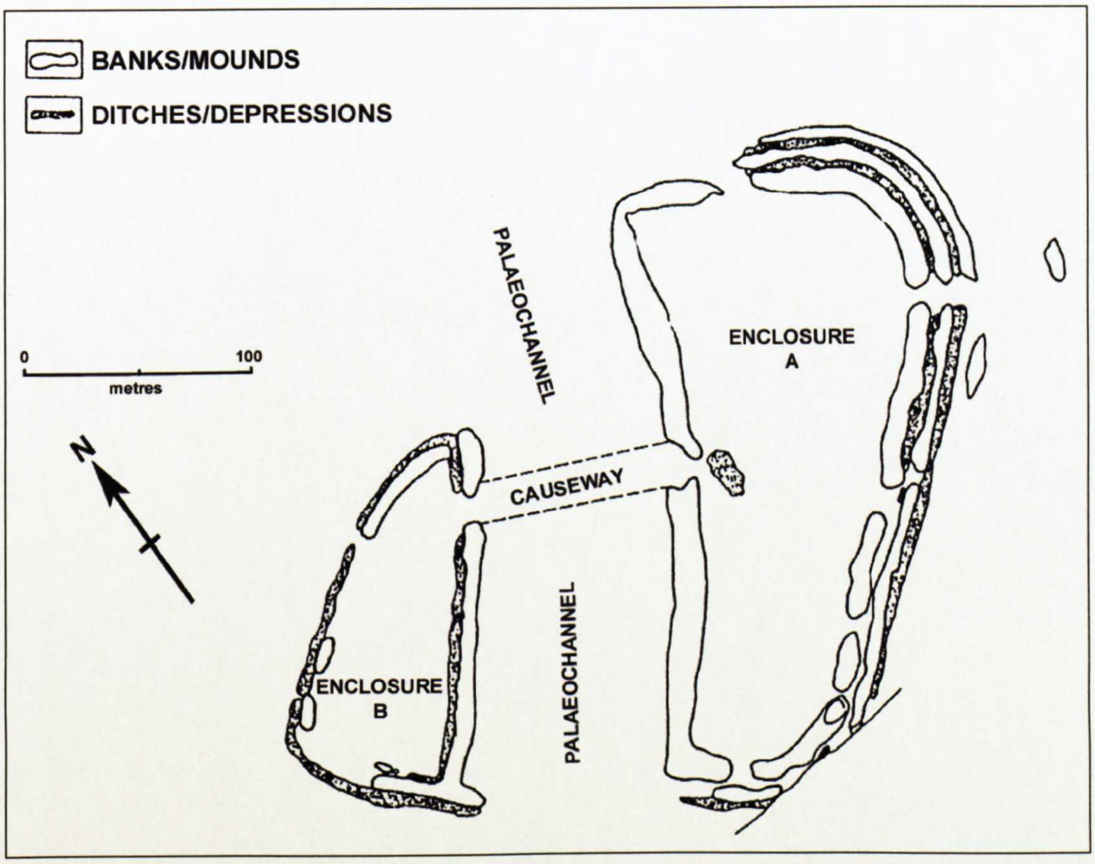


Figure 2.5 Outline of Enclosures A and B. Adapted from Parker Pearson & Merrony (1993) and based on an original survey by Whiting (1938).

Enclosure A now survives only as a crop / soil mark after being bulldozed as part of land 'improvements' around 1980, but prior to this it existed as an upstanding earthwork. It measures approximately 250 m in length by 130 m in width, with the western edge consisting of a single bank whereas the northern and eastern edges are formed by a double ditch with three banks (Head *et al.*, 1997). There are a number of breaks within the banks and ditches suggesting the presence of one or more entrances to the enclosure. Enclosure B is smaller than A, being 150 m in length by 80 m in width and is more triangular in shape. Figure 2.6 is an aerial photograph taken prior to Enclosure A being bulldozed and clearly shows the upstanding earthworks of both enclosures and the unimproved nature of the vegetation. Figure 2.7 shows a similar aerial photograph taken in 1979 following Enclosure A being ploughed for the first time. The location of the enclosure can clearly be seen in the soil marks left by the action of the plough, as can the banks and ditches. Also, the damage to the south eastern edge of Enclosure B can be seen as a lighter coloured area. Although the area around Enclosure B had not been ploughed at the time this photograph was taken, it soon was, leading to further damage to its periphery.

Figure 2.6 Aerial photograph of the Sutton Common enclosures viewed from the north taken in 1976 prior to them being damaged. (DNR877 SE5612/8/36 - 7.7.1976) NMRC © Crown Copyright.

Figure 2.7 Aerial photograph of the Sutton Common enclosures viewed from the north taken in 1979 following Enclosure A being ploughed for the first time. (DNR1586 SE5612/26/7 - 13.9.1979) NMRC © Crown Copyright.

Both enclosures have been the subject of numerous small-scale excavations and assessments dating back to the end of the nineteenth century, when they were first described and mapped by the Rev. Scott Surtees in a pamphlet entitled *A Roman Camp in South Yorkshire* (Whiting, 1938). Allcroft (1938) referred to the enclosures as being the site for "fugitives driven from the dry ground above the marshes" (Whiting, 1938). Excavations were conducted by a Dr. Corbett of Doncaster in 1909/10 during which decayed wood, thatch and arrow flints were discovered although no records were surviving in 1938. In 1926, a Mr. Day of Doncaster Grammar School excavated a number of trenches through the ramparts of Enclosure A, but again no records of the excavations have survived (Whiting, 1938).

The earliest large-scale and most detailed excavations were undertaken by C.E. Whiting between 1933 and 1935 (Whiting, 1938). These excavations are now regarded as extremely important as they are the only extensively recorded excavations that were carried out in Enclosure A whilst it was upstanding. They also clearly demonstrate the potential wealth of organic archaeological materials and artefacts preserved within the wet deposits of the site, such as a possible wheel, a plank-lined pit and a post alignment crossing the palaeochannel (Whiting, 1938). The investigations undertaken within Enclosure A revealed the construction and form of the banks and ditches, the associated stone revetment and a series of 'huts' present on the ramparts themselves (refer to Figure 2.5). The importance of this detailed record of the archaeology on Sutton Common is because no further information on such features can now be gained due to the destruction of the earthworks and the progressive desiccation that has occurred during the intervening years.

Throughout the late 1980's and early 1990's, Enclosures A and B were subjected to five assessments aimed at determining the condition of the surviving organic remains. These identified that the lower layers of the ditches contained waterlogged timbers that remained in a good state of preservation, but that there was evidence of a fluctuating water table and that the timbers were progressively drying out. Assessment of Enclosure A revealed that, despite the extensive damage caused by the bulldozing and subsequent ploughing, features still survived, including archaeological wood (Parker Pearson & Merrony, 1993). The 1993 assessment revealed that degradation of the organic archaeological resource was proceeding rapidly in those contexts that still held material and ultimately recommended that the site be subjected to extensive excavation.

More recently, Parker Pearson & Sydes (1997) provided an extensive description of the archaeological and environmental background to Sutton Common. This piece of work discusses the deterioration observed in archaeological wood and provides further details of the excavations that took place.

A series of excavations followed the acquisition of the site by the CCT in 1997, progressively increasing in size and complexity. Investigations in 1998 included targeted excavation of both enclosures to answer academic questions pertinent to site function, such as whether a causeway existed between the two enclosures crossing the palaeochannel and whether palaeoenvironmental material contemporaneous with the settlement of the site existed within the peat deposits adjacent to Shirley Wood. They were also to act as a preservation assessment for archaeological remains, determining whether archaeological features survived within Enclosure A, and if so, whether these included a waterlogged component. The excavations were also designed to provide informed recommendations for the future management of Sutton Common, specifically its suitability for re-wetting (Van de Noort & Chapman, 1999). All these questions were addressed, with archaeological features being identified immediately below the ploughsoil within Enclosure A and waterlogged contexts exhibiting wet-preserved archaeological wood being identified within the ditches. The existence of a causeway, and its structure, were confirmed and the possibilities for long-term *in situ* preservation were presented.

This was followed in 1999 by a more systematic and extensive assessment of the interior Enclosure A when ten 30 x 30 m and a single 30 x 30 m trench were excavated (Figure 2.8). The aims of these excavations included assessing the extent and preservation of features within Enclosure A and to answer academic questions on the relationship between the previously identified causeway and the western entrance of Enclosure A (Van de Noort & Chapman, 2000). The recommendations arising from this were that a programme of further excavation be carried out within the interior of Enclosure A in order to address a number of outstanding academic issues including; function, phasing of activity and dating. Further to this, it was acknowledged that wet-preserved archaeological remains within Enclosure A were rapidly desiccating and that the credibility of the wider programme of *in situ* preservation and site management would be undermined if those remains that could not be preserved were not researched (Van de Noort & Chapman, 2001).

On this recommendation, planned excavations involving the stripping of the ploughsoil from the entirety of Enclosure A were made, to take place over two excavation seasons. These took place during the summers of 2002 and 2003 (Figure 2.8).

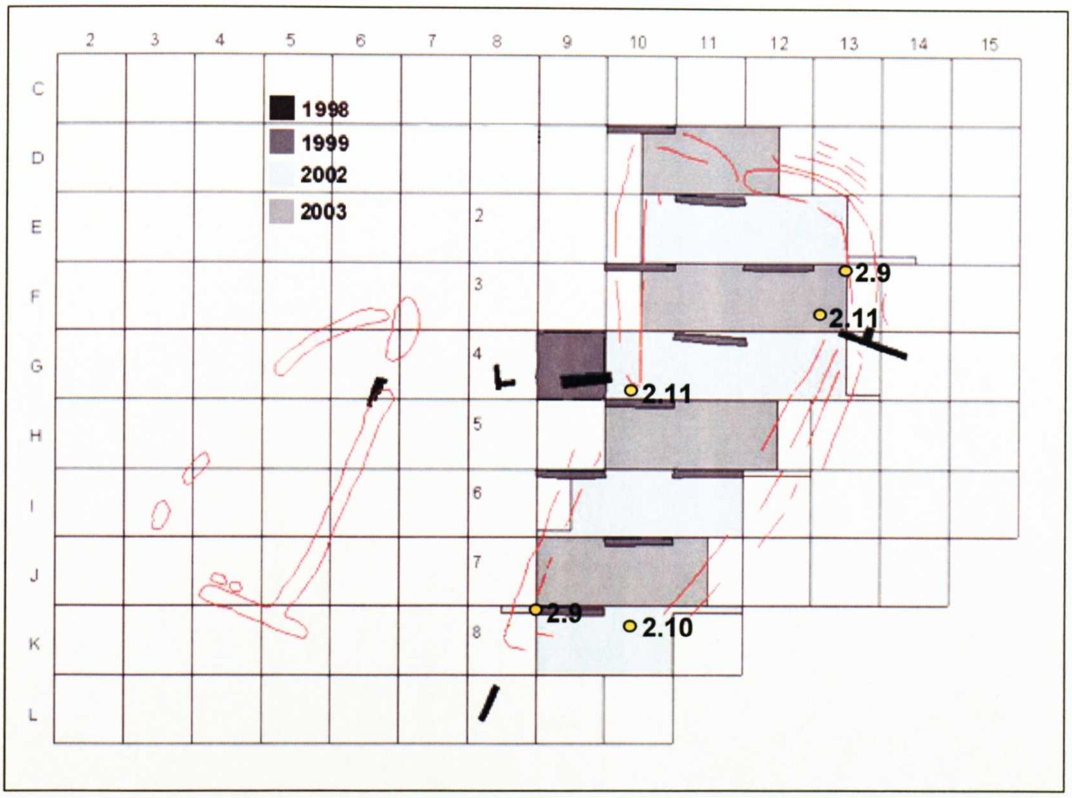


Figure 2.8 Location of trenches during four seasons of excavations at Sutton Common showing the north-south orientated 30 m grid upon which all work is based. Adapted from a GIS map generated by Henry Chapman, The University of Hull. Additional points relate to the location of materials shown in figures 2.9-9.

The types of organic archaeological remains that have been identified during excavations on Sutton Common over recent years consist mainly of the worked ends of posts or stakes. The stakes were sharpened to a pencil point, (for the most part) for the construction of a palisade, or a low earth bank bordering the entire enclosure, and also delimiting the causeway crossing the palaeochannel (refer to Figure 2.9). Large posts shaped to have flattened bases have been identified at both the eastern and western entrances of Enclosure A and smaller, similarly constructed posts, form structural elements of some of the internal features (refer to Figures 2.10 and 2.11).

The quality of preservation exhibited by excavated materials varies quite considerably depending upon its context. The interior of Enclosure A is, on the whole, characterised by severe degradation. The entrance posts in this area still retain a large amount of wood, but this is due to the large size of the pieces, as the quality of preservation is generally poor. Preservation of archaeological wood incorporated into the fills of ditches, especially along the eastern edge of Enclosure A, show good preservation, although desiccation within these contexts is evident. The best quality of preservation so far identified relates to one specific feature located in the southern part of the enclosure, this feature having been interpreted as a possible well. The structure itself consists of vertical stakes with the remnants of woven rods between them. In the base were a number of roundwood beams laid flat (refer to Figure 2.12). The reason for the exceptional quality of preservation in this location is its depth, with it existing below the level of the water table.

Figure 2.9 Exposed section of the Enclosure A palisade structure at Sutton Common. 2003 excavations. Refer to Figure 2.8 for location.

Figure 2.10 Exposed section of flat-bottomed post from internal structure of Enclosure A. 2002 excavations. Refer to Figure 2.8 for location.

Figure 2.11 Exposed section of large flat-bottomed posts associated with Enclosure A entrances. 2002 and 2003 excavations respectively. Refer to Figure 2.8 for location.

Figure 2.12 Part of the excavated 'well' within Enclosure A exhibiting very good preservation of archaeological wood. 2002 excavations. Refer to Figure 2.8 for location.

2.2.3 Recent drainage activity

Little further investigation of the site took place following Whiting's excavations, until 1987 when the South Yorkshire Archaeological Unit, supported by English Heritage, undertook an assessment of the condition of the surviving archaeological remains (Sydes & Symonds, 1987). This was in response to the observation that the site was under a very real threat of being destroyed. Around 1980, Enclosure A and the southern part of Enclosure B were bulldozed in preparation for the installation of field drains as part of Ministry of Agriculture Fisheries and Food (MAFF) funded agricultural improvements. The period of the late 1970s and early 1980s appears to be extremely significant in the history of Sutton Common as it marks a complete change in land use and drainage characteristics. Prior to this, conditions must have remained relatively stable, with high water-levels being prevalent, this being demonstrated by the survival of prehistoric organic archaeological remains.

Early drainage activities followed the enclosure of the site in 1858 when a number of small dykes were dug to improve the quality of pasture. These dykes were shallow (less than 1 m) and probably only functioned to remove surface water from the site. The effect of these activities has subsequently been assessed as minimal and are likely to have only slightly reduced the summer water levels (Geomorphological Services Ltd., 1990).

No further drainage activities appear to have occurred until 1947 when pumps were installed in the ditches that are linked to Sutton Common. The function of these pumps was to counteract the effect of subsidence caused by the collapse of mine workings in the area, which caused an increase in the persistence of surface water. However, the impact of the pumps upon the hydrology of the site was assessed as being minimal following a hydrological appraisal commissioned by English Heritage and undertaken by Geomorphological Services Limited (1990).

The initiation of major drainage improvements occurred between 1977 and 1982 when a series of works were carried out. These included the replacement of drainage pumps in the Thistle Goit Drain and Haywood Drain, the construction of a major new drain extension across Rushy Moor and the installation of substantial underfield drainage across the field within which the archaeological enclosures are located. Deepening of the open drains was also undertaken during this period, increasing the depth to below 2 m O.D. The effect of these works was substantial, with the amount and time that ponded surface water was observed on the site being significantly reduced and the open drains around the site were laid dry for much of the year (Geomorhological Services Ltd., 1990). This suggests that there had been a significant reduction in the groundwater conditions over the site, which would have had a dramatic impact upon the condition of surviving organic archaeological remains. Serious desiccation and degradation of the majority of the organic archaeological resource preserved on Sutton Common would have been initiated at this time.

Figure 2.13 shows the location and extent of underfield drainage on Sutton Common at the present time. The drains that are present across Enclosure A were installed as part of the Thistle Goit implementation between 1977-1982. The exact date of the drains outside this area is difficult to ascertain as they appear to have been installed at a number of different times. The majority of the field drains on the site were also installed during the Thistle Goit implementation, however, following excavations within the palaeochannel during 1998 by the University of Hull, drains in this area were revealed to consist of corrugated plastic field drains with permeable fill backfilling the slot trench. The presence of these drains is not recorded in the hydrological appraisal published in 1990 (Geomorphological Services Ltd, 1990), and they therefore appear to postdate this. Permeable fill has three purposes - to act as a filter, to improve drain inflow characteristics and to act as a connector for moling or subsoiling (Thomasson, 1975). Since the palaeochannel is still one of the wettest areas of the site due to its low lying character, it seems logical that these drains were installed to further combat seasonal saturation, the use of permeable fill further enhancing their effectiveness. It is not known whether such drains exist outside the area of the palaeochannel.

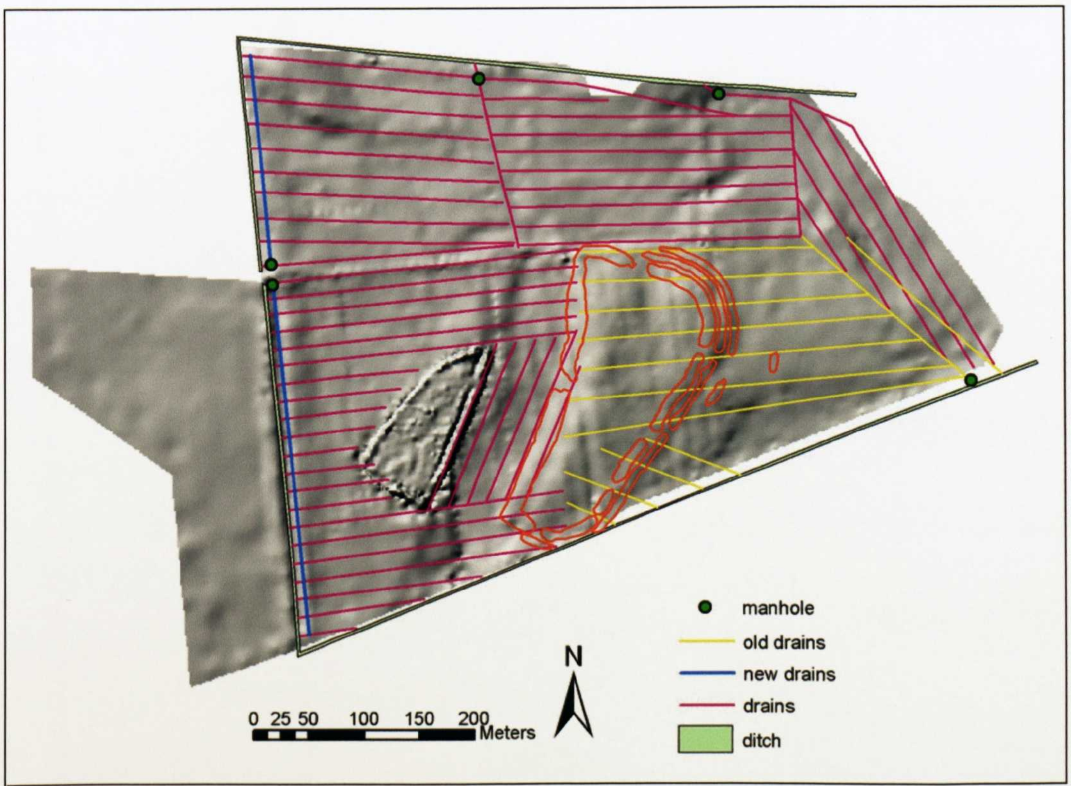


Figure 2.13 GIS generated map of the field drains present on Sutton Common. 'Old drains' relate to tile drains dating to the intensive period of drainage between 1977-1982 at the time of the Thistle Goit implementation. 'Drains' relate to drains postdating the Thistle Goit implementation. 'New drains' are those installed as part of the Sutton Common Project drainage mitigation. Digitised from a map supplied by Grantham Brundell & Farran.

2.3 The Sutton Common Project

The name 'The Sutton Common Project' relates to recent activities occurring on Sutton Common and initiatives involving the local community. In 1997 ownership of Sutton Common was transferred to the Carstairs Countryside Trust (CCT) with the aid of English Heritage and the Heritage Lottery Fund. The CCT is a small independent charity that is actively involved in the conservation of the countryside and has taken more than 15 sites into protective ownership. The CCT head up the 'Sutton Common Project' and actively involve the local community, with the site being developed as an amenity and conservation area as well as an historic resource. As part of this project, a limited reconstruction of the archaeological enclosures may occur in the future.

The CCT has been instrumental in furthering research on the site and acquired the funding for the research described herein in association with the Countryside Agency. The CCT actively manages conservation on Sutton Common and has implemented a number of improvements with the aim of re-creating the former wetland environment. Such a valuable wetland habitat would attract rare and sensitive flora and fauna, and would be combined with the *in situ* preservation of the organic archaeological remains still surviving on the site.

As part of the attempts to reinstate the former wetland environment a number of drainage mitigation works have taken place or have been proposed. In November 1999 engineering work started, aimed at capturing the outfall of field drains and reducing the effectiveness of the drainage ditches surrounding the site. Figure 2.13 shows the layout of underfield drainage over the Sutton Common site and the location of the new drains diverting flow away from their original outfall into the drainage ditches and ultimately, from the site. On the map, the 'new drains' are those that were installed as part of the recent drainage mitigation.

Trenches were dug around the periphery of the main field and drainage pipe laid perpendicular to the field drains to capture their flow. In theory, the amount of water draining from the field can be controlled via a simple mechanism as illustrated in Figure 2.14, whereby the incoming pipe rises up into a concrete manhole. The level of the water is adjusted by raising or lowering the level of the inflow pipe. In addition, dams were placed in two locations on the site to restrict the loss of water from drainage ditches, the northern one of which is shown in Figure 2.15. Further proposals include the construction of a bund to prevent subsurface flow out of the southern end of the palaeochannel, although the exact location of this is yet to be decided.

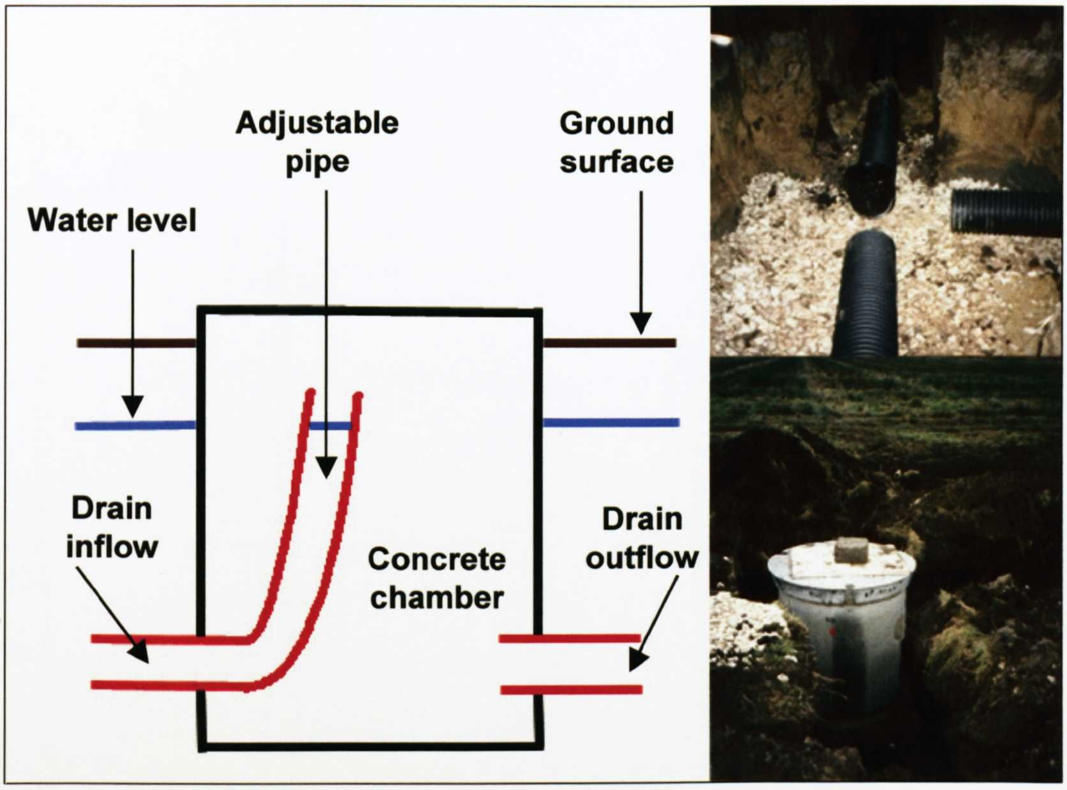


Figure 2.14 Diagram and photographs showing the re-engineered field drainage system installed on Sutton Common. The concrete chambers have a diameter of 1 m.

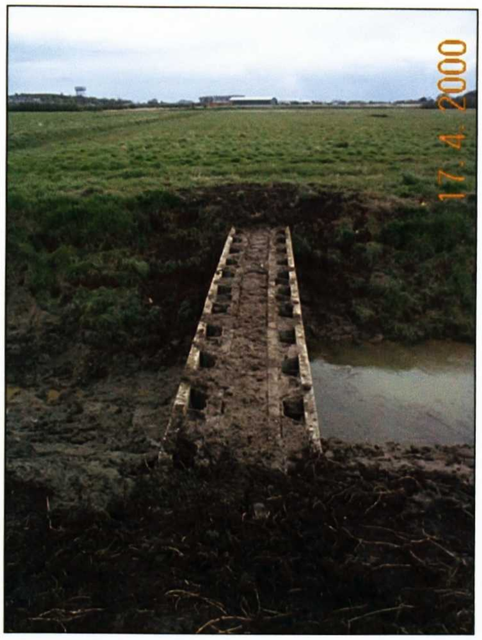


Figure 2.15 The dam installed within the drainage ditch running to the north of the archaeological enclosures. The dams are approximately 0.5 m in width.

There has also been a significant change in land management practices on the site since the change in ownership. This has involved a change from arable cropping, initially to set-aside, and more recently to pastoral use. This has resulted in the cessation of the damaging action of ploughing, an activity that has been taking its toll on the archaeological resource for over twenty years. It has also resulted in dramatically changing the vegetation cover on the site. Initially, the field was left as set-aside with only limited active management, in the form of irregular topping of the vegetation, aimed at reducing the occurrence of thistles. However, from 2000 onwards the site came under the close management of Andrew Booth, the tenant farmer for the CCT, leading to a change to pastoral use. This led to total grass coverage whereas previously, especially during the summer season, very tall vegetation was present.

2.4 Summary

As stated in Section 1.4, the aims and objectives of this study fall into two main categories; those relating directly to the influence of re-wetting activities on Sutton Common itself, and those for the development of techniques for monitoring archaeological sites containing buried, wet-preserved remains. The former is a requirement for monitoring the reaction of the burial environment to an activity that has not previously been documented. However, Sutton Common is well suited to the development of a monitoring approach and techniques for a number of reasons. Firstly, the archaeological resource is well documented and with this a comprehensive understanding of its environment has been obtained; such as its setting, geomorphology and climate. Also, the site has been actively managed for a number of years for nature and archaeological conservation/preservation and therefore access is very good. In addition to these, Sutton Common has a diverse number of burial environments relating to the variable on-site geomorphology, such as the palaeochannel, the raised drift deposits upon which the archaeological enclosures are located, and also the deep peat deposits associated with Shirley Wood. Having these environments within close proximity means that they are subjected to similar conditions and changes within the environment, therefore aiding in the interpretation of the monitoring data obtained.

This chapter has provided an overview of Sutton Common, including its geographical location and its environmental history. A background to the archaeology present on the site is given along with an overview of the archaeological investigations that have taken place and the quality of preservation of organic archaeological remains identified during the most recent excavations.

A crucial factor that has determined the character of the site, along with generating the great interest in it from the archaeological community and also determining the preservation of organic archaeological remains, is the level of drainage on the site and how this has developed over time. An overview of the drainage activity is therefore given, including details of the efforts made by the Sutton Common Project to reverse the trend of desiccation through re-engineering of the field drainage system.

The following chapter details the individual methods for monitoring of the site hydrology and soil redox potential, and also microbiological assessment of the soil profile that have taken place on Sutton Common.

Chapter 3 Methodology

3.1 Introduction

Three key variables have been studied in this thesis - soil hydrology relating to water table dynamics, soil chemistry through the measurement of redox potentials within the soil profile, and assessment of microbiological activity through the soil profile. This multidisciplinary approach has been chosen in order to provide the most accurate assessment of conditions within the burial environment as is possible. By utilising varied methods, the data acquired have the potential to provide supporting evidence for any patterns observed, something that is important when studying a complex system. For example, hydrology, soil chemistry and soil microbiological activity all influence burial conditions significantly and therefore, variations in one of these parameters could be reflected in one or more of the other assessed variables.

An additional reason for applying a multidisciplinary approach utilising hydrological, chemical and biological techniques, is to understand the dynamics of the burial environment at a greater resolution through the generation of comprehensive datasets. In previous assessments, often only a single variable is measured, usually hydrological status or variation. From this, conclusions were made upon the condition or potential for preservation of buried organic archaeological remains within the wider environment (Parker Pearson & Merrony, 1993; Cox *et al.*, 2001). However suitable, hydrological conditions alone do not ensure the persistence of remains within the burial environment. This is because degradation processes can continue under saturated conditions as a result of disturbance of the burial environment through, for example, groundwater movement or the introduction of water from an unsuitable source (Caple & Dungworth, 1998). By introducing further parameters such as soil chemistry and soil microbiology, a greater appreciation of the 'preservation environment' can be made and with it a far more accurate assessment of preservation potential.

The benefits of such a 'holistic' approach have been demonstrated by Capel & Dungworth (1998) who, by looking at a number of parameters including saturation and soil redox potentials, have produced a picture of the overall chemical balance of burial environments that exhibit well-preserved organic archaeological remains. Recent multidisciplinary work on the Sweet Track in Somerset (Brunning *et al.*, 2000) has further emphasised these findings.

In this chapter, detailed methodologies for the three approaches, hydrological monitoring, soil redox monitoring and soil microbiological assessment, will be presented. This will include field methods, laboratory techniques and analysis and presentation of the differing datasets.

3.2 Hydrological monitoring

Hydrological monitoring has been undertaken on Sutton Common in order to gain an understanding of the form and the dynamics of the water table across the site and how these vary throughout a yearly cycle. The monitoring exercise has also been used to identify the impact of the re-engineering of the field-drainage on Sutton Common to determine how this has affected the preservation potential of the archaeological material present.

It is essential to account for the degree of saturation within the burial environment when studying organic archaeological remains as it is the primary factor in their preservation. Previous studies into *in situ* preservation of wet-preserved archaeological remains have recognised this (Björdal & Nilsson, 2002b; Brunning *et al.*, 2000; Powell *et al.*, 2001). If not accounted for, the impact of factors such as seasonal variation cannot be assessed accurately and therefore no meaningful insight into preservation potential can be made. The hydrological work that has been carried out on Sutton Common is the first that has instigated a network of points for the systematic monitoring of the water table over the greater extent of a site. Previous studies have often relied upon isolated or targeted monitoring locations. For example, at the Sweet Track, early monitoring consisted of a series of 16 'boxes and tubes' (dip-wells) located along the 550 m stretch of the track contained within the Shapwick Heath nature reserve. These were monitored at weekly intervals and the results summarised into seasonal levels (Coles & Orme, 1983). This work was carried out to identify the affects of pumping water onto the reserve from an adjacent drain in order to maintain saturated conditions within the deposits containing the track remains. Prior to this it was clear that the track was not below the level of the water table, and hence unsaturated during dry seasons (Coles, 1995). A later reinvestigation of the Sweet Track aimed at determining whether the implementation of the pumping was maintaining an environment suitable for the continued preservation of the buried materials, used a far more sophisticated approach (Brunning *et al.*, 2000). This included targeted hydrological monitoring using piezometer clusters located along transects at right-angles to the orientation of the trackway. Conclusions drawn from this study were that the current management strategy was maintaining saturated conditions throughout the annual, hydrological cycle.

As Sutton Common is a large archaeological site, the benefit of using a network of piezometers is to enable understanding of the hydrological regime on a site-wide basis, rather than relying on individual or linear transects of monitoring points. Essentially, this approach creates a third dimension to the monitoring of the water table, in that the actual form of the water table can be understood. In contrast, previous studies have relied upon a two dimensional approach both for the monitoring and for the presentation of results. It has also provided the opportunity to understand the water table as a whole entity and therefore gain insights into its behaviour and interaction with archaeological features and natural topography.

3.2.1 Acquisition of hydrological data

Hydrological data for Sutton Common have been obtained through a network of fifty piezometers installed to a depth of 2 m, covering both archaeological Enclosures A and B, the palaeochannel separating them and extending to the edge of Shirley Wood, on the eastern extremity of the site. The network (Figure 3.1) is organised on a 50 m grid, and was installed during August and September 1998 as part of an archaeological assessment undertaken by the Centre for Wetland Archaeology, University of Hull. This assessment was carried out as part of an evaluation of the possibilities for future *in situ* preservation of archaeological remains and the development of a management plan following the acquisition of the site by the Carstairs Countryside Trust (CCT) in 1997 (Van de Noort & Chapman, 1999).

This short-term investigation was targeted specifically at assessing the opportunities for re-wetting the site and identifying the presence of organic archaeological remains, following almost 20 years of arable land-use (Van de Noort, 1997). A number of recommendations were made following the completion of this assessment, including the implementation of monitoring and research into the water table dynamics of the site. It is from this recommendation that the research contained within this thesis was born.

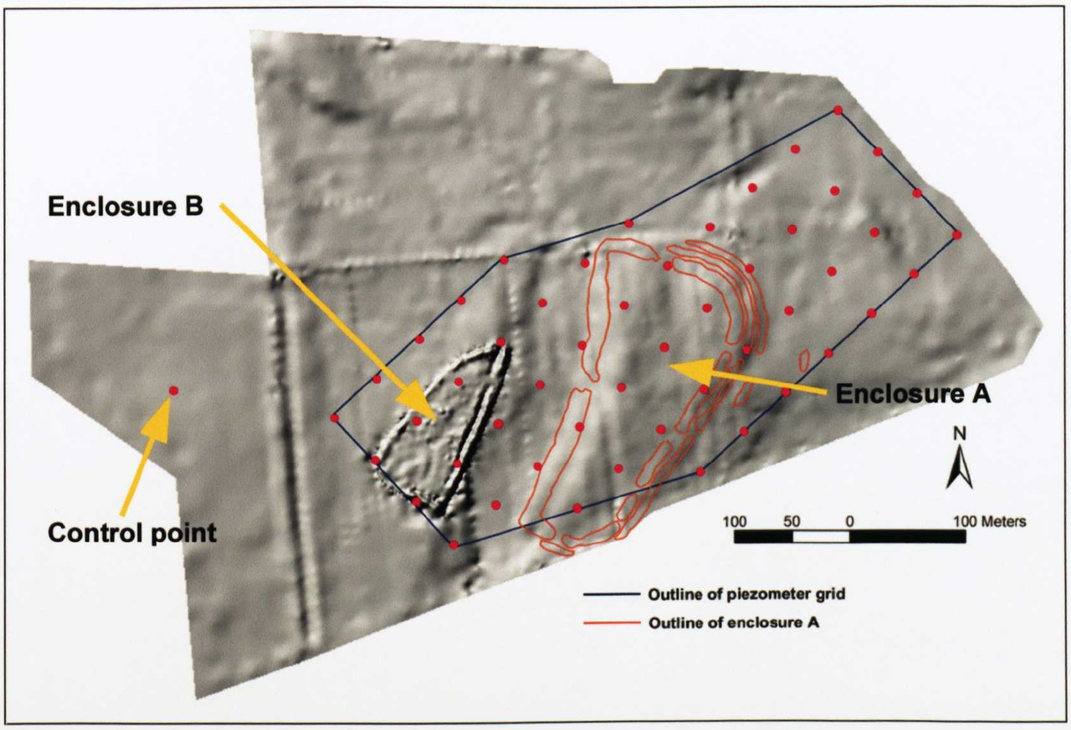


Figure 3.1 Digital Elevation Model (DEM) of Sutton Common (after Chapman & Van de Noort, 2001) showing the location of the piezometer grid. Red points represent piezometer locations.

A piezometer is a field device for measuring hydraulic head. Its basic design consists of a sealed pipe, open to the flow of water at its base and open to the atmosphere at its top. Hydraulic head consists of two components, pressure head and elevation head. With -

$$h = z + \Psi \tag{3.1}$$

Where

h = total hydraulic head

z = elevation head

Ψ = pressure head

Figure 3.2 describes this relationship. Hydraulic head measured at Sutton Common relates to height above Ordnance Datum (O.D.) and measurements are ultimately expressed as this.

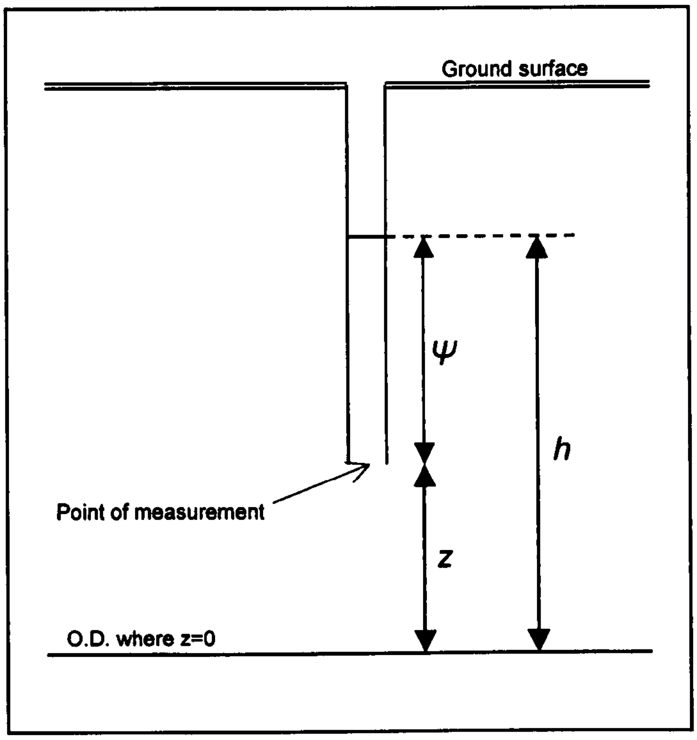


Figure 3.2 Hydraulic head *h*, pressure head Ψ and elevation head *z* for a field piezometer. After Freeze & Cherry (1979).

In conditions where the groundwater aquifer is unconfined, it can be referred to as a water table aquifer (Freeze & Cherry, 1979). At Sutton Common it is the near-surface, unconfined aquifer that has been the subject of monitoring. Under these conditions the water table corresponds to the upper level of the aquifer, i.e. the surface of the zone of saturation, and therefore the measurement of piezometers reveals the depth at which the water table lies. In order to ascertain that this situation holds true across the wider site, three locations were chosen for the installation of piezometer clusters. When installed in a cluster with each piezometer at a different depth, it is possible to identify the flow of water within the vertical plane. If piezometers located at a greater depth give higher readings than those close to the ground surface, then water movement would be upwards. In the opposite situation, movement would be downwards. The ability to see such patterns is of use when studying the water table dynamics as it can provide an insight into the possible sources of water contributing to the groundwater reservoir i.e. whether surface fed or groundwater fed. However, the main purpose of the installation of piezometer clusters was to identify the presence of confined conditions within the depth range that the piezometers within the monitoring grid were installed (0-2.0 m). If such a situation existed, then those piezometers within a cluster that were installed at depth, would be hydrologically isolated from those nearer to the ground surface and subject to different pressure heads. They would therefore show different water levels than those under confined conditions; these give readings for the potentiometric surface (Freeze & Cherry, 1979). Refer to Figure 3.3 for a diagrammatic representation of this relationship.

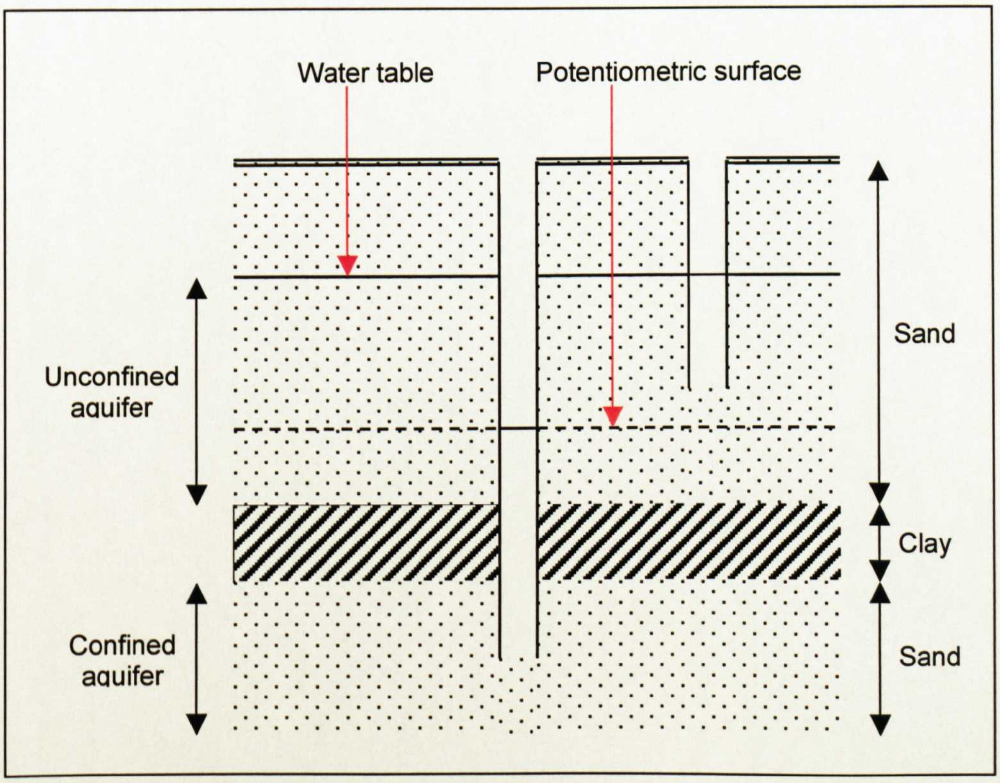


Figure 3.3 An unconfined aquifer showing its water table and a confined aquifer its potentiometric surface (after Freeze & Cherry, 1979).

Two of the piezometer clusters were located within the extent of the palaeochannel and one was located within the interior of Enclosure A. Of these, the one located within the northern part of the palaeochannel showed signs of hydrological stratification.

The piezometers were obtained from MGS Ltd of Bury St. Edmunds and comprise 2 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 3.4). The piezometers were located within a pre-planned grid by means of an Electronic Distance Meter (EDM) and were cored into place using a hand auger with a 30 mm diameter screw tip obtained from Van Walt Ltd. Readings for the level of the water table have been obtained by means of an acoustic sounder (Van Walt Ltd.), a device consisting of an electrical sensor at the end of a plastic tape measure. The sensor is lowered into the piezometer to take readings. An audible alert sounds and an LED illuminates when the sensor comes into contact with the water surface. Readings were systematically obtained for all piezometers in the network for each visit and the results recorded on a standard recording sheet.

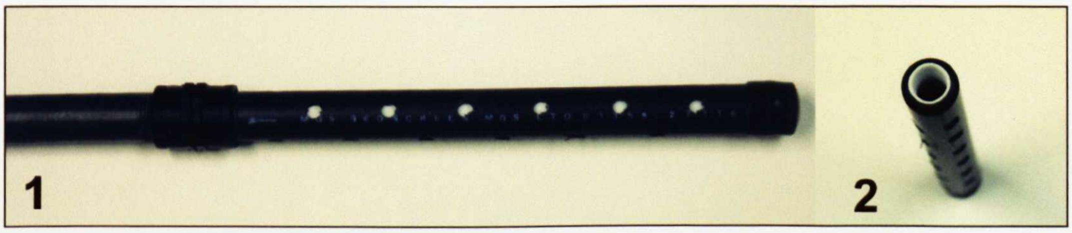


Figure 3.4 A piezometer of the design used during the hydrological monitoring at Sutton Common. (1) The perforated tip connected to the plastic piezometer tube. (2) Vertical shot showing the permeable membrane within the tip.

Due to the large number of piezometers to be monitored and the distance required to travel to Sutton Common, a frequency of every two weeks was chosen for monitoring visits during the initial site assessment. This resolution was chosen to be appropriate to identify trends within the changing levels of the water table, such as seasonality and reactions to large persistent precipitation events.

3.2.2 Data modelling

Raw data obtained from the piezometer grid are in the form of measurements of depth (in cm), below the ground surface at which the upper level of saturation was present. In order to affect more accurate modelling and manipulation of the hydrological data, it is desirable to relate these levels to O.D.

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

GPS operates by receiving radio signals from 24 satellites, these providing data on position and time. As the trajectory of the satellites is known, data from several satellites can be used to calculate a position on the earth's surface, similar to the concept of triangulation.

Prior to 01/05/00, GPS was subject to reduced accuracy due to a process termed 'Selective Availability' (SA), achieved by altering the on-board satellite clock signals. This was undertaken to maintain a positional error of approximately 100 m for civilian used GPS. However, this error could be overcome by the use of two receivers operating in unison, hence the term 'differential GPS (dGPS)'. By keeping a base station static whilst undertaking a survey, data from the mobile receiver can provide centimetre accuracy relative to it. The data obtained in this manner can then be transferred relative to National Grid through the location of known points on the ground, such as those provided by benchmarks. Accuracy of the points obtained through the use of dGPS is in the region of 0.05 m. Discussion and details of this approach including the creation of a high-resolution Digital Elevation Model (DEM) of Sutton Common itself, is given by Chapman (2003), with further information on dGPS provided by Steede-Terry (2000).

Observed depths of the water table were corrected to O.D. 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 being exported in ASCII text file format. These files were then imported into a Geographical Information System (GIS) for manipulation and modelling. ArcGIS 8.2 from ESRI has been used for the presentation of hydrological data and in the creation of location maps for all monitoring points.

The use of GIS has been crucial during this research as it has formed the basis for understanding the burial environment. The ability of the software to hold data obtained from varied sources and layer these to produce models representative of the real world has been fundamental to the approach taken. The most extensive use of the GIS has been in the creation of multiple DEMs representing the form of the near-surface water table within the monitored area of Sutton Common.

ArcGIS 8.2 consists of a suite of programmes serving different functions. The process of creating the models to represent the form of the water table started initially within ArcCatalog, where a point shapefile was generated from X, Y, Z data for the water levels at the individual piezometers, this being contained within a comma delimited text file that had been created previously. During this process, the shapefile was georeferenced to the British National Grid coordinate system. The point shapefile was then imported 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 3D-Analyst extension and a Tension Spline method using the default weight of 0.1 and an output cell size of 1. This process is represented in Figure 3.5.

The method used to create the hydrological models through the interpolation of point data has been Spline interpolation as it has often been used in the creation of terrain models and for the presentation of soil properties (Mitas & Mitasova, 1999). The resultant surfaces are aesthetically pleasing as they are smooth and they effectively provide a clear view (Burrough & McDonnell, 2000). Moreover, the application of Spline interpolation is likely to be more successful at modelling the water table as it will be inherently smooth without the abrupt localised changes associated with other methods of interpolation, such as the use of

Triangular Irregular Networks (TINs) or Kriging. In essence the elastic properties of the Spline interpolation function (Mitas & Mitasova, 1999) mimic the elastic properties of the water table. However, it is acknowledged that Splines are often too smooth and therefore are capable of misrepresenting the real world situation. In the case of the hydrological monitoring of Sutton Common, this is counteracted by the even and relatively dense nature of the sampling grid from which interpolated data has been derived.

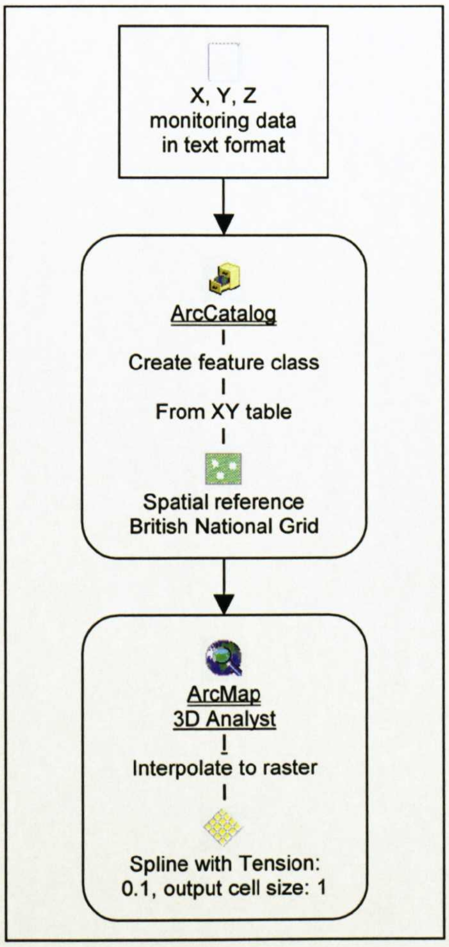


Figure 3.5 Flow diagram representing the process of creating hydrological models (DEMs) within ArcGIS 8.2.

Figure 3.6 provides a direct comparison of five available methods of interpolation - Spline, Inverse Distance Weighting (IDW), Natural Neighbours, Kriging and Triangular Irregular Network (TIN), all generated from monitoring data collected on 01/03/00. For all models, default settings were used with output cell size being 1 m. The generated TIN model was converted into a grid format to enable application of the standard colour range. The different methods are summarised below (obtained from ArcGIS help accessible from within the software).

- **Spline** estimates cell values using a mathematical function that minimises the surface curvature resulting in a smooth surface that passes exactly through the input points.
- **IDW** estimates cell values by averaging the values of those data points within the vicinity of each cell. The closer a point is to a cell, the greater the influence it has on the averaging process.
- **Natural Neighbours** estimates cell values using weighted values of the input data points that are their natural neighbours, determined by creating a triangulation of the input points.
- **Kriging** weights the surrounding measured values to derive a prediction for an unmeasured location. Weights are based on the distance between the measured points, the prediction locations and the overall spatial arrangement among the measured points.
- **TIN** connects sample points that have an X, Y coordinate and a surface Z-value by edges to form a set of non-overlapping triangles therefore creating a surface representation.

Although this is not a detailed assessment or discussion on the merits of individual interpolation methods, Figure 3.6 effectively highlights some of the broad differences arising from them. It can be seen that the use of Splining as a method of interpolation produces a smooth surface, similar to that produced by Kriging, although Kriging creates some artefacts when there is a rapid change in values over a short distance. Natural neighbours and TIN methods of interpolation create surfaces that exhibit sharp changes and hard break-lines of slope, this being especially apparent within the TIN model. This occurs as a result of the use of triangulation in both methods. Of all five representations, the one that is by far the most different, is that produced by IDW. The use of a systematic network of input points has created a localised doming within the model in the immediate vicinities of these locations. For all the differences that each interpolation method creates, there is a very strong similarity between the models generated, even with that produced by IDW, if the localised variations are overlooked and the characteristics of the monitoring data are retained.

Spline interpolation has been chosen for the creation of DEMs representing the surface of the water table of the monitored area of Sutton Common in preference to other methods, due to the smooth character of the surfaces created. This is more representative of the real-world situation where abrupt and distinct changes within the level of the water table over short distances are unlikely to occur.

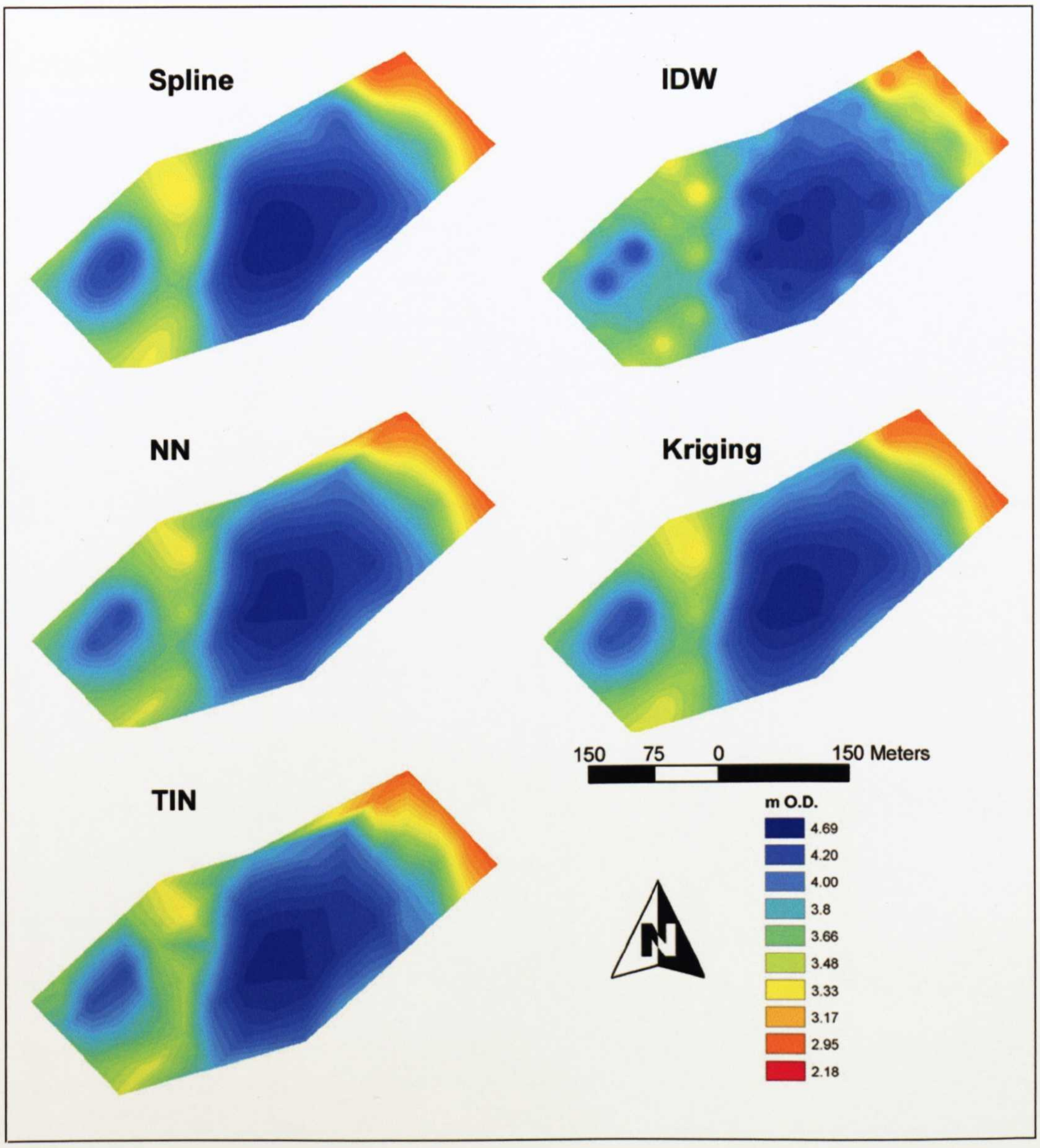


Figure 3.6 Comparison of the surfaces representing the water table created using five differing methods of interpolation using monitoring data collected on 01/03/00. IDW = Inverse Distance Weighting, NN = Natural Neighbour, TIN = Triangular Irregular Network.

3.2.3 Presenting the hydrological models

The surfaces generated through the interpolation of the hydrological monitoring data are used to understand the form of the water table present on the site and how this varies over time. For this purpose the rainbow colour ramp is utilised consisting of 32 colours from red through to blue where the colours on the models represent specific height ranges, rather like traditional contours. The same colour ramp is applied to all models created in this manner to ensure that accurate visual comparisons can be made. These are calculated by treating the entire data set as being within a normal distribution i.e. the majority of values are clustered around a central point, with relatively few, extreme values included in the dataset. This pattern is demonstrated in Figure 3.7 showing the frequency distribution of values for the height of the water table on Sutton Common, taken from the entire collected dataset.

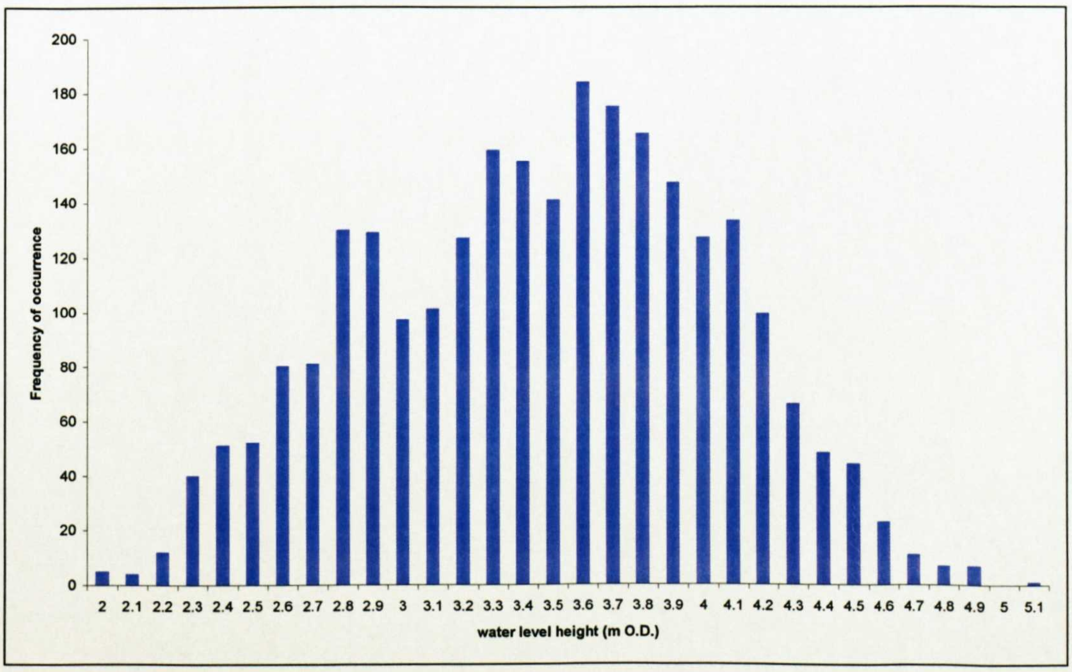


Figure 3.7 Chart showing the frequency distribution of water-levels on Sutton Common. Analysis undertaken on entire dataset.

In this situation, it is important to ensure that there is an increase in the resolution of colours within the range of heights that the majority of the dataset are clustered around, otherwise much of the detail of the model is lost. Figure 3.8 presents two models of the Sutton Common water table created using the two methods for generating the colour definitions; the adjusted method taking into account the normal distribution of the data, and the use of a straightforward equal interval. As can be clearly seen, the use of the adjusted interval method is more effective at identifying the form of the water table through the use of a greater range of colours.

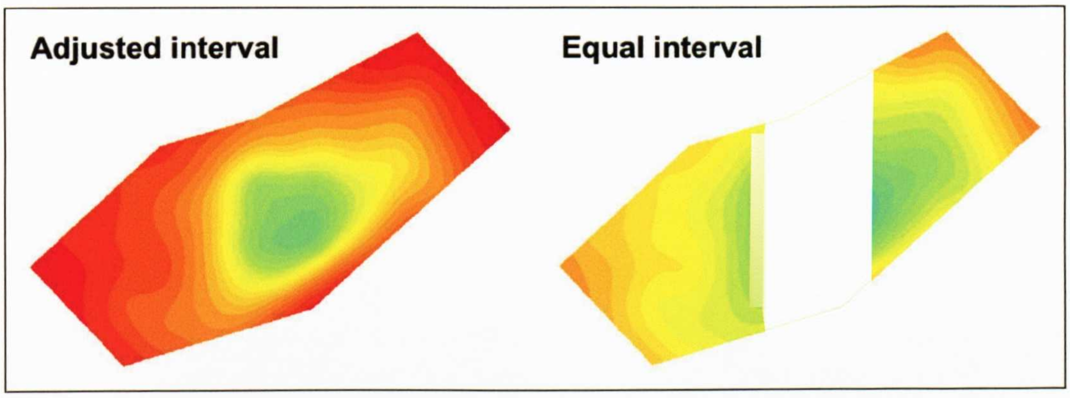


Figure 3.8 Hydrological models showing the difference between an adjusted and equal interval scale for the colour shading. See Figure 3.6 for colour key.

This is achieved by giving a specific colour to a height range within the model dependant upon which percentile of the normal distribution of results that it falls into. Using MS Excel this is undertaken using the functions NORMDIST and STANDARDIZE when the mean and standard deviation for the results set are known, in the form of:

NORMDIST(STANDARDIZE(x,mean,standard_dev)) (3.2)

This results in a number between 0 and 1 being generated for each actual piezometer reading. For example, if 5 colours are to be used to shade the model, then the heights falling within the calculated range of 0 and 0.2 are given colour 1, 0.21 and 0.4 are 2 etc.

Prior to the development of this method of creating the colour-shading definitions, if multiple models were being used to identify change over time, it was necessary to manually manipulate the colour definitions so that the maximum detail was seen, or simply rely on an equal interval. Sutton Common hydrological models using these methods are presented by Van de Noort & Chapman (1999). Although this approach is sufficient when the data is presented in isolation, it does not lend itself to a good scientific approach where all data is demonstrably reproducible at a later date or by others. In this case, the source data for the models is known and therefore the interpolated surface representing the water table can be reproduced, but without the presentation of the exact colour definitions, the published model cannot. The above method can now be used to as a standard approach to creating the most appropriate colour definitions and thus ensure a greater level of reproducibility.

3.2.4 *In situ* measurement of saturated hydraulic conductivity

Due to the relatively large size of the monitoring grid, the geomorphological and topographical variation observed within it and also a desire to understand more fully the water table dynamics, specifically shallow groundwater flow, *in situ* measurements of saturated hydraulic conductivity (K) have been made.

K is a measure of the soil's ability to transmit water when submitted to a hydraulic gradient (Yu *et al*, 1993) and is defined by Darcy's Law, which for one-dimensional flow is:

$$U = -K\left(\frac{dh}{dz}\right) \tag{3.3}$$

Where:

U = velocity of the soil water through a cross-sectional area of soil

h = hydraulic head

z = vertical distance travelled in the soil.

Together with the retention characteristics, hydraulic conductivity is one of the hydraulic properties of soil and therefore determines the ability of soil water to flow when under a hydraulic gradient.

It is possible for estimations of K to be made in the field using a single piezometer through the introduction or removal of a known volume of water, the time taken for the water level to recover then being recorded. The addition of water is called a falling head test and removal of water a rising head test. *K* has the dimensions of a velocity and is usually expressed as ms^{-1}. The approach used to calculate *K* follows the method presented by Hvorslev (1951) for a piezometer in isotropic soil. Figure 3.9 presents the variables used in the calculation.

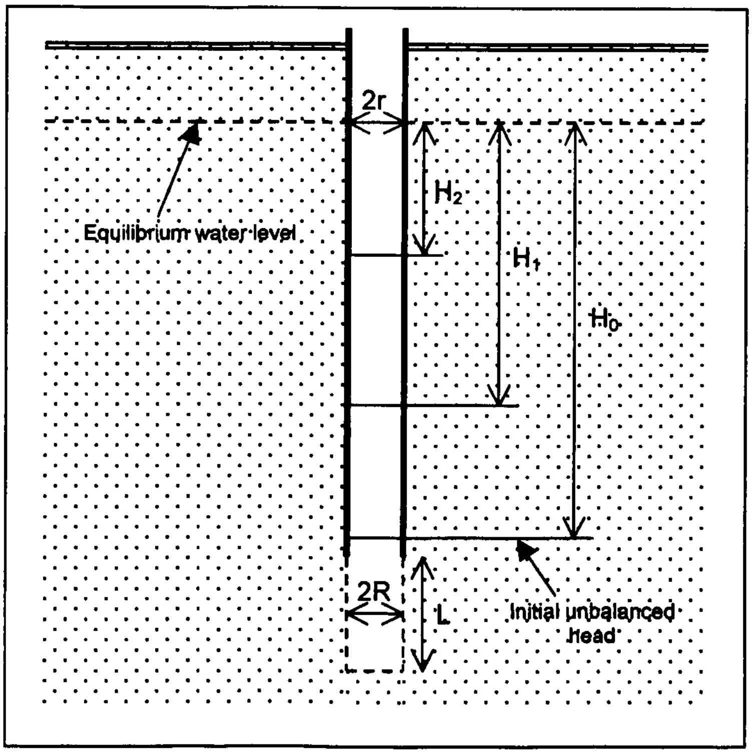


Figure 3.9 Diagram showing the arrangement of factors involved in the calculation of *K* by means of a rising head test. After Hvorslev (1951).

In this situation where there is a variable head but with a constant groundwater level, *K* is:

$$K = \frac{A}{F(t_2 - t_1)} \ln\left(\frac{H_1}{H_2}\right) \tag{3.4}$$

Where

A = Cross-sectional area of the piezometer

H_1 and H_2 = piezometer heads causing flow at

t_1 and t_2 = observation times

F = the shape factor equation provided by Hvorslev (1951).

The approach presented by Hvorslev provides a calculation for a piezometer where the radius of the intake point at the base is of a differing radius to that of the pipe extension. However, those piezometers used for the monitoring on Sutton Common had the same diameter for the pipe and the tip, this situation being equivalent to Hvorslev's 'observation well' situation. Essentially the equations for the two situations are identical.

Therefore, the F factor used is that for a 'cased hole, uncased or perforated extension of length L':

$$F = \frac{2\pi L}{\ln\left(\frac{L}{R}\right)} \tag{3.5}$$

Where:

L = the length of the perforated piezometer tip

R = internal radius of the piezometer

Therefore:

$$K = \frac{R^2}{2L(t_2 - t_1)} \ln\left(\frac{L}{R}\right) \ln\left(\frac{H_1}{H_2}\right) \tag{3.6}$$

Using this equation (3.6), the known characteristics of the equipment, its configuration in the field and the observations made during the course of the field tests, the saturated hydraulic conductivity can be estimated. This value would relate specifically to the material immediately around the piezometer tip and therefore is not representative of the entire soil profile in any one particular location.

K values are calculated from trendlines plotted on regression charts of log head ratios against time (Hvorslev, 1951). Therefore equation 3.6 can be arranged to:

$$K = \frac{R^2}{2L} \ln\left(\frac{L}{R}\right) \left(\frac{\ln \frac{H_1}{H_2}}{(t_2 - t_1)} \right) \tag{3.7}$$

but $\left(\frac{\ln\left(\frac{H_1}{H_2}\right)}{(t_2 - t_1)} \right)$ is the slope of the graph so, (3.8)

$$K = \frac{R^2}{2L} \ln\left(\frac{L}{R}\right) \times \textit{slope of the line} \qquad (3.9)$$

It is the final equation 3.9 that is used to calculate K.

Both falling and rising head tests were carried out on a selection of piezometers within the monitoring grid on Sutton Common, although not all were subjected to both due to a shortage of suitable equipment. Ideally, both tests are undertaken and an average of the results is taken (Soil Mechanics Ltd, 1973). For falling head tests, a 1 m length of clear plastic tubing was attached to the top of the piezometer, after the water level within it had been recorded. The piezometer and the clear plastic tubing were then filled and observations of the drop in the water level recorded over time. Typically, observations were made at increasing intervals i.e. 0.5, 2, 5, 10, 15, 30 minutes etc, thus enabling the identification of any rapid changes within the recovering water level, but would not lead to unnecessary readings being made if the recovery time was long.

For rising head tests, the same procedure was carried out except that following the initial reading water was removed from the piezometer as opposed to added. This was carried out by means of a portable drill and a pump attachment. Although this system operated acceptably, for depths greater than 2 m the pump was incapable of rising the water sufficiently. An alternative, simpler approach is the introduction of a solid cylinder into the piezometer in order to displace the water contained within it.

3.2.5 Creation of the archaeological wood model

The fundamental reason for the persistence of archaeological wood, and other organic materials, within the burial context is the creation and maintenance of waterlogged conditions. Such conditions exclude the main agents of decay as a direct result of the removal of aerobic conditions. Therefore, taking as the baseline principle that without saturation there will be no preservation of archaeological wood and, conversely, with saturation the potential for preservation exists, then data obtained through the spatial monitoring of the water table can be used to test this.

The methods for such an approach have been outlined by Chapman & Cheetham (2002) and are further developed in this study. Essentially, moisture conditions within the burial environment can be placed within one of three categories; permanently dry, intermittently saturated and permanently saturated. Permanently dry conditions can be expected to exist within surface deposits that are well above the level of the water table in a particular location. Permanently saturated conditions are maintained below the minimum level of the water table, and intermittently saturated conditions reflect the vertical movement of the water table, such as results from seasonal influences. Using this principle, it can be assumed that the greatest potential for preservation exists below the minimum level of the water table.

Using the GIS methods described in Section 3.2.2 for generating surfaces representing the watertable on Sutton Common, it is possible to create surfaces representing the maximum and minimum heights of the water table during the course of the hydrological monitoring programme. The maximum height therefore represents the lower limit of the permanently dry conditions and the minimum height the upper limit of saturated conditions. Using excavation archives from investigations undertaken in 1998, 1999 and 2002, it is possible to obtain the absolute locations of individual pieces of archaeological wood within 3-dimensions. Through the use of ArcGIS it is possible to compare the vertical range of the archaeological wood to the saturation conditions in that location.

The process therefore consist of:

1. The generation of maximum and minimum water table models using the maximum and minimum values obtained from the piezometer grid throughout the course of the monitoring programme
2. Creation of a spatial database with details of the 3-dimensional location of individual pieces of archaeological wood identified during excavation.

This includes x, y and z coordinates encompassing the vertical height range of the wood. This can be visually represented in ArcScene using the 'extrusion' command.

3. Integration of the two previous datasets and obtaining direct comparisons between the two. This process can again be 3-dimensionally presented in ArcScene.

Through this process it is possible to assess the potential for ongoing preservation of the archaeological remains in question. For example, those that are shown to exist within permanently dry conditions are recalcitrant and are actively degrading, those that are permanently saturated are likely to survive in the long-term and those intermittently saturated are at threat.

This information can be plotted by means of a histogram with adjacent columns representing the height range of the archaeological wood and the range of fluctuation of the water table in that location. Also, taking into account the observed quality of preservation at the time of excavation, or indeed through further assessment of the degradation afflicting a piece of archaeological wood, it may be possible to make a general assessment of the potential for *in situ* preservation

3.3 Redox monitoring

The use of redox monitoring has been applied to Sutton Common as it is able to semi-quantify the chemical status of the burial environment and therefore identify burial environments that are suitable for the ongoing preservation of organic archaeological remains (Caple & Dungworth, 1998). The method has been established as a monitoring parameter running alongside that of the hydrological investigation of the site.

Monitoring of soil oxidation / reduction potentials is an established technique that has been widely utilised in the study of soils and groundwaters especially in relation to agriculture (Aomine, 1962; Patrick & Mahapatra, 1968;

Ponnamperuma, 1972) but also in the measurement of wetland soil parameters (Faulkner *et al.*, 1989).

The use of soil redox potential (Eh) measurements within archaeology has been established for a number of years as the value of being able to identify reducing, and therefore anaerobic, conditions conducive to the preservation of organic archaeological remains, is high. Early considerations of the burial environment followed on from a change in English Heritage policy away from excavation of important remains, to their preservation *in situ*. There was recognition of a lack of understanding regarding burial conditions (Caple, 1993, 1994) and at this time the issue was closely connected to the reburial of organic remains that had been excavated and recorded, but would usually then be discarded. Since then the application of monitoring variables within the burial environment has gained greater emphasis and there has been an increase in research into possible monitoring methods (Caple & Dungworth, 1998), including the development of an effective method for the monitoring of Eh (Caple, 1996; Corfield, 1996; Caple & Dungworth, 1997). There have been an increasing number of field applications of these techniques such as at the Sweet Track within the Somerset Levels (Brunning *et al.*, 2000), where redox probes were associated with piezometers along a transect to compare water levels and soil chemical status. Cheetham (1998), also within the Somerset Levels, Caple & Dungworth (1998) at a number of locations of sensitive burial environments, Powell (1999) and Powell *et al.* (2001) at Flag Fen have all made use of *in situ* redox measurements in assessing the status of the burial environment.

It is acknowledged that the use of Eh can create unavoidable inaccuracies due to the measurement of mixed potentials within the soil environment. This has led some authors to suggest the method is not suitable as an environmental parameter, especially when it is necessary to have reproducibility within the results obtained (Lindberg & Runnells, 1984). The reasons for this are the low concentration of redox couples within oxidised environments (Bohn, 1971) and the measurement of mixed potentials in natural groundwaters meaning that strict, thermodynamic interpretation is difficult (Stumm & Morgan, 1981). However, this approach is suitable as a semi-quantitative measure of soil reduction (Ponnamperuma, 1972) and can be used very effectively in relative measurements between different locations. It is on this basis that it is applied in archaeological investigations, providing the means to generate comparable data from many different sites or, as in the current study, across a wide area of varying environments within the boundaries of the same site.

In situ probes have been used in this study as they are seen as the only effective means of obtaining reliable observations of Eh at great soil depths. Previous studies have proposed obtaining Eh readings at depth in soils using a handheld, commercially available, Eh meter in conjunction with a dipwell (Caple, 1993). The principle that this operates on is that the water contained within the dipwell is soil water from the surrounding deposits and therefore has the same characteristics. Readings are obtained through either lowering the Eh probe into the dipwell, (this having previously been purged or not), or removal of a water sample by means of a bailer. However, there are a number of potential problems with this approach and a high chance of disturbance and contamination of an inherently sensitive chemical system and therefore, the creation of misleading results. This view has been shown to be accurate through experimentation by Caple and Dungworth (1998) who compared *in situ* measurements with purged and non-purged dipwell readings. They identified that the *in situ* method was by far the most accurate.

3.3.1 Data acquisition

Nine monitoring points were established across Sutton Common, each having a cluster of sixteen redox probes installed at varying depths. The monitoring locations, (Figure 3.10), are associated with points within the piezometer network, thus providing the capability to directly relate chemical status of the burial environment to hydrological conditions across the wider site.

Construction of the redox probes follows the design presented by Faulkner *et al.* (1989) for the 'welded' type of probe. These consist of prepared platinum wire welded to copper wire, the weld then being sealed with waterproof epoxy resin which is itself then insulated using heat shrinking seals. These seals then being sealed again with epoxy resin (see figure 3.11).

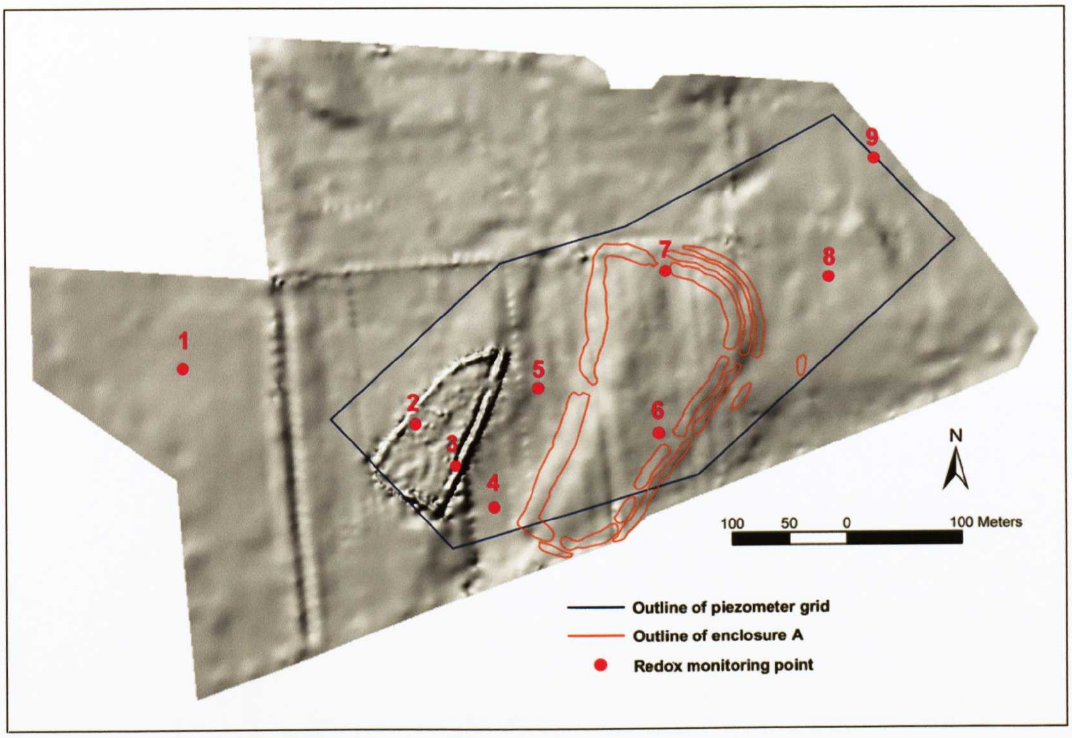


Figure 3.10 DEM of Sutton Common showing locations of redox monitoring points.

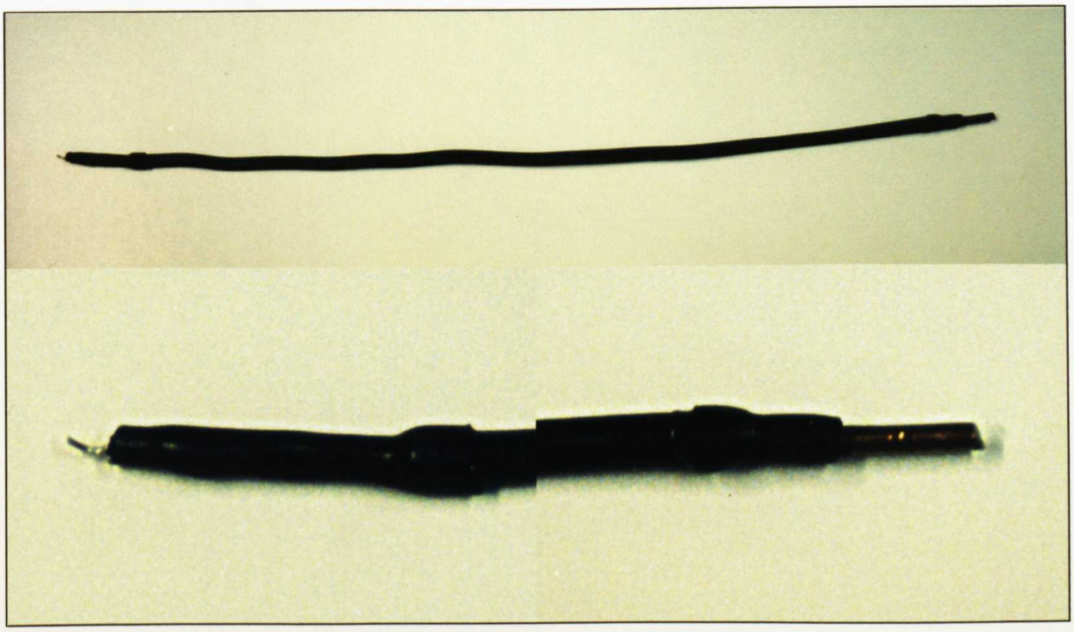


Figure 3.11 A redox probe of the 'welded' type used for the soil redox monitoring on Sutton Common.

The redox probes used during the study were specially constructed by Hunter's Dale, Berkshire to 5% tolerance. These probes were developed through work carried out at the Royal Holloway, Institute for Environmental Research (Hogan *et al.*, 2001). The tolerance is a measure of the reliability of readings obtained from the probes and is calculated by preparing a redox buffer solution at a potential of +218 mV. This is created from a solution of 10.211 g of potassium hydrogen phthalate in 1 l of deionised water, this previously having being saturated with quinhydrone (pers comm. R. Hunter). Probes giving readings outside a range of 5% of 218 mV were rejected.

Redox probes were organised into four replicate probes at four varying depths; 0.15 m, 0.5 m, 0.9 m and 1.4 m (as shown in Figure 3.12). Redox readings were obtained by means of a WTW pH340 pH / mV meter connected to a Silver Chloride (Ag/AgCl) reference probe (BDH Gelplas, double junction reference) and to the *in situ* redox probes by means of a clip. The reference electrode was inserted into a shallow hole made in the ground surface in close proximity to the redox probes. If the ground surface was dry, then a small amount of deionised water was poured into the hole and mixed with the soil to produce a slurry to ensure a good electrical contact.

Readings from each electrode were obtained in millivolts (mV) and recorded on a prepared sheet. At the same time, the surface pH of the soil was recorded using the same pH / mV meter and a temperature-compensated pH electrode (WTW SenTix 21 combination electrode / TFK 325/HC temperature sensor). Gathering pH data is necessary as it has a direct influence upon the redox system and therefore needs to be accounted for as the Eh readings may require adjustment. This was achieved by taking a sample of soil from the surface in the immediate vicinity to the redox probes, placed within a small sealable container to which a small amount of deionised water was added. This mixture was then vigorously shaken by hand for at least 30 seconds to create a homogenous soil slurry into which the pH probe was inserted and a reading taken once drift had ceased.

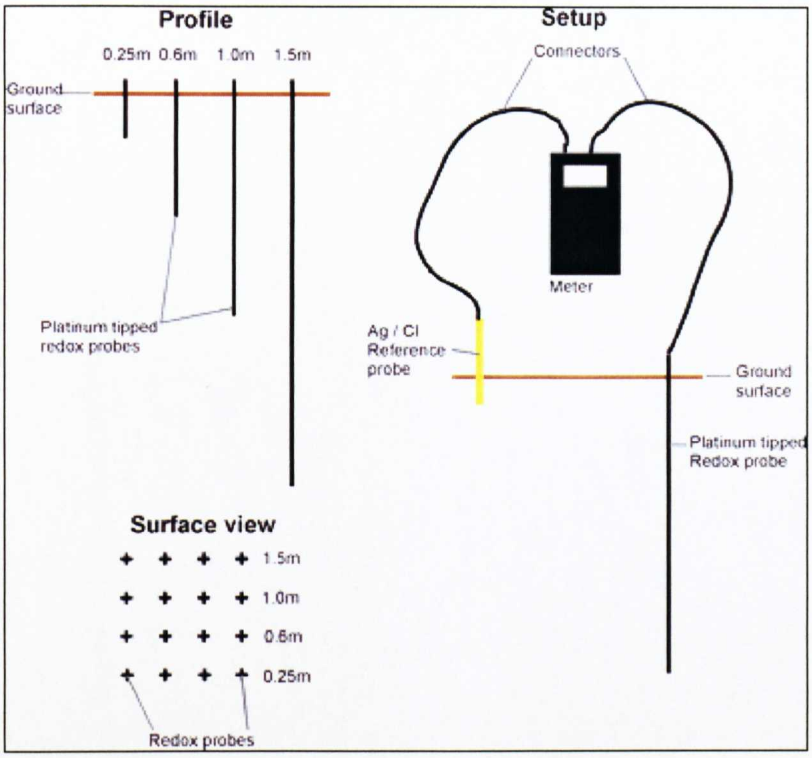


Figure 3.12 Schematic diagram showing the implementation of redox equipment on Sutton Common.

The nine soil redox potential monitoring locations were chosen for their representation of the varying soil types, and therefore burial conditions, across the site. For example, Site 2 was chosen for being representative of conditions within Enclosure B, Sites 4 and 5 for the Hampole Beck palaeochannel, 6 and 7 for Enclosure A, and 8 and 9 for conditions towards the peat deposits associated with Shirley Wood. In addition to these, Site 1 was chosen as it is outside the influence of re-wetting activities, and therefore acts as a control point, and Site 3 as it is located within an archaeological feature known to contain wet-preserved wood. An ideal monitoring frequency of every two weeks was decided upon as sufficient to monitor redox although, if necessary, this could be reduced to monthly visits, as this would still be capable of identifying changes within the burial environment that might occur during this period (Caple 1998).

3.3.2 Data processing

Once readings for each probe in each cluster were obtained, these were used to provide an average, representative reading for each sample depth. Observation of the recorded values showed that in certain circumstances there was one redox probe that exhibited an extreme value when compared to other probes at that depth. To overcome this potential problem and 'clean' the data, a standard filter was applied to readings obtained from each depth. This consisted of identifying the most extreme value, either the highest or the lowest, and disregarding it. The assumption that this is based upon is that all the readings at a particular depth will cluster around a mean value. Any that do not are therefore considered outliers. If all values do indeed cluster around a mean then the rejection of one will not adversely affect the overall outcome. However rejection of a true outlier will ensure better accuracy. The only circumstances where the adoption of this approach may generate false values is when there are two extreme values within the dataset, or where there are two pairs of extreme values. In such a case the outcome of the filter may not be representative. It is recognised that this situation should not be common as under normal circumstances readings will indeed cluster. Where this is not observed in the field, it may relate to conditions where reliable readings cannot be obtained, such as in an unsaturated burial environment (Stumm & Morgan, 1981).

Averaged results were then adjusted to the Standard Hydrogen Electrode (SHE) (British Standards Institute, 1990). By convention redox potential is measured against the SHE (Howard, 1998). Thus the adjustment takes into account the potential of the reference probe that has been used, so allowing comparison of results from different studies. During the course of this study a Silver Chloride (Ag/AgCl) reference electrode was used with a potential value of +222 mV, therefore a value of 222 mV is added to the readings obtained from the *in situ* redox probes in the field. To remove pH variability between soils (as redox potential is affected by pH) the obtained values are adjusted to pH 7 by a factor of -59 mV per pH unit (Bohn, 1971, BSI, 1990). Effectively this means that under acidic conditions, for each pH unit below pH 7, 59 mV is subtracted from the recorded redox potential. Conversely, for each unit above pH 7, 59 mV is added to the recorded value.

Redox data obtained during the course of this study will be presented in two differing formats, both having their own specific merits and also being mutually supportive. The first type is what will be referred to as 'linear' plots, where all the data are adjusted to SHE and pH7 and plotted against a time axis. This approach allows data from a variety of depths / locations along with other factors such as water levels within the associated piezometer, to be plotted on the same graph to enable easy visual comparison. Data from each monitoring location will be presented on individual charts, including data from all depths studied.

The second method of presenting redox data is as an Eh / pH diagram. This type of representation is termed a stability field diagram and can simultaneously show many chemical reactions that take place under a range of pH and redox conditions.

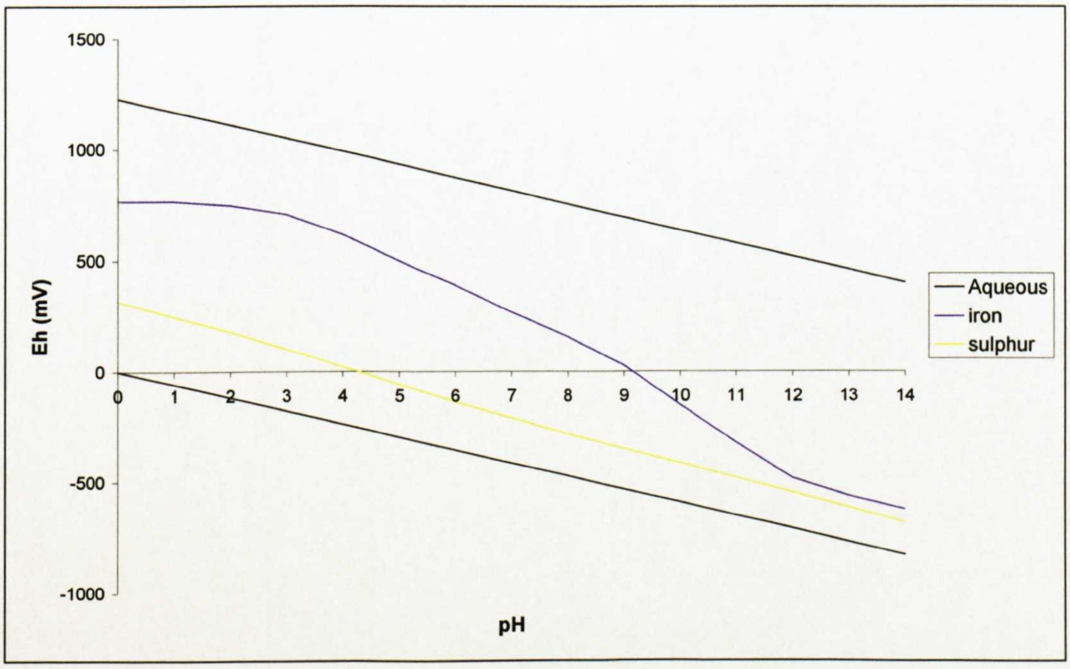


Figure 3.13 An Eh / pH diagram showing aqueous, sulphur and iron boundaries.

Figure 3.13 is an Eh/pH diagram across the full pH range. The two straight, black lines represent the boundaries of the aqueous system. Above the upper line water would be oxidised and below the lower line it would be reduced (Howard, 1998). As all measurements within the burial environment are essentially of the soil pore water, all reactions must occur within the limits of this system. The blue line represents the equilibrium potential of the Iron II/III couple, with the oxidised form (Fe^{3+}) being present above the line and the reduced form (Fe^{2+}) present below it. It has been suggested that this boundary could be used to differentiate between oxidised and reduced conditions within soils (Bohn, 1971). As such, it has been included as a relative measure of the degree of oxidation/reduction within the burial environment. The yellow line in the diagram denotes the boundary between the oxides (sulphate) and reduced (sulphide) forms of sulphur. In oxidising conditions there is a tendency for sulphur compounds to oxidise to sulphate $SO^{2}_{4}{}^{-}$ (Howard, 1998) therefore the boundary at which this occurs has been used. This means that the reduced forms of sulphur include elemental sulphur (S), H_2S and HS^-. These values are derived from Stumm & Morgan (1981) at 25 °C, standard pressure and a concentration of soluble S species of 10^{-2} M. In terms of the preservation of organic archaeological remains this boundary has far greater significance than that of iron. This is because the reduction of sulphur occurs under greater reducing conditions and is mediated by the activity of sulphur reducing bacteria (Ponnamperuma, 1972). These bacteria are obligate anaerobic bacteria, so observations that fall within this region of a stability diagram are indicative of true anaerobic conditions and are in consequence, the conditions that are most suitable for the preservation of organic archaeological materials.

It must be stressed that the boundaries shown on the Eh / pH diagram inherently suggest that a state of equilibrium exists within the burial environment when, in fact, this is not the case. As discussed at the beginning of section 3.3, environmental measurements of redox potentials include mixed potentials of unknown and variable concentrations of chemical species. Therefore, readings obtained using this approach can be considered as an average figure for all the redox couples that are present. However, the use of such a diagram greatly aids in the interpretation of the observations that have been made and therefore justifies their inclusion.

3.4 Microbiological assessment

Microbiological assessment was undertaken as part of this research as it is perceived as an essential factor when discussing the *in situ* preservation of organic archaeological remains. Preservation infers a lack of degradation, a process that is mediated by the presence or absence of microbial activity within the burial environment. A number of previous archaeological studies have discussed microbial activity, but these often relate to action directly upon artefacts, the processes of material degradation and the physical effects of these (Lawson *et al.*, 2000; Powell *et al.*, 2001). Little work has been carried out on the microbial 'status' of burial environments in relation to buried archaeology and how this varies with changes in the burial conditions; such as nutrient status, organic matter content, type of subsoil and moisture content. All these factors influence the composition of the microbial community and the potential for preservation / degradation. Therefore, a number of established techniques used previously for analysing and quantifying the microbial nature of marine and aquatic environments, have been adapted and developed for application within the soil context.

The increased amount of time and resources required to undertake the microbiological analyses has meant that it has not been applied as a regular monitoring exercise unlike the hydrological investigations or redox monitoring. Instead, the microbiological work has been focused upon the development of an understanding of the variation in the microbial communities at Sutton Common and how this may influence the burial environment. It is anticipated that this area of the investigation will create a framework within which further *in situ* studies can be developed, working towards the application of effective microbiological monitoring techniques within the burial environment of organic archaeological remains.

Three main microbiological procedures have been used, these being; assay for extracellular soil enzymes, direct counts of bacterial cells, and the measurement of metabolic activity within soil samples. Such methods have been used extensively in investigations into marine environments (Ainsworth & Goulder, 2000a&b, Mayer, 1989, MeyerReil & Köster, 1992, Poremba, 1995) and have recently been applied to the study of composting environments and waste management (Tiquia *et al.*, 2001, Tiquia, 2002).

Knowing the number of bacteria in a sample aids in the understanding of an environments microbial ecology. The technique of direct counting by means of epiflourescence microscopy is therefore of considerable importance in the study of aquatic environments (Zimmerman, 1977). The substrates that sustain these bacterial populations are usually complex macromolecules that are not readily incorporated into the bacterial cell. These molecules are made available through the action of extracellular enzymes produced by bacterial cells. Rapid and sensitive tests capable of detecting the activity of these enzymes can be undertaken using fluorogenic model substrates, these consisting of an artificial fluorescent molecule and a natural molecule, such as glucose or an amino acid, linked by a specific bond. Fluorescence is observed and can be measured following the splitting of the two linked molecules, from the action of a specific targeted enzyme. Such investigations can be undertaken on samples directly obtained from the environment being studied, and the short time required means that changes within the microbial community are reduced to a minimum (Hoppe, 1993).

The measurement of metabolic activity can be an important approach in the understanding of microbial dynamics. Substrates that are bound to a radioactive molecule can measure the metabolic activity of bacterial cells through measurement of its uptake rate (Goulder, 1991).

Although the application of techniques used in the investigation of the marine environment may appear divorced from those within a soil environment, there are often parallels that indicate a relevant application. For example, these methods have been utilised with success in the study of deep-sea sediments, foreshore environments and lacustrine sediments (King, 1986; Mayer, 1989; Poremba, 1995; Insam, 2001). The application of microbial techniques in the study of soils is also well established (Insam, 2001).

3.4.1 Field sampling

Five sites were chosen for analysis (Figure 3.14), these corresponded to monitoring points for hydrology and redox to allow a direct comparison of results.

Similarly to the soil redox locations, these sites encompass the varying soil conditions present across Sutton Common. Fewer locations were chosen due to the greater amount of time and resources required to undertake analysis of the soil samples obtained and due to the microbiological techniques being applied as an assessment procedure rather than a monitoring parameter. Therefore, no definitive sampling frequency was chosen prior to the initiation of the microbial assessment and sampling was undertaken when possible. This led to a sampling period for each location of 12 months. Low resolution sampling of depth was undertaken as it was felt necessary to encompass those depths that archaeological remains were known to exist. Therefore, three samples were taken throughout the soil profile, 0 m, 0.75 m and 1.5 m, by means of a hand auger. The head of the auger was approximately 0.16 m in length and capable of collecting 300-350 cm^3 of relatively undisturbed soil sample. The soil sample was emptied into a pristine sampling bag using a clean trowel, ensuring that material placed in the bag did not come from the edge of the auger head or areas exposed to the outside environment during retrieval. Approximately 160 g of sample were collected, this being considered to contain a suitable microbial population to assay (Van Elsas & Smalla, 1997). Samples were transported back to the laboratory and placed in a cold store (4 °C). Analysis was undertaken at the earliest opportunity, usually within four days, to ensure that there was a minimal amount of microbial change within the samples. Although in principle the storage of soil samples should be avoided if activity measurements are to be made as microbial properties can change rapidly (Fredrickson & Balkwill, 1998), storage in plastic bags to maintain the samples in a moist condition, at 4 °C for up to three weeks may be acceptable (Van Elsas & Smalla, 1997). However, some investigators studying wetland soils report the storage of soil samples under these conditions for up to three months (D'Angelo & Reddy, 1999).

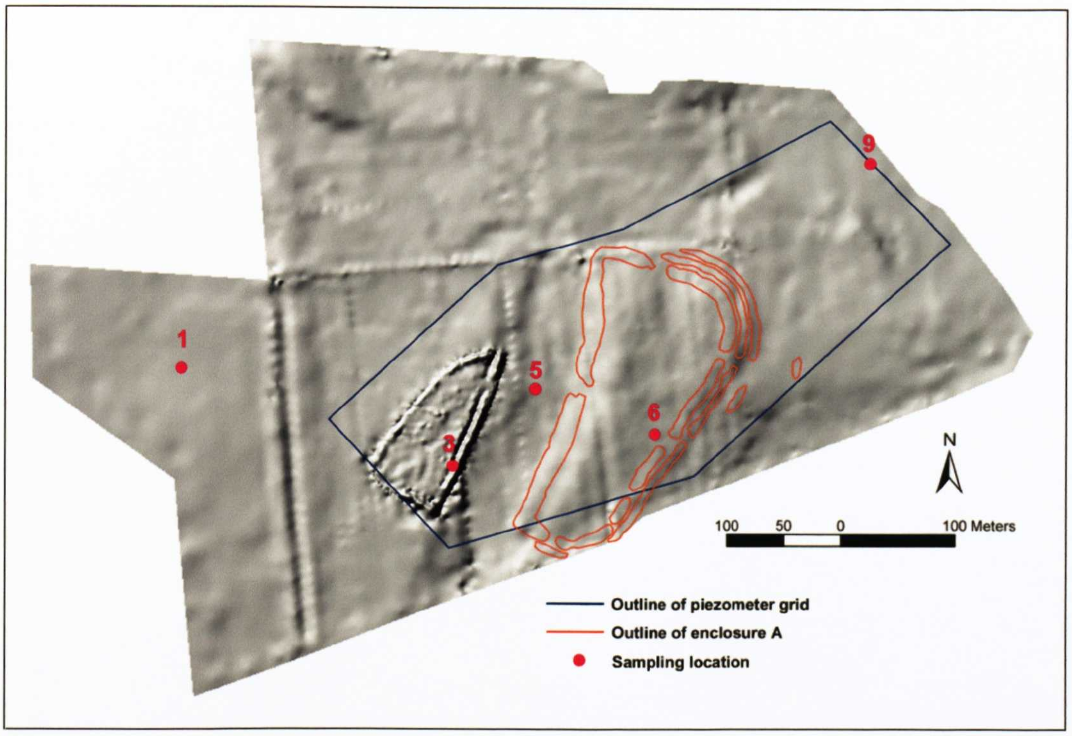


Figure 3.14 Sutton Common DEM showing microbiological sampling locations. Locations numbers relate to redox monitoring point notation.

3.4.2 Preparation of soil slurries

An initial 100 g l^{-1} concentration soil slurry was produced by taking a 5 g subsample of soil that had previously been thoroughly mixed, and making it up with 50 ml of 0.2 μm, sterile filtered Ringer's solution. Ringer's solution is an aqueous solution containing the chlorides of sodium, potassium, and calcium that is isotonic to animal tissue and usually used during animal physiological experiments. In this case, Ringer's solution was used in order to replicate the soil water conductivity from Sutton Common, this having previously been sampled and tested. Although ideally all experimentation would be undertaken using actual soil pore water, difficulties were experienced with obtaining a suitable volume of water and securing a reliable source. The use of Ringer's solution as an alternative was seen as not only being suitable in providing a solution of appropriate saline concentration, but also as providing a simple and rapid source of water to undertake the microbial techniques. A sample of soil pore water obtained from Sutton Common was measured for conductivity using a Jenway, model 4070 meter, and following this, a solution of matching concentration was made up using diluted Ringer's solution.

The soil preparation was then placed into a sterile plastic bag and homogenised for 3.5 minutes in a stomacher (Colworth Lab Blender 400; A.J. Stewart Ltd. London). This aids in breaking down the soil structure, enabling accurate measurements of microbial activity, including direct counts of bacterial cells. From this initial slurry, serial dilutions were made by taking 1 ml and adding 9 ml of the sterile filtered ringer's solution in a sterile universal bottle and repeating this until the required concentration was reached. Cell counts were generally carried out using a dilution of 0.1 g l^{-1}, although this was dependant on the concentration of bacterial cells within the soil sample. At a lower dilution, the numbers of cells present were greater but were often severely obscured by the amount of particulate matter in the field of view. At a higher dilution this problem was overcome, but often very low numbers of bacterial cells prevented accurate counting. At this point, 0.5 ml of 2 μm membrane filtered neutral formalin (final formaldehyde concentration 2% W/V) was added to stabilise the solutions and allow storage for up to two weeks at 4 °C (Daley & Hobbie, 1975).

3.4.3 Acridine orange stained, epiflourescence microscopy

Total numbers of bacterial cells were counted by means of Acridine Orange (AO) staining and epiflourescence microscopy, following the method presented by Al-Hadithi & Goulder (1989) and similar to those presented by Zimmerman (1977). AO stains the DNA material within the bacterial cells (Jones, 1974), making them fluoresce under illumination by a UV source. The AO solution was first prepared to a concentration of 1 g l^{-1} with 2 μm sterile filtered water. 0.2 μm pore, 25 mm diameter polycarbonate filters (Millipore, Ireland) were stained using an Irgalan Black solution (0.2% in 2% acetic acid). The sterile membranes were individually placed in detergent, rinsed in sterile filtered water and then placed in the stain for 10 minutes (Hobbie *et al.*, 1977). The filters were then stored in sterile filtered water until required. The soil dilution to be counted was stained for 10 minutes using the AO solution. 1 ml of the soil dilution was then filtered through a pre-stained membrane filter using a hand-operated vacuum pump. The membrane was removed and placed on a glass slide with 2 drops of immersion oil to ensure good contact. Counts were undertaken using an epiflourescence microscope (Nikon, Alphabot) with an oil immersion objective at a magnification of X1250 with ultra violet (UV) incident illumination. Under the UV light, the stained bacterial cells fluoresce orange and green, enabling them to be counted. Figure 3.15 shows a typical microscope view of a stained sample using the AO staining method. Counts were undertaken using a graticule with three different sized frames, A, B & C, marked upon it, where A has the dimensions of 0.034 mm^2, B 0.058 mm^2 and C 0.084 mm^2. With a very high density of cells within the sample then the smaller frame is used, and vice versa. These counts are used in the calculation of the numbers of cells present within the soil sample; a smaller frame prevents the calculations being based upon one individual area of the slide and therefore not being representative of the sample as a whole. 600 bacterial cells were counted from each slide or, if the density of cells was very low, 100 frames were counted. In addition to the three replicate counts made for each of the soil slurries prepared, three blank counts were undertaken on stained ringer's solution. Calculations are undertaken for wet weight as opposed to the normal use of dry weight, to allow for a better comparison between soil samples with vastly different moisture characteristics. Use of dry weight calculations would make such comparisons difficult.

The formula for calculating the number of bacterial cells per gram wet weight of original soil sample is -

$$Bacterial\ numbers = \frac{N \times A}{F \times a \times v \times c} \tag{3.10}$$

Where -

N = no. of bacteria counted per frame

A = filtered area (obtained by measurement of the filter unit used)

F = no. of frames counted

a = area of the frame

v = volume of slurry filtered (in litres)

c = concentration of the soil slurry filtered.

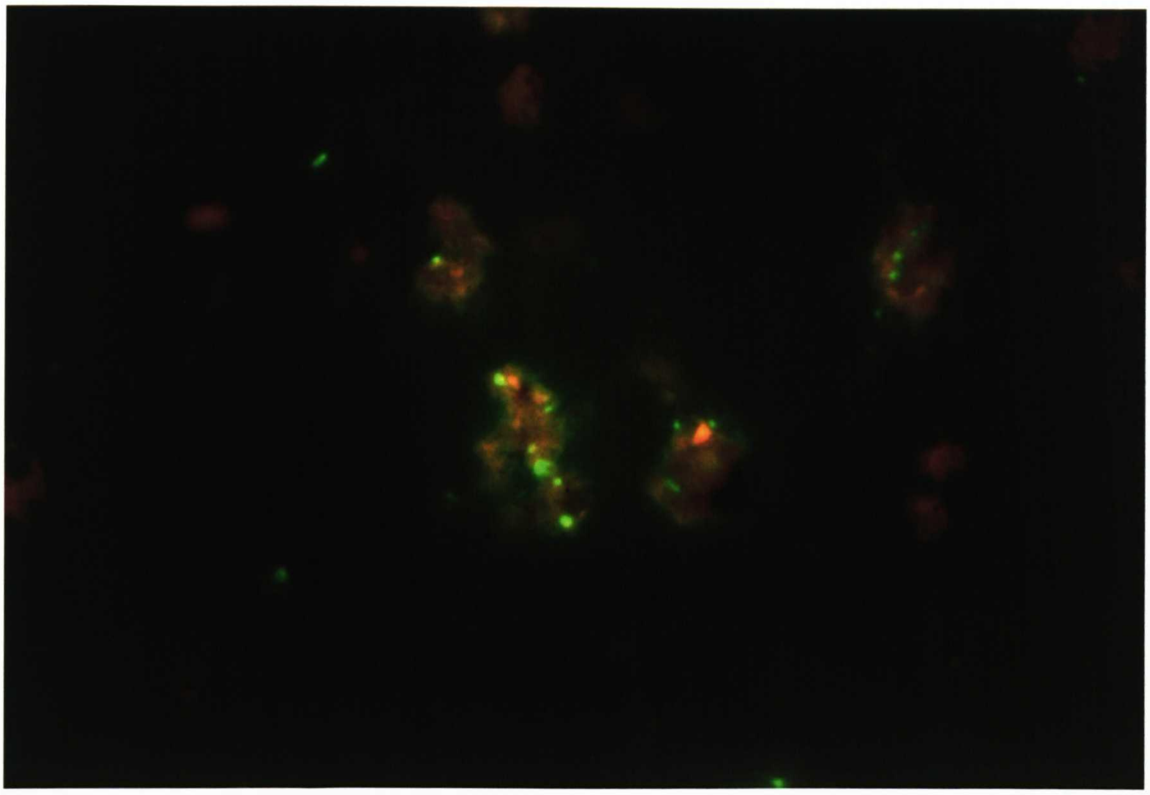


Figure 3.15 An example view of Acridine Orange (AO) stained samples observed under epiflourescence at a magnification of X1250 . The orange areas are organic / mineral matter; bacterial cells fluoresce green. (Picture Courtesy of R. Goulder).

3.4.4 Extracellular enzyme assay

Soil microorganisms are the major agents of decay of organic archaeological materials within the burial environment (Blanchette *et al.*, 1990). One mechanism by which degradation occurs is through the breakdown of molecules outside the cell wall membrane by means of extracellular enzymes. As the focus of this has been upon the preservation / degradation of archaeological wood, there follows a short discussion on the selection of the enzymes that have been targeted for assay in the context of the degradation of woody materials.

Three enzymes have been targeted for assay during this research - leucine aminopeptidase, β-glucosidase and phosphatase. Leucine aminopeptidase is an enzyme that falls within the broad class of proteinases, these being involved in the breakdown of proteins (Burns, 1983). Although not directly relevant to the degradation of archaeological wood, as this material is not proteineous in character, it is an enzyme that has been assayed for in previous work carried out at the University of Hull in aquatic environments (Ainsworth & Goulder, 1998, 2000a&b, Brown & Goulder, 1996, Chappell & Goulder, 1994, 1995). Assay for leucine aminopeptidase has been applied as a general measure of microbial activity within the soil environment.

The activity of Phosphatase enzymes within the soil environment catalyses the decomposition of organic phosphorous compounds within soils, thus making phosphate available. Since phosphate is recognised as being essential for plant and soil microbial growth and metabolism (Speir & Ross, 1978) and is therefore a crucial factor in soil microbial activity, it has been included in the soil assay work.

β-glucosidase is the only enzyme to be assayed that can be directly linked to the degradation of cellulose, the major structural component of woody materials. The enzyme is involved in the cleaving of cellobiose, in intermediary molecule in the breakdown of cellulose, to D-glucose and it has been acknowledged as being an essential component in this activity (Burns, 1983) (Figure 3.16).

The assay procedures used were based upon Hoppe (1993). The enzyme substrates used were L-Leucine-7-amido-4-methylcoumarin hydrochloride, 4-Methylumbelliferyl b-D-glucopyranoside and 4-Methylumbelliferyl phosphate (Sigma Chemical Co., Poole, UK). Enzyme substrate stock solutions were prepared to a concentration of 5 mmol l^{-1} for the three labelled substrates. For MCA-1-leucine (atomic mass of 324.8) 32.5 mg were added to 8 ml of methanol to aid dissolving (Goulder, 1990) and then made up to 20 ml with 0.2 μm sterile, filtered water. Using the same method, 25.6 mg of MUF-phosphate, (atomic mass of 256.2), and 33.8 mg of MUF-β-glucopyranoside, (atomic mass of 338.3), were made up.

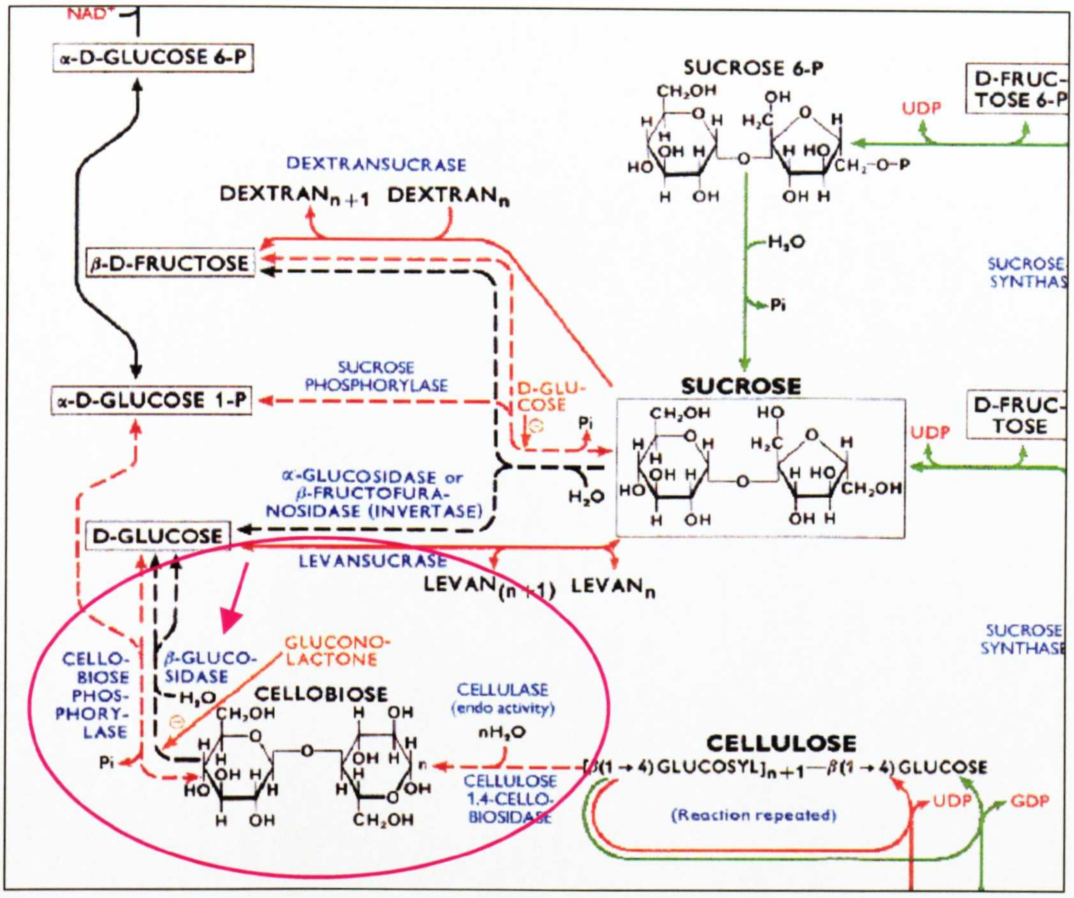


Figure 3.16 Biochemical pathway showing the location of β-glucosidase (highlighted) in the process of breakdown of cellulose to glucose. From Roche Applied Science, www[1]

A 1 g l^{-1} concentration of soil slurry was prepared using the same method as described in section 3.4.2. A blank soil slurry of 1 gl^{-1} concentration was also produced by boiling 250 ml of slurry for 3 minutes and, after cooling, centrifuged for 5 minutes at 3000 rpm. In sterile centrifuge tubes, 0.24 ml of enzyme substrate was added to 5.76 ml of slurry to give a substrate concentration of 200 μmol l^{-1}. Two replicates were produced for each sample, plus two blanks. The concentration of the substrate was chosen to represent saturated conditions, thus substrate hydrolysis was approximate to Vmax (Goulder, 1990).

The centrifuge tubes were then placed in an incubator at a temperature of 10 °C for approximately 4 hours. An incubation temperature of 10 °C was chosen as this more accurately reflects the temperature conditions within the burial environment (Morra, 1996). On two occasions temperature profile measurements were obtained at Sutton Common to a depth of 1.5 m (data not shown), the mean temperature being 10 °C. Due to the lower temperature at which the incubation was carried out, compared to the optimal temperature when maximum substrate transformation occurs (approximately 30 °C), incubation times of four hours were chosen. Morra (1996) states that incubation times of less than five hours are preferable to avoid a situation where substrate limitation causes a shift in the microbial characteristics of the sample and also that increased product formation may stimulate the production of additional enzymes.

Following incubation, samples were centrifuged for 5 minutes at 3000 rpm, then fluorescence readings were obtained from a 5 ml sample with 0.4 ml of pH10 buffer (BDH, Dorset, UK), (Hoppe, 1983), using a Turner Designs Model 10 Series fluorometer (Steptec Intrument Services, Bedfordshire, UK) fitted with excitation filter 10-069 and emission filter combination 10-059 and 10-061.

During incubation of the samples, calculation of the fluorescence units was carried out for both MCA and MUF through the construction of straight-line calibration graphs (Goulder, 1990). For MCA, 17.5 mg of MCA was dissolved in 8 ml of methanol made up to 20 ml using 0.2 μm sterile filtered water. 1 ml of this was then pipetted out and made up to 100 ml, again with 0.2 μm sterile filtered water, to give a concentration of 50 μmol l^{-1}. A calibration graph was made using the concentrations shown in Table 3.1.

Table 3.1 Concentrations used for the calibration of MCA fluorescence units.

Concentration of solution / μmol l^{-1}	Stock solution of MCA (50 μmol l^{-1}) added / ml	Boiled centrifuged 1 g l^{-1} slurry added / ml
0.25	0.05	10
0.5	0.1	9.9
1	0.2	9.8
2	0.4	9.6

For MUF, 17.6 mg of MUF was dissolved with 8 ml of methanol and made up to 20 ml with 0.2 μm sterile filtered water, 2 ml of which was made up to 100 ml, giving a concentration of 50μmol l^{-1}. A calibration graph was created using the concentrations shown in Table 3.2.

Table 3.2 Concentrations used for the calibration of MUF fluorescence units.

Concentration of solution / µmol l^{-1}	Stock solution of MUF (50 µmol l^{-1}) added / ml	Boiled centrifuged 1 g l^{-1} slurry added / ml
0.1	0.02	9.98
0.2	0.04	9.96
0.3	0.06	9.94
0.4	0.08	9.92
0.5	0.10	9.90

A blank value was also obtained using 10 ml of boiled slurry.

The calibration graphs were then used to create fluorescence units, thus enabling the product of enzyme hydrolysis to be calculated by subtracting the fluorescence of the blank from those of the samples. The result was then divided by the incubation time to provide the rate of enzyme hydrolysis of the substrate in µmol g^{-1} h^{-1}. Therefore:

$$Extracellular\ enzyme\ activity = F\frac{(R-A)}{(t \times C)} \tag{3.11}$$

where:

F = concentration of product equivalent to 1 fluorescence unit (nmol l^{-1})

R = relative fluorescence of post incubation slurry subsample

A = Relative fluorescence of blank slurry sample

t = incubation time (hours)

C = concentration of slurry (g wet weight l^{-1})

3.4.5 ^{14}C-leucine assimilation

Radio-labelled leucine assimilation was carried out to provide a measure of the metabolic activity within the soil samples, this being an important factor to study as it provides an indication of how active a microbial population is. Potentially, over time and under varying environmental conditions, metabolic activity and the secondary production of biomass, can change, but not necessarily be reflected in other factors such as the numbers of bacterial cells or the activity of extracellular enzymes (Goulder, 1991). Therefore, when studying soil microbiological activity, this is an essential factor to take into account. The method used closely follows that presented for Leucine assimilation by Ainsworth & Goulder (1998), the principal relying upon the incorporation of the radio-labelled substrate into the microbial cell itself. The more active a microbial population is, the greater the rate of substrate uptake and therefore following incubation the more radioactive the sample will be. The radio-labelled substrate used was L-[U-^{14}C]leucine (Amersham International, Amersham, UK). All determinations were undertaken under saturation conditions.

Initial attempts at measuring microbial metabolic rates within soil samples, were undertaken through the measurement of oxygen consumption. This was carried out using Rank oxygen electrodes (Rank Brothers, Cambridge, England), these were designed to measure the uptake of oxygen by cell suspensions (Hall, 1975). Although initial trials produced promising results, field sampling produced problems concerning the accuracy of the equipment. It became apparent that the anaerobic, reduced character of samples obtained from greater depths, were producing a chemical response within the oxygen electrode. This resulted in erratic readings being observed necessitating the probe to be dismantled, cleaned and reset, thus making effective measurements impossible. In response to this problem, the leucine assimilation technique was adopted.

The method was carried out by preparing a 10 ml of a 1 gl^{-1} slurry for each sample depth which was added to sterile universal bottles into which 0.1 ml of ^{14}C-leucine had previously been added (equivalent to 0.1 μCi). Four replicates were prepared, including one blank into which 1 ml of neutral filtered formalin had been added to stop microbial activity. The samples were then incubated in darkness at 10 °C for approximately 4 hours in the same manner as for the extracellular enzyme assay. At the end of the incubation period, 2 ml of each sample was filtered through 0.2 μm cellulose acetate filters (Sartorius, Goettingen, Germany) and washed with 10 ml of sterile filtered water. The filters were then transferred into scintillation vials containing 10 ml of Filtron X flour. The radioactivity was counted using a TRT-CARB 2100 TR Liquid Scintillation analyser. A positive blank was obtained by counting a clean filter with flour and 10 µl (0.01 µCi) of radio-labelled leucine.

Leucine assimilation is calculated using the saturation approach presented by Goulder (1991) where:

$$v = f\frac{A}{t} \tag{3.12}$$

where

v = the leucine uptake rate

f = the fraction of the isotope supplied which is taken up by bacteria during incubation

A = the concentration of added substrate

t = duration of incubation

A was calculated by the following:

$$A = leucine\ concentration \times \frac{volume\ incubated}{volume\ filtered} \tag{3.13}$$

where volumes represent soil slurry.

f was calculated by the following:

$$f = \frac{(mean\ count\ value) - (blank\ value)}{activity\ added(average\ from\ 10\,\mu l\ of\ active\ solution) \times 10} \tag{3.14}$$

3.4.6 Sample moisture & organic matter content

Two physical parameters were measured for each sample analysed - moisture content, and loss on ignition (this being an indicator of organic matter content). These two factors are important as they potentially influence microbial activity. Organic material in soil provides the most readily available substrate to support microbial activity.

Determination of sample moisture content was carried out by sub-sampling two 10 g replicates. These were placed in pre-weighed crucibles, weighed again and placed in an oven at 105 °C overnight (at least 16 hours). Once removed from the oven, samples were stored in a desiccator until cooled. Calculation of the percentage moisture content on a dry weight basis was achieved using formula 3.1 (Fenwick & Knapp, 1982):

$$\frac{\mathit{Mass\ of\ moist\ soil} - \mathit{Mass\ of\ oven\ dry\ soil}}{\mathit{Mass\ of\ oven\ dry\ soil}} \times 100 \qquad (3.15)$$

Samples were then placed in a furnace heated to 400 °C for a minimum of four hours and cooled in a desiccator. Calculations for the percentage mass loss on ignition were achieved using formula 3.14 (British Standards Institute, 1990):

$$LOI = \frac{m3 - m4}{m3 - mC} \times 100 \qquad (3.16)$$

where:

m3 = mass of the crucible and oven-dry sample (g)
m4 = mass of the crucible and the sample following ignition (g)
mC = of the crucible (g)

3.5 Summary

This chapter has detailed the key methods that have been employed in monitoring Sutton Common, along with the laboratory methods used for the microbiological assessment of soil samples. A background to each technique has placed them within the context of previous research and projects, and justified the use of the techniques adopted.

The results obtained from these methods are presented in chapters 5-7, reflecting the three main approaches that have been taken - hydrological monitoring, the recording of soil redox potentials and microbiological assessment of the predominant soil types and profiles present on Sutton Common.

Chapter 4 Monitoring locations

4.1 Introduction

As described in Chapter 3, on-site data has been obtained from a number of locations. Hydrological data was obtained from a network of 50 piezometers (Figure 3.1), redox data was collected from nine locations within this grid (Figure 3.10) and microbial samples were obtained from five locations, including a control point (Figure 3.14). The control point was situated in the adjacent field to the west of the main study site, an area that was not directly influenced by re-wetting.

During the collection of data, additional environmental parameters were recorded that were thought to provide a useful insight into the burial environment. These were: sediment stratigraphy and a soil pH depth profile. These parameters were recorded during sampling for microbial analysis and hence, are restricted to these five sites. The depths at which pH values were obtained reflect the depths that redox probes were installed across the site. Soil moisture content and Loss On Ignition (LOI) values were obtained from surface samples, 0.75 and 1.5 m depths

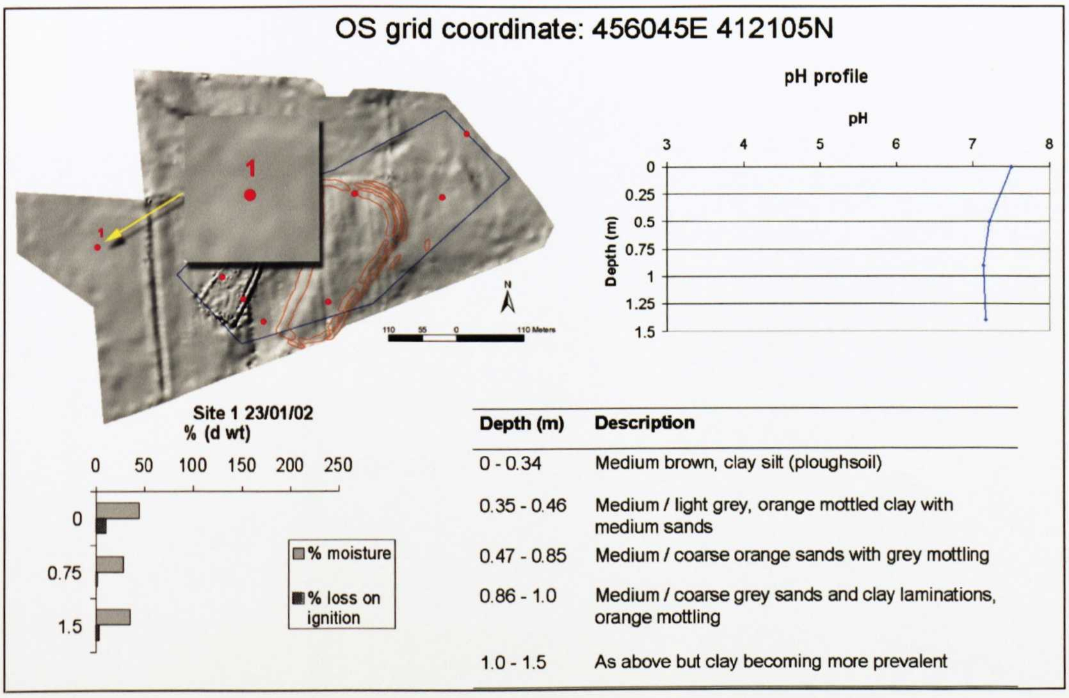
Studying soil stratigraphy can help identify factors that may influence the results of monitoring, such as relatively impermeable layers that may create perching of surface water. Also, the presence of organic-rich layers within the soil profile may influence soil redox results and also the presence and activity of soil microorganisms.

Appreciating the variation in pH through the soil profile can provide insights into the variability within the burial environment and help to understand the potential affect upon soil redox monitoring. Values obtained for redox measurements can be influenced by the ambient pH of the burial environment at any particular location, and if results are plotted in a linear fashion over time, they require adjustment to account for pH status (Bohn, 1971). Such pH readings used for adjustment were obtained directly from the surface, whereas some soil redox probes were installed at approximately 1.5 m depth and therefore assessing the potential pH variability within the soil profile is desirable.

4.2 Site descriptions

The environmental parameters measured for each location are presented here in an integrated format. The nine redox locations are shown with a detailed location map presented along with O.S. grid coordinates. However, those locations where further information exists also include details on sediment stratigraphy, pH within the soil profile, moisture content and LOI data.

Site 1



Depth (m)	Description
0 - 0.34	Medium brown, clay silt (ploughsoil)
0.35 - 0.46	Medium / light grey, orange mottled clay with medium sands
0.47 - 0.85	Medium / coarse orange sands with grey mottling
0.86 - 1.0	Medium / coarse grey sands and clay laminations, orange mottling
1.0 - 1.5	As above but clay becoming more prevalent

Figure 4.1 Integrated graphic showing location of Site 1, pH profile to a depth of 1.5 m, soil stratigraphy, soil moisture content and LOI values.

Site one was located centrally within the field immediately west of the Coalite Drain. This field was not subjected to re-engineering of the under-field drainage and therefore this monitoring point was installed to act as a control point. A direct comparison could then be made between areas affected by the re-wetting work and those that were not and therefore provide a benchmark against which change could be measured.

Like the rest of the site, this location shows a well developed plough soil with sands and clays dominating the soil matrix. With increasing depth, lamination structures become more distinct, with these being fluvial in origin.

The dominance of sands and clays is reflected in the soil moisture and LOI values obtained from here, both being relatively low. The lack of organic matter content within the soil profile may explain the neutral character of pH conditions. Values throughout the profile remain slightly above neutral with no obvious pattern of change.

Site 2

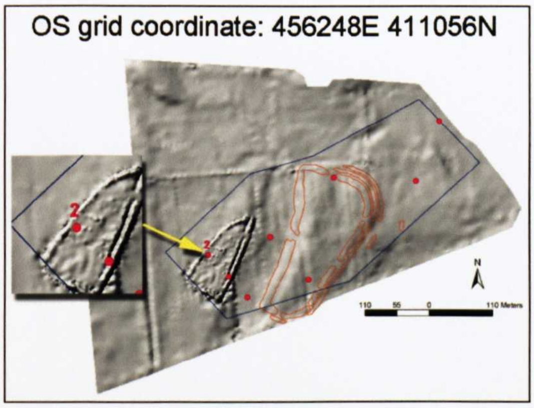
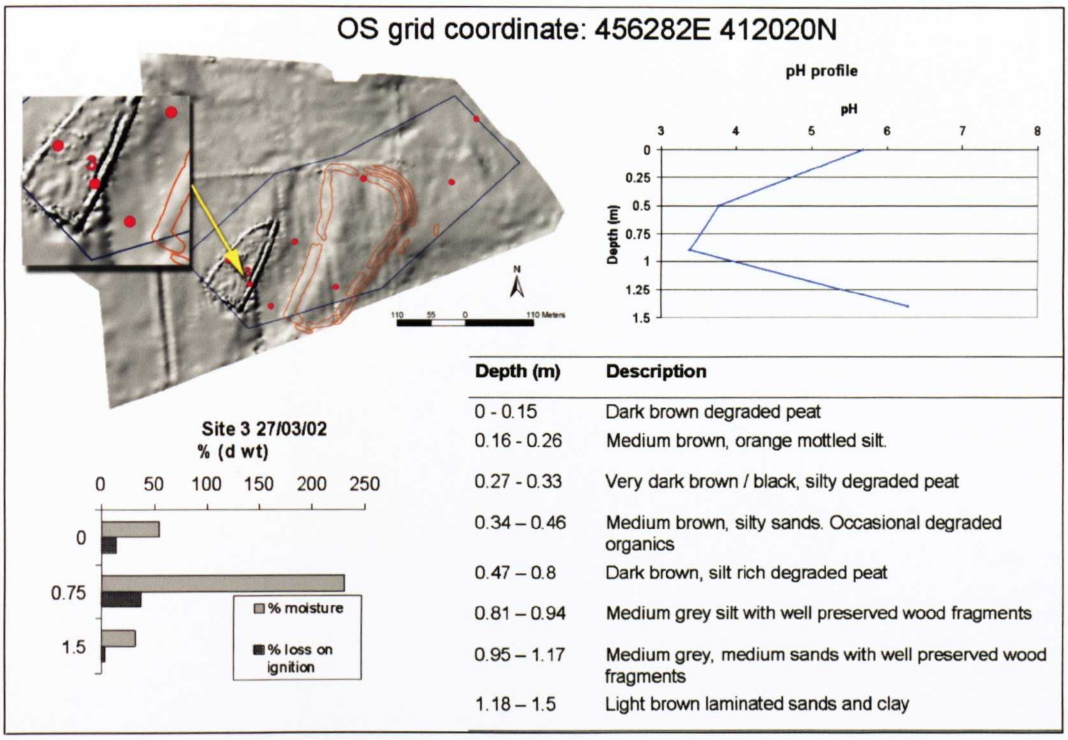


Figure 4.2 Location map of soil redox monitoring point 2.

Redox monitoring point 2, was located within Enclosure B, on the western edge of the upstanding earthworks. This location was chosen to be representative of the soil conditions within the enclosure. No additional parameters were measured for the soil profile in this location other than soil redox potentials.

Site 3



Depth (m)	Description
0 - 0.15	Dark brown degraded peat
0.16 - 0.26	Medium brown, orange mottled silt.
0.27 - 0.33	Very dark brown / black, silty degraded peat
0.34 – 0.46	Medium brown, silty sands. Occasional degraded organics
0.47 – 0.8	Dark brown, silt rich degraded peat
0.81 – 0.94	Medium grey silt with well preserved wood fragments
0.95 – 1.17	Medium grey, medium sands with well preserved wood fragments
1.18 – 1.5	Light brown laminated sands and clay

Figure 4.3 Integrated graphic showing location of Site 3, pH profile to a depth of 1.5 m, soil stratigraphy, soil moisture content and LOI values.

Site 3 is the only monitoring location directly associated with an archaeological feature that has produced well-preserved organic archaeological remains. Previous excavations that have been carried out within this feature have identified a number of significant archaeological remains, although these were made further north along the ditch in an area unaffected by bulldozing (Parker Pearson & Merrony, 1993). Site 3 is located at the southern end of the internal ditch of Enclosure B. It is in this location that the enclosure sustained damage from bulldozing and as a result, the ditch has been partially infilled (refer to Figure 2.4).

Figure 4.3 shows that the sediment stratigraphy is far more complex in this location than at Site 1. This reflects the existence of the internal ditch feature of Enclosure B and the associated deposits. The surface deposits are derived from material removed from elsewhere in the enclosure, or alternatively, bank material redeposited within the ditch at the time of the destruction of Enclosure A. Within the soil profile, it is possible that the degraded peat at a depth of 0.46 – 0.8 m depth reflects the original surface of the ditch. The pH profile, soil moisture content and LOI values reflect the changing characteristics of the soil profile very well. Although the surface pH is relatively high, at around pH 6, it becomes highly acidic between 0.5 and 0.9 m depth, dropping to approximately pH 3.5, reflecting the presence of peat, before rising again at 1.4 m depth to its former value. This reflects the change to a mineral dominated sediment matrix present below the archaeological ditch. The high values for soil moisture content and LOI at 0.75 m depth relative to the other sampling depths also reflects the same pattern.

Site 4

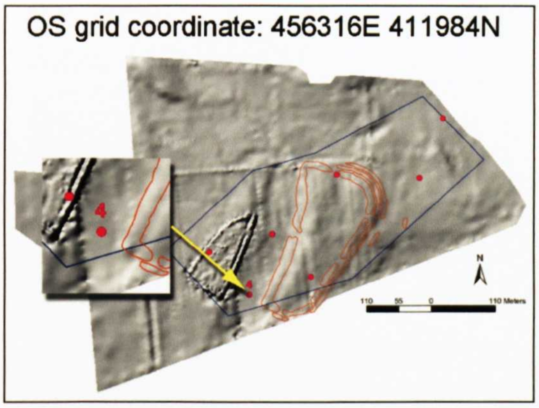
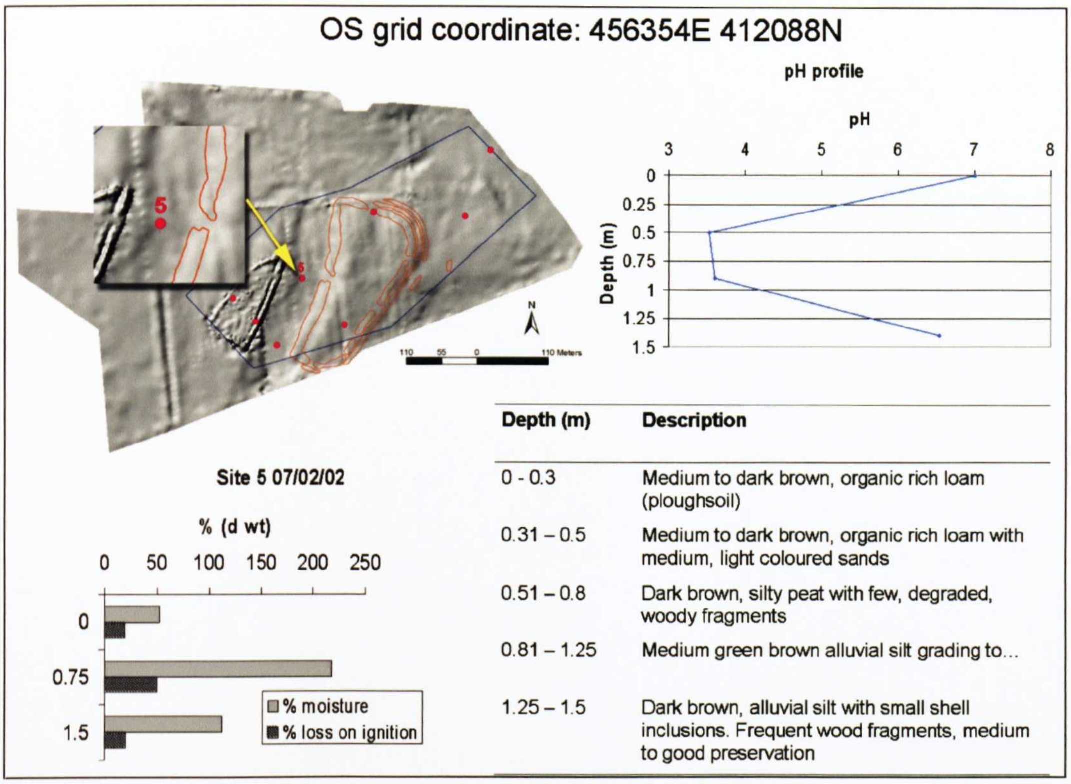


Figure 4.4 Location map of soil redox monitoring point 4.

Soil redox monitoring point 4 was located within the southern portion of the palaeochannel separating the two archaeological enclosures, chosen to be representative of the southern half of the palaeochannel, this being the portion of the site still retaining a high degree of wetness and saturation through the greater part of the soil profile. This occurs as a result of its topographically low-lying character.

Site 5



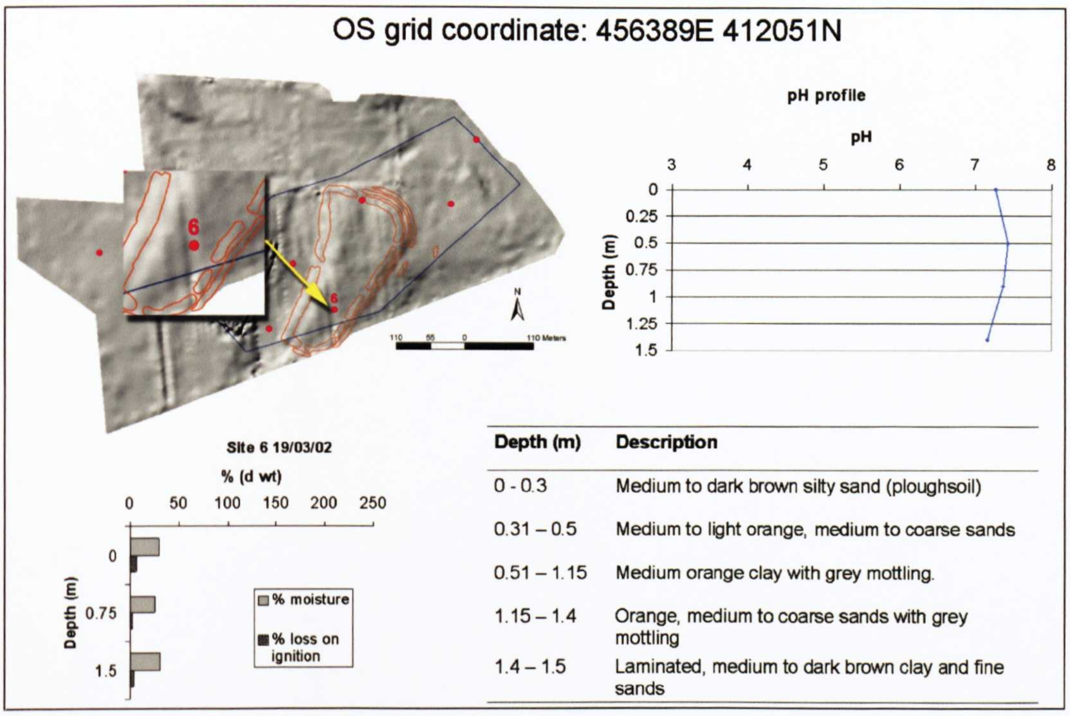
Depth (m)	Description
0 - 0.3	Medium to dark brown, organic rich loam (ploughsoil)
0.31 – 0.5	Medium to dark brown, organic rich loam with medium, light coloured sands
0.51 – 0.8	Dark brown, silty peat with few, degraded, woody fragments
0.81 – 1.25	Medium green brown alluvial silt grading to...
1.25 – 1.5	Dark brown, alluvial silt with small shell inclusions. Frequent wood fragments, medium to good preservation

Figure 4.5 Integrated graphic showing location of Site 5, pH profile to a depth of 1.5 m, soil stratigraphy, soil moisture content and LOI values.

Site 5 is located centrally within the palaeochannel feature along the line of the causeway running between Enclosures A and B.

Figure 4.5 presents the sediment stratigraphy from Site 5. This is a relatively uncomplicated sequence, showing a degraded peat to 0.8 m depth overlain by a homogenous ploughsoil, grading into minerogenic alluvial sediments. This sequence clearly reflects the formation of peat deposits within the channel following the cessation of flow. Wood preservation is relatively poor within the upper 1.0 m, with the quality of incorporated woody material then improving with at a greater depth than this. Similarly to Site 3, there is an obvious dip in the pH of the soils between 0.5 and 0.9 m depth with values of around pH 3.5 dropping from near neutral at the surface and returning to this value at 1.4 m. This again reflects the presence of a well-developed peat within this depth range. Again, soil moisture and LOI values (when compared to the surface and 1.5 m depth samples) highlight this relationship with elevated values for both.

Site 6



Depth (m)	Description
0 - 0.3	Medium to dark brown silty sand (ploughsoil)
0.31 – 0.5	Medium to light orange, medium to coarse sands
0.51 – 1.15	Medium orange clay with grey mottling.
1.15 – 1.4	Orange, medium to coarse sands with grey mottling
1.4 – 1.5	Laminated, medium to dark brown clay and fine sands

Figure 4.6 Integrated graphic showing location of Site 6, pH profile to a depth of 1.5 m, soil stratigraphy, soil moisture content and LOI values.

Site 6 is located within the southern half of Enclosure A. This location was chosen to be representative of the conditions within the greater extent of this enclosure.

Figure 4.6 presents the sediment stratigraphy at Site 6. The deposits at this location differ considerably from those recorded at the other locations. This is due to far less organic material being present throughout the entire soil profile. The soil matrix at this location is comprised of predominantly sands and clays, with the only organic component occurring within the surface ploughsoil. Similarly to Site 1, the pH does not vary greatly throughout the soil profile, remaining at around neutral. The lack of any significant organic matter is seen by the very low values for soil moisture and LOI when compared to locations such as at Site 5.

Site 7

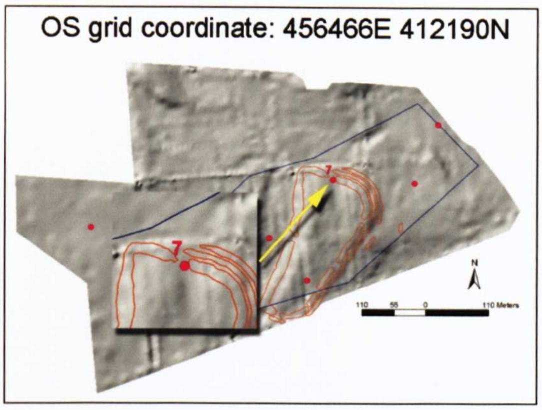


Figure 4.7 Location map of soil redox monitoring point 7.

Site 7 was located within the northern portion of Enclosure A. Soil conditions here are very similar in character to those at Site 6, with the existence of a mineral dominated sequence overlain by a ploughsoil.

Site 8

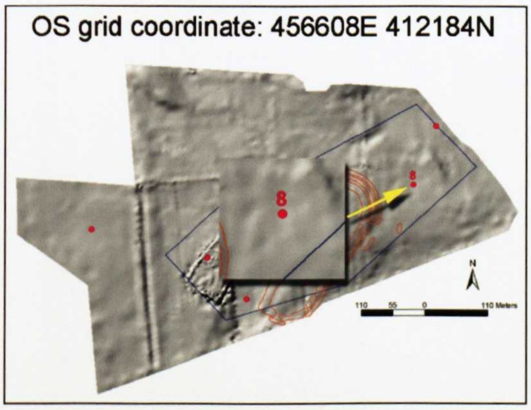
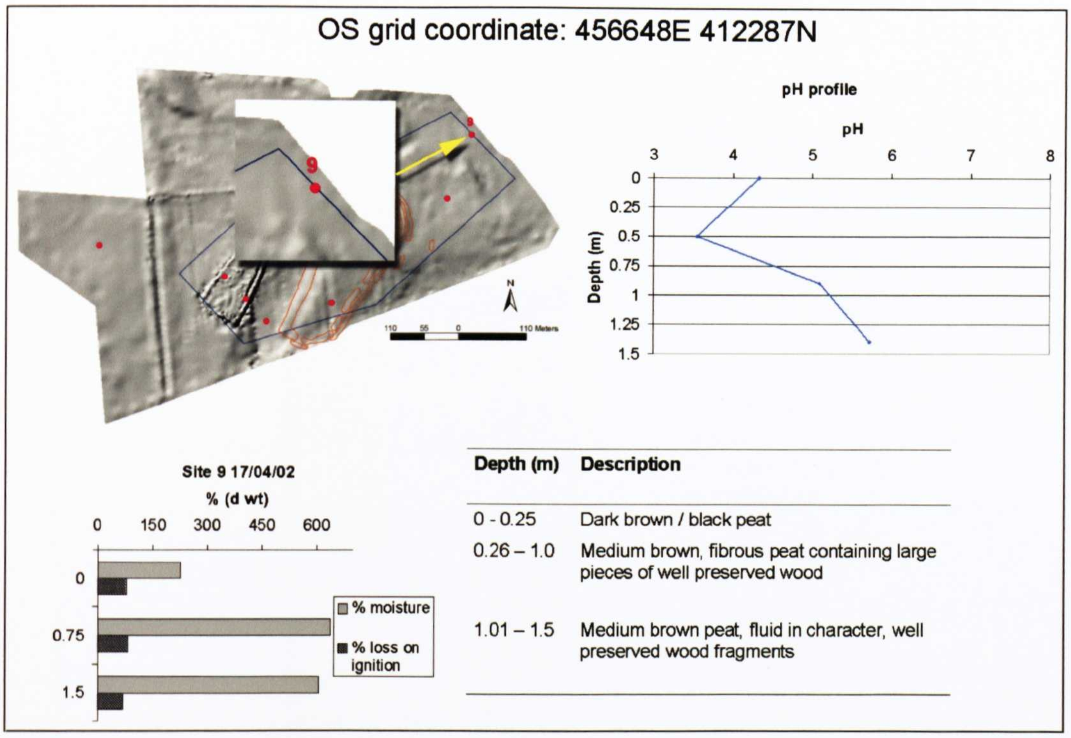


Figure 4.8 Location map of soil redox monitoring point 8.

Site 8 was located to the east of Enclosure A on the dip-slope above the peat deposits within and around Shirley Wood.

Site 9



Depth (m)	Description
0 - 0.25	Dark brown / black peat
0.26 – 1.0	Medium brown, fibrous peat containing large pieces of well preserved wood
1.01 – 1.5	Medium brown peat, fluid in character, well preserved wood fragments

Figure 4.9 Integrated graphic showing location of Site 9, pH profile to a depth of 1.5 m, soil stratigraphy, soil moisture content and LOI values.

Site 9 is located on the extreme east of the monitored area of the site, situated adjacent to Shirley Wood. The conditions in this area are significantly different to the rest of the site, with saturated conditions being prevalent for the majority of the year. From field observations, it is apparent that only during the height of the summer is the ground surface not saturated. From previous investigations carried out on the site (Lillie, 1997), there is a deep, peat-dominated sequence at this location, which is associated with presence of faulting in the area (Parker Pearson & Sydes, 1997).

The sequence at this location consists of peat, with preservation very good apart from within the immediate surface deposits, these having been exposed to desiccation and disturbance from agricultural activities. The reason for this near-surface water table is, similarly to Site 4, due to its low lying nature.

The pH values obtained from throughout the soil profile reflects the high organic matter content present especially within the upper 1 m, being acidic. At greater depths there is a change back towards more neutral conditions.

The organic nature of the soil profile is also reflected in the soil moisture and LOI values obtained; both being the greatest values obtained from across the site as a whole. Soil moisture is in excess of 600% dry weight and LOI is almost 100%, indicating almost pure organic material under saturated conditions. The moisture content within the surface deposits is slightly lower relating to drier conditions being present near to the ground surface.

4.3 The significance of variability within the burial environment

These additional environmental parameters recorded at Sutton Common have provided an insight into the variability of the soil profile. A number of locations have revealed highly consistent conditions throughout their profile, such as Site 1 and Site 6, and also the highly organic character of the profile at Site 9. However, some locations showed significant variation, such as at Site 3, 5 and the pH profile at Site 9 and this may have consequences for the investigations that have taken place.

As mentioned previously, the use of soil redox potentials requires the pH to be known so that adjustments can be made if necessary. However, the technique that has been applied on Sutton Common is incapable of accounting for pH variability throughout the soil profile and hence the accuracy of some results may be affected. pH variability is evident at Site 3, where the presence of desiccated, oxidised peat within the ditch fill has a far lower pH than the material both above and below. A similar variation in pH was observed at Site 5 within the palaeochannel where a low pH was observed, again within the organic rich material within the soil profile.

From the evidence forthcoming from the environmental observations of a number of soil profiles on Sutton Common, it seems clear that where variable pH is seen, it is directly linked to the presence of organic rich deposits, specifically desiccated peat. With a falling water table consequential of agricultural drainage, desiccation and degradation of peats and other organic rich soils is promoted, thus causing progressive acidification. At Site 5 where the surface pH is near-neutral even though the soil profile is predominantly of peat origin, the pH conditions appear to have been ameliorated through the redistribution of mineral soils through the action of ploughing, these having more of a pH buffering capacity. The presence of organic material will also influence soil microbial dynamics as it is the main substrate for microbial metabolisms within the soil environment.

4.4 Summary

This chapter has presented the locations of soil redox monitoring in detail, along with the results of soil environmental observations made at five of these. From this it is clear that great variability exists within the different soils present on Sutton Common. This is particularly apparent in areas associated with the presence of organic matter, such as archaeological features and areas of peat. Such variability could potentially influence the results of the programme of soil redox monitoring, this requiring knowledge of soil pH conditions, and also the level of microbial activity.

The variability has been significantly influenced by past agricultural activities on the site, including drainage that is likely to have promoted acidification of organic-rich soils.

The next chapter presents the results surrounding the hydrological monitoring programme that has been carried out across Sutton Common. This includes measurements of the water table within the extent of the piezometer grid and also additional parameters such as *in situ* saturated hydraulic conductivity measurements and the creation of a GIS, archaeological wood model.

Chapter 5 Hydrological monitoring results

5.1 Introduction

The following three chapters will present the results generated during this research. Each major technique will be presented in its own chapter in the context of previous research and major interpretations. This chapter will present data obtained during the hydrological monitoring phase, Chapter 6 will present soil redox potential data and finally, Chapter 7 will present the results of the microbiological assessments that have been undertaken on Sutton Common.

Data concerning the water table depth across the site was gathered during 53 monitoring visits between October 1998 and March 2002. A large-scale monitoring programme was chosen in order to understand more fully the long-term fluctuations that occur on the site, and to identify change throughout the period of monitoring. Specifically, this change will relate to the impact of work carried out with the aim of 're-wetting' the site.

As described in section 3.2.1, hydrological monitoring of the site was undertaken by means of a network of fifty piezometers. This has created a consistent dataset relating to the depth of saturation within the soil profile across the site over time. Using ArcGIS it has been possible to model this data and create Digital Elevation Models (DEMs) of the water table at the time of each monitoring visit.

5.2 Precipitation data

Within the following sections there will be reference to the influence of the quantity of precipitation being received on Sutton Common and therefore it is desirable to present this data prior to the detailed examination of the monitoring results in order to provide a clear reference.

Precipitation data was generously provided by Grantham Brundle and Farran from a monitoring station at Kirk Bramwith located approximately 6 km southeast from Sutton Common.

Figures 5.1 - 5.5 present precipitation data obtained from Kirk Bramwith. The data presented is daily precipitation (mm), represented by bars and a line representing cumulative values across the whole year (mm). Presentation of the data in this manner helps the reader appreciate the effective contribution of individual precipitation events, or periods of prolonged rainfall, to the overall annual figure.

Figure 5.1 shows the precipitation data from Kirk Bramwith for 1998. The total rainfall for the year is just over 600 mm, this is approximately the average annual rainfall for the Humberhead Levels (Ellis, 1997). This region has one of the lowest figures for annual rainfall for anywhere in the British Isles occurring as a result of the presence of the Pennine Hills to the west. With the predominant direction of the rain-bearing winds coming from the west and the Atlantic Ocean, this creates a rain-shadow effect and hence there is lower rainfall in the South Yorkshire region.

Initial monitoring took place during October 1998, therefore it is only the latter part of the year's data that will be considered here.

Figure 5.2 shows precipitation data for 1999. The rainfall patterns for 1999 were broadly similar to the previous year, although the annual total was slightly higher at just under 630 mm. Wetter conditions during the spring and autumn months were apparent, contrasted by lower levels of precipitation during the summer months.

A pattern within the precipitation data has begun to emerge that will be of significance to the hydrological monitoring results presented later in this chapter. Around the months of September and October for 1998, 1999 and 2000, there is a significant increase in the amount of rainfall received. This can be broadly assumed as the change in conditions from the relatively dry summer months to the wetter winter season.

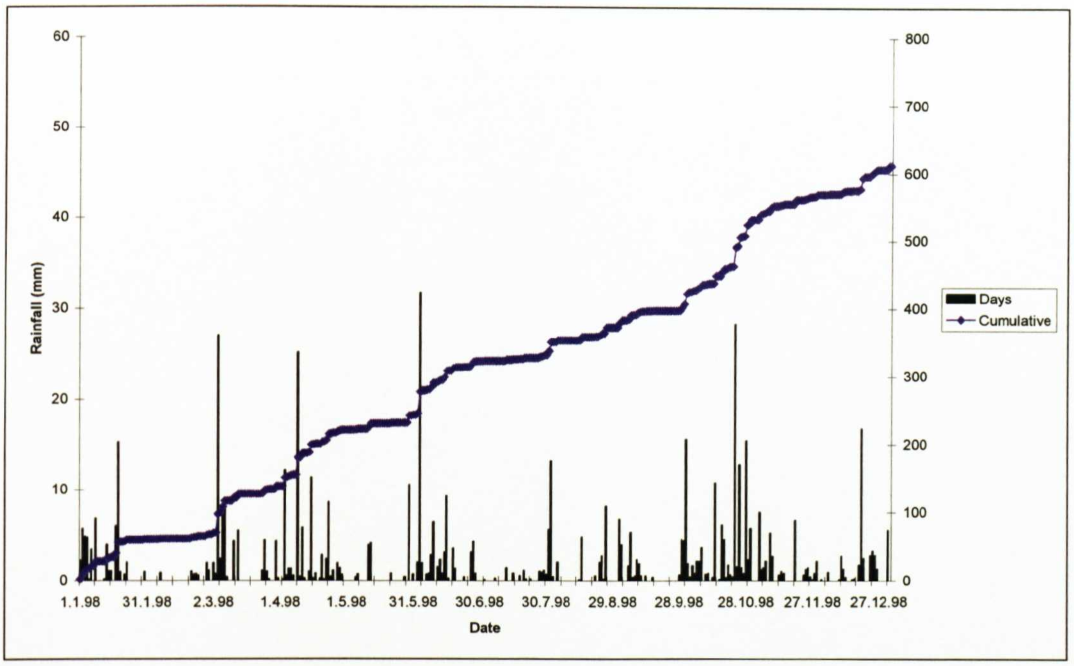


Figure 5.1 1998 precipitation data from Kirk Bramwith supplied by Grantham Brundell & Farran.

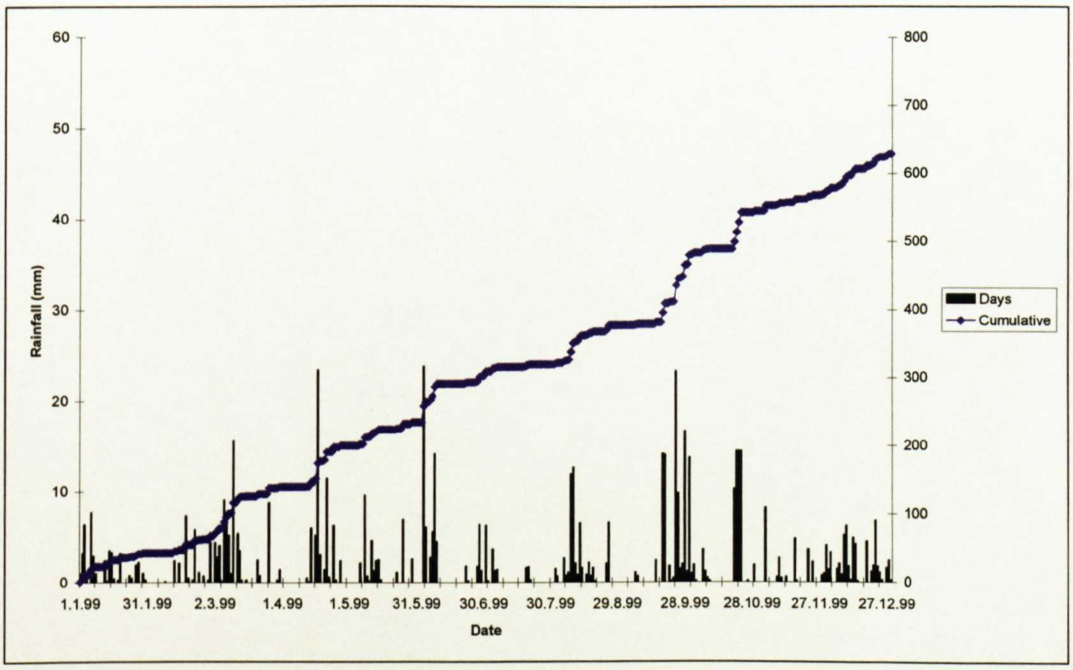


Figure 5.2 1999 precipitation data from Kirk Bramwith supplied by Grantham Brundell & Farran.

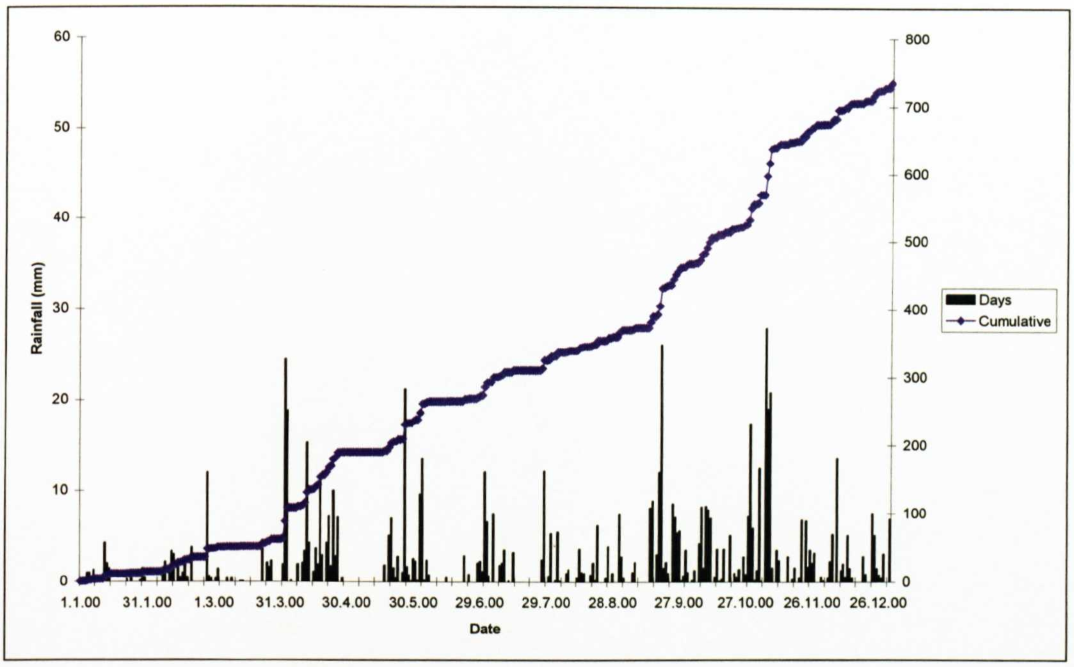


Figure 5.3 2000 precipitation data from Kirk Bramwith supplied by Grantham Brundell & Farran.

Figure 5.3 shows the precipitation data for 2000. This year was characterised by unprecedented rainfall (within the study area) during the latter part of the year. However, there were periods of high rainfall during the first half of the year and regular rainfall was also experienced during the summer. The annual total from Kirk Bramwith was just less than 734 mm, considerably greater than would normally be expected. During the latter months of 2000, many areas of the country experienced widespread flooding as a result of this level of precipitation.

Figure 5.4 shows the precipitation data for 2001. In contrast to data obtained from the other years considered here, 2001 is the only one that had an annual total of less than 600 mm, with Kirk Bramwith receiving just 561 mm. This occurred even though high rates of precipitation were experienced during the latter part of January and into February, adding to the problem of flooding at the end of the previous year. However, the rest of the year received less than would normally be expected.

Figure 5.5 shows the precipitation data for 2002. Only the first four months of 2002 will be considered, as final readings were obtained during April of that year.

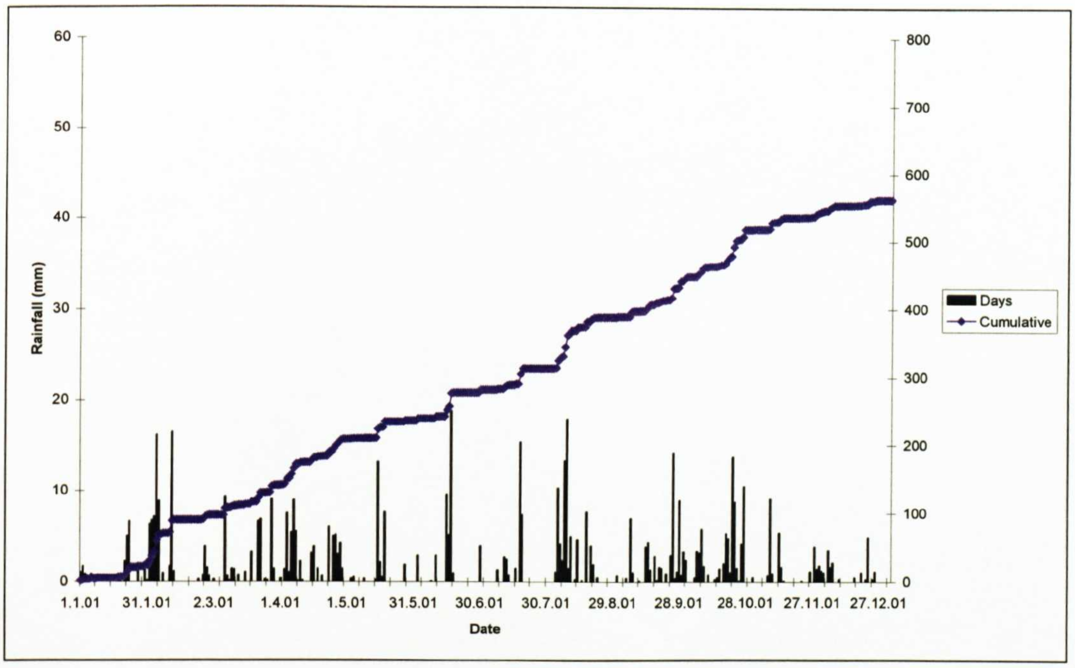


Figure 5.4 2001 precipitation data from Kirk Bramwith supplied by Grantham Brundell & Farran.

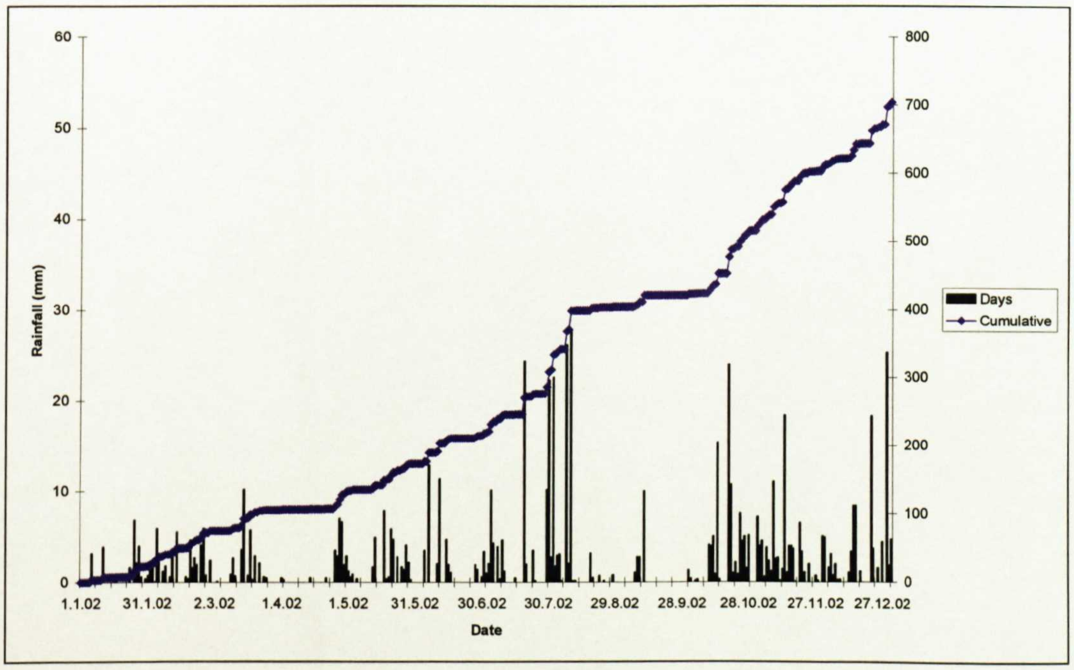


Figure 5.5 2002 precipitation data from Kirk Bramwith supplied by Grantham Brundell & Farran.

5.2.1 GIS generated representations of the Sutton Common water table

The hydrological models presented in this section are in the form of DEMs created from observations of the water table taken via the piezometer grid. Three of these models will be presented in each figure, each of which will have the main characteristics described and significant changes between them highlighted. The generation methods used to generate the hydrological models using ESRI ArcGIS are presented in section 3.2.2.

The description of each model will be preceded by the date at which the monitoring was undertaken and the period of time, in days, since the previous monitoring visits took place. This is provided to highlight the fact that the monitoring period was not uniform throughout the whole programme.

Figure 5.6 shows the Sutton Common DEM with the location and numbering of the piezometers within the monitoring grid in relation to the outline of the two archaeological enclosures.

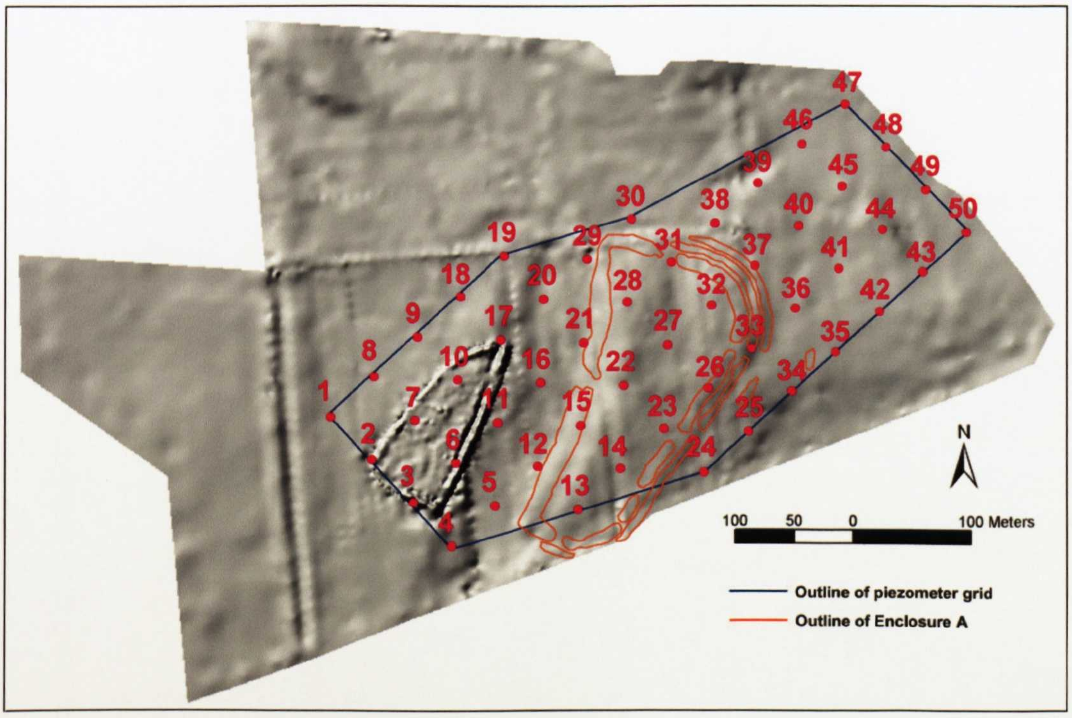


Figure 5.6 Sutton Common DEM showing the location and numbering of piezometers within the hydrological monitoring grid.

Figure 5.7

Figure 5.7A, shows the water table for the 05/10/98. The water table is low over the monitored area, illustrated by the predominance of red within the shading of the model. An area of relatively higher water table is present near to the centre, this being denoted by the yellow and blue shading. This area forms topographically the highest region within the monitored area of Sutton Common, indeed archaeologically it is the focal location as this is the location of Enclosure A. What can be termed a groundwater mound therefore appears to exist as a function of topography in this location, and it is a feature of all the hydrological models to be presented here. The lowest levels are around 2.1 m O.D. whereas the highest are approaching 3.6 m O.D.

Rainfall from the beginning of June 1998 (Figure 5.1) was low through to the monitoring date, illustrating the fact that this period was the driest of that year.

Figure 5.7B, 12/10/98. A period of 7 days. This model is striking in that it is almost identical in its form to the previous model. This could be explained by the short period of time between the two sets of readings being obtained and the lack of any significant rainfall.

Figure 5.7C, 02/11/98. A period of 21 days. There was an increase in the amount of water within the groundwater system. Observed heights across the whole area rose, with the groundwater mound present in the previous two models growing in size, both in extent and height. The highest level of water reached was 4.2 m O.D. This increase in the level of the water table is matched by an increase in precipitation during the latter part of October 1998.

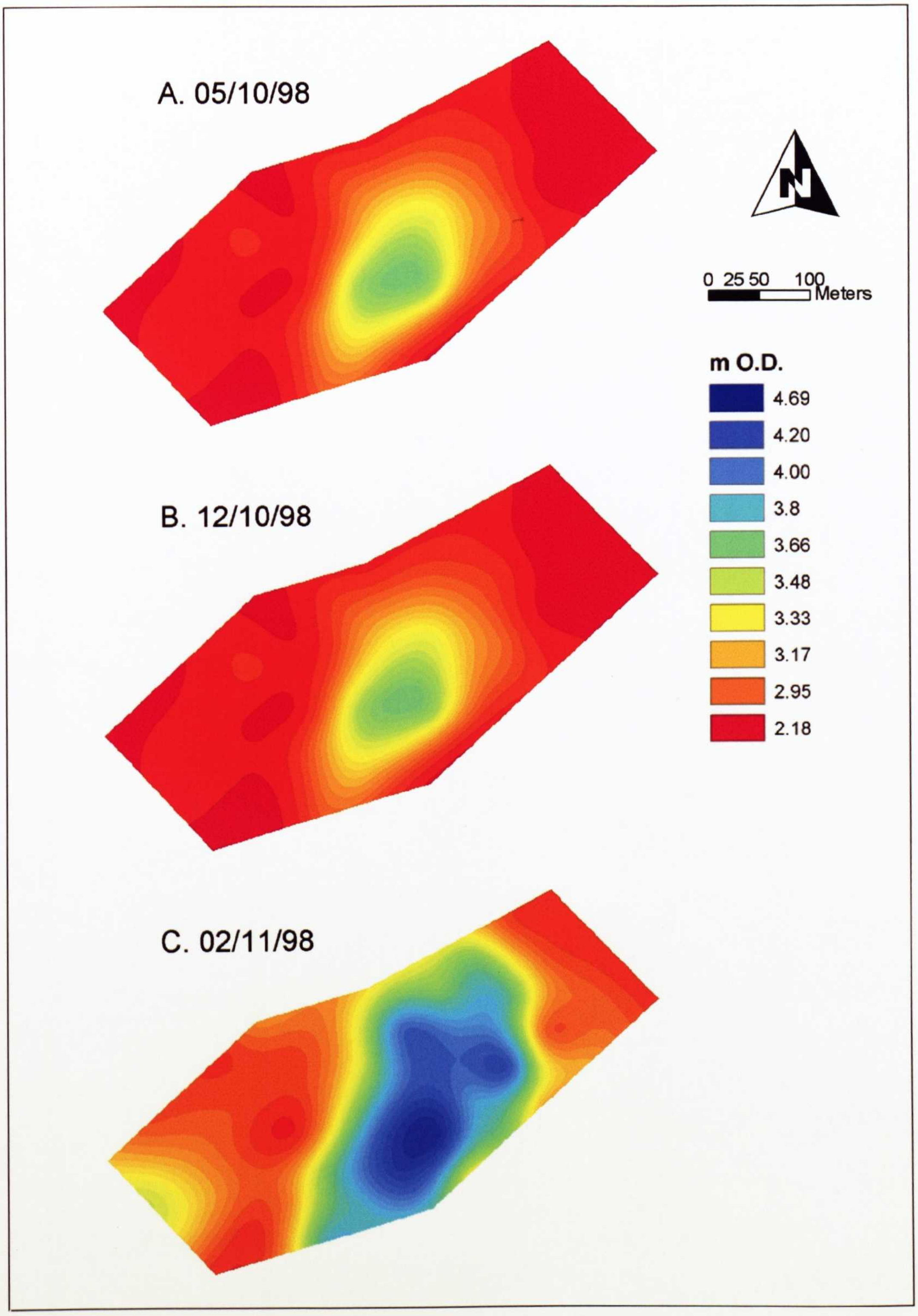


Figure 5.7 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.8

Figure 5.8A, 16/11/98. A period of 14 days. Again, there was an increase in the amount of water present within the groundwater system shown by the reduction of the red component of the model. The central groundwater mound has increased in extent. The lowest water levels were maintained along the extreme eastern edge of the modelled area with a height of less than 2.8 m O.D. The highest water level recorded on the model is in excess of 4.2 m O.D.

Interestingly, even though there was an increase in the amount of water present within the groundwater system between the 02/11/98 and the 16/11/98, there was not a significant increase in rainfall. The readings obtained on the 02/11/98 followed a short period of intense rainfall, the greatest continuous rainfall event of the whole of 1998. This discrepancy suggests that there is a period of lag within the models between the precipitation event itself and the response being observed within the water table. Evidence for a possible cause for this comes from the form of the groundwater mound observed within the model created for the 02/11/98. This is uneven in nature compared to that exhibited in the model for the 16/11/98 suggesting that the water input is being recorded in some piezometers quicker than in others; this is possibly caused through a variation in the rates of percolation from the ground surface to the level of saturation. Alternatively this could be the result of a variation in the response of the piezometers as a function of the varying hydraulic properties of the deposits within which they were installed. One possible cause for this type of pattern is the trapping of air within the unsaturated zone of the soil profile. If a rainfall event is sufficiently intense, an inverted zone of saturation can be formed at the ground surface, with air becoming trapped between this and the water table itself (Freeze & Cherry, 1979).

Figure 5.8B, 30/11/98. A period of 14 days. This is very similar to the previous model. It shows that there was a slight increase in the level of the water table over the western side of the monitored area and along the eastern edge of the groundwater mound, whereas its extent and magnitude remained almost identical. Again, this may be reflecting the fact that there is a period of lag within the system. Precipitation levels between the 16/11/98 and the 30/11/98 remained low.

Figure 5.8C, 16/12/98. A period of 16 days. This model shows that there was again another increase in the size of the groundwater mound and in the height of the water table, but also the creation of a separate smaller, but well defined, groundwater mound in the western area of the model. This is formed beneath the alluvial outcrop of the Lake Humber material upon which the smaller of the two archaeological enclosures, Enclosure B, is situated. As with the larger groundwater mound (located below the larger Enclosure A), there appears to be a relationship between surface topography and water table form and height. The lowest recorded water table heights were again along the eastern edge of the monitored area near Shirley Wood (approximately 2.85 m), relating to the topographically low, peat filled subsidence feature that forms the basin within which Shirley Pool exists.

The continued rise in the level of the water table at this time does not appear to relate to an individual event or period of precipitation. Whereas in the previous models there was evidence of a cause and effect relationship between precipitation and the water table on the site, in this case this is not present. In fact the intervening period between 30/11/98 and the 16/12/98 there is very little rainfall recorded (Figure 5.1). This suggests that the water table is still reacting to the large amount of precipitation prior to the 16/11/98.

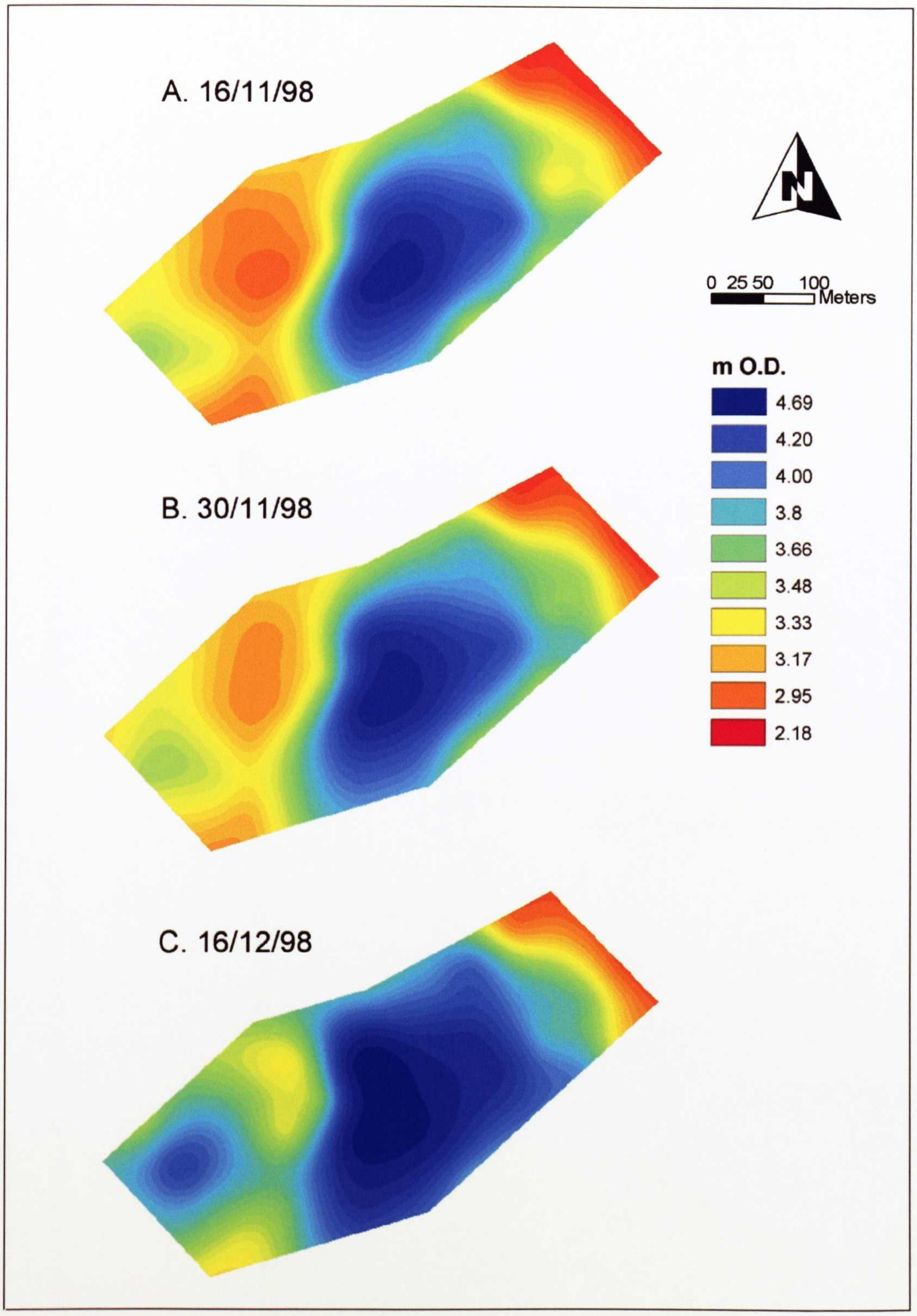


Figure 5.8 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.9

Figure 5.9A, 06/01/99. A period of 21 days. Again there was an increase in the height of the water table, with the both groundwater mounds increasing their extent. The area separating these is well defined in the model, clearly lying within the course of the palaeochannel.

Figure 5.9B, 21/01/99. A period of 15 days. The model shows that the water table was similar in form to that shown on the previous monitoring visit.

Figure 5.9C, 10/02/99. A period of 20 days. There was a decrease in the height and extent of the two groundwater mounds since the previous monitoring visit, apart from the lower southeastern area of the model where there was a slight increase. This general decrease appears to reflect a reduction in rainfall since the previous monitoring visit (Figure 5.2).

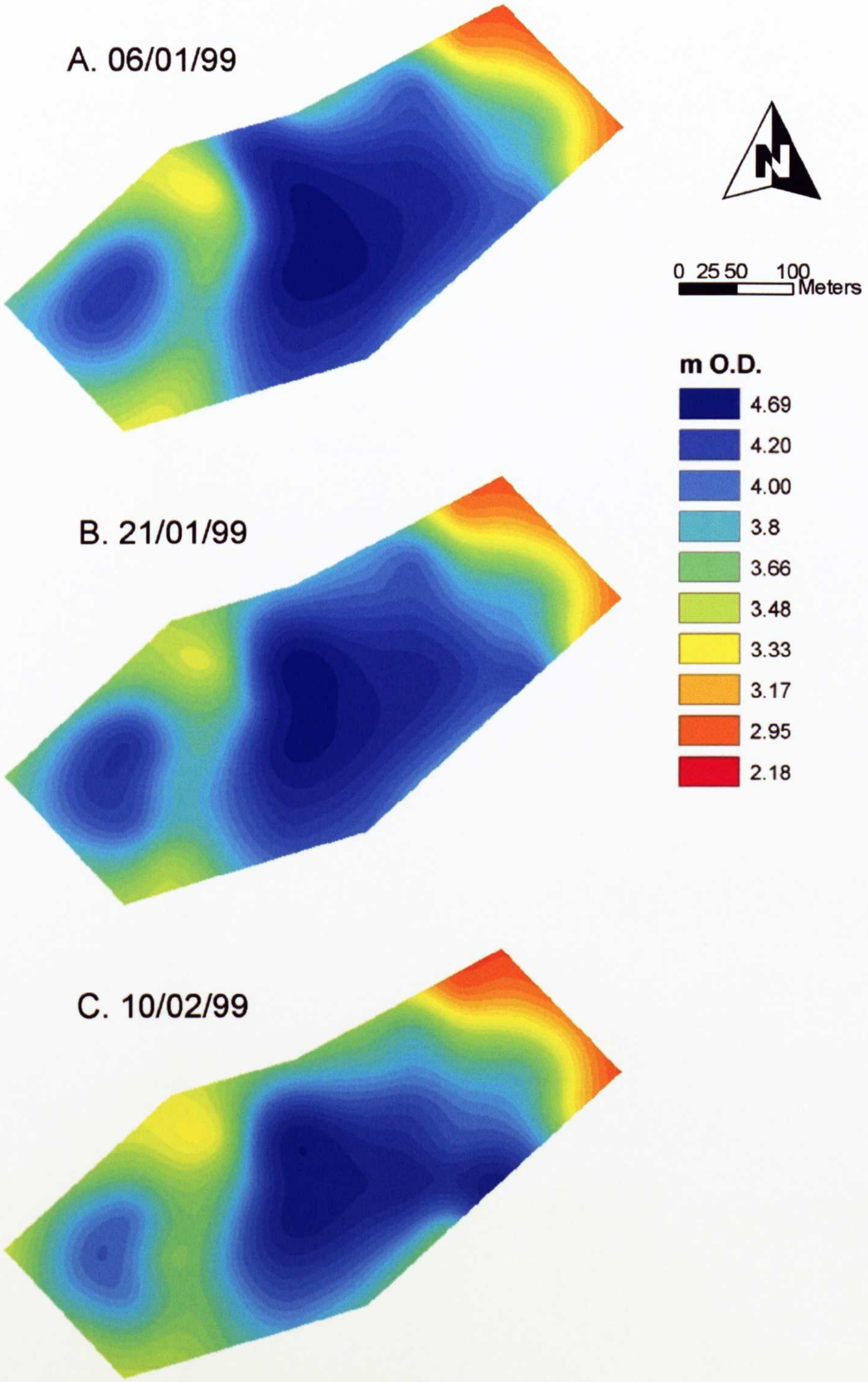


Figure 5.9 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.10

Figure 5.10A, 03/03/99. A period of 21 days. There was an increase in the level of the water table similar to the situation that was observed on the 21/01/99.

Figure 5.10B, 01/04/99. A period of 29 days. The model generated from the data collected at this date has produced a model very similar to that for the 10/02/99. There is little indication of an impact upon the water table from the relatively intense and long period of rainfall experienced from late February through to mid March of this year.

Figure 5.10C, 15/04/99. A period of 14 days. There was an overall reduction in the water table across the whole of the monitored area as compared to the previous model. The intervening period was characterised by a very low level of precipitation of 6.6 mm.

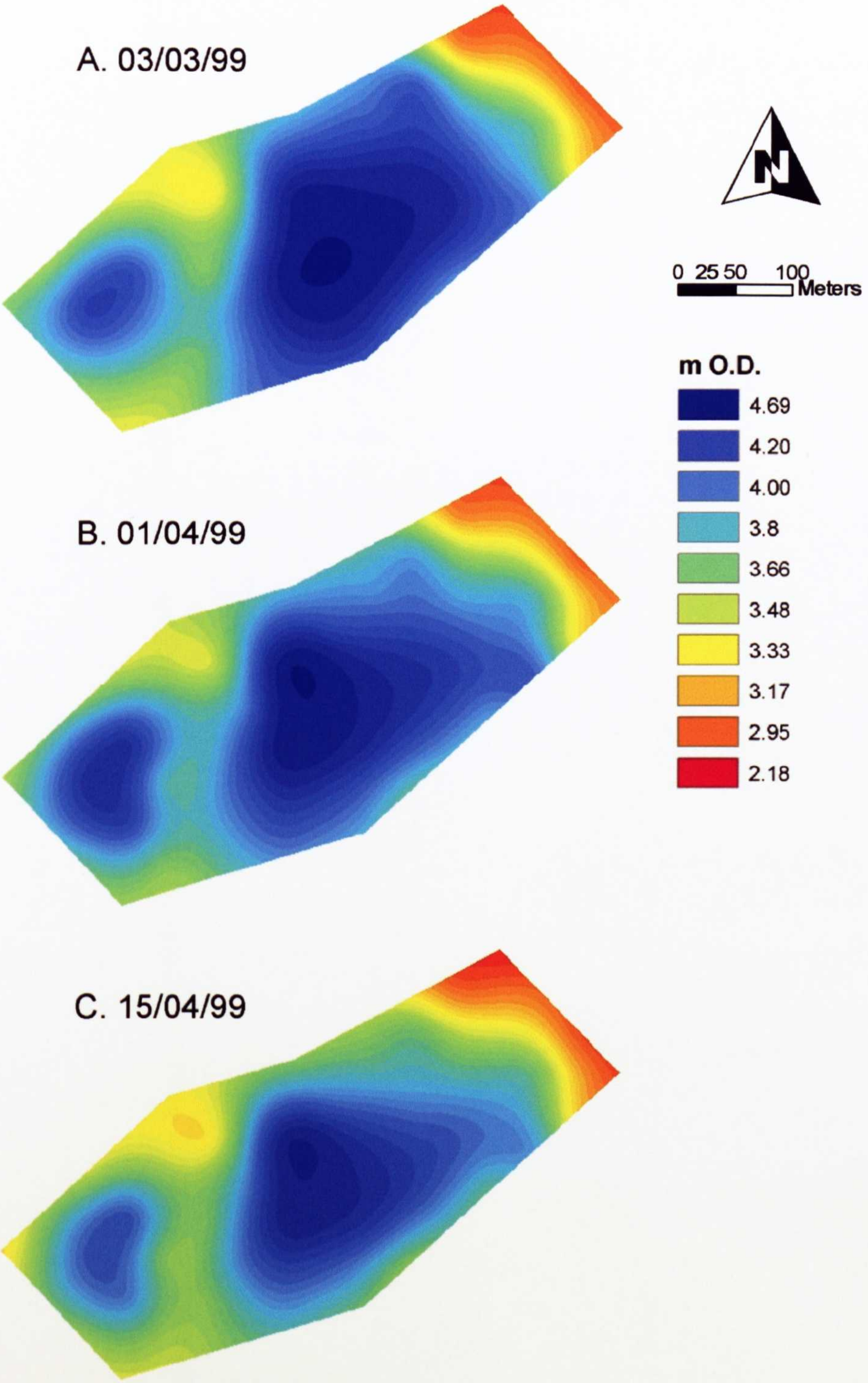


Figure 5.10 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.11

Figure 5.11A, 30/04/99. A period of 15 days. The model shows that there had been an increase in the level of the water table to a point comparable to that on the 03/03/99. This corresponds to increased precipitation in the previous 15 days, a total of 54 mm was recorded.

Figure 5.11B, 13/05/99. A period of 13 days. There was a slight decrease in the level of the water table when compared to the last monitoring visit.

Figure 5.11C, 27/05/99. A period of 14 days. The level of the water table had continued to fall and reached the lowest observed levels since the previous November.

The previous sequence of nine models represents the change in the water table across the monitored area of the site, during the winter of 1998/99. The general characteristics of the water table during this time was the formation of two groundwater mounds beneath the extent of the elevated ridges of Lake Humber material, upon which the two archaeological enclosures were constructed. Between these, following the course of the Hampole Beck palaeochannel, a lower water table has been identified. Along the eastern edge of the monitored area, bordering Shirley Wood, the lowest water table heights have been consistently recorded in the area of extensive peat deposits.

The above patterns suggest that the form of the water table on Sutton Common, at least within the monitored area of the site, is determined to an extent by the topographic variation of the site. Changes within the water table have been shown to be influenced by changes within the levels of precipitation that the site received, although representation of this within the models has also been dependant upon the monitoring interval.

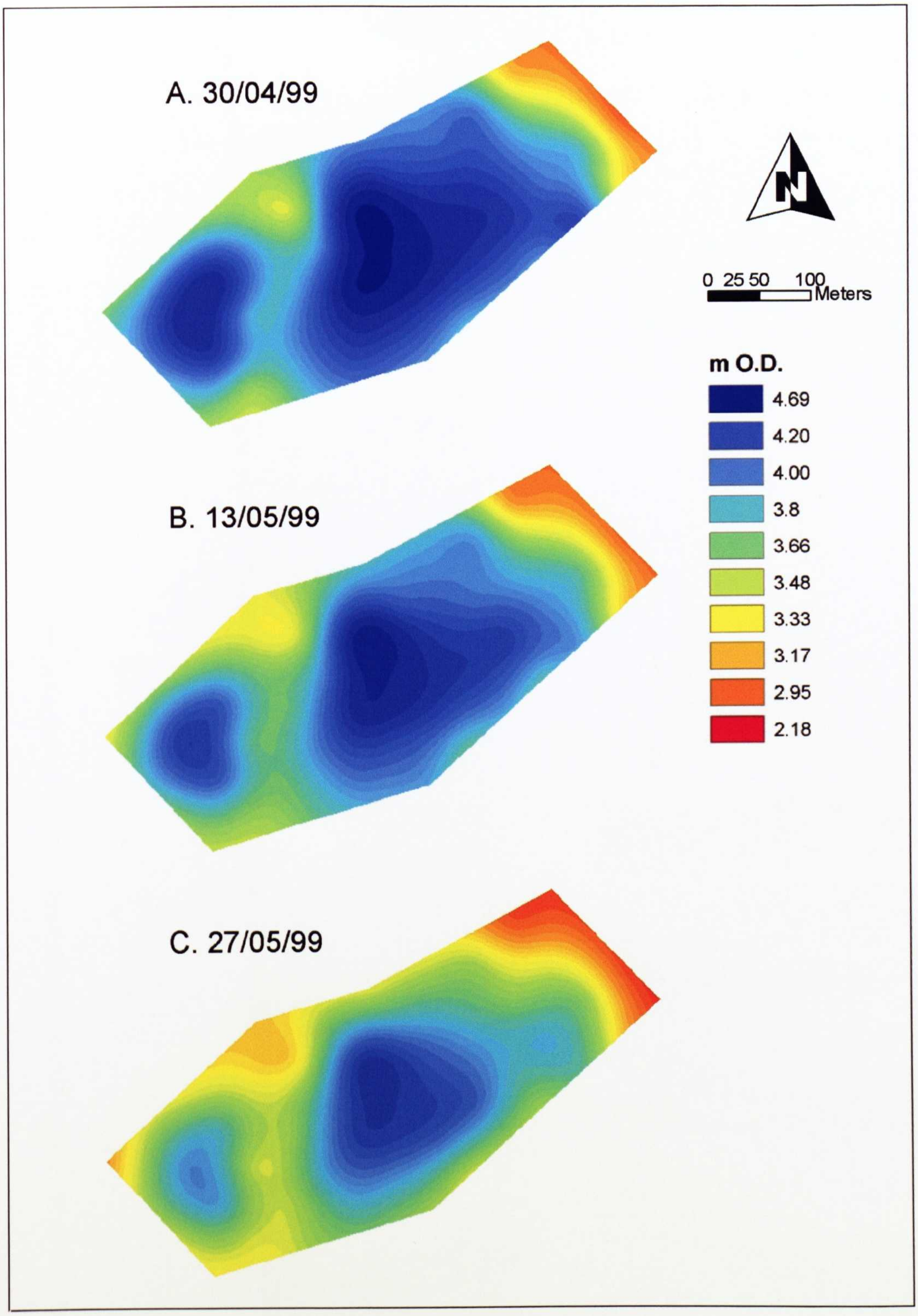


Figure 5.11 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.12

Figure 5.12A, 10/06/99. A period of 14 days. Again, the model shows that there was a positive rebound in the level of the water table in response to a period of rainfall, although the effect of this was not as great as in previous monitoring dates. During this period there had been almost 60 mm of rainfall. The fact that there is little positive response observed within the water table, may again relate to the presence of lag within the system and / or the existence of a soil moisture deficit. If the latter is present, then this will have the effect of removing a proportion of the water input meaning that it does not contribute to groundwater storage.

Figure 5.12B, 23/06/99. A period of 13 days. The height of the site water table continues to fall. There was less than 3 mm of precipitation during the interval between the 10/06/99 and the 23/06/99.

Figure 5.12C., 13/07/99. A period of 20 days. The depth of the water table increased. Very little precipitation was received in the period from the end of May and the smaller of the two groundwater mounds was less extensive than previously observed.

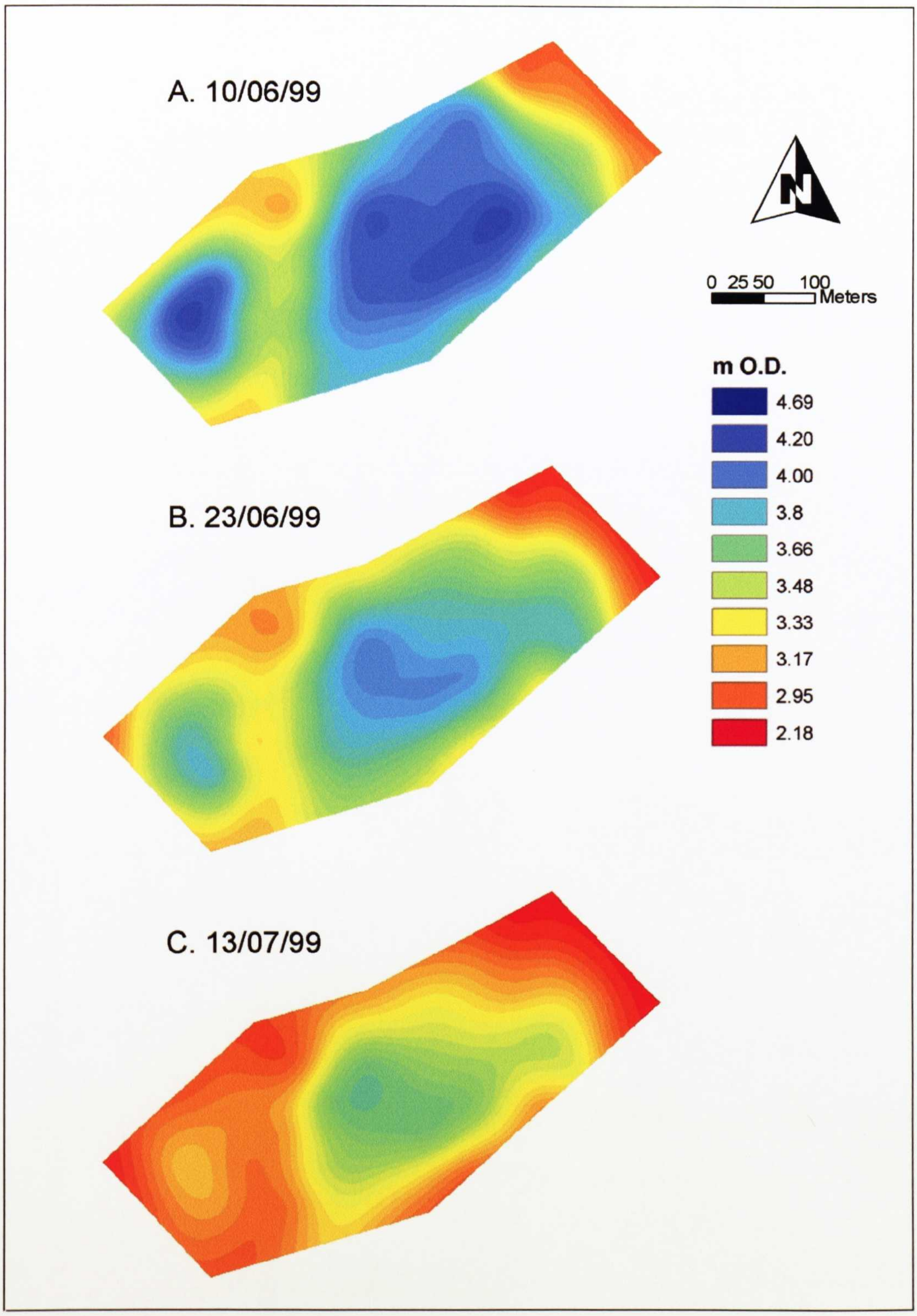


Figure 5.12 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.13

Figure 5.13A, 30/07/99. A period of 17 days. The smaller groundwater mound had completely disappeared with the larger one being severely restricted in size when compared to previous monitoring visits. Again, there had been very little precipitation, around 3 mm, during the intervening period.

Figure 5.13B, 18/08/99. A period of 19 days. The depth of the water table had again increased with the groundwater mound beneath Enclosure A continuing to decrease in size and extent. However, in contrast to previous observations, there had been a period of substantial rainfall during the period between this and the previous monitoring visit, approximately 49 mm, but with seemingly little or no impact upon the level of the water table. It is during the months of May to August that the greatest levels of water loss from the groundwater system occur as a result of evapotranspiration. During this period, a soil moisture deficit has built up, with low input levels from precipitation and high losses as a result of the demands of surface vegetation. During this period, the site was not under intense land management and vegetation was not cut during the summer months. Therefore, when rainfall was experienced this would have been intercepted by the surface vegetation or rapidly removed from the upper soil stratigraphy through evapotranspiration.

Figure 5.13C, 06/09/99. A period of 19 days. The model shows that the water table continued to fall during this period. The data obtained at this date shows the lowest water table recorded on the site during the entire period of study.

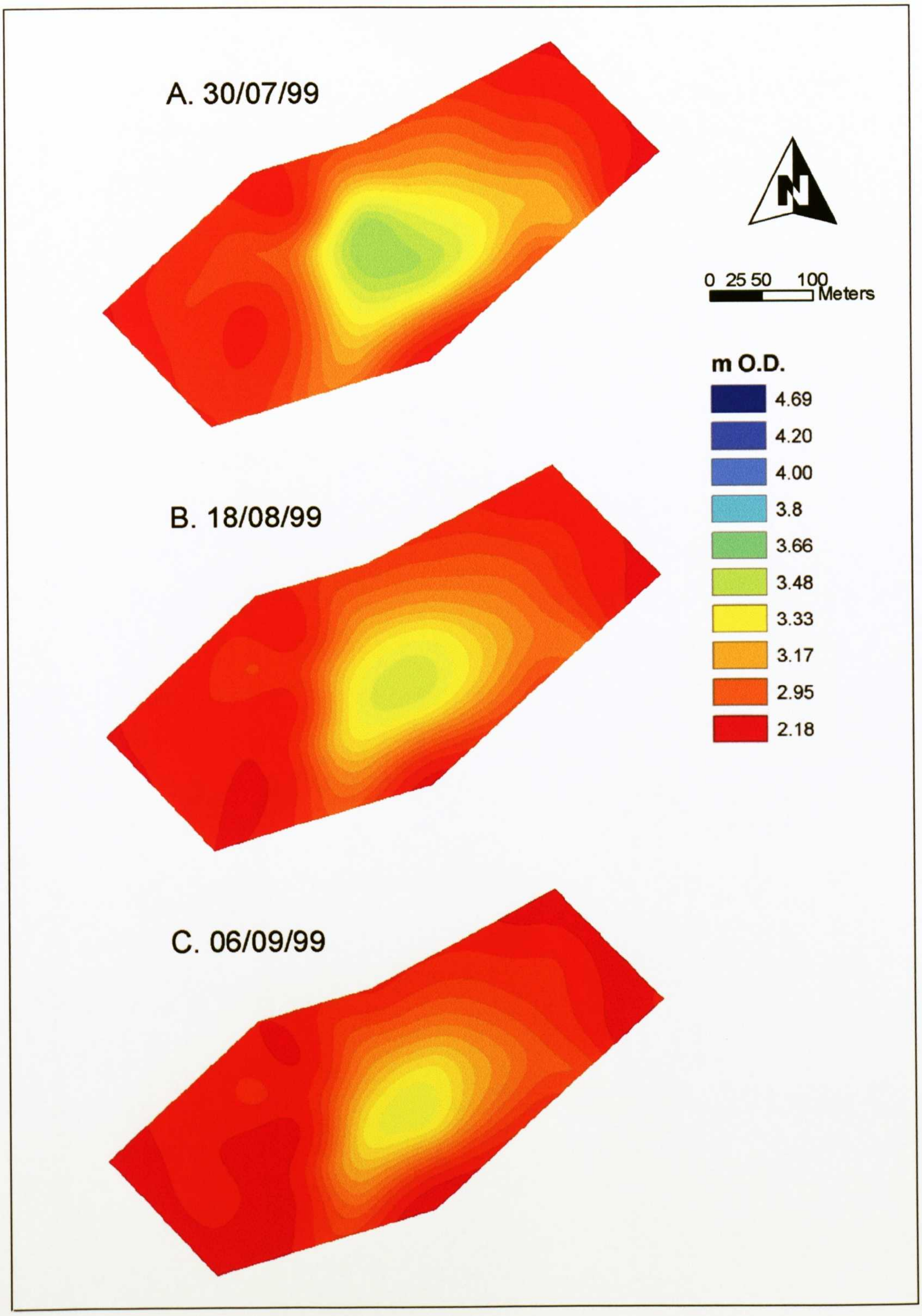


Figure 5.13 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.14

Figure 5.14A, 28/09/99. A period of 22 days. The water table showed very little response to the most sustained period of rainfall so far experienced during 1999 other than a slight expansion in the extent of the eastern groundwater mound. Again, this small reaction to the increase in precipitation was most likely due to the loss of water before it was able to contribute to the groundwater reservoir either directly from evapotranspiration and / or due to a large soil moisture deficit.

Figure 5.14B, 21/10/99. A period of 23 days. The depth of the water table had continued to decrease across the whole of the monitored areas. Of especial note in the model is the presence of a groundwater mound not seen prior to this date. The far eastern edge of the model shows an area of elevated water levels that was located adjacent to that of the larger of the two groundwater mounds identified within the data discussed so far. The eastern half of the model shows that the water table was in essence flat. It was at this time that re-engineering of the field drains in this location occurred and it is therefore possible that this was a response to this activity through the raising of the base-level for the drains.

Figure 5.14C, 08/11/99. A period of 18 days. The model is essentially the same as the previous dates other than another increase in the height of the water table across the monitored area, again in the eastern region.

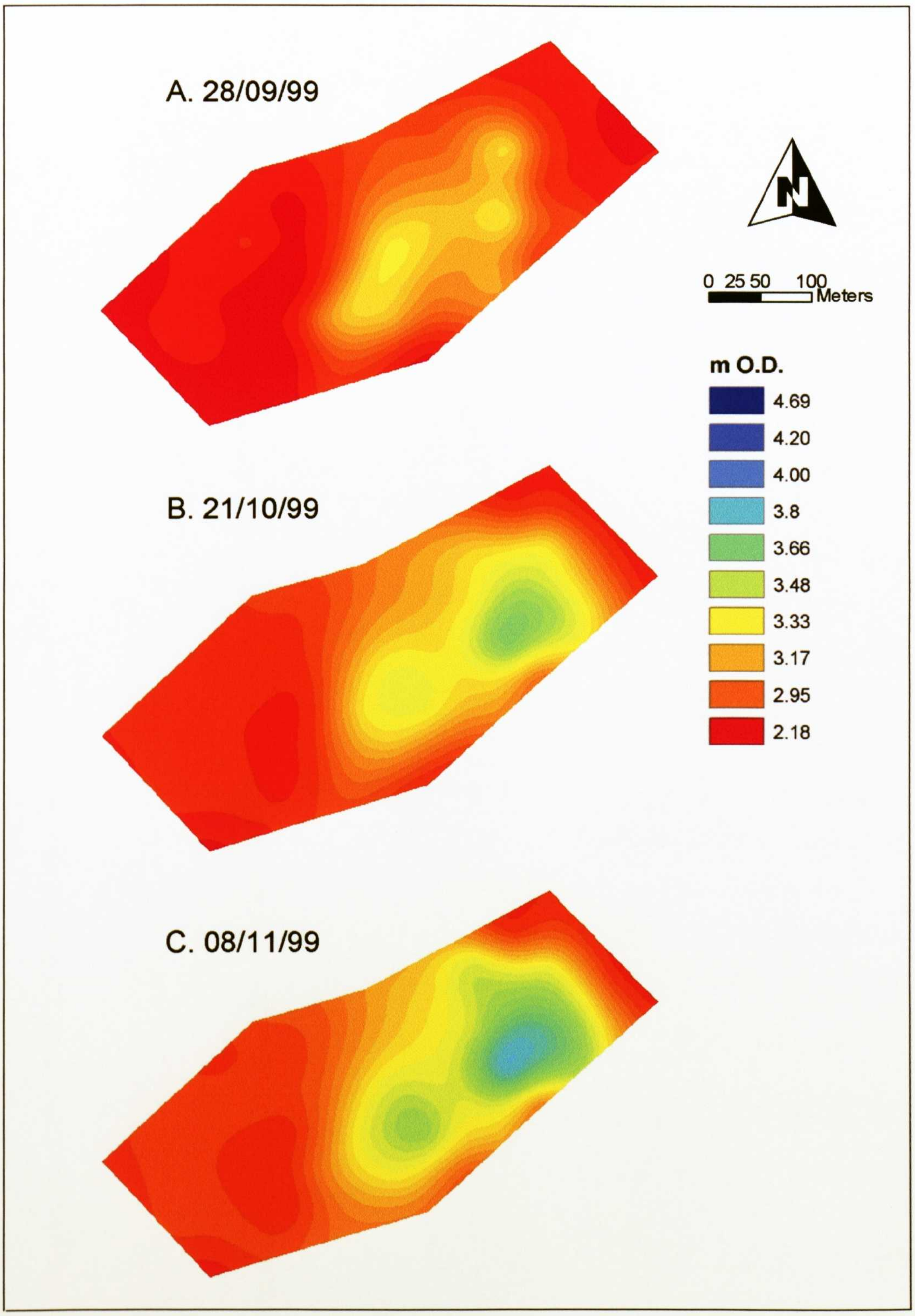


Figure 5.14 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.15

Figure 5.15A, 23/11/99. A period of 15 days. The model shows that at this time there was essentially no change in the characteristics of the water table other than again, an increase in its height.

Figure 5.15B, 06/12/99. A period of 11 days. The eastern area of elevated water table again increased in its size, now becoming far higher than the central mound, at around 4.13 m compared to 3.68 m. Similarly to Figure 5.14B, the location of the elevated water table corresponds to one of the field drains that was re-engineered to reduce water loss from the site. It is therefore possible that this has manifested itself within the form of the water table at this location. During this time there was a more regular rainfall of relatively low intensity. This, coupled with a large reduction in the amount of water lost from the groundwater system through evapotranspiration, would mean that there was a significant increase in the water available to contribute to the water table.

The previous nine models covering the period of monitoring from July to December 1999 can be classed as being representative and characteristic of the summer water table. Although you would not normally expect the latter months of the year to be included within this, it is apparent from the models generated from the monitoring data that the lowest water levels observed during August and September, did not recover until the end of the year.

Figure 5.15C, 07/01/00. A period of 32 days. The model shows that at this time the smaller western groundwater mound, had returned and that in general the level of the water table had increased substantially during the period since the previous monitoring visit. There had therefore been a return to 'winter' levels.

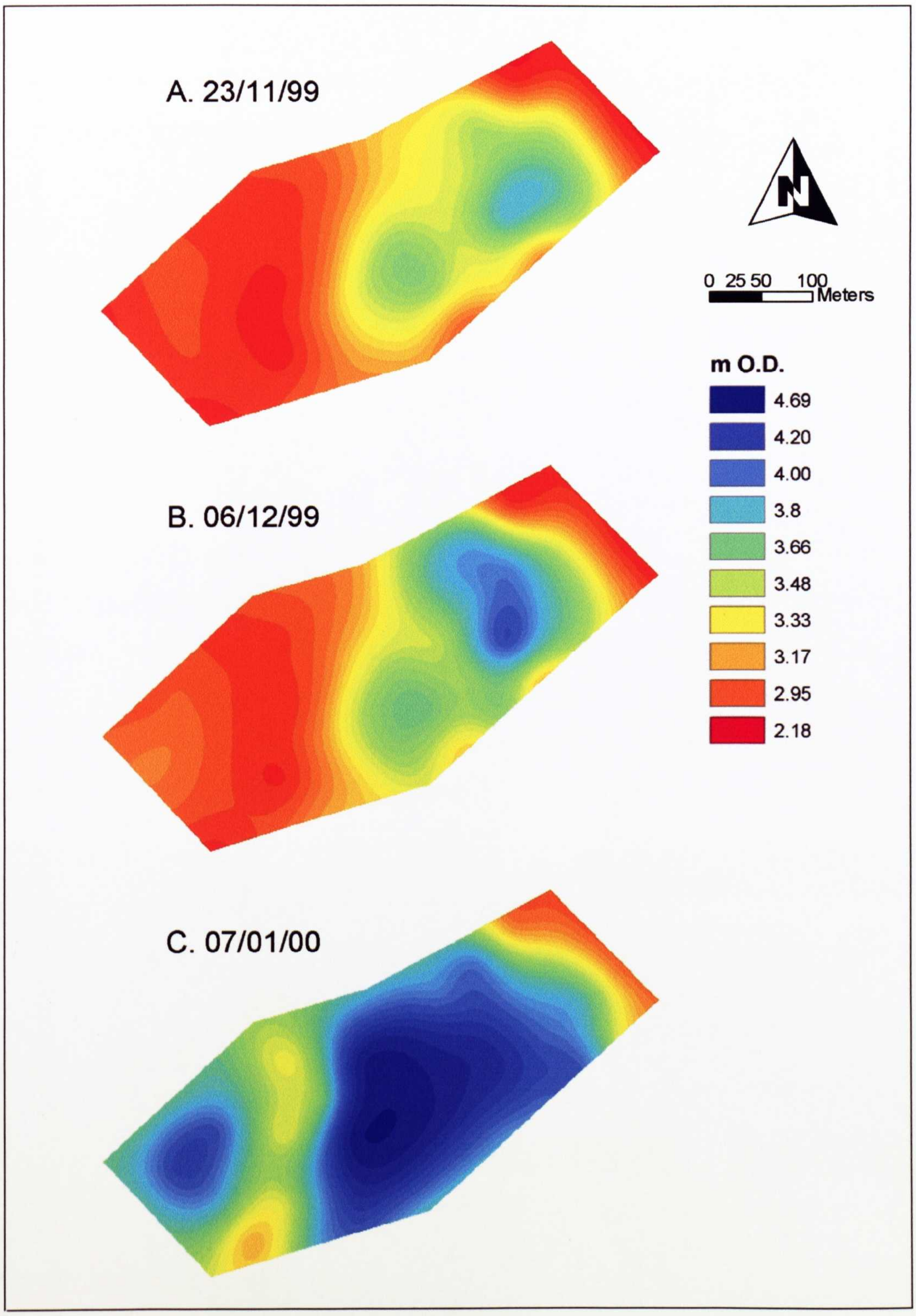


Figure 5.15 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.16

Figure 5.16A, 20/01/00. A period of 13 days. There was very little change evident in the water table between this and the previous monitoring visit.

Figure 5.16B, 03/02/00. A period of 14 days. This shows that the water table was essentially the same as the previous monitoring date apart from a slight decrease in height.

Figure 5.16C, 18/02/00. A period of 15 days. This model is essentially identical to the previous one.

Over the period that the data represented in the previous three hydrological models, there had been relatively low levels of precipitation received on the site (Figure 5.3). Due to the expected low rate of loss of water from the groundwater system during January and February due to less evapotranspiration, a degree of stability within the water table is not surprising. This stability has been reflected in the lack of change exhibited by the hydrological models.

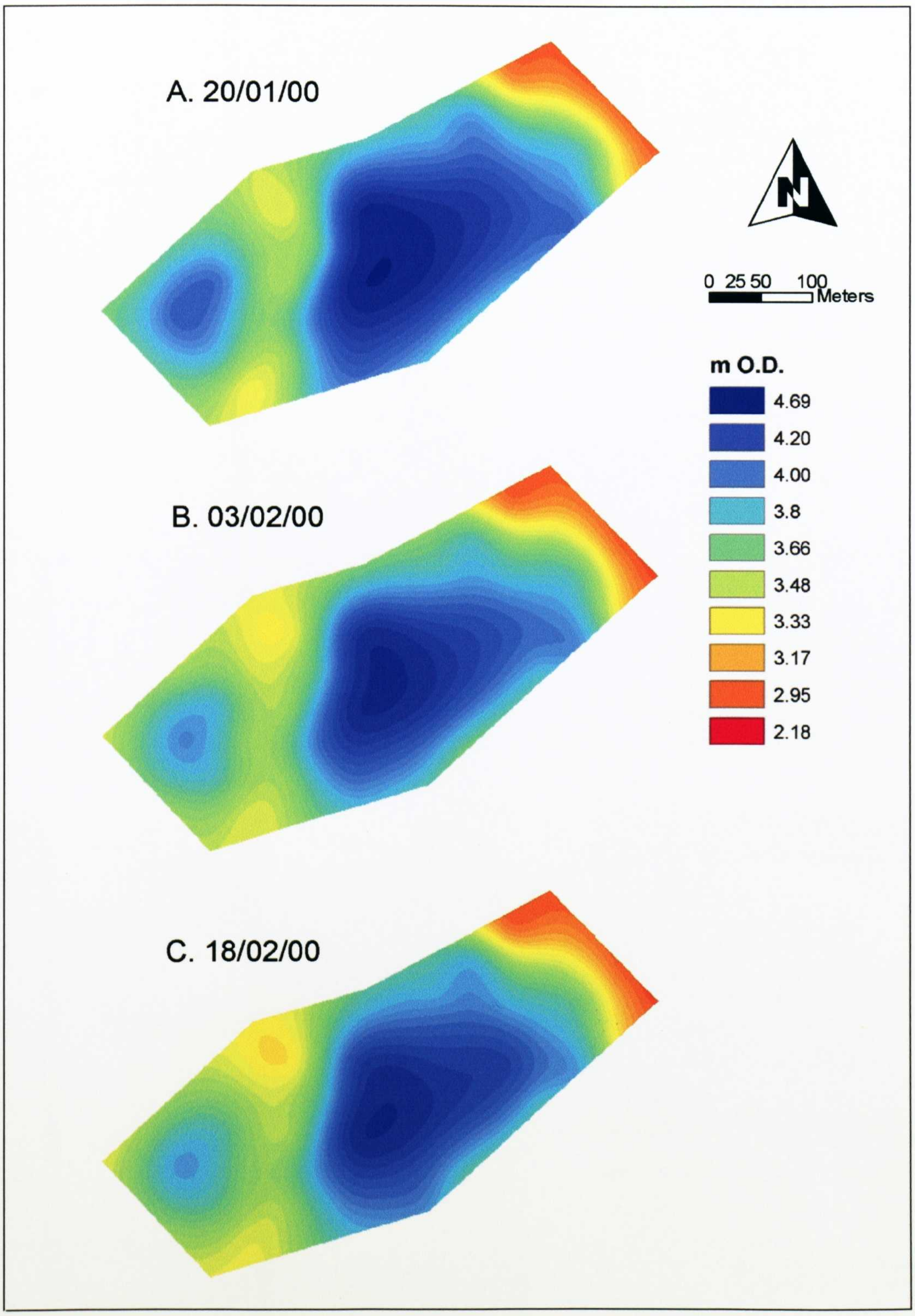


Figure 5.16 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.17

Figure 5.17A, 01/03/00. A period of 12 days. There was a rise in the height of the water table across the monitoring area in response to increased precipitation, but the general form stayed the same as the previous model.

Figure 5.17B, 23/03/00. A period of 22 days. A slight decrease in the level of the water table was observed across the whole of the monitored area since the previous monitoring visit, again in response to a very low level of precipitation reaching the site. This is demonstrated in Figure 5.3 by the flat character of the cumulative rainfall curve during this period.

Figure 5.17C, 17/04/00. A period of 25 days. The model shows that there was a clear increase in the level of the water table across the site when compared to the previous monitoring date. Both the groundwater mounds previously discussed are clearly visible in the model. This change occurred in response to a large increase in the amount of precipitation, in excess of 85 mm, during the intervening period.

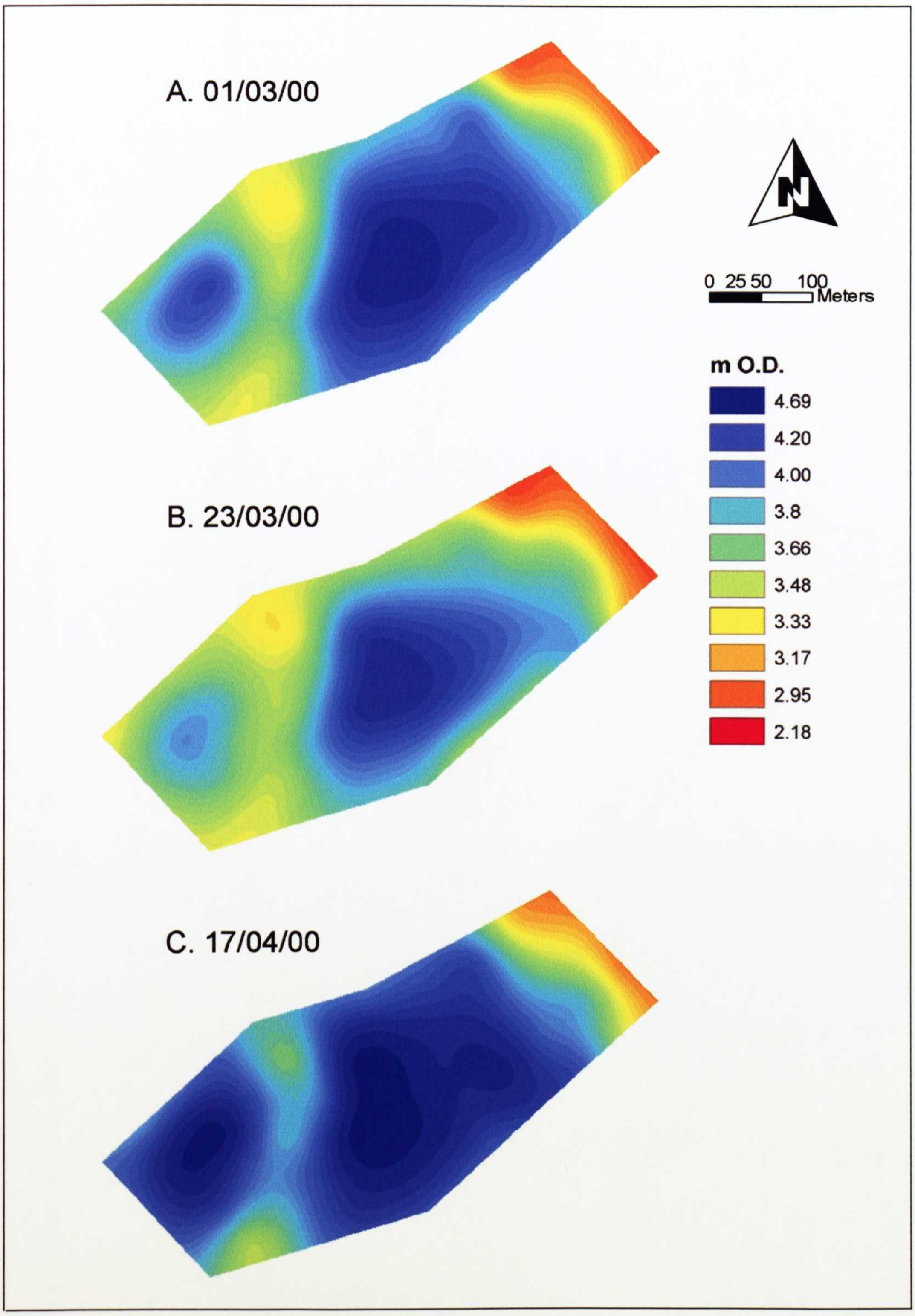


Figure 5.17 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.18

Figure 5.18A, 10/05/00. A period of 23 days. The height of the water table had dropped when compared to the previous monitoring data. There had been a period of no recorded rainfall since before the end of April, providing time for the site to drain. During the spring months, the loss of water from the site would be expected to increase due to increasing rates of evapotranspiration. This could, in conjunction with a decrease in rainfall, account for the observed drop in the height of the water table.

Figure 5.18B, 09/06/00. A period of 30 days. The model is almost identical in appearance to the previous one, in that it shows that there was a slightly lower water table across the monitored area. Reference to the precipitation data shows that there had been in excess of 74 mm of almost continuous rainfall during the intervening period. A similar situation has been noted in data obtained during August 1999. This pattern can be attributed to the effect of increased vegetation cover on the site during this time, and therefore heightened levels of evapotranspiration removing water from the groundwater system.

Figure 5.18C, 28/06/00. A period of 19 days. Very little precipitation has led to a site-wide drop in the level of the water table. The two groundwater mounds previously identified within the monitored area of the site were still present, but the smaller one, beneath the extent of Enclosure B, was less pronounced from the surrounding area.

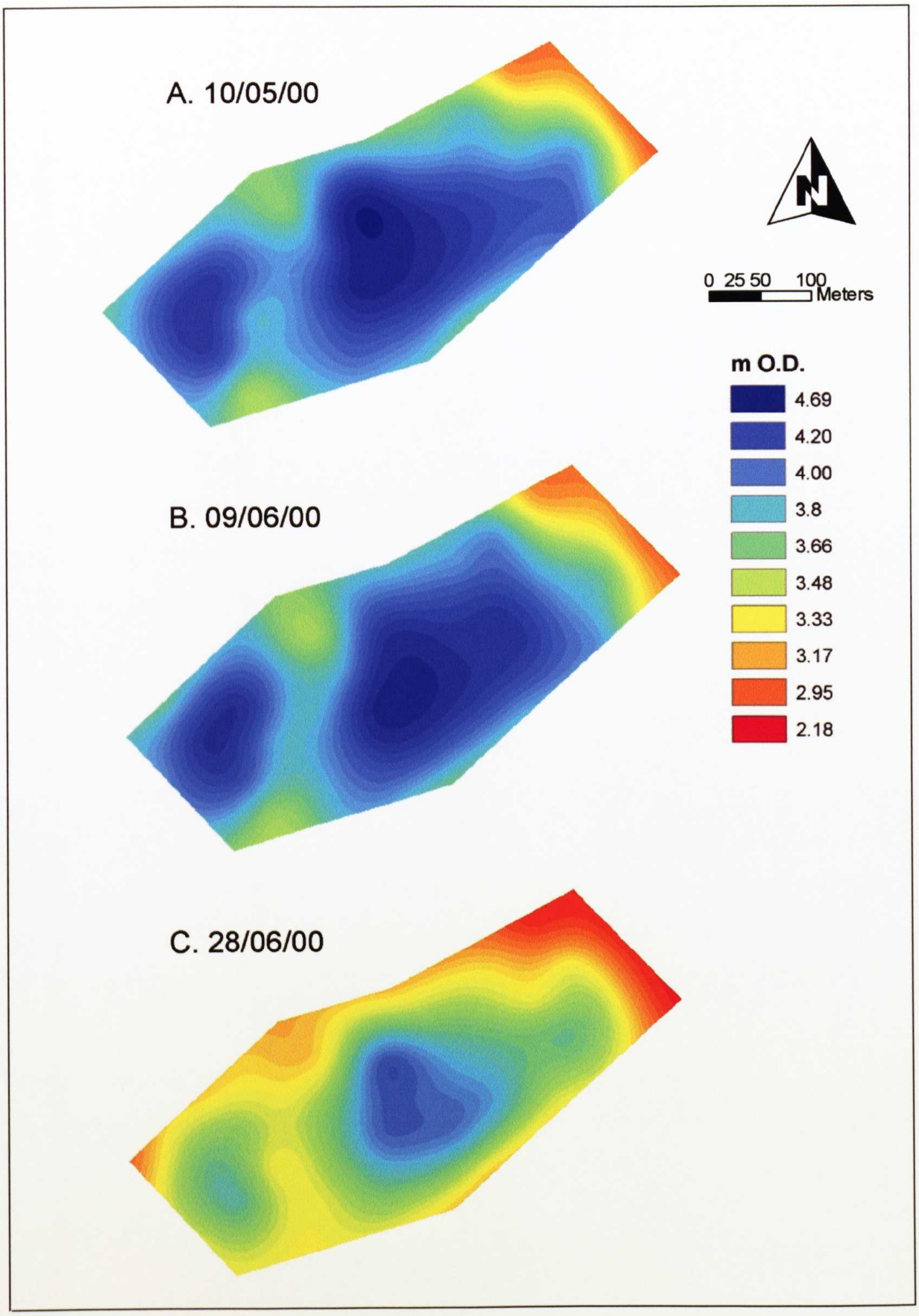


Figure 5.18 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.19

Figure 5.19A, 11/09/00. A period of 75 days. The model shows that the eastern groundwater mound was not present and that water table levels were generally low across the area of monitoring. The western groundwater mound was relatively large in extent and appears to reflect regular precipitation since the end of July.

Figure 5.19B, 26/09/00. A period of 15 days. The height of the water table increased across the monitored area of the site. This is highlighted most extensively in the eastern half of the model, where the development of isolated areas of higher water levels can be identified. It is apparent that the western half of the monitored area had witnessed a less pronounced change in the water table, which remains relatively flat, with no evidence of the formation of a groundwater mound beneath the smaller 'island' upon which Enclosure B is located.

The change observed in the model in comparison to the data obtained during the previous monitoring visit, resulted from high levels of precipitation reaching the site, this being in excess of 83 mm. Such a large amount of water entering the system from the ground surface may explain the unexpected form of the water table. Similarly to November 1998, there appears to be an element of lag within the groundwater system whereby particular pieces of equipment respond to inputs via precipitation more rapidly than others. This could potentially result in very different readings being obtained across the site whilst there was a period of stabilisation. Again, short response times appear to be more evident at this time of the year where there is little soil moisture deficit, therefore precipitation inputs contribute more effectively to the groundwater reservoir.

Figure 5.19C, 18/10/00. A period of 22 days. The large groundwater mound was clearly present along with considerably elevated water table levels across the monitored area of the site. However, there was still little indication of the formation of the smaller of the two mounds below the extent of Enclosure B, even though again there had been a considerable increase in the level of the groundwater in the order of 0.75 m. Again, this rapid change in the amount of water present within the groundwater system can be directly attributed to increased levels of precipitation reaching the site.

In the 22 days since the previous monitoring visit, there had been continued heavy rainfall, reaching almost 58 mm. This rainfall forms the start of an extensive period of rainfall that led to a major flood episode that has established a major new, UK hydrological benchmark (www[2]) and is characterised in the South Yorkshire region by prolonged, heavy and continuous rainfall. The lack of a second groundwater mound is likely to be evidence of the rapidity by which water has entered the system from the great excesses that resulted from such high levels of precipitation. In such a situation individual piezometers took time to rise and register.

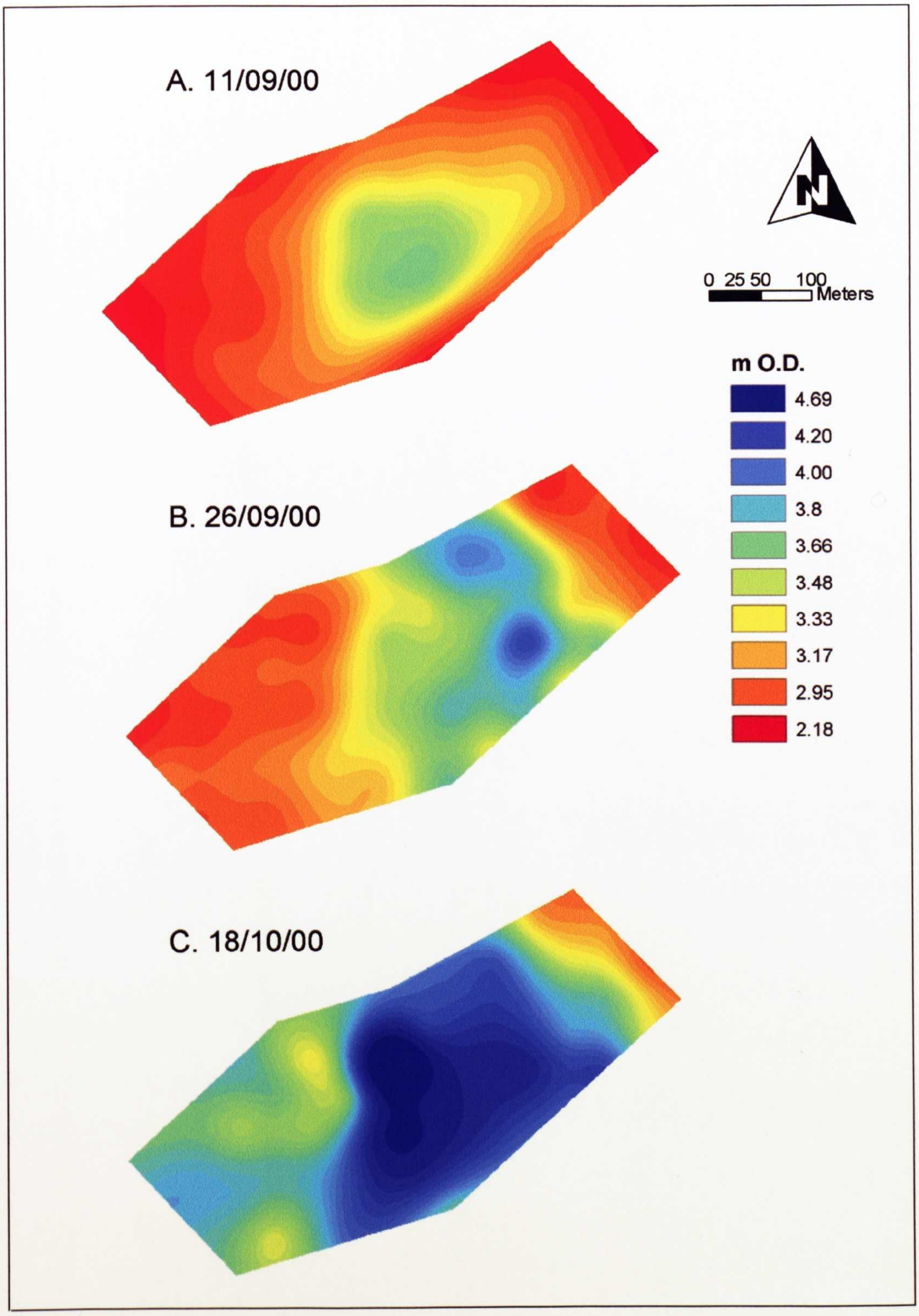


Figure 5.19 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.20

Figure 5.20A, 10/11/00. A period of 23 days. The site visit on this day revealed extensive surface flooding both within and outside of the monitored area. This had resulted from the main drainage pumps at the Thistle Goit pumping station being purposely turned off by the local Internal Drainage Board (IDB) to allow the backing up of water onto the site and to maintain bank-full conditions within the drainage ditches leading from the site. The fact that attempts were being made at re-wetting the site was decisive when peak flows resulting from the excessive rainfall reached flood levels, and as a result Sutton Common was utilised as a temporary, floodwater storage area (Pers. comm.. D. Patrick).

A number of piezometer locations were flooded and therefore readings from these were not possible. At these locations, the depth of the water above the tops of the piezometers was recorded, apart from at the eastern extreme of the monitoring grid where the depth of the floodwater was too great. Therefore the GIS model created from the data gathered, assumes that standing water was in fact where the groundwater was breaking the surface.

The highest water levels recorded during the entire period of monitoring were obtained during this site visit. The site was extensively flooded and all piezometers from which readings could be obtained were showing significantly elevated readings. To highlight this, in the area of Enclosure B, the water table height had risen in excess of 1.0 m since the previous monitoring visit. This unprecedented rise can almost wholly be attributed to the flooding event itself.

Figure 5.20B, 20/11/00. A period of 10 days. The stored surface floodwater had by this time drained from the site, providing access to the eastern end of the monitoring grid. This resulted in a lower water table being shown on the GIS model than that shown for the previous monitoring date.

There had been little precipitation during the intervening period but the model shows that a high water table was still present on the site during this time, although it had fallen slightly.

Figure 5.20C, 05/12/00. A period of 15 days. Although precipitation had been regular during the period since the previous monitoring visits, it had been at a low level. Therefore, the water table shows the same characteristics to the previous two visits but with a slightly decreased water table level.

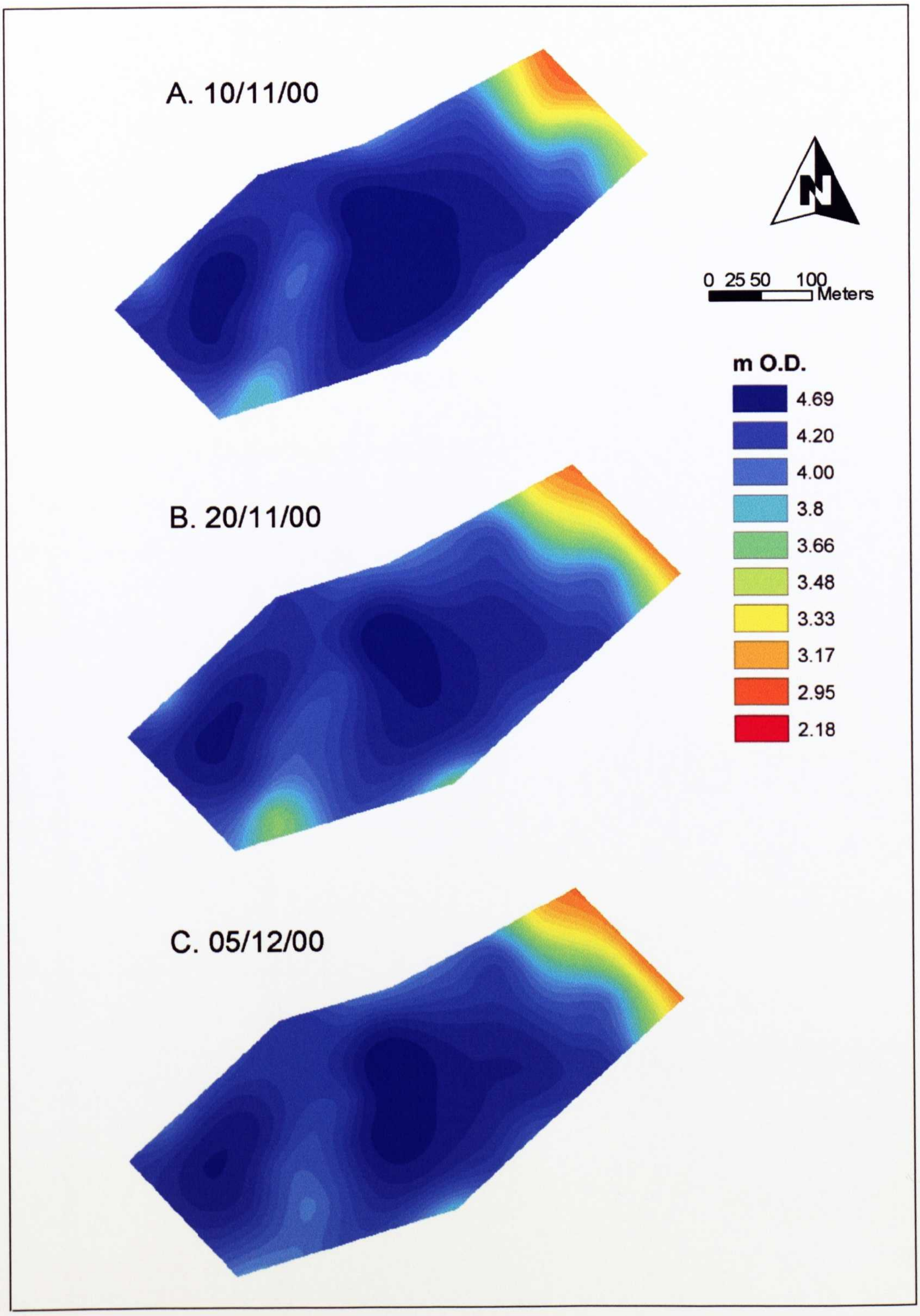


Figure 5.20 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.21

Figure 5.21A, 21/12/00. A period of 16 days. From the GIS model it is clear that the water table had maintained the same characteristics as that shown in the previous three. Precipitation levels were maintained at a more or less continuous, low rate. The low, but almost continuous, precipitation that occurred at this time maintained the saturated conditions created by the initial flooding event. This exacerbated the widespread flooding that continued to afflict areas of the country at this time (www[2]).

Figure 5.21B, 15/01/01. A period of 25 days. The water table at this time still maintained the major characteristics that had been observed since the occurrence of the flooding event, but levels had fallen slightly across the monitored area. This reflects the lack of precipitation during the first two weeks of January 2001.

Figure 5.21C, 14/02/01. A period of 30 days. The water table has risen in response to a period of rainfall at the end of January and the beginning of February 2001 when in excess of 80 mm rainfall fell.

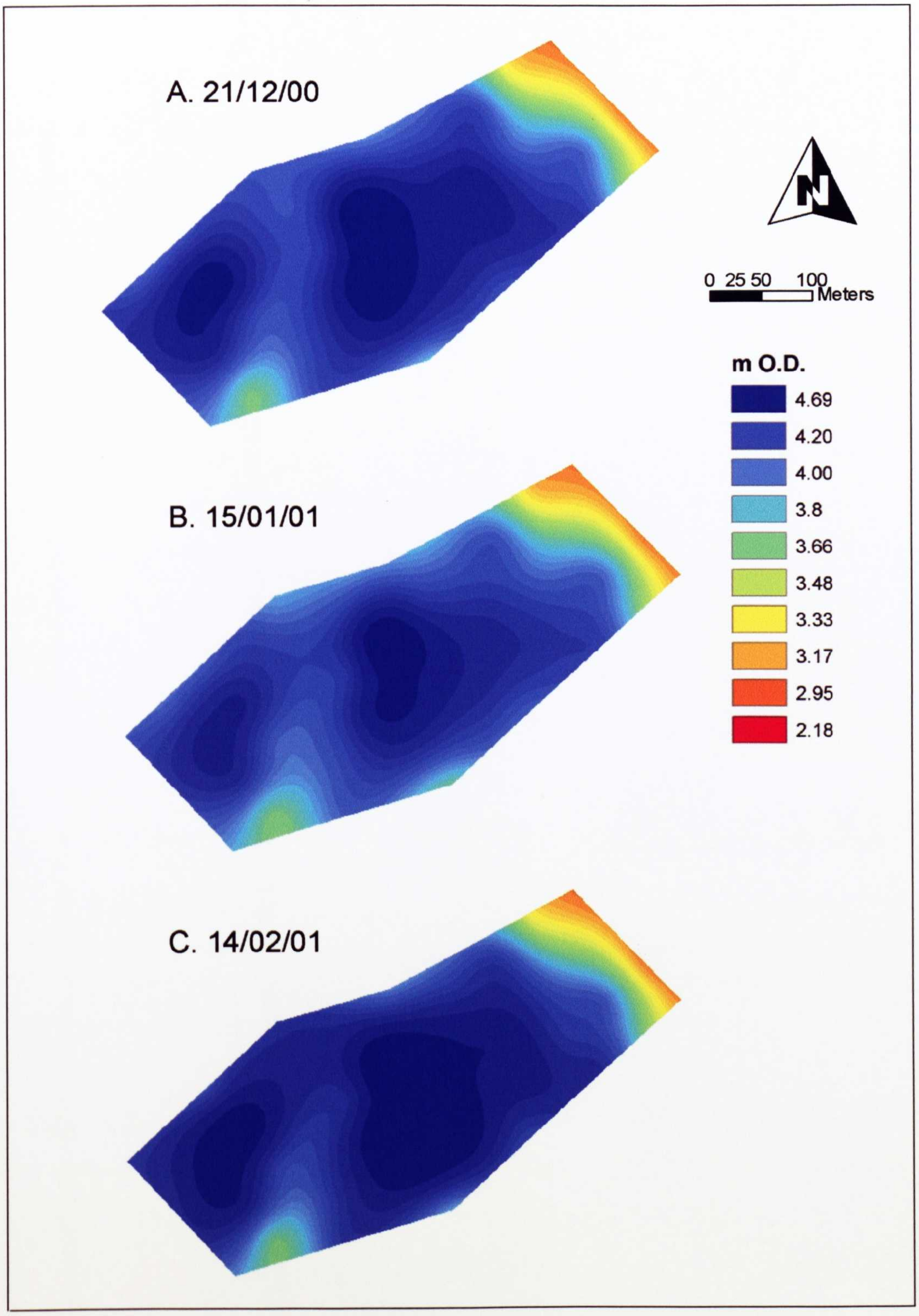


Figure 5.21 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.22

Figure 5.22A, 18/04/01. A period of 63 days. The extended period of time between this and the previous monitoring visit was due to the outbreak of Foot & Mouth disease within the British Isles. During this time, large areas of countryside were closed off in an attempt to reduce the risk of transfer of the disease to areas where infection had not occurred. Although South Yorkshire was not affected by the disease, the decision was made during February to remove access to the site as a precaution, meaning that monitoring visits could no longer take place.

By mid-April when it had been established that South Yorkshire was not immediately at threat from Foot & Mouth disease access to the site was granted again, but on certain conditions. These were; that any vehicle to enter the site had not recently visited a recognised area of infection and that prior to entering the site the vehicle was jet-washed to remove all loose mud. In addition, immediately prior to entering the site the underside of the vehicle and all areas that could potentially come into contact with site vegetation, were to be sprayed with an officially recognised disinfectant capable of killing the disease causing organism. This latter point also included the footwear and clothing of anyone entering the site.

The water table at this time had been maintained at an equivalent but slightly lower level to those observed during the previous six monitoring visits.

Figure 5.22B, 21/05/01. A period of 33 days. It is apparent from the GIS model of the data collected at this time, that the water table had fallen considerably, although the two groundwater mounds previously discussed were both maintained.

Figure 5.22C, 13/06/01. A period of 23 days. There had been a considerable fall in the level of the water table after a period of very little precipitation since the previous monitoring visit. The model shows that there was little indication of the smaller of the two groundwater mounds, although there was a localised raised mound within the vicinity of Enclosure A. From May onwards, as highlighted previously, increasing rates of evapotranspiration remove greater amounts of water from the groundwater system. This may account for the continued drop in the height of the water table observed in the previous three hydrological models.

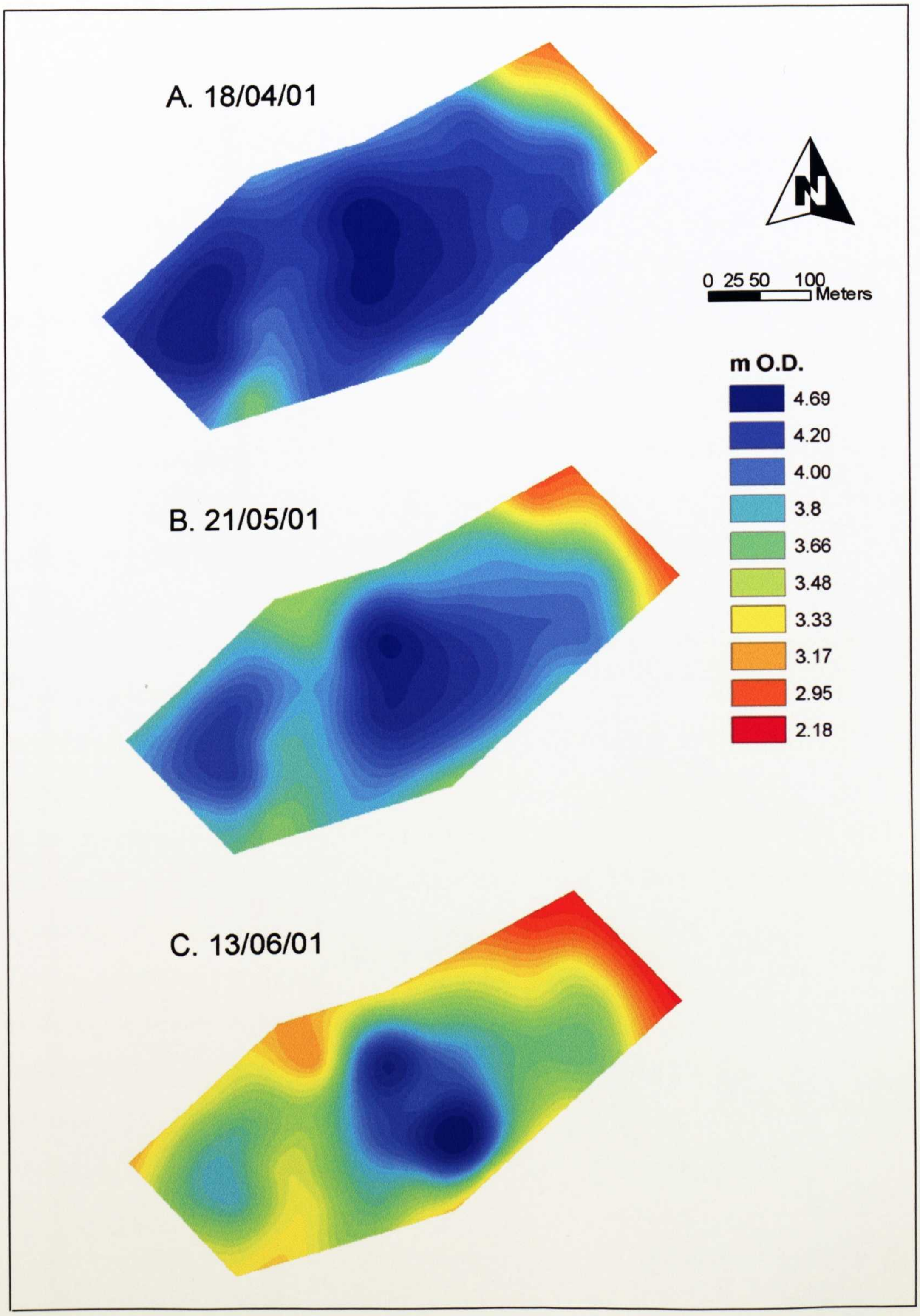


Figure 5.22 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.23

Figure 5.23A, 10/08/01. A period of 58 days. Once again, there had been a large period between monitoring visits to the site. During 2001 a new management regime had been established under the supervision of Andrew Booth, a local farmer based in the nearby village of Sutton. In previous years, management had been restricted to irregular lopping of the vegetation, primarily as a control measure against the spread of thistle. However, as part of the ongoing Sutton Common Project, it had always been a priority to maintain a proper management plan for the site. During June and July, the first phase of this began, involving the enclosure of the site and rolling and mowing. Unfortunately the rolling, used to reduce the formation of tussocks, resulted in many of the piezometers being pushed into the ground making their location difficult. Mowing for hay also took place, resulting in the cropping of the vegetation close to ground level, causing damage to a number of piezometers. This activity necessitated a number of site visits to reinstate the monitoring programme through relocation of the equipment, pulling up of the piezometers and in some cases removing broken ends.

At this time the water table was characteristic of those previously observed during summer periods, with only one groundwater mound present below the area of Enclosure A and relatively low water levels being recorded elsewhere. However, it must be noted that the levels are considerably higher than recorded during the same period in previous years. During the previous week to this, there had been a substantial amount of rainfall, with in excess of 50 mm falling. Based on previous observations of the reaction of the water table to precipitation events, it seems logical that these are related. This is unfortunate, because the lack of data from prior to, or following this date means that no conclusion on the reasons for the higher water table can be made. Such influences would include the already discussed closely related rainfall event, but also the influence of the re-wetting works on the site and the impact of the flooding during the previous winter.

Figure 5.23B, 23/01/02. A period of 166 days. As outlined previously, the increased level of management upon the site began to have an effect on the monitoring regime during the early summer of 2001. This culminated in the grazing of cattle on the main field within which are located the two archaeological enclosures and also the hydrological monitoring grid. This occurred in August / September 2001 and unfortunately rendered effective monitoring of the water table impossible. A number of attempts were made during this period to reinstate the equipment and prevent further interference by such means as concrete breezeblocks, but none were effective at preventing continued disturbance. A decision was therefore made to discontinue monitoring visits until the cattle had been removed from the site and an effective protection from further interference could be made. This occurred during December 2001 and monitoring restarted in January 2002.

It is clear from the model representing the water table at this time, that there is little evidence of a groundwater mound present beneath the extent of Enclosure B. Reference to Figure 5.4 shows that the total precipitation for 2001 was just over 560 mm, the only year between 1998 and 2002 that showed less than 600 mm. Further to this, there had been comparatively little rainfall during November and December 2001 and January 2002. This pattern suggests that there was not enough water within the near-surface groundwater system to maintain the smaller groundwater mound.

Figure 5.23C, 07/02/02. A period of 15 days. With regular rainfall of more than 30 mm during the intervening period, there was a rise observed within the water table and the smaller groundwater mound had formed. The depth of the water table has decreased across the whole of the monitored area.

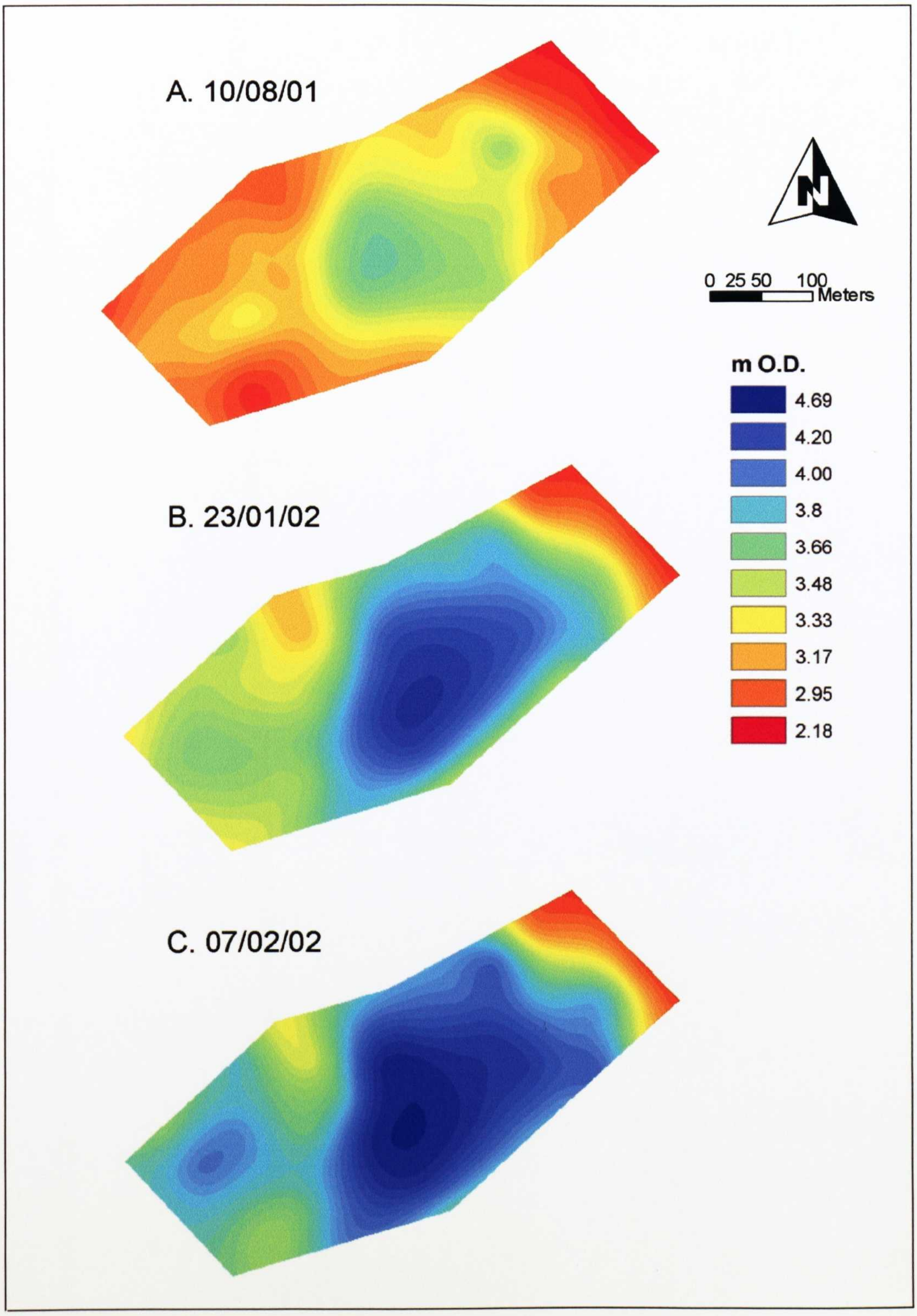


Figure 5.23 GIS generated hydrological models representing the water table of Sutton Common.

Figure 5.24

Figure 5.24A, 01/03/02. A period of 22 days. The water table within the monitored area of the site continued to rise during the intervening period, in line with the site receiving continued regular rainfall.

Figure 5.24B, 27/03/02. A period of 26 days. The model generated from the data obtained on this date shows that the water table retains the same characteristics of the previous model, but that the water table has increased in depth slightly. During the intervening period there had been a reduced level of precipitation than that leading up to the 01/03/02.

The 27/03/02 was the final hydrological monitoring visits undertaken during the course of this research, even through further soil redox potential and microbiological sampling visits were made to Sutton Common. This was again due to the impact of cattle grazing on the site. The original installation of the piezometer equipment was not designed to avoid damage from cattle grazing and simple, affordable methods of protecting it could not be found. Therefore, the monitoring programme was drawn to a close.

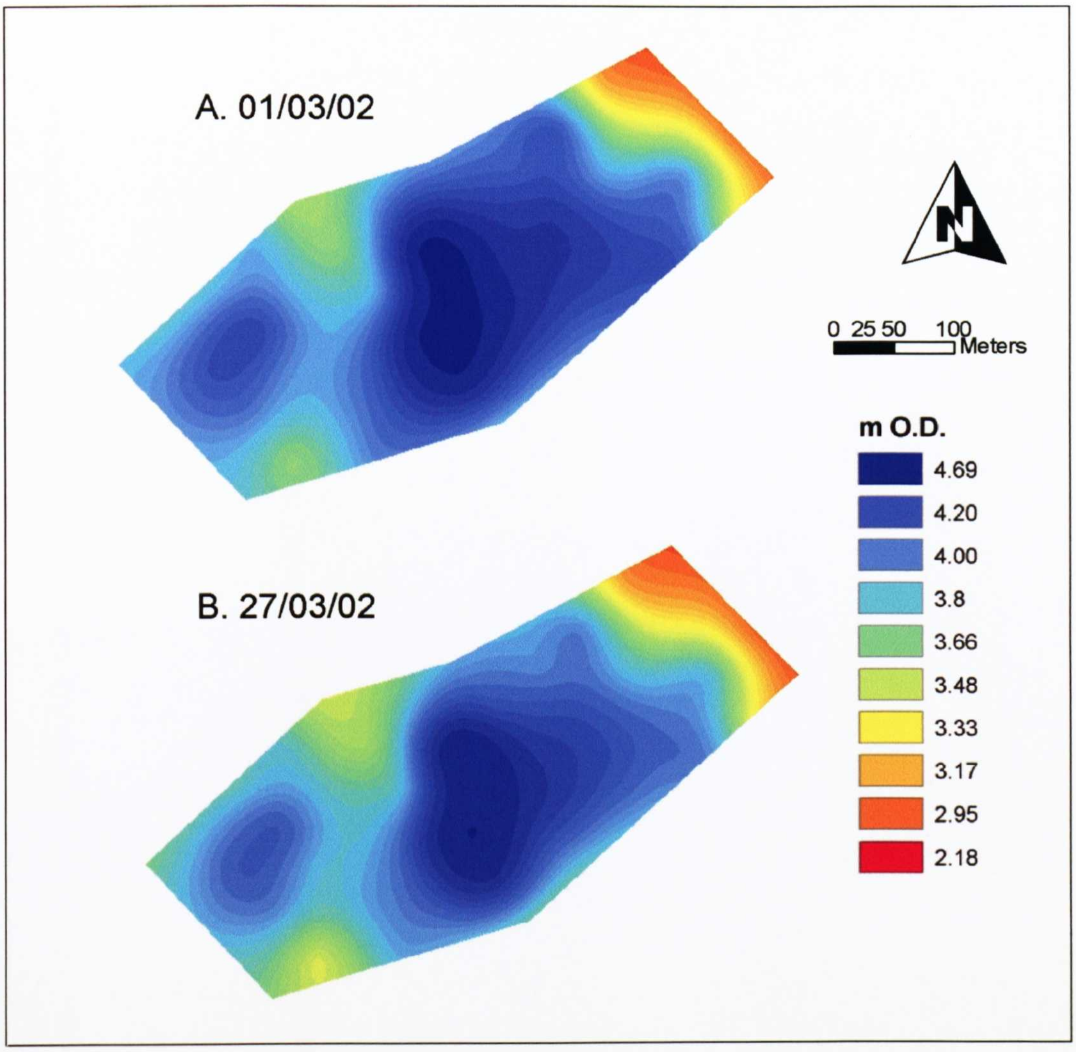


Figure 5.24 GIS generated hydrological models representing the water table of Sutton Common.

5.2.2 Characteristics of the Sutton Common water table

The previous section presented the raw data collected on the water table from within the monitored area of Sutton Common, in the form of GIS generated, colour-shaded hydrological models. In this section the major characteristics of the models, and hence the water table, will be identified and presented.

The one single characteristic that has been present in all the representations of the water table is a dome, or groundwater mound beneath the topographically higher area upon which is situated archaeological Enclosure A. The size and extent of this feature varies significantly throughout the period of monitoring and during times of greater saturation a second mound forms beneath the area of Enclosure B.

This second dome is smaller in extent and reflects the smaller size of the raised area of ground in this location. Figure 5.25 highlights this relationship between site topography and the form of the water table along with the seasonal variation observed from the monitoring results.

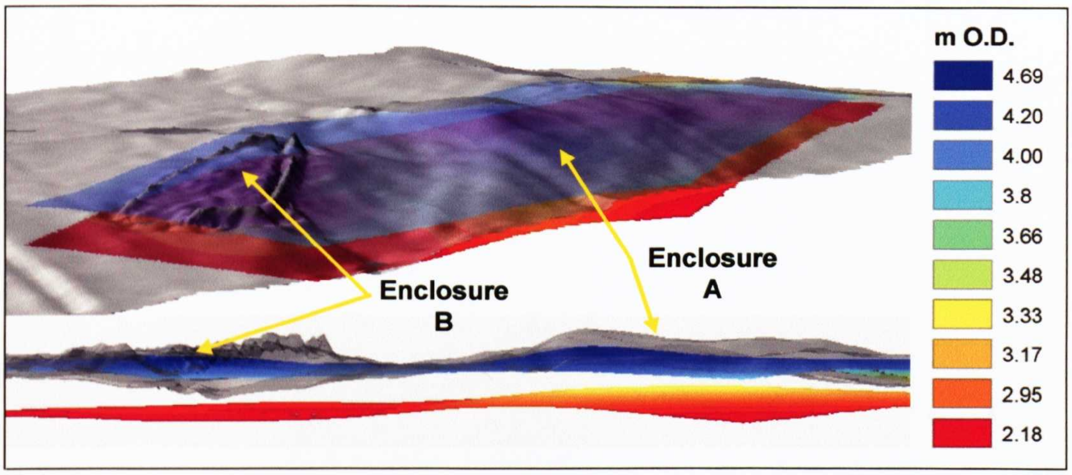


Figure 5.25 3D perspective of a GIS generated Sutton Common DEM, integrated with typical summer (06/09/99) and winter (05/12/00) hydrological models to highlight the relationship between the form of the water table and site topography. The model is subject to a 10X vertical exaggeration.

A second major characteristic is the representation of seasonal variation within the models. Figure 5.26 shows GIS models of the form of the water table at two monitoring times, 06/09/99 and the 05/12/00. The models represent some of the lowest and highest water levels observed on the site during the monitoring period. The September 1999 model represents the summer low as the preceding four months of 1999 were characterised by low rainfall, whereas the December 2000 model represents some of the highest water levels observed during the whole of the monitoring period, following the floods of November 2000. As can be clearly seen, the water table is not flat and varies in its form between the winter and summer seasons, a pattern that is consistently observed throughout the whole hydrological monitoring period.

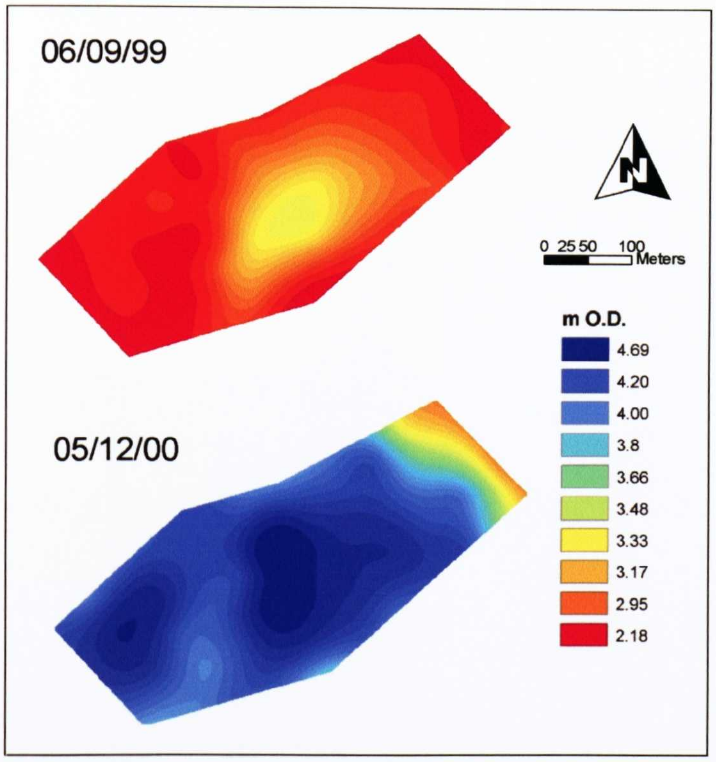


Figure 5.26 Contrasting summer and winter hydrological models from Sutton Common.

There is also possible evidence of the impact that the re-engineering work, that has taken place on the site, has had upon the water table. Two possible effects of this have been identified. Firstly, along the western edge of the model in the area where field drain outfalls were captured, the water table has taken on a flatter appearance as shown in Figure 5.15(A & B). Secondly, a raised water table in the eastern part of the model shown in Figure 5.14(B &C), not previously observed under similar conditions suggests that there has been a change within the water table. This is similarly repeated in Figure 5.19(B).

The hydrological models have shown that there have been occasions where individual precipitation events have caused a clear reaction within the water table, for example, the change observed in Figure 5.19C compared to the previous monitoring visits. However, this cause and effect process is not as clear as it first seems, with there being occasions when no reaction is observed to an event, for example, that shown in Figure 5.14A. In addition to this, positive response has been observed without a corresponding increase in precipitation (e.g. Figure 5.8C). This pattern suggests that the groundwater dynamics are inherently complex, with several influences determining the overall behaviour of the water table on Sutton Common.

5.2.3 Water table fluctuations at specific monitoring locations

Specific areas of Sutton Common have been the subject of targeted monitoring and the results of these activities will be presented here. Three differing activities have been carried out; the analysis of the movement of eight individual piezometers at soil redox monitoring locations, analysis of the impact upon the water table of the site track and the analysis of three piezometer clusters.

Piezometer levels

Nine locations across Sutton Common have been chosen for closer analysis of the water table. These locations are those chosen for the monitoring of soil redox potentials and also subsequent soil sampling for microbiological assessment. It is therefore desirable to assess the specific changes in the observed water levels in the piezometers in these locations in order to aid in the characterisation of the burial environment.

Figure 5.27 shows the piezometer levels from Sites 2 to 9, as described in Chapter 4. Data for Site 1 is not presented as this location did not have readings taken during normal hydrological monitoring visits.

It is clear from the graphs that all the locations shown were the subject of seasonal variation in the water table, although this is less pronounced in locations that have maintained a relatively higher water table level, specifically Site 9. This and Site 4 are the only locations, of those presented here, where the water table has been read at or above the ground surface during the period of monitoring and this appears to be a function of their low-lying positions within the monitoring grid.

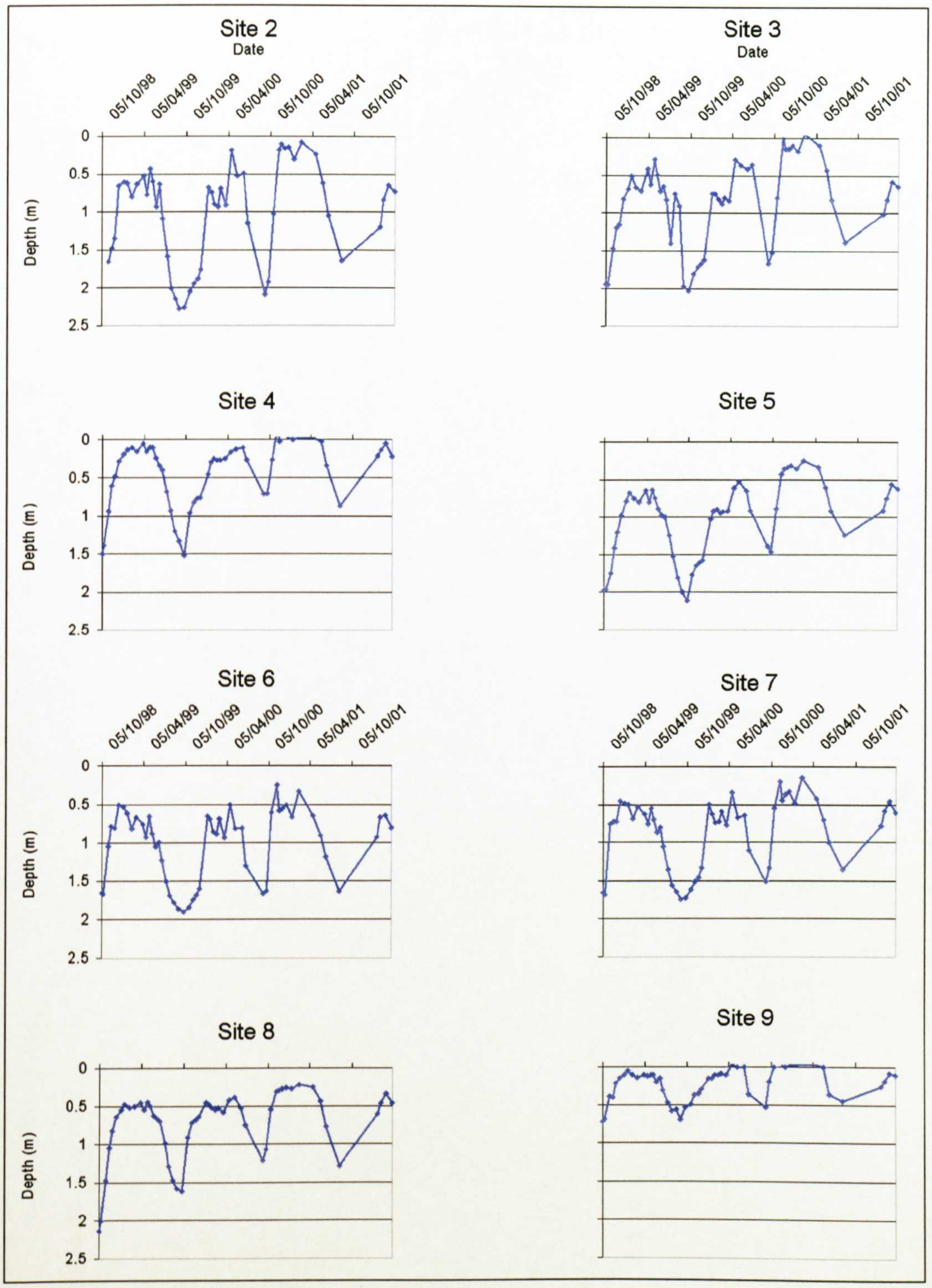


Figure 5.27 Piezometer water levels for Sites 2 - 9.

Excluding the period of flooding that took place during the winter of 2000/01, all the eight locations presented here showed a winter water table within 1.0 m of the ground surface, with this regularly approaching or exceeding 0.5 m. Of the four winter levels presented in this data, the 1998 and 1999 levels are very similar as are those recorded at the end of the monitoring period in early 2002. Therefore, in terms of the maximum water-levels recorded, it is the winter of 2000/01 that shows the greatest water table height across the site as presented in the GIS produced hydrological models shown previously. During this time, the levels recorded are approximately 0.5 m higher than the levels recorded in other years and this is maintained for the whole of the winter period. The 'normal' winter period can be estimated from the duration of the maximum water table heights for the years 1998 and 1999 as these two years received the approximate average annual rainfall for the region (refer to Figures 5.1 and 5.2), this being 600 mm (Ellis, 1997). Using this measure, the period of maximum water table height can be considered to occur between approximately December and June, subject to minor variation. The annual rainfall received during 2000 was in excess of 700 mm and was concentrated in the last quarter of the year and this therefore explains the flooding that took place. In comparison, the rainfall for 2001 and early 2002 was below average (refer to Figures 5.4 and 5.5) this explains the later rise in the water table, this occurring between February and March 2002, and also the lower water table present.

It is apparent from the graphs that there is a general upward trend in the water table heights at all eight locations presented in Figure 5.27 However, closer examination of the data must be made to ensure that this pattern does not occur as a combined result of the changing resolution of monitoring and the duration of the heightened water table following the period of flooding. The resolution of monitoring, i.e. the number of visits made during a period of time, was greatest during the first twelve months with very regular visits occurring on a two-weekly basis. However, this lessened from 2000 and as a result the summer period is less well represented. Precipitation in the period between the beginning of June and end of August in 1999 was greater by more than 10 mm than during the same period in 2000, but resulted in a lower water table height across all eight locations, this being particularly pronounced at Sites 4 and 5 located within the palaeochannel. As has already been identified, the water levels across the whole site remained very high following the flooding event that took place in November 2000 and remained so until the following June. Unfortunately, due to inaccessibility to Sutton Common due to the presence of cattle, very little data exists for the summer months of 2001 although the observation made at the end of August indicates that the water table was higher than that observed during 1998 and 1999 across many of the sites studied. This may be the consequence of a brief but intense period of rainfall experienced immediately prior to the reading being obtained.

The hydrological impact of the site track

Access to Sutton Common is via the A19 running in a north-south direction immediately to the west of the site. From here, a track enters the main field travelling in an east-west direction along the northern edge of the archaeological enclosures terminating to the northeast of Enclosure A. The track is raised above the surrounding field by approximately 0.5 m, although this becomes more pronounced when it crosses the Hampole Beck palaeochannel where presumably desiccation of the organic-rich deposits has lead to shrinkage and/or the track was built up to cross this topographically low feature. The track was constructed from hardcore and had a metalled surface.

Concerns were voiced following excavations in 1998, that the track could potentially act as a hydrological barrier (Van de Noort & Chapman, 1999). Although this was presented in the context of sourcing water onto the site with the aim of active rewetting, an opportunity existed to more fully understand the hydrological conditions relating to the feature itself. To this end, two piezometers, identical to those installed in the wider piezometer grid, were installed on both the northern and southern sides of the track on the section crossing the palaeochannel and readings were obtained during normal monitoring visits. Data were obtained from these over a period of two years from February 2000.

Figure 5.28 shows the water levels recorded from the piezometers located on the northern and southern sides of the Sutton Common site track. The levels are presented as height O.D. with the tops of the piezometers being levelled to the surface of the track.

Similarly to the levels presented in Figure 5.27 and for all the hydrological data collected on Sutton Common, the level in the track piezometers display seasonal fluctuation very clearly. However, what is very clear is the close relationship between the two pieces of equipment, with water levels being very similar across the entire monitored period. The southern piezometer appears to consistently react more rapidly to changes than the northern one with it showing a higher level during times of rising water level and conversely, a lower reading when dropping. Despite this, the minimum readings obtained over the two years are almost identical. This pattern appears to relate to a difference in the saturated hydraulic conductivity between the two pieces of equipment, with the southern one being located in material that transmits water more rapidly. Essentially this means that the northern piezometer is lagged.

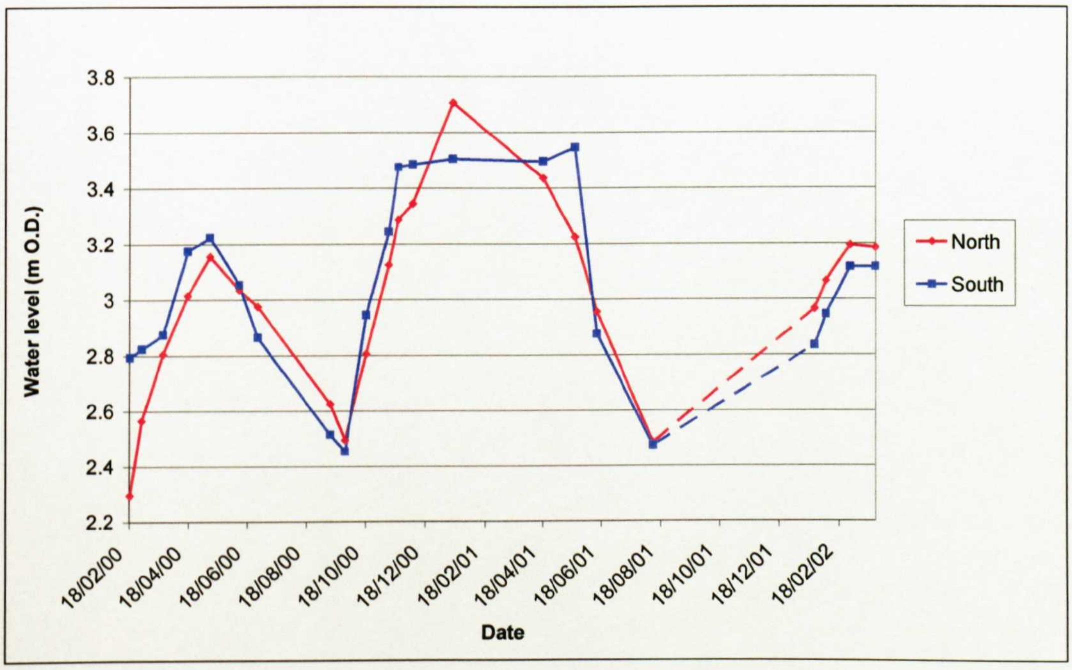


Figure 5.28 Graph showing water levels in piezometers installed on the northern and southern sides of the Sutton Common site track.

The later readings obtained during 2002 show that the opposite pattern is observed, although the two piezometers continue to react very similarly. It is suggested that this is an error in the data created as a result of disturbance to the site as a result of changing management. During this time there had been improvements to the site including the resurfacing of the trackway and mowing. As a result, and similarly to the piezometers across the wider site, this location was subjected to disturbance. Therefore, it is likely that the piezometers were relocated to different heights than those that were originally levelled into the height of the track thus creating false readings.

Piezometer clusters

Three piezometers were installed within the wider monitoring grid on Sutton Common to aid in understanding the hydrological dynamics concerning the source of groundwater and also to identify the presence of confined conditions within the water table. Two clusters were located within the palaeochannel and one within the extent of Enclosure A. Each cluster consisted of five individual piezometers installed to different depths, these being: 0.2, 0.5, 1.0, 1.5 and 2.0 m. Installation of the cluster within Enclosure A (Figure 5.29) took place in January 2001 whereas the remaining two installations were completed in August 2001. This was due to the continuing effects of flooding within the palaeochannel with surface water still being present until this time. However, the graphs (Figures 5.30 and 5.31) for these only present data collected during 2002 due to the interruption to monitoring resulting from cattle grazing.

Figure 5.29 shows the graph of the relative piezometer levels from the cluster located within Enclosure A. Despite the relatively low resolution of the data, it is apparent that the water table in this location is the subject of seasonal fluctuation, with relatively high water levels during the winter months dropping to a minimum during the summer. However, what is of importance is the fact that the levels within all the piezometers from different depths are very similar indicating that there is no element of stratification within the water table. Therefore in this location there is no evidence of confined conditions within the surface water table.

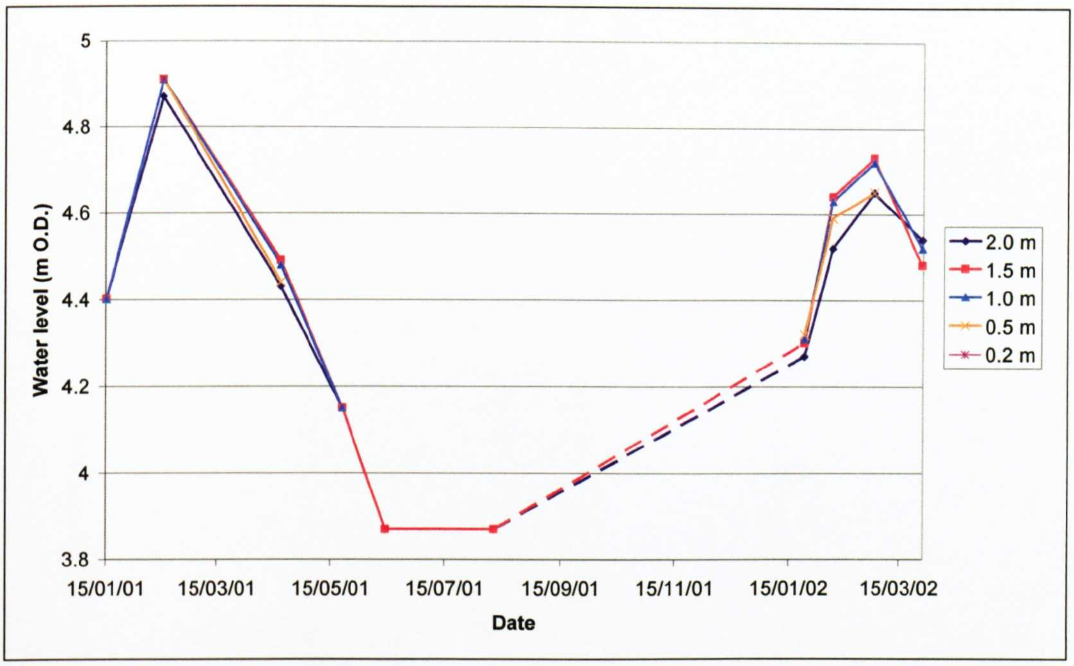


Figure 5.29 Graph showing the relative levels of the piezometers within the cluster located within Enclosure A. Hashed lined relates to the interrupted period of monitoring due to cattle disturbance.

Figure 5.30 shows the relative water levels within the piezometers in the cluster located in the northern section of the palaeochannel. Despite the relatively short length of time that the graph covers, there is a clear indication of stratification within the water table in this location. This corresponds very well to observations made during the time that surface water existed in this location during and following the flood event of 2000/01. At this time, although there was surface water present to a depth of approximately 0.3 m, piezometer reading from the single piece of equipment located to a depth of approximately 2.3 m consistently gave a reading almost 0.4 m below the level of that at the surface. This pattern is reflected in the results obtained from the piezometer cluster, where not only the reading from 2.0 m but also that for 1.5 m depth is consistently lower, although less so.

These results suggest that confined conditions exist to a degree at depth. An impermeable layer within the soil profile must exist in this location restricting vertical movement of water. Alternatively, a consistently low reading within a deeper piezometer could be indicative of vertical movement down through the soil profile. This would mean that there was a lower soil pressure at depth than at the surface. However, the fact that surface water persisted in this location for several months after the flood event suggests that this second scenario is unlikely. Therefore, it appears that within the northern extent of the palaeochannel there exists a confining layer within the upper 2.0 m of the soil profile restricting vertical flow. This most likely relates to the more complex stratigraphy within the fluvial deposits in this location.

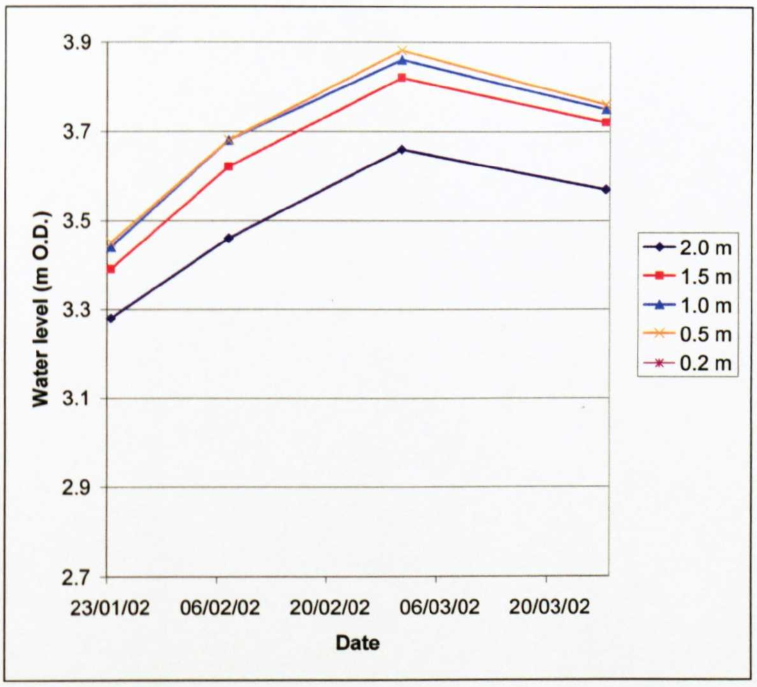


Figure 5.30 Graph showing the relative piezometer levels within the cluster located in the northern part of the palaeochannel.

Figure 5.31 shows the relative water levels within the piezometers within the cluster located in the southern part of the palaeochannel. It is clear that despite some variation within the readings, there is no consistent pattern other than similar readings. This suggests that despite there being evidence for confined conditions within the northern part of the palaeochannel, such conditions do not extend to the southern area of this feature. This can again be explained through the complexity within the fluvial deposits that exist here.

The results from the three piezometer clusters indicate that confined conditions may well exist on Sutton Common, but that these are most likely to be present within the complex and variable palaeochannel deposits rather than the more homogenous deposits forming the two 'islands' upon which the archaeological enclosures are situated.

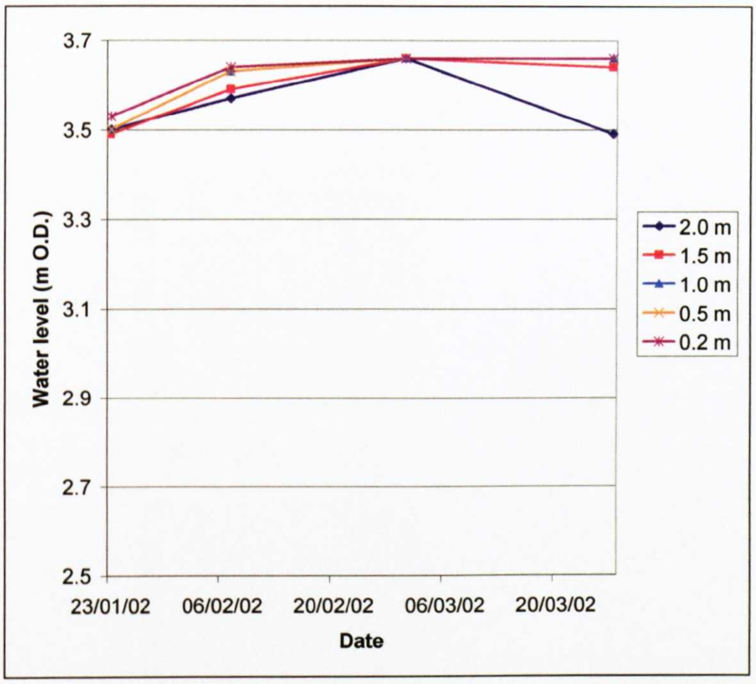


Figure 5.31 Graph showing the relative piezometer levels within the cluster located in the southern part of the palaeochannel.

5.3 Analysis of the Sutton Common water budget

In the previous sections, it has been highlighted that on several occasions the water table observed on Sutton Common has reacted to factors such as major periods of precipitation and the changing seasons. In addition to this, there have been the potential effects of the re-engineering of the site drainage system that was carried out on the site as described in Chapter 3. It is obvious therefore that the status of the water table is influenced by the inputs, outputs and dynamics of the site; factors such as evapotranspiration, precipitation and drainage. This regime can be referred to as the water balance or hydrologic budget for the site.

Such a water balance was carried out as part of a hydrological appraisal of Sutton Common (Geomorphological Services Ltd., 1990) whereby the catchment was treated as the whole of the area that contributes surface flow to the discharge drains that transit, and drain the site. These drains are pumped at the Thistle Goit and Heywood pumping stations to the east of Sutton Common. This hydrological appraisal studied the surface water component, derived mainly from the drainage of agricultural fields, and although acknowledged that there was the possibility of a large groundwater component, it assumed that over a long time period the groundwater input and output would equate. Therefore this component was not investigated and the water balance was assessed using data available on precipitation, evapotranspiration and discharge based upon pumping records from the Thistle Goit and Heywood pumping stations.

The assessment principally focused upon the catchment areas for the Thistle Goit and Heywood pumping stations, identifying sources and quantities of water passing through the system and therefore Sutton Common itself. From this, it was identified that changes within the water budget of the catchment were not due to climatic changes, or fluctuations in groundwater recharge. It did highlight the fact that deepening of the major drainage ditches running through the site, that occurred during the implementation of the Thistle Goit drainage scheme between 1977 and 1982 (Geomorphological Service Ltd., 1990) would reduce the water table by a comparable amount.

In the next section the Sutton Common hydrological budget will again be studied, but in this case, it will focus solely upon the monitored area of the site i.e. within the extent of the piezometer grid. The aim will be to study changes within the water balance throughout the period of hydrological monitoring by attempting to identify changes in the amount of water lost from the groundwater system via drainage resulting from the re-wetting activities. This exercise will also help to characterise the factors affecting the site water table and as such, those affecting the continued preservation of organic archaeological remains.

5.3.1 Constructing the Sutton Common water budget

The study of a water balance requires a delineation of boundaries of the area of study so that the inputs and outputs for this can be identified and quantified. This normally takes the form of a catchment or a watershed. In an example where the surface-water divides are the same as the groundwater divides and for which there are no external groundwater flows, the water balance equation for a period of time would be:

$$P = Q + E + \Delta S_S + \Delta S_G \qquad (5.1)$$

Where:
P = the volume of water inputted into the system through precipitation
Q = the volume of water lost from the system via surface runoff
E = the volume of water lost through evapotranspiration
ΔS_S = the change in the volume of the surface water reservoir
ΔS_G = the change in the volume of the groundwater reservoir.
(Freeze & Cherry, 1979).

With the focus of the current work on the near-surface water table over the area of the archaeological enclosures, it is desirable to attempt an assessment of the water-balance specifically affecting the groundwater storage component in this area. This is of particular interest in that this will be where any changes occurring due to the influence of re-wetting work can be identified. Therefore the boundaries for the water budget will be those created by the piezometer grid. As has been presented in section 3.2.1, through the use of GIS modelling, it is possible to create a computer representation of the water table within the monitored area, and from this to calculate the volume of ground that is saturated. In this case the base-level for this volume has been calculated to the height of the lowest recorded water level from the whole piezometer dataset (2.11 m O.D.).

Since the data for the groundwater storage component consists of the form of the water table within the bounds of the piezometer grid, then all other factors must be calculated for the same area. In the previous example given for Sutton Common, the water balance calculations were calculated on an annual basis, however, since there are many reliable observations of the water table obtained during this study, a water balance will be carried out at a far higher resolution at monthly intervals.

To construct a water balance it is necessary to delimit not only the area of study but to also make a number of assumptions. Firstly, as has been previously presented, there is little evidence of influence upon the near-surface water table by deep groundwater. It therefore is assumed that the changes that have occurred are attributable to inputs directly onto the site. If a further assumption is made that the water transported through the site via the drainage ditches from the wider artificial drainage catchment, do not have a significant impact upon the water table in terms of contribution, then the crucial variables to be considered are vastly reduced to precipitation and evapotranspiration on the site itself.

If Sutton Common is considered to be hydrologicaly isolated, both vertically as a result of underlying impermeable clays, and laterally from the presence of drainage ditches surrounding the entirety of the site, then the reaction of the water table within the piezometer grid will reflect changes of precipitation and evapotranspiration only. The changes within the surface water reservoir are usually regarded as the water stored at the ground surface and within the drainage channels themselves. As the area considered is small and lacks obvious surface water conduits this part of the equation is disregarded and the groundwater component is considered in isolation.

Therefore equation 5.1 can be simplified to:

$$P = Q + E + \Delta S \tag{5.2}$$

Where ΔS, is the change observed within the groundwater storage and Q, is the water lost through drainage.

Equation 5.2 can then be rearranged to the form:

$$Q = P - E - \Delta S \tag{5.3}$$

This enables the figure for the amount of drainage to be calculated, i.e. the amount of water lost from the near-surface groundwater reservoir and transported from the site via drainage. It is usual to present this information using the same units as those used for the other factors i.e. in mm (Freeze & Cheery, 1979), but in this case all calculations will be equated to the volume of water in m^3 in the same format as the Sutton Common hydrological appraisal.

The 2-dimensional area of the GIS hydrological models is 98,299 m^2 therefore, to calculate the volume of precipitation entering the site, the original values presented in mm, were divided by 1000 and then multiplied by 98,299 thus giving the volume of precipitation. The same method has been used to calculate the volume of evapotranspiration being lost from the system. Actual values for this are presented in Appendix 4

The GIS models have been used to calculate the volume of the saturated ground within the area of the piezometer grid at the time that observations of the water table were made. An estimate of the amount of water contained within this saturated volume can be made using the principle of specific yield, (S_y). Specific yield, which is dimensionless, is defined as the volume of water that an unconfined aquifer releases from storage, per unit area of aquifer, per unit decline in the water table (Freeze & Cheery, 1979). Freeze & Cherry (1979), state that the usual range of values for the specific yield are between 0.1 and 0.3, and general ranges of specific yields of unconfined aquifers composed of unconsolidated sediments is presented by Johnson (1967) and reproduced in Table 5.1.

Table 5.1 Ranges of specific yield of unconfined aquifers composed of unconsolidated sediments.

Material	Maximum	Minimum	Average
Clay	0.05	0.00	0.02
Sandy Clay	0.12	0.03	0.07
Silt	0.19	0.03	0.18
Fine Sand	0.28	0.10	0.21
Medium Sand	0.32	0.15	0.26
Coarse Sand	0.35	0.20	0.27
Gravelly Sand	0.35	0.20	0.25
Fine Gravel	0.35	0.21	0.25
Medium Gravel	0.26	0.13	0.23
Coarse Gravel	0.26	0.12	0.22

After Johnson, 1967.

Values for *P* have been available from daily precipitation data, recorded in mm, provided by Grantham, Brundell & Farran (Appendix 1). Values for potential evapotranspiration data, *E*, have been obtained from those presented by Geomorphological Services Ltd. (1990) (Appendix 3). These are in the form of monthly figures for the years between 1961 and 1989 and have been used to calculate an average, monthly value for potential evapotranspiration. The data was originally obtained from the then RAF base at Finningley located approximately 18 km southeast from Sutton Common.

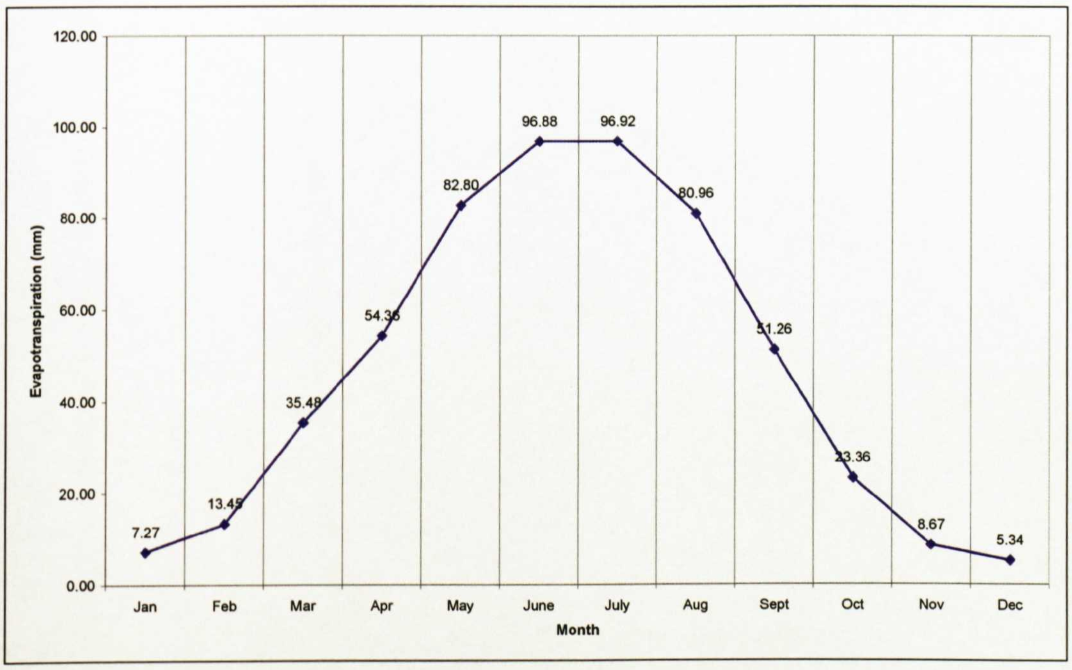


Figure 5.32 Values for potential evapotranspiration throughout a year. Values are averages derived from data obtained at RAF Finningley between 1961 and 1989 (Geomorphological Service Ltd., 1990).

Figure 5.32, presents values for potential evapotranspiration (Geomorphological Services Ltd., 1990) used during the water balance calculations for Sutton Common. Presented are monthly averages obtained from readings taken between 1961 and 1989. This data is taken as being representative of the region as readings were obtained approximately 18 km to the south east of the study site.

5.3.2 Results of the Sutton Common water budget

In this section the main results of the water balance calculations for Sutton Common will be presented. The main table of calculations can be found in Appendix 4. The monitoring data has been normalised to a monthly value instead of the actual dates of the monitoring visits themselves. The justification for this is that there was not a uniform interval for the monitoring visits over the entire period of monitoring. Presentation of this data on a monthly basis means that factors such as precipitation and evapotranspiration can be more effectively compared to the water table data. In the calculation, when there was a long period between monitoring visits, the values for precipitation and evapotranspiration were highly inaccurate. This is because if a period of several months was taken, the values for each of the factors would be grossly exaggerated. Where there are more than one set of water table observations within any monthly period, these are averaged.

The creation of a water budget for Sutton Common was originally aimed at identifying changes within the amount of drainage (*Q*) of the groundwater occurring on the site, specifically to identify the effects of re-wetting. The results of the calculations on a monthly basis are presented in Figure 5.33.

The results of this exercise demonstrate that there were periods during the monitoring of Sutton Common where there was both a surplus and deficit within the groundwater system. This is far more clearly represented during the earlier results, presented in Figure 5.33, where apparent trends can be seen within the data along with more gradual changes. However, later in the monitoring, changes become more abrupt with large swings from positive to negative without much, if any, intermediate change. This can be most clearly seen in the data presented for March 2000 and onwards. Positive drainage refers to an excess amount of water within the balance calculation that has not been accounted for by groundwater storage or losses from the system from evaporation. It is presumed that under these circumstances the excesses are removed from the system by means of drainage from the site. Where negative values are presented, this suggests that water is being made available from other sources than those being accounted for in the calculations, such as a contribution vertically from the deep groundwater, or laterally from outside the boundaries set during this exercise.

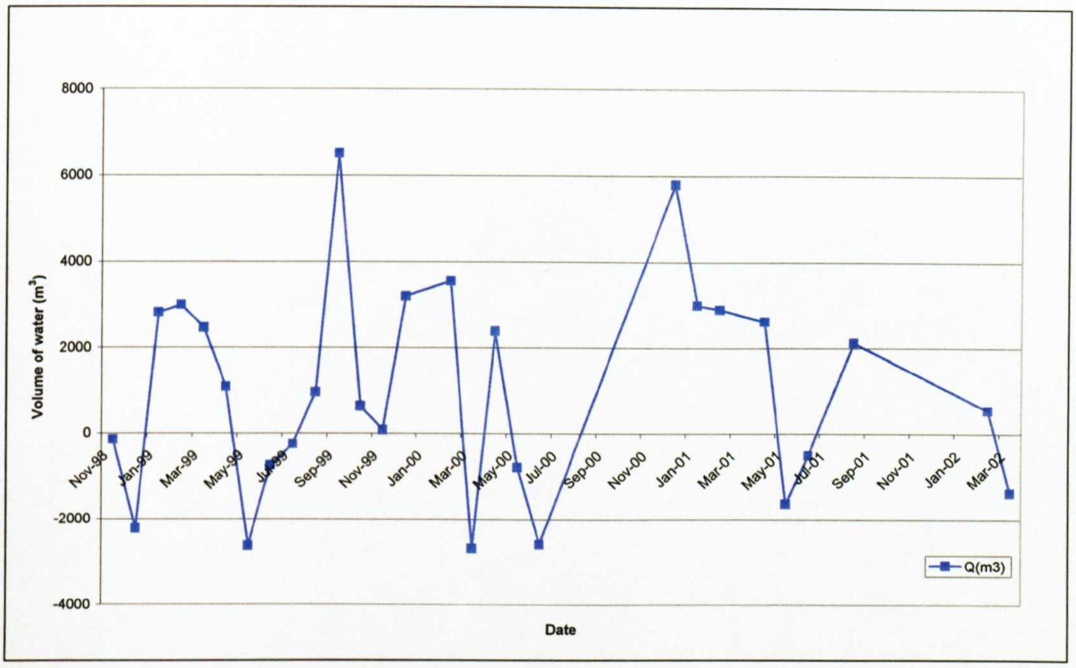


Figure 5.33 Graph showing the volume of water within the water budget calculations attributed to drainage (*Q*).

Although there are some apparent seasonal patterns within the data, it is clear that the resolution of the available data is not sufficient to correctly identify drainage of the water table. As a result of this, unfortunately, no conclusions can be made upon the effectiveness of re-wetting activities upon the site. However, during the generation of the water budget a number of relevant data sources were identified and these warrant presentation in their own right.

Presentation and comparison of the raw GIS models in section 5.2.2 created from observations of the water table, have indicated that the water table is influenced by the amount of precipitation received directly by the site. However, it has also become apparent there is a seasonal affect that has been attributed to evapotranspiration.

Figure 5.34, is a graph showing the calculated volume of water held as groundwater within the extent of the monitored area (*S*) and also the volume of water calculated as being added to the site through effective precipitation (*Pe*).

Effective precipitation is defined as the volume of water being added to the system via precipitation minus the volume lost through the action of evapotranspiration.

$$Pe = P - E \tag{5.5}$$

Figure 5.34, shows that the changes in groundwater storage component (*S*) appear to reflect changes observed in *Pe*. What is more, these changes occur on a seasonal basis, reflecting the higher water table observed during the winter months and conversely, the lower levels during the summer months. This overall pattern suggests that the changes within the groundwater storage component, and therefore the level of the water table on Sutton Common, are largely influenced by levels of precipitation.

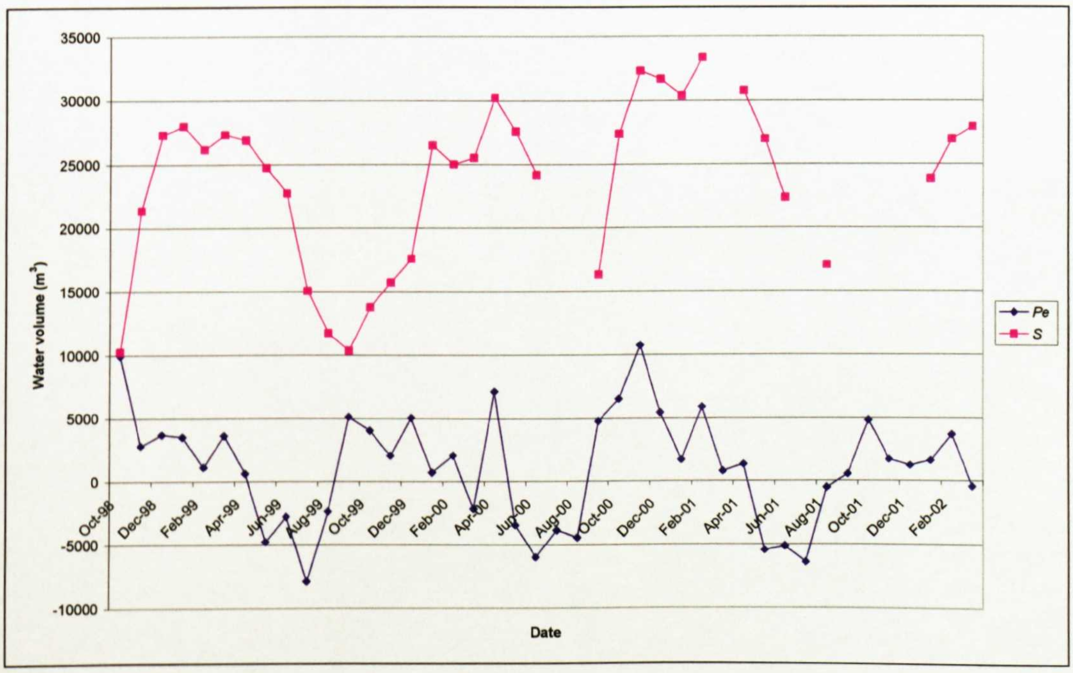


Figure 5.34 Line graph showing the volume of water in groundwater storage (*S*) and the volume of water available through effective precipitation (*Pe*).

Studying changes in the water storage component (ΔS) and *Pe*, helps appreciate the close relationship between the two factors. Figure 5.35, shows a plot of these two factors, presented on the same scale. It is clear that relative change within the two factors is similar, and this is further enhanced when they are regressed against each other. Figure 5.36, presents this regression that generates an R^2 value of

0.6453, indicating that the majority of the change observed within the levels of near-surface groundwater storage, can be attributed to *Pe*.

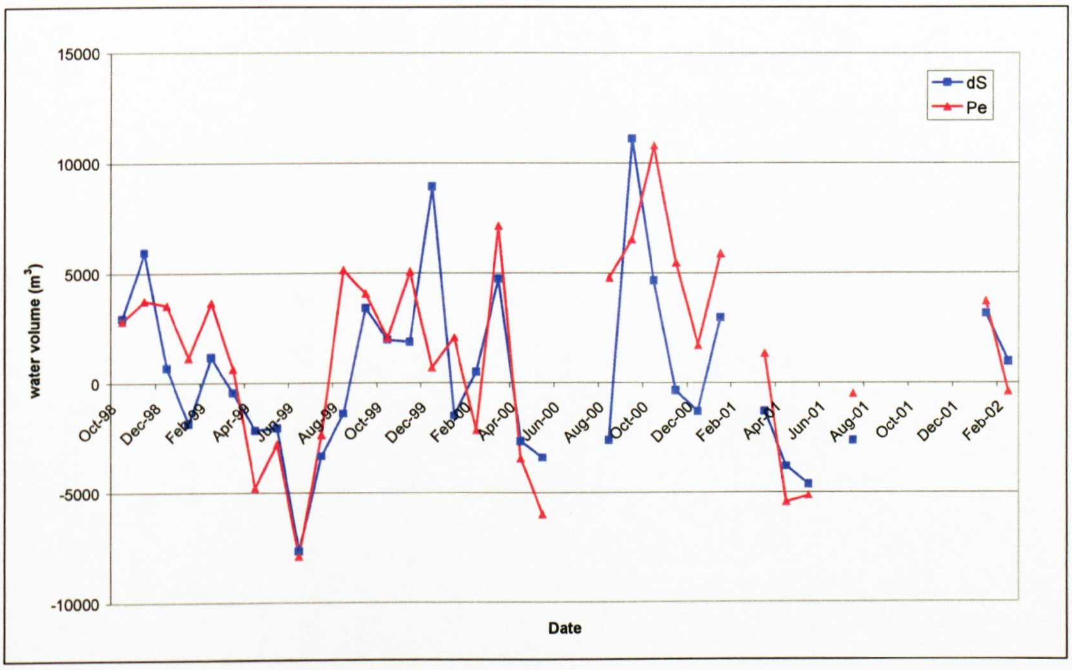


Figure 5.35 Graph showing ΔS and *Pe* for Sutton Common.

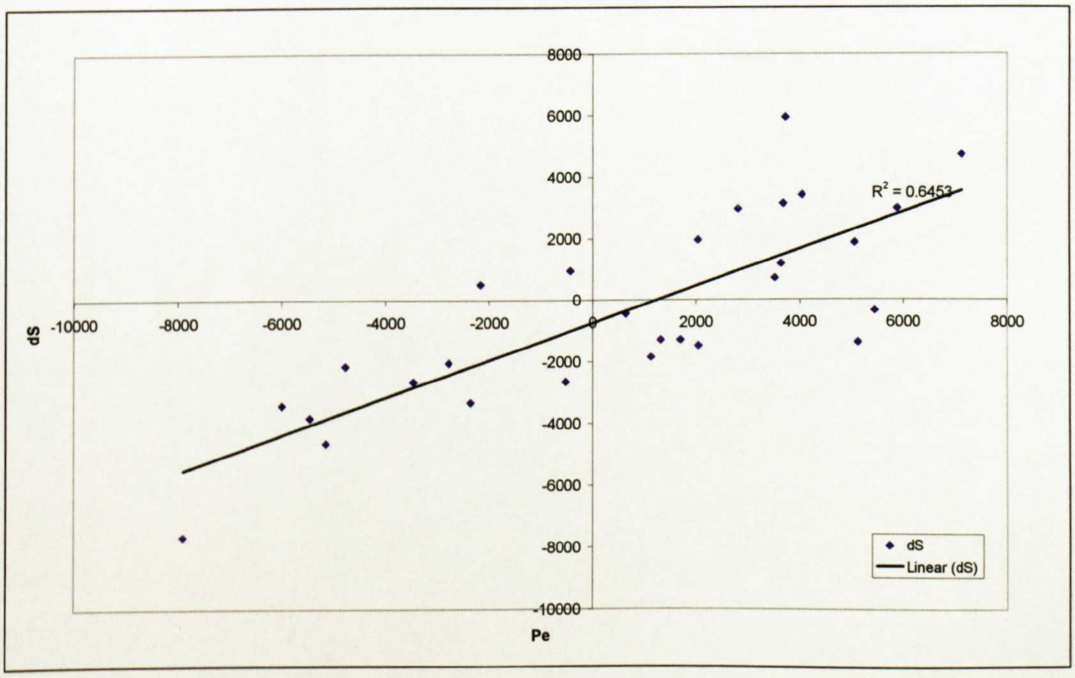


Figure 5.36 Regression of ΔS and *Pe*. Coefficient of determination, $R^2 = 0.6453$.

The data presented here indicates that the predominant influence upon the Sutton Common water table is water sourced from precipitation arriving immediately within the area of monitoring or over the local site itself, as opposed to being transported into the system either as part of channel flow from the drainage infrastructure crossing the site, or as groundwater flow.

However, even though there may not be a clear and large influence upon the Sutton Common water table from the wider, deeper groundwater, it may still contribute to the Sutton Common water table itself. This can be tested in a simple manner by studying the behaviour of deep groundwater levels within the Sutton Common area.

Data from two deep boreholes has been obtained courtesy of the British Geological Survey (BGS). The first is located at Sykehouse, (462810, 417070) approximately 6 km to the northeast of Sutton Common, penetrating to a depth of 33.5 m. The second borehole is located at Westfield Farm (452150, 415250) located approximately 6 km to the northwest of Sutton Common, that penetrates to a depth of 22 m. The Sykehouse borehole is situated off the Magnesian Limestone whereas the second is located upon this higher ground. The readings for water levels at each, during the period of monitoring on Sutton Common, are shown on Figure 5.37. The discrepancy in O.D. heights relate to the higher land surface of the Magnesian Limestone located to the west of Sutton Common.

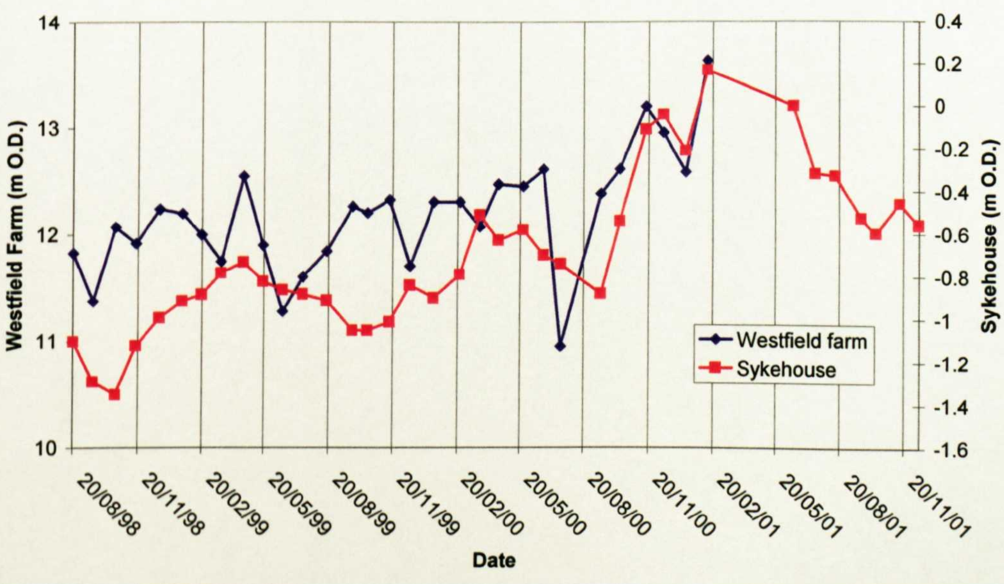


Figure 5.37 Graph showing the levels of the groundwater aquifer at Westfield Farm (452150,415250) and Sykehouse (462810, 417070).

The data obtained from the two boreholes differs in a number of respects, not only in the difference in the heights O.D. Whereas the levels obtained from the Sykehouse borehole appear to show seasonal variation in height, this is not reflected so clearly in the data obtained from Westfield Farm. What is also clear is the major difference in the degree of fluctuation that occurs between the two sites. At Sykehouse, the annual fluctuation is approximately 0.5 m whereas at Westfield Farm it is in excess of 1.5 m. This disparity can be attributed to the different geologies that exist at these two locations. The Westfield Farm borehole, as discussed previously, is located on the Magnesian Limestone that forms a low ridge to the west of Sutton Common, whereas at Sykehouse the BGS borehole logs report the underlying geology to consist of sandstone belonging to the Permo-Triassic Sherwood Sandstone group. However, whereas the Westfield Farm borehole drops straight onto the underlying bedrock and can therefore be considered an unconfined aquifer, at the Sykehouse borehole there is reported, to a depth of approximately 12 m, the presence of confining drift above the underlying geology. This situation may explain the reduced fluctuations in water height observed within the data at this location as opposed to Westfield Farm. Water level readings from the Sykehouse borehole therefore do not relate to an upper level of saturation within the aquifer, as would be the case in an unconfined situation, but to the piezometric surface of the aquifer.

Of the two borehole locations that have been discussed, the one that relates most closely to Sutton Common is the Sykehouse borehole. The deep stratigraphy in this location is similar to that found at Sutton Common, most importantly relating to the existence of the glacially derived drift deposits (Head *et al.*, 1997) that confine the underlying sandstone aquifer (pers. comm. J. Aldrick, 21 February 2003). Therefore, if the underlying aquifer is exerting an influence upon the behaviour of the Sutton Common water table, then this should be identifiable when the two are compared.

Figure 5.38, presents a regression of the height observations of water levels within the Sykehouse borehole with S at Sutton Common. An R^2 value of 0.4517 is produced indicating that there is a relationship between the two factors, although this may not be absolute or as strong a relationship as that shown between ΔS and Pe.

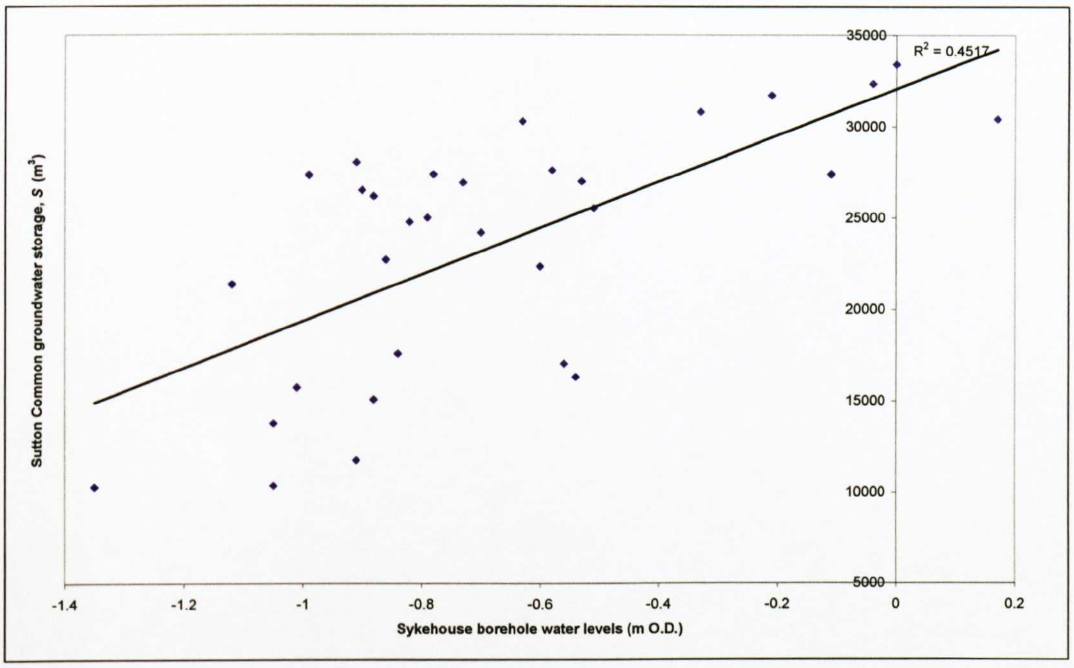


Figure 5.38 Regression of borehole water levels from Sykehouse with water storage component (*S*), at Sutton Common. An R^2 value of 0.4517 is generated.

This information suggests that the fluctuations in the near-surface groundwater on Sutton Common that have been extensively monitored throughout the period of study have been predominantly influenced by the interaction of precipitation and evaporation. However, study of BGS borehole data has provided limited evidence that changes within the deep groundwater aquifer levels may also be having a partial influence. This is limited, not only in that a very significant relationship has not been identified, but also due to the possible effect of seasonal influences upon the data. As discussed above, the Sykehouse borehole data, when plotted, shows that there are seasonal changes in the water levels at that location and a strong seasonal change has been identified within the monitoring data from Sutton Common. Therefore any relationship between these two, such as that presented in Figure 5.38, may purely be as a result of the effect of seasonality rather than a cause and effect relationship directly between the two factors themselves.

In order to test this, the relationship between the water levels at Sykehouse and *Pe* have been regressed and the resulting graph presented in Figure 5.39.

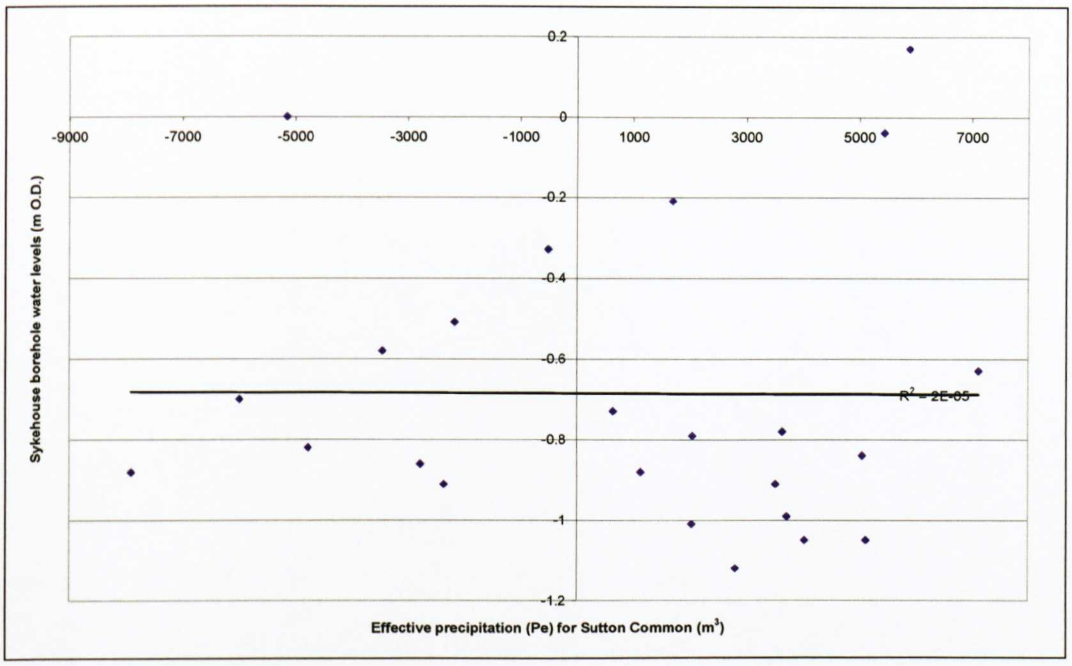


Figure 5.39 Regression graph showing the relationship between effective precipitation (*Pe*) and Sykehouse borehole water levels.

As can be clearly seen from the graph, there is absolutely no evidence of any relationship between *Pe* and the Sykehouse water levels based upon the data that is a currently being utilised. Therefore, it appears that although the Sutton Common water table is strongly influenced by the precipitation and possibly by changes within the groundwater aquifer, both of which express seasonal fluctuation, aquifer levels do not relate to *Pe*. Explanation of this may simply lie in a period of lag existing within the groundwater system, or conversely, there genuinely may not be any relationship.

This interesting outcome therefore suggests two possible scenarios concerning the relationship between the Sutton Common, near-surface water table, the deep groundwater table (at Sykehouse) and *Pe*:

1. Sutton Common is predominantly influenced by *Pe*, with a lesser contribution to the monitored water table through the deep groundwater aquifer.
2. *Pe* is the major factor contributing to the Sutton Common groundwater table that is mitigated by site drainage. The underlying aquifer is confined

by the clay rich glacial deposits that exist in the area and therefore does not contribute to the water-balance of the site.

Of the two situations it is the latter that, on balance, is the strongest for a number of reasons. Firstly, evidence from the Sykehouse borehole indicates that the underlying aquifer is confined and therefore surface water will on the whole be isolated from changes. In addition to this, the levels measured from this location indicate that the potential water heights reached by water derived from the underlying aquifer would always be at, or less than O.D. i.e. average sea level. In contrast, all observations of the Sutton Common water table are well above 0 m O.D. and therefore it is highly unlikely that water would be contributed to the near-surface water table.

Due to the inherent complexities involved in the understanding the dynamics of the water table and the limited extent and resolution of available data, it is not possible to analyse the situation further. However, it seems clear from the analyses of the water-balance of Sutton Common and through the study of the wider hydrological situation, that the local near-surface water table, that has been the subject of monitoring during the course of this research and therefore directly relates to the preservation of organic archaeological remains, is influenced predominantly by effective precipitation (*Pe*).

Returning to the original aims of this exercise, namely to further enhance the understanding of the drainage of the site and be able to quantify changes in this due to the re-wetting work that has taken place. Although results concerning this have been generated, they have not been able to approach this question effectively and reasons for this will be discussed here. The resolution of the data generated for drainage within the water budget calculations (*Q*), was too low to reveal any useful information regarding changes to the drainage of the site. The reasons for this include:

1. Inconsistent monitoring readings of the Sutton Common water table. Earlier observations were greater in number and therefore when averaged to a monthly value were more representative. Later observations were

either missing, affected greatly by flooding on the site or values relied upon one observation date only. As has been shown within the GIS models earlier in this chapter, single observations were subjected to influences from individual precipitation events and therefore may not be representative of a monthly value.

2. The source and quality of data used in the calculation of values was not ideal. Although the precipitation data obtained was of high quality and high resolution and therefore can be considered accurate, the source of information regarding evapotranspiration is not ideal. The data on evapotranspiration used during this exercise was obtained from the hydrological appraisal undertaken on Sutton Common by Geomorphological Services Ltd. (1990). This data was obtained from a location approximately 18 km from Sutton Common, so can only be considered to be regionally representative. In addition to this, the data is in the form of monthly averages for several years, with the latest being almost a decade prior to this research taking place.
3. The calculation used has been too simplistic. On the scale that has been attempted with the quality of background data available, the outcome of the calculations has included a high level of error. Although the basic theory is considered sound, the situation is far more complex than has been accounted for, and as a result there are obviously significant omissions in terms of sources and sinks of groundwater. In order to use all the available data a number of major assumptions were made upon the behaviour of the water table, including those upon the boundary conditions of the site.

Taking the previous points into account means that no significant conclusions can be made upon the drainage of the site or any changes that have occurred to it. However, this process has generated very significant results in terms of identifying the interaction of the near-surface and deep groundwater and therefore the behaviour of the site water table itself. It is this fact that is important in terms of understanding further, the status of the site, preservation potential of the remaining archaeological materials and also aspects concerning the future management of the site.

5.4 The measurement of saturated hydraulic conductivity

The methods covering the *in situ* measurement of saturated hydraulic conductivity (*K*) have been presented in section 3.2.4.

Observations using this approach have been obtained from 11 of the 50 piezometers that form the monitoring grid. The locations of these and the values for *K* (in ms^{-1}) are presented on Figure 5.40.

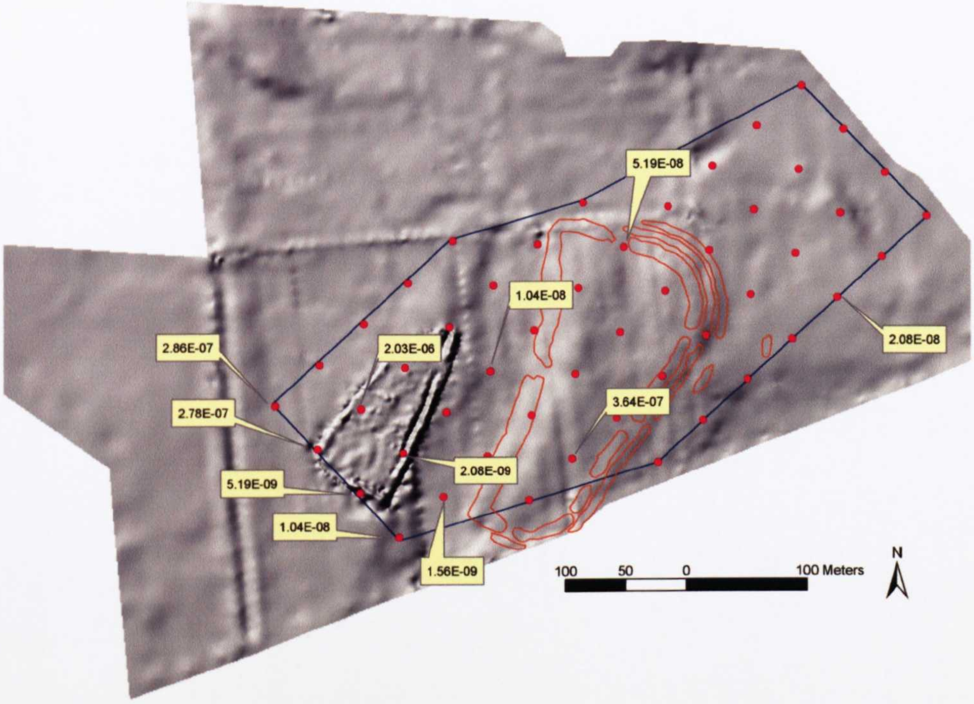


Figure 5.40 Sutton Common DEM map showing the location and value of saturated hydraulic conductivity measurements. Values are expressed as ms^{-1}.

The range of values obtained from all the measurement locations range between 10^{-6}-10^{-9} ms^{-1}. The types of material that show these magnitudes for *K* (also sometimes referred to as the coefficient of permeability) range from fine sands, through silts to sandy clay for mineral soils, and peat for organic soils (Table 5.2).

Table 5.2 Values for saturated hydraulic conductivity for some natural soils. After Berry & Reid (1987).

Soil type	K (ms^{-1})
Clay	$<10^{-9}$
Sandy clay	10^{-9} - 10^{-8}
Silt	10^{-8} - 10^{-7}
Peat	10^{-9} - 10^{-6}
Fine sand	10^{-6} - 10^{-4}
Coarse sand	10^{-4} - 10^{-3}
Gravelly sand	10^{-3} - 10^{-2}
Gravel	$>10^{-2}$

The majority of observations fall within the range 10^{-7}-10^{-8}, or silty material. This corresponds very well to observations of the type of sediments present over Sutton Common made during excavations (Van de Noort & Chapman, 1999 & 2000).

There is not a strong pattern within the distribution of values for K, mainly due to the relatively low resolution of the observations made. However, there is a possible trend in that the three lowest values obtained, with a value of 10^{-9} ms^{-1}, were all identified from adjacent piezometers from within or immediately adjacent to the palaeochannel. The types of material that exhibit this rate of flow are clay and peat. Therefore, there is a possibility these result from the presence of degraded peat associated with the palaeochannel itself. Conversely, higher values of 10^{-6} and 10^{-7}, are located within the extent of Enclosures A and B and may represent the fine sands and silts known to exist there.

These results, although tentative, may indicate that lateral flow of groundwater within the palaeochannel is lower than the material surrounding it. Although the values obtained do not account for the relative depth of measurement, they may still be evidence that groundwater flow may preferentially be around the palaeochannel and not through it. This situation could have implications for the continued preservation of archaeological remains across the whole site. Firstly, excavations in 1999 assumed that the palaeochannel deposits had exhibited a high value for *K* and were therefore more susceptible to desiccation (Van de Noort & Chapman, 1999). The results presented here suggest that the opposite situation may in fact be true and that therefore the burial environment within the palaeochannel may in fact be far more stable than previously considered. Secondly, such previous assumptions, coupled with the topographically low character of the palaeochannel, have led to suggestions that groundwater may be lost through the southern part of the palaeochannel. Possible ways to mitigate against this have been suggested including the installation of a bund in this location. However, the measurements of *K* reveal that the opposite situation may exist. Clarification of the situation may help target future mitigation and help enhance the burial environment further.

5.5 The interaction of archaeological wood and the changing water table

The results presented so far, are the GIS models created from the hydrological monitoring data gathered from the piezometer grid during monitoring visits to Sutton Common. These models have been used to describe the form of the water table and how this has changed throughout the period of monitoring. It is now possible to use this data in a more proactive way, taking advantage of the power of the GIS to integrate data detailing the location of archaeological wood, within archaeological deposits that have been the subject of excavation.

As previously discussed, the site has been subject to continual desiccation through increased levels of agricultural drainage for in excess of 20 years. Not only has this led to the physical destruction of Enclosure A, but also to the extensively documented desiccation of the archaeological deposits, these having previously been shown to contain important and well preserved organic remains predominantly of wood. Since the site was taken into protective ownership by the CCT, there have been a number of excavations to identify the condition of these remains, and also to excavate those that are deemed non-sustainable through *in situ* preservation. These excavations have revealed the presence of archaeological wood, some of which continues to survive in a very good condition, and it is now possible to integrate this information with the data obtained on the location of the water table. This will enable a greater degree of understanding of the impact of changes within the water table, and provide an opportunity to assess the influence of remedial drainage work carried out on the site.

5.5.1 Creation of an archaeological wood database

Chapman and Cheetham (2002), present the issue of the preservation of archaeological wood within a burial environment subject to a fluctuating water table. Although often there are circumstances where variation within the soil matrix will cause such features as a perched water table to form, within a well-mixed soil matrix three broad categories regarding the amount of saturation may be identified. These are:

- Permanently dry: Surface soils may be subject to periodic saturation as a result of individual precipitation events causing waterlogging.
- Intermittently saturated: A depth range that is subject to seasonal saturation as a result of an increase in the amount of effective precipitation reaching the groundwater reservoir.
- Permanently saturated: Below the depth of the lowest annual water table where the soil matrix remains permanently saturated.

In practice these three zones may vary quite markedly within a relatively short distance, especially where distinctive geomorphological features exists. In turn, this means that changes within the level of preservation of organic archaeological materials would also reflect this variability.

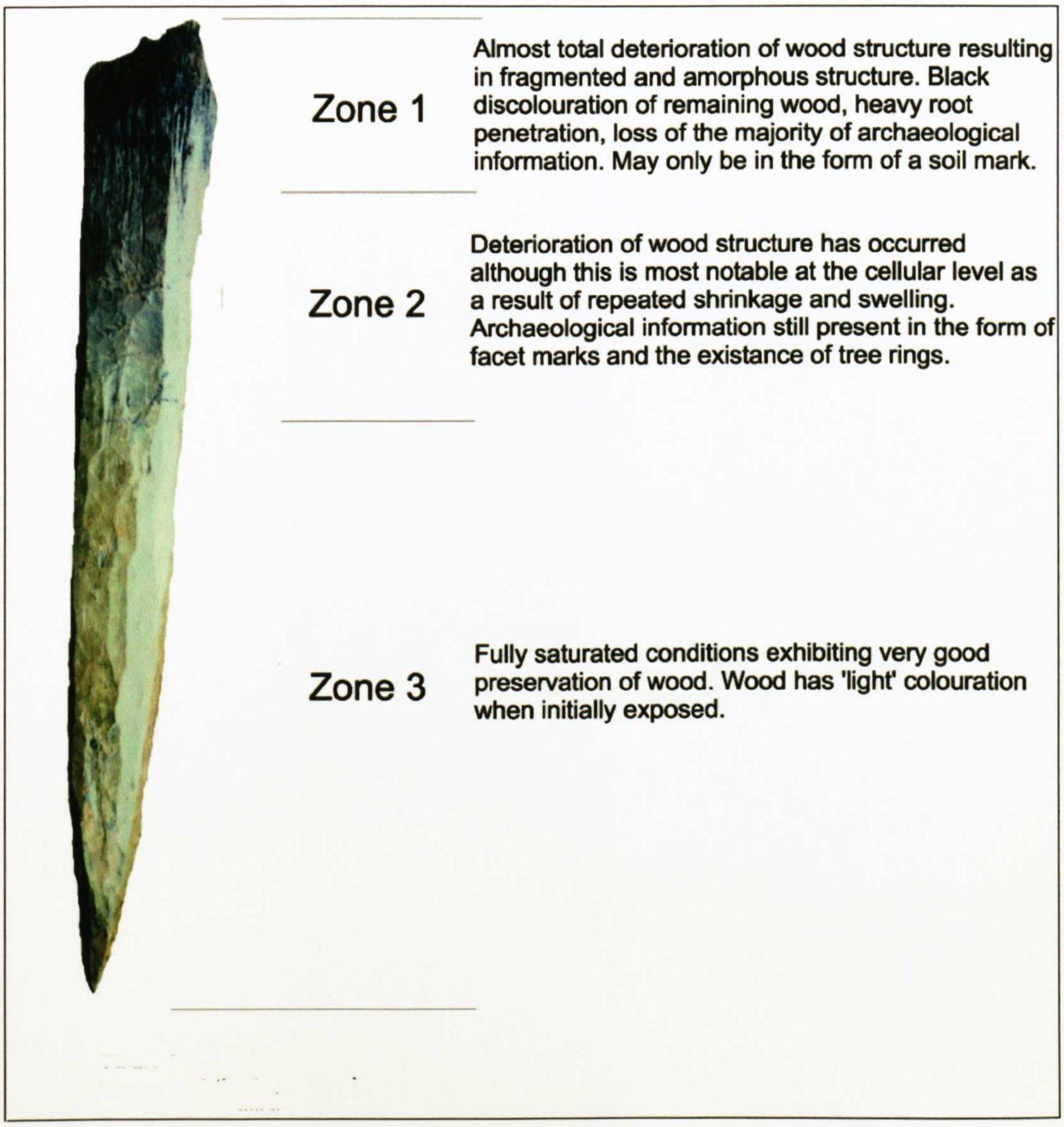
On wetland archaeological sites, or those that contain high levels of saturation, the predominant material preserved is very often wood. In particular, this wood is in the form of wooden stakes, posts or piles, this type of artefact being prevalent on Sutton Common itself. Therefore, this type of material is useful in providing a vertical index of the conditions within the burial environment throughout the soil profile and therefore be able to identify changes within the groundwater dynamics through comparison of the quality of preservation of wood to the range of the water table in that particular location.

As stated previously, for archaeological wood to exist within any burial environment it must have become stabilised, otherwise it would have been removed via the processes of degradation. It is therefore useful to understand the differences in the quality of preservation exhibited by wood as a result of the three zone model. This is shown in Figure 5.41.

- Zone 1: This is characterised by the almost total degradation of the wood material from the cellular level up, resulting in a fragmented and an almost amorphous structure. Indeed, where such conditions have persisted for more than a few years, nothing more than a soil mark is observed. Where wood does exist, this identifies that there has been a recent lowering of the predominant water table in this location. The material would exhibit severe desiccation cracks, soil macrofauna, such as earthworms and insects will be present, the wood colour will be dark and the material itself will be very friable.

- Zone 2: This zone is characterised by some deterioration to the wood structure at the cellular level as a result of repeated wetting and drying, although the macro structure of the wood is often retained. Desiccation cracks may be present, extending down from material present within zone 1. Such conditions would mean that the material retained a high degree of moisture from periodic saturation. This would slow deterioration of the wood but not halt it. Therefore, in time the complete removal of the wood would be expected under these conditions, although the time taken for this to occur would be dependant on factors such as the size of the artefact, the hydrological properties of the surrounding soil matrix and the period of time that it was subject to fully saturated conditions. As for Zone 1, if archaeological wood persists under such conditions, it is indicative of relatively recent lowering of the water table at that particular location.

- Zone 3: Characterised by fully saturated, anaerobic conditions with little or no identifiable microbial activity. Deposits exhibiting these conditions have the potential to contain wood that is in a state of extremely good preservation. This is particularly true if conditions have remained stable with no lateral movement of the groundwater that could disturb the burial environment and transport nutrients necessary for microbiological activity. Wood retains a pale colouration, similar to that of fresh wood, but this fades rapidly upon exposure to air. Such wood retains fine detail of woodworking.



Almost total deterioration of wood structure resulting in fragmented and amorphous structure. Black discolouration of remaining wood, heavy root penetration, loss of the majority of archaeological information. May only be in the form of a soil mark.

Deterioration of wood structure has occurred although this is most notable at the cellular level as a result of repeated shrinkage and swelling. Archaeological information still present in the form of facet marks and the existance of tree rings.

Fully saturated conditions exhibiting very good preservation of wood. Wood has 'light' colouration when initially exposed.

Figure 5.41 The three zones of saturation: 1. The dry zone, 2. The zone of fluctuation, 3. The zone of saturation.

It has been possible to identify the location and height range of 25 individual pieces of archaeological wood identified during excavations that took place in 1998, 99 and 2002. This information has been used to identify the relationship between the wood and the fluctuating water table, how this has changed through the period of monitoring and in response to the remedial drainage works.

Through studying the excavation archives, the location of pieces of archaeological wood has been identified and recorded along with the height range, in m O.D. at which it exists, i.e. its top and base heights. Once entered into an ArcGIS geodatabase, this information was manipulated within the GIS environment and compared to models created from the hydrological monitoring data. Figure 5.42, shows the locations of the pieces of wood along with their context numbers (refer to Appendix 6).

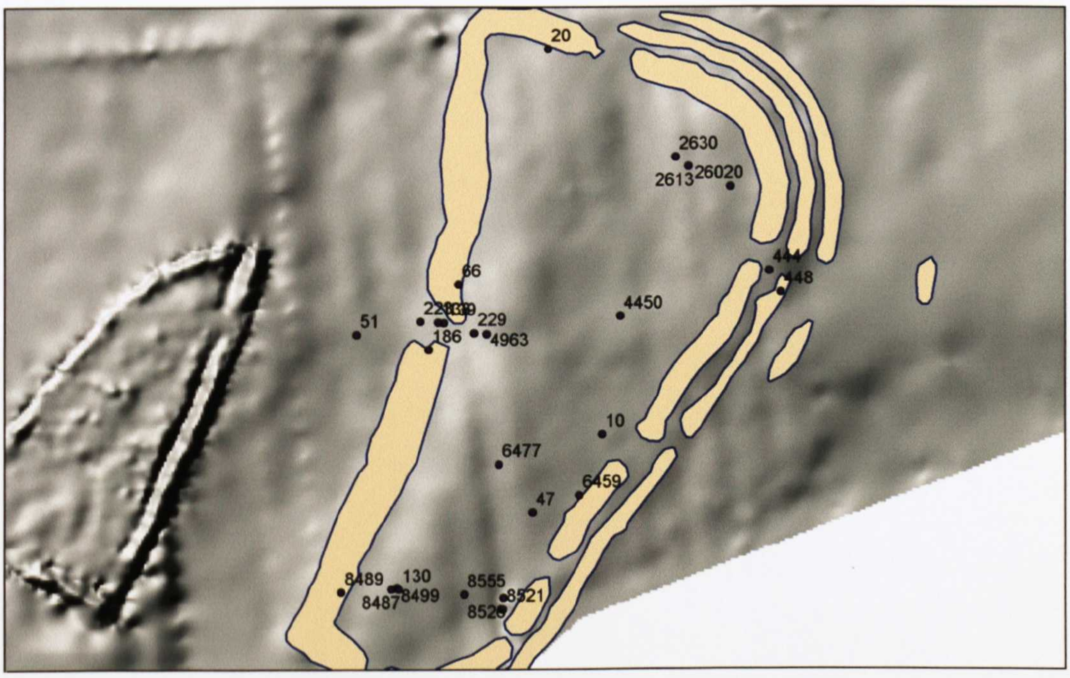


Figure 5.42 Sutton Common, Hillshaded DEM showing the location and context numbers of excavated pieces of archaeological wood. The outline of the former banks of enclosure A are also depicted.

5.5.2 Results of the archaeological wood model

The aims of this exercise were to assess where the archaeological wood identified within the site, exists in relation to the water table and identify the level of threat to the continued preservation of this material from desiccation. The assumption is that continued preservation would require full and continuous saturated conditions within the burial environment, i.e. conditions characteristic of Zone 3. For wood to exist on the site in the first place, this material must have been continually saturated since prehistory. This leads further to the assessment of the impact of new land management practices and remedial drainage work, aimed at securing the preservation into the future.

To undertake these tasks a number of specific hydrological models have been created representing the maximum and minimum water table across the monitored area of the site for three differing situations. Firstly, models have been created representing the maximum and minimum water level readings obtained from all the piezometers, from the whole of the hydrological monitoring data obtained from the site, including the period of flooding during the winter of 2000/01. Secondly, the maximum and minimum levels from before the remedial drainage work were carried out, and thirdly the same from after the re-working of the field drainage had occurred (Figure 5.43). The models were created using Arc GIS and the same method as that used for the individual monitoring visits.

From Figure 5.43, it can be seen that when taking the whole monitoring dataset into account, there are considerably higher water table levels than from either prior to, or following the re-wetting on the site taking place. This is because of the readings obtained from the winter of 2000/01 during periods of flooding and excessively high rainfall, have been included when generating the model. Also, the maximum values ever recorded in each of the piezometers, has been used to create this specific model and so cannot necessarily be expected to represent the actual situation. However, this can be seen as a 'best case scenario' of what may be possible to achieve in terms of water levels across the site under current circumstances without the requirement for very major engineering works designed to significantly alter the hydrological dynamics. These readings have been included, as they closely reflect the desired levels for the water table on the site.

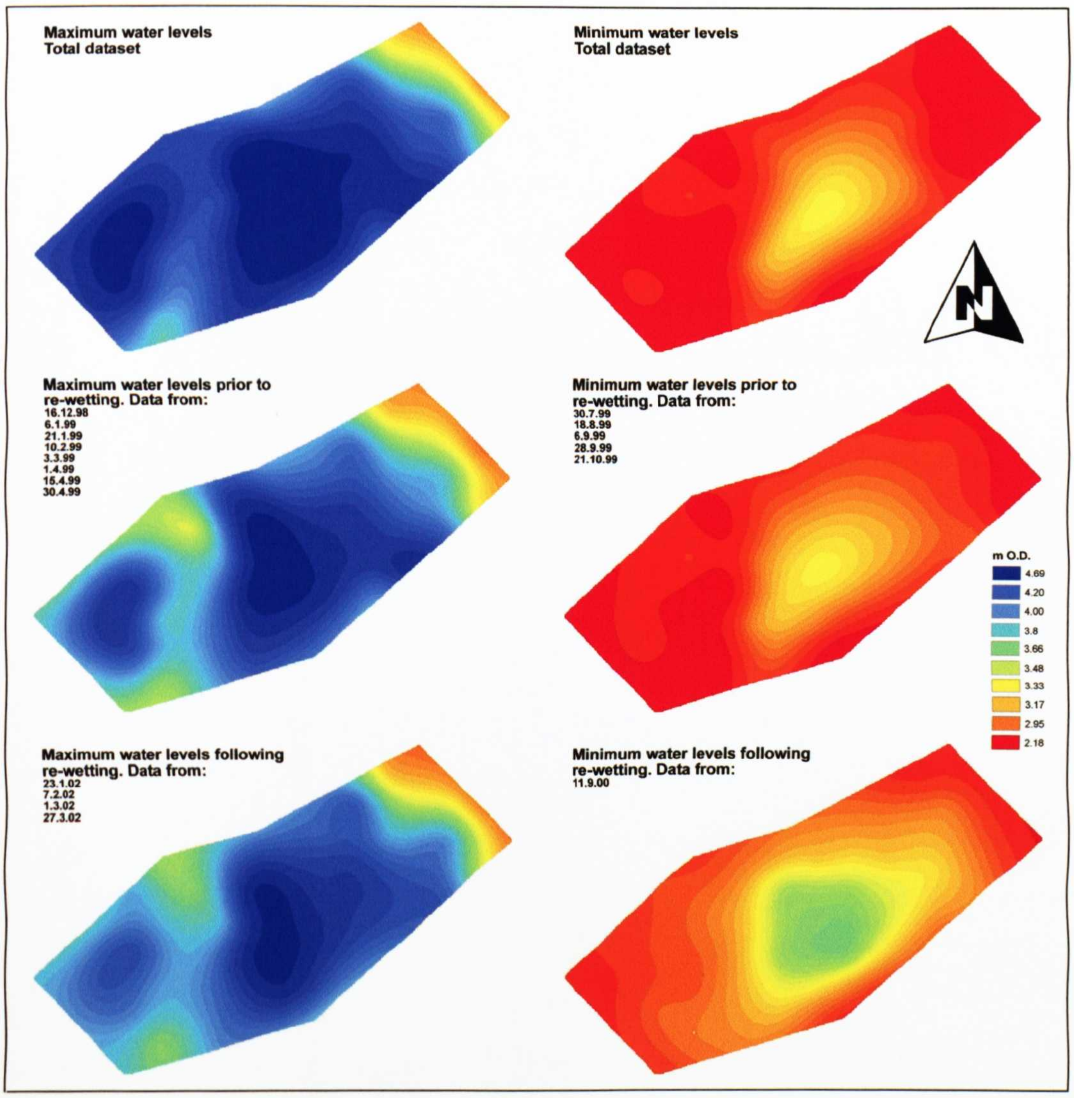


Figure 5.43 Minimum / maximum hydrological models derived from the whole dataset, from prior to re-wetting taking place, and following re-wetting. Dates from which data has been taken are shown adjacent to the relevant models.

Comparison of the maximum water level models from both prior to, and after the re-wetting shows that there was very little difference using the data obtained from these dates shown in Figure 5.43. Contrary to this, comparison of the minimum models shows that there were clearly higher readings following the re-wetting taking place. Unfortunately, this may not be truly representative, as the minimum levels have been obtained from data collected on one monitoring visit only, 11/09/00. This was due to the small number of monitoring visits undertaken during the summer months of 2000. Additional readings from the summer of 2001 were not obtained due to the impact of increased land management including cropping for hay, and disturbance caused by cattle, as discussed previously.

Figure 5.44, shows a 3-dimensional DEM model of Sutton Common generated in ArcScene, integrated with the locations of the archaeological wood that had been identified by reference to the archives of the three excavations previously undertaken by the Universities of Exeter and Hull. The Figure shows that archaeological wood has been identified in all the areas excavated to date and that there is considerable variation in the range of depths within which this wood exists.

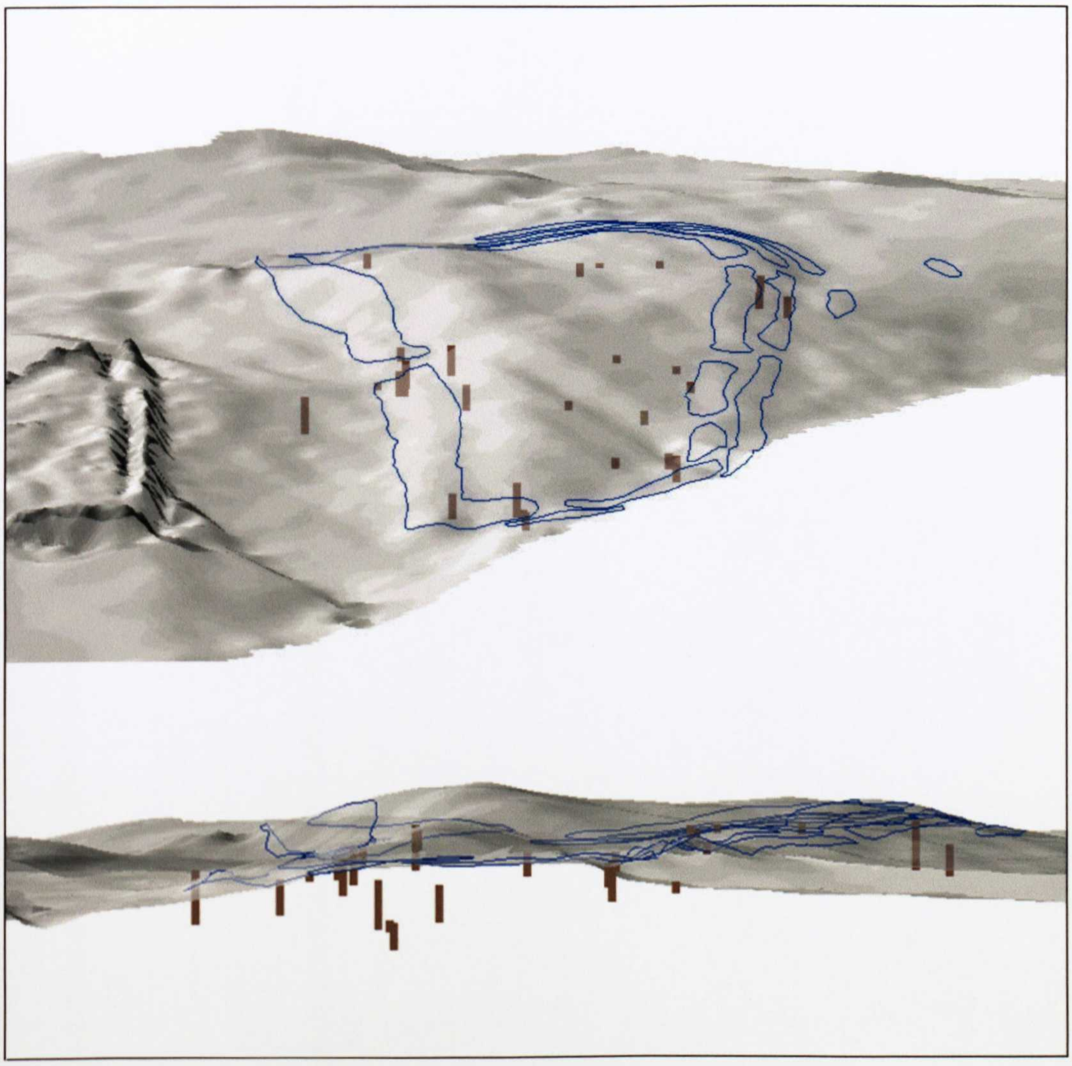


Figure 5.44 An integrated Sutton Common DEM, marked with the location of archaeological wood displayed in brown. The depth range at which wood preservation exists is represented by the vertical height of the columns. All heights are at 10X vertical exaggeration. The outline of Enclosure A is marked in blue for scale purposes.

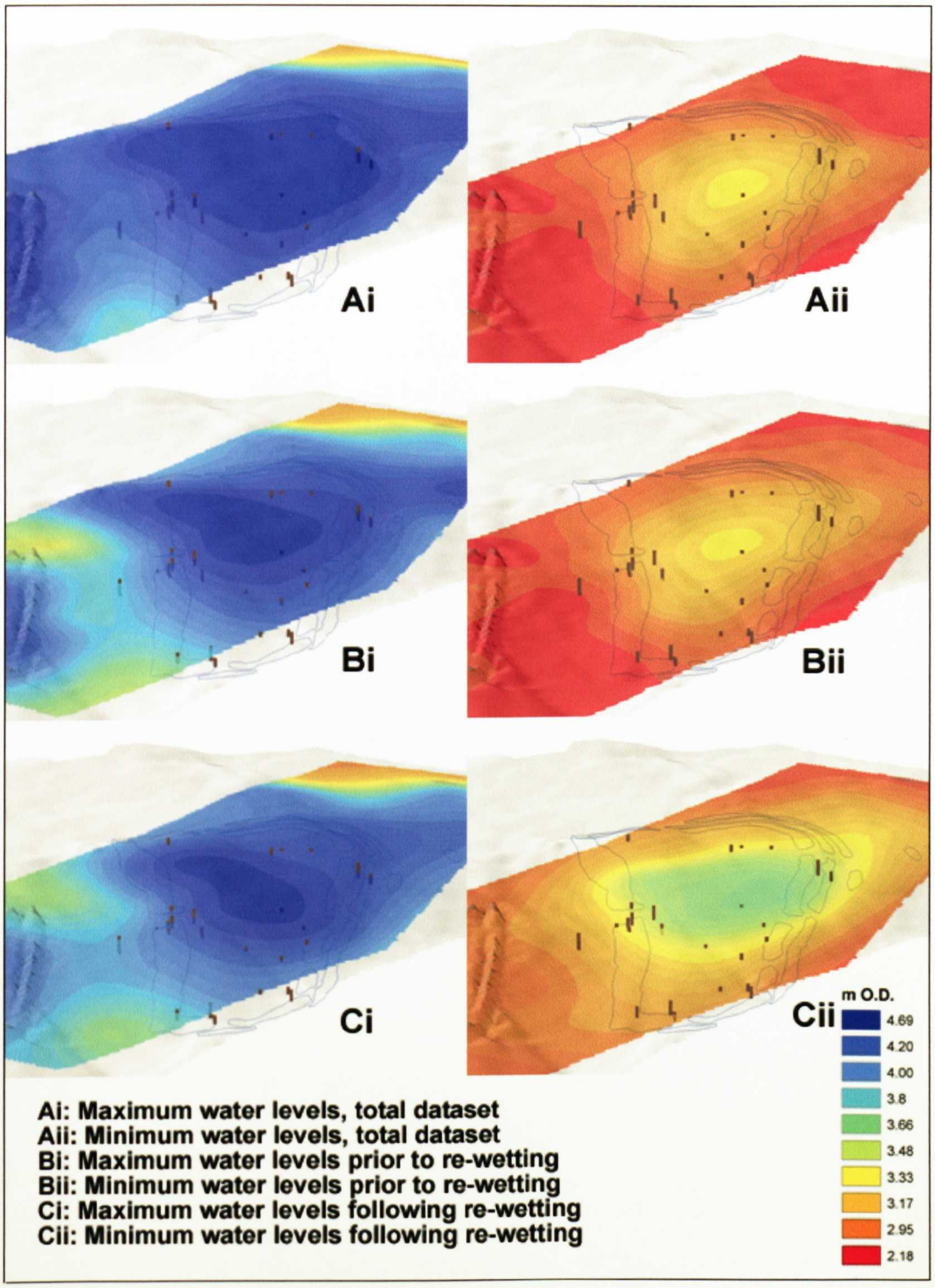


Figure 5.45 3D perspective of the integrated hydrological and archaeological models of Sutton Common. Sutton Common DEM and enclosure A outline are transparent, all models have 10X vertical exaggeration.

It has been possible to integrate this data with the hydrological models displayed in Figure 5.43 in order to investigate the interrelationship between the archaeological wood present on Sutton Common and the different states of the water table. Figure 5.45, shows these integrated models from a 3-dimensional perspective generated in ArcScene. Upon examination of these models, it can be seen that the vast majority of the archaeological wood represented lies between the minimum and maximum levels of the recorded water table, or Zone 2. Also, it is apparent that even during times of the highest water table, this is still not sufficient to fully saturate all the archaeological wood that has been identified. Therefore, there are elements that are subject to permanently unsaturated conditions, or Zone 1. However, the level of the minimum water level model, for the period following the re-wetting work shows that there has been an increase in recorded levels and that more archaeological wood fell within the desired Zone 3.

Comparison of this data is more effective in a graphical format. Figures 5.46, 5.47 and 5.48, are height range graphs, in metres O.D., showing the range of depth of the individual pieces of archaeological wood identified, compared directly to the height ranges recorded for the water table in that particular location. These graphs have been generated using SPSS 11 for Windows.

As these graphs present a large amount of information, a brief explanation of how to read them will be given. The X-axis of the graph shows the excavation context numbers, these being given to the individual pieces of archaeological wood used in this exercise. The Y-axis scale is in m O.D. The vertical brown bar represents the height range of the piece of archaeological wood, and the associated vertical blue bar the maximum and minimum height of the water table in that particular location. In essence, the height range of the water table represents Zone 2 within the burial environment and therefore, above the blue bar represents Zone 1 and below, Zone 3. The information regarding the water table height has been derived from the hydrological models presented in Figures 5.43 and 5.45.

Figure 5.46, shows the full range of water table heights for each location of archaeological wood, obtained from the whole hydrological monitoring dataset, including those readings obtained during periods of flooding. The majority of the wooden artefacts are located within a height range between the maximum and minimum water heights. However, not all are, indicating that there are elements of preserved wood identified on the site that are located within a burial environment that do not experience any saturation. Wood in such conditions, equated to Zone 1, would not be expected to survive for any length of time, therefore there must be a reason for the persistence of this material. Reference to the excavation records (see Appendix 6) shows that these pieces are either considerable posts or are heavily degraded. For example contexts 444 identified from the 1998 excavations, and 229 from the 1999 excavations, are massive posts associated with entrances to Enclosure A. Therefore, their large size has meant that a greater length of time is required for the complete removal of wood material from the burial environment and they persist for longer compared to smaller, more fragile pieces. Also, contexts 2602 and 6459 are described as being heavily degraded and therefore in the latter stages of complete removal from the archaeological record.

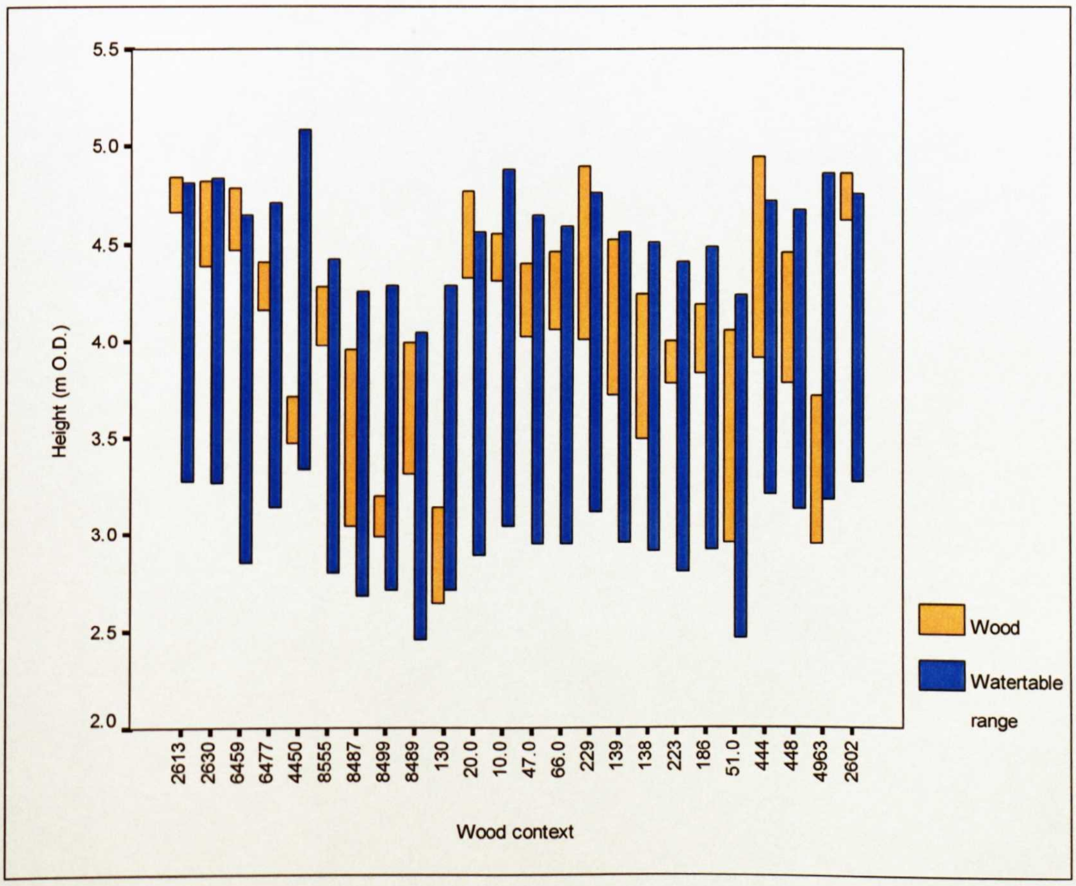


Figure 5.46 Height range graph for archaeological wood identified on Sutton Common and the range of the water table in that location, created from all water table observations including those obtained during flooding.

From the sample of excavated archaeological wood, there are only two pieces that remain below the level of the lowest recorded water table depths, and this is only partially and not for the whole piece: these being 130 and 4963.

Figure 5.47, shows the range of the water table associated with each piece of archaeological wood, obtained from data obtained from prior to the re-wetting activity taken place on Sutton Common. The dates for this are presented in Figure 5.43.

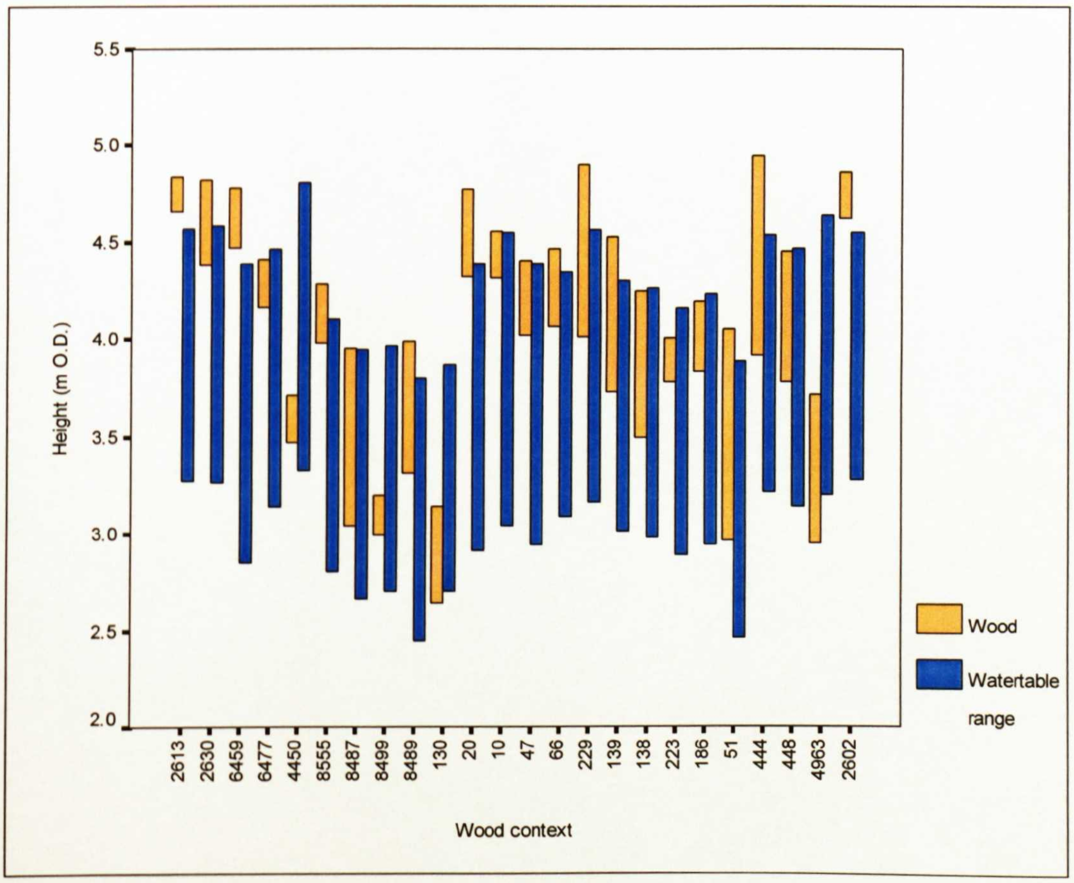


Figure 5.47 Height range graph for archaeological wood identified on Sutton Common and the range of the water table in that location, created from water table observations prior to re-wetting.

The minimum water levels are essentially identical to those presented in Figure 5.46 but the maximum levels reached are lower as they do not include any period of flooding on the site where the water table was artificially raised. Therefore in comparison, far more of the archaeological wood is shown to have been located within Zone 1, the zone of permanent aeration. Again, reference to the description of the wood shows that all these pieces have suffered extensive degradation and are therefore recalcitrant.

Figure 5.48, shows the same information but for after the re-wetting work has taken place. In comparison with the previous graph, it is obvious that there has been a restriction within the range of the water table across the whole site. Although the maximum levels remain very similar to those presented in Figure 5.47, the minimum ones are higher, five pieces of identified wood now being located within the zone of permanent saturation.

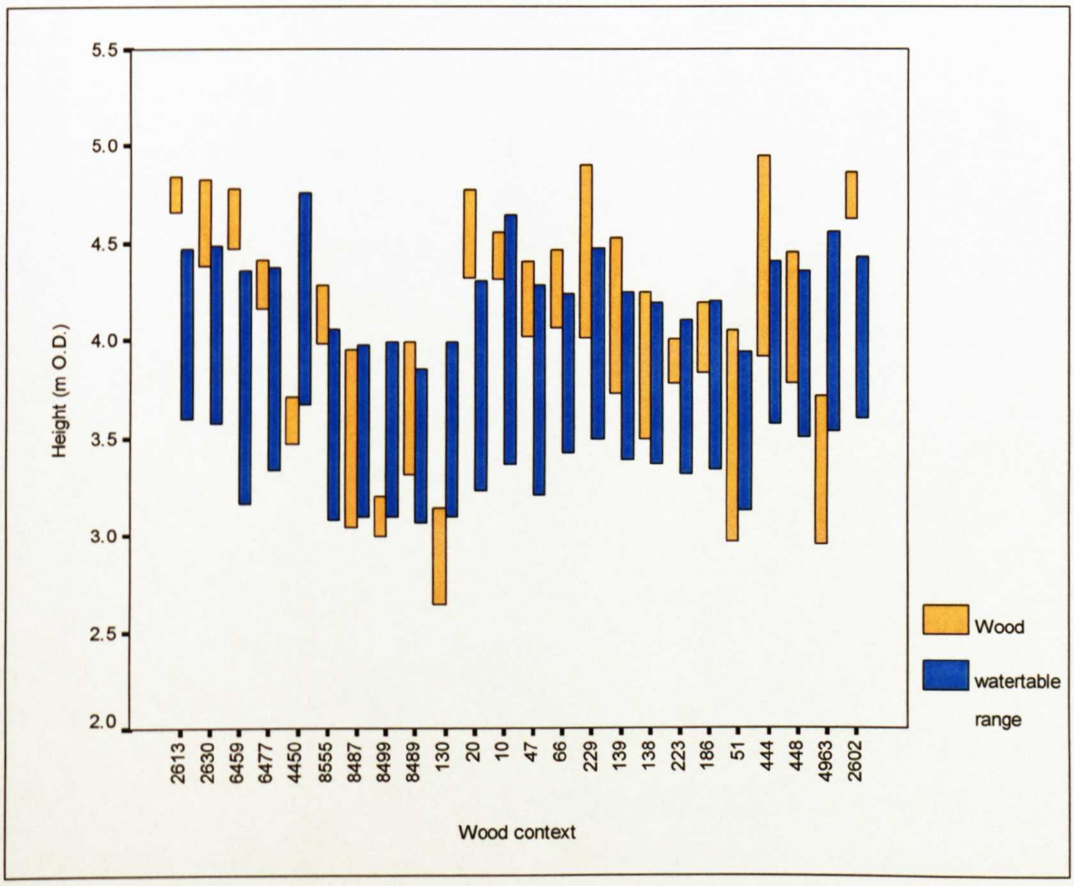


Figure 5.48 Height range graph for archaeological wood identified on Sutton Common and the range of the water table in that location, created from water table observations obtained following re-wetting.

This finding suggests there may have been a positive effect upon the level of the water table on the site from the re-wetting work that has been carried out. However, this must be seen within the context of the sample data. Predominantly due to the impact of cattle upon the monitoring equipment during the summer months, there was a lack of monitoring data during periods of low water table following the re-engineering of the drainage system on Sutton Common. Therefore, the data obtained for the minimum water table levels was derived from one monitoring visit only, the 11/09/00. Although not ideal, this monitoring date is seen as representative as leading up to this date there had actually been less precipitation than during the similar period prior to re-wetting.

To highlight this, comparison of precipitation figures for both years reveals that from 31/07/99 to 11/09/99 a total of 58.8 mm of precipitation was recorded at Kirk Bramwith. However, in the same period in 2000 the figure recorded was 41.6 mm. Reference to the precipitation around the dates (refer to Figures 5.2 and 5.3) reveals that not only during this period but prior to and following it, 1999 received greater precipitation. However, as the water budget calculations have highlighted, precipitation is offset by the loss of groundwater as a result of evapotranspiration. Therefore, the higher water table observed in the latter hydrological model may be due to changes within the management of the site vegetation impacting upon the degree of evapotranspiration. Whether this is accurate, or the response is a result of the drainage mitigation that has occurred on Sutton Common, there is tentative evidence that the burial environment of the archaeological remains on Sutton Common has improved through the effective management of the site.

5.6 Summary

This chapter has presented the results obtained from the programme of hydrological monitoring that has taken place on Sutton Common. Precipitation data pertaining to the site have been presented with the main characteristics summarised. The GIS hydrological models generated from the data collected during individual monitoring visits to the site, have been presented along with a description of the major features and changes that occurred. These include the form of the water table and how this is influenced by the site topography resulting in the formation of distinctive groundwater mounds, how this changes over time, especially on the seasonal scale, and how individual precipitation events have influenced the water table. The major impact of extensive flooding during the winter of 2000/01 has been highlighted along with changes in the form of the water table following re-engineering of the site drainage. These specifically relate to a possible flattening of the water table along the eastern edge of the monitored area and in the isolated creation of raised water levels in response to the capturing of drains in the western area of the monitoring grid.

Following the presentation of the GIS models, the data obtained from isolated monitoring locations has been presented including the water levels within individual piezometers, piezometer clusters located on the site along with those pieces of equipment installed to assess the hydrological impact of the site track. The results from individual piezometers provide tentative evidence of the positive impact of re-wetting activities on the water table but also highlight that these are possibly a result of data resolution. Evidence from the three piezometer clusters located on the site indicates that unconfined conditions exists within Enclosure A but that there is possible complexity within the watertable in the northern part of the Hampole Beck palaeochannel resulting in an element of hydrostratigraphy. Results from the study of the impact of the site track shows that this feature has no significant impact upon the water table.

The GIS models generated from the hydrological monitoring data, have been used in the construction of a water-balance for the area of monitoring on Sutton Common. Aspects of this are then assessed against data from BGS boreholes leading to an assessment of these upon the near-surface water table. The results of this exercise show that the seasonality clearly exhibited by the water table is a function of the changing levels of evapotranspiration occurring on Sutton Common and that comparison with deep aquifer water levels in the area show little correlation. This suggests that the Sutton Common water table is predominantly precipitation fed.

The results of measurements of saturated hydraulic conductivity on Sutton Common have been presented along with the patterns that they show and how these may influence future work on Sutton Common and hence the future survival of organic archaeological remains. The results indicate the possibility that although the area of the palaeochannel, due to its topographically low character, may be acting in some way as a hydrological sink that significantly lower hydraulic conductivity may in fact be influencing groundwater movement. This may have implications for future hydrological mitigation.

The final part of the chapter is taken up with the construction of the archaeological wood model. This incorporates hydrological data with location information of archaeological wood identified during previous excavations on the site providing the framework for the assessment of the potential for continued *in situ* preservation of such material. The results of this again tentatively point to a positive impact upon the water table from changing management practices on Sutton Common and also from the re-wetting work that has been carried out there.

The next chapter will describe the results from the programme of monitoring of redox potentials within soil profiles on Sutton Common.

Chapter 6 Redox monitoring results

6.1 Introduction

When studying or assessing the potential for the *in situ* preservation of organic archaeological remains, the use of soil redox potentials is well recognised as being capable of providing a semi-quantifiable measure of this. Through a number of previous studies it has been identified that sites exhibiting well-preserved organic archaeological remains show consistently reduced conditions (Caple, 1997, Caple & Dungworth, 1997, 1998) and therefore the identification of such conditions through the monitoring provides a measure of the potential for preservation. The use of soil redox potentials has been successfully applied to the monitoring of burial environments of sensitive, organic archaeological remains (Brunning *et al.*, 2000, Hogan *et al.*, 2002) and has therefore been seen a crucial element of the monitoring programme that has taken place on Sutton Common. Although the equipment used is essentially identical to that used in these previous studies, the application differs quite markedly in terms of the characteristics of the study site, and the scale and duration of the monitoring programme. It is therefore perceived that the Sutton Common monitoring programme can be considered progressive in its approach.

Of added significance to the results obtained from Sutton Common is the monitoring of flood conditions on the site and how these impacted upon the burial environment. Therefore, the results will be related to this event.

This chapter presents the results obtained during a long-term monitoring programme of more then two years of soil redox potentials at nine monitoring locations on Sutton Common. Full descriptions of the monitoring points, both location and environmental characteristics, have been provided in Chapter 4.

6.2 Redox monitoring results

The data gathered for soil redox potentials across Sutton Common will be presented by two means - linear redox graphs where values are adjusted to pH 7 and plotted over time, and in Eh/pH diagrams. The former are location specific and show clearly temporal patterns within the data; such as seasonal variation, the influences of specific events and long-term changes in the burial environment. Eh/pH diagrams display results for all monitoring points on a single diagram for a specific monitoring date and are excellent for characterisation of the burial environment as they are capable of presenting specific boundary conditions relating to significant conditions within the burial environment. This helps to place results within a definitive context of conditions that are or are not capable of good quality preservation.

The majority of published material presenting the results of redox monitoring programmes make use of 'linear' graphs (Brunning *et al.*, 2000, Caple & Dungworth, 1998, Hogan *et al.*, 2002) or limited use of Eh/pH diagrams (Caple, 1996, Caple & Dungworth, 1997).

Figure 6.1 shows the location of the soil redox monitoring points on Sutton Common. Nine monitoring locations were chosen for the acquisition of soil redox data, each associated with piezometer equipment providing concurrent data on the height of the water table.

Redox probes were put in place during November 1999, with data being collected from January 2000. Monitoring continued until March 2002, although little data were collected during 2001 for some monitoring locations due to the continued effects of flooding experienced on the site from November 2000 through to mid 2001. This situation was further exacerbated by more intensive management of Sutton Common, including mowing and the introduction of cattle grazing, requiring the re-identification of the locations of monitoring points. Redox monitoring Sites 4 and 9 were also particularly prone to surface flooding during the wetter months of the year and therefore were subject to a lower number of monitoring visits.

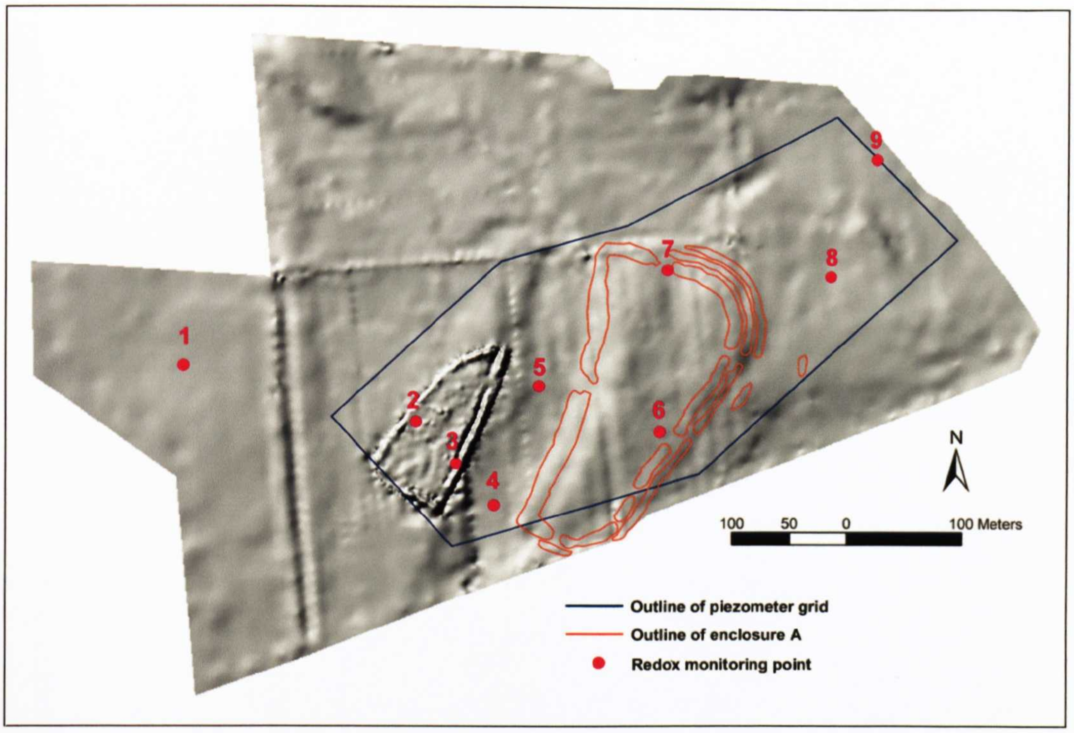


Figure 6.1 The locations of the nine soil redox monitoring points on Sutton Common.

Monitoring point 1 was located away from the main study area and as such was not affected by the re-engineering of the field drainage. This therefore has provided a control point with which to compare the results obtained from the rest of the monitoring locations.

6.2.1 Adjusted redox values

This section will present redox data in the form of linear graphs over time with values having been adjusted to pH 7. This approach has been successfully implemented in monitoring programmes of in excess of 12-months duration on the Sweet Track in the Somerset Levels (Brunning *et al.*, 2000) and in the monitoring of reburied organic archaeological remains within the Solent estuary in Southern England (Hogan *et al.*, 2003).

This type of presentation of data has primarily been used to identify the effects upon the burial environment of the hydrological regime at Sutton Common, i.e. to identify variation throughout the yearly cycle.

All graphs present data with the same range on the axes to aid comparison of the results from each of the monitoring locations.

Brunning *et al.* (2000) and Hogan *et al.* (2002), use standard categories to define the redox status of the burial environment, presented in Table 6.1. These categories were originally derived for both well-drained and waterlogged soils by Patrick & Mahapatra (1968), during studies into rice production. In the interests of comparison, this same scheme will be used to describe the results obtained from the Sutton Common monitoring programme.

Table 6.1 Categories of redox potential (derived from Patrick & Mahapatra, 1968)

Oxidation/reduction status	Range of redox potential
Oxidised	> +400 mV
Moderately reduced	+100 to +400 mV
Reduced	-100 to +100 mV
Highly reduced	-300 to -100 mV

Redox monitoring Site 1

Figure 6.2 shows a linear redox plot for Site 1 at four depths from 0.1 m to 1.4 m. In addition, the water-level within the associated piezometer is presented on a secondary axis on the right-hand side of the graph.

Characteristically, with increasing depth there is a trend towards reducing conditions; by this it is meant that those probes located at a greater depth consistently provide lower readings on the redox scale. Low readings are negative with those of greater negative magnitude representing 'more reduced' conditions i.e. -400 mV. Conversely, high readings are positive and of greater magnitude, i.e. +400 mV. This pattern is replicated consistently within the results of the monitoring programmes previously mentioned, undertaken on the Sweet Track and within the Solent estuary. The prevalence of reduced conditions at depth will be shown to be repeated across the majority of the monitoring locations on Sutton Common. Observations not following this trend are exceptions to the rule and can usually be comprehensively explained by studying environmental controls, such as water table fluctuation, and soil characteristics. The soil conditions at Site 1 are of a surface organic rich ploughsoil overlying a predominantly mineral subsoil (refer to Chapter 4).

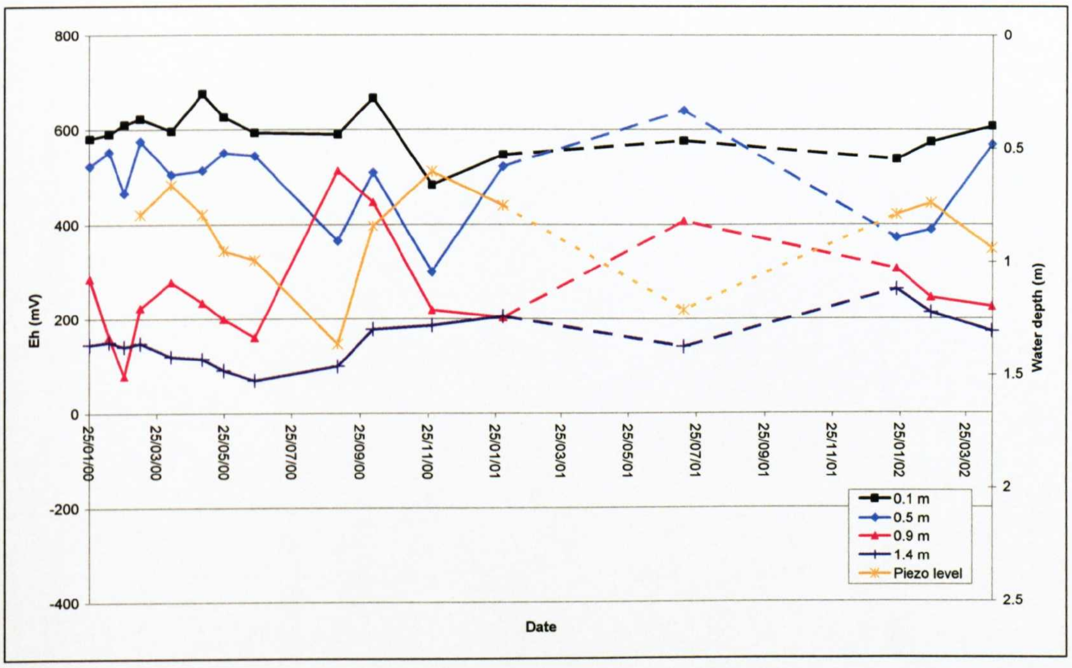


Figure 6.2 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 1. Redox values are adjusted to pH 7.

Throughout the early readings to May 2000, there is an apparent distinction between near-surface conditions and those at depth, with values of around +500 to +600 mV being recorded between the surface and 0.5 m, indicating the presence of oxidised conditions. Lower readings, recorded at 0.9 m depth and below, are in the range of +100 to +300 mV, indicating moderately reduced conditions. The differentiation between the upper 0.5 m of the soil profile and greater depths corresponds to the depth of the water table at this time. Piezometer readings indicate a depth of less than 1 m, meaning that the readings within the upper 0.5 m were obtained under non-saturated, well-aerated conditions. This situation suggests that there was a degree of stability within the burial environment during this period leading to stratification of redox conditions, with highly oxidised conditions forming at the surface and reducing conditions at depth. Stable conditions occur when there is little or no disturbance of the burial environment, either physical, through for example the action of soil macro-fauna, or chemically through the movement of groundwater. In such conditions, the upper soil profile would exhibit oxidised conditions where the soil was aerated and there was aerobic microbial activity, but at depth anaerobic conditions would be prevalent thus reducing conditions would be present. If such stability persisted, the burial environment at depth would become progressively reduced in character as a result of sequential reduction.

Sequential reduction relates to the sequence of chemical reductions that take place in a soil at some point following submergence. The greater the length of submergence the more prevalent reducing conditions become (Ponnamperuma, 1972). This sequence is heavily influenced by soil factors such as nitrate levels, organic matter content, manganese and iron concentrations.

From June to August 2000 there was an increase in the redox potentials at 0.9 m depth from moderately reduced to oxidised conditions, reflecting the change from a state of saturation to non-saturation. The requirements for reduction are the absence of oxygen, the presence of decomposable organic matter and anaerobic bacterial activity (Ponnamperuma, 1972) therefore, with the removal of saturation due to a falling water table, oxygen once more is able to penetrate the soil to a depth of in excess of 0.9 m. With this comes the re-emergence of aerobic microbial conditions and the rapid oxidation of previously reduced compounds.

The most significant trend identified on the graph occurs from October 2000 through to the end of November 2000. During this time there was a significant increase in the amount of precipitation, (Figure 5.3), associated with widespread flooding, including extensive flooding on Sutton Common. Readings obtained in the latter part of October 2000 show an increase in the redox potentials obtained from all depths other than at 0.9 m. This suggests that there is a degree of disturbance occurring within the burial environment through the rapid introduction of water to the site, this effect being seen at 1.4 m depth also where conditions of permanent saturation existed. The opposite pattern observed at 0.9 m depth indicates the start of sequential reduction following a rise in the water table and the reinstating of saturated conditions. Readings obtained in November 2000 indicate that increasing water table height and extensive flooding on the site has led to a reduction in redox values throughout the soil profile apart from at a depth of 1.4 m, where a slight increase was continued to be observed.

A lack of observations throughout 2001 prevents a clear pattern being identified in the soil redox potentials. However, an individual reading obtained during July 2001 suggests that the water table has dropped below the level of redox probes installed at a depth of 0.9 m, creating an oxidised environment. Readings from early 2002 indicate a return to stratified conditions with oxidised conditions prevailing within the unsaturated soil horizons and moderately reduced conditions at saturated levels.

Site 1, the control site, is characterised by predominantly oxidised conditions to a depth of 0.5 m. At 0.9 m, soil conditions are highly influenced by a fluctuating water table, with oxidised conditions being present during low-water summer conditions and moderately reduced during times of saturation.

The impact of site flooding can be identified within the results obtained from this site, but it does not appear to have had a significant impact upon the redox status within the observations.

Redox monitoring Site 2

Figure 6.3 shows a linear plot of redox values for Site 2 for four depths, from 0.1 m to 1.4 m and associated piezometer levels. Initially readings from all depths exhibit similar high values of around +500 mV, indicating the presence of oxidised conditions throughout the monitored soil profile. From March 2000, values for 0.9 m and 1.4 m depth decrease sharply to less than +100 mV, a reduced environment, before rising again to former levels by August 2000. This pattern relates to a period where a higher water table created saturated conditions at these depths. The decrease observed in the values relates to the process of sequential reduction described previously. The rapid rise in redox potentials observed occurs as the water table once again drops below the monitored depths leading to the re-emergence of oxidised conditions, this occurring during the low-water conditions associated with the summer months. There is a significant drop in values at all depths between the 9 October and 28 November 2000 to readings of around +100 mV, indicating the presence of moderately reduced conditions throughout the monitored soil profile similar to that observed at Site 1 (Figure 6.2). This situation continued through to the end of January 2001. This corresponds to a rapid rise of almost 2 m in the water table following flooding of Sutton Common.

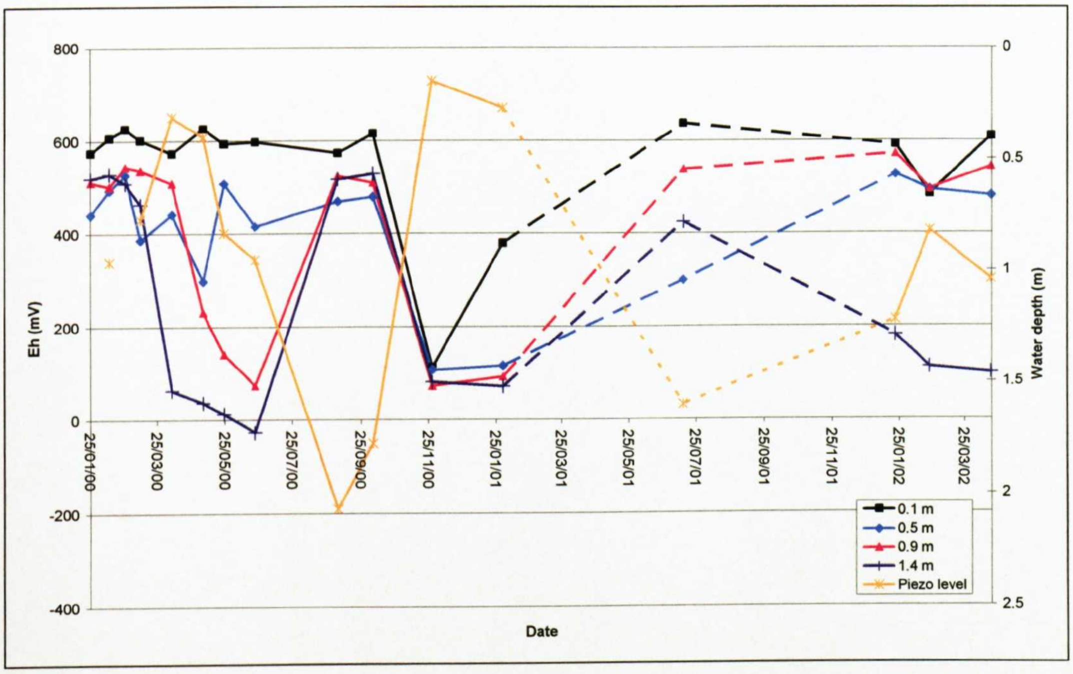


Figure 6.3 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 2. Redox values are adjusted to pH 7.

It is highly significant that redox potentials throughout the monitored soil profile indicate identical redox conditions immediately following the flooding event. This shows that there had been a complete disturbance of the burial environment and possibly the complete displacement of groundwater at this location; it being replaced by floodwater derived from off-site sources.

Again, there is little available data for 2001. However, a single monitoring visit in July 2001 indicates a low water table and a corresponding domination of oxidised conditions throughout the soil profile.

Final observations during early 2002 indicate, as observed at Site 1, a stratification of redox conditions with lower, moderately reduced conditions, being apparent at 1.4 m depth, this being below the observed level of the water table.

Site 2 is characterised by highly fluctuating redox conditions throughout the monitored profile, dictated by the level of the water table and therefore it was the subject of seasonal oxidised conditions penetrating to at least 1.4 m. The impact of flooding in this location was very great, with the rapid and extreme reaction in redox status of the burial environment being apparent.

Redox monitoring Site 3

Figure 6.4 shows redox values obtained from Site 3 from four depths, plus the water level readings for the associated piezometer.

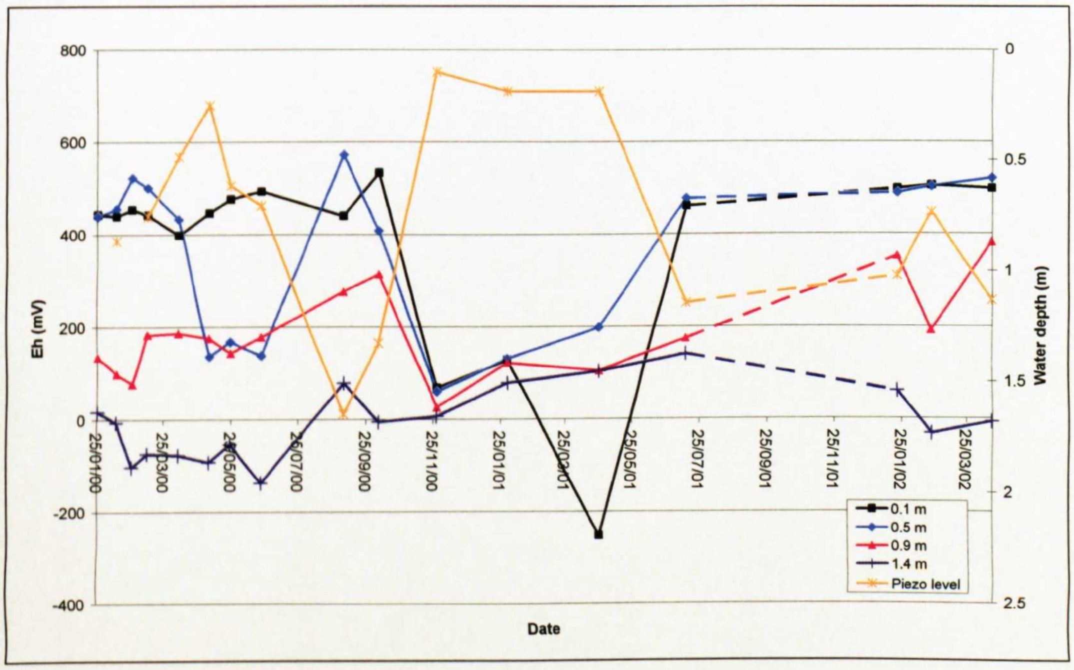


Figure 6.4 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 3. Redox values are adjusted to pH 7.

Initially there is a pattern of moderately reduced to reduced conditions at depth and oxidised surface conditions, this pattern being maintained through to June 2000. A decreasing trend is observed at this time at a depth of 0.5 m, possibly relating to sequential reduction taking place following a rise in the water table above this depth. Through to August 2000 there is a trend of increasing redox potentials relating to a drop in the water table below 1.5 m.

Readings obtained at the end of November 2000 once again highlight the impact of site flooding. There was a significant rise in the level of the water table in this location and, similarly to Site 2, redox conditions at all monitored depths are very similar providing values of between 0 and +100 mV. This indicates a positive trend, whereas at other depths there is an opposing, negative trend.

Following the flooding event, conditions slowly return to their initial pattern, although the lowest redox reading obtained at this site was recorded by the 0.1 m depth probes during March 2001. Although this reading may seem erroneous, it may well indicate a very rapid onset of anaerobic conditions close to the ground surface. Site 3 is located within the archaeological ditch of Enclosure B, with the surface deposits in this feature consisting of highly organic peats. From the onset of flooding in November 2000, through to May 2001, the water table at this location was close to the ground surface. Therefore, a readily available organic substrate for microbial activity and removal of atmospheric oxygen within the soil matrix as a result of saturation, may explain the highly reduced readings observed (Ponnamperuma, 1972).

Site 3 is characterised by oxidised surface conditions and reduced conditions at depth. Seasonal fluctuation of the water table is to, or slightly below, the deepest observed level of 1.4 m. Similarly to Site 2, the episode of flooding has had an impact throughout the monitored soil profile and has clearly had an ongoing affect over a period of more than six months.

Redox monitoring Site 4

Figure 6.5 shows soil redox values and piezometer readings from Site 4. This was one of the two low lying monitoring sites studied and has suffered regular flooding, resulting in a reduced number of monitoring results.

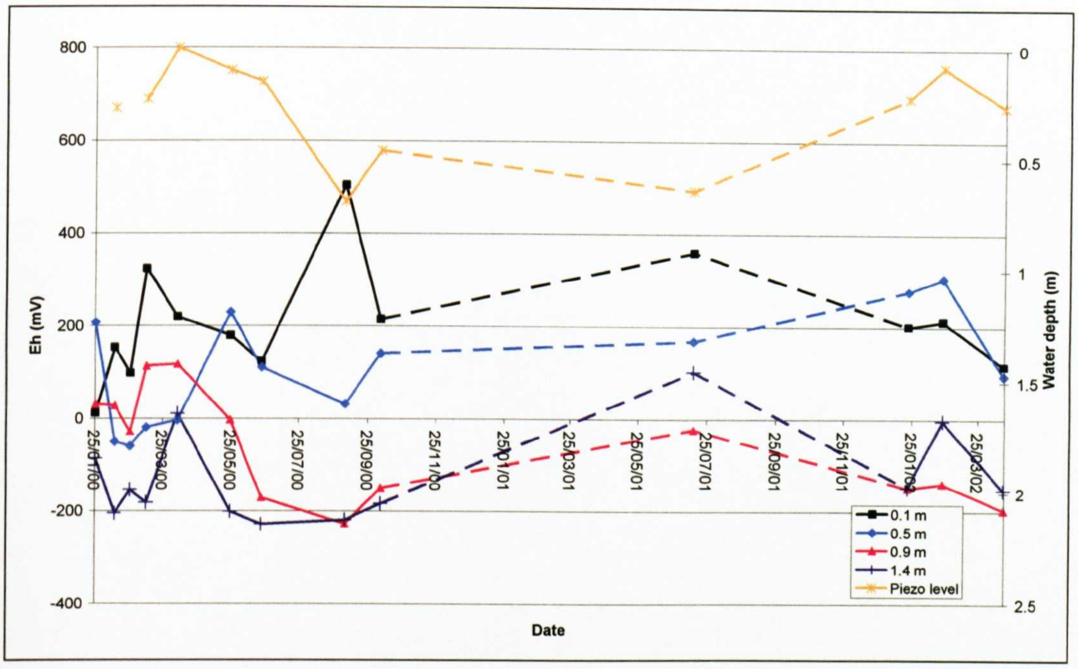


Figure 6.5 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 4. Redox values are adjusted to pH 7.

Initially, values from all depths are clustered between +200 and -200 mV, indicating moderately reduced to reduced conditions. From May 2000 through to the beginning of September values follow a decreasing trend, apart from at 0.1 m where they increase markedly. This pattern is in contrast to that described for the previous three sites which showed a significant increase during the same time period, corresponding to low levels of precipitation during the summer months of 2000. This pattern can be explained by understanding the monitoring location further. As already described, Site 4 was one of two low-lying monitoring locations on Sutton Common, located within the southern part of the Hampole Beck palaeochannel. As such, this location may be subjected to groundwater flow in response to precipitation activity. Variability within the observed redox values through the early part of 2000 relate well to higher precipitation and thus a possible increase in the movement of groundwater, leading to the disturbance of the burial environment manifested by fluctuating redox conditions. Hogan *et al.* (2002) describe similar fluctuation in deposits within the Solent estuary. A falling water table from March 2000 indicates less precipitation leading to less groundwater flux and the creation of a more stabilised environment within which sequential reduction can occur unhindered. A change to oxidised conditions at 0.1

m observed in August 2000, occurred as the level of the water table dropped below this depth, resulting in the removal of saturated soil conditions.

No values were obtained during the period through to May 2001 due to surface water being present at the monitoring site. Final values are within the same range as the initial ones recorded two years previously, as is the level of the associated piezometer.

Due to its topographically low location, Site 4 was inaccessible for monitoring throughout the period that standing water, resulting from the flooding, was present. Therefore, there is unfortunately no indication of the impact of this event upon the burial environment at this location. However, the site is characterised by generally reduced conditions within a predominantly saturated burial environment.

Redox monitoring Site 5

Figure 6.6 shows redox values from Site 5, along with associated piezometer readings.

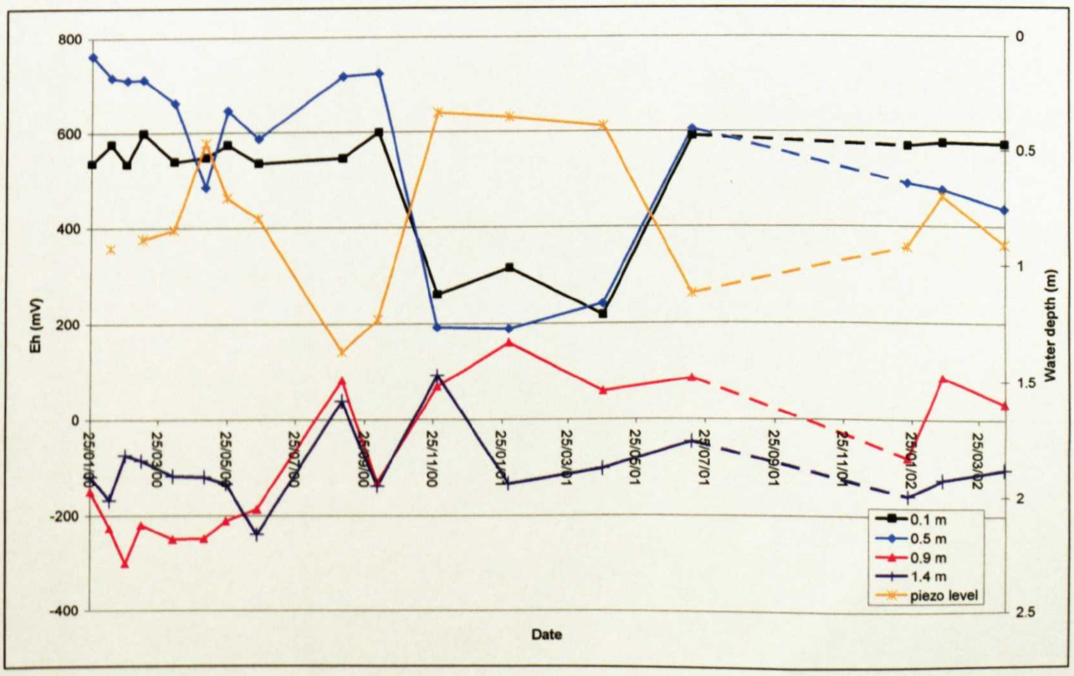


Figure 6.6 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 5. Redox values are adjusted to pH 7.

Readings obtained from the start of the monitoring programme through to June 2000 show a distinctive pattern of oxidised conditions existing through to a depth of 0.5 m, exhibiting values of +500 to +700 mV, and reduced to highly reduced conditions apparent at greater depths, with readings of -100 to almost -300 mV being observed. The depth of the water table during this time is less than 1 m. A falling water table from the end of May 2000 through to August 2000 (associated with low summer precipitation and an increase in the loss of groundwater through evapotranspiration), had an impact upon the redox readings from 0.9 and 1.4 m depths, these showing a positive change although conditions within the burial environment remained reduced.

As has been observed previously, between October and November 2000, a distinct pattern emerges within the data, with values from all depths being highly similar. This corresponds to the flood event which was observed at previously described locations by an associated rapid rise in the level of the water table. However, in contrast to other sites, redox values at depth increase markedly in response to the event, whereas previously values have generally fallen, suggesting that the flooding has disturbed the burial environment. This is further supported by the fact that these elevated values persist at a depth of 0.9 m whilst the raised water table persists in this location through to approximately June 2001. Following on from this, readings require a number of months to return to their former values and again, final readings exhibit very similar patterns to initial ones, with stratification of redox conditions occurring determined by the depth of the water table.

Site 5 is characterised by a strong stratification within the observed redox conditions, with oxidised conditions within the surface soil profile and highly reduced conditions at depth. The extreme nature of this difference is a reflection of the high organic matter content present throughout the soil profile, due to its location within the Hampole Beck palaeochannel. The high organic matter content therefore aiding rapid sequential reduction under saturated conditions. Observations suggest that even at the greatest monitored depth of 1.4 m, the seasonal fall in the water table has an impact upon redox conditions, although these still remain reduced.

The effects of flooding at the end of 2000 are apparent throughout the entire monitored profile causing a positive response towards oxidised conditions even at a depth of 1.4 m. What's more, these effects persist within the burial environment for several months following the event itself. By the end of the period of monitoring, redox and water table conditions have reverted to their initial values.

Redox monitoring Site 6

Figure 6.7 shows redox data and piezometer levels obtained from Site 6.

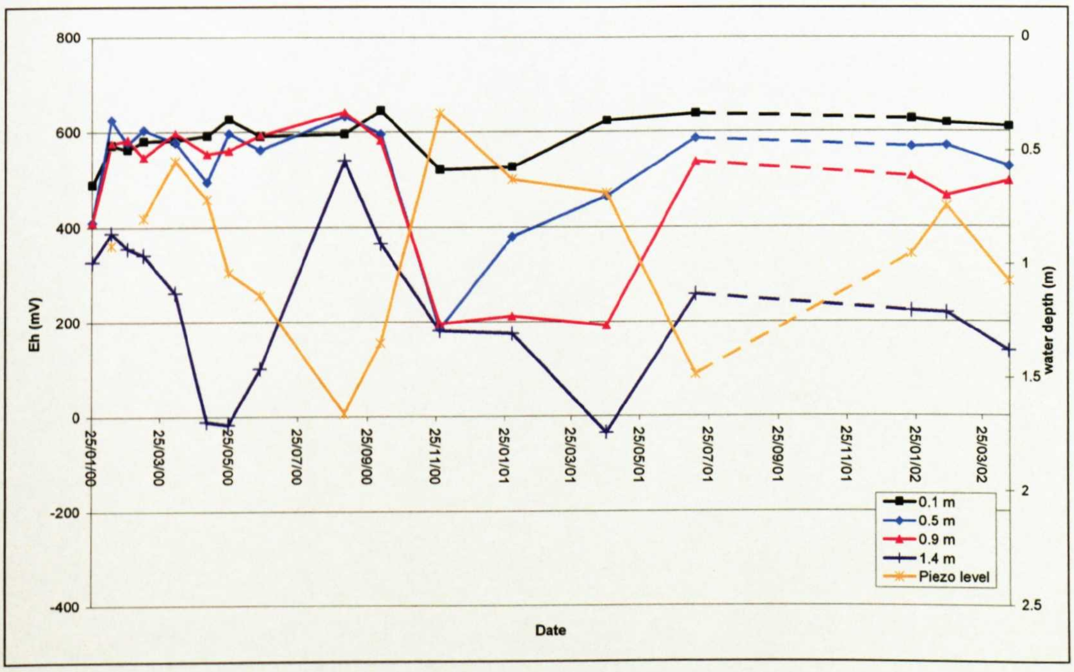


Figure 6.7 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 6. Redox values are adjusted to pH 7.

This location is topographically high relative to the other monitoring locations, being situated within the extent of Enclosure A and upon sandy silt. This situation is reflected in the fact that initial conditions at all depths are clearly oxidising, producing readings of approximately +400 mV. Readings from the upper three depths exhibited very similar values through to the end of October 2000. However, at a depth of 1.4 m, values drop markedly through until the end of May before rising rapidly to match those at the other three monitored depths. This drop in soil redox values appears to occur slowly, even though the soil is clearly saturated with the water table at the time being almost 1 m above the monitored depth. This slow change is most likely due to the low organic matter content within the soil profile immediately below the ploughsoil (refer to section 4.2). A high content of organic matter within a soil yields a rapid decline in redox potential (Patrick & Mahaoatra, 1968, Ponnamperuma, 1972) conversely, a low organic content will mean a slower decline. Therefore, the reaction to saturation at a depth of 1.4 m, is a slower rate of reduction. This is further supported by a lack of any significant reaction in readings at a depth of 0.9 m during the same monitoring period.

As at the previous sites, there is a distinctive drop in values at all depths during the period of flooding, although in this location the influence is not so great at 0.1 m depth. In addition to this, readings appear to return to their former levels more rapidly than the rate observed at previously discussed sites, such as Site 5. The maintenance of a high water table at approximately 0.5 m depth from the ground surface throughout the period from the end of November 2000 to April 2001, enabled reduced conditions to be established at 1.4 m depth and moderately reduced conditions at 0.5 m. The fact that this situation was not apparent in observations obtained at the same time the previous year suggests that this situation has occurred as a direct result of the falsely high water table resulting from the flooding of Sutton Common. Final readings appear to be very stable and once again exhibit a very similar patter to those observed at the start of the monitoring period.

Site 6 is characterised by generally oxidising conditions throughout the monitored soil profile and during a large range of depth of the water table. There is little evidence of reduced conditions, with only readings from 1.4 m depth exhibiting any trends towards a reduced environment. Changes in redox conditions that were observed, occurred relatively slowly due to the low organic matter content throughout the soil profile.

The effects of flooding at this monitoring location can be clearly seen within the monitoring data presented. Moderately reduced conditions were induced as a result of the event apart from at the ground surface, although these effects were limited only to the time during which a high water table was maintained.

Redox monitoring Site 7

Figure 6.8 displays redox results and associated piezometer levels for Site 7.

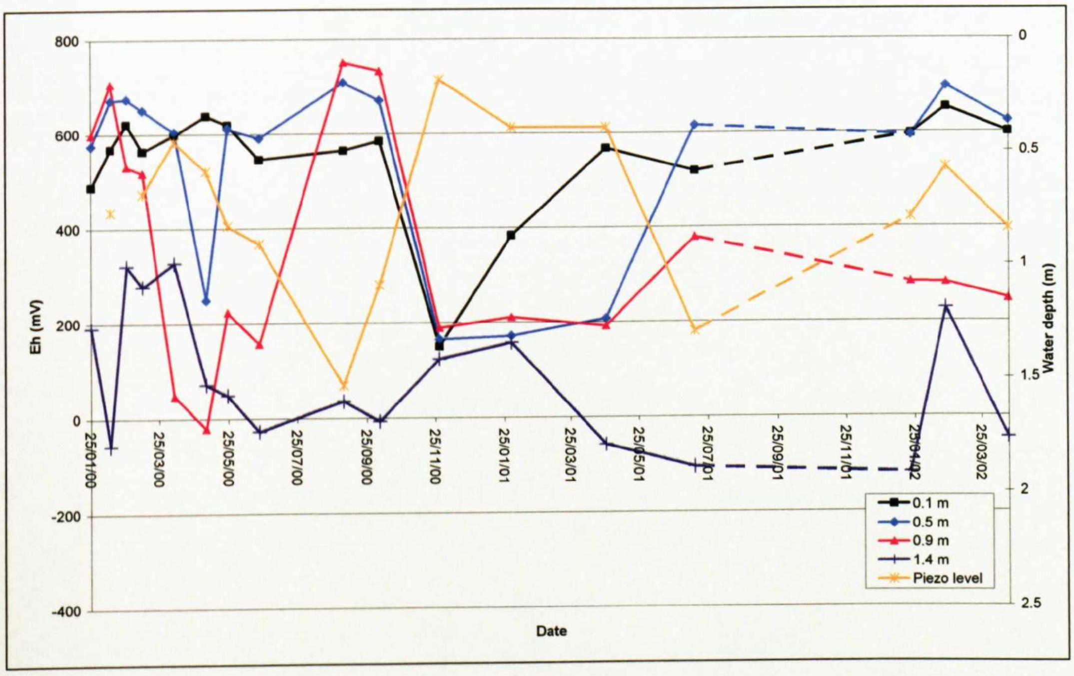


Figure 6.8 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 7. Redox values are adjusted to pH 7.

At this site soil redox values fluctuate greatly from the onset of monitoring through to the end of November 2000 when flooding occurs. Initially, oxidised conditions are apparent from 0.9 m and above. At 1.4 m depth, initial values indicated a reduced environment, rapidly rising to become moderately reduced, before again dropping from May 2000. From February through to May 2000, redox readings at 0.9 m depth drop indicating a change from highly oxidised to reduced, this reflecting a rise in the water table above this depth during this period. From the end of May through to September 2000 this trend is reversed in response to a lowering of the water table during the low-water summer months. Conditions within the top 0.5 m remain oxidised although an apparently erroneous reading occurs at 0.5 m depth in May 2000 onwards. This significant drop in redox potential occurs at a single monitoring visit only and may be a reflection of the variable nature of the redox conditions in this particular location.

Readings at the end of November 2000 once again show the impact of flooding, with redox potentials throughout the monitored soil profile indicating moderately reduced conditions. At 1.4 m depth, there is clear indication that this had a positive impact in terms of redox values. During the period of maintained high water table, redox potentials are suppressed throughout the upper soil profile, although surface readings start to recover towards their original values relatively quickly after the event.

Observations made during the early part of 2002 indicate that redox conditions had reverted to reflect those observed at the onset of monitoring, although conditions at 0.9 m were moderately reduced as opposed to oxidised.

Site 7 is characterised by highly variable redox conditions, especially so at a depth of 0.9 m. This depth corresponds to the depth around which the water table fluctuates and is therefore the subject of the greatest degree of change in terms of saturation. The impact of flooding is clear and unambiguous at this location, with redox conditions becoming uniform throughout the entirety of the monitored profile. Although during the period following the flood event, when a high water table was retained, redox conditions were suppressed, this was only a temporary impact and following removal of this increased saturation, redox values returned to their previous levels.

Redox monitoring Site 8

Figure 6.9 shows redox readings and associated piezometer levels obtained from Site 8.

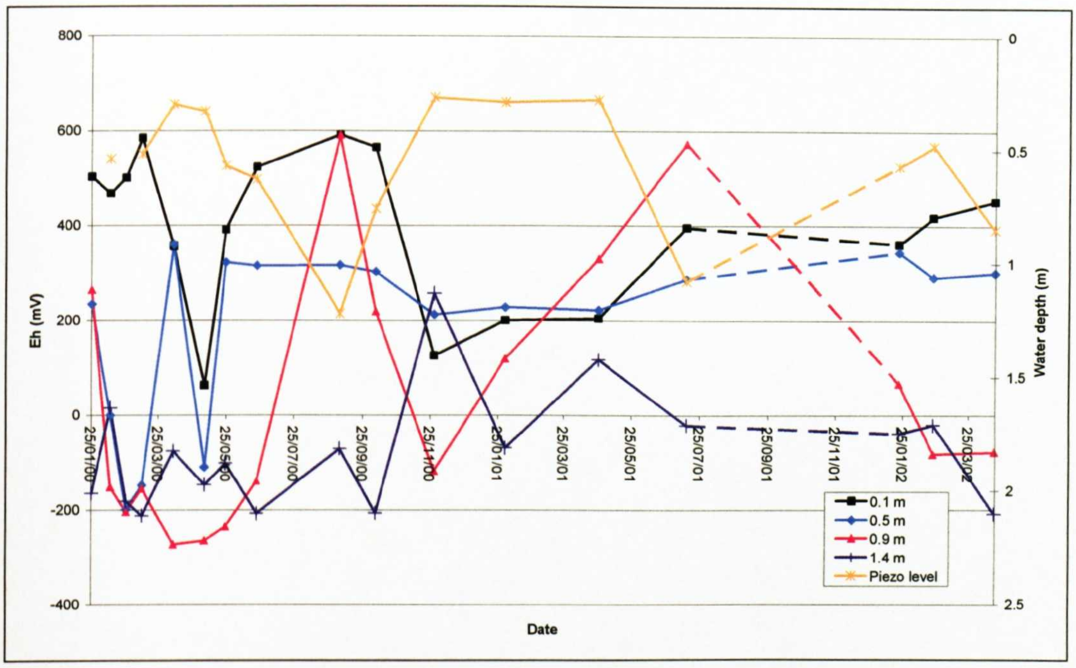


Figure 6.9 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 8. Redox values are adjusted to pH 7.

On first inspection, the results obtained from this location appear to be highly, almost randomly, variable. However, on closer inspection, and also taking into account the characteristics of the site, the variability observed does follow an appreciable pattern. Initially, the water table is close to the ground surface at less than 0.5 m, thus suppressing monitored redox values below a depth of 0.1 m to create highly reducing conditions. However, a slight fluctuation of the water table from March through to June 2000 causes a relatively rapid and alternating change in redox conditions at a depth of 0.5 m, from highly reduced to moderately reduced. Similarly, during the period of peak water table height, following flooding of Sutton Common in November 2000, there was a rapid and significant decrease in the surface redox potential. Redox conditions at a depth of 0.9 m remained highly reduced, apart from during September 2000 when there is a change to oxidised conditions. This is reflected by the low height of the water table experienced during the summer months.

The impact of the flooding event at the end of November 2000 is not as clear as in the data collected from other monitoring locations. However, a trend can be discerned whereby there is a major movement to reduced conditions at 0.1 m and 0.9 m depths and a movement from highly reduced to moderately reduced conditions at 1.4 m. Interestingly, redox values at 0.5 m remain moderately reduced both prior to, and following the flooding occurring. Throughout the period of higher water table caused by the flooding event, redox conditions are generally suppressed. However, following a return to normal hydrological conditions, redox conditions also return to their previous ranges.

The rapid changes in redox conditions observed at this location are again mediated by the high levels of organic matter within the soil profile. As outlined previously, rapid declines in redox values following submergence require the presence of such material. At Site 8 there exists a highly organic ploughsoil derived from a surface peat with a distinct change to a more mineral subsoil at a depth of between 0.5 and 1.0 m. This arrangement of soil horizons can therefore explain the rapid changes in redox potentials observed within the upper soil profiles.

Site 8 is characterised by variable redox conditions, although a definite pattern of greater reduction with increasing depth does exist. Similarly, to other monitoring locations, the impact of flooding can be identified although it did not produce such a clear signature as that observed elsewhere.

Redox monitoring Site 9

Figure 6.10 displays the redox results and associated piezometer levels from Site 9.

Like Site 4, this site is prone to regular flooding and unfortunately throughout the period of monitoring has regularly been inundated, particularly during the time of flooding and for a long period thereafter. The results from this location are characteristically low throughout the monitored profile and there is little change observed within the data from different depths. Values predominantly range between +100 and -200 mV, indicating an established reduced environment. A significant change in readings from all depths was observed from June to the beginning of October 2000, where there was a rise in all values to approximately +100 mV. This was followed by a drop in values at all depths, coinciding with increased precipitation but prior to the flooding of the site, during which the probes were inaccessible. Final readings obtained were within a similar range to those from the beginning of the monitoring period.

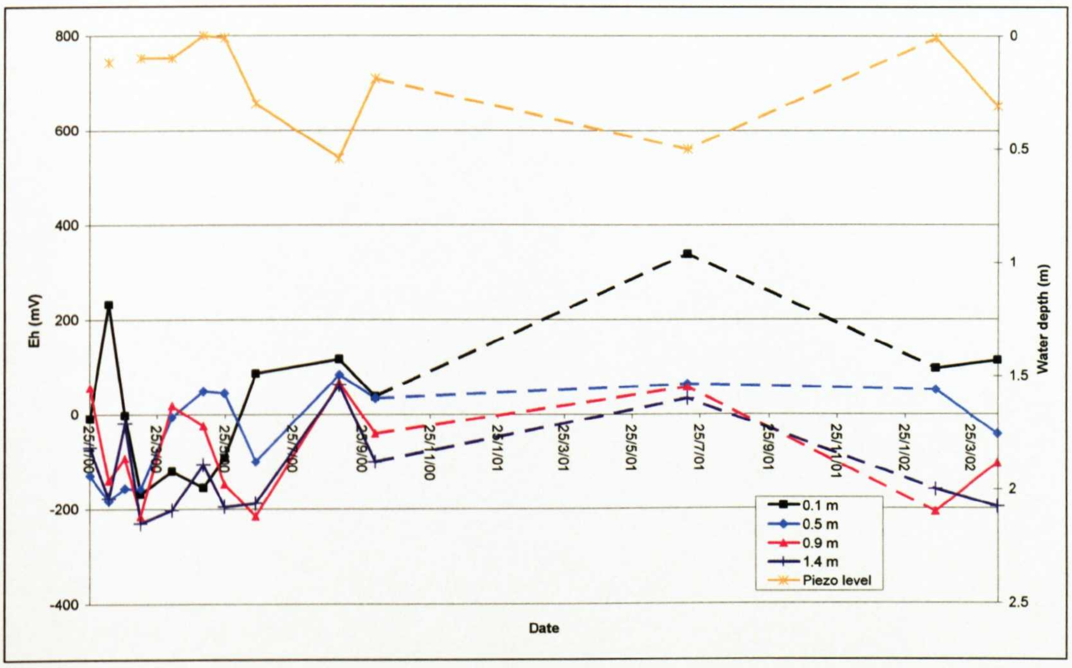


Figure 6.10 Linear plots of soil redox potentials and piezometer readings (orange line) for monitoring Site 9. Redox values are adjusted to pH 7.

The range of the values observed throughout the period of monitoring in this location was small. This was probably as a result of permanent saturation of the entire soil profile, apart from at the very surface, at this location. The fact that the entire soil profile was influenced by periods of significant precipitation indicates that a similar situation exists at this location as at Site 4. This therefore meant that the soil profile was subjected to groundwater flow and thus a degree of disturbance within the burial environment.

6.2.2 Eh / pH diagrams

The construction of the Eh/pH diagrams and the boundaries displayed upon them, are presented in Section 3.3.2. The diagram is structured in such a way as to show the limits of the aqueous system, shown as the upper and lower black lines, within which all observed data must fall, as all values were taken in the presence of water. It is argued that in natural systems there are no naturally occurring chemical species that are strong enough reducing agents to reduce water to hydrogen and conversely there are not strong enough oxidising agents to break down water to oxygen (Raiswell, 2001). Other boundaries of significance are also presented, these being the iron II/III and the sulphide/sulphate boundaries. The linear graphs for redox potentials have used categories of redox potential as presented by Patrick & Mahapatra (1968). However, the benefit in using Eh/pH diagrams is in their ability to identify truly reducing conditions that can therefore provide an insight into the chemical status of the burial environment, something that is not possible with the normal 'linear' method. For example, the reduction of sulphate only occurs under extremely reduced conditions in a strictly anaerobic environment (Patrick & Mahapatra, 1968). Therefore, by presenting this boundary condition within the Eh/pH diagram it is possible to identify redox observations made under anaerobic conditions, with such conditions being identified as ideal for the preservation of organic archaeological remains. The use of this boundary has been used previously to identify such conditions by Caple, (1996), Caple & Dungworth (1997, 1998) The use of the iron II/III boundary identifies soil conditions associated with waterlogged soils, this having previously been used as a marker for reduced conditions due to the associated colour changes that occur within soils (Bohn, 1971). Therefore, a new category system has been created for the interpretation of Eh/pH diagrams that reflects the differences in the presentation of data between this and the linear method. This is where conditions between the iron II/III and the upper limit of the aqueous system represent oxidised soil conditions, those between the sulphur/sulphide and the iron II/III boundaries represent reduced soil conditions and those between the sulphate/sulphide and the lower limit of the aqueous system represent highly reduced and anaerobic conditions. Figure 6.11, shows those regions of the Eh/pH diagram representing each category. Therefore, the ideal conditions for the preservation of organic materials within the burial environment will be those exhibiting the Eh/pH characteristics of the third category, that being highly reduced.

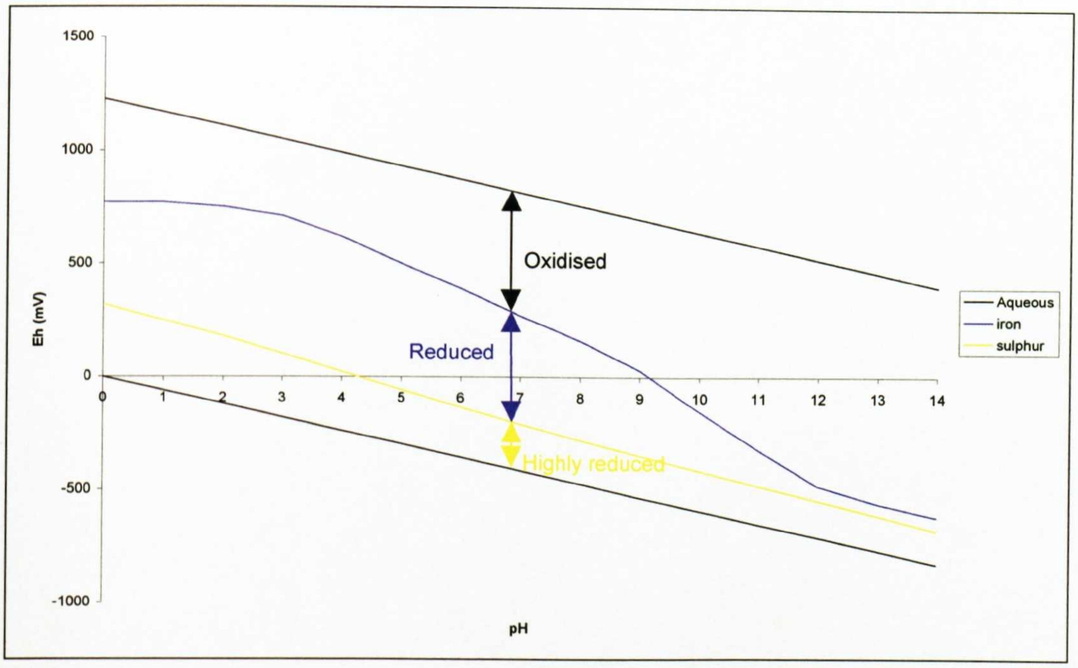


Figure 6.11 Basic Eh/pH diagram construction highlighting the three different categories used to classify redox results.

All the Eh/pH diagrams are presented within a specific, narrow range of Eh and pH due to clustering within the redox and pH data. For the purposes of comparison, all diagrams show the same ranges of Eh and pH units. For information on the level of the water table for each monitoring location, consult Figures 6.2 - 6.10.

Figure 6.12 shows an Eh/pH diagram for redox data from all four probe depths and all nine monitoring locations, obtained on 21/06/00. This graph can be taken as representative of the figures generated prior to this date and therefore not all will be presented here. However, these data are included in appendix 8 for further reference and include the monitoring dates - 24/01/00, 11/02/00, 25/02/00, 10/03/00, 07/04/00, 05/05/00, 24/05/00, 21/06/00, 04/09/00, 06/10/00, 28/11/00, 31/01/01, 24/04/01, 13/07/01, 21/01/02, 21/02/02 and 17/04/02. Graphs for 21/06/00, 06/10/00, 28/11/00, 31/01/01 and 13/07/01 are the ones that will be presented in this section as representative of the redox conditions that existed on Sutton Common.

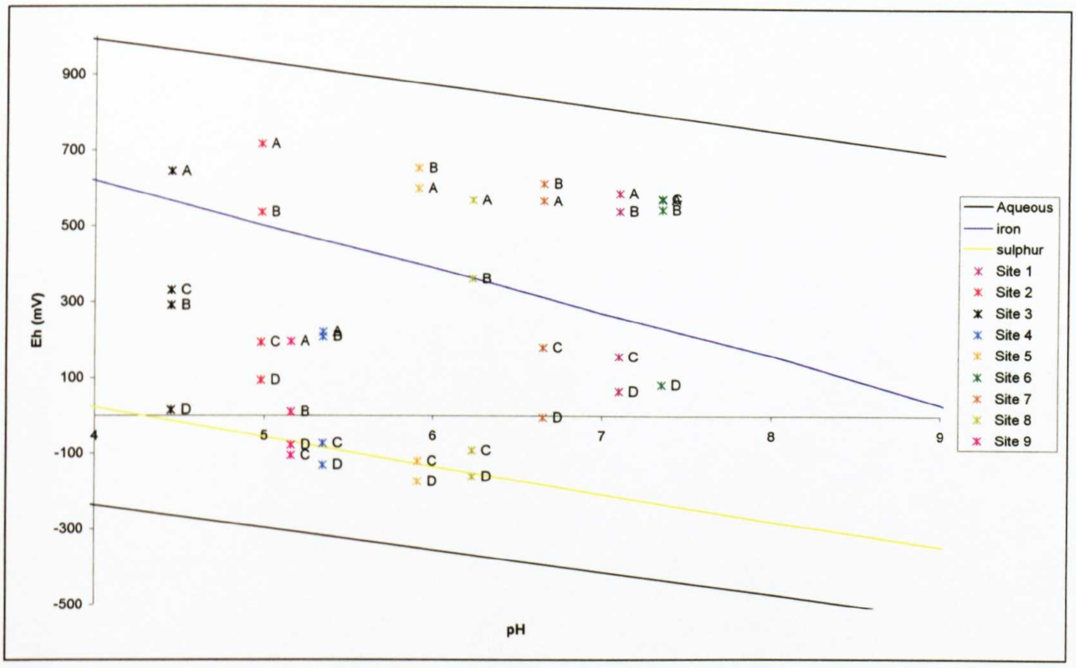


Figure 6.12 Eh/pH diagram from 21/06/00. Data from individual sites are colour coded and displayed in the key. The depths that the readings were obtained are noted by the letter associated with them; A=0.1 m, B=0.5 m, C=0.9 m & D=1.4 m.

The main characteristics of Figure 6.12 are the relatively wide spread of the data, both on the pH and the Eh axis. Generally, more oxidising conditions are prevalent in the upper soil layers, this shown by the prevalence of As and Bs within the oxidised zone. From field observations at the time of monitoring, it was noted that if surface deposits were wet from recent rainfall, readings for 0.1 m were often slightly lower than those obtained for 0.5 m. Some observations are present within the highly reduced zone below the sulphide/sulphate line, all of which come from a depth of 0.9 or 1.4 m, suggesting that at this time only at these depths does a true anaerobic environment exist. These occur at Sites 4, 5, 8 and 9. In fact, when taking into account all observations obtained up to 06/10/00, it is only these four monitoring locations that yield values below the sulphur boundary. As discussed in the previous section, Sites 4 and 9 are the two topographically lowest monitoring locations and therefore maintain the highest water tables relative to the ground surface, and as such the greatest levels of saturation. It is therefore expected that these locations would consistently exhibit conditions suitable for the preservation of organic materials as it is acknowledged that water levels are without doubt the most important single parameter when it comes to the preservation of waterlogged archaeological materials *in situ* (Gregory *et al.*, 2002).

Figure 6.12 reveals that pH variation across the site is quite marked, with Site 3 having a relatively acidic character of below pH 5 whereas Site 6 was more alkaline with a pH of over 7. Oxidising conditions, taken as being those that occur above the Iron II/III boundary, generally occur within the upper monitored depths from all the sites, except at Sites 4 and 9, these being the two lowest lying monitoring locations within the palaeochannel and the peat deposits bordering Shirley Wood. Due to a generally higher water table present for much of the annual cycle, these two locations exhibit a higher degree of saturation and therefore oxidised conditions are suppressed. This is confirmed by a lack of readings indicative of highly oxidised conditions. The majority of redox observations that are located within the reduced zone, i.e. between the sulphate/sulphide and the iron II/III boundaries, are those obtained from the depths of 0.9 and 1.5 m. This, along with the fact that at the majority of redox monitoring locations there exists a wide range in the readings, reinforces the previous observations made from the linear graphs of redox results, that stratification of redox conditions exists within the soil profile. By this it is meant that oxidised conditions exist nearer to the ground surface and reduced conditions at depth.

6.2.3 The effect of flooding upon soil redox potentials

The use of Eh/pH diagrams in the study of redox data from Sutton Common has been particularly useful in identifying the effects of flooding that occurred at the end of 2000. This event has already been noted in the linear plots of redox values in the previous section, but the use of Eh/pH diagrams can provide an added insight into the event. Figures 6.13, 6.14 and 6.15 show data obtained during site visits immediately prior to, immediately following, and a period after the flooding event. These will show how burial conditions changed over time in response to the flooding.

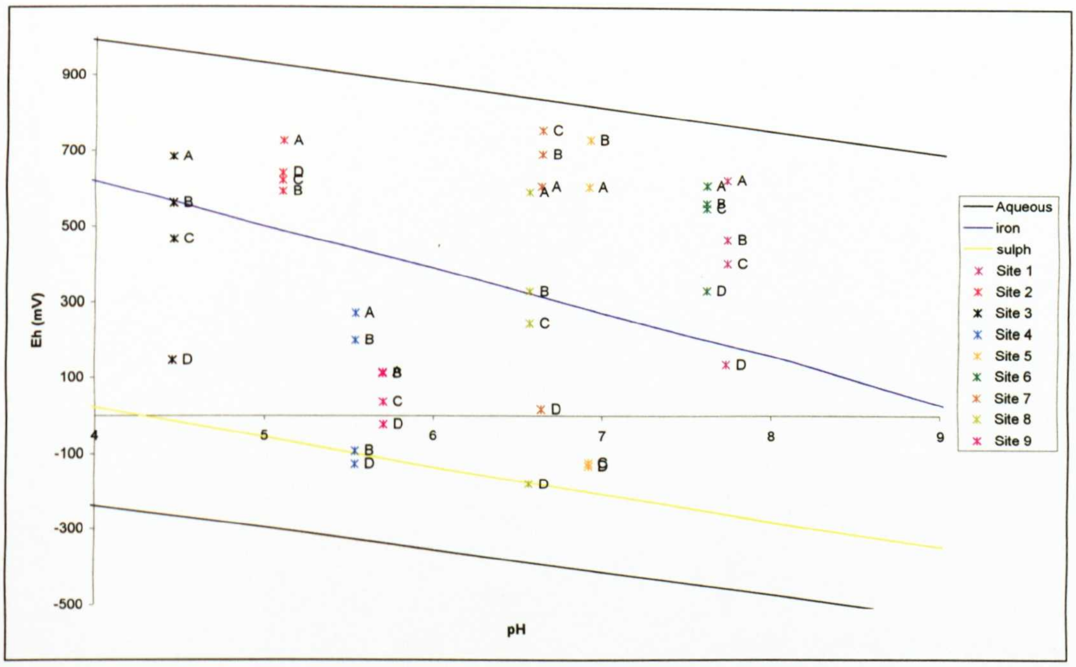


Figure 6.13 Eh/pH diagram from 06/10/00. Data from individual sites are colour coded and displayed in the key. The depths that the readings were obtained are noted by the letter associated with them; A=0.1 m, B=0.5 m, C=0.9 m & D=1.4 m

Figure 6.13 presents monitoring data obtained on 06/10/00 and shows a pattern similar to that described for Figure 6.12. There is a large spread of readings on both the Eh and pH axes and a definite stratification within the results, with generally oxidised conditions dominating the results and with Sites 4 and 9 showing the lowest recorded redox values. Flooding on the site occurred around 10/10/00.

Figure 6.14 presents data obtained on 28/11/00 and shows a dramatic change within the burial environment compared to the previous monitoring visit. The strongest change observed is in the clustering of the data, with the element of stratification almost completely missing and redox observations from all depths being almost identical. This shows that the entire soil profile has been affected by the inundation of floodwater onto the site. In addition to this, the pH characteristics of the monitoring locations have changed when compared to Figure 6.13, with there being a slight restriction in the range of the pH values observed and also a clustering of the pH values recorded at the monitoring locations around pH 7. Observations from Sites 4 and 9 are missing due to these locations being inaccessible at the time of monitoring due to the presence of flood water.

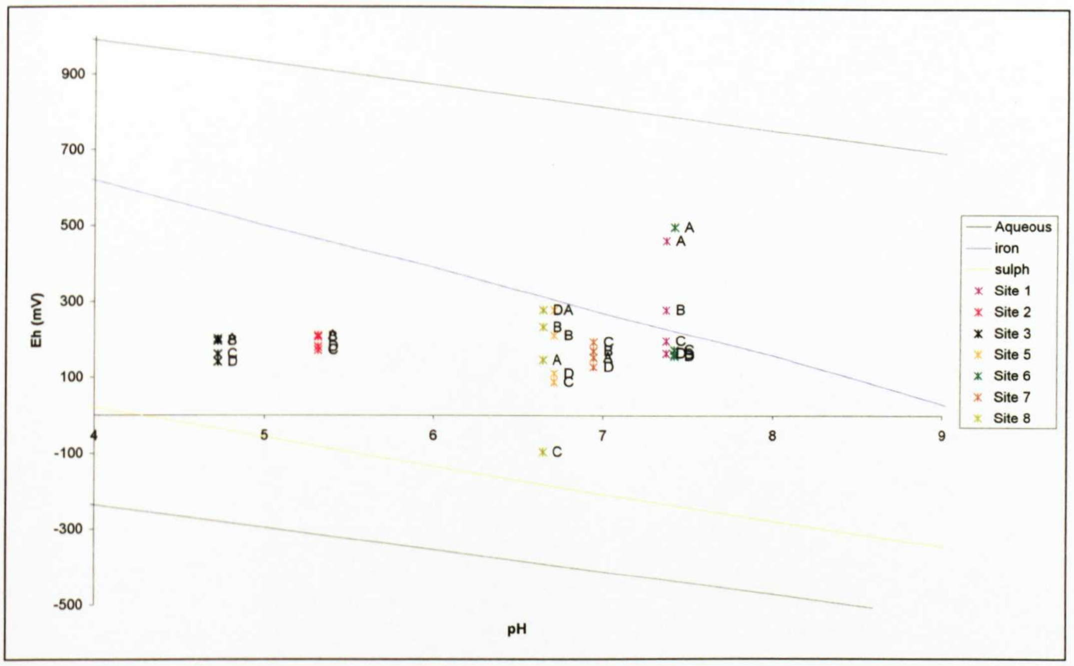


Figure 6.14 Eh/pH diagram from 28/11/00. Data from individual sites are colour coded and displayed in the key. The depths that the readings were obtained are noted by the letter associated with them; A=0.1 m, B=0.5 m, C=0.9 m & D=1.4 m

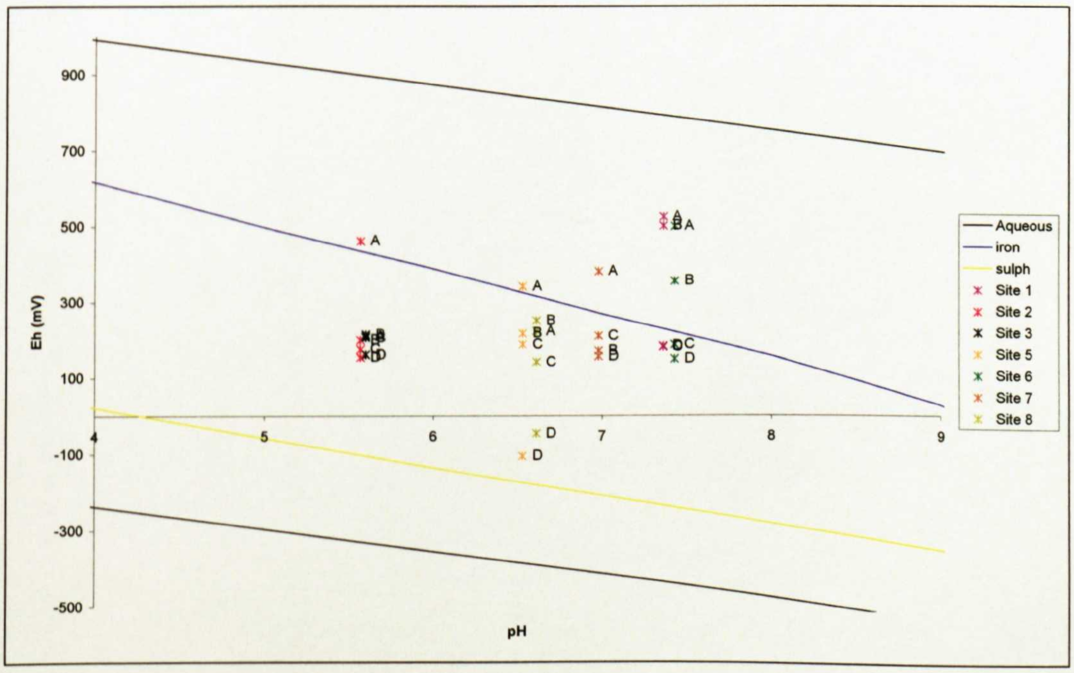


Figure 6.15 Eh/pH diagram from 31/01/01. Data from individual sites are colour coded and displayed in the key. The depths that the readings were obtained are noted by the letter associated with them; A=0.1 m, B=0.5 m, C=0.9 m & D=1.4 m

Figure 6.15 show observations from 31/01/01, approximately three months following the flood event. Although values have begun to revert to their previous patterns (i.e. vertical stratification within the soil profile) there is still an element of clustering observed on the Eh axis, and clustering of values on the pH axis is even more pronounced, with a significant shift of previously acidic conditions towards neutrality. This is particularly noticeable when studying the results from Sites 2 and 3. This trend of recovering Eh values but with constrained pH values, continues through to the end of April 2001, although by July 2001 values have reverted to a similar distribution to that prior to the flooding event, as shown in Figure 6.16 from 13/07/01. However Eh and pH values are still less distributed with there being no indication of highly reduced, anaerobic conditions within any of the presented data.

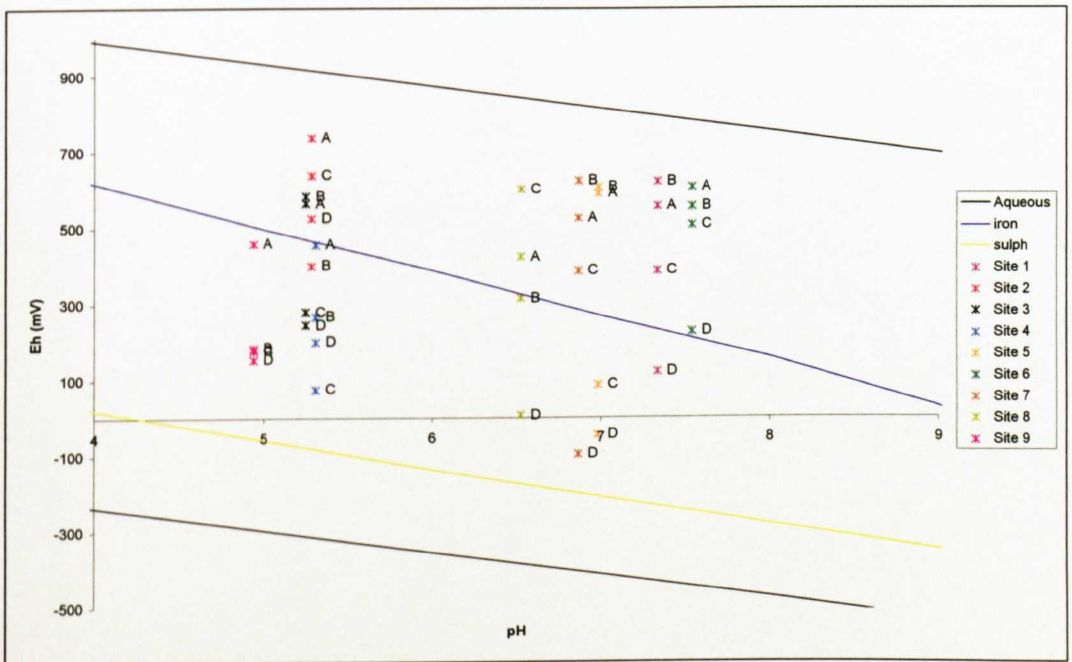


Figure 6.16 Eh/pH diagram from 13/07/01. Data from individual sites are colour coded and displayed in the key. The depths that the readings were obtained are noted by the letter associated with them; A=0.1 m, B=0.5 m, C=0.9 m & D=1.4 m

The change in the pH of the burial environment on Sutton Common is interesting in that it identifies that there is a medium-term (months) impact from the flooding, as opposed to a short-term (days) response. This has implications in terms of management of Sutton Common and other sites if they are subjected to flooding. Ponnamperuma (1972) describes the effects of submergence on the pH of soils as being to increase the pH of acidic soils and to depress the pH of more alkaline soils i.e. submergence makes the pH of acidic and alkaline soils converge upon pH 7. This pattern is clearly demonstrated within the redox data from Sutton Common. The process by which this occurs is through the retention and accumulation of CO_2 within alkaline soils causing a fall in pH and in acid soils the creation of reduced conditions involves the consumption of H^+ ions and hence a rise in pH.

6.3 Relationship between redox potentials and the water table

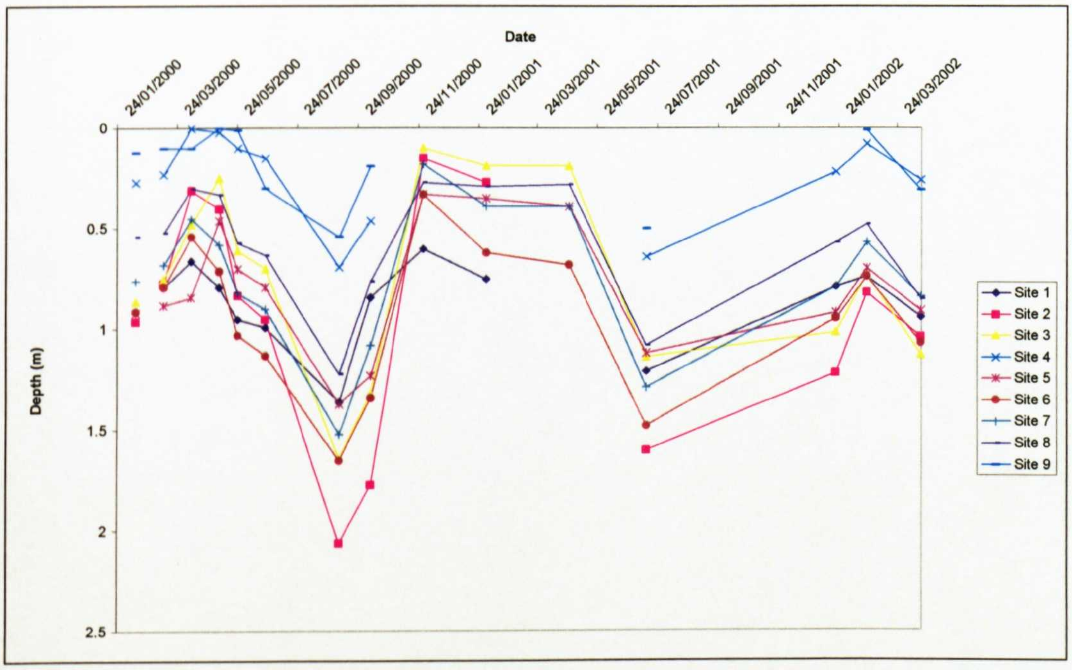


Figure 6.17 Water table depth for redox monitoring locations obtained from associated piezometers.

Figure 6.17, presents water-level data for piezometers located in association with the redox monitoring points. This data has already been presented along with the 'linear' redox data in Figures 6.2 - 6.10 but is presented here as a whole in order to assess more fully the relationship between monitoring locations. All exhibit a similar behaviour in terms of the fluctuation within the water levels with only Sites 4 and 9 being noticeably different. As highlighted previously, these locations are the lowest lying of all the monitoring points and are subject to a relatively continuous high water table. This is shown in Figure 6.17 by little variation in the piezometer levels in these locations. It is also apparent that the period of flooding had a dramatic and long lasting affect, maintaining high water-levels for a number of months. The impact of this period of flooding has been identified within the adjusted redox data presented in Figures 6.2-6.10 and also by the Eh/pH covering this period in Figures 6.14-6.16.

Comparison of redox data and associated water-level data has shown that the chemical status of the burial environment is highly influenced by the degree of saturation (Gregory *et al.*, 2002). Further understanding of this relationship can be gained by plotting this relationship graphically by means of scatter diagrams shown in Figures 6.18 - 6.21, these showing 'cleaned data', not including those readings gathered during the period of flooding itself.

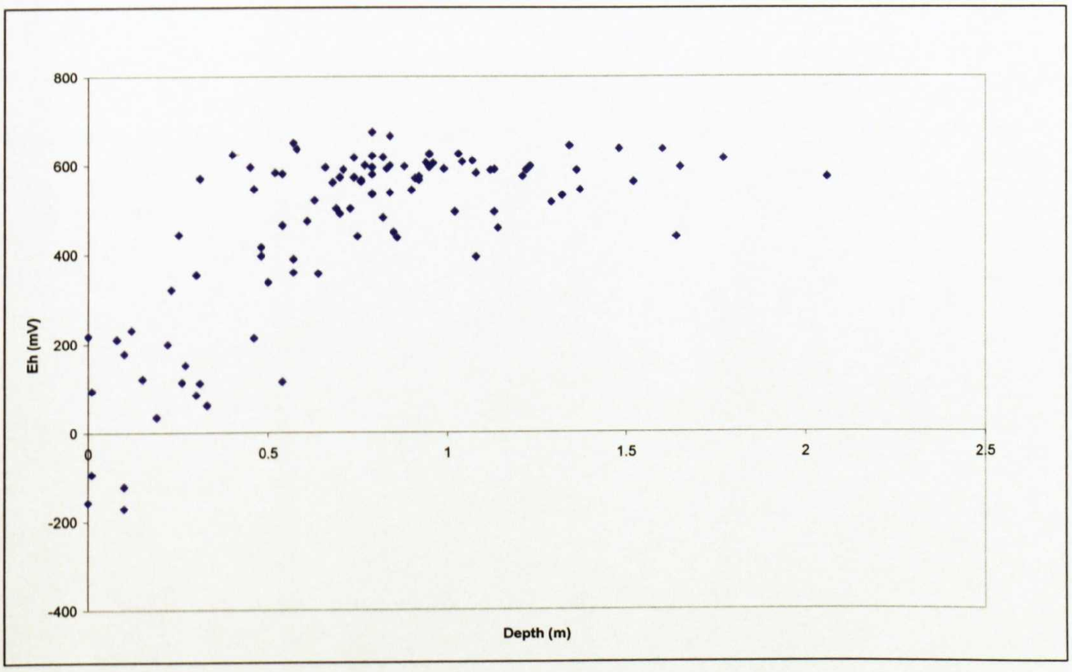


Figure 6.18 Scatter diagram showing the relationship between water-levels and redox potentials (adjusted to pH 7) from 0.1 m depth for all redox monitoring locations.

Figure 6.18 shows a scatter diagram of water level against redox potential from 0.1 m depth for all nine redox monitoring locations. A number of distinctive patterns can be identified from this graph and related to redox status. Firstly, the majority of the readings shown are highly positive, with an upper ceiling being apparent at just above +600 mV. However, at water depths below approximately 0.5 m, lower redox potentials are apparent. What is more, the relationship appears to be positive and linear, i.e. there is a trend for increasing redox values with an increasing depth from the ground surface to the water-level within the associated piezometer. This shows that the redox status of the burial environment at 0.1 m depth is influenced by a water table within 0.5 m depth of the ground surface. At a greater depth of the water table, the general pattern observed is that a maximum redox value of between +500 and +700 mV is achieved.

Figure 6.19 shows the same type of graph but for data obtained from a soil depth of 0.5 m. In comparison to Figure 6.18, there is a greater spread of points but a similar overall pattern can be discerned. Again, the points form a pattern with a positive linear relationship being observed initially, followed by a levelling off of values. The initial relationship shows that with a greater depth of observed water-level, there is an associated increase in the observed redox potential. This continues until a depth of approximately 0.75 m when the redox potentials measured level off with a ceiling value of approximately +700 mV.

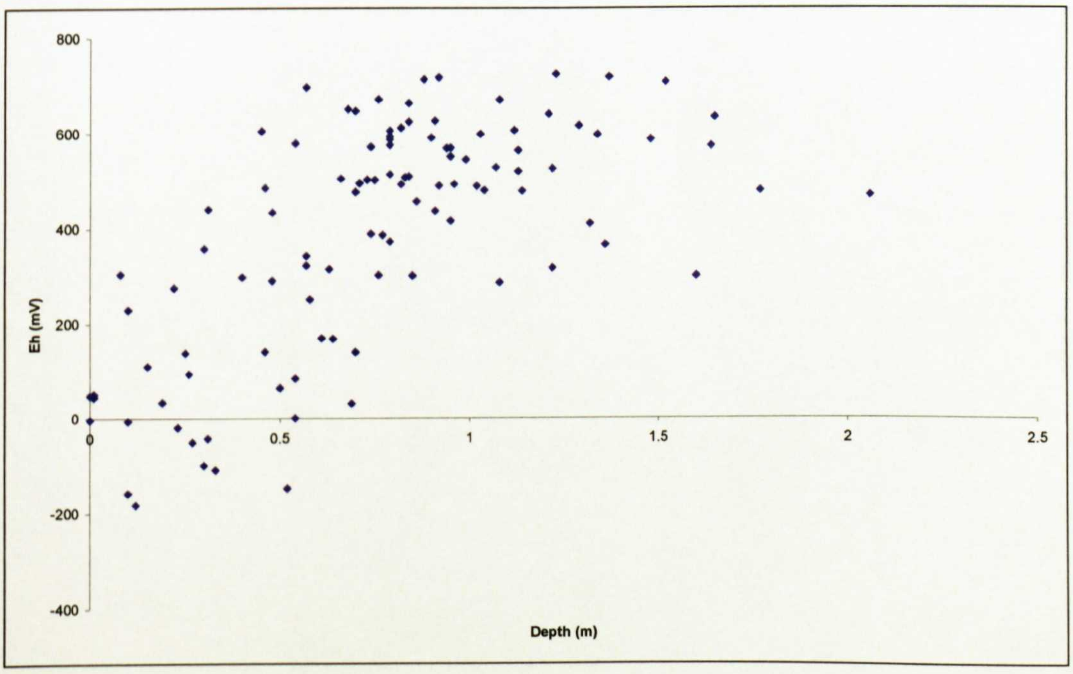


Figure 6.19 Scatter diagram showing the relationship between water-levels and redox potentials (adjusted to pH 7) from 0.5 m depth for all redox monitoring locations.

In comparison to Figure 6.18, the depth at which the change in pattern occurs is approximately 0.25 m deeper, suggesting that the soil redox potentials at a depth of 0.5 m are influenced by a water table within a depth of approximately 0.75 m depth. Below this, maximum redox potentials are observed.

Figure 6.20 displays the same type of graph but for data obtained from a depth of 0.9 m. This graph shows that with greater depth there is a greater distribution within the redox data, however a new relationship between water-levels and soil redox potentials becomes apparent. Whereas in Figures 6.18 and 6.19, an upper 'ceiling' for redox values can be identified, Figure 6.20 shows that a lower 'floor' also exists for these observations at approximately -300 mV. This is shown in the graph as the minimum values obtained when the piezometer levels are within approximately 1 m of the ground surface, suggesting that within that range of depth, soil redox values are at their minimum. There is also a slight trend of increasing redox potentials with increasing water-level depth, although this is not as strongly shown as in the previous two figures.

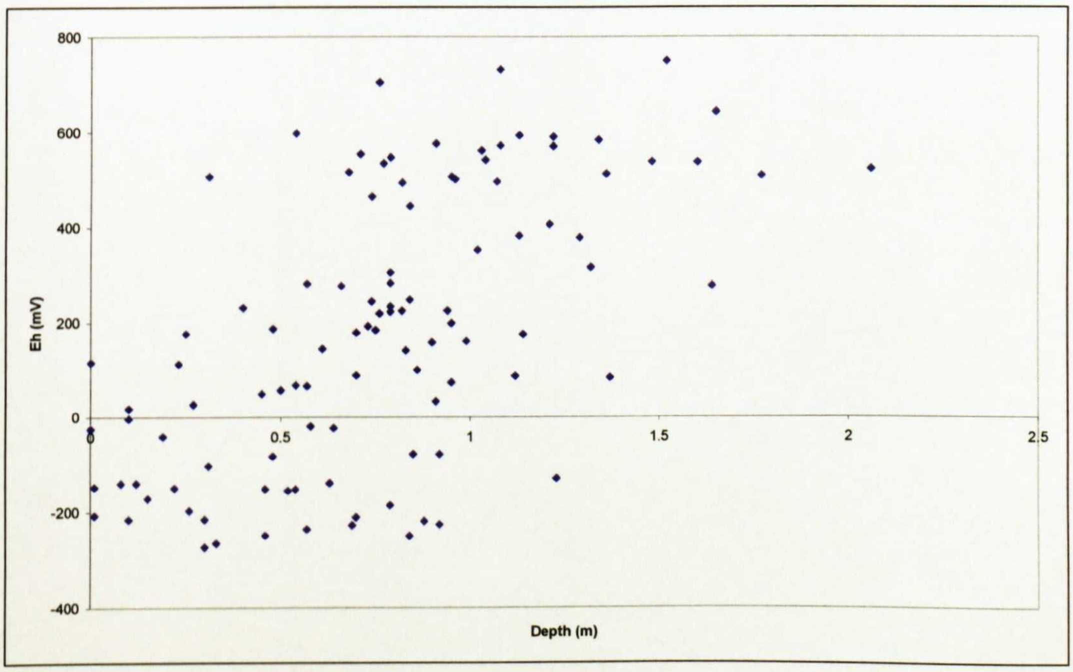


Figure 6.20 Scatter diagram showing the relationship between water-levels and redox potentials (adjusted to pH 7) from 0.9 m depth for all redox monitoring locations.

Figure 6.21 is the same type of scatter diagram as the previous three figures but showing the data obtained from a depth of 1.4 m. As in figure 6.20, there is evidence for a lower 'floor' being reached within the redox data of approximately

-300 mV. This extends to a depth of in excess of 1 m and is also associated with a less pronounced distribution of points within the diagram. Although a strong trend cannot be identified within the diagram, at greater water-level depths there appears to be a tendency for higher soil redox values.

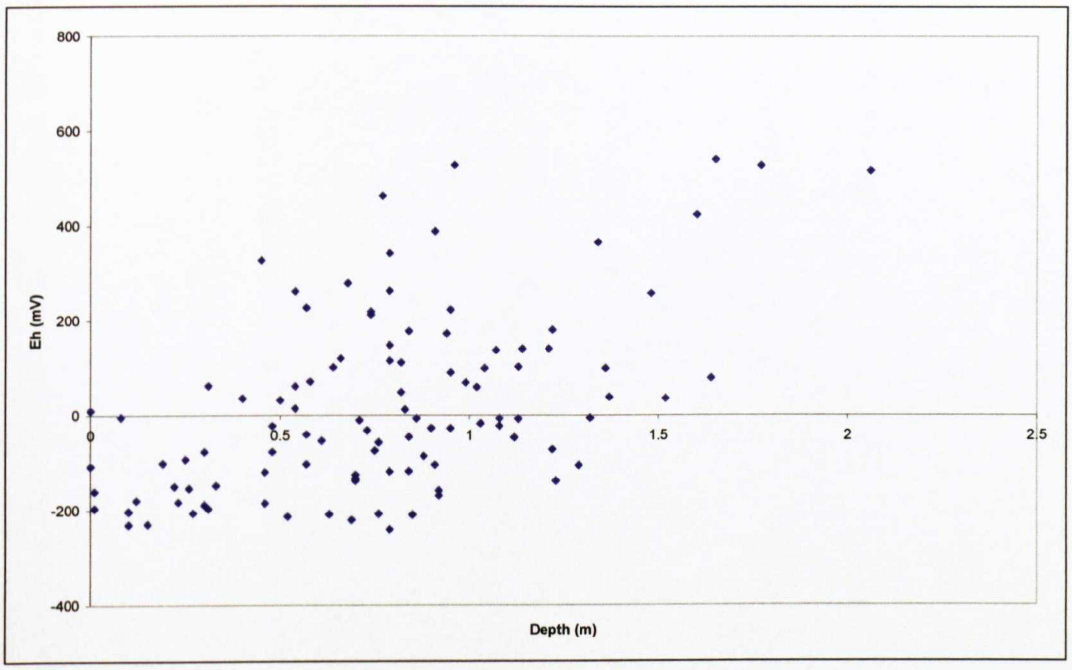


Figure 6.21 Scatter diagram showing the relationship between water-levels and redox potentials (adjusted to pH 7) from 1.4 m depth for all redox monitoring locations.

Figure 6.18 - 6.21 have helped to identify a soil redox potential dynamic influenced by the degree of saturation present within the burial environment. This relationship can be illustrated graphically as shown in Figure 6.22, where the curve represents the changing average redox potential with observed water table depth. The additional curve, shifted to the left, represents how the relationship changes for shallower redox observations made nearer to the ground surface, that to the right of the central curve, the relationship for redox observations made at a greater depth.

Essentially, there is an upper and lower limit for redox values, these being approximately +700 and -300 mV. Under saturated conditions the minimum redox value may be experienced whereas under aerated conditions the maximum is.

However, during intermediate, or transition, conditions a positive relationship is exhibited between observed redox values and proximity to the water table.

This observation is based solely upon data collected from Sutton Common, however it is suggested here that a similar pattern will be present within data collected in a similar manner at other sites.

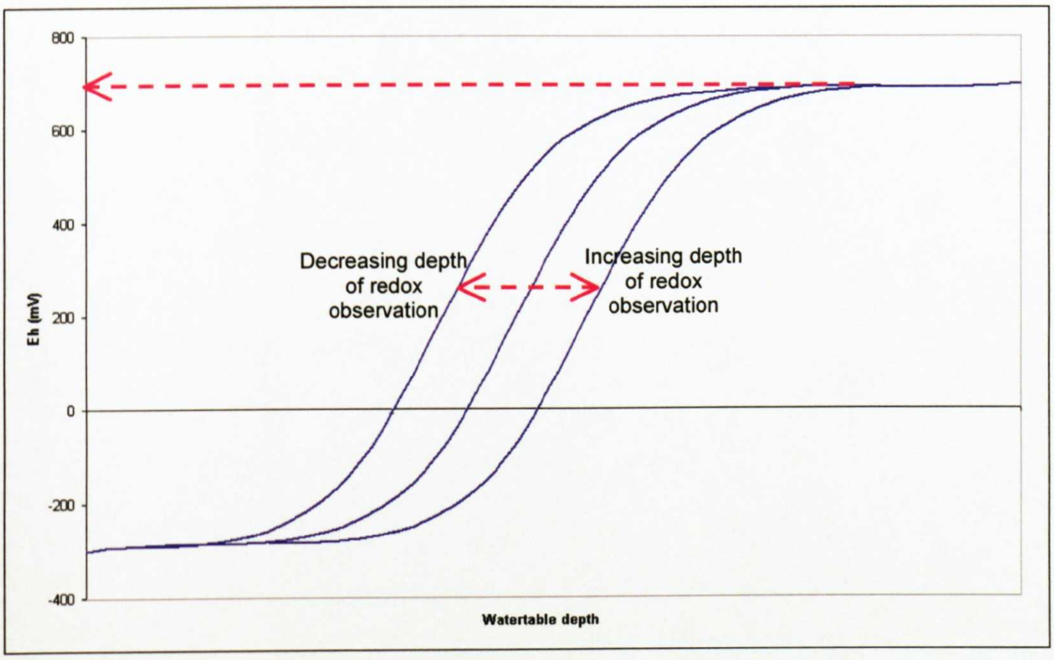


Figure 6.22 Diagrammatic representation of the relationship between water table depth and soil redox potential.

6.4 Summary

The results from the programme of soil redox monitoring have identified a number of distinctive patterns within the burial environment across Sutton Common. Study of the results in the form of adjusted values has enabled the identification of relative changes over time, whereas the use of Eh/pH diagrams has revealed the influence of pH variation on the site, in addition to characterising conditions within certain boundaries.

Common patterns have been observed within the majority of results. There is a general trend of less oxidising conditions with depth, a pattern that is prevalent across almost all the locations from which data have been obtained. The degree of variation of this pattern is somewhat dependent on the characteristics of individual locations and also the environmental changes that they experience; such as the degree of saturation relating to the fluctuation in the water table, and also the amount of organic matter present within the soil profile. For example, the differences observed in the degree of saturation and the varying soil type is strongly reflected in the results obtained from sites such as 6 and 9. Site 6 is dominated by a low water table relative to the ground surface, low organic matter content resulting in oxidised conditions through the greater part of the soil profile. In contrast, Site 9 is dominated by a high water table, high organic matter content and reduced conditions are prevalent with relatively low variability within the observed redox values.

The occurrence of a flood event during November 2000 has provided clear evidence of how the burial environment reacts to such an event and has at the same time provided a valuable insight into possible management strategies, such as proposals to increase the level of the water table and subject the site to seasonal flooding. Although the monitoring programme was not specifically designed to identify the impact of flooding on Sutton Common, this event has been very well recorded and its effects upon the burial environment clearly documented. The identification of the effects on soil pH have provided a clear indication of the processes that occur within the burial environment during flood conditions such as sequential reduction and amelioration of pH conditions. The flooding has also been shown to affect the entire monitored soil profile, causing medium-term changes to occur in terms of soil chemistry. The observed changes in pH show that flooding disturbs the delicate stability present within anaerobic deposits and that a period several months is required, following the flood event, for the original conditions to re-establish. The reaction of redox conditions to the on-site flooding clearly indicates that the chemical status of the burial environment is predominantly determined by the presence, absence, or variability of saturation.

By comparison of both the linear redox graphs and Eh/pH diagrams to the depth of saturation at the monitoring locations, it is clear that during times of normal falling water tables i.e. during the summer months, a degree of stability is observed within the burial environment. This is due to the slow drop of the water table where disturbance to the burial environment is at a minimum, thus allowing sequential reduction and therefore stabilisation to occur at depths where conditions of permanent saturation exist. This process is observed clearly at the greatest monitored depths where during the low-water, summer months, some of the most reduced conditions are observed coupled with an increase in the stratification of redox conditions. However, at the time of the flood event where water-levels increase very rapidly across all monitoring locations, a very rapid change of conditions is observed within the burial environment. These observations show that it is the rate at which water-levels within the soil profile change that determine the burial conditions, at least in terms of redox potentials. Change in the depth of the water table itself is therefore not the only variable to account for, but the rate of change is also of crucial importance, an important fact when interpreting monitoring data.

From the combined soil redox potential and associated water-level measurements undertaken during the course of monitoring, the potential for good quality preservation of organic archaeological remains on Sutton Common can be assessed. Of particular value when undertaking this are the Eh/pH diagrams. Sutton Common can be classed as a former wetland and this is reflected in the oxidised conditions experienced within the upper 0.5 m of the soil profile across the majority of the monitored locations when the site was under normal conditions. Therefore, the locations that consistently exhibited redox conditions recognised as indicative of a burial environment capable of preserving organic materials, are those that showed the greatest degree of saturation, namely Sites 4 and 9 although Site 5, located within the palaeochannel also exhibited a degree of stable, reducing conditions. Therefore, it is these locations that are likely to contain well-preserved material, if it is located there, and are therefore good candidates for *in situ* preservation. Other than this, across the wider site, only organic archaeological materials buried at depths in excess of approximately 1.5 m are likely to be subjected to conditions suitable for preservation.

This chapter has presented the results from the programme of redox monitoring that was undertaken on Sutton Common. Results from individual sites have been presented in two forms; variation of redox values adjusted to pH 7 over time and

Eh/pH diagrams. The results have been interpreted with special emphasis directed towards the results obtained around and during site flooding that occurred at the end of 2000. Evidence has been found that throughout the 'normal' hydrological regime, stability exists within the deeper monitored soil profile in a number of monitoring locations. It was also identified that the impact of flooding may be detrimental to the long-term preservation of organic archaeological materials if not managed correctly, as a result of disturbance to previously stable conditions.

The following chapter will present results obtained from the microbiological techniques applied to the site.

Chapter 7 Microbiological results

7.1 Introduction

In this chapter, the results of the programme of microbiological analyses will be presented and notable patterns within the results will be highlighted and interpreted in the context of previous research.

Gaining an understanding of microbial activity within the burial environment is essential if serious consideration of preservation *in situ* of organic archaeological remains is to be made. This is because microbiological activity is the major agent of decay of organic artefacts (Corfield, 1996, 1998) and the vector for carbon recycling within the soil environment (Alexander, 1977).

The material of predominant consideration during this study has been archaeological wood, specifically structural timbers, as it is this material that is considered to be the primary archaeological resource on Sutton Common. There is extensive evidence for the impact of microbial activity upon archaeological wood from varying burial environments and under varying conditions, from both experimental evidence (Powell *et al.*, 2001) and analysis of ancient archaeological wood materials (Björdal *et al.*, 1999, Björdal & Nilsson, 2002a&b).

Although the majority of the organic archaeological materials identified on Sutton Common have been directly associated with the two archaeological enclosures, archaeological wood has also been recovered from within the deposits of the Hampole Beck palaeochannel (Van de Noort & Chapman, 1999). Excavations on the site during 2003 have also generated evidence that the wetland deposits to the east of Enclosure A were of recognisable importance to the people who constructed the site through the identification of an eastern entrance that leads directly to the wetlands in this area. Therefore, locating sampling sites outside, as well as inside, the area of the archaeological enclosures is justified.

The aims of the microbiological investigations at Sutton Common were to gain an understanding of the microbial population across the different burial environments present on the site and to characterise the changes that occur through the vertical soil profile. Developing this understanding provides a possible tool for the assessment of the potential for *in situ* preservation of organic archaeological remains and aiding in identifying threats to this resource.

Samples for microbiological analysis were obtained from five locations, each associated with a redox monitoring and piezometer location as shown in Figure 7.1. The numbering of the sampling sites follows the same format as that for the soil redox monitoring. The site locations take into account the main variations in the soils present on Sutton Common. Refer to Chapter 4 for a more thorough discussion of the geomorphology of the site. Only Site 3 is located directly within a recognised archaeological feature, this being the internal ditch of Enclosure B.

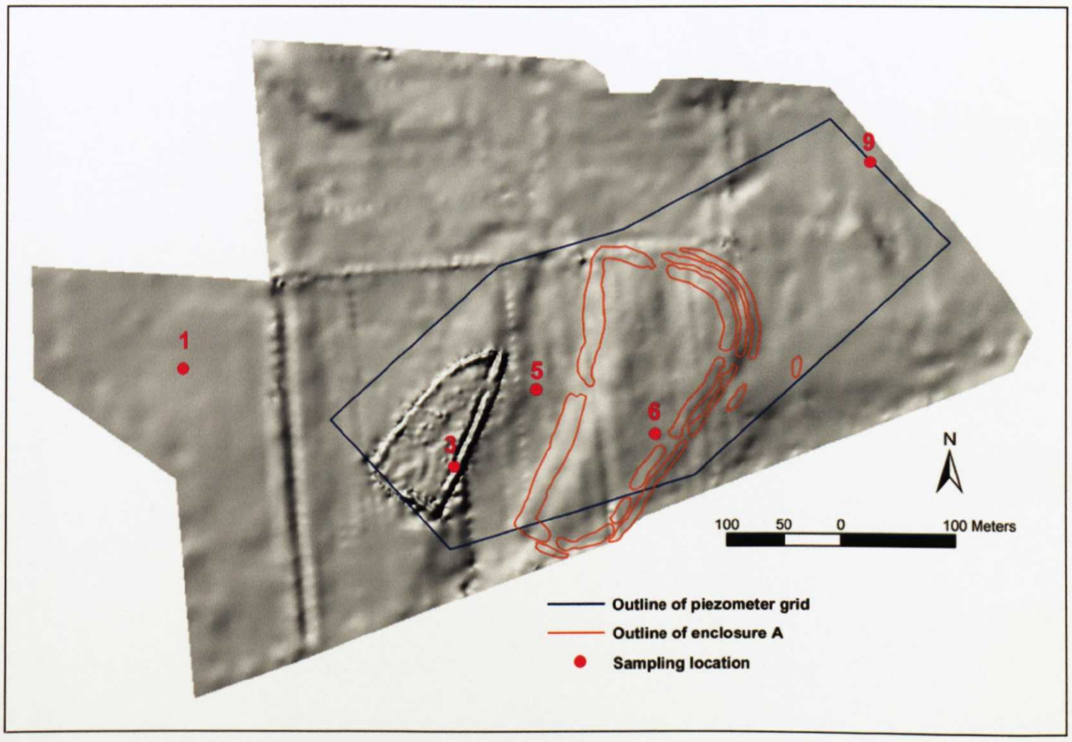


Figure 7.1 Location map for microbiological sampling sites. Numbers are associated with soil redox monitoring locations.

In contrast to the previously monitored variables of hydrology and soil redox potential, the microbiological work undertaken can be considered as an assessment rather than a monitoring exercise. The reason for this is due to the relatively large amount of time and resources that are required to undertake the analyses. However, due to the essential role of microbiological activity in the degradation of organic archaeological remains, this work is seen as providing a framework for future investigations and also as being an explorative exercise into appropriate techniques that can be applied to the burial environment.

7.2 Microbiological results

For each sample location, two sampling visits were made approximately 1 year apart. As this provides only two observations at each site, any differences observed between the two dates cannot be regarded as a trend. For example, observed changes over 1 year cannot be treated as evidence of the impact of changing management practices without supporting data. However, some trends between sites can be inferred due to the variation in the characteristics of the sampling locations themselves. Due to the low resolution of monitoring visits made, no definite conclusions relating to seasonal variation can be made. In order to avoid the possible influence of seasonality upon the results, the two samples from each site were obtained at approximately the same time of the year.

All results are presented in the form of histograms, with depth of sample shown on the Y-axis so as to represent more clearly the pattern through the soil profile, and the measurement figure on the X-axis. The actual values used are presented in Appendix 9. Sample dates are displayed on all the graphs adjacent to the sample site number and graphs are displayed on common scales except where shown. At each location the results from different samples are distinguished by referring to the 'first' or 'second' samples instead of the date that it was collected; the 'first' samples refer to those collected during 2001 and the 'second' samples are those collected during 2002. The 2001 samples are presented in the left-hand column and those obtained in 2002, in the right-hand column.

7.2.1 Acridine orange direct counts

Results for Acridine Orange Direct Counts (AODC) are shown on Figure 7.2. Results from all locations are shown on the same axis apart from those for Site 1. Only one set of results is available from Site 6 due to problems experienced in counting cells in soil suspensions that had been previously stabilised with formalin (refer to Chapter 3). This occurred when counting was undertaken several weeks after the soil sample collection, leading to a degradation of the bacterial cells rendering staining ineffective and counting impossible. The histograms show the mean values from three replicate counts, with range bars indicating the range of values about the mean.

Although there is variation in the numbers of cells counted at each sampling site, it is clear that there are greater numbers of bacterial cells within surface samples. There is also a strong similarity between the results from 2001 and 2002. This is particularly clear at Sites 1, 3 and 9.

It should be highlighted that the counts obtained from Site 1 are shown on a different axis due to the very high surface counts obtained from the second sample. In addition to the large increase in values observed from surface samples, the number of bacterial cells identified at both 0.75 m and 1.5 m increased by two orders of magnitude in the second sample. Although in comparison to the numbers of bacterial cells observed within the surface samples those counts at depth are small, they still constitute a very large number of individual cells. In addition, the fact that there had been a change from little or no identifiable bacterial cells to clearly quantifiable cell numbers between the two samples is of significance. Interestingly, the soil in this location is predominantly mineral, with relatively little organic matter content throughout the soil profile, especially when compared to other monitoring locations (except Site 6). A similar pattern is observed at Site 3, where there had been a noticeable increase in bacterial cells throughout the soil profile in the second sample when compared to the previous year.

Compared to Site 1, the second sample from Site 3 had approximately half the number of bacterial cells present at the ground surface. However, because this figure is comparable to the count obtained from the first sample from Site 1 it reinforces the significance of the considerable increase observed at this location.

At Site 5, although there was a recognisable presence of bacterial cells throughout the soil profile, in contrast to Sites 1 and 3 there had been a noticeable decrease in counts for the second sample especially at 1.5 m depth. At this depth, the first sample resulted in a greater figure for bacterial numbers than at 0.75 m, contrasting the general pattern described for Sites 1 and 3. Since all the sampling locations had been subjected to broadly the same management practices during the intervening year, the differences observed are likely to be a function of the characteristics of the soil profile in this location. For example, reference to the values for Loss On Ignitions (LOI, representing organic matter content) and moisture content (refer to Chapter 4), shows that this location exhibits some of the highest values for both of these factors indicating that soil conditions in this location are markedly different and therefore could be subject to different influences.

Although only one set of results is available from Site 6, it can be observed that counts were the lowest recorded from any site. Out of all the sampling locations, it is only Site 1 that has similar soil characteristics in terms of organic matter and moisture content, these both being very low. However, in contrast to Site 1, Site 6 records the lowest recorded number for bacterial cells from surface samples from all the sampling locations. This contrast may therefore highlight a difference in the effects of management between the two locations or another, as yet unclear influence. One possibility is that the proximity to an archaeological trench that was previously excavated in 1999 may have had a negative influence upon bacterial biomass. Hopkins (1996) presents a discussion of the potential effects of soil disturbance and suggests that the consequences of mixing different soil horizons can result in long-term changes to the soil microbial community as a result of dilution of active components, such as the microorganisms themselves, but also of available substrate such as organic matter. Also, there is a potential reduction of the rate at which organic matter is added to the soil following

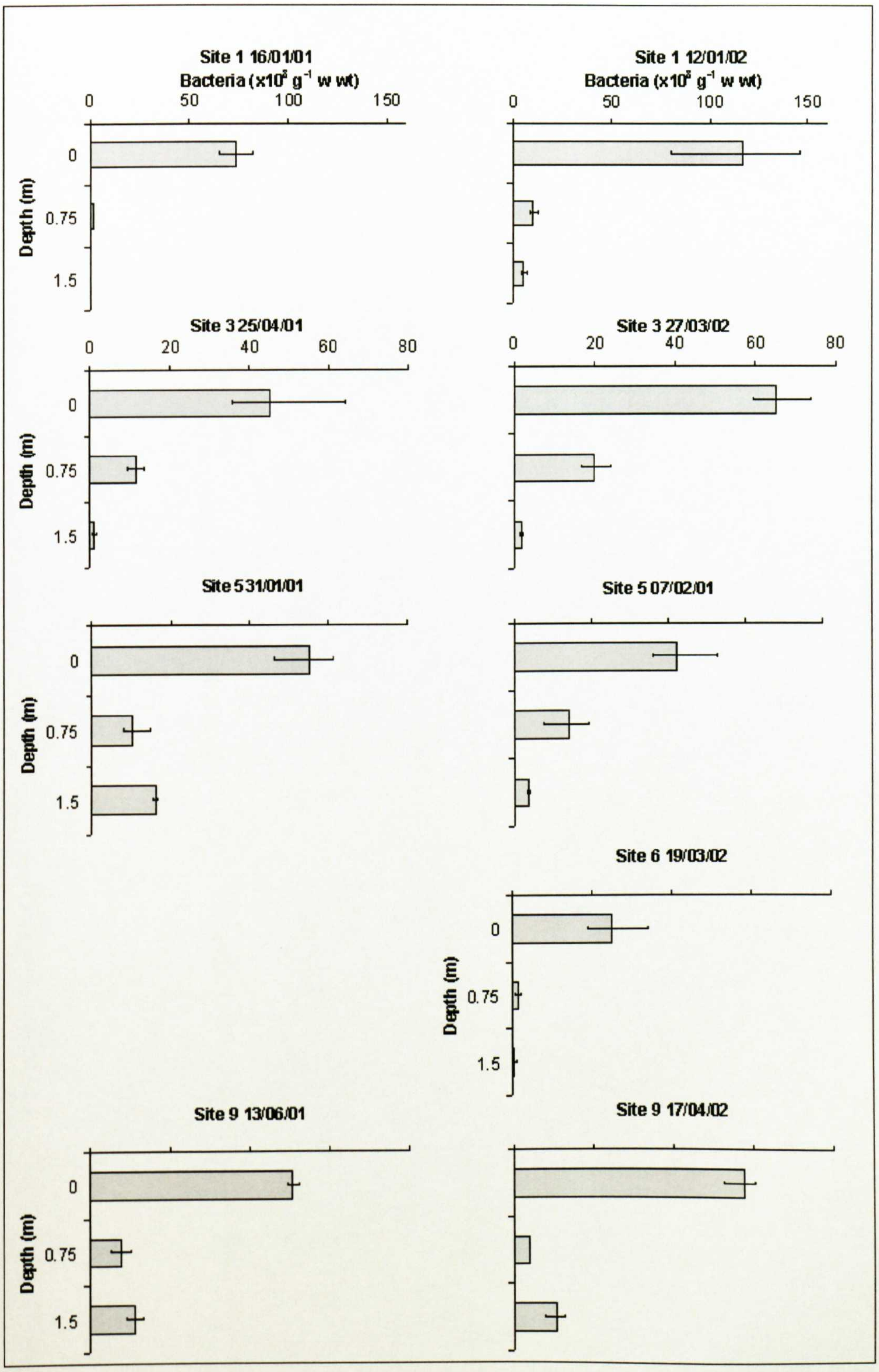


Figure 7.2 Acridine Orange Direct Counts (AODC) for samples from Sutton Common.

disturbance due to the impact upon seed viability. This second point is demonstrated when consulting aerial photographs of Sutton Common taken in 2000/01 (unpublished) which clearly show the outline of the previous archaeological excavations from 1999 indicating a long-term change in the flora covering the extent of the backfilled areas.

The results from Site 9 are very similar between the two sampling visits, although there is was a slight increase in surface values in the second sample. During the previous chapter, Site 9 was characterised by a permanently high water table throughout the period of monitoring and was unique in exhibiting only a small amount of change in soil redox potential. The fact that there was little noticeable change within the numbers of bacterial cells between the two sampling dates when other sampling locations exhibited more pronounced changes, suggests that the maintenance of a high water table may have buffered the burial environment.

In comparison with other sampling locations, Site 9 exhibits noticeably higher counts at 1.5 m than at 0.75 m, similar to the pattern exhibited at Site 5 for the sample obtained in 2001. Both Sites 5 and 9 have the highest values for organic matter content throughout the monitored soil profile. The values of in excess of 70% LOI at Site 9 indicate that the base material for the soil profile is organic, with very little mineral content. Site 3 has also produced high values for organic matter content for 0 m and 0.75 m, these relating to the organic rich deposits within the archaeological ditch of Enclosure B. The relatively high bacterial biomass associated with the soil profiles at these locations indicates that there is a strong relationship between this and the organic matter content. This finding also relates well to the soil redox results presented in the previous chapter showing the rapid establishment of highly reduced conditions in these locations, this being associated with high levels of organic matter and an active microbial population.

It should be noted that the numbers of bacterial cells identified within the surface soil samples corresponds to the values presented in the literature. The numbers quoted are within an order of magnitude, with the numbers from Sutton Common being around 10^9 cells g^{-1} wet weight (Alexander, 1977, Gray & Williams, 1971, Hopkins, 1996, Taylor *et al.*, 2002).

7.2.2 Extracellular enzyme assays

Figure 7.3 shows graphs of extracellular enzyme activities for leucine aminopeptidase, β-glucosidase and phosphatase.

The main pattern in these data is of decreasing activity with depth at all sampling locations. Although there are variations observed between sampling visits for each location, these are not considerable apart from at Site 1, where there was an approximate doubling in leucine aminopeptidase activity throughout the sampled profile. The pattern for leucine aminopeptidase and β-glucosidase remains the same for each visit to this location.

Site 3 showed a slight decrease in recorded enzyme activity at the second sampling visit, apart from the surface leucine aminopeptidase activity, which had increased.

The results obtained from Site 5 exhibit a slightly more complex pattern, with suppression of activity from surface samples at the second sampling visit but a noticeable increase at depth for all three enzymes assayed.

Results from Site 6 are very similar for both sampling dates. There was however, a noticeable increase in phosphatase activity at 1.5 m depth in the 2002 sample. These results are the lowest enzyme activity measurements recorded from Sutton Common as a whole, reflecting the data shown for AODC at this location.

In contrast to the general pattern of increasing enzyme activities at depth at Sites 1, 5 and 6 for the second samples obtained, Site 9 showed a reduction in activity, particularly for leucine aminopeptidase and phosphatase activity. Here there was a very noticeable reduction at 0.75 m and 1.5 m depths. This pattern contrasts with that exhibited in the AODC results from this location, indicating very little change between the two samples taken.

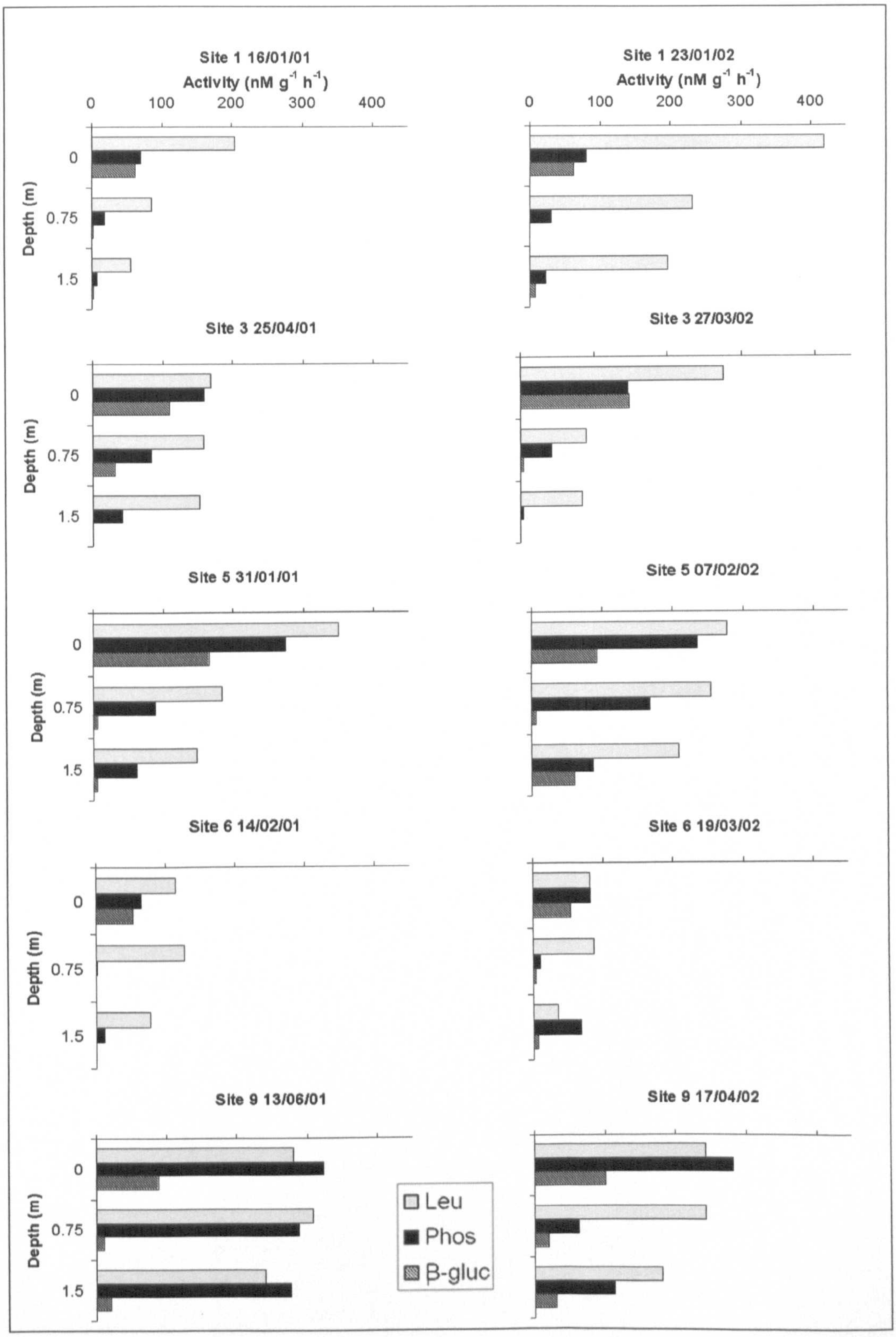


Figure 7.3 Extracellular enzyme assay results for Leucine aminopeptidase (Leu), Phosphatase (Phos) and β-Glucosidase from samples obtained from Sutton Common.

Taking into account all three enzymes assayed for, the sampling sites displaying the greatest activities throughout the measured profile are Sites 5 and 9. Values for LOI indicate that the soil profiles at these locations contain the largest amount of organic matter. Conversely, Site 6 exhibits the least extracellular enzyme activity and the lowest values obtained for LOI.

The greatest enzyme activities were for leucine aminopeptidase, with β-glucosidase being the least active. This pattern is consistent throughout the vast majority of the results obtained.

7.2.3 ^{14}C-labelled leucine assimilation

Figure 7.4 shows graphs for the ^{14}C-labelled leucine assimilation experiments. Range bars represent the range of values obtained from three replicate counts; the histogram values represent means.

In a similar pattern to AODC values, and to a lesser extent for the extracellular enzyme activity measurements, values for the leucine assimilation rates were significantly higher within the surface deposits across all sampling locations. Again, graphs for sampling Site 1 are presented on a different scale as a result of the very high values obtained from the second set of data. The results from the surface samples from the second sampling date were significantly higher than for any of the other sampling sites, following the same pattern presented for Site 1 for both AODC and extracellular enzyme assay. However, this increase was not reflected at 0.75 m and 1.5 m where there was hardly any identifiable activity, when previously there had been in the sample obtained in 2001.

The Site 3 results showed a slight, but definite, increase in values for the surface and 0.75 m sample depths for the second sampling visits, but the pattern of decreasing activity with depth remains.

Surface values from Site 5 were noticeably greater in the second sample. At this site, activity was also identified at 1.5 m in the second sample, whereas no activity was identified in the sample obtained from 2001.

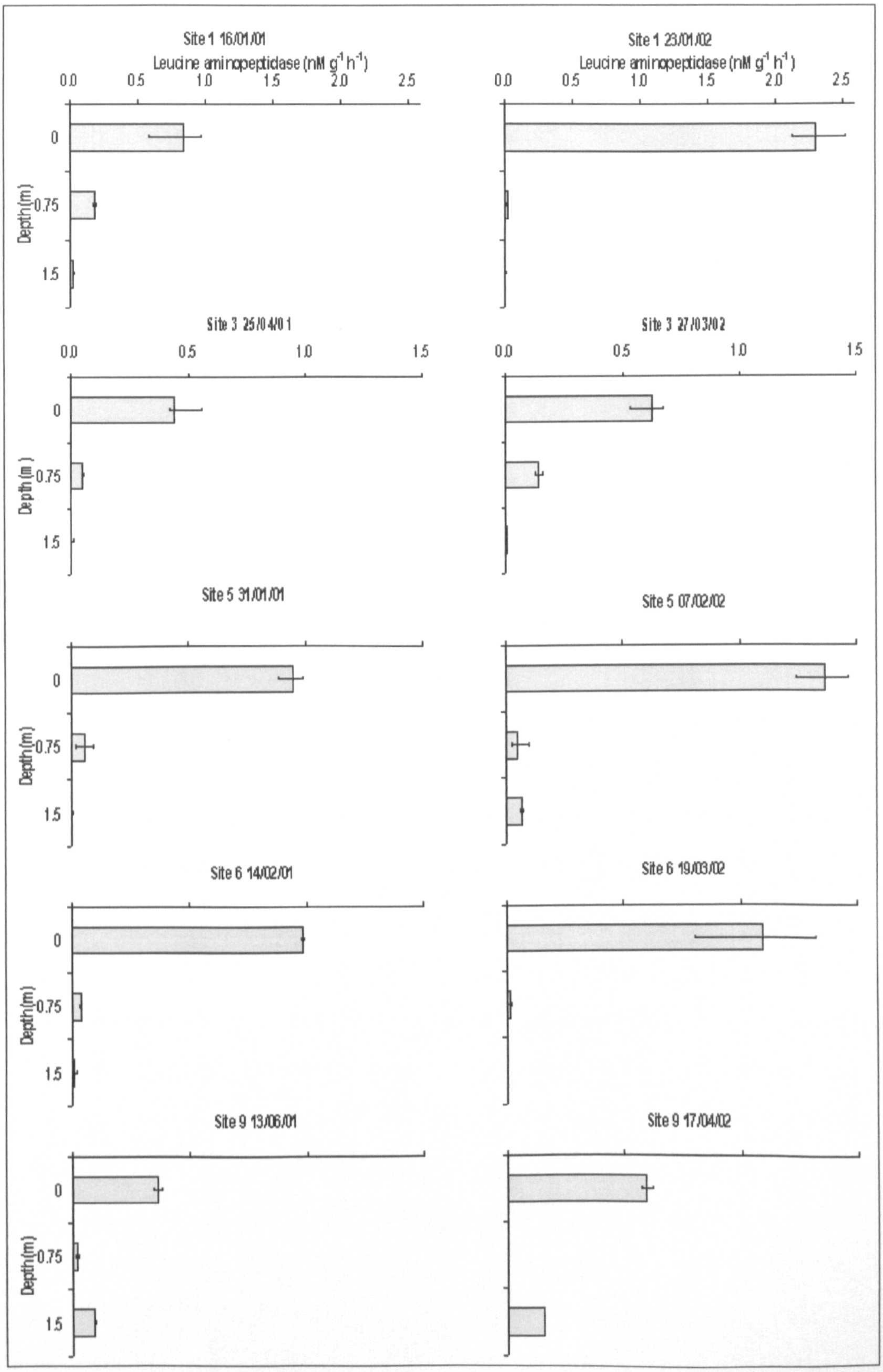


Figure 7.4 ^{14}**C-labelled leucine assimilation rates for samples collected from Sutton Common.**

The results of leucine assimilation from Site 6 indicate that there was very little identifiable change in microbial metabolic activity throughout the measured soil profile between the samples obtained in 2001 and 2002. A slight increase in surface activity was noted along with a drop in activity at 0.75 m and 1.5 m depths.

At Site 9 similar, although again slightly greater, results were observed for the second sample. Interestingly there were higher values observed from 1.5 m depth than at 0.75 m from both sample dates, this matching a similar pattern in the results for AODC at this location.

7.3 The interpretation of microbial analysis

In the previous sections, results from the individual techniques were presented separately, with only cursory reference to each other. In this section the microbial data will be assessed as a whole and the relationship between the separate factors approached.

From the results of the microbiological analysis techniques applied on Sutton Common, it is clear that there are patterns which are consistently present; such as the relationship between the microbial activity and depth and the presence of organic matter. Across the majority of the site bacterial biomass, as denoted by AODC, the measured activities of extracellular enzymes and microbial metabolic activity, shown by leucine assimilation rates, all decrease with depth. On occasion this pattern does not occur, when values at the greatest sampled depth of 1.5 m are higher than those at 0.75 m. However, the strength of the relationship with depth identifies this as being the major determining factor in terms of the representation of microbial population and its activity throughout the soil profile.

The presence of organic matter within the soil profile, shown by values for LOI, again appears to be a determining factor for the degree of microbial activity with there being an obvious difference in the values obtained from organic rich locations and those with a predominantly mineral soil matrix.

7.3.1 Correlating the microbial variables

To identify the significance of these patterns and to help identify more subtle relationships between the measured variables, all results obtained, including values for soil moisture content and loss on ignition, have been correlated.

Table 6.1 displays a Spearman's rank correlation matrix created using all available data from the variables measured in the field on the two sampling occasions, including the depth from which the samples were obtained. Only statistically significant values are presented. This method is a simple way of displaying strong associations within the data and provides an aid to highlighting any patterns. The correlations were carried out using SPSS 11.

Table 7.1 Spearman's rank correlation matrix. Leu-assim = ^{14}C-leucine assimilation, Phos_en = Phosphotase, Leu_en = Leucine aminopeptidase, Bgluc_en = β-glucosidase. ** - correlation is significant at the .01 level (2-tailed), * - correlation is significant at the .05 level (2-tailed).

	Depth	AODC	Leu_assim	Phos_en	Leu_en	Bgluc_en	Moisture	LOI
Depth								
AODC	-0.789**							
Leu_assim	-0.778**	0.765**						
Phos_en	-0.462*	0.585**	0.378*					
Leu_en	-0.453*	0.585**	0.499**	0.713**				
Bgluc_en	-0.689**	0.773**	0.732**	0.602**	0.766**			
Moisture	-	-	-	0.568**	0.693**	0.406*		
LOI	-	0.397*	-	0.623**	0.779**	0.511**	0.957**	

As well as the factors already discussed, the correlation exercise has identified clear relationships between the extracellular enzyme activities and leucine assimilation rates. It has also identified factors that seemingly do not possess any relationship, such as the effects of variable moisture content upon bacterial biomass and leucine assimilation.

It has been established that LOI and soil moisture content are very closely related and this is further supported in Table 7.1, showing that there is a near perfect positive correlation between the two. LOI and moisture content can help characterise the type of soil at each sample location. For example, organic rich peat soils retain large amounts of water, or mineral rich sandy soils are characterised as having low moisture retention qualities. The factors affecting water retention in soils are referred to collectively as matric suction. Organic-rich soils tend to retain water preferentially over more sandy soils because of greater adsorptive forces and smaller pore sizes within the soil matrix, and therefore have increased capillarity (Ellis & Mellor, 1995). Interestingly, the correlation results do not show any statistically significant relationship between depth and LOI or indeed between LOI and leucine assimilation, with only a slight correlation between LOI and AODC. This suggests that the amount of organic matter within the soil profile is independent of depth and that the presence of bacterial cells and their metabolic activity is independent of the amount of organic matter present within the soil environment. These patterns are unexpected as organic matter is predominantly present within surface soils as this is where the greatest amount of organic deposition occurs and also because it forms the substrate for the vast majority of microbiological activity (Blume *et al.*, 2002, Haynes, 1999, Hopkins, 1996, Taylor *et al.*, 2002). This apparent contradiction can be understood more fully through the study of the physical characteristics of the site. The variation in the distribution of organic rich deposits on Sutton Common, both in location and distribution within the vertical soil profile, appear to be the cause of the lack of any significant correlation.

The lack of a correlation between LOI and sample depth results from the presence of peaty soils on Sutton Common within the palaeochannel at Site 5, and adjacent to Shirley Wood at Site 9. In addition, there is an uneven distribution at Site 3 due to the presence of the organic-rich archaeological ditch-fill. In contrast, the typical profile of a soil that receives organic material, is of a surface horizon that contains a higher amount of organic material than the underlying horizons, this being termed the O or A horizon (Ellis &Mellor, 1995). Under these circumstances microbial activity, specifically aerobic activity, will be concentrated within the immediate surface soil horizon and will decrease rapidly with depth along with the relative organic matter content. By studying the LOI values for Sites 1 and 6, these sites being located away from peaty areas, it can be seen that this scenario exists, with proportionally higher levels of organic matter within the surface samples. Upon closer examination the data from AODC, extracellular enzyme activity and leucine assimilation at these two sites, the expected relationship of decreasing activity and bacterial biomass with depth is observed.

It has been established that depth plays a decisive role in terms of microbiological activity. One of the major reasons for this can be considered to be the change from aerobic to anaerobic conditions through the soil profile, usually expected to occur with the change to saturated conditions experienced below the level of the water table. The existence of anaerobic saturated conditions within the soil profile has been demonstrated across many locations on Sutton Common from the soil redox monitoring and through the discovery of well-preserved organic archaeological remains. The effects of anaerobic conditions upon the parameters that have been studied can be understood better with an appreciation of anaerobic conditions.

Although seemingly the balance between aerobic and anaerobic conditions in soil can be fine, with anaerobic conditions occurring on the micro-level around individual soil colloids that have water adsorbed to them (Gray & Williams, 1971), in general a change from aerobic to anaerobic conditions will occur at the level of saturation. This is due to the exclusion of the vast majority of oxygen from the soil fabric by water; due to oxygen diffusion in water being very slow (in the order of $2.62 \times 10^{-7}\ ms^{-1}$) (Caple & Dungworth, 1998). In contrast, the rate of oxygen diffusion through well-drained soil is in the order of 10,000 times faster (Mitsch & Grosselink, 1993). In saturated soil, oxygen that is diffused into the soil water at the saturation interface will rapidly be consumed and removed by microorganisms. Therefore, a stable saturated soil environment can lead to the predominance of anaerobic metabolism. This is inefficient in comparison to aerobic activity and there is evidence that the rate of carbon mineralization in wetland soil under aerobic conditions is about three times faster than that under anaerobic conditions (D'Angelo &Reddy, 1999) resulting in incomplete breakdown of organic substrates. This is because there is less energy yielded during anaerobic fermentation, leading to the formation of fewer microbial cells per unit of organic carbon degraded (Alexander, 1977). The presence of anaerobic conditions within the monitored soil profiles on Sutton Common is supported by the strong negative correlation between AODC and depth.

There is clearly a strong relationship between depth and the other variables measured during this exercise. A strong negative correlation exists between depth and bacterial cell numbers, as previously described, but also between leucine assimilation and β-glucosidase activity, with less significant correlations with the other enzyme activities. These can be summarised as –

- A negative correlation with depth, this being particularly strong for β-gluosidase activity.
- A significant, positive correlation between extracellular enzyme activity and organic matter content (proxied by LOI).
- A significant positive correlation between extracellular enzyme activity and bacterial biomass (AODC).

A decreasing enzyme activity with depth is to be expected as the greatest microbial turnover rates will occur in proximity to the ground surface due to the greater availability of Soil Organic Matter (SOI) and prevalence for aerobic activity (Hopkins, 1996). Therefore, a strong relationship with depth and AODC supports this theory, in that soil bacteria will be a major contributing source of the extracellular enzymes present within the soil environment (Morra, 1996). Such a relationship was identified by Turner *et al.* (2002) during studies into β-glucosidase activity in soil profiles.

The significant positive relationship shown between LOI and the activity of all the enzymes assayed, fits with the dynamics of microbial activity outlined above. However, it is clear that there is a far stronger relationship between LOI and enzyme activity than between AODC and enzyme activity. This is something that seems contradictory if bacteria are considered a major contributory source of extracellular enzymes within the soil environment.

Two possible scenarios explain this relationship of concentrated extracellular enzyme activity in association with organic content of soils. Firstly, the process of enzymes being produced by proliferating organisms in the presence of a suitable substrate (Turner *et al.*, 2002) and secondly, as a result of the accumulation of immobilised enzymes within the soil environment associated with clay and humus complexes (Haynes, 1999). This second process occurs when enzyme molecules are adsorbed to the anionic clay constituents of soil and soil colloidal organic matter. Such complexes can retain a proportion of their original activity and therefore represent extracellular biological catalysts that can be long-lived but unrelated to the actual microbial biomass present within the soil (Burns, 1983). With both of these processes occurring, it would be possible to identify a more significant relationship between LOI and extracellular enzyme activity than between LOI and AODC, i.e. a stronger relationship between enzyme activity and organic matter content than between enzyme activity and bacterial biomass. However, this pattern is not observed as clearly for β-glucosidase activity and a strong positive relationship does exist between AODC and leucine assimilation, this having no significant relationship with LOI. This situation, and the fact that β-glucosidase activity is the least represented of the three enzymes assayed, suggests that this enzyme is produced by microbial cells actively metabolising in the presence of a suitable organic substrate. It also suggests that this enzyme is the least susceptible to complexing, and therefore retention within the soil environment. A similar relationship was identified for β-glucosidase by Turner *et al.* (2002).

To summarise the relationship between the extracellular enzymes and the other parameters measured; it is clear that a significant relationship with both LOI and moisture content exists, with phosphatase showing the greatest correlation and β-glucosidase the least. This suggests that soil characteristics influence the activity of soil extracellular enzyme activity, with the exception of β-glucosidase where there is clear evidence that the presence of this enzyme relates directly to microbial activity.

The use of a simple correlation technique such as Spearman's rank has allowed distinct patterns to be observed within the microbial data obtained from Sutton Common. However, some patterns are clear from the data plots that are not highlighted using this technique. For example, the data from Site 6 show that there is little moisture and organic material, relatively few bacterial cells and little enzyme activity throughout the soil profile. There is practically no enzyme activity below the surface, whereas high values for microbial metabolism are measured within the surface samples. It is also clear that there are high enzyme activities throughout the full depth of the soil profile where the organic content is high; such as at Sites 5 and 9. Such patterns fall outside the general relationship of depth and the presence of organic matter and therefore are not identified in the correlation exercise. In addition to this, the application of correlation analysis to the microbial data does not identify changes between the first and second sampling visits, since all available data obtained during 2001 and 2002 were used. This therefore merits a closer examination of the available data to identify possible patterns of variation between the two visits for each sampling location.

An overview of the results obtained from all sampling locations for the three parameters measured indicates that apart from at Site 1, there are not any clearly identifiable differences between the samples obtained in 2001 and those in 2002. Samples were collected at approximately the same date, twelve months apart, although Site 9 had a two month difference with the 2001 sampling being in June and in 2002 it was in April. This was undertaken in an attempt to reduce the influence of seasonality upon the results. Therefore a lack of any great change across the results is not unexpected, and the significant change observed in the results from Site one can be considered real.

Site 1 has shown a more than doubling of bacterial biomass, leucine aminopeptidase activity and microbial metabolic activity between the two samples. This is in comparison to the remaining four sampling locations that show only a slight increase and for some of the analyses, a drop in values.

7.3.2 The impact of site flooding

Of greatest physical influence in terms of change to the burial environment during the study period, is from the impact of flooding on Sutton Common during the winter of 2000/01, this having already been shown to have had a significant impact upon both site hydrology and soil redox conditions. Figure 7.5 presents the water-levels within the piezometers associated with the microbial sampling locations, represented by line graphs, showing variation in the water table height over time. Also shown are the times that sampling for microbial analysis was undertaken; these are shown by vertical bars, the colour of which correspond to the piezometer data. What can clearly be seen in Figure 7.5 is that the 2001 sampling programme was undertaken during the period of heightened water table resulting from the flooding of Sutton Common. In comparison, the 2002 sampling programme was undertaken when the water table across the site had recovered to level comparable to those prior to the flooding event. However, the first Site 9 sample was taken once the water table had begun to recover in June 2001 and that location became accessible once again. The influence of this event upon Sites 1 and 9 was apparently not great with the depth of the water table within 0.2 m of the ground surface at the time that samples were taken in both years. Sites 3 and 5 show the greatest variation in water table depth, this being approximately 0.8 m and 0.4 m respectively.

Although Site 1 is one of the two locations that was in terms of the reaction of the water table height, least affected by the flooding event, it is this site that shows the greatest magnitude of change in the analysed variables between the two sample dates, both of which occurred in mid January. Although it is possible that the flooding has influenced the results of the analyses carried out in this location, the available evidence suggests that the observed changes are not attributable to the flood event but to some other influence. A major change that occurred within the vicinity of Site 1 during this period was in the type of land management that was subjected to the area. Prior to 2001, the whole of the Sutton Common site had been set-aside, being characterised by very heavy vegetation growth during the spring and summer months. However, during 2001 this was altered to regular mowing and the instigation of grazing on the site by cattle. It has been shown that the grazing of cattle can lead to increased microbiological activity in areas of stock camping (areas where livestock concentrate their activity) as a result of the concentration of organic materials through manuring and grazing (Haynes & Williams, 1999). However, there is no indication that the location of sampling at Site 1 was subjected to stock camping, and any effect would be expected to be offset to an extent by the reduction of organic input to the soil surface as a result of mowing for hay, this ultimately resulting in the removal of organic matter. In addition to this, as the rest of the monitoring locations were subjected to the same changes in management, although possibly not as concentrated due to the smaller size of the field within which Site 1 was located, a similar response in the analysed variables would be expected.

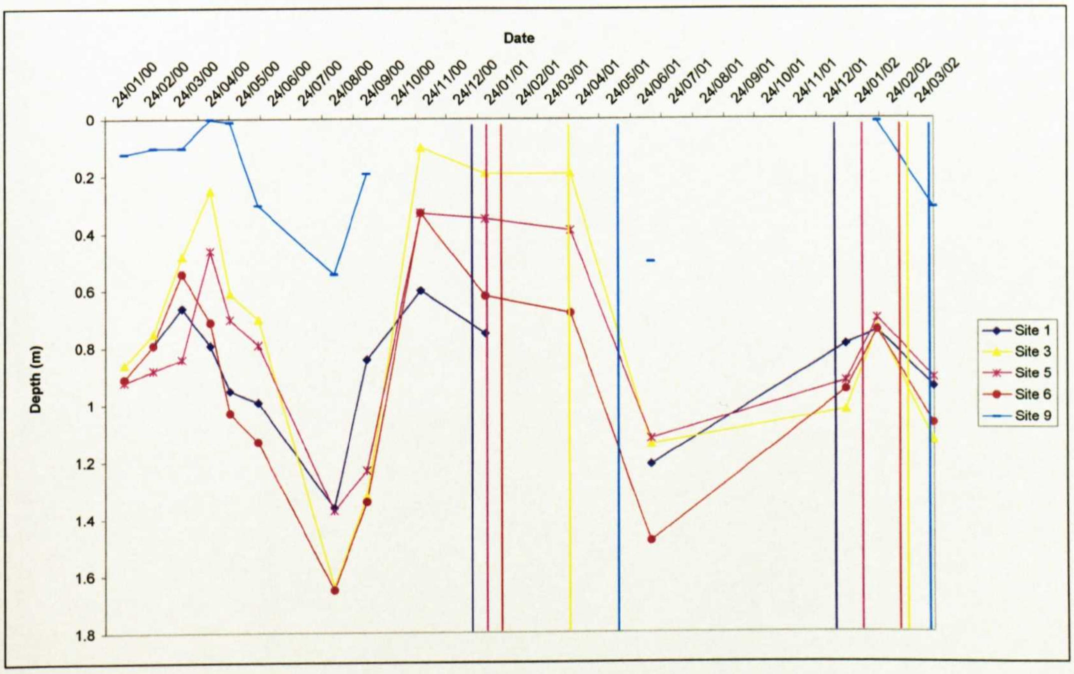


Figure 7.5 Piezometer water-levels (line graphs) associated with microbiological sampling sites and sampling dates (vertical bars).

Site 9 showed a slight increase in enzyme and metabolic activities, but a significant drop in phosphatase activity after a year. Such a change may be attributable to the affects of flooding. As discussed in the previous results chapters, Site 9 had maintained a water table close to the ground surface throughout the entire period of monitoring. Also shown was that this location may be subjected to groundwater movement during times of increased precipitation. This, coupled with the fact that this location was openly flooded to a depth of almost 1.0 m, means that the burial environment was potentially influenced by chemical contamination brought in by the flood water from the surrounding area. Bandick & Dick (1999), in their study of the effects of field management techniques upon soil enzyme activities, purposefully avoided using phosphatase activity as it can be influenced by phosphate fertilisers. There is no available data concerning the possible concentration of such materials in the flood water that inundated Sutton Common during the winter of 2000/01, but if the flood water did indeed contain elevated levels of phosphate then out of all five sampling sites it is Site 9 that may be the one most likely would record a change.

Similarly to Sites 1 and 9, Sites 3 and 5 do not show any clear effects of the flooding upon microbial activity. In fact, in terms of bacterial biomass, these sites show contradictory changes in the second samples, with an increase in bacterial biomass at Site 3 but a decrease at Site 5. The only other indication of change is a small but noticeable increase in metabolic activity within the surface, 2002 samples, although this could be explained by the removal of saturated conditions close to the surface, encouraging an increase in aerobic microbial activity.

The overall increase in observed metabolic activity across all five sampling locations does suggest that there has been a site-wide influence that has encouraged an increase in microbial turnover. This could relate to the flooding event, with activity being subdued during the time of raised water-levels in 2001, or through the changes in land management practices causing a change in organic matter input. Alternatively, there could be an environmental influence such as an increased ambient temperature. However the changes that do occur are slight across the greater part of Sutton Common apart from those observed at Site 1.

7.3.3 The influence of cattle grazing upon soil microbiological activity

To investigate the possible influence of cattle upon soil microbial activity, surface samples were obtained from three locations and were subjected to the same three analyses as the main sampling locations. A control location was selected outside the enclosed areas of the site and therefore assumed not to have been influenced by the presence of cattle, a sample was obtained from immediately next to a water trough, this being a concentrated area of activity, and a sample from within a 'scrape' within the internal ditch of Enclosure B, Figure 7.6. This location was chosen as the feature is known to contain well-preserved archaeological wood and an assessment of the potential impact of the camping behaviour upon this resource is desirable.

Figure 7.6 Location of cattle scrape from which a soil sample was obtained. Facing southwest located at the southern terminus of the internal ditch of Enclosure B.

The results of this exercise were inconclusive. There was evidence of increased extracellular enzyme activity at both targeted locations where there was cattle activity and increased levels of bacterial biomass within the archaeological feature were identified as compared to the control site. A pattern was identified, as described previously, of increased activity with increased organic matter content of the soil sample and also due to the lack of data from the locations prior to the onset of grazing. Since the organic matter content of the control sample was far lower than the two targeted location (approximately 13% as opposed to 34-35%) it cannot be conclusively stated that the increased levels are directly associated with an increase in microbial enzyme activity as a result of the instigation of cattle grazing. However, presentation of the results here is desirable as they create potential discussion points regarding the direction of possible future research.

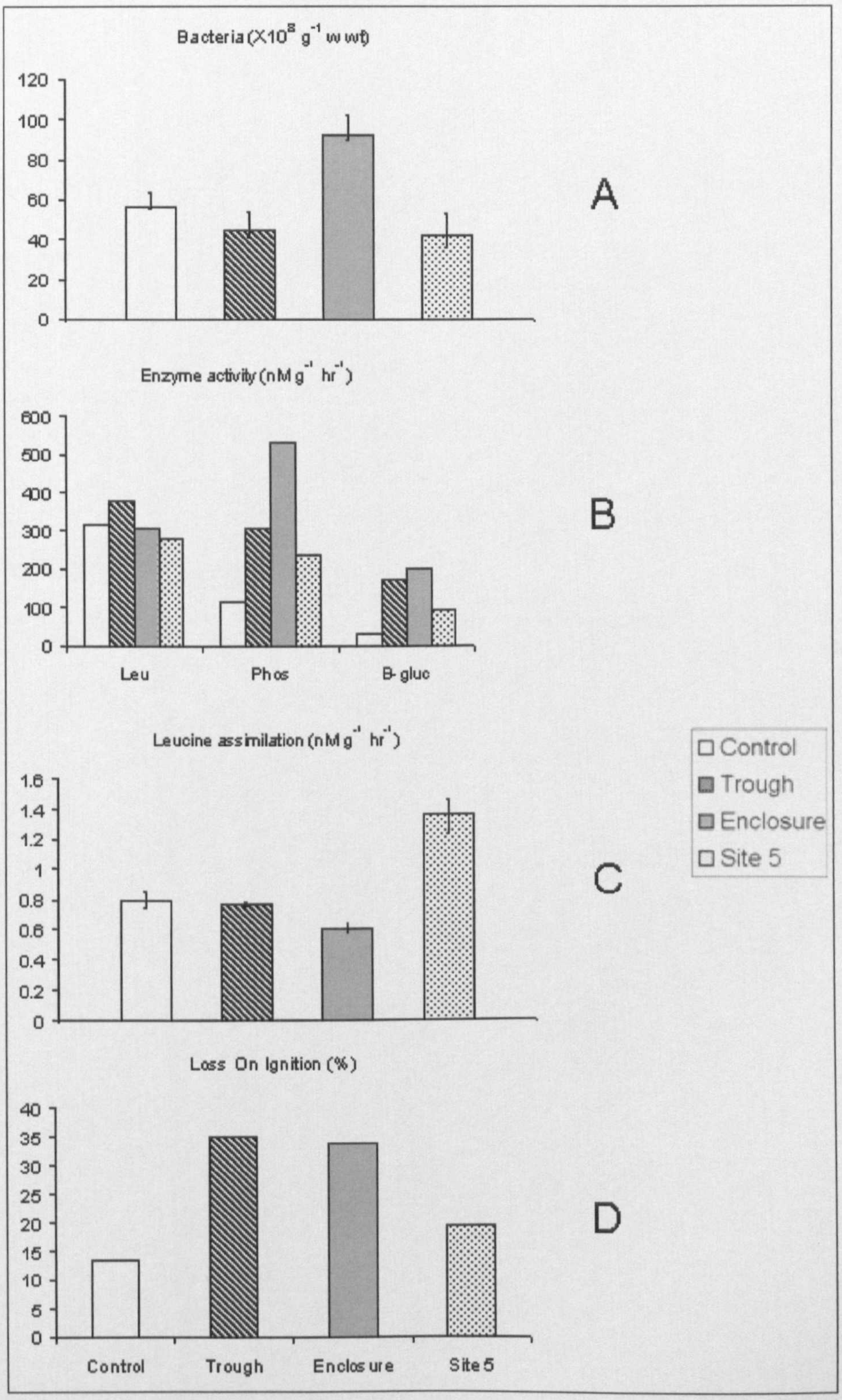


Figure 7.7 Results from targeted sampling to assess the effect upon the measured microbial parameters from cattle grazing. A – bacterial counts, B – extracellular enzyme activity, C – leucine assimilation rates & D - LOI.

Figure 7.7 presents the results from the targeted sampling and for comparison, the results from the surface, 2002 sample from Site 5 is included, this having been sampled in February 2002, as were the other locations for this exercise. From these results, it can be seen that the trough and enclosure ditch locations show elevated values for phosphatase and β-glucosidase activity and that the latter has elevated bacterial biomass compared to the other sites. However, measurement of microbial metabolism is relatively low when compared to Site 5, being approximately half. As mentioned previously, these two locations have provided high readings for organic matter content compared to the control location and Site 5, and as such elevated readings for parameters such as enzyme activity would be expected. However, comparison of the actual figures shows that readings for phosphatase within the enclosure ditch are almost twice those recorded from any sampled location and for β-glucosidase, at this location and the trough, the activity is also the highest recorded.

These results suggest that even though high activity would be expected in these two locations due to the large organic matter component of the soils, the activity is so great that the burial environment, at least within the surface soil horizons, is indeed being affected by the presence of cattle. However, as this exercise was not undertaken under strictly controlled circumstances, particularly with respect to sampling and a lack of measurements prior to cattle grazing, no definitive conclusions can be drawn. However, this particular question is of importance and an area requiring further research.

7.3.4 The assessment of anaerobic activity within the burial environment

With the impact of site flooding well recorded within the hydrological monitoring and soil redox potential results presented in previous chapters, a similar influence may be expected within the results of the microbiological assessment. However, it is clear that such an impact has not been clearly identified. Since all the techniques that have been carried out as part of the assessment were carried out under aerobic conditions and that there is evidence for the presence of anaerobic conditions present within the soil profile from redox monitoring, it is possible that the techniques adopted are incapable of identifying all the changes that are occurring. Such a hypothesis is also supported by the fact that extracellular enzyme activity has been identified at depth but in association with an almost complete lack of microbial metabolic activity, although as discussed previously, this may be as a result of clay-humus complexing resulting in the retention and accumulation of soil enzymes over long periods of time. Alternatively, activity may be because of the presence of anaerobic microbial activity, not identified previously. β-glucosidase is known to be active within an oxygen-free environment (King, 1986) and to be produced microbially under anaerobic soil conditions (Glissman & Conrad, 2002).

In an attempt to identify the presence of anaerobic metabolism, the leucine assimilation technique was adapted to be undertaken under anoxic conditions. This was achieved by obtaining a soil sample anoxically from Sutton Common using an anaerobic jar, creating a soil slurry using nitrogen saturated ringers solution and undertaking incubations within a nitrogen atmosphere. A control incubation was undertaken on an identical sample collected at the same time but under aerobic conditions, being subjected to the same procedure in an aerobic environment. Ten replicate subsamples were incubated under both anaerobic and aerobic conditions. The Mann-Whitney U-test was then applied to the results of this in an attempt to identify whether there was any significant difference in the outcomes.

Two locations were chosen for sampling and analysis using this approach, Site 3 within the archaeological ditch of Enclosure B at a depth of 0.75 m was sampled on 02/05/02 and Site 9 at 1.5 m depth on 15/11/01. Site 3 was chosen as well-preserved archaeological timbers have been identified within this feature during past excavation and previous measurement of microbial metabolic activity has indicated aerobic activity. The archaeological deposit at a depth of 0.75 m was targeted in an attempt to demonstrate that it was the subject of anaerobic metabolism. This in effect has a number of potential consequences as it demonstrates that a desirable anaerobic burial environment may exist but at the same time, that degradation via anaerobic digestion may be occurring. Site 9 was chosen as high readings of extracellular enzyme activity have been identified in comparison to those measured at other sampling locations.

At Site 3, a significant difference in the rate of leucine uptake under aerobic and anaerobic conditions was identified with average activity values under aerobic conditions being 132.817 pM g^{-1} hr^{-1} and anaerobic being 20.785 pM g^{-1} hr^{-1}. These results are important as they show that the actual methodology employed can successfully discriminate between aerobic and anaerobic activity therefore placing confidence in the results that have been obtained. The figure for the average aerobic activity correlates with that previously obtained from Site 3 at that depth and the value obtained anaerobically falls within the range of values obtained for leucine assimilation as a whole. This shows that the deposits in this location are actively aerobic but also are subject to a small, but identifiable anaerobic element.

At Site 9, no significant difference was identified in the results from aerobic and anaerobic incubations. The reason for this appears to be in the very low activity measurements recorded for both states, with average anaerobic activity being recorded as 1.137 pM g^{-1} hr^{-1} and aerobic activity actually being lower at -0.79 pM g^{-1} hr^{-1}. The negative sign indicates that the amount of leucine uptake within the sample is so small that it is beyond the resolution of the technique itself. These figures compare to an activity of 93.358 pM g^{-1} hr^{-1} for leucine from the same location and depth in a previous sample obtained on 13/06/01.

Comparing the two sets of results shows that there is a difference in the average activity values. The very low activity observed in November 2001 at Site 9 appears to be real, as the technique applied has been shown to be able to discriminate between aerobic and anaerobic activity from the results at Site 3. Since samples that were obtained before, in June 2001, and after this date, in April 2002, both showed the presence of activity, it appears that an alternative, perhaps environmental, influence was acting upon the sample. This factor was successful in subduing activity at 1.5 m depth at Site 9. The complexity of the microbial environment means that using the data at hand it is impossible to say conclusively what this influence is and how it operates. However, one possibility is that seasonality influences microbial activity, even at a depth of 1.5 m, and it is this influence that is being recorded in the results outlined above as sampling for this technique occurred during the winter season whereas the other two sampling times occurred during the warmer, spring and summer months of April and June.

Blume *et al.* (2002), in a study of microbial biomass, size and community structure as well as microbial activity in samples obtained from three depths in two soils, identified a distinct seasonal variation in activity in subsurface soil. Essentially a strong relationship between temperature and microbial activity but not between temperature and microbial biomass size was identified, this being especially so at greater depths. Therefore, such a response could have been observed within the samples obtained from Site 9 in November 2001, whereby a microbial population exists at depth but its activity varies on a seasonal basis.

However, Blume *et al.* (2002) highlight the sometimes contradictory nature of findings of studies that have been undertaken into the influence of seasonal changes upon microbial biomass and activity in subsurface soils. For example, there have been studies that have shown greater microbial biomass during the summer months, this being attributed to higher ambient temperatures (Buchannan & King, 1992, Kaiser & Heinemeyer, 1993). However, others show greatest microbial biomass in the spring and autumn months, this being a response to the changing rates of organic input such as leaf drop (Bååth & Söderström, 1992, Sarathchandra *et al.*, 1989).

Taking the sample data obtained during this research as a whole, we see that the majority of samples were obtained during the period between January and April; apart from the 2001 sample from Site 9, this being taken during June. Therefore, samples were obtained during the winter and spring months. No observed differences within the variables measured can be clearly attributed to seasonal variation, especially since the samples from each site were mostly obtained twelve months apart and therefore during the same season.

It is clear that the relationship between microbial activity, both aerobic and anaerobic, soil depth and seasonality, is potentially a very complex one. Without any reliable temperature data for 1.5 m depth at Site 9 throughout a twelve-month period, it is impossible to identify any potential influence upon microbial metabolic activity of temperature change as a result of seasonal variation. However, this exercise has revealed an area of potential further research that if undertaken, will broaden the knowledge of microbial dynamics within the soil burial environment and hence its potential affects upon the buried, organic archaeological resource, both at Sutton Common and at other similar sites.

It has become apparent that there is no clear evidence within the data obtained on Sutton Common on the soil microbial population, of an impact resulting from the flooding that took place during the winter of 2000/01. This is in contrast to the hydrological and soil redox monitoring, both of which clearly document this event. Additional work looking at the impact of cattle grazing, the analysis of aerobic and anaerobic microbial activity, and an overview of the potential impact of seasonality have highlighted the potentially complex nature of soil microbial dynamics. This is not only based upon the explanation of variation observed within results but also in an appreciation of the general lack of variation in an environment that is subjected to great change. Lawlor *et al.* (2000), in the study of soils subjected to large differences in land management practices, noted that microbial populations remained similar in size and overall composition. A similar situation may therefore exist on Sutton Common, whereby changes in the microbial population to such events as flooding or changing management, are inherently subtle. Lawlor *et al.* (2000), highlight the need for integrated approaches when looking at microbial populations that are either under different management practices or are perturbed in some way. This type of approach has been applied to Sutton Common and has yielded positive results, and enabled the effective characterisation of the microbial population across the site. However, the low resolution of sampling and a restricted number of samples throughout the soil profile have highlighted areas that require further work. These include the presence or absence of anaerobic activity within the Sutton Common burial environment, the impact of seasonality upon the microbial community and also the potential effects of cattle grazing. Overall, these suggestions relate to the requirement for an increase in sampling resolution in order to provide a real monitoring capability of the microbial dynamics, but also the addition of other environmental parameters, specifically temperature.

However, the lack of change observed as a result of the flooding may relate to the period of sampling. Initial samples were obtained a number of months after the actual flooding event occurred, and although there is evidence that the effects, shown by the hydrological and redox data, persisted until the summer of 2001, microbial changes within the burial environment may have already taken place. In this situation, both the sampling dates, 2001 and 2002, can be considered as postdating the flood event. Also, the effects of such an event may not be very great due to the differentiation between aerobic and anaerobic conditions. For example, an aerobically highly active soil may be inhibited through the inundation caused by flooding, however even under these conditions it may be significantly more active than a disturbed anaerobic environment. Therefore, to some extent, soils can be expected to retain their relative microbial characteristics even during and after times of change.

Other parameters not accounted for during this study were the effects of changes in pH on microbial dynamics, soil water salinity and parameters such as phosphate and nitrate concentrations. In the previous chapter, a medium-term change in pH occurred across the whole of the monitored site as a direct consequence of the flooding event and this therefore could potentially influence the status of the microbial population within the burial environment. Without higher resolution sampling and pH data from throughout the soil profile it is difficult to account for any changes that may have occurred specifically as the result of this. However, it is recognised that pH variability is a potential factor influencing microbial activity within the soil burial environment (Bååth, 1998).

Salinity has been shown to have an effect upon microbial activity (Frankenburger & Bingham, 1982) as has nutrient levels (Bandick & Dick, 1999), therefore measurement of these would provide an additional layer of information from which understanding can be drawn on top of those already assessed.

7.4 Summary

The microbiological assessment has not been carried out as a monitoring exercise in the same way as the hydrological and soil redox potential monitoring. As a result, the data obtained is not at a high resolution. However, samples for the analysis of microbial biomass (AODC), extracellular enzyme activity and microbial metabolic activity (leucine assimilation rates), have provided a detailed insight into the variation of microbial activity within the changing soil profile across Sutton Common.

The characteristics of each sampling site can be summarised as follows:

Site 1. The soil profile has a low organic matter content and moisture content, with high bacterial counts within the surface deposits rapidly decreasing with depth. Microbial metabolism follows a similar pattern. There was decreasing enzyme activity with depth, with leucine aminopeptidase activity being very high. Of significance at this location is the large increase in microbial metabolic activity at the surface observed within the second sample obtained in 2002.

Site 3. Results indicate that there is a relatively high organic matter content within the samples and values for moisture content at 0.75 m depth, this relating to the presence of organic rich archaeological ditch deposits at this depth. There was decreasing microbial activity for all measured factors with depth. An increase in activity was observed within the second, 2002, sample apart from for enzyme activities these showing a decrease in activity at 0.75 and 1.5 m, though there is a slight increase for surface values.

Site 5. There is a high organic matter and moisture content throughout the soil profile with the lowest values at the surface, this relating to drainage and breakdown of the surface peats, redistribution and mixing of adjacent mineral deposits resulting from previous ploughing and wind erosion. There is generally decreasing activity with depth for all measured factors and these show only a slight variation between the two sampling dates. Differences between the two sampling dates include a decrease in the number of bacterial cells with a contrasting increase in observations of metabolism and enzyme activity, this being especially apparent at depth.

Site 6. This location has very low moisture and organic matter contents throughout the whole soil profile, although there is a slight concentration within the near-surface deposits, with correspondingly low activity apart from for leucine assimilation, which shows relatively high rates. There is almost no variation in observed activity between the two sampling dates.

Site 9. There are very high organic matter and moisture contents throughout the whole soil profile at this location compared to all the other sampling sites. This is matched by relatively high values for observed enzyme activity and the presence of bacterial cells, but slightly reduced metabolic activity. There was, however, a consistently higher activity level at 1.5 m depth compared to 0.75 m for bacterial numbers and leucine assimilation, although this pattern is not as clear within the results from the enzyme assays. However, the results obtained for leucine assimilation during November 2001 show an almost complete lack of microbial activity, suggesting that this location may be subject to the influences of seasonal variation.

This chapter has presented the data from the microbial investigations that have been carried out on Sutton Common. Results from each individual parameter have been discussed and then patterns within the data as a whole, highlighted through the introduction of statistical analysis. Characteristics within the burial environments have been identified and interpreted.

General patterns identified during the course of this study are greater microbial biomass and activity associated with greater organic matter content, a decrease in activity and biomass with soil depth and a significant increase in activity between the samples obtained in 2001 and 2002 at Site 1.

From this work, it has been identified that there is a requirement for greater resolution of sampling and the use of additional parameters, specifically pH and temperature profiles at sample locations. Through the implementation of these changes it will be possible to identify the impact of seasonality and other factors, such as changes in the hydrological regime, upon the soil microbiological community. There is also a requirement for identifying anaerobic activity within the soil profile so that a truly stable environment, with near zero aerobic or anaerobic activity can reliably be identified. In addition, the ability to identify anaerobic activity could also help to identify positive impacts to the burial environment. These could be in response to changes in management practices or engineering activities, specifically those aimed at raising the water table.

The following chapter will integrate the findings from all the monitoring and investigated parameters, discuss their significance and attempt to interpret the main characteristics of the site.

Chapter 8 Discussion

8.1 Introduction

The three previous chapters have presented the results from the main research techniques employed on Sutton Common, hydrological and soil redox potential monitoring and soil microbiological assessment. These chapters have highlighted the main patterns identified within the results and discussed them within the context of Sutton Common and the wider literature. The present chapter will provide an overview of these factors in a holistic manner through integration of the different approaches made, identifying similar patterns within the data obtained during the study and therefore providing the means to apply an integrated approach to other archaeological sites. A critical assessment of the techniques will be undertaken, leading to a discussion of how improvements can be made to enhance the accuracy of monitoring of the burial environment and identifying areas that will benefit from further research.

The results of the study will also be used in the discussion of the important events that have occurred on the site, these being the impact of the re-wetting works through the re-engineering of the drainage system present on Sutton Common and the impact upon the burial environment of the flooding that occurred during the winter of 2000/01. The knowledge of the dynamics of the burial environment obtained from the monitoring will be related to these activities to enable discussion of the future survival of the organic archaeological remains that exist within the burial contexts of Sutton Common.

8.2 An overview of the work undertaken on Sutton Common

Interpretation of the results from the techniques applied to Sutton Common was undertaken in the previous three chapters, but there has been little integration of the results. It is therefore useful to outline the main findings that relate to each of the techniques.

8.2.1 Hydrological monitoring

The hydrological monitoring that has taken place on Sutton Common has enabled the water table and its dynamics to be characterised very effectively. The work has showed that the water table is relatively shallow across the whole site, being predominantly within 2 m of the ground surface throughout the monitored area. There were occasions during the monitoring when in specific locations the water table appeared to fall to depths greater than this, but this only occurred for short periods during the driest times of the year.

It was established early on through the creation of GIS surfaces that the water table was not uniformly flat but that it in fact followed closely the contours of the surface topography. The form of the water table was very characteristic, with there being a substantial groundwater mound lying below the extent of the archaeological Enclosure A, this relating to the topographically higher ground in this area. There were two low areas of the water table, in terms of elevation, these being along the eastern edge of the monitoring grid and also within the southern part of the Hampole Beck palaeochannel. Again, this correlates very closely to the topographically low points of the site.

Similarly to the groundwater mound being present below the extent of Enclosure A, a smaller, more ephemeral, but still represented groundwater mound was shown to exist below Enclosure B. However, this feature was seasonal and during the summer and autumn months was not present. The reason for this was due to what has been the most dramatic characteristic of the water table on Sutton Common, the annual variation in the height of the water table attributable to seasonal variation. The results of the hydrological monitoring have clearly shown that this pattern exists, with the lowest water table levels being recorded in late summer and early autumn when the water deficit is at its peak. These changes have manifested themselves differently over the monitored portion of the site in relation to the topographical changes and hydrological characteristics of different areas. For example, the greatest seasonal variation is observed below the topographically higher regions, whereas the smallest variation has been observed in the lower areas mentioned previously, suggesting that these locations are perhaps acting as hydrological sinks.

These locations are characterised by having a generally higher organic matter content within the deposits, this being a reflection of the maintenance of a high water table and predominantly saturated conditions resulting in the formation and retention of peat. However, although it seems likely that these low areas are currently acting as hydrological sinks, and therefore the location of water loss from the groundwater reservoir, this is complicated by the fact that there are a number of diverse influences acting upon this process. Observations of the saturated hydraulic conductivity of the deposits present on Sutton Common, although limited in extent, have provided an indication that there may be a difference between the conditions present within the palaeochannel, which demonstrates a slower movement of water, and the surrounding areas of greater elevation, which have a greater hydraulic conductivity. This situation of more restricted groundwater flow within the deposits of the palaeochannel may result in flow around this area with the consequence that significant groundwater loss was occurring along the boundaries of the monitored area. Alternatively because there was a low resolution of the measurements of saturated hydraulic conductivity, these readings could be a reflection of the inherent complexity of the fluvial deposits present and that there are stratigraphic elements of these that form high flow conduits. The complexity of this location is further supported by the observations from the piezometer cluster located in the northern part of the palaeochannel, data from which indicated the presence of a localised perched water table at the ground surface resulting in the surface ponding of water.

The variation in hydrological characteristics of the deposits also has an influence upon the form of the water table, as well as the variable topography of the site. The water table can simply be defined as the upper surface of the zone of saturation (Ward & Robinson, 1990), although this does not adequately account for the presence of a near-saturated capillary fringe lying above this. A more sophisticated definition can be given as the point at which the fluid pressures within the pores of a porous medium exactly match atmospheric pressure (Freeze & Cherry, 1979).

As previously stated, the shape or profile of the water table closely resembles that of the surface topography and is determined by this factor along with the amount of precipitation and the hydraulic properties of the deposits themselves, specifically the saturated hydraulic conductivity. Essentially, water accumulates within deposits as a result of retentive soil forces up to a point where flow occurs along a hydraulic gradient from areas of high to low potential. Hubbert (1940) was first to present this situation in the form of a flow net (Freeze & Cherry, 1979) as shown in Figure 8.1

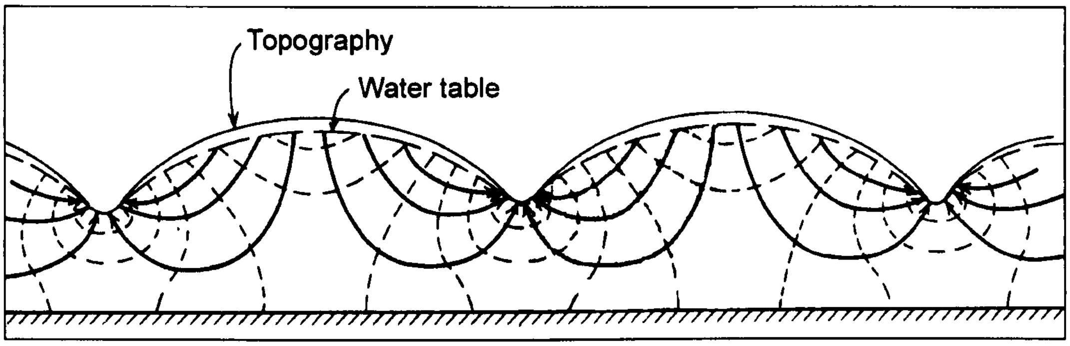


Figure 8.1 A cross-section groundwater flow net through a homogenous, isotropic system bounded at its base by an impermeable boundary (adapted from Freeze & Cherry, 1979, after Hubbert, 1940).

A flow net consists of a series of lines of equal potential, and flow lines that indicate the direction of groundwater flow, this being perpendicular to the lines of equipotential. The two main determining factors for soil water potential are elevation and fluid pressure, and in the simple homogenous, isotropic example provided in Figure 8.1, the equipotentials can be determined from the estimation of how these two factors vary. The DEMs representing the form of the water table over the monitored area of Sutton Common are also a representation of hydraulic head and therefore can be used to understand groundwater flow within the vertical plane. Essentially groundwater flow occurs from areas of higher ground to those that are lower, these broadly relating to areas of recharge and discharge. Areas of recharge can be defined as an area of the drainage basin where the net saturated flow of groundwater is away from the water table and in such a situation there is a component of direction to flow that is downward. In a discharge area the opposite situation occurs where the net saturated flow is directed toward the water table and a component of this is upward (Freeze & Cherry, 1979). A consequence of this situation is potentially the upward flow of groundwater in low-lying areas.

An appreciation of this theory explains the observations of the form and the changes that occurred within the water table on Sutton Common throughout the monitoring period. The groundwater mound observed below the extent of Enclosure A occurs due to the raised topography in this area and the size and extent of this feature varies in response to effective precipitation within the system. In consequence the groundwater mound enlarges during the winter months as opposed to the drier months where a soil moisture deficit occurs. In contrast, the groundwater dome observed beneath Enclosure B, only occurs during wetter periods and this is due to its smaller size and therefore less water is retained. This process also explains the observations of a persistent near-surface water table within the southern area of the palaeochannel and along the eastern fringes of the monitoring grid adjacent to Shirley Wood. These areas are topographically the lowest and therefore at the lower end of the hydrological gradient. Logically therefore, it is from these areas that groundwater would be expected to be lost, however, without any indication of surface flowing water this is difficult to verify.

It is clear from the monitoring results and the analysis of the water budget on Sutton Common, that the water table is influenced significantly by seasonal variation. This is reflected in the rising and falling water table heights through a yearly cycle reflecting excesses and deficits within the groundwater system. Through the creation of a water balance making use of the hydrological models generated from monitoring data, precipitation and evapotranspiration data, and through comparison with the reaction of the levels deep, within the regional groundwater aquifer, it has been established that the water table on Sutton Common is predominantly precipitation fed. The consequence of this is that the water table is seriously impacted upon during times of soil moisture deficit. It is under these conditions of low rainfall and high rates of evapotranspiration, that very low water table heights have been observed.

The effects of the flooding that occurred during the winter of 2000/01 have been very well recorded by the hydrological monitoring, with the highest water table heights being recorded during this period. Although during this time large areas of the Hampole Beck palaeochannel held surface water, the results of monitoring the northern piezometer cluster has revealed that this is most likely to be surface ponding and not where the water table has broken the surface, at least within the northern extent of the palaeochannel (of the monitoring grid). This was shown by consistently different readings being obtained (refer to section 5.2.3) indicating the presence of different hydraulic heads in this particular location.

The effects of the flooding event persisted long after the surface water that had been allowed to accumulate had dissipated. Piezometer readings were consistently high across the whole of the monitored area of the site until April 2001, with many locations recording a near-surface water table during this period. Since this type of event had not occurred prior to the re-engineering of the field drains and installation of the dams in the drainage ditches, it is difficult to estimate the contribution that these had in retaining the wet conditions. However, in times of water excess the dams could clearly be seen to hold back water on the site, whereas previously this would have immediately been lost through drainage. Therefore, it is likely that this work has had a beneficial effect in terms of the maintenance of a higher water table although it is not significant enough to be observed clearly within the monitoring data as a whole.

Possibly the most significant development in terms of assessing the relationship between the water table and changes therein and the archaeological resource, is the development of the archaeological wood model. With ArcGIS it has been possible to show within 3-dimensions, the interaction between archaeological timbers and the water table and therefore assess more accurately than ever before the impact of management changes upon the archaeological record. This approach has led to the recognition of three 'zones', dry, intermittently wet and saturated, within the burial environment each relating to particular conditions and the impact of these on archaeological remains has been recognised. This has been possible solely through the use of a monitoring grid, thus providing knowledge of the form of the water table.

8.2.2 Redox monitoring

The results of the redox monitoring have shown that very distinct patterns exist within the burial environment in terms of soil chemistry, but also that there is a very great diversity in the character of the burial environment across Sutton Common as a whole.

A very strong pattern observed within the results is the relationship between depth and Eh, with the vast majority of values observed indicating reduced conditions at depth across the whole site; this pattern has been termed redox stratification during this study. The only real circumstances where this pattern is not observed are either under continually saturated or very dry conditions. An example of the former is at Site 9, located within the deep peat deposits adjacent to Shirley Wood, where due to this area being topographically low, the water table remains within approximately 0.5 m of the ground surface. This has led to a relatively narrow range of Eh values being observed throughout the 1.5 m of the monitored soil profile, with readings varying between +100 and -200 mV. Sites 7 and 8 are located upon relatively high topography, and as such have a deeper and more fluctuating water table. Since measurement of Eh in the field relies largely upon the presence of soil moisture (Stumm & Morgan, 1981), obtaining accurate results under very dry conditions will potentially yield a high degree of variation. Although under these conditions the expected oxidised nature of the burial environment can easily be identified, there can be little clear evidence for redox stratification as shown at other locations. Locations experiencing such conditions can also exhibit a large degree of variation throughout the period of monitoring.

These examples also highlight the strong relationship between saturation and Eh, with significantly lower readings being obtained under saturated conditions than under dry. The presence of redox stratigraphy is in part the result of the presence of saturation at depth, this leading to the exclusion of air and removal of aerobic conditions, and thus a trend towards a reduced environment. The changing depth of the water table also highlights this relationship very clearly at certain monitoring locations, such as at Site 2, where a change of in excess of 500 mV has been observed in response to a fluctuating water table. Here, rising water levels resulted in a drop in the observed Eh values and conversely a drop in the water table resulted in increased Eh readings.

The reaction to a changing water table also shows that soil redox monitoring is capable of identifying seasonal variation within the burial environment as such fluctuations have been shown to be a function of seasonal change. However, such changes are not always uniform across all the monitored locations highlighting the capability of redox monitoring as a means of effectively characterising the different burial environments present on Sutton Common. For example, as previously outlined the drier areas of Sites 7 and 8 are characterised by generally oxidised conditions, with readings fluctuating greatly, whereas in other saturated areas, readings reflect reduced conditions with a restricted range. In addition to environments that are oxidising and highly variable and those that are reduced and relatively stable, a third situation exists, such as that at Sites 3 and 5, where stratified conditions indicate highly reduced conditions at depth whilst oxidised conditions exist within the proximity of the ground surface. This shows that the approach taken in terms of the redox monitoring is capable of identifying a range of burial conditions, including those that are stable, providing a very effective tool for characterisation purposes.

The influence of organic material upon soil redox conditions has also been identified at Site 5, located within the palaeochannel. This location has a high organic matter content, and extreme redox stratification occurred. This is a function of the associated high potential for microbial activity in organic rich soils with this material acting as an effective substrate. Under dry aerobic conditions, observed in the upper soil profile, extremely high Eh readings were obtained. Conversely, at depth where saturation has been maintained, the opposite pattern was observed with very low Eh values recorded. In addition to this, redox values appear to react quickly and more extremely than elsewhere indicating that in this location the soil redox conditions are heavily mediated by microbial activity.

The most significant results obtained from the programme of soil redox monitoring, has been the identification of the effects of the flooding that took place upon Sutton Common in the winter of 2000/01. The impacts of this event, and its consequences, have been clearly recorded and this has provided an understanding of the reaction of the burial environment to such events. Across the whole site the presence of excess water has been recorded as a movement of Eh towards a value of approximately +100 mV (when readings are adjusted to pH 7), although this pattern is not as clearly observed in the drier monitoring locations. This indicates that the presence of the floodwaters, in effect flushed through almost the entire soil profile creating very similar redox conditions throughout. In addition, it is clear that for several months following the event, the water table across the majority of the site was maintained in a high state and that this continued to influence soil redox conditions. During the following spring redox conditions on the whole reverted to their previous ranges following a drop in the water table. However, through the development of a simple method to create Eh/pH stability diagrams, it has been possible to identify more subtle redox changes and patterns within the soil profile not observed in the linear diagrams where Eh values are adjusted to a standard pH of 7.

The use of Eh/pH diagrams has shown that under 'normal' conditions on Sutton Common, i.e. with no flooding, there is a wide distribution of redox conditions on the site and that in general this distribution does not alter too significantly over time. However, the effect of the flooding can be observed very clearly, with Eh values being severely restricted across all the recorded monitoring locations following the event. In addition, there was a gradual restriction in the range of recorded pH from the monitoring locations and this pattern continued to be apparent until at least July 2001, almost nine months after the flooding took place. There can therefore be little doubt that the flooding event caused a significant and lasting change within the burial environment.

8.2.3 Microbiological assessment of the soil on Sutton Common

As microbiological activity within the soil profile is the major agent of decay of organic materials, including those that are archaeological, it is logical that such activity should be accounted for to some degree when assessing the virtues of *in situ* preservation. To date, very little work targeted specifically at the interaction of microorganisms and archaeological remains has been carried out and the research in this field has been targeted almost entirely on the microbial impact upon wooden materials, such as Powell *et al.* (2001), and not upon characterising the microbial activity itself. Studies that have approached characterisation have tended to rely upon techniques that are not best suited to assessing the degrading activity upon archaeological wood, such as scanning electron microscopy (Brunning *et al.*, 2000).

The work undertaken on Sutton Common has provided baseline information using easily available and established techniques that are to able provide a holistic overview of microbial dynamics within the soil profile. The use of three approaches covering the assessment of microbial biomass, extracellular enzyme activity and microbial metabolic activity, can account for the inherent complexities in soil microbial dynamics. Some very strong patterns have been identified across the sampling locations on Sutton Common, such as generally decreasing enzymatic, metabolic activities and biomass with depth; although the relative variation between these factors is more complex. For example, there is a significantly stronger association between enzyme activity and organic matter content than enzyme activity and depth. This association appears to be related to two possible, separate processes; enzymatic complexing with organic matter resulting in the accumulation of extracellular enzymes within the burial environment and secondly, the fact that microbial activity is associated with organic matter which forms an available substrate. However, even within this there is another layer of complexity with the data suggesting that β-glucosidase activity is more associated with metabolic activity and therefore not subject to accumulation within the burial environment.

Metabolic activity, identified through the measurement of assimilation rates of radio-labelled leucine, is particularly well represented within the surface soil stratigraphy. This indicates that the greatest amount of microbial turnover takes place here, something that is to be expected as it is within these regions of the soil profile where the majority of aerobic soil microbial activity will be present. In contrast to this, the presence of bacterial biomass was identified throughout the profile and not concentrated within the surface profile to the same degree. This suggests that microbial activity, although present at depth, may have less turnover and it indicates the possible presence of anaerobic activity at greater soil depths. To test such an assertion, the leucine assimilation method was developed so that collection, transport, preparation and incubation of soil samples could be undertaken within anaerobic conditions. Although such an approach was not widely implemented and the majority of work was carried out under aerobic conditions, it was successful in identifying anaerobic activity within archaeological contexts and as such proves that such field measurements can be implemented in future studies.

Across the wider site little variation was identified between the two samples obtained in consecutive years apart from at Site 1, which saw a significant increase in bacterial biomass and microbial metabolic activity. Although differences were identified at other locations, these were not as clear as at Site 1 and therefore could not be used to identify changes within the microbial population. Those changes observed at Site 1 were attributed to the possible influence of changing management practices taking place upon Sutton Common at this time. This location was outside the main site and was subject to earlier, and more intensive, changes due to its smaller size.

To assess the impact of one particular change, the grazing of cattle upon the site, samples were analysed that were obtained from stock camping areas and areas of concentrated activity. Although the findings were not conclusive, due to there being a lack of previous comparable data, this work suggested that there was a possible promotion of microbial activity through this activity.

There has been no clear indication of the impact of the site flooding upon the microbial population on Sutton Common. Although there are indications of changes in soil redox potentials and pH that could be attributable to microbial activity, no significant evidence for similar changes in microbial dynamics have been forthcoming. However, initial soil samples were only obtained from the site actually following the flood event, and although the site was still subject to a raised water table, if changes occurred rapidly then they could not have been identified. Although the second round of sampling occurred twelve months later, when conditions had reverted to those prior to the flooding, no significant changes attributable to this could be identified. Reasons for this may be that any changes that occurred as a result of the flooding persisted during the entire period of sampling. Alternatively, it is possible that the opposite is true and that the flood event had little impact and that the microbial conditions observed approximate those prior to it occurring.

The approach taken to the microbial assessment of the burial environment has allowed the different sampling locations to be accurately characterised. For example, the variation in activity between Site 6, within the extent of Enclosure A and Site 9, within the deep peat deposits adjacent to Shirley wood, is very great. Site 9 is characterised by the presence of enzyme activity and bacterial biomass throughout the soil profile, whereas Site 6 presents the opposite scenario but has a greater concentration of metabolic activity within its surface profile. The ability to undertake this type of assessment within archaeological contexts could prove to be incredibly important when attempting to understand and characterise the burial environment in terms of *in situ* preservation. However, it is recognised that the work carried out on Sutton Common has not targeted specific archaeological contexts other than the internal ditch of Enclosure B, and therefore there is little evidence of the relationship between archaeological remains, such as wooden posts, and the wider soil medium. For example, during recent excavations within Enclosure A, the vast majority of organic archaeological remains identified were vertically aligned wooden posts. Inspection of these revealed that the quality of preservation improved with depth, with some deeply lying, fully saturated material being very well preserved indeed. This concurs with the very strong patterns of decreasing microbial activity and representation with depth, but there can also be little doubt that the organic content, acting as a substrate, is sustaining a far greater and probably a far more active microbial population than that represented in the surrounding soils that have a low organic content. The fact that the activity levels within the subsoil at Site 6 were shown to be very low, but that degradation of archaeological posts was shown to be well advanced supports this. It therefore seems logical that the archaeological posts are providing their own microenvironment that is likely to be highly complex. For the application of microbial techniques, further understanding of the sphere of influence of this microenvironment and how it develops over time is required.

The assessment of microbial activity has not only provided baseline data in understanding microbial dynamics within the soil profile, specifically in relation to the presence of organic archaeological remains, but it has also highlighted the areas and parameters that require further research if such a technique is to become a useful tool. The current work has provided tentative evidence for a number of different processes, such as seasonal variation and the impact of changes in land management practices, but has been unable to make strong conclusions. This has mainly been due to the low resolution of sampling from Sutton Common and the fact that samples were obtained at each location at the same time of year. This has meant that although the sampling programme was carried out over a relatively long period seasonal variation has not been identified conclusively. Also, a number of additionally measured parameters, such as soil ambient temperature and changes within the pH of the soil, could explain the variation observed within the samples analysed but were not undertaken as part of this study.

Of the three parameters studied on Sutton Common, microbiological assessment possibly holds the most potential for further enhancing the knowledge of the burial environment of organic archaeological remains, specifically that of archaeological wood.

8.2.4 Integrating the different parameters

The previous three sections have provided an overview of the main findings from the work carried out on Sutton Common. As the techniques used have been very different, effectively encompassing three different disciplines, it is useful to discuss the results in relation to each other in an attempt at integration.

Throughout the presentation of the results obtained from the programme of monitoring and assessment, patterns have been observed and highlighted. There has been a particularly strong relationship between changes observed within the site hydrology and changes in soil redox potentials. This can be summarised as saturated conditions being necessary for the creation of a reduced burial environment, and therefore during dry conditions the burial environment is predominantly oxidised. This also means that during periods of change from saturated to dry conditions, or vice-versa, there will be a similar change observed in soil redox conditions.

There was little evidence of a strong relationship existing between microbiological activity and hydrology or soil redox conditions. However, this may be a consequence of the low resolution of the microbial analysis therefore making comparisons difficult. In addition, the microbial dynamics appear to be influenced by other physical factors, such as depth and organic matter content within the soil, making it harder to ascertain strong relationships.

It is clear that using techniques to obtain data on the hydrological, soil redox and microbiological conditions on Sutton Common has successfully enabled the characterisation of the burial environment at different locations on the site to an unprecedented level. These findings are presented below for the nine locations used for soil redox monitoring.

Site 1

This location has a water table that is subjected to seasonal fluctuation in the region of 0.7 m, with the upper limit being at approximately 0.7 m depth. Oxidised conditions prevail throughout the soil profile, although moderately reduced conditions exist at 1.5 m. Microbial activity is concentrated at the soil surface with a high turnover rate indicated.

Conditions at this location are indicative of a poor preservation environment, especially those within the upper 1.0 m. This location can be considered to be unstable.

Site 2

This location is subjected to a highly fluctuating water table throughout almost the entire monitored soil profile, with a range of approximately 2.0 m. As a result, oxidised conditions prevail, although these vary in response to changes in saturation.

This location can be characterised as being highly unstable and would not be expected to support good preservation of organic archaeological remains.

Site 3

Site 3 is also subjected to a water table that fluctuates highly with changes throughout the monitored period of almost 2.0 m. This has resulted in a generally oxidised to only moderately reduced burial environment, with some fluctuation reflecting the variable levels of saturation present. However, at 1.4 m depth there appears to be relative stability, with redox readings indicating that reduced conditions are being sustained.

Overall, this location is again relatively unstable and therefore good preservation would only be expected at a depth in excess of 1.5 m.

Site 4

Although Site 4 is located within the southern part of the palaeochannel and maintains a near-surface water table during the wetter winter months, it was still subject to approximately 1.5 m fluctuation in the depth of the water table during the first annual cycle up to October 1999. Redox data obtained after this date showed less fluctuation in the water table and these indicate a far more stable burial environment with highly reduced conditions being regularly observed at below 0.9 m depth.

Due to the greater length of time that the soil profile remains saturated in this location, preserved archaeological wood should be present, especially at or below

1.5 m as this has maintained constant saturation throughout the period of monitoring.

Site 5

Site 5 is characterised by very strong redox zonation in the soil profile. Results have shown that there is a prevalence of highly reduced conditions at 1.4 m, but that this is disturbed during the annual low-water periods as the water table level drops below the monitored levels. This results in a change in conditions from highly reduced to moderately reduced. Similarly to Site 4, the summer low observed during 2000 is significantly higher than previous years. Microbial activity is identified through the entire monitored soil profile, although this may be a reflection of the high organic content of the soil in this location.

Predominantly due to a continued marked variation in the depth of the water table throughout the period of monitoring, preservation of archaeological wood within the upper 1.0 m is unlikely to be good. However, reduced conditions have been identified below this depth indicating a degree of stability, and therefore preservation at and below this depth may occur.

Site 6

During normal seasonal fluctuations, the depth of the water table rarely reaches 0.5 m from the surface and for the majority of the monitoring period it remained far lower. This situation is reflected in the highly oxidised conditions identified within the upper 1.0 m of the soil profile. During periods of higher water table, reduced conditions are briefly attained at 1.4 m depth.

High quality preservation of archaeological wood is unlikely at this location as a result of the low levels of saturation present within the soil profile and the resultant oxidised conditions.

Site 7

This location shows very similar characteristics to those of Site 6 with a highly fluctuating, generally low water table and oxidised conditions throughout the soil profile, other than at 1.4 m depth where reduced conditions are occasionally recorded during periods of greater saturation. The preservation potential therefore reflects that of the previous location, being poor.

Site 8

Site 8, like the wider area, is heavily influenced by seasonal changes in the water table with winter highs being consistently within 0.5 m of the ground surface and the annual fluctuation is in excess of 1.0 m. The seasonally low water table appears to decrease progressively in depth from the beginning of monitoring until August 2000.

The fluctuating water table encompasses the entire depth of the monitored soil profile and this is reflected in the redox results obtained from this location. There is a great range in redox conditions, from oxidised through to highly reduced, with this type of variation occurring at all depths apart from at 1.5 m, this remaining lower due to the greater length of time that saturated conditions remain at this depth.

The fluctuating water table height and soil redox conditions indicate that this location is not stable and would not therefore be expected to contain well-preserved archaeological wood.

Site 9

Site 9 has remained the most saturated location of all the monitored locations, with the water table never dropping below 0.75 m and has remained at, or very close to, the ground surface for long periods of time. This stability is reflected in the soil redox conditions that have had a restricted range and indicate that a reduced or highly reduced environment has persisted. The difference between this location and the others, is also reflected in the microbial dynamics with metabolic activity seemingly being subdued throughout the soil profile in comparison to some other locations, but with a more evenly distributed presence, especially in terms of bacterial biomass and extracellular enzyme activity.

Due to its inherent stability, coming from the continual saturation, this location would be expected to exhibit very well preserved archaeological wood below 0.5 m depth if it exists in this location.

This work has highlighted a natural 'hierarchy' within the monitoring parameters. From the above individual site characterisations, the defining influence of saturation, and hence the water table, upon the burial environment is very clear. The preservation of organic archaeological remains is greatly influenced by the degree of saturation within the burial environment and this therefore must be perceived as the primary variable in any monitoring approach. This position is further enhanced through the relative ease with which the necessary equipment can be obtained and its inherent flexibility and cost effectiveness. The hydrological data can be considered as baseline data, covering a wide area of the site and to this soil redox monitoring can provide an added insight into the dynamics and status of the burial environment. For example, it is clear that the whole site is influenced greatly by seasonal variation in the water table and that burial conditions vary in response to this. However, different responses in the burial environment can be observed as a result of these influences. It is such differences that soil redox monitoring is capable of identifying and therefore providing an extra level of information. To this, information on the microbiological status of the burial environment can identify the intensity of microbial activity within the burial environment and hence assess the level of threat posed to the buried archaeological resource from this major agent of decay.

This pattern is also a major characteristic of the findings from other monitoring programmes that have taken a similar approach to monitoring the burial environment and that have used similar techniques. For example, Brunning *et al* (2000) in their study into the *in situ* preservation of the Sweet Track, recognised that the water regime (this being the seasonal pattern of wetting and drying determining the amount of water within a hydrological system) determines the balance between oxidation and reduction within the soil profile. This in turn plays a major role in the microbiological activity that leads to the decomposition of organic materials. Hogan et al (2001) support this finding in studies carried out in estuarine and coastal environments, these contrasting to the peatland environment of the Sweet Track and the diverse soil environments present on Sutton Common. Therefore, factors affecting the hydrological regime such as seasonal variation determined by the balance of evapotranspiration and precipitation can have the greatest potential impact upon the burial environment. This is one of the strongest findings at Sutton Common that is supported in those studies identified above. Overall, all the studies identify hydrological conditions as being the primary factor affecting the potential for *in situ* preservation of organic archaeological remains.

Where the work carried out on Sutton Common differs most from these other, similar studies, is in the approach undertaken for the study of microbiological activity. Brunning *et al* (2000), focus upon the condition of archaeological wood, and although Hogan *et al* (2001) tested for a more diverse range of microorganisms, the technique of quantifying colony forming units can be seen as a relatively unsophisticated approach, and therefore the results generated are also relatively restricted. In comparison, the techniques employed on Sutton Common are diverse, provide a far greater insight into the microbiological status of the burial environment, and have highlighted the potential benefits of being able to monitor changes to this in both space and time. As stated previously, it is possible to utilise these techniques in collaboration with hydrological, soil redox and other monitoring parameters, such as soil chemical analysis, to provide a suite of tools that can effectively characterise the burial environment.

This has been possible through work carried out into the microbiological impact upon archaeological wood, but also making use of monitoring techniques to characterise the burial environment. Powell et al (2001) have carried out such work in their experiment/study at Flag Fen (see 1.2.1) and confirmed the conditions under which degradation takes place within environments containing archaeological wood. They also identified that the primary factor dictating burial conditions, is the presence or absence of saturation.

In the early 1990s when the problems facing the *in situ* preservation of wet-preserved, organic archaeological remains began to be highlighted, studies identified the possible means by which conditions within the burial environment could be understood. These included the use of hydrological techniques and of soil redox potentials (Caple, 1993, 1994). This approach was further refined through preliminary monitoring programmes and the creation of a framework for future monitoring (Caple & Dungworth, 1998). The work carried out at Sutton Common can in some ways be considered the third generation of study into the burial environments with the aim of *in situ* preservation of organic archaeological remains, along with those carried out by Brunning *et al* (2000), Hogan *et al* (2001) and Powell *et al* (2001). However, the large-scale monitoring programme running for almost three years, and the approach taken for assessing microbial activity on Sutton Common, defines the progressive approach taken in the current study.

8.3 Critical assessment of the techniques used

The techniques used on Sutton Common have provided a wealth of information regarding the dynamics of the burial environment and the factors that influence it. However, difficulties were experienced during the course of the study, both in the fieldwork component, but also with the desk and lab-based elements. Therefore, it is prudent to provide a critical assessment of these issues and to identify possible sources of error and where possible, to quantify this.

8.3.1 Hydrological monitoring

The monitoring of the water table present on Sutton Common has been effective in characterising the dynamics of the site in detail but it is necessary to assess the accuracy of the methods used and to identify the problems that have been experienced. Through this approach, future work can be progressive and build upon the experiences at this site. Three broad areas will be discussed in terms of error, these being: problems associated with the monitoring equipment, problems with data acquisition and finally problems associated with the use of GIS software to create and interpret hydrological data.

Equipment

The use of piezometers to undertake hydrological monitoring is advantageous due to the ease and relative low cost of sourcing and installing the equipment. However, during the course of this project a number of problems were identified with the use of this equipment that potentially impacted upon the accuracy of the data obtained.

No routine maintenance was undertaken upon the piezometers within the monitoring grid unless there was a specific reason; such as visible damage. However, because of the duration that the piezometer grid was in place, there is a possibility that silting up or blocking of the piezometers tips could have occurred and thus adversely influencing the readings obtained. It is assumed that such a process would result in a longer period being required for the observed water level within a piezometer to react to changes in the water table, this being due to a reduction in the ability of the piezometer tip to conduct water. Although it is likely that this process has occurred to some extent, no evidence of problems with specific pieces of equipment has been identified and as routine removal and cleaning of 50 piezometers would be prohibitively costly, it was not carried out. Future long-term monitoring programmes making use of similar equipment must bear in mind that this process may influence readings. Therefore, based upon the experiences of this monitoring programme, the removal, cleaning and if necessary replacement of some or all piezometers should be considered if monitoring is to continue in excess of three years.

Another possible cause of error within the results obtained from the piezometer grid results is from vertical movement of the equipment over time. As described in Chapter 3, the absolute height of the water table was obtained by relating the piezometer water level with the absolute height of the ground in that location, this information being obtained through GPS survey. Over time, through changes in ground flora and disturbance, the absolute height of the ground in any location will have changed, and this coupled with vertical movement of the piezometer can create an ongoing source of error. However, as there have been no obvious changes in ground level other than that which occurred in relation to the site tracks, it is assumed that such changes are relatively small, within the range of approximately 0.1 m. With regards to future monitoring programmes, if this is considered a potential problem then equipment installations should either be protected against movement by fixing, or periodically checked and resurveyed.

Possibly the greatest single physical influence upon the ability to collect water table data was the impact of changing management practices on the site. It was found that the plastic tubes of the piezometers were susceptible to damage from mowing for hay as they were raised above the ground surface resulting in a number of pieces of equipment being smashed on separate occasions. Suitable marking of the locations was effective in preventing this from occurring but removal of the markers by the cattle that were introduced to the site at a later stage, once again meant that piezometers were vulnerable to damage. It was also found that maintaining an effective monitoring programme during the time that cattle were present on the site was impossible when piezometers were left unprotected. Cattle are naturally inquisitive animals and following their introduction to Sutton Common in the summer of 2001 it was found that piezometers were subjected to trampling and removal of the tops of the equipment preventing water level readings being obtained.

Simple methods for the protection of the piezometers were tested but were found to be ineffective and thus during the times that cattle were present on the site, hydrological monitoring ceased. This has highlighted the requirement for an effective method for the protection of monitoring equipment where cattle and other animals will potentially interfere. A simple, but untested approach could be through the creation of a recessed 'manhole', this meaning that the piezometer would not protrude above the ground surface and therefore be vulnerable to damage from farm machinery and also secure enough to prevent interference from animals.

Data quality

Piezometers were chosen over dip wells for the monitoring on Sutton Common because of their simplicity, ease of installation (as they have a small diameter and can easily be hand-cored into place) and flexibility (as they measure hydraulic head). However, the fact that they measure hydraulic head may pose problems if confined conditions occur within the soil profile as a result of the presence of an impermeable layer. Where confined conditions are not present, piezometer readings are equivalent to the water table and this condition was expected within the monitoring grid. In order to check this, three piezometer clusters were installed on the site, one within the extent of Enclosure A and two within the palaeochannel. Although limited in resolution, data collected show that there is very little hydrostratigraphy at the three locations, especially at piezometer 23. However, differences in the readings obtained from piezometer 20, located within the northern part of the palaeochannel, have shown that there is potentially an element of stratification in this area. Although this is consistent within the results obtained, the actual difference is small, in the region of 0.15 m and therefore can be considered minor. Therefore, the reasons for the presence of this pattern cannot be definitively explained other than indicating a level of complexity within the deposits in this location that is not observed elsewhere. Detailed explanation of this would require further, high resolution investigation of the sediment stratigraphy and associated hydrological properties in this location, along with monitoring of its hydrological dynamics. Overall then, this exercise has shown that across the main topographically characteristic areas of the monitored site, the potential for major hydrostratigraphy that could impact upon the quality of the hydrological data obtained is small.

Another possible influence upon the quality of hydrological data obtained from the site is in terms of the resolution of the data itself, both in time and spatially. Of greatest impact is the fact that there were relatively large monitoring intervals and these varied throughout the period of monitoring. Due to time constraints and the distance involved in travelling to the site, a monitoring period of two weeks was chosen and this was maintained throughout the first twelve months of monitoring. However, following this the regularity of monitoring visits deteriorated in response to the changing emphasis of the other parameters studied on the site and to the difficulties experienced in obtaining data. From the hydrological results, it seems clear that the resolution of the data has had an impact upon the explanation of some of the patterns observed, especially in terms of the response of the site water table to individual precipitation events or prolonged periods of rainfall. It seems that if these occur within a short time prior to a monitoring visit, then they have a greater chance of being recorded within the data. However, the fact that a response may not be observed within the data does not necessarily mean that there was none, it may just mean that the water table has reacted to a point where it can no longer be identified within the observations due to the extended period of time between these being made and the event itself. This situation is further complicated by the influence of seasonality upon the hydrological dynamics, whereby during times of great soil moisture deficit there may be little observed response to precipitation events.

The monitoring resolution could be dramatically improved through the utilisation of dataloggers in the collection of water table data. This has been shown to work effectively and to be capable of identifying clear response to individual precipitation events (Cheetham, 1998). The major drawback of the use of such equipment is the expense of purchasing and the risk of damage and interference, especially at the scale used during the present study. However, valuable additional data could be made available from the use of a few targeted pieces of equipment and problems of security can be overcome through the use of secure containers.

The spatial resolution of the monitoring grid was specifically designed with a view to create GIS modelled surfaces from the observations made and can therefore be considered unprecedented in terms of the size of the area being monitored, especially in comparison to other archaeological monitoring programmes. However, on several occasions during the course of the monitoring, data was not obtained from individual or groups of piezometers. Reasons for this include the piezometers being dry, being covered by standing water, or from the equipment not being found during the course of a monitoring visit. Two piezometers were recorded as being dry on relatively regular occasions, numbers 10 and 28, these being found in the topographically highest areas within the two archaeological enclosures, this occurring during the driest time of the year in late summer and early autumn. In contrast, some of the piezometers locations were occasionally vulnerable to inundation by standing water rendering observations impossible. These factors have led to 20 of the interpolated surfaces relying upon less than the intended 50 data points, with the most points missing being six. However, the majority of these models have less than three missing data points.

GIS-generated water table surfaces

Throughout this work the GIS generated continuous, interpolated surfaces are referred to as models. This term is used as they are virtual representations of the water table surface at the time that monitoring was undertaken. When the models are presented in the form of colour-shaded images, the interpretation of change over time involves the direct comparison of the images generated and therefore is unavoidably subjective and potentially biased. However, the potential drawbacks of this have been avoided as far as possible through the reliance of accurate additional data, such as precipitation data, that can be adequately related to changes observed in the GIS models. This has been taken further, through numerical and statistical comparison of data derived from the GIS surfaces, specifically the volume of saturation, and other sources such as precipitation and evapotranspiration data, and therefore patterns observed through image comparison are reinforced.

The GIS models have also been used in an objective and quantitative manner through the creation of an archaeological wood model, where spatial data concerning the location of archaeological wood identified through excavation, has been incorporated with the water table data in order to understand in greater detail the relationship between them.

The use of continuous, interpolated surfaces generated from sampled point data has therefore provided a useful tool to assess the threat to surviving organic archaeological remains on Sutton Common. However, with these surfaces sometimes being generated with points missing and then being compared to surfaces created with the full 50 data points, it is necessary to assess the likely degree of resultant error. 'Data points' refers to the spatial location of the piezometers within the monitoring grid from which water table height data was obtained.

The methods used to analyse the quality of the interpolated surface follows the introspective analysis method presented by Chapman (2000), whereby it is assumed that interpolation will generate minimum and maximum values slightly outside the range of the original data but with minimal variation in the mean. Secondly, the effects of increasing error are assessed through direct comparison of surfaces created sequentially from data of progressively lower resolution to the originally observed values.

A set of piezometer data relating to the height of the water table on 07/01/00 was chosen, this date not being affected by factors such as flooding and therefore contained a full set of 50 readings. Ten piezometer locations were randomly chosen - 12, 14, 9, 1, 45, 47, 36, 34, 42, 21 (refer to piezometer location map in Appendix 2). Ten surfaces were created, systematically removing these points and then the resultant values for the height of the interpolated water table at these locations were obtained along with the maximum, minimum and mean of each of the surfaces.

Table 8.1 presents the range and mean values of the models derived from the sequential removal of data points. Overall, there is little change apart from for the minimum range values, which see a drop of over 0.2 m following the removal of the six data points. The mean values vary across all the models by approximately 0.01 m. The original values presented in Table 8.1 are those derived from the GIS surface interpolated from the full original dataset. The values for range and mean from the source piezometer data are – maximum 4.67, minimum 2.98 and mean 3.8284. Comparison of these to the derived values, shows that the mean is close to the source data mean and that there is little variation, with maximum values being approximately 0.06 m greater and minimum values being less than 0.01 m until the relatively large reduction observed with the removal of the sixth point. Excluding this last point, the models fit with the assumptions placed by the introspective analysis described by Chapman (2000).

Table 8.1 Max, min and mean values from error models. Original = values derived from 50 data points. Units are m O.D.

Number of points removed	Maximum	Minimum	Mean
Original	4.7268	2.9768	3.9073
1	4.7299	2.9768	3.9131
2	4.732	2.9768	3.9107
3	4.732	2.9768	3.9122
4	4.732	2.9768	3.9118
5	4.732	2.9772	3.9109
6	4.732	2.7309	3.9105
7	4.7319	2.7309	3.9088
8	4.7319	2.7309	3.9091
9	4.7319	2.7309	3.9066
10	4.724	2.7309	3.9132

The drop observed in the minimum values when six data points are removed is interesting and highlights some unique characteristics of the Sutton Common monitoring grid. As has become clear during the course of this study, the water table on Sutton Common is highly influenced by topographic variation on the site. This means that in locations where there are relatively large changes in topography, there are also similar changes within the water table. In essence, anisotropy exists within the GIS model where the removal of certain data points will have a greater effect upon the resultant model than others do. This effect can be particularly acute where relatively rapid changes in the slope of the water table are observed adjacent to the edges of the grid, where there are no surrounding data points. Such a situation exists with the removal of the point representing piezometer 47. This piezometer is located in the low topography adjacent to Shirley Wood along the eastern edge of the monitoring grid where the water table slopes down eastwards from the relatively higher ground of Enclosure A. With the removal of this location, and without surrounding data points, the slope of the water table was interpolated downwards further, creating an overly low reading in the region of 2.7 m O.D, whereas in reality the actual water level in this location was nearer 2.98 m O.D.

An alternative method of assessing the impact of point removal from the data grid is through comparison of the changing heights at specific points on the interpolated surface as more points are removed. However, these locations are not the same as the source locations thus avoiding the potential problems associated with using Spline interpolation where the surface will go through the origin. This method can therefore assess the effects experienced over the surface away from the input points. Figure 8.2 shows the location of the five points chosen.

Figure 8.3 shows that the reaction of the height of the interpolated surface in the locations detailed in Figure 8.2 is small. This demonstrates that the removal of individual data points has little effect upon the surface generated outside the area immediately adjacent to them and that even where change does occur it is generally small.

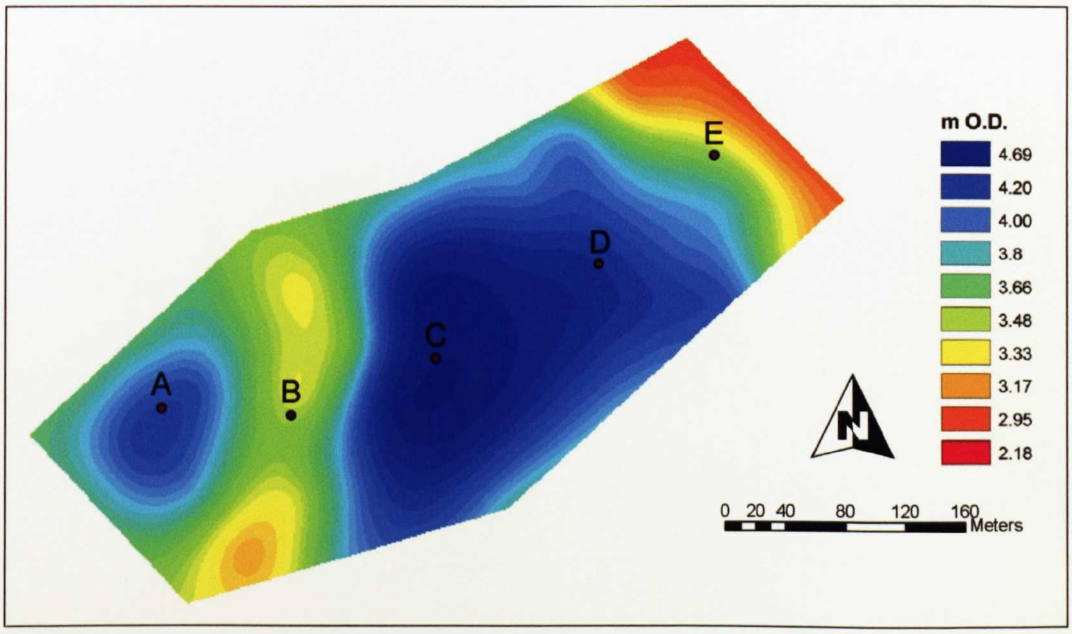


Figure 8.2 Location of points used to test variation in the interpolated surfaces on a surface generated from data collected on 07/01/00.

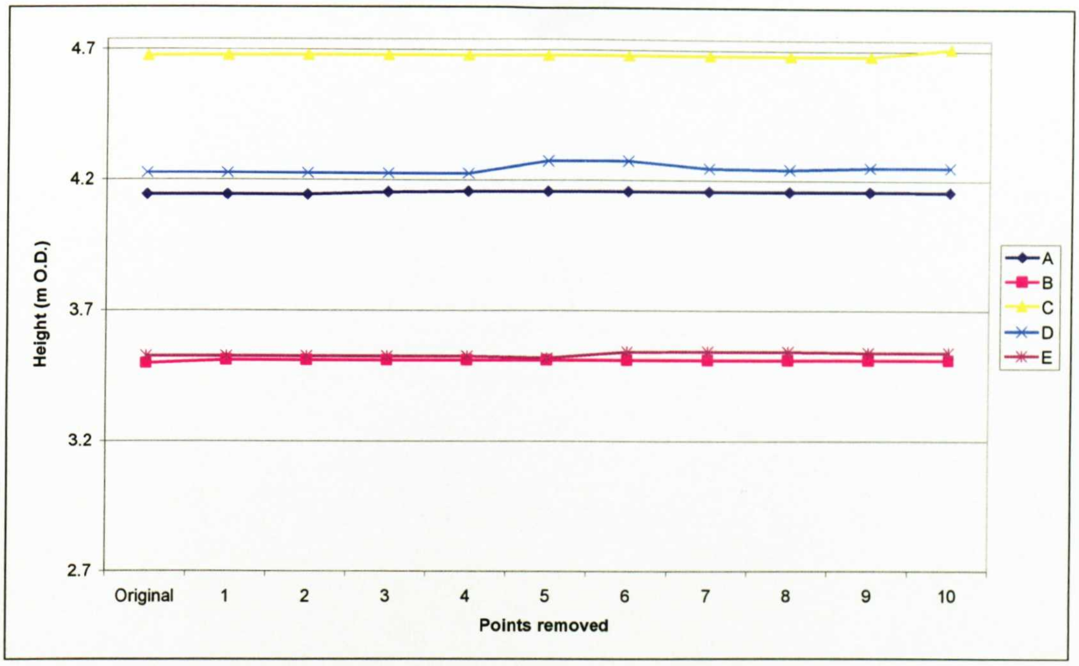


Figure 8.3 A graph showing the reaction of the surface generated from data collected on 07/01/00 at five points with systematic removal of 10 datapoints.

Another method of testing the relative accuracy of the monitoring grid and its robustness to the removal of individual data points, is to vary the resolution of the grid itself. Figure 8.4 presents the interpolated surfaces from the original 50 m resolution grid and also that produced from a grid of a reduced resolution of 100 m. The original 50 data points have been reduced to 14, but from visual comparison, or externalised analysis, it can be seen that the main features of the water table are still largely identifiable; such as the groundwater mound, the location of the palaeochannel and the low water table adjacent to Shirley Wood. This highlights the inherent benefit of using a regular grid for the input of data to be interpolated to create a surface. Robinson and Zubrow (1999) show that the use of a grid is more efficient in the reconstruction of an original surface than other, non-regular forms such as polygons, and that increasing the resolution of the grid reduces the amount of error encountered.

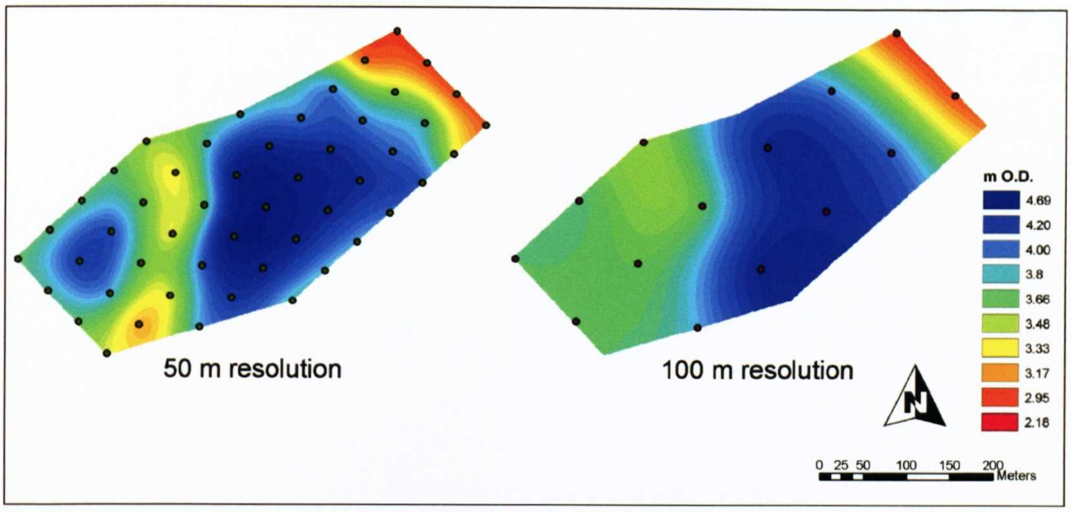


Figure 8.4 Interpolated surfaces representing Sutton Common water table using grid resolution of 50 m and 100 m, using data collected on 07/01/00.

This assessment of error has demonstrated that the method for creating interpolated surfaces from source data retrieved from the piezometer grid on Sutton Common is robust, and that no significant changes occur with the removal of up to 10 data points. Also demonstrated are the benefits of using a monitoring grid to maintain a uniform resolution of water table data and that even with a considerably reduced resolution, the main artefacts identified within the water table are still seen. It has also shown that missing data points along the eastern edge of the monitoring grid will produce a possible interpolation error of approximately 0.25 m.

It is recognised that this assessment has been specifically focused upon the effect of missing data points upon the interpolated surfaces and therefore relative accuracy between the individual models presented. As such, it does not necessarily reflect the accuracy of the water table model with the situation in reality. Therefore, it is acknowledged that future work along these lines would require an element of ground truthing to be undertaken to determine the degree of correlation between the model surface and the water table proper. A simple method for this would be through the placing of randomly located piezometers within the monitoring grid but between the grid nodes, and then comparing the actual water table height at that location with the predicted level obtained from the model. This could ultimately yield a tolerance level for the models created by this approach.

8.3.2 Soil redox monitoring

The programme of monitoring of soil redox potentials has been very successful in helping to characterise the variable burial environment on Sutton Common. The strength of this technique is that it can be used as a proxy indicator for the identification of truly anaerobic environments, rather than purely saturated conditions, these being the ideal conditions for the continued preservation of organic archaeological remains. However, throughout the course of the programme a number of issues have arisen that could impact upon the effectiveness of the results presented in this study and are also highly relevant for future programmes.

These issues will be discussed in relation to the equipment used, acquiring the field data, manipulation and presentation of this data and finally the interpretations based upon these.

Equipment

Although the operation of the redox monitoring equipment is based upon fundamental principles and the *in situ* probes used are inert, 'off the shelf' equipment that can undertake the same operations is not commercially available. Handheld Eh meters and probes are commercially available but these are unsuitable for *in situ* use, something that is essential for effective monitoring of the burial environment. Previous studies making use of such equipment have made use of a dipwell to obtain Eh readings. For example Caple (1993), proposed such a method to investigate parameters within anoxic burial environments, including Eh. However, such an approach has been shown, through experimentation, to produce misleading results, and cannot therefore be recommended (Caple and Dungworth, 1998). The equipment used in this study has been designed specifically to remain *in situ* to maintain the accuracy of readings. A drawback of this is the requirement for access to a laboratory environment for the construction and testing of the probes, both prior to and at the conclusion of a monitoring programme. Although the probes used during the study were procured, future implementation will require resources for their construction, thus possibly making it unattractive. In addition to this, the construction of platinum tipped probes of this design can be expensive if a relatively large number are required. As the method relies upon the use of clusters of probes to generate reliable data, the monitoring of several locations would require a significant financial outlay with the price for individual probes being approximately £15 at the time of writing.

Problems were experienced with the reference probe utilised during the course of data collection, requiring the purchase of a replacement. Although storage of the probe followed the recommended procedures, it became clear that over a period of more than twelve months the accuracy of the readings were becoming questionable. Laboratory testing of the probe was carried out using a redox standard solution and an unused redox probe. The reference probe consistently produced results outside the expected range of +/- 15 mV as compared to an unused piece of equipment.

There can be little doubt that the occurrence of this problem impacted upon the accuracy of Eh results obtained from Sutton Common. However, the changes that occurred were gradual, probably over a number of weeks or months, as a detailed review of the results obtained with this probe did not indicate changes outside those that were expected. It is therefore estimated that any error in the results that had occurred was in the region of tens of mV rather than hundreds. Crucially, this event highlighted the fragility of the probes used and entrenched improved practice with regular testing of the probes.

During the course of testing the redox probes within the Department of Biological Sciences, University of Hull, laboratory constructed Ag/AgCl were operated and found to maintain a higher degree of accuracy than those that were purchased. Also, this type of probe proved to be far more stable and if errors were identified, the probe can be quickly and easily reconstituted through the replacement of the electrolyte. Such electrodes are easily maintained and can be of rugged construction so enabling effective field monitoring to at least the standard of reproducibility of commercially available reference electrodes (Farrell *et al.*, 1991).

The redox probes used during this study remained *in situ* whilst readings were being obtained for approximately 2.5 years. Throughout that time there was little evidence of inaccurate readings and probes were only replaced as a result of damage to the insulation or the heat shrunk seals, or when probes were lost from interference. There has therefore been a reliance on the probes retaining their accuracy throughout the period of monitoring. However, the 'poisoning' of platinum tipped redox electrodes in the soil environment has been documented, this being attributed to the absorption of organic substances on the platinum surfaces or to platinum-sulphide reactions (Bohn, 1971). Recent research into the viability of permanently installed platinum redox electrodes has contradicted this, with evidence that electrode performance was not significantly impaired after five years in the field. Also, laboratory testing of the probes used in this study following removal showed that very few, 3 out of 102, were faulty (Austin & Huddleston, 1999). In order to gain an idea of the numbers of possibly faulty probes installed on Sutton Common, three clusters were removed from the site prior to excavations in June 2002 and were laboratory tested using a redox buffer solution. Similarly to the above study, only 1 out of the 47 probes recovered was found to give a faulty reading, showing that the vast majority of the probes installed have maintained their integrity throughout the monitoring period.

Problems in obtaining accurate soil redox measurements at times of dry soil conditions, especially during the summer months, has sometimes led to erratic and inconsistent readings being taken in the field. The irreproducibility of redox potentials in dry, oxidised conditions due to the low concentration of redox couples is well documented (Bohn, 1971). However, the situation is further complicated through problems associated with poor electro-connection of the reference electrode with the soil as a result of the low level of soil moisture present. Although this is seen as a relatively minor problem as the results obtained from Sutton Common follow expected patterns, there can be little doubt that this problem will have influenced the quality of results. Veneman and Pickering

(1983), present a method by which such problems can be avoided using a (semi)permanently installed salt bridge, consisting of a plastic tube containing KCL-agar-phenol solution into which the reference electrode is placed at the time that Eh readings are taken. The use of such an approach in future monitoring programmes could ensure greater accuracy and reproducibility of results obtained during the measurement of soil redox potentials.

Data acquisition

The resolution of the monitoring of soil redox potentials has been relatively low, being less than monthly, and is therefore possibly only identifying the more dominant patterns within the environment. The reason for this low resolution of monitoring visits is due to the time taken to obtain the data and the distance required to travel to the site, meaning that relatively few visits could be made. In addition to this is the fact that taking readings was very difficult in anything other than dry and still conditions. This was because if the equipment connections became wet, variable and drifting readings were observed therefore affecting the reliability of the results. Similarly to the problems experienced with taking piezometer readings, sometimes results were not obtained due to the monitoring locations not being identified as a consequence of disturbance.

As with the hydrological monitoring, there is a potential role for datalogging in future monitoring programmes. The use of such equipment, although not of the same construction as that used in the present study and over shorter timescales, has been applied on a number of other sites during an extensive study by Caple and Dungworth (1998).

Data manipulation and presentation

The area of soil redox monitoring that possibly has the greatest potential for the creation of error within the data is during the manipulation and presentation of the results. The biochemical principles behind the theory of redox conditions within soils are relatively easy to grasp in basic terms and the literature available on the application of this technique in an archaeological context reflects this. However, none of the available information, including the detailed English Heritage sponsored work carried out by Caple and Dungworth (1998), provides enough detail to enable application of the techniques without prior knowledge or use of the equipment. During the course of the current study it has become clear that in order to ensure accuracy within the data presented, a firm knowledge of the chemical principles involved is required, not just an appreciation of the significance of the results obtained.

Raw data requires adjustment to the Standard Hydrogen Electrode (S.H.E.) for comparison purposes and also to account for variation of pH. However, pH readings are obtained from the ground surface only whereas redox conditions are measured at depth where pH may vary significantly. The current study has not been able to take this factor into account and this problem requires further investigation, but there may be a pH influence upon the reference electrode that has not been accounted for.

The presentation of redox data can be in two forms, the 'linear' pH adjusted form over time, or the Eh/pH stability diagram. As stated within Chapter 6, the use of stability diagrams can be misleading as they are designed to be used to predict the chemical form of particular chemical species under particular conditions. Within the environmental context of the soil environment this is not possible and the user needs to be aware of this in order to avoid making false statements. Therefore, the large number of ways that the raw data can be/is manipulated must have the potential for introducing error into the results. During the course of this study every effort has been made to ensure the accuracy of the calculations and of the means by which the gathered data is collected.

8.3.3 Soil microbiological assessment

The aim of the microbiological assessment portion of this work was to generate baseline data and explore the feasibility of using microbiological techniques as effective tools in understanding the burial environment and how such factors vary within it. This was perceived as a progressive step towards the implementation of such techniques in the regular monitoring of archaeological sites. An assessment of the likely sources of error in the data generated during the course of the investigations is desirable to judge the accuracy of the results and to highlight potential problems for future work.

Sampling

When attempting to measure some aspect of the activity of microorganisms, a crucial source of error will be through contamination of either a sample itself, or at some stage during the analysis of it, and if it occurs, this can produce misleading results. Therefore every effort must be made to prevent this from occurring. Possibly the greatest opportunity for contamination to occur is during the sampling of the soil material itself. This is because the samples obtained from lower down the soil profile must be withdrawn to the surface past other soil stratigraphic layers. In saturated conditions where soil pore water fills the auger hole, the possibility of such contamination increases. During sampling on Sutton Common the risk of this occurring was minimised as far as possible through the swift removal of samples from the ground and by taking material from within the middle of the auger equipment only, thus reducing the potential for taking material that had been exposed to external conditions. Contamination of soil samples was not identified through the course of the assessment and this may be as a result of the naturally low level of microbial activity within the soil itself.

The frequency of sampling visits to Sutton Common was very low, with only one repeat visit being made to each location. This was because the microbiological component was not the primary focus of the work carried out, with the relative expensive nature of the reagents and substrates along with transport to the site, the number of sampling visits made was restricted. This has meant that a major factor, such as seasonal variation, that has been demonstrated to significantly affect hydrological and soil redox conditions, has not been accounted for. There is no doubt that such an influence induces a reaction within the soil microbial community, but at present this is not understood on Sutton Common. Also, additional factors have been identified as necessary to take into account if the microbial dynamics are to be accurately understood; these being temperature change throughout the soil profile and pH variation. Although both of these factors were measured as part of the assessment exercise, they were not monitored routinely at the time of sampling.

The storage of samples has been discussed in detail in Chapter 3. The emphasis throughout the course of the assessment has been on undertaking the analyses as rapidly as possible following sampling taking place and thereby reducing the opportunity for the characteristics of the samples to alter. However, it is recognised that the conditions of soil storage are dramatically different than those within the soil itself and therefore changes within the samples are unavoidable to a certain degree. This will be especially apparent in samples obtained from anoxic burial environments that were shown to be sensitive to exposure to air during early activity measurements using an oxygen electrode (data not shown).

Laboratory analysis

The laboratory techniques employed for the analysis of samples were established methods with the necessary equipment already in place; apart from the anoxic leucine assimilation technique, this being developed from the standard leucine assimilation technique specifically for the purpose. Therefore, the opportunity for error to occur is seen as minimal, apart from experimental error associated with the techniques themselves. However, throughout the entire assessment there was an emphasis on the use of sterile media, equipment and the maintenance of sterile conditions through the use of proper aseptic technique.

Within the laboratory environment the greatest potential source for contamination was through the use of contaminated water and ringers solution, where filtering through a 2 μm filter and/or autoclaving had failed to sterilise/remove bacterial cells. However, the counting of blanks during the course of AODC enabled contaminated media to be identified and disposed of.

Interpretation

Due to the limited number of observations made it has been difficult to generate firm conclusions about the burial environment other than for the clearest patterns exhibited. It has also become clear that in order to present the results of the microbiological assessment in an effective manner, a detailed understanding of soil microbiology is required, something that has been difficult to achieve due to this being a relatively small component of the study.

It is essential to recognise that the observations may not relate directly to the conditions that the organic archaeological remains that survive are exposed to. From the excavations that have been undertaken on Sutton Common, it is clear that the materials themselves create their own microenvironment within which active and rapid degradation can take place even though there is little microbial activity or biomass recorded within the soil parent material. Therefore, conclusions made on the basis of microbial investigations into the burial environment need to account for this apparent contradiction.

8.4 Further development of techniques

During the course of the monitoring taking place on Sutton Common, a number of areas where improvements can be made in the methods used and the approaches made, have been identified. These ideas have developed as a result of the problems that have been directly experienced during this study, along with searching for ways of increasing the accuracy and reliability of the results generated, and also from developing ideas on how understanding of the processes taking place within the environment can be improved. This latter part is possibly the most important factor as it is progressive and builds upon the knowledge that has been acquired giving direction to future research. For *in situ* monitoring to become ever more successful, accessible and cost effective, there must be continued development of the techniques, equipment and the theories upon which they are based. The recommendations based upon the current study are presented individually for the three main disciplines used.

8.4.1 Hydrological monitoring

During the course of the hydrological monitoring programme a number of general improvements in the way it was carried out were identified. Although this programme has now been concluded, and is unlikely to be reinstated in its previous guise, the issues identified are still relevant to other programmes, both on Sutton Common and elsewhere.

The greatest improvement that could made to the gathering of hydrological data is by increasing the resolution of the data gathered and ensuring regular data collection. The experience on Sutton Common is that a large effort was required to undertake the monitoring in both time and resources, and that it is always difficult to undertake regular and high resolution monitoring. This inevitably leaves gaps within the data that automatically generate questions that cannot easily be answered; such as the response to events such as flooding and prolonged rainfall.

The use of data loggers in previous studies (Caple & Dungworth, 1998, Cheetham, 1998), have shown the benefit of the very high resolution data that is obtained. From this it is possible to identify and estimate the impact upon the burial environment of events such as prolonged rainfall. The major drawback of using automated data collection are the costs involved in purchase and maintenance. For example, it would be very difficult to maintain a long-term monitoring programme on the same scale as that undertaken on Sutton Common due to the amount of equipment required. Indeed, if this was possible, the amount of data generated would be overwhelming! However, the use of even a small number of automated data collection points would provide a substantial insight into the dynamics of the burial environment, used in conjunction with the normal approach that was taken.

The use of hydrological monitoring techniques within engineering industries, including construction, waste and environmental applications, means that there is continuous development and improvement of technologies, and over time, this means falling costs and greater accessibility. Although prices for equipment are relatively high, when monitoring a site in the long-term the economics of automatic data collection as opposed to manual collection, become viable. For example, based upon current prices provided by Soil Instruments Ltd (www.soil.co.uk), the price for an automated monitoring system including a 30-

channel data-logger, solar power supply, software, 10 vibrating wire piezometers and all necessary cables and sundries is approximately £7000. This could potentially provide overall cost savings when compared to the travel requirements and time for a single person to undertake regular site visits over a prolonged period of time. Therefore moving towards a position where the widespread use of automated data collection is used is highly recommended.

The access to locally read, high resolution and accurate precipitation data has been very useful in the studies that have taken place at Sutton Common. This data has not only enabled trend within the monitoring data to be matched with trends in precipitation, but has also been used to quantify the amount of water being received on the site. When monitoring sites over a long period of time, it is necessary to account for seasonal variation and consultation with precipitation data can identify the relative influence of this upon the groundwater hydrology. The lack of similarly detailed data for potential evapotranspiration rates on the site has been unfortunate. The use of averaged data sourced from the hydrological appraisal undertaken on Sutton Common (Geomorphological Services Ltd, 1990), took into account coarse patterns within the evapotranspiration rates on Sutton Common, but with extreme weather experienced on the site during the course of the monitoring, this data proved inadequate. Therefore, it is recommended that similar, large-scale, long-term monitoring programmes also source accurate estimates for potential evapotranspiration rates. As with precipitation data, this can identify the characteristics of the hydrology of a site in terms of the source of the water contributing to the water table i.e. whether it is groundwater fed or precipitation fed. If monitoring is taking place over a short period of time and in isolated locations, then the use of these data may be limited and therefore not necessary.

Limited investigation into the saturated hydraulic conductivity of the deposits on Sutton Common has provided an insight into the possible complexities involved in the movement of groundwater where it plays a determining role. The estimation of this factor on Sutton Common has demonstrated that where information on the movement of groundwater is sought, it is possible to obtain it through the use of a simple and rapid method using little more than the piezometer equipment already installed. This approach can be particularly useful on large sites similar to Sutton Common, but may also help in characterising archaeological deposits and their vulnerability to desiccation and therefore preservation potential. The use of saturated hydraulic conductivity as an indicator of preservation potential has been undertaken by Van de Noort *et al.* (1995). Here they matched conditions of very low saturated hydraulic conductivity, and hence restricted water movement, with good quality preservation.

One area where it is regarded that significant progress can be made in terms of hydrological monitoring, and especially in the effective management of archaeological sites, is in the 3D-modelling of groundwater flow using software such as Visual MODFLOW from Waterloo Hydrogeologic. The potential use of such a modelling capacity in relation to protecting sensitive, waterlogged archaeological remains has been demonstrated by Welch and Thomas (1996) using the finite element model SEFTRANS produced by Oxford Geotechnica. This study was studying ways at mitigating the water table against the effects of drawdown caused through the excavation and dewatering of a trench during the construction of a supermarket.

Visual MODFLOW has been evaluated as part of the current study with the aim of developing an interpretive model to characterise the groundwater movement and understand the dynamics of the site. It was envisaged that once this model had then been created it could be adapted to be used as a predictive model and used to identify the impacts on the site hydrology of the mitigating engineering works that have been carried out. However, during the evaluation period it was identified that not enough information was known about the physical characteristics of the site, especially in terms of the varying hydraulic conductivity present on the site and the resultant model was highly inaccurate. In addition to this, boundary conditions for the site could not be established easily and because the processes of verification and calibration (Welch & Thomas 1996) would take too long, the model became unviable and further work did not progress. However, in terms of demonstrating the value of computer modelling to the management of archaeological sites, Sutton Common remains a perfect site to use. Many other software packages are available that can potentially undertake this modelling including MicroFEM (www.microfem.com) and Aqua3D from the Scientific Software Group (www.scisoftware.com). The use of computer modelling has the potential of being extended to include additional parameters such as movement of nutrients and microbes themselves within the burial environment with the software package 3DFATMIC, again from Scientific Software Group.

Having a model that reflected the hydrological situation on Sutton Common accurately, that could then be used as a predictive model, would be of considerable benefit in terms of site management. It has been established from the results of this study that the impact re-wetting has had in terms of raising the water table has not been as great as initially anticipated. As a result, the possibility of further engineering work being carried out is being considered for the site. With access to an accurate computer model it would be possible to apply the proposed changes and anticipate the effects. Such a model could prove critical in the planning stages of further engineering work as ideas could be adapted to maximise the effects prior to work being carried out. This approach would also help maximise cost effectiveness of work carried out, something that is essential if active management of sensitive archaeological sites is to prove successful in the future. Based upon the experience of the current study, the use of hydrological modelling in a predictive manner is seen as a very strong area for future research and for Sutton Common should be considered as relatively urgent.

This study has attempted to integrate techniques and approaches from a number of highly different disciplines in order to create a multifaceted approach to the *in situ* preservation of well-preserved organic archaeological remains. However, to progress, future research will require a greater depth of knowledge of each individual discipline and therefore a greater number of people. Ideally, the application of specialists from individual disciplines, or students with a background in these disciplines, would aid with progression on the research front especially if working closely under the umbrella of 'research into the preservation of archaeological remains *in situ*'.

8.4.2 The monitoring of soil redox potentials

The monitoring of soil redox potentials undertaken during the course of this study has shown that the technique is effective in characterising the burial environment. The added dimension of understanding redox conditions, especially change, and not just saturation within the burial environment, has led to the appreciation of complex interactions which may have otherwise been overlooked. Interactions such as the role of organic matter content within the soil profile and the effects of fluctuation within the water table have been observed. This has also been highlighted by the realisation that potentially the soil profile, to a depth of several meters, is significantly affected by the action of flooding. This finding potentially has a major bearing on activities such as flood management, where potentially sensitive archaeology may be subjected to flooding. However, the methods employed for the *in situ* measurement of redox potentials are ungainly and complex and thus not easily accessible to those other than specialists and academics. This, ultimately means that such techniques are not widely implemented and other, less reliable but more easily accessible techniques, are employed, or even worse, monitoring is not taking place in circumstances where it ideally should.

As described in section 3.3, current, 'off the shelf' solutions are not suitable for *in situ* measurements for reasons including the use of probes that are fragile and not suitable for long-term *in situ* placement within soil. However, with the technique that has been applied on Sutton Common, there is no current way that automated data collection can be undertaken as the equipment cannot be connected to a datalogger. Short-term *in situ* monitoring was undertaken extensively in the study undertaken by Caple & Dungworth (1998), but the probes that were used during this were not suitable for burial at depth, posing problems in gaining access to archaeological materials without causing significant disturbance. Therefore, there is a requirement for a suitable *in situ* redox monitoring system, using similarly constructed probes as those used on Sutton Common, but that is simpler to use and readily available. The platinum tipped, copper *in situ* probes used on Sutton Common, are capable of being placed within the burial environment with minimal disturbance and can be left for a number of years but retain accuracy, unlike those currently available that can be connected to a datalogger. If this issue is not addressed, then the use of such monitoring will remain within the realms of academic research where the necessary skills and facilities are already available for the production and maintenance of the necessary equipment. If this happens, then this technique will not be capable of widespread application. It is therefore recommended that at the earliest opportunity, the manufacturers of similar environmental equipment are engaged with the academic community in order to explore the possibilities of further developing the technique. If this is undertaken with the aim of producing equipment suitable for *in situ* redox measurements then there is little doubt that the technique will be far more accessible and therefore will encourage widespread use.

In terms of the measurement of soil redox potentials, there is a need for further monitoring of more diverse burial environments in order to understand redox dynamics further. For example, the reactions and rates of change of soil redox conditions to varying hydrological conditions and how these differ with varying organic matter contents. There is also a need for further integration with the hydrological and especially the microbial variables that can only come with more integrated and concurrent monitoring of soil conditions. The monitoring of soil pH is also essential as this factor can significantly influence the redox readings obtained from a soil profile. The influence of changing pH upon soil redox potentials needs to be further investigated along with potential methods of alleviating problems such as by the permanent installation of salt bridges.

As with hydrological monitoring discussed in the previous section, to ensure the successful progression of research into the use of soil redox potentials in the monitoring of sensitive archaeological sites, the inclusion of specialists in this field, or continuing research with students who have a chemistry background under the guise of '*in situ* preservation' is required.

8.4.3 The monitoring of soil microbiology

To date, the measurement of microbial activity and dynamics has contributed little to the monitoring of the burial environment of wet-preserved organic archaeological remains. Where microbial techniques have been applied they have focused directly upon the type and extent of degradation observed within archaeological materials themselves (Brunning *et al.* 2000, Powell *et al.* 2001) and not the measurement of contemporary activity. The microbiological work carried out as part of this study has been used as a 'proof of concept' approach to assessing the viability of using microbial techniques in the monitoring of the burial environment. The results of this exercise have shown that it is possible to characterise the activity level of the microbial population using a suite of techniques. However, a number of possible improvements to this approach have been identified.

The greatest area where improvement can be made is in the resolution of the data. Since only two samples were collected for each of the sample locations on Sutton Common, no account has been made concerning the influence of seasonal variation upon the measured variables. Such an influence has been well documented in other studies undertaken into the soil burial environment. Similarly to accounting for seasonal variation in hydrology and soil redox conditions, there is a requirement for higher resolution monitoring to be undertaken through at least one annual cycle on Sutton Common. In addition to this, more parameters need to be accurately measured at the time that soil samples are obtained; these being soil pH and temperature as these have been shown to influence microbial activity and presence and can vary considerably with changing seasonal conditions. The parameters of soil moisture content and soil organic matter content that were measured in addition to the microbial techniques themselves should continue to be used in future work.

In addition to a need for greater resolution of sampling in order to take the current assessment carried out on Sutton Common into account and make it a monitoring variable proper, there is a need to integrate further the data collected for the microbial assessment and the other parameters measured. Such an approach will help understand the changes that occur within the environment more fully. For example, changes in soil redox potential are influenced by changing levels of saturation but are potentially mediated by microbial activity. However, these are also dependant on the organic matter content of the soil. Increased integrated monitoring will help identify the factors that influence microbial dynamics within the soil environment.

The observation that archaeological timbers on Sutton Common create their own microenvironment that can be significantly different from that of the surrounding soil, requires further investigation. Although this will require excavation of such material, understanding the dynamics of such a situation will help anticipate the condition of archaeological timbers under varying conditions.

As with hydrological and redox monitoring, there is an opportunity for specialist microbiologists to work within the field of *in situ* preservation and contribute to the effectiveness of monitoring programmes. However, whereas the previous two types of monitoring may be capable of 'off the shelf' solutions, it is unlikely that this will be the case with the monitoring of microbial activities, due to the necessity to have access to specialist laboratory facilities. However, if such work could be carried out on a commercial basis, then there is a possibility of widespread use of such techniques to characterise burial environments in the future.

8.5 The impact of re-wetting activities upon the burial environment of Sutton Common

The re-engineering of the drainage system on Sutton Common was undertaken with the hope of significantly raising the water table over the site and begin to revert it back to a wetland environment. However, observation made after the work was carried out did not identify any obvious changes, even though the dams were effective in holding back water within the drainage ditches and groundwater was being prevented from draining through the field drainage system. In addition to these field observations, study of the piezometer data did not reveal any significant positive change that could not be attributed to other influences. Therefore, the evidence for increased water table height in response to the re-wetting activities that have taken place on Sutton Common is small, and tentative in nature.

The engineering work was aimed at reducing the loss of water from the site as a result of drainage. If an assumption is made that the lowering of the water table observed in the summer is predominantly due to the amount of drainage that the site is subjected to, then impeding the drainage by a significant amount, which has been done, would therefore result in a significant response in the water table. Attempts have been made at identifying such a response through the creation of a water budget for the site, taking into account the water inputs, outputs and response of the water table. However, this exercise did not reveal any significant component that could be attributed to field drainage, but instead revealed that during the summer months the site was the subject of a considerable soil moisture deficit.

Another way of assessing the impact of the drainage work that was carried out is by means of studying the spatial response of the water table. The basis for this is that since the field drains present on the site are fixed in location, the backing up of these following re-engineering would result in a changing form of the water table. In order to assess this two models, one from before and one after the re-engineering was carried out, were spatially compared to the location of the field drains. The data used were from 01/03/99 and 03/03/00, as these were taken during the same time of the year, but also the precipitation received on the site from the beginning of the year was also very similar, in 1999 75.3 mm and in 2002 74.3 mm. Figure 8.5 shows the two models with the drainage network overlaid.

In Figure 8.5 it can be seen that the water table within the monitored area was noticeably higher in 2002 than during the same time in 1999. Bearing in mind that 2002 received slightly less precipitation, this suggests that there has been a positive change in the water table in response to the re-wetting work. However, the characteristics of the water table are essentially identical, suggesting that has been no significant change.

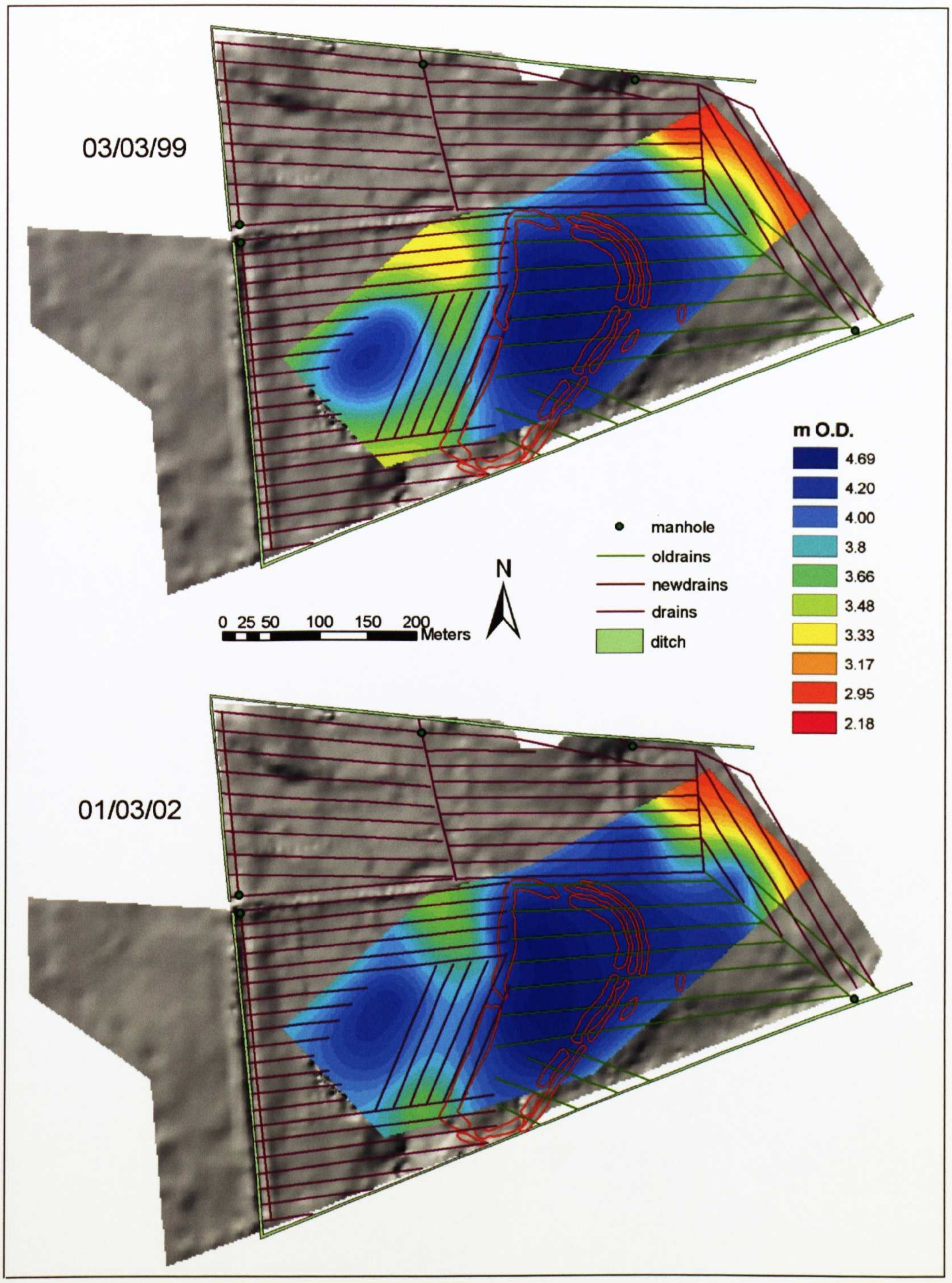


Figure 8.5 Integrated GIS maps showing the different elements of the Sutton Common field drainage and two hydrological models representing the site water table.

Figure 8.6 presents the weekly precipitation for 1999 and 2002 for Sutton Common from the beginning of the year until the monitoring time for the models presented in Figure 8.5. These show that in 1999, a large proportion of the rainfall occurred at the beginning of the year whereas in 2002 there was little rainfall during this period, but more or less continuous rainfall during the latter half.

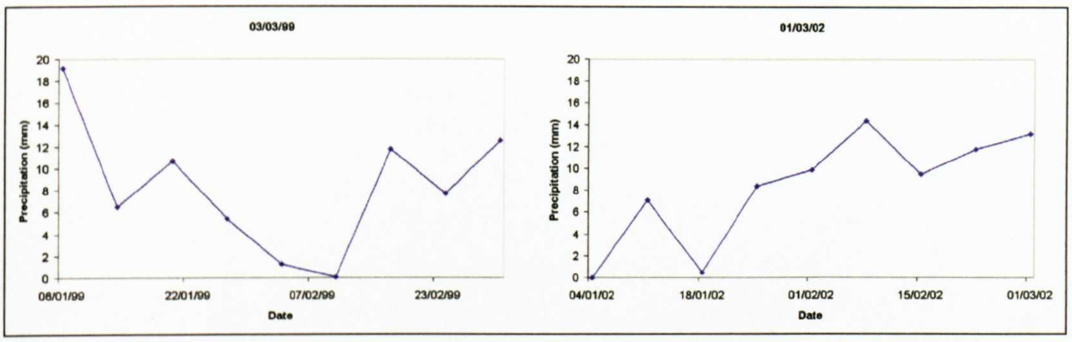


Figure 8.6 Graphs showing the precipitation in a weekly interval until early March for 1999 and 2002.

The data presented in Figure 8.6 demonstrates that the higher water table observed during 2002 and presented in Figure 8.5, is likely to have occurred as a result of the greater amount of precipitation input during the weeks before monitoring took place rather, than as a manifestation of the effects of drainage mitigation.

The positive trend of a generally increasing water table throughout the period of the hydrological monitoring, identified in Figure 5.26, indicates that there has been a slight increase in the level of the overall water table. A rise in the water table is also identified within the results of the archaeological wood model, although this suffers somewhat from the reliance on the data obtained during a single monitoring visit only. There is little doubt that the re-engineering work that has taken place will have contributed to this rise, however part of this, probably a significant part, can be attributed to the effects of changing management practices upon the site. This specifically relates to the maintenance of low vegetation for the grazing of livestock. Prior to this, the site had developed rough vegetation since the site had been put into set aside. Figure 8.7 highlights this with a mosaic of four images covering two views, facing eastwards and northwards, for 1999 before effective management of the vegetation, and 2001 after two years of management. All the pictures used were obtained either during the late summer or early autumn period.

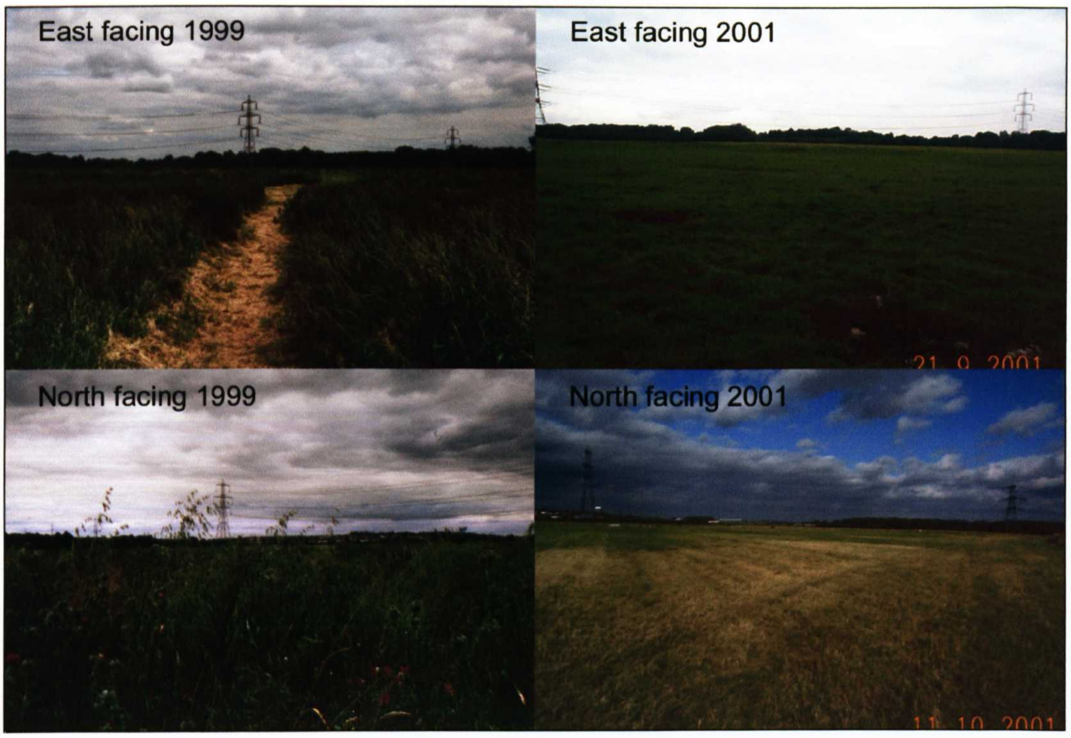


Figure 8.7 East and North facing images from Sutton Common for before and after effective management of the site vegetation.

The water budget exercise has identified that the site suffers from large soil moisture deficits during the dry parts of the annual cycle. With the more effective management of vegetation on the site, this will have reduced the soil moisture deficit significantly and therefore potentially induced a positive response in the water table across the site.

Although there is little evidence for any significant changes to the water table in response to the changes made to the drainage network on Sutton Common, as described in Section 5.2.1, there are indications that the water table was influenced during periods of change. For example during times of a rising water table in response to rising levels of precipitation at the end of the summer period, an eastern groundwater mound was temporarily identified that had not previously been seen prior to the re-engineering of the field drains. Figure 8.8 presents an integrated GIS map of the site and the location of the field drains therein, along with an overlay of the hydrological model generated from data collected on 06/12/99, this corresponding to the period during which the drainage work took place on Sutton Common. Along the eastern half of the hydrological model, the surface appears to be relatively flat, suggesting that the re-capturing of the drains along the eastern edge of the site may be influencing the base-level of the water table in this location. Perhaps more obvious is the development of a groundwater mound along the eastern edge of the model. From the map the outfalls of the drains in this location can be seen to have been captured by the installation of manholes controlling the height of the outfall. There is a possibility that the drains in this location had therefore backed up and restricted the flow of groundwater resulting in the creation of a groundwater mound.

Although from the previous comparison of before and after reveals that there was not a significant change in the water table, the patterns observed in Figure 8.8 do suggest that there may have been an influence exerted on the water table by the re-engineering of the drainage system on Sutton Common.

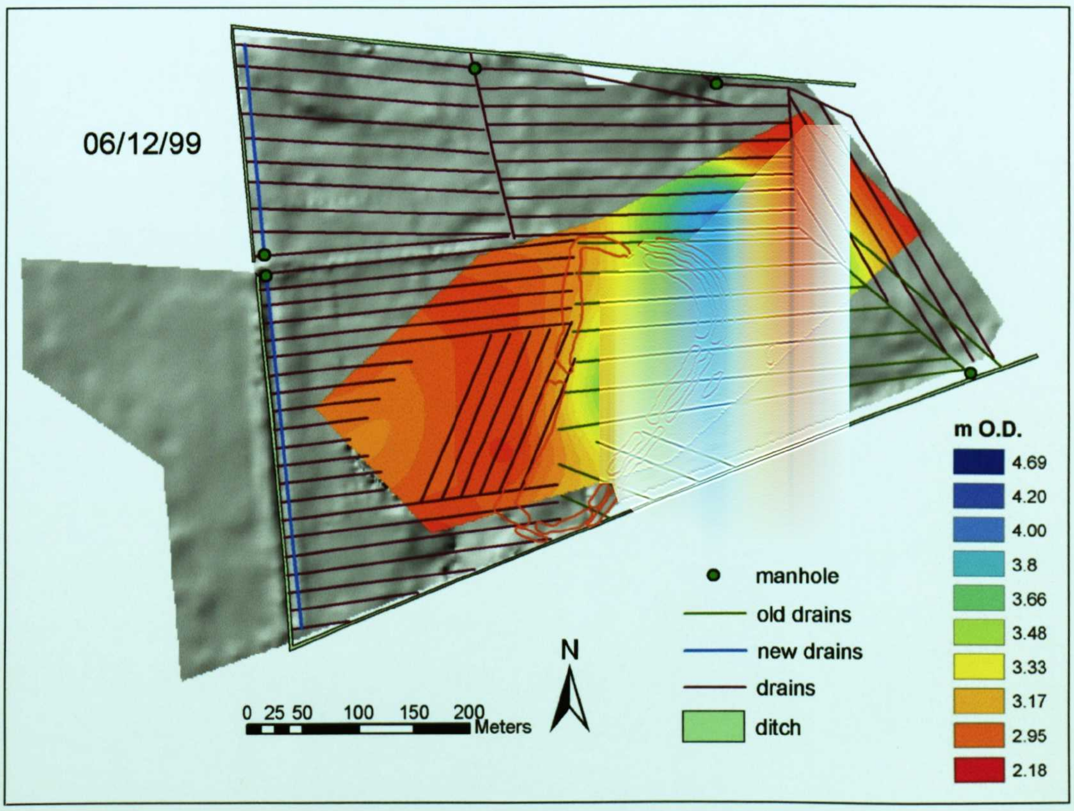


Figure 8.8 Integrated GIS map of the Sutton Common DEM with the field drainage overlaid. The hydrological model for 06/12/99 highlights the possible effects of drainage mitigation.

The drainage mitigation, based upon the fact that there is no evidence of a long-lasting rise in the water table that can be clearly attributed to it, has produced insignificant results. However, the fact that the legacy of the 2000/01 flooding was a raised water table for several months until removal of the water during warmer conditions shows that the re-wetting work was effective in preventing this excess water being removed from the site.

Identifying the effects of the drainage mitigation work has been difficult for a number of reasons. The site has been the subject of flooding during the monitoring programme and this resulted in unnaturally high water table rises, the effects of which persisted for several months. This has reduced the amount of data that can be reliably be compared, as has the unfortunate effects of increased management of the site; this resulting in a lack of readings during the latter half of 2001. Further to this, there is evidence that the level of the water table is influenced predominantly by precipitation and not by the amount of drainage. This suggests that the near surface water table that must have been present for several thousand years was not removed solely due to the direct drainage of Sutton Common itself, but through drainage of the wider landscape within which it is located.

This situation is adequately demonstrated when studying the borehole water-levels from Sykehouse, these previously being presented in Figure 5.36. Figure 8.9 presents the annual range of heights from this location in similar format as the regional groundwater levels presented in Figure 2.2. From the 1970's there is a consistent annual drop in the levels within the groundwater aquifer, although in 1980 there was a slight recovery of levels. This rise is also reflected somewhat in the levels recorded in Figure 2.2. It is interesting to note that it was about this time that the Thistle Goit drainage scheme was implemented that ultimately appears to be the reason why the water table on Sutton Common has dropped. The causes for such a change in the groundwater levels may relate to changes in mining activity in the region such as pumping and subsidence that have been documented as occurring (Geomorphological Services Ltd, 1990). A more consistant recovery is witnessed in the data from the late 1990's. Despite this, the general trend is of falling levels and greater fluctuation indicating a loss of groundwater in the area. Such a pattern must provide significant evidence for the drying out of the landscape in the vicinity of Sutton Common.

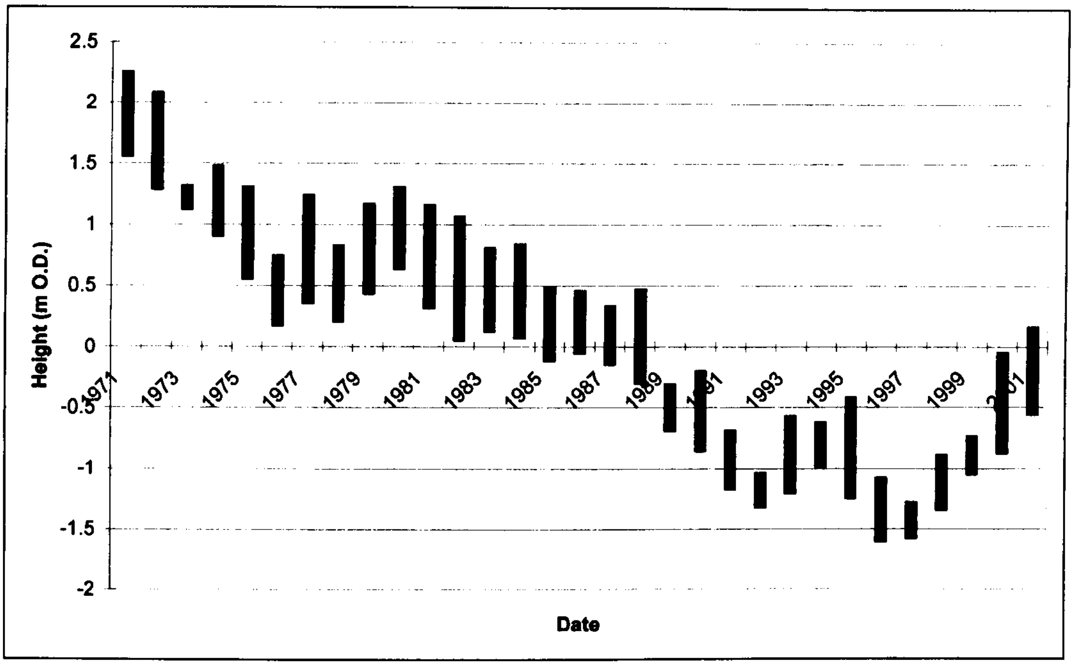


Figure 8.9 Graph showing the annual range in the height of the borehole located at Sykehouse (SE 462810, 417070).

8.6 The impact of flooding upon the burial environment of Sutton Common

The flooding event that took place during the winter of 2000/01 has provided an insight into the impact of using site flooding as a management tool aimed specifically at increasing saturation of the burial environment along with the potential influence of flood management schemes. Such an insight would not have normally been available and as such the results obtained during this period have proved to be very important.

Initial flooding involved the deposition of large volumes of flood water on the site during a very short period of time. After a residence time of only two days, the surface water was allowed to drain, again very rapidly. However, the majority of the water held within the soil profile remained on the site for many months; aided by the drainage mitigation work that had been carried out. This water was removed the during the summer of 2001 by the action of evapotranspiration.

There was no negative reaction to the flooding event at the time as it was seen as a positive step towards the general aim of returning Sutton Common to its former wetland environment. However, analysis of the monitoring parameters, especially the results obtained from soil redox monitoring, indicated that there had been a significant impact upon the burial environment as a consequence of the rapid deposition and then removal of large volumes of flood water. In fact, the results showed that there had been a significant reaction throughout almost the whole monitored soil profile across all the monitored locations. Although generally the reaction was a subduing of the redox conditions, something that could broadly be considered beneficial to the ongoing preservation of organic archaeological materials, this occurred within the dry soil contexts where degradation is well advanced. More significantly, there is clear evidence that the burial environment within the deeper soil profile was also disturbed, leading to the possibility that archaeological contexts that had previously escaped the impact of site drainage were now being disturbed by the action of flushing of the soil profile as a consequence of flooding.

The results obtained during the flooding event have highlighted the benefits of maintaining a multidisciplinary approach to any monitoring regime of the burial environment. Whereas the monitoring of water-levels on the site would have indicated a purely beneficial reaction to the event, the integration of soil redox monitoring has shown that the opposite can in fact be the case, but further to this it has allowed the reaction of the burial environment to be characterised in detail.

During the winter of 2002/03 Sutton Common was once again allowed to flood in a similar manner (*pers. Comm.* A. Booth) showing that there is every possibility that this could occur on a regular basis in the future. The understanding gained from the monitoring programme has indicated that this could be detrimental to those archaeological remains located within deep enough contexts to have survived in good condition until recent years. These include deep penetrating piles and posts and features such as the possible well identified within Enclosure A. However, the results also indicated that during the period of a raised water table, stabilisation of the burial environment had begun to occur. There is little doubt that if a high water table could be maintained throughout the year, this would lead to a burial environment that was able to sustain preservation of organic archaeological remains.

8.7 The future preservation of the organic archaeological resource on Sutton Common

The excavations that have been undertaken on Sutton Common since the destruction of Enclosure A have all been focused upon, or involve, assessing the quality of preservation of organic archaeological remains that have survived. A series of excavations carried out by the South Yorkshire Archaeological Unit and Sheffield University identified progressive degradation (Parker Pearson & Sydes, 1995). One of the aims of the current Sutton Common Project was to halt this trend and ensure the continued preservation of those remains that still survived. The programme of monitoring that was initiated at this time, and forms the focus of this research, was aimed at identifying the changes that occurred within the burial environment in response to the drainage mitigation and to assess whether this achieved the aim of recreating a burial environment, stable and suitable for the continued preservation of organic archaeological remains.

The monitoring results generated, have shown that there has not been any significant or easily identifiable change to conditions relating to preservation within the burial environment across the monitored area of Sutton Common. This has been demonstrated through the archaeological wood model which integrated spatial information regarding the location of identified archaeological wood and the water table on the site. This model showed, through analysis of before and after the drainage mitigation had taken place, that there was little difference in the location of the water table relative to preserved archaeology, although there is tentative evidence for a positive response in the water table. In addition to this, the model has shown that the majority of archaeological wood so far identified on Sutton Common still remains within a depth range that is subjected to ongoing degradation. On this basis, without further changes to the hydrological regime of Sutton Common, either through engineering or a reversal of drainage across a wider area producing a significant rise in the water table, this material will continue to degrade to a point where little more than a soil mark will remain.

From more recent excavations during 2002/03 which the author was involved in, a large amount of material on the site is already close to this condition.

Preservation 'hotspots' such as the possible well identified in the southern part of Enclosure A, appear to have been little affected by the extensive drainage that has occurred on Sutton Common and the surrounding area due to their greater depth and therefore maintenance of saturation and stable burial conditions. Monitoring of the burial environment during flood conditions has identified that such environments may potentially be the subject of disturbance as a direct result of flushing of the burial environment by flood water. This poses an additional threat to these few remaining areas that are capable of retaining well-preserved organic archaeological remains as there is a possibility that if periodic flooding continues to occur in the future, this will destabilise these environments and contribute to the degradation of the material contained within them.

8.8 Summary

This chapter has presented an overview of the fieldwork that has been undertaken on Sutton Common and the results that have been generated from it; covering the three main parameters of hydrological monitoring, soil redox monitoring and soil microbiological assessment. A critical assessment of the techniques used during the study has been made with the aim of identifying potential problems with data gathering and considering the accuracy of the data obtained. This was undertaken with the view of identifying areas of the approaches that require improvement and possible further research.

As the re-wetting of the site has been a fundamental part of the Sutton Common Project, a discussion of this has been presented including analysis using GIS to assess the spatial relationship between water table form and the location of field drainage. The impact of the flooding event of 2000/01 is also discussed as this has provided evidence of the detrimental effects of such events upon the burial environment and also has potential bearing on the future management of the site. The final area of discussion concerns the future preservation of the buried organic archaeological remains that still survive on Sutton Common in the context of the findings of this research.

The following chapter will reiterate the aims of the research first stated in the introductory chapter, followed by a brief overview of the major findings of the research. A reflection will then be made upon the aims of the work that has been carried out followed by specific recommendations and a short discussion on the legacy of this work.

Chapter 9 Conclusions

9.1 Introduction

The broad aim of this research was to develop a methodological approach to the monitoring of archaeological sites that contained, or had the potential to contain, well-preserved organic archaeological remains, by means of a multidisciplinary approach. Such sites could generally be referred to as wetland archaeological sites, as material is preserved as a function of an existing or former wetland environment. Such an approach would provide high quality data from different sources that could be considered mutually supportive, generating information that could therefore be considered reliable. The more specific aims of the research can be considered as:

1. To develop a monitoring package that can effectively and accurately identify conditions that are conducive to the long-term preservation of organic archaeological materials, specifically wood.
2. To understand in detail the burial dynamics of Sutton Common
3. To identify the changes within the burial environment on Sutton Common that occurred as a direct consequence of activities aimed at raising the watertable and to assess whether these aided the potential for *in situ* preservation

Of significance is the amount and quality of the data collected, with the techniques used generating high resolution data over an extended period of time. Such data concerning the burial environment has not previously been collated to such an extent.

To satisfy these three specific aims, a monitoring approach was chosen that made use of multiple factors; these being hydrological monitoring, soil redox monitoring and microbiological assessment. The most crucial of these, and the one that has been the focus of the monitoring effort, has been the hydrological monitoring as this is essential at identifying saturated conditions, which are the basic conditions required for good preservation. Soil redox monitoring closely supported this by being capable of identifying anaerobic conditions that indicate stable conditions, ideal for preservation. As soil redox monitoring requires more resources in terms of time and funds, this variable has not been as widely implemented as the piezometer grid installed for hydrological monitoring. Such factors have also influenced the implementation of microbial techniques on Sutton Common, with these being applied as an assessment, and a means of gathering baseline data, rather than a monitoring variable proper.

The presentation of these techniques and the specific methods used have been detailed in Chapter 3, with the results of the monitoring programme for each of the approaches being presented in Chapters 5, 6 and 7 in the context of previous monitoring exercises and published literature. The significant findings were discussed and specific reference made to the impact of flooding on Sutton Common and the influence of re-wetting activities in Chapter 8.

This concluding chapter will summarise the main findings of each of the three disciplines studied along with the findings obtained from the analysis of the flooding event of 2000/01, and the effects of the drainage mitigation implemented on Sutton Common. These will then be related to the original aims set out in Chapter 1, followed by the wider implications of this research and the main recommendations arising from it.

9.2 Overview

The range of techniques used during this research have produced a number of significant results relating to the effectiveness of the technique in the role of monitoring and also the significance of the results to Sutton Common itself. These have provided a new insight into the dynamics of the burial environment of buried organic archaeological remains, specifically on Sutton Common, but also applicable to many other sites containing wet-preserved archaeological remains.

9.2.1 A review of the main findings

Hydrological monitoring

The approach of implementing a grid of piezometers has enabled the identification of the form of the watertable to a resolution that has not been carried out on other archaeological sites. This has provided quantifiable data relating to the changing watertable throughout the monitoring period and has highlighted the absolute requirement for monitoring wetland archaeological sites through at least one annual cycle.

The monitoring has identified that the watertable across the site is not flat in character, but strongly follows the ground topography. Of significance is the formation of two groundwater mounds below the topographically high areas of the site during the winter cycle, these relating to the two archaeological enclosures that are present.

The height, form and behaviour of the watertable are strongly influenced by seasonal changes relating to a deficit of water during the summer season and an excess during winter. The main factors that control this are the amount of precipitation received on site and the loss of water as a consequence of evapotranspiration. The balance between these two is referred to as the effective precipitation. No clear relationship between the patterns was observed within the near-surface watertable and deep aquifer levels and the fact that no clear signature of drainage was forthcoming within the results, shows that the site is predominantly precipitation fed.

The impact of the mitigation of the field drainage that has been carried out on the site has been negligible. This is because the effects of field drainage are not the direct cause of the lowered watertable; field drainage purely increases the rate at which water is removed from the soil profile. The real cause for the lowering of the watertable from the height that existed in the past, and that ensured the preservation of organic archaeological remains on the site, was improved drainage instigated during the late 1970's and early 1980's termed the Thistle Goit implementation. This involved the excavation of new and the deepening of existing drainage ditches across the site and may have resulted in a net drop in the watertable of more than 1.0 m, possibly more, across a wider area than Sutton Common alone (Geomorphological Services Ltd., 1990). It therefore seems that during periods of soil moisture deficit prior to the implementation of this scheme, the watertable remained near to the surface due to a large reservoir of groundwater. Restricting drainage on Sutton Common, although effective at keeping excess water on the site as identified with the maintenance of high watertable conditions following the flood event of 2000/01, ultimately fails in preventing water being removed via evapotranspiration during phases of high vegetation growth.

This situation was effectively demonstrated by the creation of the archaeological wood model. By integrating watertable data with the spatial locations of pieces of excavated archaeological wood, it has been possible to identify the changing saturation conditions throughout an annual cycle and compare the situations both prior to and following the implementation of the re-wetting activities. This along with analysis of piezometer data directly, showed that although there is some evidence of a slight rise in the watertable, this is not nearly great enough to significantly alter the burial conditions. The majority of the archaeological material identified does not exist within the desired 'Zone 3', the zone of permanent saturation, and therefore the outlook in terms of continued preservation, of the organic archaeological remains surviving on Sutton Common is poor.

Soil redox potential monitoring

The use of soil redox potentials as a monitoring parameter proved to be successful by enabling the effective characterisation of the burial environment in terms of the presence or absence of stable, anaerobic conditions. However, the complexities involved in the practical use of the equipment were highlighted and it was realised that there was a need to have a firm appreciation of the possible problems that could be encountered and also the concepts driving its use. The presentation of a suitable method for presenting Eh/pH stability diagrams is seen as a possible significant benefit for the presentation of future soil redox results and not only those from Sutton Common.

The results from the soil redox monitoring programme identified that across the site there exists a redox gradient through the vertical soil profile, with oxidised conditions being present at the ground surface and becoming progressively less oxidised, and more reduced, with greater depth. The degree of variation was dependant on environment variables, the most significant of which was the degree of saturation, relating to the location of the watertable. The range of redox conditions observed during the monitoring was also related to organic matter content of the soils, with the most extreme readings being obtained from those with a relatively high organic matter content, such as the locations within the palaeochannel. This factor also influenced the rate at which redox conditions changed within a soil, with rapid change again observed within those soils with a high organic content. This points to the influence of microbial mediation of redox conditions in these soils, where microbiological assessment has identified a higher microbial presence relating to a more abundant substrate source.

Few of the monitoring locations exhibited readings that were indicative of stable anaerobic conditions and these were restricted, in general, either to the greatest depths or the wettest locations. These support the findings of the hydrological monitoring programme indicating that only in a very few locations, and at depth, do the required conditions for the continued preservation of organic archaeological remains exist. Also, the impact of the re-engineering of the field drainage on the site cannot be identified within the results, suggesting that this has had little impact upon the burial environment.

Microbiological assessment

The application of the suite of techniques used for the assessment of microbiological presence and activity, has yielded significant results through the production of baseline data for soils. The application of this type of approach has not been previously used within the context of the burial environment of organic archaeological remains and is therefore considered as a potentially significant tool in the future investigation of the burial environment.

The results showed a clear pattern, across all the sample locations, of decreasing bacterial biomass and metabolic activity with depth. This is directly related to the organic matter content of the soils, with those at the surface having a greater proportion of incorporated organic matter content than further down the soil profile. This pattern was especially strong within the more mineral rich soils. Where soils had high organic matter content, or a more uneven content throughout the profile, this relationship was still apparent but not so clear. This shows that the majority of aerobic microbial activity is within the surface soils, but that there is a requirement for an available source of substrate to support it.

A strong relationship between extracellular enzyme activity and bacterial biomass exists, however this is not reflected in the metabolic activity rates. Attempts at identifying anaerobic metabolic activity have proved that it possibly exists at depth which may explain this pattern. However, the presence of high levels of extracellular enzyme activity in deposits that are high in organic matter provides evidence for the presence of complexing occurring, meaning that the enzymes may be recalcitrant in nature. This relationship highlights the complex nature of the burial environment and the interaction of soil microorganisms within it.

Flooding

The flooding that occurred during the winter and spring of 2000/01 was of such great significance in terms of the increased understanding of burial dynamics that it generated and also in the potential repercussions for *in situ* preservation, that it is presented here separately.

The data generated during the time of the flooding itself, and during the twelve months following the event, demonstrated that flooding an archaeological site is potentially destructive in circumstances where it may be assumed to be constructive. This is therefore highly significant in terms of the future management of Sutton Common and also for other sites and locations of high archaeological potential that have the potential to be flooded. Soil redox potential data was particularly effective at identifying the effect of flushing occurring within the burial environment, whereby the redox conditions throughout the soil profile match those of the flood water itself. This shows that, at least within a relatively dry soil profile, the burial environment is significantly influenced by the event. However, in a number of locations there was evidence that even below the level of the watertable there was a shift in redox conditions towards that of the flood water.

In addition to the changes in redox conditions it was demonstrated that changes occurred in soil pH over a period of weeks and months that could impact upon the preservation potential of the burial environment, something that was revealed through the presentation of data by means of Eh/pH stability diagrams.

These facts show that a controlled flood event, such as that which occurred on Sutton Common, has the potential to disturb and impact upon conditions throughout the soil profile, not just near to the surface, and also have a detrimental impact upon previously stable conditions, even when the watertable was previously low. Regular flooding could therefore have a long-term, detrimental impact upon the potential for *in situ* preservation of organic archaeological remains.

9.2.2 Reflection on aims

The three main aims presented at the start of this chapter are both site specific to Sutton Common and also have a wider application within the realms of the management of wetland archaeological sites. They can be placed in a hierarchical order as presented, with the achievement of the first being required before the second. For example, in order to understand the burial dynamics of Sutton Common, it was first necessary to implement an effective monitoring programme. Similarly, in order to identify the impact of re-wetting it was necessary to first be able to monitor and understand the burial environment.

1. Development of an effective monitoring package

The use of previously demonstrated methods for assessing and monitoring the burial environment has helped ensure that effective monitoring has been carried out. Although the technologies applied have been used previously, the integrated approach, the extent, resolution and duration of the monitoring programme are novel. Also, the microbiological techniques used have not been applied within an archaeological, and indeed soil, context before.

The approach taken for the hydrological monitoring is unique and unprecedented in terms of the resolution of monitoring. It has enabled the characterisation of the watertable on Sutton Common to very high detail through the creation of watertable surfaces using GIS software. The strength of the GIS is further demonstrated by the creation of the archaeological wood model, where watertable data has been integrated with spatial data regarding archaeological wood. Such an approach, both for the hydrological monitoring using a grid of piezometers and the integration of further factors, such as the location of known archaeology, could be applied to other archaeological sites relatively easily.

Implementation of such a large soil redox monitoring programme, both in extent and duration, has not been undertaken previously. The gathering of such data has provided evidence for processes occurring within the burial environment, such as seasonal variation within the watertable and flooding. Such evidence supports the findings of previous research (Brunning *et al.*, 2000; Hogan *et al.*, 2002) whilst at the same time enhancing knowledge directly as a result of the monitoring of such diverse environments that are present across Sutton Common.

The development of an effective means of presenting redox data in the form of Eh/pH stability diagrams has allowed detailed characterisation of the preservation potential of a burial environment. Such diagrams have successfully been used previously to present soil redox data from archaeological sites but these have been simplified and non-reproducible (Caple, 1996; Caple & Dungworth, 1998). The Eh/pH diagrams presented in this thesis have been derived from literature and the values used are available in Appendix 8 and therefore the reproduction of this type of graph is possible. The presentation of data in the form of both linear graphs over time and stability diagrams has shown that these are mutually supportive and provide a deeper insight into the dynamics of the burial environment. The use of soil redox data has proved to be highly useful in the characterisation of the burial environment on Sutton Common.

The use of microbial techniques has provided good baseline data for the characterisation of microbial representation within the burial environment. The data that has been generated has integrated well with the other monitoring parameters and has provided evidence for the possible explanation for patterns observed within them. For example, the rapid changes in redox potential observed in some soils with a high organic content following changes within the watertable, can be explained by microbial mediation of conditions within the burial environment. This has the potential to significantly enhance our understanding of the burial environment and the effectiveness of monitoring techniques. The microbial techniques have shown that they have the potential to become a crucial factor in the assessment of the preservation potential for wet-preserved organic archaeological remains.

It is considered that the monitoring approach taken on Sutton Common and the suite of techniques used, along with the further development of means to present the results, have been effective at generating precise data that has been used to characterise accurately the burial environment on Sutton Common. The benefit of the use of an integrated approach to monitoring using diverse factors has been demonstrated. Also, the success of this approach has shown that the application of such techniques on other wetland archaeological sites would produce similar results.

2. Understanding the burial environment of Sutton Common

The quality of the data generated during the course of monitoring has helped to characterise the burial environment on Sutton Common. This understanding covers many levels, from the general understanding of the burial environment, through to the complex interactions that take place between a number of variables. For example, the form that the watertable takes is now well understood along with the changes that occur through an annual cycle, but in addition to this there is a better understanding of the range of variation within the watertable. The range of soil redox conditions over the different environments represented on the site is now well understood, as are the type of variations observed. The reasons for such changes are understood to a greater degree as are the consequences of significant events such as flooding.

Overall, the burial environment and the changes that occur within it, are well understood as a consequence of the data that has been gathered.

3. The impact of re-wetting on Sutton Common

The implementation of an effective monitoring package resulting in the understanding of the burial environment, and the changes within it, has enabled an accurate assessment to be made regarding the impact of the re-engineering of the site drainage. There was evidence that there had been an overall positive response to the work that had been carried out and that the work was effective at retaining water on-site. However, this was small and demonstrably not sufficient to affect the preservation potential of the archaeological materials identified on the site.

9.3 Recommendations for future research and management

The recommendations that have been generated as a result of this research come under two broad headings; those concerning the techniques used and their application on any wetland archaeological site and secondly, those that are specific to the management of Sutton Common itself.

9.3.1 Techniques

Detailed recommendations regarding the development and improvement of specific techniques were made in section 8.4. A summary of these recommendations is presented here.

During the course of this study it was recognised that there was a very real opportunity for the development of predictive models concerning the hydrology of sites such as Sutton Common. Although preliminary attempts at creating such a model from the data obtained during the monitoring programme were not successful, the reasons for this were identified as being a lack of sufficient knowledge of the boundary conditions of the site and the hydraulic properties of the deposits therein. As such, focused specialist research aimed at identifying the parameters required and using modelling software, such as Visual MODFLOW, could succeed in creating such a model. This would prove extremely useful in the future management of wetland archaeological sites through enhanced understanding of the hydrological processes that occur. This is especially so where drainage mitigation is being considered as a means of obtaining *in situ* preservation, since varying scenarios could be modelled in order to identify the most effective. This would therefore mean a more cost effective solution rather than a 'hit and miss' approach.

Specialist research and development of microbiological techniques is required in order to create an effective monitoring parameter. Microorganisms are the main agent of decay of organic archaeological remains, and as such accurate knowledge of their presence and activity by means of monitoring would be of very real use. Obtaining this goal requires field proven methods and effective presentation of the results obtained and therefore there is a requirement for an in depth microbiological monitoring programme on a wetland archaeological site.

Applying specialist knowledge within an archaeological context will be more productive than encouraging archaeologists to learn new disciplines.

The monitoring that has taken place on Sutton Common has been what can be considered random location monitoring. Although areas of the site were chosen with great care to be representative of the differing burial environments present, specific locations relating to known archaeology were not chosen. As a result, only one location is associated with a known archaeological context. During excavations it is noticeable, especially with archaeological timbers, that the material is located within a microenvironment. This situation means that the monitored conditions may not truly reflect the conditions being experienced by the archaeology. As such, there is a requirement for research to be undertaken into the environment immediately surrounding organic archaeological materials, especially those that are held within mineral soils, with an aim to gauge how the conditions within the wider area reflect those of the objects themselves.

The Sutton Common monitoring programme has produced significant and useful results. However, it describes one site only and therefore there is a need to demonstrate that such an approach can be made on other wetland archaeological sites.

9.3.2 The management of Sutton Common

Currently, the fate of the majority of the known organic archaeological material on Sutton Common, if conditions remain as they are, is complete degradation within a matter of years. If *in situ* preservation is seen as preferable over preservation by record, then further activities aimed at re-wetting the site are necessary.

As the site is strongly influenced by drainage in the wider area, specifically relating to the Thistle-Goit implementation, then efforts need to be focused on reversing this, rather than on ways to retain water on site. From the evidence at hand, it seems that the mitigation that has taken place to date is effective at retaining water on-site, but during times of low rainfall and high evapotranspiration this water is rapidly removed. Whereas in the past, prior to the implementation of the Thistle-Goit drainage scheme, there was a large groundwater reservoir on Sutton Common and the surrounding area that was able to absorb the effects of soil moisture deficits.

A possible solution to this problem would be to maintain the high water levels within the drainage ditches on the site, especially the Coalite, Heywood and Shirley Wood Drains, throughout the year. If this was possible it would most likely require careful management of the pumping regime and would only be possible if there was no impact upon the surrounding area outside the management of the CCT and those involved in the Sutton Common Project. However, times of water deficit, when the drainage ditches do not flow, would probably result in a drop in the watertable comparable to that observed in the past. Guarding against this possibility would require water being brought onto the site, although the means by which this could be achieved are unclear, and such an approach would require mitigation in terms of water quality and the actions of flushing as highlighted by the results obtained during flooding. This method may also require the Sutton Common site, or at least the area around the enclosures, to be isolated hydrologically to prevent drainage.

It is clear that to ensure the future preservation of the majority of the organic archaeological remains on Sutton Common, including those within the palaeochannel, a significant rise in the watertable in the order of 1.0 or 2.0 metres from its current level is required. This will necessitate more proactive solutions that produce a more significant impact upon the watertable than those that have been implemented to date. If the current situation is maintained, or further activities focus on inhibiting drainage, then only the materials located within isolated 'hotspots' of preservation hold any potential for *in situ* preservation.

Further monitoring of Sutton Common should take place, although on a much smaller scale and could be focused predominantly on the monitoring of the watertable in representative locations across the site. This would help identify whether archaeological contexts located at depth and are currently in good condition retain the saturated conditions necessary for preservation. Such an approach would identify the changes within the watertable that could potentially influence the burial environment arising as a consequence of off-site influences, such as changes in the pumping regime for the Thistle Goit Drain.

9.4 Legacy

Elements of this work have contributed to various publications including conference proceedings (Van de Noort *et al.*, 2001) and occasional papers (Chapman & Cheetham, forthcoming). A preliminary approach to the integration of watertable and archaeological wood data has been published (Chapman & Cheetham, 2002) and a contribution has been made to a debate on the relationship between urban and rural aspects of preservation (Van de Noort *et al.*, 2001).

In addition to this, some of the techniques developed during the course of the monitoring of Sutton Common have been applied to other sensitive archaeological sites in Beverley, East Yorkshire (Lillie & Cheetham, 2002a & 2002b) and at Flag Fen (Lillie & Cheetham, 2002c).

The application of microbiological techniques in the assessment of soil samples undertaken during this research have formed the foundation of a further PhD studentship, tasked with developing and exploring microbiological monitoring within archaeological and palaeoenvironmental contexts.

This research has played an active role in the management of Sutton Common itself, with information generated influencing future aspects of monitoring and re-wetting on the site. This has also included a contribution to a popular publication detailing the history of the site and the work carried out by the Sutton Common Project (Smith, forthcoming).

As a result of the flooding event that took place on the site during the winter of 2000/01, the understanding that this generated concerning the impact upon the burial environment, has been recognised by English Heritage as significant. As a result, this work has directly contributed to the planning phase of flood defence work being carried out on the Lower Witham flood defence strategy by the Environment Agency, specifically regarding the potential impact upon known wet-preserved archaeological remains within potential flood storage areas (www[3]). The methods for presenting soil redox data developed during the course of this research have also contributed to monitoring work being carried out by English Heritage upon remains within the Witham area.

As highlighted in Section 1.2, the development of more accessible monitoring techniques would benefit the *in situ* preservation of organic archaeological remains by encouraging more widespread implementation of monitoring programmes. Accurate data concerning the status of the burial environment would then feedback into the management plans of such sites and help ensure their effective conservation, this approach fitting well with the English Heritage strategy for wetlands. On the basis of this, and the experiences forthcoming from the work carried out on Sutton Common, it seems that accurate protocols covering the implementation of hydrological and redox monitoring programmes would go some way to obtain this goal. Such protocols could be in the form of a field guide for workers involved in such programmes that can be practically used to source and install appropriate monitoring equipment and handle the data that is generated. It is the desire of the author to identify a means by which this can be carried out now that the research into Sutton Common has drawn to a close.

9.5 Summary

This thesis has presented the data collected as part of a long-duration, integrated, multidisciplinary monitoring programme of the burial environment at Sutton Common, South Yorkshire. Methods of presenting this data have been developed to maximise the understanding of burial environment dynamics with the aim of being accessible, so as to encourage further monitoring programmes on similarly significant archaeological sites containing well-preserved organic archaeological remains.

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Appendix 1

Precipitation data

All precipitation data used in this thesis was kindly provided by Grantham, Brundell & Farran, Consulting Engineers. All data was collected from Kirk Bramwith (National Grid 462100, 411800).

Data is presented as daily precipitation for the years 1998 – 2002 (mm).

Table A1-1 Precipitation data from Kirk Bramwith, 1998 (mm).

	January	February	March	April	May	June	July	August	September	October	November	December
1	2.3	-	2.0	0.2	-	2.1	0.1	0.5	4.0	1.9	-	-
2	5.8	-	0.8	12.2	-	31.7	-	-	-	0.5	7.6	-
3	4.9	-	27.0	0.6	-	2.0	-	2.1	-	1.7	1.3	1.0
4	4.8	-	2.5	1.4	0.4	-	-	-	1.7	0.9	1.5	-
5	0.2	-	7.4	1.4	0.8	0.8	-	-	5.4	2.2	2.2	-
6	3.5	0.9	8.7	0.6	-	0.9	0.3	-	0.4	2.2	-	-
7	-	-	0.4	-	-	2.9	-	-	0.6	3.7	5.3	-
8	6.9	-	-	25.2	-	6.5	-	-	2.4	-	2.7	0.2
9	-	-	-	0.5	-	-	-	-	1.9	0.8	-	2.7
10	-	-	4.4	5.9	4.0	1.6	-	-	0.6	0.9	-	1.3
11	-	-	-	0.3	4.2	2.4	1.5	-	-	-	0.7	0.4
12	0.2	-	5.6	-	-	0.9	-	-	0.6	0.4	1.1	-
13	4.0	-	-	1.1	-	3.2	-	0.1	-	10.8	0.9	-
14	1.1	-	-	11.4	-	9.4	0.9	4.9	-	-	-	0.2
15	1.1	-	-	0.3	-	0.3	-	-	0.4	0.2	-	0.3
16	-	-	-	0.9	-	-	-	-	-	6.2	-	-
17	6.1	-	-	-	-	3.6	0.6	-	-	4.6	-	1.8
18	15.3	-	-	0.3	-	1.4	-	-	-	0.4	6.7	16.8
19	1.0	-	-	2.9	-	-	1.2	-	-	1.8	-	2.5
20	-	1.1	-	0.2	0.9	-	0.2	0.6	-	0.7	-	-
21	0.7	0.7	-	2.5	-	-	-	-	-	0.5	-	-
22	2.1	0.8	-	8.7	-	0.4	0.2	2.1	-	28.3	0.7	2.8
23	-	0.6	1.2	0.5	-	-	-	2.8	-	1.6	1.3	3.3
24	-	-	4.5	1.2	-	-	-	0.2	-	12.8	1.5	2.8
25	-	-	1.1	-	-	3.2	-	8.2	-	1.5	0.5	1.3
26	-	-	0.2	2.0	0.4	4.4	1.1	-	-	0.9	0.2	-
27	-	2	-	1.5	-	0.9	1.0	-	0.7	15.5	0.9	-
28	-	1.2	-	0.7	10.6	-	1.2	-	4.6	2.4	2.2	-
29	-	-	4.4	-	-	-	0.8	-	4.5	5.8	-	-
30	1		0.3	-	0.8	-	5.7	-	15.6	-	0.2	5.6
31	-		-		-		13.2	6.8		-		-
Total	**61.0**	**7.3**	**70.5**	**82.5**	**22.1**	**78.6**	**28.0**	**28.3**	**43.4**	**109.2**	**37.5**	**43.0**
cumulative	**61.0**	**68.3**	**138.8**	**221.3**	**243.4**	**322.0**	**350.0**	**378.3**	**421.7**	**530.9**	**568.4**	**611.4**
Year total	**611.4**											

Table A1-2 Precipitation data from Kirk Bramwith, 1999 (mm).

	January	February	March	April	May	June	July	August	September	October	November	December
1	1.0	-	4.4	-	-	-	0.2	1.5	-	13.8	-	1.0
2	3.2	-	2.8	-	-	23.9	-	0.7	-	1.0	-	4.1
3	6.4	-	4.1	-	-	6.1	3.7	-	-	1.9	-	1.4
4	0.9	-	0.2	-	-	-	1.3	-	-	0.2	-	3.3
5	-	-	9.1	-	2.1	2.8	1.4	2.7	-	-	8.2	-
6	7.7	-	6.8	-	-	5.6	-	0.8	-	-	-	-
7	2.9	-	5.2	-	9.6	14.2	-	1.1	1.1	3.6	-	1.5
8	1.0	0.1	1.0	-	0.7	4.5	-	12.0	0.7	1.2	-	2.1
9	-	-	15.6	-	0.2	-	-	12.7	-	0.5	-	0.9
10	-	-	-	-	4.6	-	-	2.1	-	0.2	0.6	5.2
11	-	-	5.4	0.5	1.3	-	-	0.9	-	-	2.7	6.2
12	2.4	2.4	3.5	0.1	2.4	-	-	6.5	-	-	0.5	1.8
13	0.2	-	0.3	6.0	2.5	-	-	1.6	-	-	-	0.3
14	3.5	2.1	-	-	0.3	-	-	-	-	-	0.6	4.9
15	3.3	-	0.3	5.2	-	-	-	0.9	-	-	-	4.2
16	0.4	-	-	23.5	-	-	-	2.2	2.5	-	-	0.2
17	-	7.3	-	3.1	-	-	-	0.8	-	-	-	-
18	0.3	0.5	-	-	-	-	1.6	1.6	-	-	4.8	-
19	3.2	-	-	1.4	-	-	1.7	0.2	14.2	-	0.2	-
20	-	0.3	2.5	11.5	-	-	0.3	-	14.1	-	-	4.5
21	-	5.8	0.8	0.6	1.1	1.8	-	-	-	10.3	-	-
22	-	-	-	-	-	0.2	-	-	1.8	14.5	-	1.2
23	0.8	1.1	-	6.3	-	-	-	-	0.2	14.5	-	1.9
24	0.5	-	-	0.3	6.9	-	-	2.1	0.5	14.5	3.6	6.8
25	-	0.7	8.8	-	-	-	-	6.6	23.3	-	-	1.8
26	1.9	-	-	2.4	-	1.8	-	-	9.8	-	2.3	1.1
27	2.2	0.3	-	-	-	6.4	-	-	1.5	0.2	-	0.3
28	-	4.4	-	-	2.6	1.3	-	-	2.0	-	-	-
29	1.0	-	0.3	-	-	-	-	-	16.7	-	-	1.6
30	0.3		1.4	-	-	6.3	-	-	1.2	1.9	0.8	2.5
31	-		-		-							0.3
Total	**43.1**	**25.0**	**72.5**	**60.9**	**34.3**	**74.9**	**10.2**	**57.0**	**89.6**	**78.3**	**24.3**	**59.1**
cumulative	**43.1**	**68.1**	**140.6**	**201.5**	**235.8**	**310.7**	**320.9**	**377.9**	**467.5**	**545.8**	**570.1**	**629.2**
Year total	**629.2**											

Table A1-3 Precipitation data from Kirk Bramwith, 2000 (mm).

	January	February	March	April	May	June	July	August	September	October	November	December
1	-	-	-	1.9	-	0.2	12.0	-	2.7	1.0	1.2	0.1
2	0.4	-	0.4	24.5	-	9.6	6.6	0.2	0.4	-	12.5	-
3	-	-	1.4	18.8	-	13.5	0.6	5.5	-	0.2	0.1	0.4
4	1.0	-	-	-	-	0.2	-	0.1	-	1.2	-	2.2
5	1.0	-	-	0.2	-	2.3	7.4	-	-	-	27.9	5.2
6	-	-	-	-	-	0.7	-	-	1.0	4.2	19.0	-
7	1.3	1.2	0.4	-	-	-	-	0.9	2.1	8.2	20.8	13.6
8	-	2.2	-	1.9	-	-	1.8	1.3	-	1.5	1.5	-
9	-	-	0.4	-	-	-	2.0	-	-	8.3	-	1.2
10	-	1.2	-	2.1	-	-	3.5	-	-	7.9	3.5	1.9
11	-	3.4	-	3.4	-	-	-	-	-	7.0	2.3	0.5
12	4.3	3.0	-	15.3	-	-	0.1	0.4	-	-	-	5.1
13	2.0	-	0.1	4.3	-	-	-	3.6	-	0.5	-	1.4
14	1.5	2.3	0.1	-	-	0.5	3.2	1.0	8.1	3.6	-	0.4
15	-	0.5	-	1.1	-	-	-	0.9	8.9	0.1	2.8	-
16	-	1.0	-	3.7	-	-	-	-	-	0.3	-	-
17	-	2.2	-	1.9	1.8	-	-	-	3.0	3.6	0.3	-
18	-	0.5	-	11.3	-	-	-	0.7	12.0	-	1.5	-
19	-	-	-	2.9	5.1	-	-	2.0	26.1	-	-	2.8
20	-	3.8	-	-	7.0	-	-	0.2	1.5	5.1	0.4	0.8
21	-	-	-	4.3	1.5	-	-	6.2	2.1	-	6.8	-
22	0.3	-	-	7.2	0.4	2.8	-	-	0.9	0.9	-	-
23	-	-	4.6	1.7	2.7	-	-	-	-	0.5	6.7	7.5
24	0.4	-	-	10.0	-	0.8	-	-	8.6	1.3	1.6	5.1
25	-	-	2.1	2.8	1.0	-	-	0.4	7.1	-	3.5	1.4
26	-	-	1.6	7.1	21.1	-	-	3.9	5.4	2.7	2.0	0.7
27	-	12.0	2.3	-	1.6	-	2.4	-	5.6	0.8	3.2	0.4
28	0.2	0.6	-	0.4	0.7	2.0	12.1	0.9	0.2	7.2	-	3.1
29	1.5	0.4	-	-	0.1	2.2	-	-	0.6	17.4	-	-
30	0.5		-	-	2.5	1.1	0.6	-	3.5	5.9	0.5	-
31	-		-		2.2		5.3	7.4		0.2		6.9
Total	**14.4**	**34.3**	**13.4**	**126.8**	**47.7**	**35.9**	**57.6**	**35.6**	**99.8**	**89.6**	**118.1**	**60.7**
cumulative	**14.4**	**48.7**	**62.1**	**188.9**	**236.6**	**272.5**	**330.1**	**365.7**	**465.5**	**555.1**	**673.2**	**733.9**
Year total	**733.9**											

Table A1-4 Precipitation data from Kirk Bramwith, 2001 (mm).

	January	February	March	April	May	June	July	August	September	October	November	December
1	1.1	6.4	0.3	-	-	2.9	-	-	-	-	-	1.0
2	1.8	6.8	-	1.4	0.4	-	-	1.1	-	-	-	-
3	0.9	7.2	-	7.6	0.6	-	-	10.3	0.4	-	-	3.5
4	-	16.2	-	1.1	-	-	-	4.2	-	0.5	-	1.6
5	-	8.9	-	5.5	-	-	-	2.4	7.0	3.4	-	2.1
6	0.9	-	9.4	9.0	-	-	-	13.3	1.0	3.2	0.7	-
7	0.1	1	0.7	5.6	-	0.1	1.3	17.9	-	5.8	9.2	-
8	-	-	0.2	0.1	0.4	-	-	1.5	-	1.7	0.9	0.3
9	0.7	-	1.5	2.3	-	2.9	-	5.0	0.1	-	-	-
10	0.2	1.8	1.4	0.2	-	-	2.7	-	-	0.8	-	-
11	-	16.5	-	-	-	-	2.5	0.3	-	-	5.4	-
12	-	1.2	0.8	-	-	-	0.8	4.7	3.9	-	1.6	-
13	-	-	-	-	0.3	-	-	-	4.4	0.3	0.1	-
14	-	-	-	3.2	13.2	9.6	-	0.2	1.3	0.5	-	-
15	-	-	1.1	3.9	2.2	5.2	1.5	-	-	1.4	-	0.5
16	-	-	-	-	0.6	18.8	-	7.7	2.8	-	-	-
17	-	-	-	1.5	7.7	1.0	15.4	-	0.2	2.0	-	-
18	0.9	-	3.3	-	-	-	7.4	4.0	1.6	5.3	-	1.0
19	0.5	-	-	0.7	-	-	-	1.9	1.5	4.8	-	-
20	-	-	-	-	-	-	-	-	-	1.0	-	0.3
21	2.3	-	6.7	-	-	-	-	0.5	0.9	13.8	0.1	4.9
22	5.1	-	6.9	6.1	-	-	-	-	-	8.8	-	-
23	6.7	0.3	-	-	-	-	-	-	2.9	1.5	-	0.3
24	-	-	0.3	5.1	-	-	-	-	14.2	0.1	-	1.1
25	-	0.8	0.2	5.2	-	-	-	-	0.4	4.2	1.1	-
26	-	3.9	-	3.1	1.9	-	-	-	1.1	10.5	-	-
27	1.4	1.6	9.1	4.3	-	-	-	-	9.0	-	3.9	-
28	-	0.7	1.5	1.5	-	-	-	-	0.8	-	1.4	-
29	-	-	-	-	-	4.0	-	-	3.3	-	1.8	-
30	1.7		-	-	-	-	-	0.7	2.4	0.5	1.2	-
31	0.2		0.4		-		-	-		-		-
Total	**24.5**	**73.3**	**43.8**	**67.4**	**27.3**	**44.5**	**31.6**	**75.7**	**59.2**	**70.1**	**27.4**	**16.6**
cumulative	**24.5**	**97.8**	**141.6**	**209**	**236.3**	**280.8**	**312.4**	**388.1**	**447.3**	**517.4**	**544.8**	**561.4**
Year total	**561.4**											

Table A1-5 Precipitation data from Kirk Bramwith, 2002 (mm).

	January	February	March	April	May	June	July	August	September	October	November	December
1	-	2.0	-	0.5	1.2	-	3.4	22.6	-	1.3	7.2	4.9
2	-	2.4	-	0.3	0.6	-	1.0	1.8	-	0.4	4.0	-
3	-	0.1	0.1	-	0.9	-	2.1	3.0	-	-	4.5	1.7
4	-	5.9	-	-	-	3.5	10.1	3.1	-	0.2	0.6	3.1
5	-	3.0	-	-	0.4	-	4.3	0.2	-	0.3	3.8	0.8
6	3.2	-	-	-	-	12.9	-	-	-	-	2.4	2.0
7	-	1.2	-	-	-	-	3.9	26.2	1.1	-	1.2	0.3
8	-	1.8	-	-	-	-	0.4	2.1	2.8	-	11.1	0.3
9	-	-	0.9	-	-	-	4.6	27.8	2.8	-	2.6	-
10	-	0.6	2.7		-	2.0	1.2	0.2	-	4.1	2.7	-
11	3.9	3.4	0.7	-	-	11.4	-	0.2	10.0	4.0	0.2	-
12	-	-	-	-	1.7	-	-	-	-	5.0	1.5	1.1
13	-	5.5	-	-	4.9	-	-	-	-	0.9	18.4	3.4
14	-	-	3.6	0.5	-	4.7	-	-	-	15.4	1.1	8.4
15	-	-	10.2	-	-	1.9	0.5	-	-	0.3	4.0	8.4
16	0.2	-	-	-	-	1.1	-	-	-	-	4.0	-
17	0.3	0.6	0.8	-	7.9	-	-	-	-	-	3.7	1.2
18	-	0.4	5.7	-	0.4	-	-	3.2	-	-	0.1	-
19	-	4.6	0.3	-	0.6	-	24.4	0.5	-	24.0	-	-
20	-	1.6	2.9	-	5.8	-	2.0	-	-	10.8	6.5	-
21	-	2.7	-	0.5	4.7	-	-	-	-	1.0	3.4	-
22	-	1.9	2.1	-	-	-	-	0.7	-	2.2	1.1	18.3
23	1.6	-	-	-	2.8	-	3.5	-	-	0.9	-	3.7
24	-	4.1	0.6	-	-	-	0.2	0.2	-	7.6	2.0	-
25	6.8	5.9	0.5	3.5	1.7	-	-	-	-	4.5	-	1.6
26	2.1	0.8	-	2.9	1.4	-	-	-	-	5.0	-	-
27	4.0	-	-	7.0	4.1	1.9	-	-	-	1.6	0.7	4.4
28	0.6	2.4	-	6.6	2.2	1.4	-	0.8	-	5.1	0.2	-
29	-		-	1.9	0.3	-	10.2	-	-	-	-	25.3
30	0.4		-	2.9	-	-	22.3	-	-	-	5.0	1.9
31	0.8		-		-	0.6	2.8	-		-		4.7
Total	**23.9**	**50.9**	**31.1**	**26.6**	**41.6**	**40.8**	**96.9**	**92.6**	**16.7**	**94.6**	**92.0**	**95.5**
cumulative	**24.5**	**75.4**	**106.5**	**133.1**	**174.7**	**215.5**	**312.4**	**405.0**	**421.7**	**516.3**	**608.3**	**703.8**
Year total	**703.2**											

Appendix 2

Hydrological monitoring data

This appendix contains the hydrological monitoring data collected from Sutton Common. The piezometer location numbers are shown in Figure A2-1

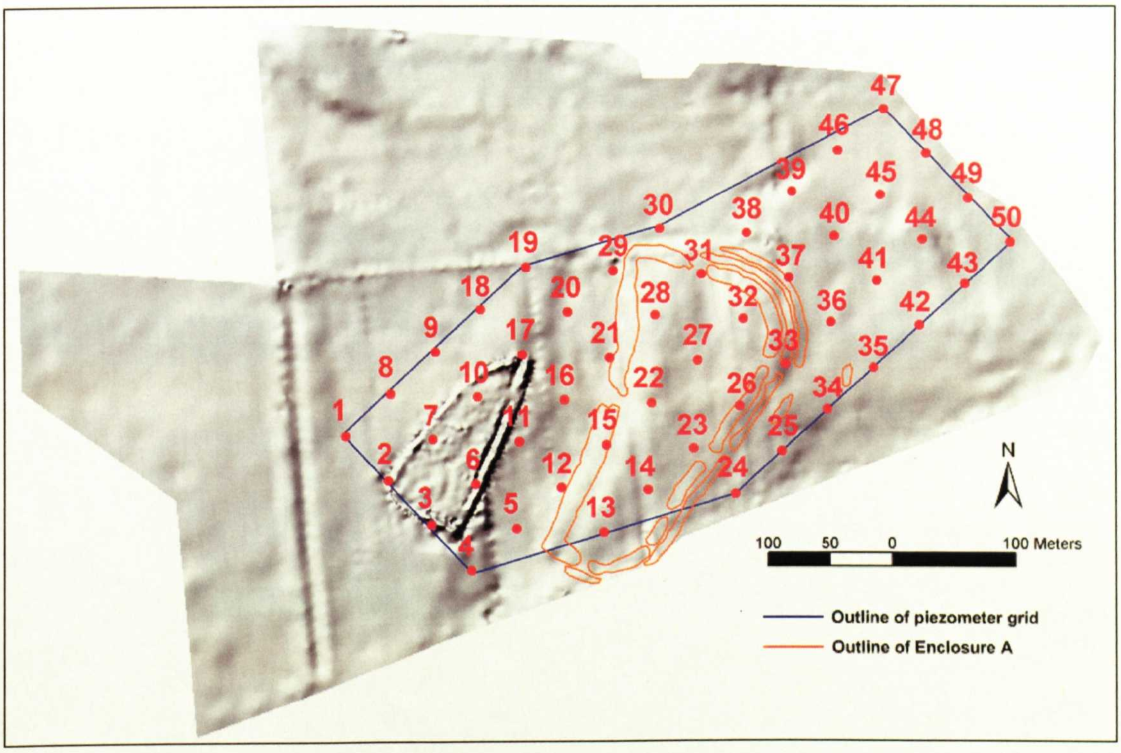

Figure A2-1. Piezometer grid location numbers.

As described in Section 3.2.2, water level readings for the piezometers were collected by means of a handheld acoustic dipper. Readings were obtained for the depth below the ground surface, the absolute height (m O.D.) of the ground surface in each location being known.

The locations of each piezometer are presented in Table A2-1, with the actual absolute water-level heights (m O.D.) being presented in Tables A2-2 to A2-10

Table A2-1 Coordinate (National Grid) and absolute Height (O.D.) of piezometer locations (From Chapman, 2000).

	North	East	Height (O.D.)
Piezo_1	456177.1	412059.5	4.29
Piezo_2	456211.8	412023.6	4.4
Piezo_3	456247.1	411987.7	4.24
Piezo_4	456279.5	411950.6	4.09
Piezo_5	456316.3	411984.4	3.71
Piezo_6	456283	412020.5	4.62
Piezo_7	456248.1	412056.8	4.85
Piezo_8	456213.6	412093.2	4.33
Piezo_9	456250.3	412127.2	4.47
Piezo_10	456284.5	412090.9	5.15
Piezo_11	456318.6	412054.4	4.39
Piezo_12	456352.7	412017.8	4.07
Piezo_13	456387	411981.4	4.8
Piezo_14	456423	412015.4	4.87
Piezo_15	456389.2	412051.7	4.8
Piezo_16	456355.2	412088.3	4.46
Piezo_17	456321.1	412124.7	4.99
Piezo_18	456286.9	412161.1	4.54
Piezo_19	456324	412195.7	4.28
Piezo_20	456357.7	412158.9	4.08
Piezo_21	456391.6	412122	4.44
Piezo_22	456425.8	412085.5	5.49
Piezo_23	456459.8	412048.9	5.03
Piezo_24	456494	412012.2	4.22
Piezo_25	456531.6	412046.6	4.33
Piezo_26	456497.5	412083.1	5.34
Piezo_27	456463	412119.8	5.41
Piezo_28	456428.5	412156.4	5.71
Piezo_29	456394.4	412192.8	4.81
Piezo_30	456432.4	412226.9	4
Piezo_31	456466.2	412190.1	4.79
Piezo_32	456500.2	412153.5	5.4
Piezo_33	456534.3	412116.8	5.01
Piezo_34	456568.3	412080.4	4.27
Piezo_35	456605.5	412113.8	4.69
Piezo_36	456571.2	412150.5	4.73
Piezo_37	456537.1	412187	4.9
Piezo_38	456502.9	412223.3	4.61
Piezo_39	456539.7	412256.8	4.51
Piezo_40	456574.1	412220.6	4.4
Piezo_41	456608.4	412184.4	4.47
Piezo_42	456642.8	412148.2	4.73
Piezo_43	456679.6	412182	4.06
Piezo_44	456645.4	412217.9	4.4
Piezo_45	456611.1	412254	4.05
Piezo_46	456576.7	412290.2	3.59
Piezo_47	456613.7	412323.8	3.07
Piezo_48	456648.1	412287.6	3.15
Piezo_49	456682.3	412251.5	3.12
Piezo_50	456716.5	412215.7	3.21

Table A2-2 Piezometer level readings for dates shown in table (m OD).

	5.10.98	**12.10.98**	**2.11.98**	**16.11.98**	**30.11.98**	**16.12.98**
Piezo_1	2.43	2.48	3.25	3.33	3.30	3.76
Piezo_2	2.57	2.55	3.48	3.60	3.53	3.86
Piezo_3	2.62	2.61	3.30	3.37	3.35	3.71
Piezo_4	2.25	2.34	2.78	3.05	3.15	3.34
Piezo_5	2.21	2.33	2.77	3.11	3.23	3.43
Piezo_6	2.68	2.67	3.15	3.42	3.46	3.80
Piezo_7	No data	No data	3.19	3.37	3.50	4.19
Piezo_8	2.46	2.51	2.97	3.37	3.41	3.59
Piezo_9	2.51	2.53	2.90	3.26	3.37	3.68
Piezo_10	No data	No data	No data	3.09	3.22	3.94
Piezo_11	2.55	2.54	2.95	3.12	3.23	3.82
Piezo_12	2.65	2.68	3.12	3.37	3.55	3.68
Piezo_13	2.98	2.95	3.81	3.57	3.78	3.95
Piezo_14	3.23	3.21	3.83	4.09	4.07	4.37
Piezo_15	3.23	3.13	3.61	3.92	3.99	4.15
Piezo_16	2.49	2.50	2.71	3.05	3.26	3.48
Piezo_17	2.99	2.77	2.94	3.05	3.13	3.58
Piezo_18	2.63	2.64	2.83	3.12	3.24	3.52
Piezo_19	2.48	2.47	3.13	3.24	3.24	3.59
Piezo_20	2.44	2.52	2.90	3.15	3.20	3.37
Piezo_21	2.75	2.85	3.15	3.37	3.52	3.73
Piezo_22	3.58	3.56	3.89	4.52	4.53	4.80
Piezo_23	3.40	3.37	4.27	4.25	4.25	4.55
Piezo_24	2.52	2.47	3.75	3.75	3.84	4.06
Piezo_25	2.56	2.52	3.41	3.52	3.60	3.93
Piezo_26	3.61	3.55	4.43	4.32	4.32	4.62
Piezo_27	3.61	3.59	4.09	4.54	4.56	4.79
Piezo_28	No data	No data	3.50	4.10	4.30	4.85
Piezo_29	2.84	2.83	3.13	3.34	3.46	4.00
Piezo_30	2.65	2.68	3.35	3.49	3.55	3.82
Piezo_31	3.14	3.11	4.04	4.07	4.07	4.34
Piezo_32	3.43	3.40	4.09	4.33	4.35	4.53
Piezo_33	3.25	3.17	3.91	4.20	4.22	4.44
Piezo_34	2.69	2.66	3.59	3.71	3.64	3.99
Piezo_35	2.75	2.73	3.20	3.55	3.59	4.04
Piezo_36	3.00	2.98	4.11	4.15	4.14	4.35
Piezo_37	3.06	3.04	3.98	4.03	4.03	4.37
Piezo_38	2.93	2.91	3.66	3.82	3.83	4.08
Piezo_39	2.72	2.71	3.64	3.70	3.71	4.00
Piezo_40	2.76	2.74	3.70	3.75	3.77	3.97
Piezo_41	2.33	2.46	3.00	3.42	3.65	3.83
Piezo_42	2.51	2.57	3.22	3.71	3.77	3.95
Piezo_43	2.16	2.32	3.01	3.25	3.28	3.33
Piezo_44	2.29	2.41	3.02	3.41	3.53	3.68
Piezo_45	2.16	2.34	2.98	3.28	3.37	3.55
Piezo_46	2.52	2.54	2.90	2.93	2.93	3.10
Piezo_47	2.40	2.48	2.79	2.83	2.83	2.92
Piezo_48	2.43	2.47	2.76	2.75	2.94	3.00
Piezo_49	2.41	2.45	2.76	2.81	2.82	2.93
Piezo_50	2.46	2.47	2.77	2.81	2.81	2.93

Table A2-3 Piezometer level readings for dates shown in table (m OD).

	6.1.99	21.1.99	10.2.99	3.3.99	1.4.99	15.4.99
Piezo_1	3.76	3.68	3.49	3.65	3.57	3.33
Piezo_2	3.89	3.88	3.73	3.82	3.87	3.67
Piezo_3	3.73	3.78	3.64	3.65	3.77	3.60
Piezo_4	3.45	3.55	3.49	3.43	3.58	3.46
Piezo_5	3.52	3.58	3.61	3.56	3.66	3.56
Piezo_6	3.93	4.11	3.95	3.90	4.20	3.99
Piezo_7	4.24	4.23	4.04	4.21	4.32	4.07
Piezo_8	3.67	3.76	3.67	3.60	3.73	3.59
Piezo_9	3.66	3.72	3.60	3.59	3.66	3.51
Piezo_10	4.22	4.27	3.99	4.13	4.29	4.09
Piezo_11	3.87	3.87	3.67	3.88	3.81	3.63
Piezo_12	3.74	3.84	3.71	3.72	3.82	3.62
Piezo_13	3.97	3.90	3.78	3.98	3.83	3.69
Piezo_14	4.35	4.26	4.06	4.21	4.12	3.95
Piezo_15	4.14	4.18	4.10	4.08	4.13	4.01
Piezo_16	3.67	3.79	3.71	3.66	3.82	3.66
Piezo_17	3.73	3.74	3.58	3.66	3.80	3.60
Piezo_18	3.51	3.57	3.46	3.42	3.48	3.39
Piezo_19	3.51	3.53	3.42	3.42	3.49	3.35
Piezo_20	3.41	3.49	3.41	3.36	3.48	3.36
Piezo_21	3.90	3.97	3.97	3.94	4.02	3.98
Piezo_22	4.78	4.74	4.57	4.62	4.63	4.44
Piezo_23	4.52	4.42	4.21	4.53	4.25	4.11
Piezo_24	4.10	4.05	3.75	4.13	3.86	3.67
Piezo_25	3.95	3.96	3.70	4.02	3.76	3.60
Piezo_26	4.62	4.44	4.30	4.57	4.32	4.24
Piezo_27	4.78	4.71	4.58	4.69	4.61	4.44
Piezo_28	4.72	4.83	4.65	4.49	4.68	4.50
Piezo_29	4.38	3.99	3.83	3.88	3.90	3.77
Piezo_30	3.83	3.90	3.70	3.88	3.85	3.64
Piezo_31	4.31	4.30	4.11	4.27	4.17	4.04
Piezo_32	4.52	4.45	4.37	4.52	4.39	4.26
Piezo_33	4.45	4.40	4.45	4.48	4.29	4.20
Piezo_34	4.00	3.96	3.77	3.96	3.87	3.75
Piezo_35	4.03	3.99	4.61	4.04	3.91	3.74
Piezo_36	4.36	4.32	4.15	4.39	4.23	4.09
Piezo_37	4.36	4.29	4.14	4.35	4.16	3.98
Piezo_38	4.08	4.06	3.83	4.10	3.94	3.76
Piezo_39	4.01	4.00	3.73	4.05	3.87	3.65
Piezo_40	3.98	3.94	3.80	4.00	3.89	3.75
Piezo_41	3.93	4.00	3.96	3.97	4.02	3.93
Piezo_42	4.02	4.11	4.01	3.96	4.08	3.91
Piezo_43	3.33	3.36	3.32	3.31	3.36	3.30
Piezo_44	3.72	3.78	3.70	3.67	3.78	3.67
Piezo_45	3.55	3.57	3.48	3.49	3.55	3.43
Piezo_46	3.17	3.17	3.05	3.11	3.14	3.04
Piezo_47	2.97	2.97	2.93	2.93	2.92	2.77
Piezo_48	3.05	3.10	3.05	3.01	3.05	3.03
Piezo_49	No data	No data	No data	2.97	3.00	2.96
Piezo_50	2.99	3.03	2.94	2.98	3.06	2.92

Table A2-4 Piezometer level readings for dates shown in table (m OD).

	30.4.99	13.5.99	27.5.99	10.6.99	23.6.99	13.7.99
Piezo_1	3.69	3.43	3.17	3.40	3.03	2.75
Piezo_2	3.96	3.80	3.54	3.77	3.40	2.94
Piezo_3	3.87	3.69	3.51	3.63	3.42	3.07
Piezo_4	3.57	3.49	3.36	3.29	3.23	2.99
Piezo_5	3.61	3.61	3.47	3.37	3.31	3.03
Piezo_6	4.33	4.12	3.90	3.97	3.79	3.21
Piezo_7	4.42	4.25	3.92	4.21	3.76	3.26
Piezo_8	3.72	3.64	3.47	3.39	3.36	3.02
Piezo_9	3.76	3.56	3.41	3.36	3.32	3.00
Piezo_10	4.47	4.11	3.81	4.09	3.60	3.18
Piezo_11	3.90	3.75	3.50	3.62	3.35	3.09
Piezo_12	3.87	3.71	3.50	3.51	3.37	3.10
Piezo_13	3.90	3.75	3.59	3.77	3.49	3.28
Piezo_14	4.22	4.00	3.82	3.88	3.65	3.37
Piezo_15	4.20	4.03	3.90	3.86	3.72	3.45
Piezo_16	3.83	3.71	3.57	3.49	3.46	3.22
Piezo_17	3.90	3.67	3.46	3.49	3.31	3.13
Piezo_18	3.59	3.41	3.30	3.27	3.22	2.98
Piezo_19	3.57	3.41	3.26	3.29	3.18	2.94
Piezo_20	3.48	3.41	3.31	3.24	3.22	2.99
Piezo_21	4.01	3.99	3.92	3.85	3.78	3.59
Piezo_22	4.70	4.46	4.25	4.09	3.91	3.64
Piezo_23	4.35	4.15	3.96	3.97	3.74	3.44
Piezo_24	3.95	3.89	3.53	3.79	3.40	3.01
Piezo_25	3.87	3.74	3.47	3.71	3.35	3.01
Piezo_26	4.40	4.25	4.09	4.11	3.88	3.61
Piezo_27	4.67	4.47	4.27	4.10	3.95	3.69
Piezo_28	4.74	4.60	4.31	4.11	3.94	3.67
Piezo_29	4.01	3.82	3.65	3.58	3.49	3.25
Piezo_30	4.00	3.83	3.46	3.74	3.35	3.18
Piezo_31	4.25	4.10	3.93	4.00	3.74	3.44
Piezo_32	4.43	4.28	4.10	4.07	3.84	3.57
Piezo_33	4.36	4.25	4.08	4.18	3.93	3.62
Piezo_34	3.98	3.88	3.56	3.83	3.45	3.20
Piezo_35	3.99	3.79	3.56	3.72	3.42	3.16
Piezo_36	4.32	4.24	3.84	4.22	3.79	3.49
Piezo_37	4.27	4.05	3.85	4.05	3.76	3.43
Piezo_38	4.06	3.97	3.69	4.01	3.63	3.34
Piezo_39	4.01	3.89	3.50	3.92	3.43	3.13
Piezo_40	3.99	3.86	3.60	3.86	3.55	3.25
Piezo_41	4.03	3.97	3.85	3.81	3.77	3.49
Piezo_42	4.21	3.92	3.73	3.79	3.73	3.37
Piezo_43	3.40	3.34	3.28	3.28	3.24	2.96
Piezo_44	3.79	3.71	3.58	3.52	3.50	3.21
Piezo_45	3.57	3.50	3.39	3.35	3.35	3.08
Piezo_46	3.26	3.14	2.99	3.09	2.89	2.76
Piezo_47	3.07	3.02	2.88	3.02	2.79	2.62
Piezo_48	3.05	3.05	2.95	3.00	2.84	2.68
Piezo_49	2.96	3.02	2.91	2.95	2.82	2.67
Piezo_50	3.06	3.01	2.81	3.00	2.71	2.56

Table A2-5 Piezometer level readings for dates shown in table (m OD).

	30.7.99	18.8.99	6.9.99	28.9.99	21.10.99	8.11.99
Piezo_1	2.51	2.50	2.40	2.53	2.72	2.80
Piezo_2	2.62	2.53	2.43	2.50	2.73	2.84
Piezo_3	2.73	2.58	2.44	2.44	2.74	2.86
Piezo_4	2.72	2.54	2.41	2.27	2.48	2.64
Piezo_5	2.78	2.51	2.38	2.19	2.75	2.89
Piezo_6	3.87	3.71	2.65	2.58	2.81	2.90
Piezo_7	2.84	2.70	2.58	2.59	2.80	2.91
Piezo_8	2.71	2.61	2.54	2.48	2.79	2.89
Piezo_9	2.74	2.64	2.56	2.56	2.84	2.92
Piezo_10	2.88	No data	No data	No data	No data	2.90
Piezo_11	2.68	2.56	2.41	2.45	2.72	2.76
Piezo_12	2.85	2.65	2.50	2.40	2.68	2.77
Piezo_13	3.08	2.93	2.81	2.74	2.87	3.01
Piezo_14	3.19	3.10	3.01	2.97	3.03	3.14
Piezo_15	No data	3.16	3.04	3.07	No data	3.10
Piezo_16	2.94	2.65	2.47	2.35	2.69	2.81
Piezo_17	2.94	2.87	2.77	2.73	2.83	2.95
Piezo_18	No data	2.69	2.64	2.57	2.75	2.82
Piezo_19	2.68	2.68	2.54	2.67	2.89	2.94
Piezo_20	2.72	2.63	2.52	2.48	2.83	2.90
Piezo_21	3.35	3.13	2.96	No data	No data	3.06
Piezo_22	3.48	3.40	3.34	3.27	3.30	3.37
Piezo_23	3.24	3.16	3.05	3.19	3.24	3.37
Piezo_24	2.52	2.40	2.17	2.46	2.73	3.05
Piezo_25	2.69	2.72	2.48	2.95	2.90	2.99
Piezo_26	3.39	3.31	3.24	3.15	3.35	3.50
Piezo_27	3.53	3.47	3.41	3.35	3.40	3.49
Piezo_28	3.49	No data	No data	No data	No data	No data
Piezo_29	3.03	2.94	2.85	2.77	2.94	3.02
Piezo_30	2.96	2.89	2.72	2.91	3.07	3.17
Piezo_31	3.23	3.15	3.05	3.07	3.18	3.28
Piezo_32	No data	3.37	3.32	3.26	3.31	3.40
Piezo_33	3.39	3.30	3.19	3.18	3.33	3.42
Piezo_34	2.92	2.92	2.72	3.16	3.12	3.20
Piezo_35	2.96	2.92	2.80	2.86	3.04	3.11
Piezo_36	3.25	3.18	3.09	3.30	3.63	3.83
Piezo_37	3.23	3.16	3.09	3.18	3.37	3.48
Piezo_38	3.09	2.99	2.93	2.99	No data	3.34
Piezo_39	2.90	2.87	2.77	2.97	3.19	3.41
Piezo_40	2.99	2.99	2.86	3.27	3.44	3.56
Piezo_41	3.18	3.00	2.89	2.85	3.56	3.75
Piezo_42	3.13	3.04	2.92	2.89	3.34	3.50
Piezo_43	2.58	2.58	2.45	2.57	3.09	3.21
Piezo_44	2.84	2.72	2.62	2.65	3.22	3.38
Piezo_45	2.81	2.80	2.74	2.76	3.25	3.35
Piezo_46	2.64	2.64	2.54	2.69	2.74	2.79
Piezo_47	2.50	2.54	2.40	2.57	2.62	2.73
Piezo_48	2.57	2.59	2.46	2.62	2.66	2.78
Piezo_49	2.54	2.54	2.43	2.43	No data	2.67
Piezo_50	2.47	2.51	2.57	2.55	2.58	2.68

Table A2-6 Piezometer level readings for dates shown in table (m OD).

	23.11.99	6.12.99	7.1.00	20.1.00	3.2.00	18.2.00
Piezo_1	2.84	3.04	3.71	3.67	3.48	3.33
Piezo_2	2.89	3.11	3.77	3.74	3.66	3.62
Piezo_3	2.90	3.02	3.69	3.67	3.59	3.56
Piezo_4	2.74	2.83	3.45	3.51	3.49	3.43
Piezo_5	2.94	2.95	3.26	3.41	3.46	3.44
Piezo_6	2.94	2.99	3.87	3.87	3.80	3.74
Piezo_7	2.97	3.09	4.17	4.10	3.95	3.92
Piezo_8	2.95	3.00	3.74	3.70	3.61	3.54
Piezo_9	2.96	3.02	3.73	3.72	3.53	3.56
Piezo_10	2.94	2.99	4.08	4.05	3.84	3.79
Piezo_11	2.83	2.91	3.66	3.69	3.57	3.60
Piezo_12	2.82	2.86	3.45	3.56	3.57	3.54
Piezo_13	3.05	3.17	3.89	3.87	3.70	3.70
Piezo_14	3.20	3.28	4.22	4.18	4.02	3.99
Piezo_15	3.11	3.16	4.01	4.10	4.05	3.97
Piezo_16	2.86	2.89	3.44	3.54	3.56	3.52
Piezo_17	2.89	2.92	3.64	3.64	3.47	3.50
Piezo_18	2.87	2.91	3.71	3.63	3.50	3.45
Piezo_19	2.96	3.01	3.54	3.48	3.40	3.35
Piezo_20	2.91	2.95	3.41	3.45	3.40	3.34
Piezo_21	3.07	3.10	3.69	3.80	3.84	3.82
Piezo_22	3.44	3.50	4.65	4.65	4.49	4.47
Piezo_23	3.43	3.60	4.39	4.32	4.18	4.21
Piezo_24	3.16	3.42	3.80	3.85	3.75	3.92
Piezo_25	3.03	3.29	3.86	3.82	3.67	3.75
Piezo_26	3.57	3.66	4.39	4.38	4.26	4.25
Piezo_27	3.61	3.60	4.67	4.67	4.53	4.49
Piezo_28	No data	No data	4.47	4.52	4.41	4.27
Piezo_29	3.03	No data	3.81	3.81	3.70	3.67
Piezo_30	3.23	3.25	3.82	3.79	3.67	3.75
Piezo_31	3.34	3.46	4.30	4.17	4.06	4.07
Piezo_32	3.45	3.49	4.44	4.44	4.30	4.29
Piezo_33	3.46	3.59	4.32	4.31	4.21	4.24
Piezo_34	3.27	3.59	3.90	3.87	3.74	3.81
Piezo_35	3.14	3.26	4.01	3.97	3.79	3.79
Piezo_36	3.81	4.11	4.27	4.22	4.11	4.22
Piezo_37	3.53	3.86	4.26	4.22	4.08	4.12
Piezo_38	3.41	3.82	3.98	3.93	3.80	3.89
Piezo_39	3.44	3.77	3.94	3.88	3.74	3.84
Piezo_40	3.60	3.97	3.96	3.93	3.80	3.83
Piezo_41	3.79	3.83	4.02	4.00	3.96	3.93
Piezo_42	3.46	3.50	4.07	4.03	3.95	3.89
Piezo_43	3.23	3.26	3.43	3.42	3.36	3.34
Piezo_44	3.41	3.45	3.76	3.74	3.68	3.63
Piezo_45	3.36	3.39	3.54	3.54	3.52	3.48
Piezo_46	2.80	2.84	3.14	3.12	3.06	3.05
Piezo_47	2.74	2.80	2.98	2.99	2.97	2.97
Piezo_48	2.80	2.86	3.00	3.00	3.05	3.05
Piezo_49	2.74	2.79	3.04	3.03	2.98	2.99
Piezo_50	2.68	2.77	3.07	2.97	2.91	2.91

Table A2-7 Piezometer level readings for dates shown in table (m OD).

	1.3.00	23.3.00	17.4.00	10.5.00	9.6.00	28.6.00
Piezo_1	3.65	3.36	4.01	3.74	3.80	3.08
Piezo_2	3.80	3.63	4.14	3.94	3.97	3.44
Piezo_3	3.66	3.56	4.12	3.95	3.99	3.48
Piezo_4	3.46	3.43	3.74	3.78	3.64	3.38
Piezo_5	3.44	3.46	3.55	3.59	3.61	3.45
Piezo_6	3.82	3.78	4.33	4.25	4.20	4.26
Piezo_7	4.15	3.94	4.66	4.32	4.36	3.70
Piezo_8	3.61	3.53	3.95	3.86	3.75	3.34
Piezo_9	3.70	3.52	4.04	3.82	3.86	3.30
Piezo_10	4.20	3.85	4.78	4.32	4.36	3.59
Piezo_11	3.77	3.60	4.12	3.88	3.91	3.40
Piezo_12	3.57	3.53	3.86	3.87	3.80	3.39
Piezo_13	3.88	3.68	4.01	3.82	3.86	3.40
Piezo_14	4.19	3.94	4.37	4.06	4.07	3.58
Piezo_15	4.09	3.96	4.22	4.08	4.09	3.66
Piezo_16	3.53	3.54	3.85	3.94	3.81	3.55
Piezo_17	3.61	3.53	4.13	3.95	3.91	3.38
Piezo_18	3.61	3.48	4.07	3.78	3.85	3.29
Piezo_19	3.41	3.34	3.79	3.65	3.63	3.22
Piezo_20	3.35	3.36	3.67	3.67	3.54	3.31
Piezo_21	3.84	3.83	4.06	4.08	3.95	3.78
Piezo_22	4.53	4.40	4.83	4.58	4.59	4.05
Piezo_23	4.38	4.12	4.62	4.21	4.27	3.78
Piezo_24	4.03	3.72	4.15	3.79	3.70	3.27
Piezo_25	3.90	3.58	4.13	3.72	3.80	3.26
Piezo_26	4.50	4.26	4.60	4.31	4.32	3.95
Piezo_27	4.63	4.45	4.77	4.57	4.55	4.04
Piezo_28	4.33	4.31	4.80	4.73	4.35	4.11
Piezo_29	3.77	3.68	4.15	3.98	3.90	3.49
Piezo_30	3.83	3.61	4.00	3.74	3.81	3.27
Piezo_31	4.20	4.03	4.45	4.12	4.15	3.69
Piezo_32	4.44	4.28	4.51	4.36	4.33	3.87
Piezo_33	4.35	4.20	4.46	4.26	4.30	3.89
Piezo_34	3.94	3.66	4.13	3.82	3.86	3.34
Piezo_35	4.04	3.69	4.31	3.94	3.96	3.37
Piezo_36	4.34	4.06	4.53	4.17	4.27	3.69
Piezo_37	4.28	4.02	4.46	4.13	4.28	3.67
Piezo_38	4.01	3.75	4.24	3.84	3.98	3.48
Piezo_39	3.99	3.64	4.14	3.77	3.92	3.25
Piezo_40	3.96	3.74	4.05	3.82	3.92	3.40
Piezo_41	3.95	3.89	4.05	4.09	3.95	3.72
Piezo_42	3.93	3.89	4.15	4.04	3.91	3.45
Piezo_43	3.37	3.32	3.52	3.50	3.40	3.21
Piezo_44	3.66	3.63	3.80	3.86	3.68	3.44
Piezo_45	3.50	3.47	3.54	3.58	3.48	3.35
Piezo_46	3.10	2.99	3.33	3.19	3.22	2.85
Piezo_47	2.99	2.92	3.07	3.03	3.03	2.72
Piezo_48	3.06	3.05	3.19	3.15	3.15	2.79
Piezo_49	3.02	2.95	3.10	3.07	3.04	2.77
Piezo_50	2.96	2.89	3.10	2.96	3.01	2.65

Table A2-8 Piezometer level readings for dates shown in table (m OD).

	11.9.00	26.9.00	18.10.00	10.11.00	20.11.00	5.12.00
Piezo_1	2.59	2.77	3.73	4.33	4.29	4.24
Piezo_2	No data	3.07	3.90	4.40	4.40	4.40
Piezo_3	2.75	2.95	3.80	4.29	4.26	No data
Piezo_4	2.74	2.99	3.66	3.94	3.94	3.95
Piezo_5	3.00	3.00	3.45	3.86	3.68	No data
Piezo_6	2.95	3.09	3.82	4.63	4.47	4.47
Piezo_7	2.76	2.93	3.82	4.67	4.75	4.69
Piezo_8	2.74	2.85	3.67	4.01	3.96	4.05
Piezo_9	2.80	3.00	3.74	4.29	4.18	4.14
Piezo_10	2.89	2.96	3.55	4.96	4.70	4.65
Piezo_11	2.89	2.11	3.78	4.27	4.17	4.17
Piezo_12	No data	3.22	3.80	4.07	4.02	3.99
Piezo_13	3.07	3.22	4.02	4.33	4.13	4.16
Piezo_14	3.21	3.25	4.27	4.62	4.29	4.32
Piezo_15	3.26	3.34	4.09	4.36	4.23	4.26
Piezo_16	3.07	3.00	3.57	4.03	4.11	4.13
Piezo_17	No data	3.06	3.70	4.49	4.44	4.29
Piezo_18	2.87	2.91	3.80	4.28	4.21	4.19
Piezo_19	2.81	3.02	3.60	4.30	4.28	4.26
Piezo_20	No data	2.92	3.40	4.31	4.28	No data
Piezo_21	3.31	3.28	3.69	4.17	4.24	4.29
Piezo_22	3.59	3.51	4.68	4.98	No data	4.87
Piezo_23	3.37	3.56	4.51	4.89	4.48	4.55
Piezo_24	2.66	3.75	3.73	4.02	3.67	3.82
Piezo_25	2.80	3.43	3.98	4.21	4.06	4.17
Piezo_26	3.61	3.78	4.48	5.01	4.58	4.52
Piezo_27	3.64	3.56	4.68	4.98	4.77	4.76
Piezo_28	3.55	3.53	5.26	5.02	5.04	5.02
Piezo_29	3.08	3.17	3.91	4.39	4.24	4.23
Piezo_30	3.05	3.55	4.00	4.00	4.00	4.00
Piezo_31	3.28	3.46	4.25	4.59	4.35	4.43
Piezo_32	3.58	3.58	4.47	4.77	4.51	4.53
Piezo_33	3.51	3.81	4.40	4.62	4.43	4.46
Piezo_34	2.97	3.76	4.05	4.20	4.09	4.10
Piezo_35	2.99	3.43	4.10	4.41	4.24	4.25
Piezo_36	3.37	4.19	4.42	4.62	4.43	4.48
Piezo_37	3.30	3.71	4.32	4.57	4.42	4.41
Piezo_38	3.14	3.94	4.12	4.33	4.18	4.20
Piezo_39	2.95	3.82	4.06	4.16	4.11	4.16
Piezo_40	No data	3.79	3.99	4.17	4.06	4.09
Piezo_41	3.25	3.40	3.93	4.16	4.18	4.20
Piezo_42	3.08	3.67	4.21	4.42	4.33	4.32
Piezo_43	2.82	3.09	3.50	3.79	3.75	3.71
Piezo_44	2.94	3.12	3.71	3.96	3.98	3.99
Piezo_45	3.01	3.08	3.43	3.43	3.59	3.65
Piezo_46	2.67	2.90	3.28	No data	3.41	3.39
Piezo_47	2.57	2.88	3.03	No data	3.07	3.07
Piezo_48	2.62	2.96	3.15	No data	3.17	3.15
Piezo_49	2.58	2.79	3.02	No data	3.12	3.12
Piezo_50	2.50	2.83	3.09	No data	3.14	3.14

Table A2-9 Piezometer level readings for dates shown in table (m OD).

	21.12.00	15.1.01	14.2.01	18.4.01	21.5.01	13.6.01
Piezo_1	4.29	4.13	4.33	4.14	3.80	3.25
Piezo_2	4.40	4.32	4.40	4.40	4.00	3.59
Piezo_3	4.27	4.20	4.44	4.21	3.86	3.50
Piezo_4	3.95	3.89	3.97	3.91	3.72	3.34
Piezo_5	3.73	3.71	3.73	3.73	3.68	3.37
Piezo_6	4.52	4.44	4.67	4.52	4.19	3.79
Piezo_7	4.70	4.54	4.77	4.61	4.23	3.80
Piezo_8	4.10	4.05	4.33	4.10	3.77	3.37
Piezo_9	4.16	4.08	4.18	4.13	3.79	3.38
Piezo_10	4.89	4.55	4.96	4.65	4.21	3.74
Piezo_11	4.21	4.09	4.23	4.09	3.84	3.47
Piezo_12	4.02	3.96	4.03	3.97	3.76	3.40
Piezo_13	4.19	4.06	4.30	4.11	3.85	3.55
Piezo_14	4.37	4.21	4.54	4.22	3.97	3.69
Piezo_15	4.32	4.21	4.44	4.24	3.99	3.73
Piezo_16	4.15	4.11	4.22	4.13	3.86	3.54
Piezo_17	4.34	4.25	4.54	4.32	3.96	3.54
Piezo_18	4.21	4.14	4.32	4.17	3.79	3.37
Piezo_19	4.12	3.90	4.32	3.93	3.58	3.22
Piezo_20	4.12	No data	No data	No data	3.68	3.21
Piezo_21	4.29	4.28	4.37	4.32	4.08	3.89
Piezo_22	4.85	4.74	5.01	4.76	4.47	4.16
Piezo_23	4.63	4.40	4.87	4.43	4.15	3.87
Piezo_24	3.86	3.72	3.88	3.73	3.59	3.28
Piezo_25	4.16	4.06	4.27	4.11	3.75	3.32
Piezo_26	4.55	4.42	4.96	4.44	4.25	5.02
Piezo_27	4.81	4.69	4.90	4.68	4.46	4.14
Piezo_28	5.01	4.94	4.99	4.88	4.74	4.53
Piezo_29	4.26	4.15	4.41	4.19	3.86	3.58
Piezo_30	4.00	No data	4.00	4.00	3.75	3.36
Piezo_31	4.47	4.31	4.64	4.37	4.09	3.79
Piezo_32	4.55	4.49	4.73	4.49	4.30	4.03
Piezo_33	4.49	4.40	4.60	4.41	4.22	3.94
Piezo_34	4.14	4.07	4.20	4.11	3.81	3.39
Piezo_35	4.32	4.21	4.42	4.23	3.81	3.43
Piezo_36	4.53	4.35	4.59	4.18	4.07	3.66
Piezo_37	4.62	4.31	4.65	4.34	4.05	3.71
Piezo_38	4.27	4.12	4.34	4.15	3.89	3.53
Piezo_39	4.21	4.07	4.24	4.08	3.77	3.27
Piezo_40	4.08	4.03	4.28	4.15	No data	3.43
Piezo_41	4.21	4.20	4.25	4.22	4.04	3.70
Piezo_42	4.31	4.23	4.38	4.29	3.94	3.61
Piezo_43	3.71	3.65	3.71	3.62	3.45	3.23
Piezo_44	4.03	4.01	4.06	4.03	3.81	3.46
Piezo_45	3.68	3.69	3.76	3.74	3.62	3.35
Piezo_46	3.40	3.33	3.46	3.37	3.13	2.91
Piezo_47	3.08	3.08	3.08	3.07	2.99	2.75
Piezo_48	3.17	3.17	3.19	3.18	3.15	2.79
Piezo_49	3.13	3.12	3.13	3.12	3.02	2.77
Piezo_50	3.14	3.13	3.15	3.09	2.95	2.68

Table A2-10 Piezometer level readings for dates shown in table (m OD).

	10.8.01	23.1.02	7.2.02	1.3.02	27.3.02
Piezo_1	2.89	3.35	3.73	3.86	3.71
Piezo_2	3.18	3.55	3.81	3.97	3.89
Piezo_3	3.07	3.49	3.77	3.92	3.83
Piezo_4	3.05	3.41	3.67	3.82	3.64
Piezo_5	2.84	3.50	3.57	3.66	3.49
Piezo_6	3.23	3.61	3.79	4.03	3.97
Piezo_7	3.20	3.65	4.01	4.20	4.12
Piezo_8	3.02	3.48	3.64	3.82	3.79
Piezo_9	3.09	3.51	3.73	3.83	3.78
Piezo_10	3.14	3.52	3.95	4.26	4.13
Piezo_11	3.36	3.61	3.84	3.96	3.86
Piezo_12	3.07	3.59	3.73	3.90	3.86
Piezo_13	3.10	3.82	3.97	4.00	3.90
Piezo_14	3.24	3.95	4.20	4.23	4.07
Piezo_15	3.32	3.93	4.10	4.16	4.07
Piezo_16	3.22	3.55	3.71	3.90	3.84
Piezo_17	3.22	3.41	3.69	3.87	3.81
Piezo_18	3.04	3.52	3.79	3.89	3.80
Piezo_19	2.99	3.24	3.42	3.58	3.49
Piezo_20	3.06	3.28	3.46	3.66	3.57
Piezo_21	3.46	3.74	3.86	3.96	3.91
Piezo_22	3.68	4.28	4.62	4.70	4.60
Piezo_23	3.43	4.27	4.52	4.65	4.54
Piezo_24	3.17	3.52	3.74	3.88	3.73
Piezo_25	3.41	3.59	3.86	3.94	3.76
Piezo_26	3.60	4.26	4.47	4.49	4.33
Piezo_27	3.71	4.36	4.68	4.73	4.62
Piezo_28	3.64	4.11	4.52	4.73	4.63
Piezo_29	3.23	3.65	3.88	4.01	3.84
Piezo_30	3.33	3.75	3.91	3.98	3.92
Piezo_31	3.44	4.02	4.21	4.34	4.19
Piezo_32	3.55	4.25	4.42	4.42	4.35
Piezo_33	3.58	4.18	4.32	4.36	4.26
Piezo_34	3.52	3.60	3.90	4.01	3.86
Piezo_35	3.22	3.56	3.95	4.15	3.95
Piezo_36	3.46	4.08	4.28	4.32	4.17
Piezo_37	3.42	4.06	4.26	4.34	4.17
Piezo_38	3.29	3.83	4.03	4.13	3.98
Piezo_39	3.32	3.79	4.02	4.13	3.96
Piezo_40	3.53	3.81	3.89	3.94	3.86
Piezo_41	3.18	3.87	4.01	4.13	4.01
Piezo_42	3.15	3.75	4.06	4.17	3.99
Piezo_43	3.03	3.30	3.42	3.53	3.41
Piezo_44	3.15	3.54	3.81	3.94	3.82
Piezo_45	3.05	3.35	3.46	3.51	3.42
Piezo_46	2.88	3.01	3.10	3.26	3.20
Piezo_47	2.68	2.79	2.83	2.94	2.93
Piezo_48	2.70	2.89	2.97	3.07	3.05
Piezo_49	2.60	2.84	2.93	3.07	3.02
Piezo_50	2.69	2.78	2.86	3.03	2.96

Appendix 3

Evapotranspiration data

Evapotranspiration data has been obtained from hydrological appraisal undertaken by Geomorphological services Ltd (1990) on Sutton Common. This source documented potential evapotranspiration rates at RAF Finningley, located approximately 18 km southwest of Sutton Common, from 1961 through to 1989. The raw data are presented in table A3-1. Values are given in mm per calendar month.

Table A3-1 Evapotranspiration data from RAF Finningley, 1961 - 1989 (Geomorphological Services Ltd., 1990).

year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
1961	5.59	14.99	44.20	42.16	80.01	108.20	88.14	84.84	44.70	23.88	6.10	0.25	543.06
1962	6.35	24.89	36.07	56.13	78.23	107.44	80.52	81.79	44.96	19.05	4.57	3.05	543.05
1963	2.54	5.84	31.75	50.04	92.20	97.28	92.96	67.56	50.80	30.99	12.70	4.57	539.23
1964	3.56	15.49	26.92	60.45	108.20	82.80	101.09	91.44	60.71	18.54	10.16	6.60	585.96
1965	9.40	23.11	33.27	62.74	83.06	93.73	76.45	79.25	42.67	18.03	6.10	1.52	529.33
1966	4.83	14.22	43.43	43.18	86.11	92.71	89.66	73.91	46.99	16.00	9.65	8.89	529.58
1967	2.54	17.78	58.42	55.88	69.09	102.36	103.63	74.93	44.96	32.26	0.00	4.32	566.17
1968	9.14	7.62	48.51	58.67	67.06	98.30	70.10	70.87	41.40	21.34	6.86	1.52	501.39
1969	5.84	9.40	21.59	55.12	63.25	98.55	105.92	67.56	43.43	20.57	6.35	2.29	499.87
1970	0.51	14.73	33.02	53.85	93.22	114.81	100.58	78.99	54.61	28.70	7.87	1.52	582.41
1971	0.00	10.10	28.30	45.00	82.60	76.60	102.00	70.60	47.40	22.80	8.30	5.20	498.90
1972	1.40	9.50	26.50	56.60	80.00	82.10	81.80	79.00	40.60	22.70	3.20	2.40	485.80
1973	0.40	11.30	35.30	60.90	79.40	109.30	80.00	78.10	45.70	16.20	7.00	3.70	527.30
1974	12.30	16.80	29.00	50.10	93.40	95.40	98.70	84.10	48.10	27.20	9.30	20.70	585.10
1975	16.90	7.60	30.70	54.60	83.30	125.90	105.40	104.50	59.70	22.90	8.00	2.70	622.20
1976	20.30	14.50	38.30	60.50	78.10	120.50	131.40	96.40	44.60	17.70	3.60	0.00	625.90
1977	2.30	8.50	33.80	68.10	87.80	89.70	96.80	74.70	57.00	22.50	15.40	4.60	561.20
1978	7.20	6.90	40.40	44.20	79.70	92.40	82.70	66.20	58.30	25.30	10.90	0.00	514.20
1979	1.80	9.30	33.50	50.00	70.90	96.60	104.70	77.60	59.40	18.80	11.20	5.90	539.70
1980	0.80	9.70	27.90	61.00	93.20	83.60	86.30	71.40	52.10	25.00	16.40	14.70	542.10
1981	9.30	13.00	32.10	48.50	73.70	99.30	101.60	83.30	59.80	24.70	14.60	0.00	559.90
1982	4.50	14.10	40.50	63.70	104.90	82.80	98.60	88.50	54.20	22.70	15.20	7.30	597.00
1983	26.00	12.70	36.40	48.30	60.70	91.70	107.00	85.80	53.40	34.00	6.70	4.80	567.50
1984	11.30	13.70	27.60	62.40	76.70	101.40	113.30	84.70	52.60	27.70	9.50	0.00	580.90
1985	7.10	12.40	30.00	57.90	73.60	90.80	101.80	83.20	55.10	25.80	6.30	8.70	552.70
1986	15.60	9.70	40.00	48.20	95.40	103.00	103.80	76.30	50.50	27.80	13.20	15.10	598.60
1987	4.70	12.20	37.20	59.80	85.00	72.10	93.90	71.30	52.80	18.40	11.10	7.90	526.40
1988	6.70	23.00	41.00	50.10	80.90	87.60	91.10	90.50	58.90	22.50	2.40	11.30	566.00
1989	11.90	27.00	43.20	48.20	101.40	112.40	120.70	110.60	61.00				
month tot	7.27	13.45	35.48	54.36	82.80	96.88	96.92	80.96	51.26	23.36	8.67	5.34	552.55
per day	0.23	0.48	1.14	1.81	2.67	3.23	3.13	2.61	1.71	0.75	0.29	0.17	

Appendix 4

Sutton Common hydrological budget calculations

This appendix presents the table of calculations generated during the analysis of the Sutton Common water budget exercise. All values are presented as monthly averages.

P = precipitation.

E = evapotranspiration.

Pe = effective precipitation.

Satvo = saturated volume of ground within the piezometer monitoring grid, generated from the GIS surface models derived from watertable observations.

dS = The monthly change in the volume of water within the saturated ground within the piezometer grid. Derived from *satvo* and includes the conversion factor of 0.15 for specific yield.

Q = calculated discharge from the piezometer grid.

Table A4-1 Table of calculations generated for the Sutton Common water budget.

date	*P*(mm)	*P*(m^3)	*E*(mm)	*E*(m^3)	*Pe* (m^3)	*satvo* (m^3)	*dS*(m^3)	*Q*(m^3)
10/98	124.80	12267.72	23.37	2297.64	9970.07	68586.24	0	
11/98	37.30	3666.55	8.67	852.25	2814.30	142550.46	2958.57	-144.27
12/98	43.20	4246.52	5.33	524.13	3722.39	182166.52	5942.41	-2220.02
01/99	43.10	4236.69	7.25	713.06	3523.63	186867.45	705.14	2818.49
02/99	25.00	2457.48	13.44	1321.14	1136.34	174484.56	-1857.43	2993.77
03/99	72.50	7126.68	35.46	3486.08	3640.60	182336.84	1177.84	2462.76
04/99	60.90	5986.41	54.36	5343.53	642.88	179368.36	-445.27	1088.15
05/99	34.30	3371.66	82.80	8139.26	-4767.60	165083.22	-2142.77	-2624.82
06/99	68.60	6743.31	96.87	9522.22	-2778.91	151498.81	-2037.66	-741.25
07/99	16.50	1621.93	96.91	9525.76	-7903.83	100463.56	-7655.29	-248.54
08/99	57.00	5603.04	80.97	7959.47	-2356.42	78354.29	-3316.39	959.97
09/99	103.40	10164.12	51.27	5039.79	5124.33	69090.81	-1389.52	6513.85
10/99	64.50	6340.29	23.37	2297.64	4042.64	91848.80	3413.70	628.95
11/99	29.40	2889.99	8.67	852.25	2037.74	104897.98	1957.38	80.36
12/99	56.80	5583.38	5.33	524.13	5059.25	117305.58	1861.14	3198.11
01/00	14.40	1415.51	7.25	713.06	702.44	176678.01	8905.86	-8203.42
02/00	34.30	3371.66	13.44	1321.14	2050.52	166718.60	-1493.91	3544.43
03/00	13.40	1317.21	35.46	3486.08	-2168.87	170135.16	512.48	-2681.35
04/00	126.80	12464.31	54.36	5343.53	7120.78	201700.77	4734.84	2385.94
05/00	47.70	4688.86	82.80	8139.26	-3450.39	183956.49	-2661.64	-788.75
06/00	35.90	3528.93	96.87	9522.22	-5993.29	161259.40	-3404.56	-2588.73
07/00	57.60	5662.02	96.91	9525.76	-3863.74			
08/00	35.60	3499.44	80.97	7959.47	-4460.02			
09/00	99.80	9810.24	51.27	5039.79	4770.45	108845.62	-2620.69	7391.14
10/00	89.60	8807.59	23.37	2297.64	6509.95	182661.83	11072.43	-4562.48
11/00	118.10	11609.11	8.67	852.25	10756.86	213749.27	4663.12	6093.74
12/00	60.70	5966.75	5.33	524.13	5442.62	211390.34	-353.84	5796.46
01/01	24.50	2408.33	7.25	713.06	1695.26	202712.73	-1301.6415	2996.91
02/01	73.30	7205.32	13.44	1321.14	5884.18	222609.78	2984.56	2899.62
03/01	43.40	4266.18	35.46	3486.08	780.10			
04/01	67.80	6664.67	54.36	5343.53	1321.14	205300.88	-1298.17	2619.31
05/01	27.30	2683.56	82.80	8139.26	-5455.69	179886.44	-3812.17	-1643.53
06/01	44.50	4374.31	96.87	9522.22	-5147.92	148964.59	-4638.28	-509.64
07/01	31.60	3106.25	96.90	9525.76	-6419.51			
08/01	75.70	7441.23	80.97	7959.47	-518.23	113693.60	-2645.33	2127.10
09/01	56.80	5583.38	51.27	5039.79	543.59			
10/01	72.50	7126.68	23.37	2297.64	4829.04			
11/01	26.20	2575.43	8.67	852.25	1723.18			
12/01	17.80	1749.72	5.33	524.13	1225.59			
01/02	23.90	2349.35	7.25	713.06	1636.29	158968.63		
02/02	50.90	5003.42	13.44	1321.14	3682.28	179884.45	3137.37	544.91
03/02	31.10	3057.10	35.46	3486.08	-428.98	186291.83	961.11	-1390.08

Appendix 5

British Geological Survey groundwater levels for Sykehouse and Westfield Farm

This appendix presents the raw data for deep groundwater levels for Sykehouse (462810, 417070), and Westfield Farm (452150, 415250) kindly provided by the BGS.

Table A5-1 contains the recorded levels from Sykehouse and Table A5-2 those from Westfield Farm.

Table A5-1a Sykehouse borehole water levels from 04/01/71 - 04/03/83 (courtesy of the BGS).

Date	Level	Date	Level	Date	Level
04/01/71	2.07	29/05/75	1.28	08/08/79	0.69
11/01/71	1.57	26/06/75	1.06	05/09/79	0.62
06/02/71	2.26	24/07/75	1.01	10/09/79	0.55
04/03/71	1.97	19/08/75	0.86	01/10/79	0.49
01/04/71	2.07	19/09/75	0.69	08/10/79	0.49
03/05/71	2.09	21/10/75	0.59	06/11/79	0.43
05/06/71	1.94	30/10/75	0.62	03/12/79	0.5
06/07/71	1.79	25/11/75	0.57	05/01/80	0.76
04/08/71	1.86	23/12/75	0.55	08/01/80	0.84
07/09/71	1.67	22/01/76	0.63	06/02/80	1.32
30/09/71	1.6	26/02/76	0.59	04/03/80	1.15
01/11/71	1.58	29/03/76	0.54	02/04/80	1.2
06/12/71	1.55	29/04/76	0.43	08/04/80	1.04
04/01/72	1.63	26/05/76	0.4	06/05/80	0.97
07/02/72	1.94	23/06/76	0.37	07/05/80	0.98
02/03/72	1.92	27/07/76	0.25	03/06/80	0.76
05/04/72	2.09	24/08/76	0.17	09/06/80	0.83
08/05/72	1.9	28/09/76	0.24	08/07/80	0.85
14/06/72	1.77	27/10/76	0.46	14/07/80	0.77
04/07/72	1.77	23/11/76	0.58	05/08/80	0.72
03/08/72	1.62	21/12/76	0.76	15/08/80	0.71
04/09/72	1.46	25/01/77	1.11	03/09/80	0.77
05/10/72	1.38	22/02/77	1.25	03/10/80	0.65
01/11/72	1.28	23/03/77	1.11	03/11/80	0.73
29/11/72	1.29	26/04/77	1.04	07/11/80	0.63
17/01/73	1.29	24/05/77	0.95	08/12/80	0.88
26/02/73	1.3	22/06/77	0.91	05/01/81	0.85
23/03/73	1.29	26/07/77	0.79	03/02/81	0.92
17/04/73	1.23	23/08/77	0.65	02/03/81	1.17
25/05/73	1.15	27/09/77	0.5	06/04/81	1.09
26/06/73	1.12	26/10/77	0.38	05/05/81	1.15
30/07/73	1.32	22/11/77	0.35	08/06/81	0.94
31/08/73	1.33	21/12/77	0.45	06/07/81	0.76
28/09/73	1.31	24/01/78	0.53	03/08/81	0.57
23/10/73	1.26	22/02/78	0.76	07/09/81	0.45
23/11/73	1.27	21/03/78	0.84	09/09/81	0.41
02/01/74	1.29	25/04/78	0.73	09/10/81	0.41
24/01/74	1.42	24/05/78	0.73	06/11/81	0.31
26/02/74	1.43	20/06/78	0.61	04/12/81	0.42
22/03/74	1.49	26/07/78	0.5	05/01/82	1.08
24/04/74	1.35	21/08/78	0.5	05/02/82	0.63
22/05/74	1.21	26/09/78	0.39	05/03/82	0.5
05/07/74	1.07	24/10/78	0.29	02/04/82	0.66
24/07/74	1	22/11/78	0.2	07/05/82	0.45
20/08/74	0.9	22/12/78	0.38	04/06/82	0.31
18/09/74	0.94	24/01/79	0.87	02/07/82	0.56
15/10/74	1.01	27/02/79	0.97	06/08/82	0.3
14/11/74	1.18	27/03/79	1.18	06/09/82	0.17
03/12/74	1.18	01/05/79	1.06	28/09/82	0.11
02/01/75	1.25	05/06/79	1.13	02/11/82	0.05
28/01/75	1.32	08/06/79	0.79	03/12/82	0.14
25/02/75	1.26	02/07/79	0.72	05/01/83	0.42
25/03/75	1.3	06/07/79	0.9	03/02/83	0.39
22/04/75	1.32	06/08/79	0.59	04/03/83	0.4

Table A5-1b Sykehouse borehole water levels from 06/04/83 - 24/09/96 (courtesy of the BGS).

Date	Level	Date	Level	Date	Level
06/04/83	0.53	05/10/87	-0.15	23/04/92	-1.2
09/05/83	0.82	05/11/87	0.01	22/05/92	-1.31
07/06/83	0.73	07/12/87	0.01	22/06/92	-1.31
06/07/83	0.47	07/01/88	0.44	21/07/92	-1.26
03/08/83	0.31	08/02/88	0.48	21/08/92	-1.33
02/09/83	0.24	07/03/88	0.3	29/09/92	-1.19
05/10/83	0.19	07/04/88	0.3	27/10/92	-1.12
03/11/83	0.17	09/05/88	0.17	24/11/92	-1.03
05/12/83	0.12	08/06/88	0.04	22/12/92	-1.03
05/01/84	0.51	08/07/88	0.06	21/01/93	-0.91
02/02/84	0.85	09/08/88	0.04	18/02/93	-0.97
06/03/84	0.59	08/09/88	-0.06	22/03/93	-1.03
09/04/84	0.6	11/10/88	-0.22	22/04/93	-0.94
14/05/84	0.47	09/11/88	-0.31	20/05/93	-1
08/06/84	0.42	07/12/88	-0.23	22/06/93	-1.06
06/07/84	0.19	24/01/89	-0.35	22/07/93	-1.14
06/08/84	0.19	22/02/89	-0.39	19/08/93	-1.21
05/09/84	0.08	17/03/89	-0.32	20/09/93	-0.86
04/10/84	0.07	19/04/89	-0.14	25/10/93	-0.92
05/11/84	0.18	22/05/89	-0.24	22/11/93	-0.86
05/12/84	0.3	22/06/89	-0.36	24/12/93	-0.56
07/01/85	0.36	21/07/89	-0.36	20/01/94	-0.66
06/02/85	0.5	21/08/89	-0.54	24/02/94	-0.61
06/03/85	0.38	20/09/89	-0.6	23/03/94	-0.63
03/04/85	0.42	20/10/89	-0.62	21/04/94	-0.68
02/05/85	0.46	20/11/89	-0.7	26/05/94	-0.71
04/06/85	0.36	20/12/89	-0.3	23/06/94	-0.87
08/07/85	0.24	08/01/90	-0.47	26/07/94	-0.95
09/08/85	0.2	16/02/90	-0.19	26/08/94	-0.99
10/09/85	0.11	20/03/90	-0.25	22/09/94	-0.95
14/10/85	-0.08	23/04/90	-0.45	19/10/94	-0.92
11/11/85	-0.12	23/05/90	-0.58	24/11/94	-0.92
09/12/85	-0.08	25/06/90	-0.64	24/11/94	-0.81
06/01/86	0.13	25/07/90	-0.77	21/12/94	-0.7
06/02/86	0.42	24/08/90	-0.85	24/01/95	-0.47
10/03/86	0.29	21/09/90	-0.85	24/02/95	-0.41
09/04/86	0.31	22/10/90	-0.84	23/03/95	-0.56
06/05/86	0.47	20/11/90	-0.86	26/04/95	-0.62
10/06/86	0.44	17/12/90	-0.86	23/05/95	-0.72
08/07/86	0.24	21/01/91	-0.82	21/06/95	-0.88
06/08/86	0.09	25/02/91	-0.75	21/07/95	-0.96
04/09/86	0.14	25/03/91	-0.69	24/08/95	-1.08
07/10/86	-0.06	26/04/91	-0.68	21/09/95	-1.11
05/11/86	-0.06	22/05/91	-0.84	02/11/95	-1.27
04/12/86	0.04	20/06/91	-0.86	24/11/95	-1.25
08/01/87	0.26	22/07/91	-0.97	22/12/95	-1.2
05/02/87	0.24	21/08/91	-1.03	23/01/96	-1.29
05/03/87	0.16	26/09/91	-1.06	21/02/96	-1.23
06/04/87	0.34	22/10/91	-1.17	25/03/96	-1.07
06/05/87	0.21	25/11/91	-1.18	23/04/96	-1.26
03/06/87	0.11	19/12/91	-1.1	23/05/96	-1.36
06/07/87	0.03	23/01/92	-1.08	24/06/96	-1.49
06/08/87	0.34	27/02/92	-1.2	23/08/96	-1.47
07/09/87	-0.1	27/03/92	-1.23	24/09/96	-1.5

Table A5-1c Sykehouse borehole water levels from 22/10/96 - 11/12/01 (courtesy of the BGS).

Date	Level
22/10/96	-1.61
22/11/96	-1.5
23/12/96	-1.2
24/01/97	-1.41
24/02/97	-1.27
24/03/97	-1.34
22/04/97	-1.48
23/05/97	-1.58
23/06/97	-1.56
21/07/97	-1.45
21/08/97	-1.47
23/09/97	-1.45
22/10/97	-1.53
24/11/97	-1.54
21/01/98	-1.19
24/02/98	-1.3
24/03/98	-1.11
20/04/98	-0.88
21/05/98	-1.08
22/06/98	-0.92
17/07/98	-0.95
20/08/98	-1.1
17/09/98	-1.29
19/10/98	-1.35
17/11/98	-1.12
21/12/98	-0.99
22/01/99	-0.91
19/02/99	-0.88
19/03/99	-0.78
20/04/99	-0.73
18/05/99	-0.82
15/06/99	-0.86
14/07/99	-0.88
17/08/99	-0.91
23/09/99	-1.05
14/10/99	-1.05
15/11/99	-1.01
14/12/99	-0.84
17/01/00	-0.9
23/03/00	-0.79
18/04/00	-0.51
24/05/00	-0.63
22/06/00	-0.58
17/07/00	-0.7
14/08/00	-0.74
13/09/00	-0.88
10/10/00	-0.54
16/11/00	-0.11
11/12/00	-0.04
12/01/01	-0.21
12/02/01	0.17
15/06/01	0
16/07/01	-0.32
14/08/01	-0.33
20/09/01	-0.53
11/10/01	-0.6
14/11/01	-0.46
11/12/01	-0.56

Table A5-2a Westfield Farm borehole water levels from 04/03/71 - 10/03/86 (courtesy of the BGS).

Date	Level	Date	Level	Date	Level
04/03/71	13.51	**21/12/76**	11.64	**03/08/81**	13.54
01/04/71	13.5	**25/01/77**	9.58	**07/09/81**	13.66
03/05/71	13.54	**22/02/77**	10.66	**06/11/81**	13.33
06/07/71	13.36	**23/03/77**	10.7	**04/12/81**	13.32
04/08/71	13.2	**26/04/77**	11.8	**05/01/82**	13.28
07/09/71	13.3	**24/05/77**	11.63	**05/02/82**	13.59
30/09/71	13.22	**22/06/77**	10.62	**05/03/82**	13.62
01/11/71	13.17	**26/07/77**	11.68	**02/04/82**	13.55
06/12/71	13.12	**23/08/77**	11.6	**07/05/82**	13.98
04/01/72	13.14	**27/09/77**	11.33	**04/06/82**	13.83
05/10/72	13.15	**25/10/77**	11.28	**02/07/82**	13.5
01/11/72	13.05	**01/11/77**	11.29	**06/08/82**	13.57
28/11/72	12.47	**24/01/78**	11.3	**06/09/82**	13.1
20/12/72	12.98	**22/02/78**	11.38	**02/11/82**	13.57
17/01/73	13.11	**21/03/78**	11.42	**03/12/82**	13.19
26/02/73	12.85	**25/04/78**	11.44	**05/01/83**	13.4
23/03/73	12.8	**24/05/78**	11.38	**03/02/83**	13.03
26/04/73	12.81	**20/06/78**	11.35	**04/03/83**	13.18
25/05/73	12.7	**26/07/78**	11.17	**06/04/83**	13.23
26/06/73	12.6	**21/08/78**	11.1	**09/05/83**	13.36
30/07/73	12.69	**26/09/78**	11.02	**07/06/83**	13.97
31/08/73	12.62	**24/10/78**	10.81	**06/07/83**	13.59
28/09/73	12.62	**22/11/78**	10.79	**03/08/83**	12.76
23/10/73	12.62	**22/12/78**	10.75	**02/09/83**	13.08
23/11/73	12.58	**24/01/79**	11.12	**05/10/83**	13.51
14/12/73	13.56	**27/02/79**	11	**03/11/83**	13.39
21/03/74	12.83	**27/03/79**	11.84	**05/12/83**	13.28
24/04/74	12.79	**01/05/79**	12.09	**05/01/84**	13.5
22/05/74	12.75	**05/06/79**	12.24	**02/02/84**	13.58
24/07/74	12.59	**06/07/79**	12.26	**06/03/84**	13.44
14/11/74	12.44	**08/08/79**	12.43	**11/04/84**	13.4
03/12/74	12.49	**05/09/79**	12.04	**15/05/84**	13.3
02/01/75	12.66	**01/10/79**	11.78	**08/06/84**	13.73
30/01/75	12.58	**06/11/79**	11.72	**06/07/84**	13.32
25/02/75	12.6	**04/12/79**	11.66	**06/08/84**	13.16
25/03/75	12.62	**08/01/80**	13.91	**05/09/84**	13.29
24/04/75	12.6	**06/02/80**	14.2	**04/10/84**	13.31
26/06/75	12.48	**04/03/80**	14.32	**05/11/84**	13.25
21/07/75	12.42	**02/04/80**	14.73	**05/12/84**	13.31
18/08/75	12.45	**07/05/80**	14.74	**07/01/85**	13.13
23/09/75	12.28	**03/06/80**	14.3	**06/02/85**	13.29
20/10/75	12.33	**08/07/80**	14.52	**06/03/85**	13.16
20/11/75	12.04	**05/08/80**	14.24	**03/04/85**	13.19
22/12/75	12.22	**03/09/80**	14.28	**02/05/85**	13.08
22/01/76	12.18	**03/10/80**	14.35	**04/06/85**	13.11
29/03/76	12.1	**03/11/80**	13.8	**08/07/85**	13.02
29/04/76	12.1	**08/12/80**	13.77	**09/08/85**	13.09
26/05/76	12.04	**05/01/81**	13.8	**10/09/85**	13.02
23/06/76	12	**03/02/81**	13.76	**14/10/85**	13.06
27/07/76	11.88	**02/03/81**	13.74	**11/11/85**	13.04
24/08/76	11.8	**06/04/81**	14.07	**09/12/85**	13
28/09/76	12	**05/05/81**	14.1	**06/01/86**	13.08
27/10/76	12.36	**08/06/81**	14.02	**06/02/86**	13.11
23/11/76	11.66	**06/07/81**	13.88	**10/03/86**	12.9

Table A5-2b Westfield Farm borehole water levels from 09/04/86 - 15/11/99 (courtesy of the BGS).

Date	Level	Date	Level	Date	Level
09/04/86	13.08	**20/11/90**	12	**23/05/95**	12.34
06/05/86	13.19	**17/12/90**	11.91	**21/06/95**	12.56
10/06/86	13.18	**21/01/91**	12.01	**21/07/95**	13.02
08/07/86	13	**25/02/91**	11.97	**24/08/95**	12.92
06/08/86	13.13	**25/03/91**	12.04	**21/09/95**	12.62
04/09/86	12.98	**25/04/91**	12	**02/11/95**	12.54
07/10/86	13.02	**22/05/91**	11.78	**24/11/95**	12.68
05/11/86	13.03	**20/06/91**	11.83	**22/12/95**	12.36
04/12/86	13.05	**22/07/91**	11.74	**23/01/96**	12.28
08/01/87	13.03	**21/08/91**	11.62	**21/02/96**	12.11
05/02/87	12.97	**26/09/91**	11.54	**25/03/96**	12.15
05/03/87	13.27	**22/10/91**	11.4	**23/04/96**	11.6
06/04/87	13.28	**21/11/91**	11.45	**23/05/96**	12.16
03/06/87	13.63	**19/12/91**	11.4	**24/06/96**	11.64
06/06/87	13.14	**23/01/92**	11.32	**22/07/96**	11.45
06/07/87	13.51	**27/02/92**	11.27	**23/08/96**	11.75
06/08/87	13.19	**27/03/92**	11.25	**24/09/96**	11.78
07/09/87	13.28	**23/04/92**	11.27	**22/10/96**	10.79
05/10/87	13.2	**22/05/92**	11.19	**22/11/96**	11.81
05/11/87	13.29	**22/06/92**	11.15	**23/12/96**	11.85
07/12/87	13.26	**21/07/92**	11.21	**24/01/97**	11.28
07/01/88	13.39	**21/08/92**	11.14	**24/02/97**	11.85
08/02/88	13.42	**29/09/92**	11.29	**24/03/97**	10.51
07/03/88	13.26	**27/10/92**	11.24	**22/04/97**	11.72
07/04/88	13.29	**24/11/92**	11.3	**23/05/97**	11.64
09/05/88	13	**22/12/92**	11.32	**23/06/97**	11.43
08/06/88	12.98	**21/01/93**	11.44	**21/07/97**	11.28
08/07/88	12.9	**18/02/93**	11.14	**21/08/97**	11.58
09/08/88	12.84	**22/03/93**	11.2	**23/09/97**	11.1
08/09/88	12.92	**22/04/93**	11.37	**22/10/97**	11.15
02/10/88	13.12	**20/05/93**	11.3	**24/11/97**	11.24
23/11/88	13.06	**22/06/93**	11.82	**21/01/98**	11.71
22/12/88	12.99	**22/07/93**	11.14	**24/02/98**	11.87
24/01/89	12.85	**19/08/93**	11.21	**24/03/98**	11.93
22/02/89	12.77	**20/09/93**	11.24	**20/04/98**	11.63
17/03/89	12.63	**25/10/93**	12.37	**21/05/98**	11.18
19/04/89	12.65	**22/11/93**	12.45	**22/06/98**	12.27
22/05/89	12.59	**20/12/93**	12.48	**17/07/98**	12.23
22/06/89	12.42	**20/01/94**	12.9	**20/08/98**	11.83
21/07/89	12.37	**24/02/94**	12.72	**17/09/98**	11.38
21/08/89	12.26	**23/03/94**	12.88	**19/10/98**	12.07
20/09/89	12.28	**21/04/94**	12.9	**17/11/98**	11.92
20/10/89	12.04	**26/05/94**	12.99	**21/12/98**	12.24
20/11/89	11.8	**23/06/94**	12.8	**22/01/99**	12.2
20/12/89	11.85	**26/07/94**	12.37	**19/02/99**	12
18/01/90	12.43	**26/08/94**	11.6	**19/03/99**	11.75
16/02/90	12.51	**22/09/94**	12.58	**20/04/99**	12.55
20/03/90	12.45	**19/10/94**	11.97	**18/05/99**	11.9
23/04/90	12.33	**24/11/94**	12.03	**15/06/99**	11.28
23/05/90	12.21	**21/12/94**	12.6	**14/07/99**	11.6
25/06/90	12.14	**24/01/95**	12.96	**17/08/99**	11.84
25/07/90	12.02	**24/02/95**	12.43	**23/09/99**	12.26
24/08/90	11.92	**23/03/95**	13.43	**14/10/99**	12.2
21/09/90	11.98	**26/04/95**	13.21	**15/11/99**	12.32

Table A5-2c Westfield Farm borehole water levels from 14/12/99 - 12/02/01 (courtesy of the BGS).

Date	Level
14/12/99	11.7
17/01/00	12.3
23/02/00	12.3
23/03/00	12.07
18/04/00	12.47
24/05/00	12.45
22/06/00	12.61
17/07/00	10.95
13/09/00	12.38
10/10/00	12.61
16/11/00	13.2
11/12/00	12.95
12/01/01	12.58
12/02/01	13.63

Appendix 6

Archaeological wood

Details of the archaeological wood used in the GIS modeling of the Sutton Common watertable. The locations of the individual pieces of wood detailed below, shown by their context numbers assigned during excavation, are presented in Figure A6-1

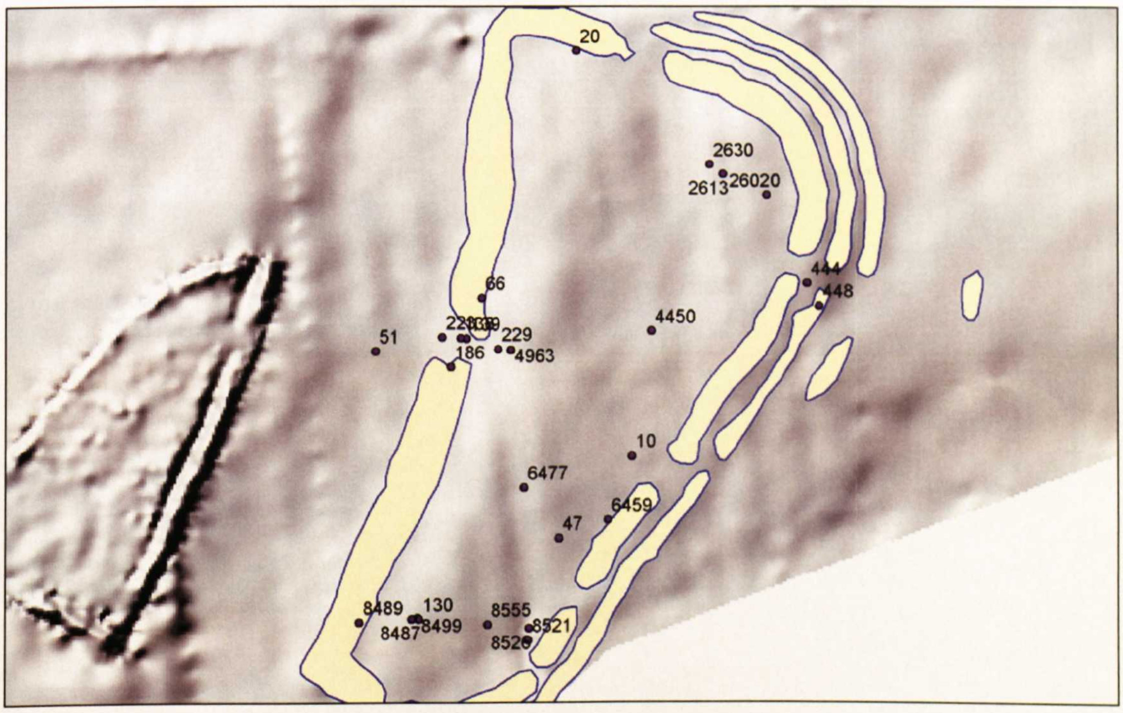

Figure A6-1 The location of the pieces of archaeological wood used in the archaeological wood model.

SCOM-98

051 - Causeway post

Located within the palaeochannel deposits, this stake exhibited good preservation, especially at its tip.

OS grid coordinates: 456363.95, 412086.74

Top: 4.05 **Base:** 2.96

444 - Entrance post

Excavated during the 1998 season of excavations, this large post is associated with the eastern entrance to enclosure A.

OS grid coordinates: 456528.12, 412103.46

Top: 4.45 **Base:** 3.78

448 - Palisade post

This piece is one of a number of wooden stakes at this location, making up part of what has been referred to as the 'palisade'.

OS grid coordinates: 456523.11, 412111.21

Top: 4.94 **Base:** 3.91

SCOM-99

010 - Wooden post

This flat-bottomed, oak post was heavily degraded.

OS grid coordinates: 456459.14, 412048.26

Top: 4.55 **Base:** 4.31

020 - Palisade stake

Excavated during the 1999 season of excavations, this piece is part of the structure referred to as a 'palisade' although its true function is yet to be determined. A number of stakes were located in association with this but this has been taken as representative of this location. The stake was heavily degraded.

OS grid coordinates: 456437.91, 412198.22

Top: 4.77 **Base:** 4.32

047 - Post

Heavily degraded, flat-bottomed post.

OS grid coordinates: 456432.07, 412018.03

Top: 4.40 **Base:** 4.02

066 - Palisade post

One of several 'palisade' posts excavated in this location. This has been taken as a representative sample, encompassing the maximum in height range.

OS grid coordinates: 456403.29,412106.20

Top: 4.46 **Base:** 4.06

130 - Well stake

Stake from the base of the 'well' feature.

OS grid coordinates: 456380.10, 411988.37

Top: 3.14 **Base:** 2.64

138 - Causeway stake

One of a number of posts excavated in this location, this stake is associated with the causeway that crosses the palaeochannel and is directly associated with the archaeological enclosures. This piece represents the greatest depth at which a stake was present. With 139, these show the full range of depths at which preservation exists.

OS grid coordinates: 456395.51, 412091.64

Top: 4.24 **Base:** 3.49

139 - Causeway stake

As above.

OS grid coordinates: 456397.70, 412091.43

Top: 4.52 **Base:** 3.72

186 - Causeway stake

Taken as representative of a number of stakes in this location.

OS grid coordinates: 456391.87, 412081.11

Top: 4.19 **Base:** 3.83

223 - Causeway stake

One of a number of posts excavated in this location, this stake is associated with the causeway that crosses the palaeochannel and is directly associated with the archaeological enclosures. It has been taken as a representative sample.

OS grid coordinates: 456388.64, 412092.05

Top: 4.00 **Base:** 3.78

229 - Entrance post

Large, flat bottomed, oak post making up part of the eastern entrance structure of enclosure A.

OS grid coordinates: 456409.48, 412087.47

Top: 4.90 **Base:** 4.01

SCOM-02

2602 - Wooden post

Flat-bottomed, heavily degraded post.

OS grid coordinates: 456508.53, 412144.01

Top: 4.86 **Base:** 4.62

2613 - Wooden post

Excavated during 2002, this post was heavily degraded.

OS grid coordinates: 456492.13, 412151.76

Top: 4.84 **Base:** 4.66

2630 - Wooden post

Excavated during 2002, this post was heavily degraded.

OS grid coordinates: 456487.58, 412155.86

Top: 4.82 **Base:** 4.38

4450 - Wooden post

Heavily degraded wooden post.

OS grid coordinates: 456466.16, 412093.89

Top: 3.71 **Base:** 3.47

4963 - Entrance post

A large, flat bottomed, oak post making up part of the eastern entrance structure of enclosure A.

OS grid coordinates: 456414.27, 412087.16

Top: 3.71 **Base:** 2.95

6459 - Post

Flat-bottomed, heavily degraded post.

OS grid coordinates: 456450.12, 412024.80

Top: 4.78 **Base:** 4.47

6477 - Post

Flat-bottomed, heavily degraded oak post.

OS grid coordinates: 456418.98, 412036.08

Top: 4.41 **Base:** 4.16

8487 - Tree

Tree trunk within 'well' feature.

OS grid coordinates: 456377.27, 411988.49

Top: 3.95 **Base:** 3.04

8489 - Palisade stake

Heavily degraded stake from the palisade in this location. This piece was taken as representative of a number of individual pieces of wood found in this location.

OS grid coordinates: 456357.97, 411987.39

Top: 3.99 **Base:** 3.31

8499 - Well stake

Worked stakes at the base of the 'well' feature.

OS grid coordinates: 456379.61, 411988.98

Top: 3.20 **Base:** 2.99

8521 - Post

Flat-bottomed post.

OS grid coordinates: 456420.68, 411980.62

Top: 4.25 **Base:** 3.52

8526 - Post

Flat-bottomed post.

OS grid coordinates: 456420.80, 411985.05

Top: 4.22 **Base:** 3.77

8555 - Post

Flat-bottomed post.

OS grid coordinates: 456405.43, 411986.28

Top: 4.28 **Base:** 3.98

Appendix 7

Soil redox potentials

Tables A7-1 to A7-9 present the raw soil redox potentials collected during the course of the soil redox monitoring programme on Sutton Common for monitoring locations 1 - 9 respectively.

The values are arranged in the table in the same format as they were installed in the field with each probe having an alpha-numeric identifier. A = probes located at 1.4 m depth, B = 0.9 m, C = 0.5 m and D = 0.1 m.

The yellow cells denote the values that were rejected as they were the most extreme of those collected at any particular depth. Where data is missing for a particular sampling date, no data was obtained for that particular location.

Table A7-1a Soil redox potentials for Site 1.

Date	**Mean pH**			**Date**	**Mean pH**		
24/01/00	7.563333			11/02/00	7.63		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-377	-115	-112	-99	-129	-49	-112	-80
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-42	180	-48	-362	-159	-150	16	-375
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
232	270	396	305	346	172	367	137
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
364	309	305	393	325	344	-170	325
Date	**Mean pH**			**Date**	**Mean pH**		
25/02/00	7.97			10/03/00	7.866667		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-149	-110	-136	-127	-151	-92	-129	-37
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-64	-190	-169	-241	-28	-88	-34	-205
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
227	204	360	131	362	184	364	126
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
360	313	234	320	320	368	157	360
Date	**Mean pH**			**Date**	**Mean pH**		
07/04/00	7.72			05/05/00	7.72		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-166	-64	-150	-115	-143	-76	-168	-135
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-45	37	48	-399	-60	-404	57	-87
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
319	-97	294	112	324	-47	320	107
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
361	260	274	362	407	415	343	411
Date	**Mean pH**			**Date**	**Mean pH**		
24/05/00	7.56			21/06/00	7.1		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-197	-82	-188	-106	-26	-118	-186	-168
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-63	-511	28	-132	-58	-478	38	-180
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
393	-72	383	115	359	-56	366	228
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
385	382	346	311	366	386	300	344
Date	**Mean pH**			**Date**	**Mean pH**		
04/09/00	7.27			06/10/00	7.735		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-241	-125	-118	-170	-426	-135	-133	7
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
158	322	121	346	70	260	103	293
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
149	48	365	188	160	72	347	228
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
348	354	354	376	366	405	387	412

Table A7-1b Soil redox potentials for Site 1.

Date	Mean pH
28/11/00	7.37

Redox readings

1A	-69	2A	-32	3A	-9	4A	-71
1B	-8	2B	-103	3B	-43	4B	-24
1C	117	2C	35	3C	18	4C	195
1D	219	2D	305	3D	226	4D	273

Date	Mean pH
31/01/01	7.36

Redox readings

1A	-34	2A	-45	3A	-41	4A	-26
1B	-11	2B	-163	3B	-76	4B	-33
1C	242	2C	55	3C	308	4C	290
1D	330	2D	293	3D	200	4D	288

Date	Mean pH
25/04/01	

Redox readings

1A		2A		3A		4A	
1B		2B		3B		4B	
1C		2C		3C		4C	
1D		2D		3D		4D	

Date	Mean pH
13/07/01	7.335

Redox readings

1A	-248	2A	-108	3A	-105	4A	-86
1B	54	2B	339	3B	103	4B	422
1C	453	2C	78	3C	414	4C	331
1D	336	2D	320	3D	348	4D	461

Date	Mean pH
21/01/02	7.725

Redox readings

1A	-9	2A	3	3A	1	4A	-30
1B	26	2B	56	3B	42	4B	212
1C	376	2C	58	3C	210	4C	57
1D	267	2D	333	3D	181	4D	311

Date	Mean pH
21/02/02	7.33

Redox readings

1A	-44	2A	19	3A	-12	4A	-75
1B	0	2B	20	3B	55	4B	-10
1C	477	2C	141	3C	174	4C	130
1D	373	2D	335	3D	331	4D	333

Date	Mean pH
17/04/02	7.21

Redox readings

1A	-72	2A	-69	3A	-41	4A	-11
1B	-74	2B	-40	3B	87	4B	-27
1C	344	2C	90	3C	350	4C	311
1D	421	2D	373	3D	350	4D	396

Table A7-2a Soil redox potentials for Site 2.

Date	Mean pH		
24/01/00	5.596667		
Redox readings			
1A	2A	3A	4A
107	410	340	390
1B	2B	3B	4B
315	360	396	361
1C	2C	3C	4C
256	404	388	263
1D	2D	3D	4D
248	456	433	416

Date	Mean pH		
11/02/00	5.493333		
Redox readings			
1A	2A	3A	4A
95	364	407	415
1B	2B	3B	4B
351	377	430	380
1C	2C	3C	4C
237	389	356	338
1D	2D	3D	4D
211	477	480	462

Date	Mean pH		
25/02/00	5.706667		
Redox readings			
1A	2A	3A	4A
54	351	387	350
1B	2B	3B	4B
485	375	423	395
1C	2C	3C	4C
302	400	386	358
1D	2D	3D	4D
192	486	485	468

Date	Mean pH		
10/03/00	5.48		
Redox readings			
1A	2A	3A	4A
46	251	375	367
1B	2B	3B	4B
397	407	400	405
1C	2C	3C	4C
195	402	298	272
1D	2D	3D	4D
241	483	490	434

Date	Mean pH		
07/04/00	5.28		
Redox readings			
1A	2A	3A	4A
-30	-251	-98	-28
1B	2B	3B	4B
313	392	396	390
1C	2C	3C	4C
218	372	236	371
1D	2D	3D	4D
261	485	457	429

Date	Mean pH		
05/05/00	5.28		
Redox readings			
1A	2A	3A	4A
-52	-233	-146	-51
1B	2B	3B	4B
-97	64	86	184
1C	2C	3C	4C
-378	99	125	311
1D	2D	3D	4D
299	507	519	490

Date	Mean pH		
24/05/00	4.97		
Redox readings			
1A	2A	3A	4A
-64	-131	-154	-71
1B	2B	3B	4B
-249	20	39	59
1C	2C	3C	4C
328	458	295	432
1D	2D	3D	4D
350	486	505	484

Date	Mean pH		
21/06/00	4.98		
Redox readings			
1A	2A	3A	4A
-63	-136	-150	-101
1B	2B	3B	4B
-128	32	300	9
1C	2C	3C	4C
317	448	257	367
1D	2D	3D	4D
314	500	487	497

Date	Mean pH		
04/09/00	4.59		
Redox readings			
1A	2A	3A	4A
83	443	430	440
1B	2B	3B	4B
454	425	447	432
1C	2C	3C	4C
417	360	394	448
1D	2D	3D	4D
242	503	484	495

Date	Mean pH		
06/10/00	5.11		
Redox readings			
1A	2A	3A	4A
98	406	417	432
1B	2B	3B	4B
403	402	394	300
1C	2C	3C	4C
373	381	355	420
1D	2D	3D	4D
225	516	533	467

Table A7-2b Soil redox potentials for Site 2.

Date	**Mean pH**			**Date**	**Mean pH**		
28/11/00	5.32			31/01/01	5.32		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-40	-73	-12	-107	-8	-63	-69	-66
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-53	-46	-51	-30	-47	-37	-55	-43
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
-11	15	-17	-17	-211	-13	-1	-49
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
-20	-58	-14	2	-29	34	323	367
Date	**Mean pH**			**Date**	**Mean pH**		
25/04/01				13/07/01	5.285		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
				0	356	359	199
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
				405	114	426	422
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
				318	113	107	423
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
				249	548	511	490
Date	**Mean pH**			**Date**	**Mean pH**		
21/01/02	5.475			21/02/02	4.97		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
51	0	98	251	21	-64	43	-35
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
437	373	419	462	404	395	351	380
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
70	267	455	462	64	351	410	414
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
473	452	452	368	331	347	403	396
Date	**Mean pH**						
17/04/02	5.14						
Redox readings							
1A	**2A**	**3A**	**4A**				
37	-104	31	-281				
1B	**2B**	**3B**	**4B**				
420	67	469	404				
1C	**2C**	**3C**	**4C**				
85	252	434	420				
1D	**2D**	**3D**	**4D**				
500	499	491	488				

Table A7-3a Soil redox potentials for Site 3.

Date	**Mean pH**		
24/01/00	4.643333		
Redox readings			
1A	**2A**	**3A**	**4A**
-50	-60	-85	-350
1B	**2B**	**3B**	**4B**
87	12	-180	63
1C	**2C**	**3C**	**4C**
419	8	443	213
1D	**2D**	**3D**	**4D**
381	266	358	343

Date	**Mean pH**		
11/02/00	4.6		
Redox readings			
1A	**2A**	**3A**	**4A**
-146	-51	-60	-496
1B	**2B**	**3B**	**4B**
-51	50	-339	60
1C	**2C**	**3C**	**4C**
395	-65	476	262
1D	**2D**	**3D**	**4D**
392	227	344	341

Date	**Mean pH**		
25/02/00	4.56		
Redox readings			
1A	**2A**	**3A**	**4A**
-308	-135	-96	-485
1B	**2B**	**3B**	**4B**
-117	12	-172	107
1C	**2C**	**3C**	**4C**
463	-62	503	374
1D	**2D**	**3D**	**4D**
379	211	350	400

Date	**Mean pH**		
10/03/00	4.34		
Redox readings			
1A	**2A**	**3A**	**4A**
-154	-139	-89	-121
1B	**2B**	**3B**	**4B**
93	58	-168	209
1C	**2C**	**3C**	**4C**
384	3	524	406
1D	**2D**	**3D**	**4D**
392	90	327	412

Date	**Mean pH**		
07/04/00	4.035		
Redox readings			
1A	**2A**	**3A**	**4A**
-170	-123	-75	-361
1B	**2B**	**3B**	**4B**
152	89	-288	182
1C	**2C**	**3C**	**4C**
391	-14	425	349
1D	**2D**	**3D**	**4D**
360	337	357	420

Date	**Mean pH**		
05/05/00	4.035		
Redox readings			
1A	**2A**	**3A**	**4A**
-164	-155	-96	-504
1B	**2B**	**3B**	**4B**
80	76	-387	234
1C	**2C**	**3C**	**4C**
265	-240	250	-369
1D	**2D**	**3D**	**4D**
299	410	341	447

Date	**Mean pH**		
24/05/00	4.73		
Redox readings			
1A	**2A**	**3A**	**4A**
-231	-112	-77	-475
1B	**2B**	**3B**	**4B**
-60	63	-385	169
1C	**2C**	**3C**	**4C**
137	-257	403	366
1D	**2D**	**3D**	**4D**
332	408	527	425

Date	**Mean pH**		
21/06/00	4.45		
Redox readings			
1A	**2A**	**3A**	**4A**
-343	-187	-93	-491
1B	**2B**	**3B**	**4B**
67	61	-425	196
1C	**2C**	**3C**	**4C**
72	-39	39	95
1D	**2D**	**3D**	**4D**
398	427	338	440

Date	**Mean pH**		
04/09/00	4.385		
Redox readings			
1A	**2A**	**3A**	**4A**
13	4	20	-91
1B	**2B**	**3B**	**4B**
147	118	365	438
1C	**2C**	**3C**	**4C**
493	484	541	162
1D	**2D**	**3D**	**4D**
370	380	367	320

Date	**Mean pH**		
06/10/00	4.46		
Redox readings			
1A	**2A**	**3A**	**4A**
-92	-134	-71	-66
1B	**2B**	**3B**	**4B**
416	136	180	467
1C	**2C**	**3C**	**4C**
400	359	515	255
1D	**2D**	**3D**	**4D**
342	436	505	443

Table A7-3b Soil redox potentials for Site 3.

Date	Mean pH		
28/11/00	4.725		
Redox readings			
1A	**2A**	**3A**	**4A**
29	-97	-45	-99
1B	**2B**	**3B**	**4B**
-50	-43	-69	-63
1C	**2C**	**3C**	**4C**
-41	-31	-8	-96
1D	**2D**	**3D**	**4D**
-17	-10	55	-34

Date	Mean pH		
31/01/01	5.6		
Redox readings			
1A	**2A**	**3A**	**4A**
21	-66	-37	-77
1B	**2B**	**3B**	**4B**
-21	31	-6	-20
1C	**2C**	**3C**	**4C**
-25	40	9	-6
1D	**2D**	**3D**	**4D**
-49	-3	-1	-30

Date	Mean pH		
25/04/01	5.75		
Redox readings			
1A	**2A**	**3A**	**4A**
-42	-114	-41	-49
1B	**2B**	**3B**	**4B**
-225	38	-425	60
1C	**2C**	**3C**	**4C**
21	80	52	-193
1D	**2D**	**3D**	**4D**
-400	-413	-393	-236

Date	Mean pH		
13/07/01	5.25		
Redox readings			
1A	**2A**	**3A**	**4A**
26	19	24	2
1B	**2B**	**3B**	**4B**
83	46	-98	42
1C	**2C**	**3C**	**4C**
308	357	418	103
1D	**2D**	**3D**	**4D**
362	316	100	350

Date	Mean pH		
21/01/02	4.88		
Redox readings			
1A	**2A**	**3A**	**4A**
-40	-5	-47	-50
1B	**2B**	**3B**	**4B**
127	504	140	547
1C	**2C**	**3C**	**4C**
404	399	377	266
1D	**2D**	**3D**	**4D**
364	443	167	394

Date	Mean pH		
21/02/02	4.89		
Redox readings			
1A	**2A**	**3A**	**4A**
-145	-146	-80	-93
1B	**2B**	**3B**	**4B**
100	172	15	334
1C	**2C**	**3C**	**4C**
386	418	415	192
1D	**2D**	**3D**	**4D**
352	413	209	456

Date	Mean pH		
17/04/02	5.25		
Redox readings			
1A	**2A**	**3A**	**4A**
-60	-283	-95	-219
1B	**2B**	**3B**	**4B**
255	255	15	284
1C	**2C**	**3C**	**4C**
370	407	430	345
1D	**2D**	**3D**	**4D**
316	428	160	391

Table A7-4a Soil redox potentials for Site 4.

Date	**Mean pH**			**Date**	**Mean pH**		
24/01/00	5.996667			11/02/00	6.06		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-179	-231	-292	-223	-368	-382	-334	-363
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-158		-106	-51	-344		-164	-113
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
158	-430	-190	166	73	-428	-295	294
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
-165	-20	100	-267	-97	-56	114	-292
Date	**Mean pH**			**Date**	**Mean pH**		
25/02/00	5.873333			10/03/00	5.803333		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-198	-328	-274	-327	-375	-282	-164	-341
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-297	-381	-151	-105	-64	-119	-18	-32
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
89	-418	-316	270	-214	-59	-237	280
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
-92	-66	-15	-287	219	136	159	298
Date	**Mean pH**			**Date**	**Mean pH**		
07/04/00	5.803333			05/05/00			
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-146	-116	-60	-159				
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-99	-18	-46	-39				
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
68	-271	-368	177				
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
123	52	30	260				
Date	**Mean pH**			**Date**	**Mean pH**		
24/05/00	5.615			21/06/00	5.35		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-301	-341	-341	-341	-372	-358	-328	-303
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-107	-187	-259	-135	-309	-106	-313	-264
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
104	-43	-406	208	89	-31	-244	234
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
172	-50	-5	-293	77	-45	-36	-348
Date	**Mean pH**			**Date**	**Mean pH**		
04/09/00	5.08			06/10/00	5.54		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-219	-352	-344	-286	-345	-353	-359	-346
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-308	-80	-297	-402	-304	-205	-319	-322
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
56	-167	-120	177	89	-42	-116	193
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
455	428	304	40	257	100	82	-30

Table A7-4b Soil redox potentials for Site 4.

Date	Mean pH		
28/11/00			
Redox readings			
1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH		
31/01/01			
Redox readings			
1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH		
25/04/01			
Redox readings			
1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH		
13/07/01	5.31		
Redox readings			
1A	2A	3A	4A
-51	-48	38	-150
1B	2B	3B	4B
-183	-33	-75	-177
1C	2C	3C	4C
77	53	8	324
1D	2D	3D	4D
400	246	241	221

Date	Mean pH		
21/01/02	5.53		
Redox readings			
1A	2A	3A	4A
-322	-334	-223	-255
1B	2B	3B	4B
-283	-286	-309	-283
1C	2C	3C	4C
115	95	214	245
1D	2D	3D	4D
-65	9	105	84

Date	Mean pH		
21/02/02	5.75		
Redox readings			
1A	2A	3A	4A
-274	-206	-105	-142
1B	2B	3B	4B
-281	-282	-298	16
1C	2C	3C	4C
141	-64	124	206
1D	2D	3D	4D
85	17	69	86

Date	Mean pH		
17/04/02	4.93		
Redox readings			
1A	2A	3A	4A
-362	-248	-228	-282
1B	2B	3B	4B
-290	-298	-314	-300
1C	2C	3C	4C
105	-261	616	139
1D	2D	3D	4D
-6	43	365	10

Table A7-5a Soil redox potentials for Site 5.

Date	Mean pH		
24/01/00	7.45		
Redox readings			
1A	2A	3A	4A
-366			
1B	2B	3B	4B
-448	-398	-400	-393
1C	2C	3C	4C
489	518	503	524
1D	2D	3D	4D
302	269	292	392

Date	Mean pH		
11/02/00	7.343333		
Redox readings			
1A	2A	3A	4A
-410			
1B	2B	3B	4B
-517	-481	-435	-487
1C	2C	3C	4C
430	489	509	160
1D	2D	3D	4D
324	265	340	338

Date	Mean pH		
25/02/00	6.373333		
Redox readings			
1A	2A	3A	4A
-318	-246	-210	-390
1B	2B	3B	4B
-499	-395	-478	-478
1C	2C	3C	4C
502	540	541	385
1D	2D	3D	4D
323	258	340	384

Date	Mean pH		
10/03/00	7.06		
Redox readings			
1A	2A	3A	4A
-338	-289	-242	-303
1B	2B	3B	4B
-272	-399	-458	-475
1C	2C	3C	4C
444	506	516	128
1D	2D	3D	4D
334	207	380	406

Date	Mean pH		
07/04/00	6.54		
Redox readings			
1A	2A	3A	4A
-353	-338	-302	-293
1B	2B	3B	4B
-369	-411	-457	-464
1C	2C	3C	4C
448	466	494	-8
1D	2D	3D	4D
330	243	340	365

Date	Mean pH		
05/05/00	6.54		
Redox readings			
1A	2A	3A	4A
-404	-306	-274	-358
1B	2B	3B	4B
-437	-430	-479	-461
1C	2C	3C	4C
299	304	272	-206
1D	2D	3D	4D
353	339	368	388

Date	Mean pH		
24/05/00	6.98		
Redox readings			
1A	2A	3A	4A
-384	-323	-352	-504
1B	2B	3B	4B
-371	-439	-482	-196
1C	2C	3C	4C
430	425	426	-61
1D	2D	3D	4D
339	339	383	392

Date	Mean pH		
21/06/00	5.91		
Redox readings			
1A	2A	3A	4A
-377	-12	-328	-485
1B	2B	3B	4B
-469	-407	-289	-333
1C	2C	3C	4C
446	454	227	392
1D	2D	3D	4D
386	333	376	372

Date	Mean pH		
04/09/00	6.675		
Redox readings			
1A	2A	3A	4A
-151	-351	-108	-229
1B	2B	3B	4B
-202	-325	-99	-58
1C	2C	3C	4C
335	537	529	482
1D	2D	3D	4D
339	257	333	357

Date	Mean pH		
06/10/00	6.92		
Redox readings			
1A	2A	3A	4A
-395	-360	-337	-366
1B	2B	3B	4B
-335	-353	-353	-204
1C	2C	3C	4C
151	507	519	497
1D	2D	3D	4D
408	315	348	390

Table A7-5b Soil redox potentials for Site 5.

Date	**Mean pH**		
28/11/00	6.71		
Redox readings			
1A	**2A**	**3A**	**4A**
-67	-357	-159	-109
1B	**2B**	**3B**	**4B**
-165	-176	-62	-300
1C	**2C**	**3C**	**4C**
-21	7	-19	120
1D	**2D**	**3D**	**4D**
167	195	-76	77

Date	**Mean pH**		
31/01/01	6.53		
Redox readings			
1A	**2A**	**3A**	**4A**
-124	-341	-340	-299
1B	**2B**	**3B**	**4B**
-391	-25	-38	-35
1C	**2C**	**3C**	**4C**
-15	-5	9	42
1D	**2D**	**3D**	**4D**
145	80	-49	137

Date	**Mean pH**		
25/04/01	6.825		
Redox readings			
1A	**2A**	**3A**	**4A**
-256	-346	-175	-337
1B	**2B**	**3B**	**4B**
-390	-38	-25	-429
1C	**2C**	**3C**	**4C**
0	108	41	50
1D	**2D**	**3D**	**4D**
190	34	-62	45

Date	**Mean pH**		
13/07/01	6.985		
Redox readings			
1A	**2A**	**3A**	**4A**
-103	-355	-59	-341
1B	**2B**	**3B**	**4B**
-121	-137	-144	-81
1C	**2C**	**3C**	**4C**
100	484	492	180
1D	**2D**	**3D**	**4D**
186	390	372	346

Date	**Mean pH**		
21/01/02	6.89		
Redox readings			
1A	**2A**	**3A**	**4A**
-381	-371	-347	-367
1B	**2B**	**3B**	**4B**
-326	-194	-411	-244
1C	**2C**	**3C**	**4C**
171	510	486	170
1D	**2D**	**3D**	**4D**
180	319	343	397

Date	**Mean pH**		
21/02/02	6.91		
Redox readings			
1A	**2A**	**3A**	**4A**
-261	-351	-321	-349
1B	**2B**	**3B**	**4B**
-231	-134	-108	-142
1C	**2C**	**3C**	**4C**
141	522	492	150
1D	**2D**	**3D**	**4D**
211	339	340	396

Date	**Mean pH**		
17/04/02	7.11		
Redox readings			
1A	**2A**	**3A**	**4A**
-438	-347	-294	-353
1B	**2B**	**3B**	**4B**
-290	-181	-190	-212
1C	**2C**	**3C**	**4C**
122	474	407	100
1D	**2D**	**3D**	**4D**
254	322	328	381

Table A7-6a Soil redox potentials for Site 6.

Date	Mean pH		
24/01/00	7.873333		
Redox readings			
1A	**2A**	**3A**	**4A**
77	102	-13	245
1B	**2B**	**3B**	**4B**
175	140	126	149
1C	**2C**	**3C**	**4C**
226	138	125	152
1D	**2D**	**3D**	**4D**
74	245	187	217

Date	Mean pH		
11/02/00	8.153333		
Redox readings			
1A	**2A**	**3A**	**4A**
103	128	67	250
1B	**2B**	**3B**	**4B**
159	322	280	261
1C	**2C**	**3C**	**4C**
373	252	364	274
1D	**2D**	**3D**	**4D**
281	287	267	280

Date	Mean pH		
25/02/00	7.966667		
Redox readings			
1A	**2A**	**3A**	**4A**
83	149	-1	-373
1B	**2B**	**3B**	**4B**
292	316	311	136
1C	**2C**	**3C**	**4C**
356	281	325	290
1D	**2D**	**3D**	**4D**
273	287	266	293

Date	Mean pH		
10/03/00	7.953333		
Redox readings			
1A	**2A**	**3A**	**4A**
83	112	-1	-375
1B	**2B**	**3B**	**4B**
192	318	302	67
1C	**2C**	**3C**	**4C**
343	293	343	298
1D	**2D**	**3D**	**4D**
299	268	304	305

Date	Mean pH		
07/04/00	7.793333		
Redox readings			
1A	**2A**	**3A**	**4A**
26	-17	-92	-28
1B	**2B**	**3B**	**4B**
364	340	329	322
1C	**2C**	**3C**	**4C**
313	310	347	311
1D	**2D**	**3D**	**4D**
335	229	297	310

Date	Mean pH		
05/05/00	7.793333		
Redox readings			
1A	**2A**	**3A**	**4A**
-65	-16	-371	-398
1B	**2B**	**3B**	**4B**
261	320	281	150
1C	**2C**	**3C**	**4C**
274	198	293	211
1D	**2D**	**3D**	**4D**
326	330	355	314

Date	Mean pH		
24/05/00	7.79		
Redox readings			
1A	**2A**	**3A**	**4A**
-65	-21	-387	-401
1B	**2B**	**3B**	**4B**
288	316	332	279
1C	**2C**	**3C**	**4C**
298	266	357	336
1D	**2D**	**3D**	**4D**
353	350	372	293

Date	Mean pH		
21/06/00	7.35		
Redox readings			
1A	**2A**	**3A**	**4A**
-89	-26	-419	-304
1B	**2B**	**3B**	**4B**
355	344	283	356
1C	**2C**	**3C**	**4C**
331	262	300	335
1D	**2D**	**3D**	**4D**
332	361	354	295

Date	Mean pH		
04/09/00	7.65		
Redox readings			
1A	**2A**	**3A**	**4A**
312	221	39	310
1B	**2B**	**3B**	**4B**
384	370	349	397
1C	**2C**	**3C**	**4C**
394	370	185	358
1D	**2D**	**3D**	**4D**
338	336	350	333

Date	Mean pH		
06/10/00	7.615		
Redox readings			
1A	**2A**	**3A**	**4A**
121	27	-300	177
1B	**2B**	**3B**	**4B**
312	340	327	400
1C	**2C**	**3C**	**4C**
356	321	406	342
1D	**2D**	**3D**	**4D**
347	366	398	398

Table A7-6b Soil redox potentials for Site 6.

Date	Mean pH		
28/11/00	7.42		
Redox readings			
1A	**2A**	**3A**	**4A**
-21	-39	-134	-351
1B	**2B**	**3B**	**4B**
-53	-11	-54	-40
1C	**2C**	**3C**	**4C**
-63	-116	-42	-74
1D	**2D**	**3D**	**4D**
163	289	320	215

Date	Mean pH		
31/01/01	7.43		
Redox readings			
1A	**2A**	**3A**	**4A**
-38	-11	-164	-252
1B	**2B**	**3B**	**4B**
-48	-33	-62	-20
1C	**2C**	**3C**	**4C**
165	130	198	108
1D	**2D**	**3D**	**4D**
308	291	203	238

Date	Mean pH		
25/04/01	7.34		
Redox readings			
1A	**2A**	**3A**	**4A**
-35	-359	-248	-219
1B	**2B**	**3B**	**4B**
66	-31	-86	-30
1C	**2C**	**3C**	**4C**
291	98	350	160
1D	**2D**	**3D**	**4D**
403	336	377	367

Date	Mean pH		
13/07/01	7.54		
Redox readings			
1A	**2A**	**3A**	**4A**
19	22	-217	-26
1B	**2B**	**3B**	**4B**
311	331	109	214
1C	**2C**	**3C**	**4C**
418	328	373	301
1D	**2D**	**3D**	**4D**
387	293	373	394

Date	Mean pH		
21/01/02	7.5		
Redox readings			
1A	**2A**	**3A**	**4A**
-33	6	-289	-56
1B	**2B**	**3B**	**4B**
253	270	260	256
1C	**2C**	**3C**	**4C**
370	290	358	308
1D	**2D**	**3D**	**4D**
210	339	375	415

Date	Mean pH		
21/02/02	7.605		
Redox readings			
1A	**2A**	**3A**	**4A**
-59	10	-384	-65
1B	**2B**	**3B**	**4B**
193	272	210	224
1C	**2C**	**3C**	**4C**
329	300	355	316
1D	**2D**	**3D**	**4D**
272	327	397	360

Date	Mean pH		
17/04/02	7.46		
Redox readings			
1A	**2A**	**3A**	**4A**
-222	-4	-429	-105
1B	**2B**	**3B**	**4B**
155	265	266	213
1C	**2C**	**3C**	**4C**
250	265	357	325
1D	**2D**	**3D**	**4D**
236	338	351	398

Table A7-7a Soil redox potentials for Site 7.

Date	**Mean pH**			**Date**	**Mean pH**		
24/01/00	7.31			11/02/00	7.6		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-54	-58	-33	-1	-462	-408	-70	178
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-351	337	432	307	-465	447	476	424
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
274	308	346	354	342	264	459	444
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
307	231	247	265	254	311	321	300
Date	**Mean pH**			**Date**	**Mean pH**		
25/02/00	7.66			10/03/00	7.39		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
130	-346	-135	189	-56	-385	-60	219
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-483	-94	505	400	-476	-54	439	434
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
393	332	426	424	395	241	467	358
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
68	357	360	365	-100	213	361	381
Date	**Mean pH**			**Date**	**Mean pH**		
07/04/00	7.37			05/05/00	7.37		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
158	-311	-105	200	54	-267	-300	214
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-410	-27	-145	272	-413	-15	-360	147
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
340	363	480	383	100	300	-21	-57
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
12	295	380	387	93	380	410	394
Date	**Mean pH**			**Date**	**Mean pH**		
24/05/00	7.06			21/06/00	6.65		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
132	-320	223	-338	-334	-248	79	-99
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-451	77	-45	-33	-458	-26	-136	34
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
403	339	504	418	391	344	490	436
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
147	383	375	424	352	345	336	369
Date	**Mean pH**			**Date**	**Mean pH**		
04/09/00	6.925			06/10/00	6.64		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-320	-153	-69	111	-396	-291	-170	-157
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
342	518	544	537	278	516	520	559
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
452	424	520	501	426	383	513	472
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
328	350	360	310	305	368	385	397

Table A7-7b Soil redox potentials for Site 7.

Date	**Mean pH**		
28/11/00	6.945		
Redox readings			
1A	**2A**	**3A**	**4A**
-468	-95	-120	-65
1B	**2B**	**3B**	**4B**
-96	0	-64	-21
1C	**2C**	**3C**	**4C**
-79	-53	-48	-55
1D	**2D**	**3D**	**4D**
-66	-96	-43	58

Date	**Mean pH**		
31/01/01	6.98		
Redox readings			
1A	**2A**	**3A**	**4A**
-294	-108	-43	-41
1B	**2B**	**3B**	**4B**
-67	4	-21	-14
1C	**2C**	**3C**	**4C**
-58	-27	-38	-53
1D	**2D**	**3D**	**4D**
241	303	121	118

Date	**Mean pH**		
25/04/01	6.9		
Redox readings			
1A	**2A**	**3A**	**4A**
-336	-358	-123	-48
1B	**2B**	**3B**	**4B**
-475	-92	-17	41
1C	**2C**	**3C**	**4C**
-18	-66	64	5
1D	**2D**	**3D**	**4D**
258	383	358	313

Date	**Mean pH**		
13/07/01	6.865		
Redox readings			
1A	**2A**	**3A**	**4A**
-348	-398	-208	-57
1B	**2B**	**3B**	**4B**
166	154	499	175
1C	**2C**	**3C**	**4C**
479	403	435	370
1D	**2D**	**3D**	**4D**
289	334	366	291

Date	**Mean pH**		
21/01/02	7.2		
Redox readings			
1A	**2A**	**3A**	**4A**
-355	-388	-27	-308
1B	**2B**	**3B**	**4B**
-396	38	35	78
1C	**2C**	**3C**	**4C**
435	355	516	292
1D	**2D**	**3D**	**4D**
298	396	366	327

Date	**Mean pH**		
21/02/02	7.525		
Redox readings			
1A	**2A**	**3A**	**4A**
165	-409	34	-273
1B	**2B**	**3B**	**4B**
-373	35	-10	64
1C	**2C**	**3C**	**4C**
414		476	322
1D	**2D**	**3D**	**4D**
236	364	443	391

Date	**Mean pH**		
17/04/02	7.06		
Redox readings			
1A	**2A**	**3A**	**4A**
-265	-328	-82	-216
1B	**2B**	**3B**	**4B**
-360	31	-20	58
1C	**2C**	**3C**	**4C**
424	407	495	368
1D	**2D**	**3D**	**4D**
309	345	398	383

Table A7-8a Soil redox potentials for Site 8.

Date	**Mean pH**			**Date**	**Mean pH**		
25/01/00	6.996667			11/02/00	7.076667		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-230	-460	-468	-101	-242	-220	-514	-170
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
101	26	-407	1	-331	-379	-423	-124
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
-454	-305	94	250	-435	-341	-175	-161
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
350	294	19	200	265	245	-267	213
Date	**Mean pH**			**Date**	**Mean pH**		
25/02/00	7.24			10/03/00	7.04		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-268	-474	-509	-229	-303	-487	-517	-251
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
	-470	-408	-183	-290	-439	-406	-171
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
-459	-410	-113		-424	-402	-234	-289
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
361	298	102	298	358	344	144	380
Date	**Mean pH**			**Date**	**Mean pH**		
07/04/00	6.18			05/05/00	6.18		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
-323	-185	-531	-239		-337	-497	-303
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-420	-487	-431	-72	-421	-458	-435	55
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
69	-368	137	351	-382	-426	-40	336
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
278	98	-118	171	-57	-32	-242	350
Date	**Mean pH**			**Date**	**Mean pH**		
24/05/00	6.79			21/06/00	6.23		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
	-279	-480	-343		-250	-497	-270
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
-427	-476	-430	115	-60	-470	-415	100
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
157	39	143	453	164	140	112	431
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
106	308	131	375	306	363	174	370
Date	**Mean pH**			**Date**	**Mean pH**		
04/09/00	6.535			06/10/00	6.57		
Redox readings				**Redox readings**			
1A	**2A**	**3A**	**4A**	**1A**	**2A**	**3A**	**4A**
	-299	-505	-231		-472	-529	-333
1B	**2B**	**3B**	**4B**	**1B**	**2B**	**3B**	**4B**
5	457	483	250	175	-482	-379	273
1C	**2C**	**3C**	**4C**	**1C**	**2C**	**3C**	**4C**
98	106	162	524	85	83	149	457
1D	**2D**	**3D**	**4D**	**1D**	**2D**	**3D**	**4D**
367	392	88	432	300	385	97	420

Table A7-8b Soil redox potentials from Site 8.

Date	**Mean pH**		
28/11/00	6.645		
Redox readings			
1A	**2A**	**3A**	**4A**
	-69	-457	181
1B	**2B**	**3B**	**4B**
30	-408	-383	-165
1C	**2C**	**3C**	**4C**
15	18	2	-66
1D	**2D**	**3D**	**4D**
-65	-50	-82	-78

Date	**Mean pH**		
31/01/01	6.61		
Redox readings			
1A	**2A**	**3A**	**4A**
	-202	-487	-333
1B	**2B**	**3B**	**4B**
-37	-431	-263	62
1C	**2C**	**3C**	**4C**
16	35	37	104
1D	**2D**	**3D**	**4D**
-6	5	-33	5

Date	**Mean pH**		
25/04/01	6.795		
Redox readings			
1A	**2A**	**3A**	**4A**
	-65	-435	-119
1B	**2B**	**3B**	**4B**
-5	-418	128	236
1C	**2C**	**3C**	**4C**
29	14	-7	187
1D	**2D**	**3D**	**4D**
228	-6	16	-27

Date	**Mean pH**		
13/07/01	6.525		
Redox readings			
1A	**2A**	**3A**	**4A**
	-189	-444	-241
1B	**2B**	**3B**	**4B**
347	22	437	354
1C	**2C**	**3C**	**4C**
45	138	95	426
1D	**2D**	**3D**	**4D**
168	408	142	295

Date	**Mean pH**		
21/01/02	6.61		
Redox readings			
1A	**2A**	**3A**	**4A**
	-150	-503	-326
1B	**2B**	**3B**	**4B**
-80	-27	341	-291
1C	**2C**	**3C**	**4C**
-108	226	148	61
1D	**2D**	**3D**	**4D**
92	353	100	293

Date	**Mean pH**		
21/02/02	6.76		
Redox readings			
1A	**2A**	**3A**	**4A**
	-271	-500	-186
1B	**2B**	**3B**	**4B**
-273	-267	-330	-383
1C	**2C**	**3C**	**4C**
47	188	382	15
1D	**2D**	**3D**	**4D**
121	431	106	403

Date	**Mean pH**		
17/04/02	6.31		
Redox readings			
1A	**2A**	**3A**	**4A**
	-311	-468	-7
1B	**2B**	**3B**	**4B**
-386	-311	194	-80
1C	**2C**	**3C**	**4C**
51	245	334	63
1D	**2D**	**3D**	**4D**
90	358	122	333

Table A7-9a Soil redox potentials for Site 9.

Date	**Mean pH**		
25/01/00	5.83		
Redox readings			
1A	**2A**	**3A**	**4A**
-205	-440	-316	-145
1B	**2B**	**3B**	**4B**
242	-186	-347	-453
1C	**2C**	**3C**	**4C**
-34	-368	-125	-350
1D	**2D**	**3D**	**4D**
227	-62	-193	-232

Date	**Mean pH**		
11/02/00	5.84		
Redox readings			
1A	**2A**	**3A**	**4A**
-314	-521	-412	-269
1B	**2B**	**3B**	**4B**
-276	-206	-395	-501
1C	**2C**	**3C**	**4C**
137	-405	-241	-361
1D	**2D**	**3D**	**4D**
239	24	-27	-294

Date	**Mean pH**		
25/02/00	6.04		
Redox readings			
1A	**2A**	**3A**	**4A**
-255	-490	-153	-145
1B	**2B**	**3B**	**4B**
-203	-191	-378	-490
1C	**2C**	**3C**	**4C**
46	-378	-109	-475
1D	**2D**	**3D**	**4D**
227	-86	-60	-358

Date	**Mean pH**		
10/03/00	5.536667		
Redox readings			
1A	**2A**	**3A**	**4A**
-369	-370	-355	-111
1B	**2B**	**3B**	**4B**
-348	-333	-369	-478
1C	**2C**	**3C**	**4C**
39	-381	-91	-406
1D	**2D**	**3D**	**4D**
247	-171	-324	-419

Date	**Mean pH**		
07/04/00	5.725		
Redox readings			
1A	**2A**	**3A**	**4A**
-68	-471	-271	-303
1B	**2B**	**3B**	**4B**
-41	-305	-37	-435
1C	**2C**	**3C**	**4C**
-184	-391	-84	-188
1D	**2D**	**3D**	**4D**
222	-48	-423	-330

Date	**Mean pH**		
05/05/00	5.725		
Redox readings			
1A	**2A**	**3A**	**4A**
-158	-444	-362	-237
1B	**2B**	**3B**	**4B**
-150	-138	-225	-501
1C	**2C**	**3C**	**4C**
-8	-404	-70	-215
1D	**2D**	**3D**	**4D**
202	-151	-352	-402

Date	**Mean pH**		
24/05/00	5.55		
Redox readings			
1A	**2A**	**3A**	**4A**
-305	-443	-412	-276
1B	**2B**	**3B**	**4B**
-260	-276	-313	-506
1C	**2C**	**3C**	**4C**
-6	-382	-77	-190
1D	**2D**	**3D**	**4D**
142	44	-319	-410

Date	**Mean pH**		
21/06/00	5.16		
Redox readings			
1A	**2A**	**3A**	**4A**
-314	-445	-332	-256
1B	**2B**	**3B**	**4B**
-410	-265	-307	-510
1C	**2C**	**3C**	**4C**
-31	-238	-105	-295
1D	**2D**	**3D**	**4D**
77	-92	-65	-350

Date	**Mean pH**		
04/09/00	5.42		
Redox readings			
1A	**2A**	**3A**	**4A**
-69	-48	-26	-81
1B	**2B**	**3B**	**4B**
-89	-36	-58	-429
1C	**2C**	**3C**	**4C**
-40	-55	-38	-93
1D	**2D**	**3D**	**4D**
118	-2	-32	-2

Date	**Mean pH**		
06/10/00	5.705		
Redox readings			
1A	**2A**	**3A**	**4A**
-276	-234	-292	-225
1B	**2B**	**3B**	**4B**
-264	-125	-169	-496
1C	**2C**	**3C**	**4C**
-129	-132	-72	-194
1D	**2D**	**3D**	**4D**
119	-69	-82	-173

Table A7-9b Soil redox potentials for Site 9.

Date	Mean pH
28/11/00	

Redox readings

1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH
31/01/01	

Redox readings

1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH
25/04/01	

Redox readings

1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH
13/07/01	4.94

Redox readings

1A	2A	3A	4A
-63	-73	5	-65
1B	2B	3B	4B
-3	-43	-83	-469
1C	2C	3C	4C
-7	-260	-7	-95
1D	2D	3D	4D
289	209	-31	217

Date	Mean pH
21/01/02	

Redox readings

1A	2A	3A	4A
1B	2B	3B	4B
1C	2C	3C	4C
1D	2D	3D	4D

Date	Mean pH
21/02/02	4.82

Redox readings

1A	2A	3A	4A
-267	-306	-124	-184
1B	2B	3B	4B
-256	15	-285	-357
1C	2C	3C	4C
-73	-7	-44	-215
1D	2D	3D	4D
112	-147	-253	44

Date	Mean pH
17/04/02	4.37

Redox readings

1A	2A	3A	4A
32	-299	-274	-213
1B	2B	3B	4B
-78	-158	-273	-405
1C	2C	3C	4C
-63	-212	-51	-459
1D	2D	3D	4D
103	-6	-110	43

Appendix 8

Eh/pH diagrams

This appendix will present the remaining 12 Eh/pH diagrams not presented in Chapter 6. This data was omitted as the majority of the graphs showed little variability and therefore only those that demonstrated changing conditions were included in the results section.

Figure A8-1 and Table A8-1 show the basic structure of the Eh/pH diagram and the values used to create it. The values for the upper and lower limits of the aqueous system were derived from Howard (1998), the values being for pE (electron activity) and are dimensionless. Since measurements are taken for redox potential (Eh) the use of a conversion is used taken from Freeze & Cherry (1979):

$$pE = 16.9Eh$$

The sulphur boundary values were derived from Stumm & Morgan (1981), and again converted from pE to Eh using the above equation. The values for the boundary between the oxidised and reduced forms of iron were directly obtained from Bohn (1971).

The values presented Table A8-1 can be used to create an Eh/pH diagram to which observational data can be added. This can be achieved easily using spreadsheet software widely available.

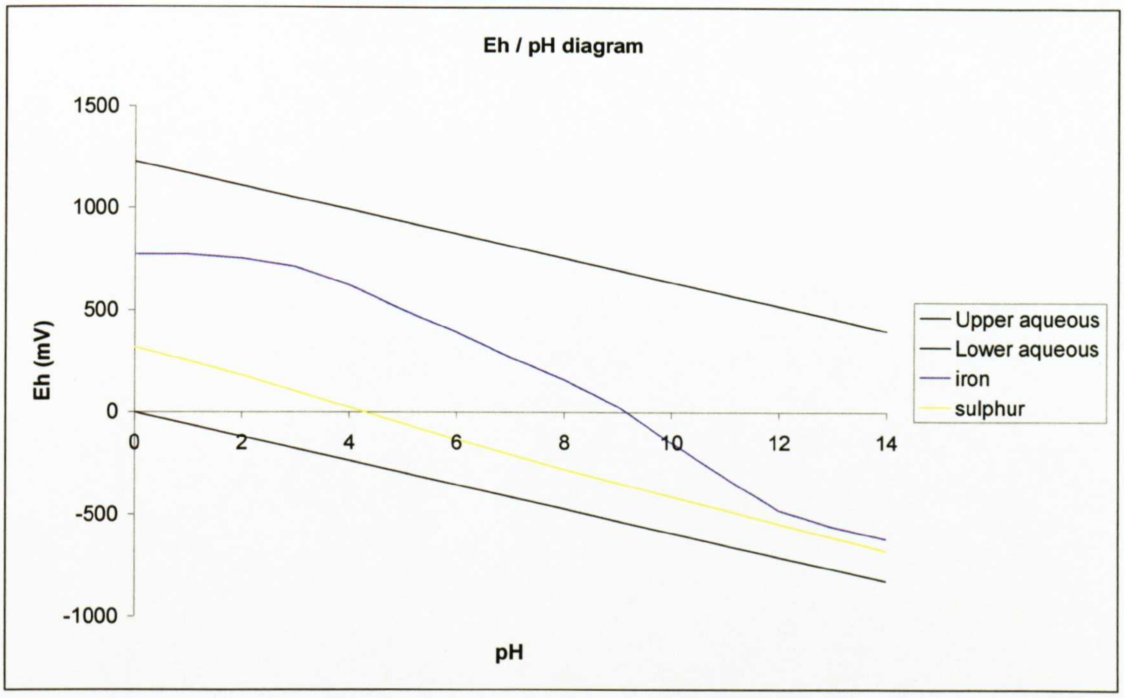

Figure A8-1 The basic Eh/pH diagram

Table A8-1 Eh/pH diagram boundary conditions.

ph	Upper aqueous	Lower aqueous	iron	sulphur
0	1228	0	771	318
1	1169	-59	770	248
2	1109	-118	750	179
3	1050	-178	710	101
4	991	-237	620	21.7
5	932	-296	500	-57.2
6	873	-355	390	-136
7	814	-414	270	-209
8	754	-473	160	-281
9	695	-533	30	-348
10	636	-592	-150	-414
11	577	-651	-320	-481
12	518	-710	-480	-547
13	459	-769	-560	-614
14	399	-828	-620	-680

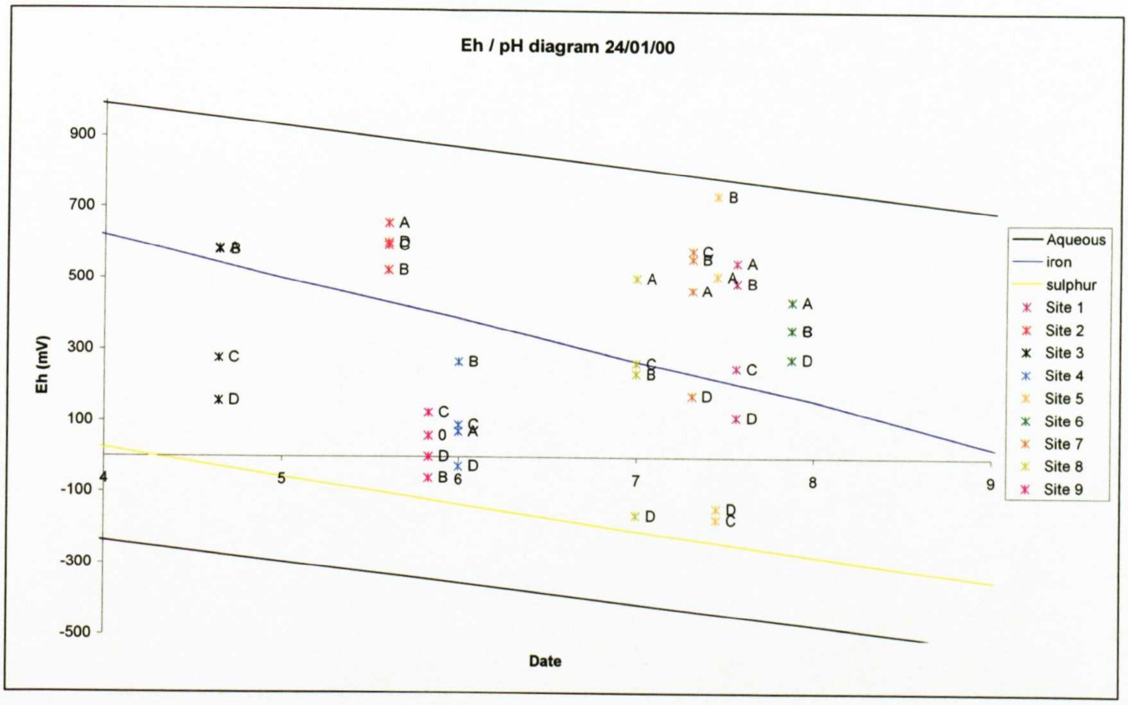

Figure A8-2 Eh/pH diagram from 24/01/00

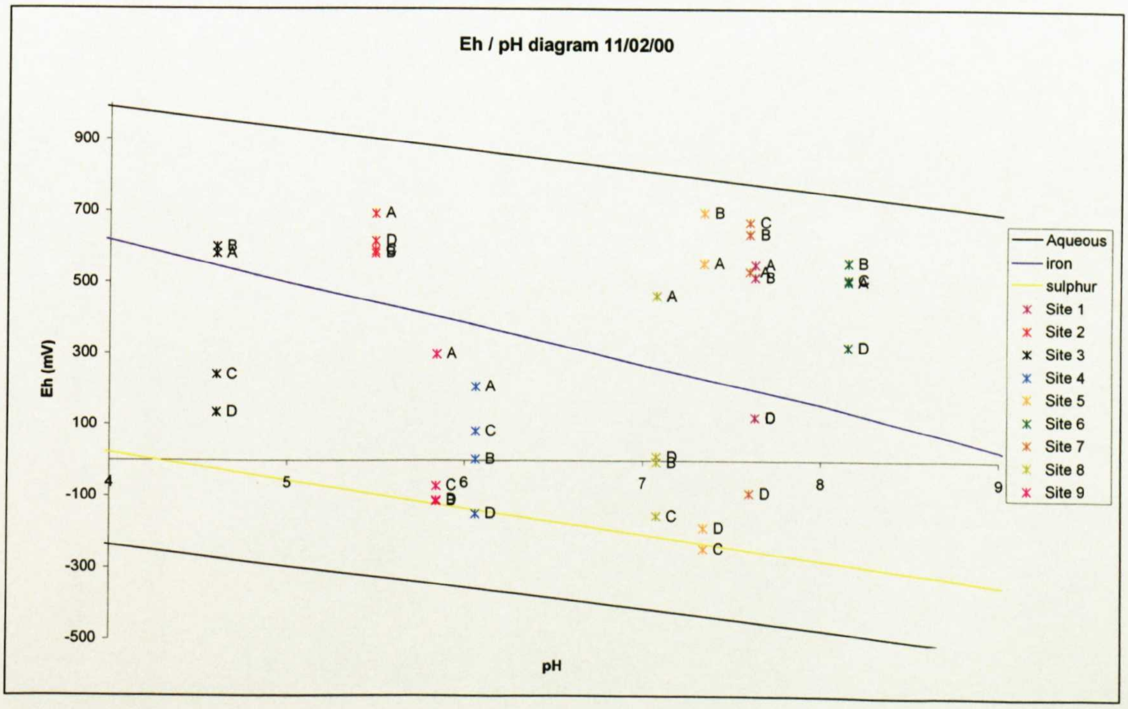

Figure A8-3 Eh/pH diagram from 11/02/00

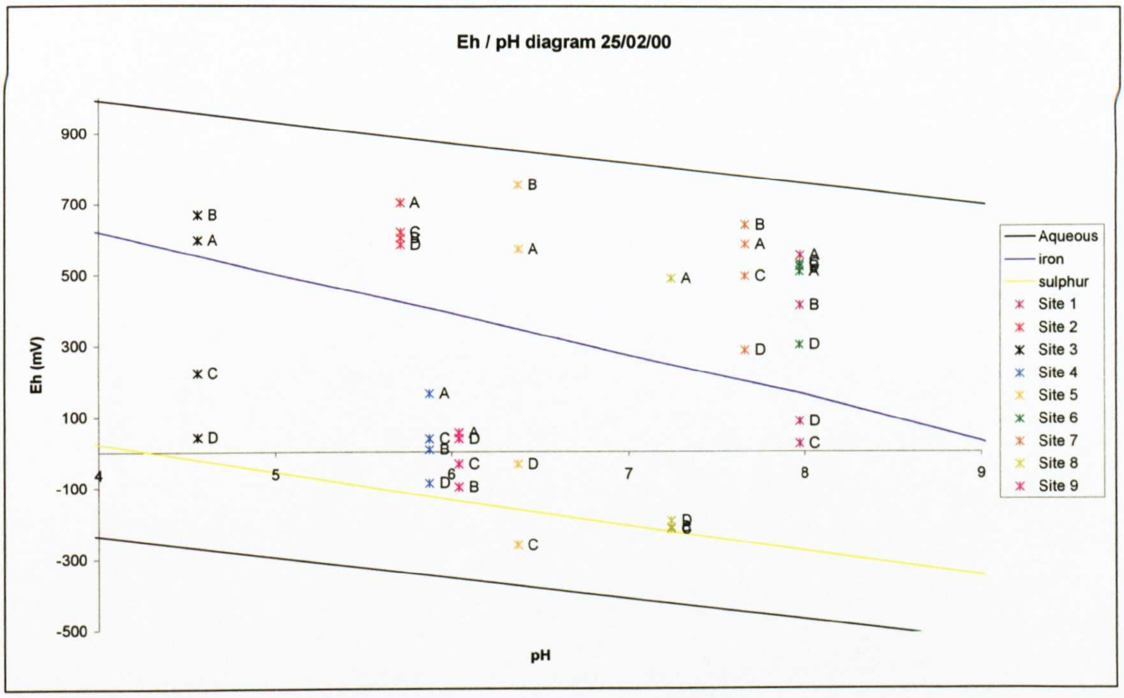

Figure A8-4 Eh/pH diagram for 25/02/00

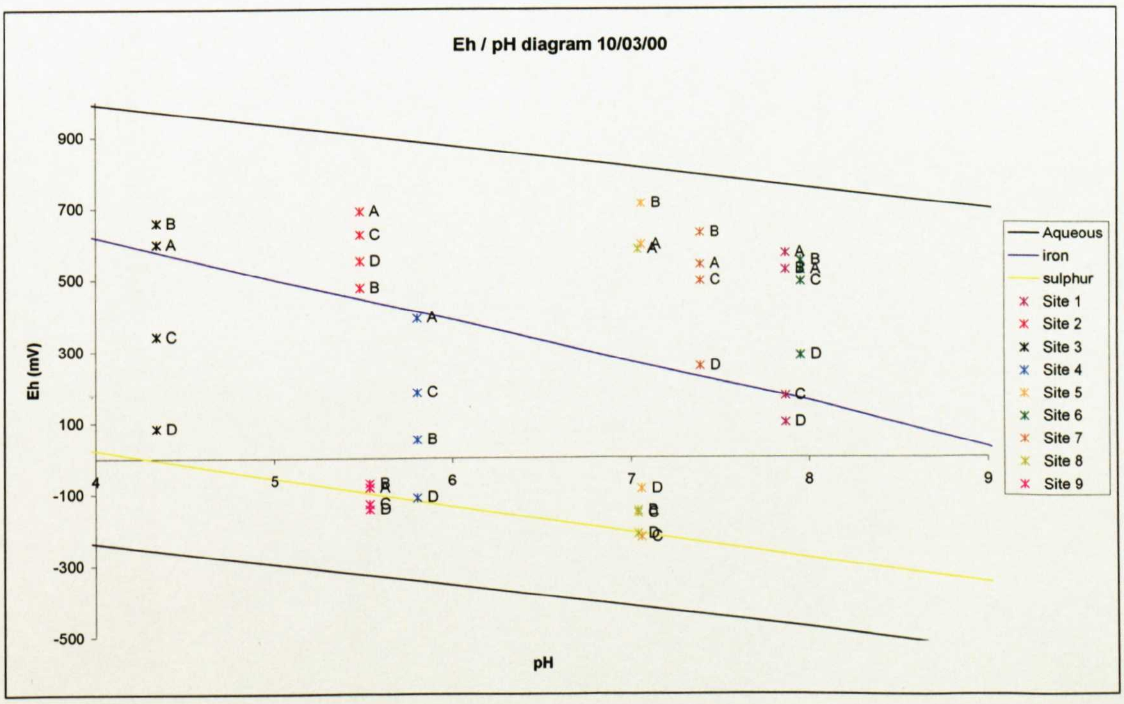

Figure A8-5 Eh/pH diagram for 10/03/00

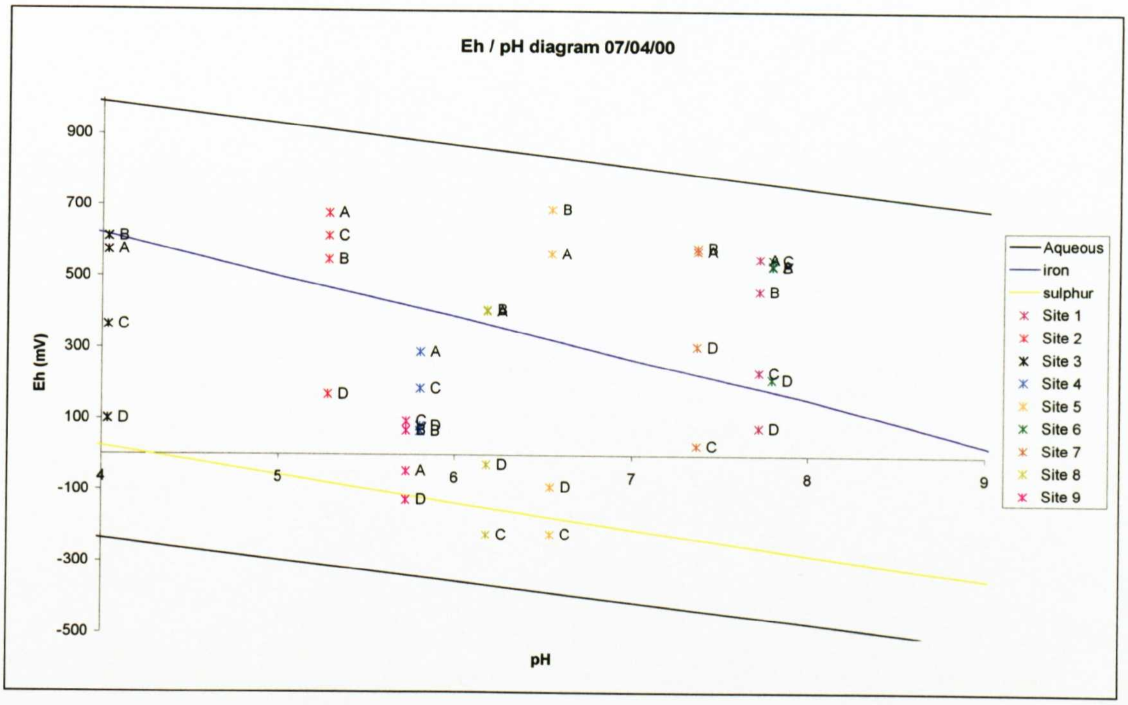

Figure A8-6 Eh/pH diagram for 07/04/00

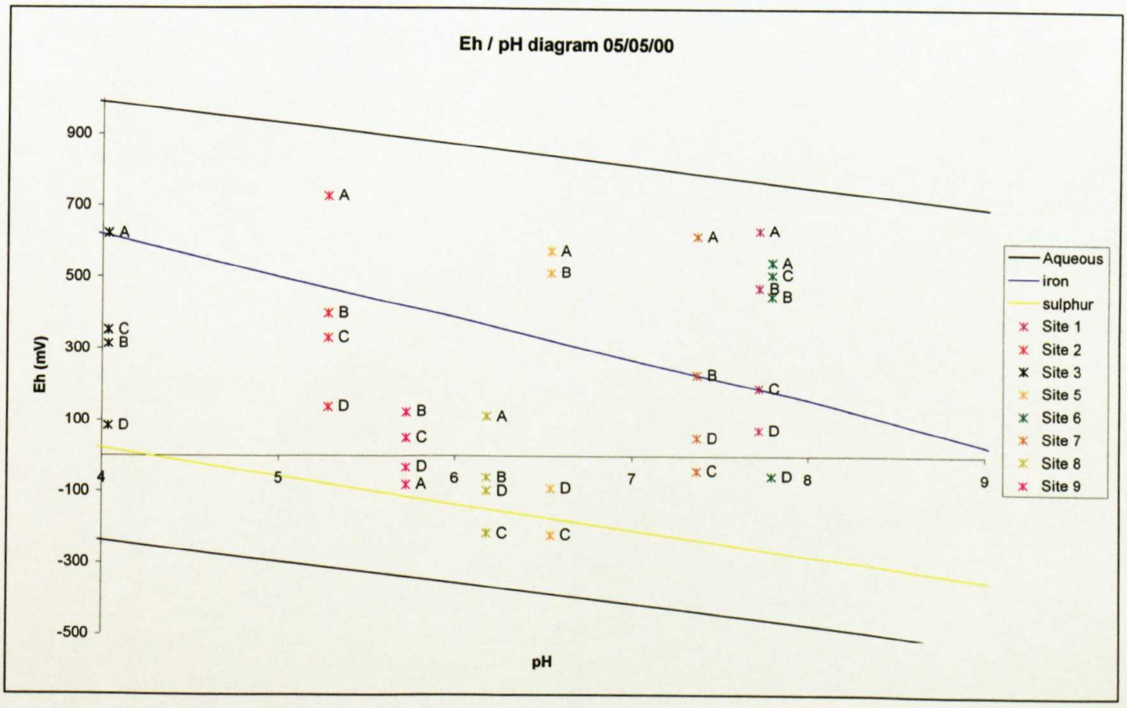

Figure A8-7 Eh/pH diagram for 05/05/00

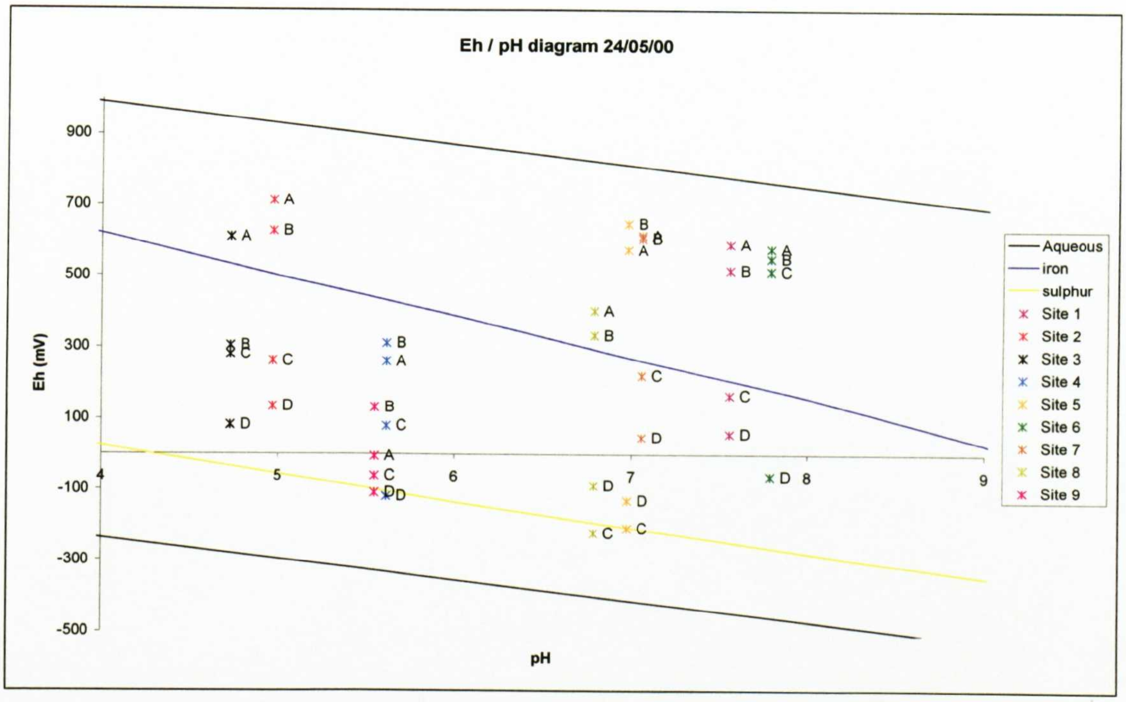

Figure A8-8 Eh/pH diagram for 24/05/00

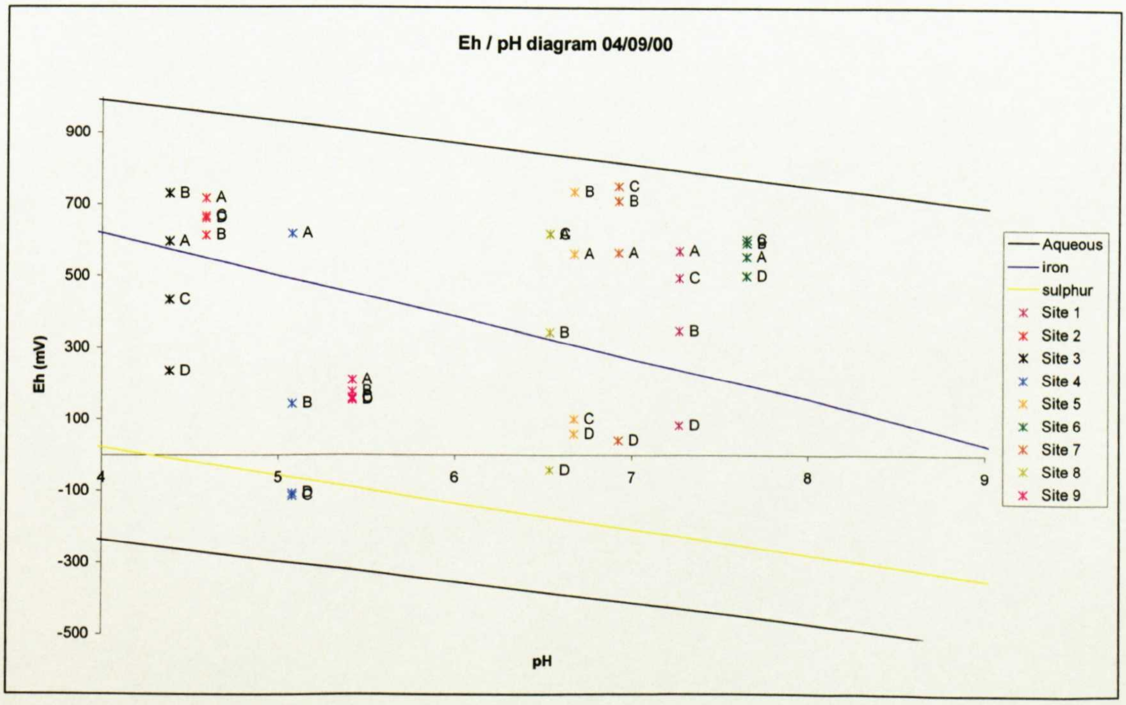

Figure A8-9 Eh/pH diagram for 04/09/00

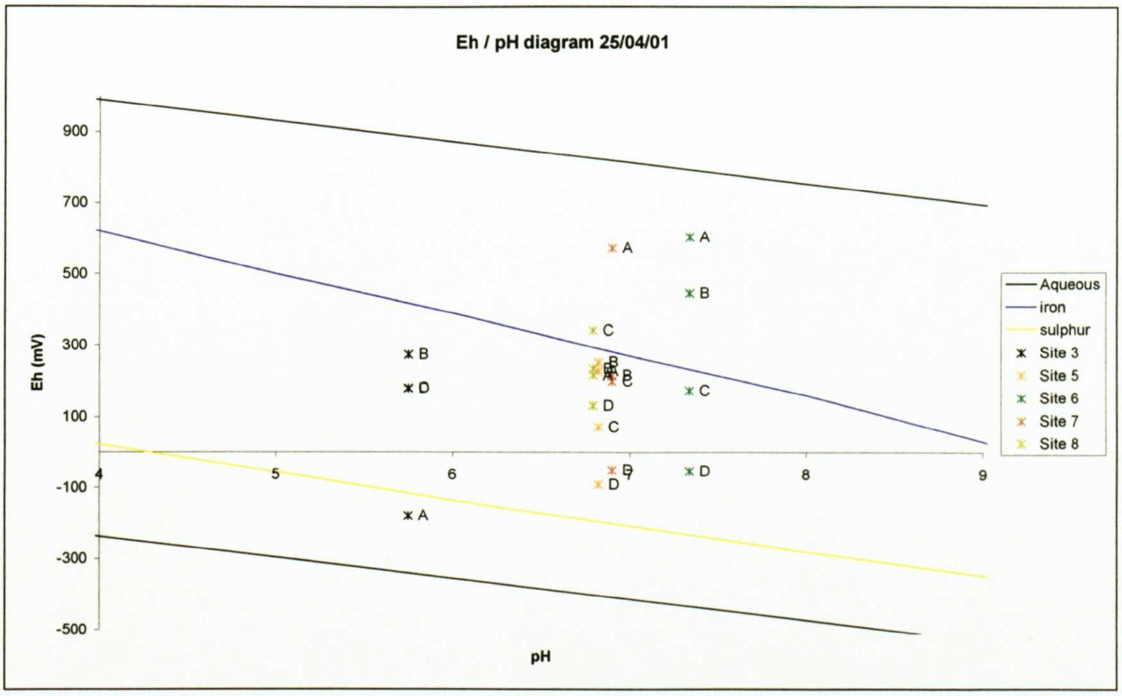

Figure A8-10 Eh/pH diagram for 25/04/01

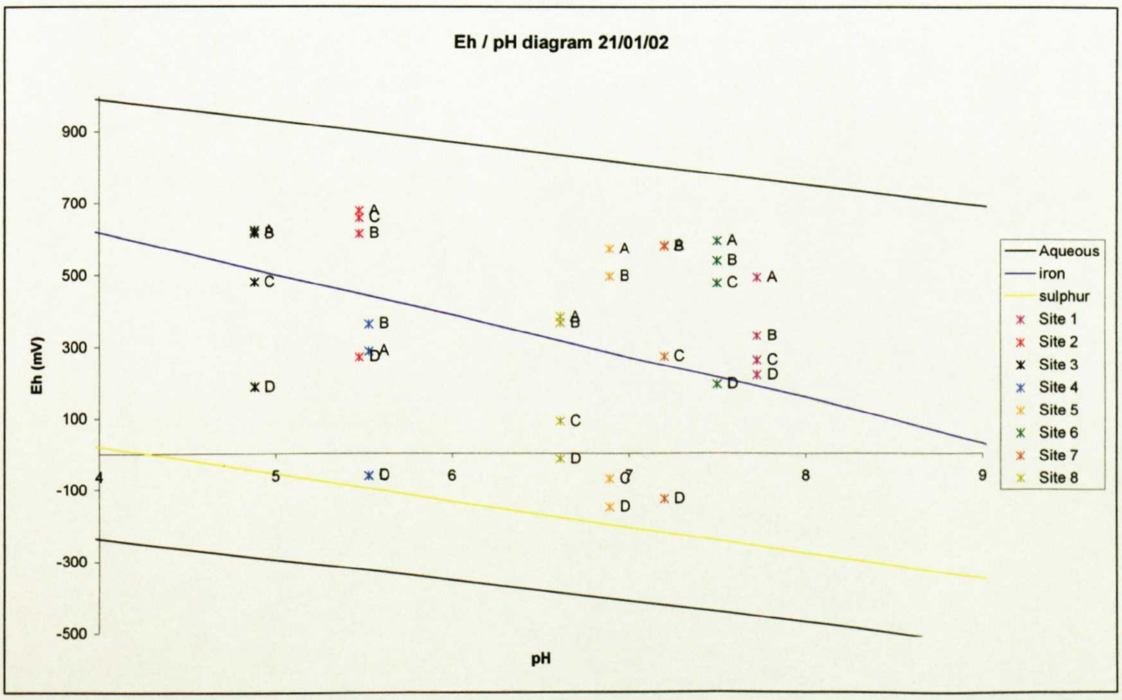

Figure A8-11 Eh/pH diagram for 21/01/02

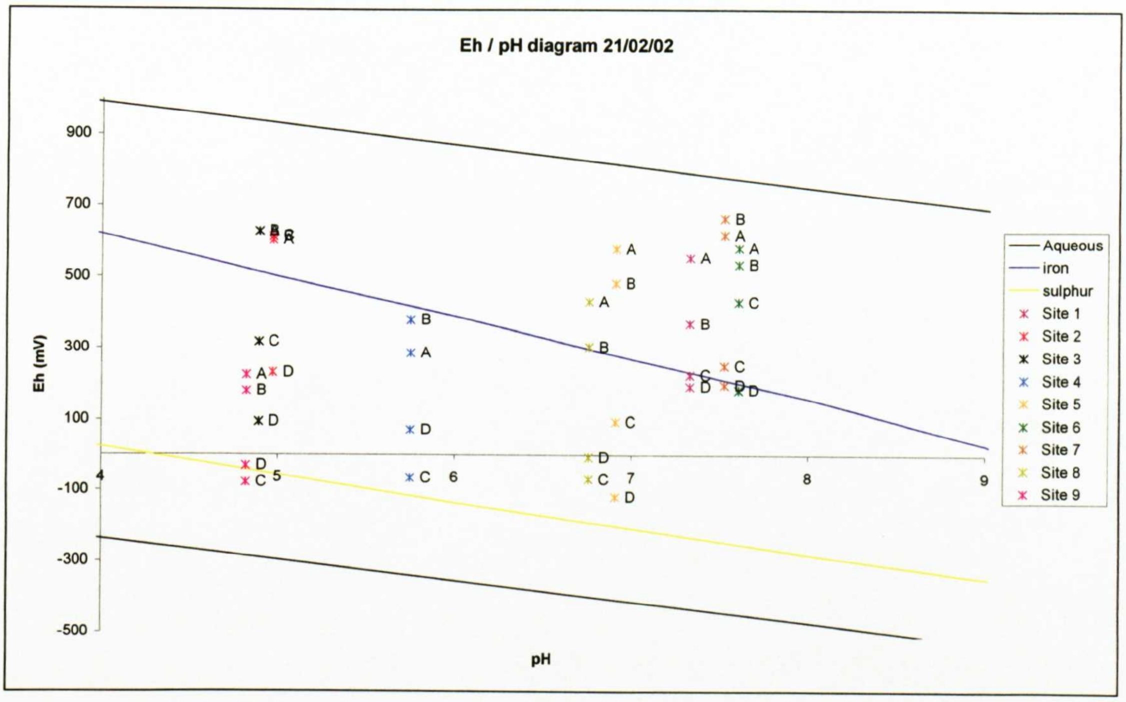

Figure A8-12 Eh/pH diagram for 21/02/02

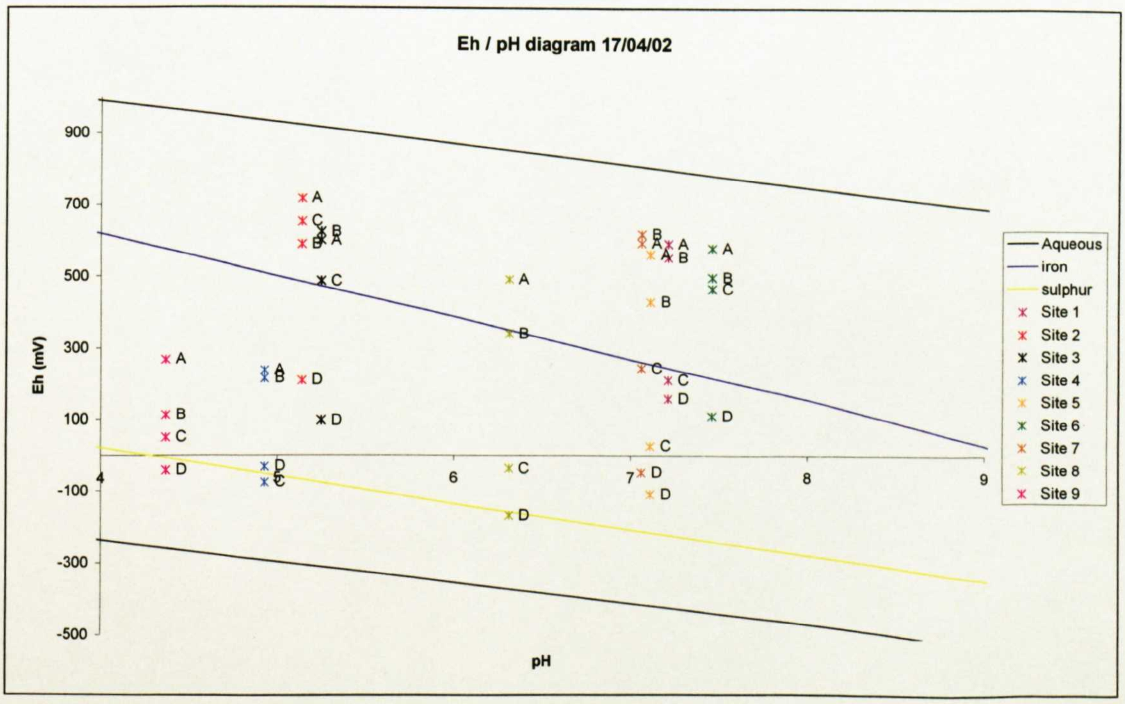

Figure A8-13 Eh/pH diagram for 17/04/02

Appendix 9

Microbiological results

This appendix presents the average values for the individual techniques undertaken on samples obtained from Sutton Common. All the values are the average values calculated from raw data.

Table A9-1 Average values for AODC ($\times 10^8$ g^{-1} wet weight).

Date	Sampling depth		
	0 m	**0.75 m**	**1.5 m**
Site 1			
16/01/2001	73.5	1.34	0.303
23/01/2002	117	10.2	5.26
Site 3			
25/04/2001	45.3	11.4	1.01
27/03/2002	64.9	19.8	1.85
Site 5			
31/01/2001	55.3	10.4	16.2
07/02/2002	42.1	14.1	2.85
Site 6			
14/02/2001	No Data	No Data	No Data
19/03/2002	24.8	1.25	0.48
Site 9			
13/06/2001	50.5	7.52	11.1
17/04/2002	57.3	3.83	12.6

Table A9-2 Average values for enzyme assay (nM g^{-1} h^{-1}).

Date	Sample depth		
	0 m	0.75 m	1.5 m
Site 1			
16/01/2001			
Leucine amino peptidase	203.965	85.215	55.139
Phosphatase	70.496	18.544	7.272
β-glucosidase	61.777	1.927	1.818
23/01/2002			
Leucine amino peptidase	418.891	231.343	196.707
Phosphatase	79.268	30.537	21.799
β-glucosidase	62.162	-0.872	7.546
Site 3			
25/04/2001			
Leucine amino peptidase	168.195	157.795	151.061
Phosphatase	158.380	83.750	42.093
β-glucosidase	109.282	31.588	-1.403
27/03/2002			
Leucine amino peptidase	275.002	89.287	83.415
Phosphatase	146.363	41.886	4.660
β-glucosidase	147.752	5.174	-1.059
Site 5			
31/01/2001			
Leucine amino peptidase	350.248	183.000	147.095
Phosphatase	274.329	87.156	61.058
β-glucosidase	165.468	6.600	5.355
07/02/2002			
Leucine amino peptidase	276.490	254.269	208.922
Phosphatase	235.563	167.679	86.681
β-glucosidase	91.382	5.655	60.336
Site 6			
14/02/2001			
Leucine amino peptidase	114.295	126.606	76.931
Phosphatase	64.623	1.969	11.214
β-glucosidase	52.610	0.197	1.161
19/03/2002			
Leucine amino peptidase	79.940	86.285	34.013
Phosphatase	80.793	9.454	67.410
β-glucosidase	53.468	3.825	6.229
Site 9			
13/06/2001			
Leucine amino peptidase	280.084	308.484	240.547
Phosphatase	323.404	288.750	276.946
β-glucosidase	87.691	11.847	20.763
17/04/2002			
Leucine amino peptidase	242.293	242.585	179.975
Phosphatase	281.807	62.626	112.096
β-glucosidase	101.464	19.457	29.997

Table A9-3 Average leucine assimilation values (nM g^{-1} h^{-1}).

Date	**Sample depth**		
	0 m	**0.75 m**	**1.5 m**
Site 1			
16/01/01	0.839	0.183	0.027
23/01/02	2.298	0.019	0.006
Site 3			
25/04/01	0.443	0.047	0.002
27/03/02	0.627	0.139	0.003
Site 5			
31/01/01	0.944	0.060	-0.004
07/02/02	1.363	0.052	0.069
Site 6			
14/02/01	0.981	0.036	0.005
19/03/02	1.094	0.015	-0.001
Site 9			
13/06/01	0.364	0.017	0.094
17/04/02	0.593	-0.011	0.156

Table A9-4 Average values for percentage soil moisture.

Date	**Sample depth**		
	0 m	**0.75 m**	**1.5 m**
Site 1			
16/01/01	38	25.1	28.145
23/01/02	44.033	28.421	35.183
Site 3			
25/04/01	74.931	200.127	32.346
27/03/02	54.907	230.237	32.167
Site 5			
31/01/01	71.295	228.28	178.94
07/02/02	52.442	217.309	111.483
Site 6			
14/02/01	31.555	23.648	31.068
19/03/02	29.139	25.301	30.646
Site 9			
13/06/01	201.7	629.244	693.298
17/04/02	227.193	638.817	606.696

Table A9-5 Average values for percentage loss on ignition (LOI)

Date	Sample depth		
	0 m	0.75 m	1.5 m
Site 1			
16/01/01	9.79	0.955	0.745
23/01/02	10.814	1.312	3.572
Site 3			
25/04/01	14.714	38.33	5.663
27/03/02	14.418	37.593	3.511
Site 5			
31/01/01	20.322	36.87	27.425
07/02/02	19.509	49.484	19.856
Site 6			
14/02/01	6.519	2.312	3.126
19/03/02	6.443	2.54	3.392
Site 9			
13/06/01	77.912	88.088	76.985
17/04/02	78.355	82.889	69.343

Appendix 10

Saturated Hydraulic Conductivity Measurements

This appendix presents the calculation of a value for the saturated hydraulic conductivity (*K*) from one location on Sutton Common to demonstrate the process.

In Section 3.2.4 it was shown that *K* could be calculated using the equation:

$$K = \frac{R^2}{2L}\ln\left(\frac{L}{R}\right) \times \textit{slope of the line} \qquad (3.9)$$

Where the slope of the line is:

$$\left(\frac{\ln\left(\frac{H_1}{H_2}\right)}{(t_2 - t_1)}\right) \qquad (3.8)$$

and H_1 and H_2 = piezometer heads causing flow at

t_1 and t_2 = observation times.

Table A10-1 presents the raw measurements obtained for a rising head test for piezometer 5 on the 19/03/02.

Table A10-1 Raw data from rising head test for piezometer 5, 19/03/02.

Time (S^{-1})	Head (m)	Ratio	ln(ratio)
0	-1.06	1	0
60	-1.06	1	0
180	-1.055	0.995283	-0.00473
300	-1.055	0.995283	-0.00473
840	-1.05	0.990566	-0.00948
1200	-1.05	0.990566	-0.00948
2520	-1.045	0.985849	-0.01425
4740	-1.04	0.981132	-0.01905
8760	-1.025	0.966981	-0.03358
12960	-1.01	0.95283	-0.04832

Figure A10-1 presents the regression chart of log head ratios against time for the values presented in Table A10-1.

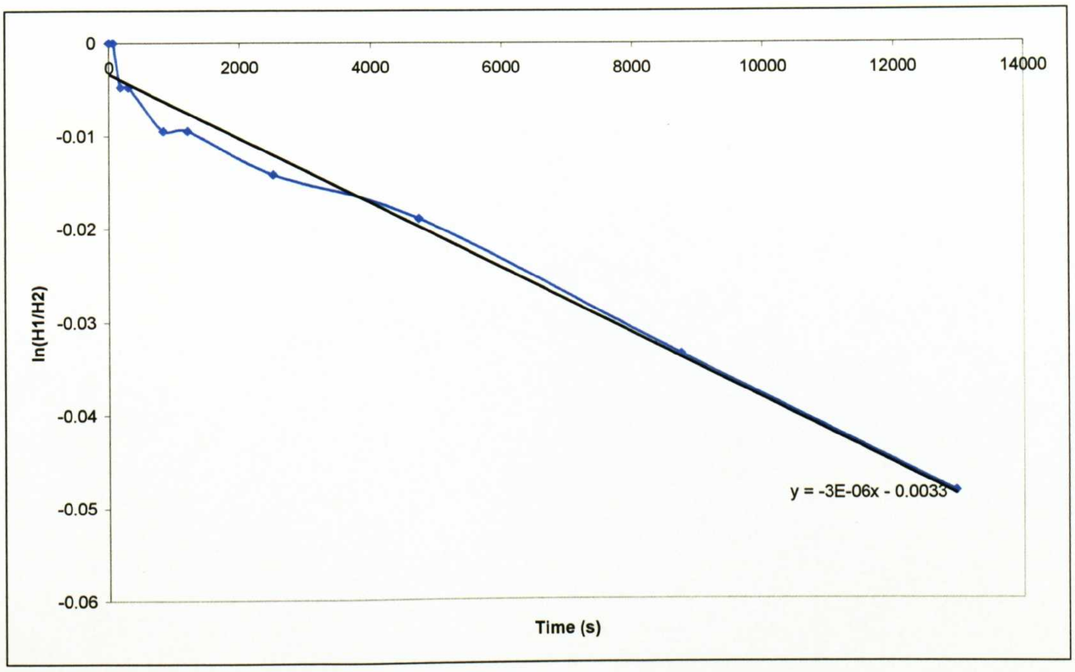

Figure A10-1 The regression chart of log head ratios against time for piezometer 5 on the 19/03/02.

The final value for *K* calculated by this process is 1.55794 X10^{-09} ms^{-1}.