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Holden, Joseph, West, L. Jared, Howard, Andy J. et al. (2006) Hydrological controls of in situ preservation of waterlogged archaeological deposits. Earth-Science Reviews, 78 (1-2). pp. 59-83. ISSN: 0012-8252

https://doi.org/10.1016/j.earscirev.2006.03.006

Published paper
Holden, Joseph, West, L. Jared, Howard, Andy J., Maxfield, Eleanor, Panter, Ian and Oxley, John (2006) *Hydrological controls of in situ preservation of waterlogged archaeological deposits.* Earth-Science Reviews, 78 (1-2). pp. 59-83.

HYDROLOGICAL CONTROLS OF *IN SITU* PRESERVATION OF WATERLOGGED ARCHAEOLOGICAL DEPOSITS

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Abstract

Environmental change caused by urban development, land drainage, agriculture or climate change may result in accelerated decay of *in situ* archaeological remains. This paper reviews research into impacts of environmental change on hydrological processes of relevance to preservation of archaeological remains *in situ*. It compares work at rural sites with more complex urban environments. The research demonstrates that both the quantity and quality of data on preservation status, and hydrological and chemical parameters collected during routine archaeological surveys needs to be improved. The work also demonstrates the necessity for any archaeological site to be placed within its topographic and geological context. In order to understand preservation potential fully, it is necessary to move away from studying the archaeological site as an isolated unit, since factors some distance away from the site of interest can be important for determining preservation. The paper reviews what is known about the hydrological factors of importance to archaeological preservation and recommends research that needs to be conducted so that archaeological risk can be more adequately predicted and mitigated. Any activity that changes either source pathways or the dominant water input may have an impact not just because of changes to the water balance or the water table, but because of changes to water chemistry. Therefore efforts to manage threatened waterlogged environments must consider the chemical nature of the water input into the system. Clearer methods of assessing the degree to which buried archaeological sites can withstand changing hydrological conditions are needed, in addition to research which helps us understand what triggers decay and what controls thresholds of response for different sediments and types of artefact.

1. Introduction

Research into the burial environment of archaeological deposits has a long history. This history is, in large part, a catalogue of examples of *in situ* preservation and examples of archaeological destruction following either direct physical disturbance or indirect environmental change (e.g. wetland drainage). Swiss Lake Villages were found preserved in a waterlogged state in the 1850s and prehistoric wooden villages were also found in good condition at Glastonbury in the UK in the late 19th century (Dewar, 1966). This led to the realisation that permanent waterlogging could lead to good *in situ* preservation. Later excavations began to inform us about losses of archaeological deposits such as the loss of the timber boat and burial chamber at Sutton Hoo, UK in 1939 (Carver, 1998) and wetlands surveys undertaken throughout England in the 1980s and 1990s to ascertain the extent of archaeological loss following drainage (Van de Noort *et al*., 2001b). It was also around this time that the extent of the preservative environment along river margins in urban areas across Europe and North America (Howard *et al.,* 2003) became apparent and the idea that deliberate reburial of archaeological artefacts following excavation might be feasible. Classic examples include the reburial of timbers under water in Red Bay, Canada (Stewart and Murdock, 1994) and the Rose and Globe Theatres in London which drew public attention towards preservation *in situ* (Corfield, 2004).

In many countries archaeology is now firmly embedded in the planning process when new building developments or changes to land management are considered (e.g. Goodburn-Brown and Panter, 2004). Often this comes with a presumption of archaeological preservation where possible. Long term *in situ* preservation of the archaeological resource is a stated objective of agencies such as the Council of Europe in the Valetta Treaty (Willems, 1998), the United Nations International Council of Monuments and Sites (ICOMOS, 1996; Van de Noort *et al*.,

2001) and it is formally asserted by many national governments too. In England, Planning Policy Guidance 16 (PPG 16) has proven a major driver of approaches to archaeological resource management (Sidell *et al.*, 2001). PPG 16 Clause 8 states that "where nationally important archaeological remains, whether scheduled or not, and their settings, are affected by the proposed development, there should be a presumption in favour of their physical preservation *in situ*" (Department of Environment, 1990). This means that developers must include the cost of archaeological evaluation and mitigation measures aimed at preserving nationally important remains *in situ*. Where preservation *in situ* is not possible then a local planning authority may refuse planning permission or ensure that the remains are recorded prior to destruction (so called preservation by record). Mitigation measures which are intended to preserves deposits or remains *in situ* may include changes to design techniques and use of landscaping. Through PPG 16 and a series of EU directives such as the European Spatial Development Perspective (10 May 1999) and the Environmental Impact Assessment Directive it is envisaged that the archaeological resource is preserved in its 'natural' environment until a future point when the means for better excavation, analysis and storage could be guaranteed.

Full excavation and subsequent analysis of archaeological sites can be extremely costly and therefore in some instances, the policy of *in situ* preservation offers an attractive alternative mitigation strategy provided that it is based on sound scientific research. However, despite the implementation of this strategy, there is a still a lack of understanding of the threats posed to archaeological materials which are maintained *in situ* (Caple *et al.*, 1996; Goodburn-Brown and Panter, 2004). Such threats include changes to soil moisture content, pH, redox (reduction-oxidation) status, waterlogging and many other often poorly understood factors resulting from land management practices such as agriculture and urbanisation, and perhaps even climate change. In most archaeological contexts, cases of *in situ* preservation can be divided into two discrete groups: i) where deposits have been identified, but since they will not be affected directly by destruction, they are left unexcavated or physically disturbed; ii) where deposits have been disturbed, but are reburied relatively quickly as part of a mitigation strategy. Reburial schemes have been carried out with varying degrees of success but often without an integrated scientific approach (Lucas, 1982; Caple, 1994a); key problems include the lack of information on the type of reburial environment required and the implementation of long term monitoring strategies to determine the success of the approach. This scarcity of information is partly related to the infancy of the policy; few sites have been excavated where *in situ* preservation was part of the development scheme (Williams and Corfield, 2002). In addition, a number of opportunities have been missed. For example, timbers were re-excavated and re-examined following an initial period of study at Glastonbury Lake Village, UK, and yet no scientific measurements were made to compare present preservation conditions with those before excavation (Caple, 1994b). Other sites where conditions were not measured before reburial of the resource (with the aim of preservation) include Biskupin (a waterlogged fortified Iron-Age settlement in Poland; Arlet, 2004) and the Corlea Trackway (Ireland). Even large projects such as the Coppergate and Hungate excavations in York, UK, (Carrott *et al.*, 1994; 1998; 1999) or the London, UK, waterfront sites which have encouraged research have not produced detailed work on the nature of the burial environment (Brigham, 2004).

Increasing emphasis on environmental archaeology has led to a re-evaluation of approach and the development of new technologies (*Clavel*-Leveque *et al.*, 2002), as well as the use of more inter-disciplinary teams in archaeological investigations (Stein, 2000). As part of this it has been realised that a hydrological perspective is often required when examining the potential threats posed to the archaeological resource. In particular, this often concerns processes operating outside of the ‘archaeological investigation area’. This is because the archaeological site has to be placed within the context of the hillslope or the water catchment in order to understand its hydrological position. For example, an archaeological site at the foot of a long gentle gradient hillslope may be more likely to remain waterlogged than that in the middle of a short steep hillslope. However, there are many other factors that require analysis too. This paper reviews the research into hydrological parameters influencing *in situ* preservation of archaeological deposits. The paper will show that if we are to improve *in situ* archaeological management, then archaeological investigations need to involve a broader range of environmental analyses including improved classification of preservation status, a greater degree of systematic recording to incorporate hydrological, geological and geochemical processes, improved use of meteorological records, and improved understanding of the spatial and hydrological context of the local environment. Despite the important role of water in preservation at many sites, surface and subsurface water flowpaths have largely been ignored in archaeological studies.

2. Basic features of the preservation environment

Archaeological remains can be divided into organic (e.g. leather, wood, bone, insects, pollen) and inorganic (e.g. stone, metal) materials. Generally, organic materials are more susceptible to damage and degradation than inorganics. This paper will mainly focus on organic archaeological deposits. It should also be noted that organic deposits are those which contain a large proportion of organic materials, but they may also contain inorganic remains. It should be recognised that there may be conditions which are favourable for organic preservation which are not as favourable for the preservation of inorganic deposits such as metalwork (Fell and Williams, 2004). Nevertheless, the exclusion of oxygen combined with saturation will usually favour preservation of both.

In undisturbed sites, anoxia inhibits the activity of certain organisms such as Basidiomycete fungi, the principal agents of decay of celluloic organic materials, and allows only those bacteria that respire anaerobically to survive. This impedes the natural breakdown of organic remains (Van de Noort *et al.*, 2001b). A range of different chemical and physical environments create waterlogged anaerobic conditions for organic archaeological preservation such as those found in peat, alluvial silts and clays. Recent monitoring has exposed some important parameters described below.

2.1 Waterlogging

The sediment characteristics, local geology, impeded drainage and the location of the site with respect to topography and water supply are important factors leading to waterlogging. Soils with a high hydraulic conductivity (fast water transmission capability), such as those developed on sandy materials, often do not retain sufficient water and consequently cannot develop the conditions required for preservation unless there is constant supply of water. Conversely, soils developed upon silt and clay substrates have smaller particles and pore sizes, which impede water movement (low hydraulic conductivity) and retain water, suppressing oxygen diffusion to a greater degree. Research in the Humber Wetlands, UK, indicated that local soil conditions, and in particular the saturated hydraulic conductivity, contributed more to the wet preservation of archaeological sites than any other factor investigated (Van de Noort, 1996). In some cases the nature of the enclosing sediments is important. For example, French *et al.,* (1999) found that soil moisture at Willingham, Cambridgeshire, UK, was influenced by fine silty alluvial clays overlying archaeological deposits providing a cap and retaining moisture. Similarly a late Bronze Age site on Shinewater Marsh, East Sussex, UK, discovered in 1995, had remarkably well-preserved wooden remains due to their protection by a layer of clay deposited over the site by a flood some 2000 years ago.

It should be noted that it may not be necessary for a deposit to be completely saturated for it to maintain organic preservation and there are other factors that are important. Many organic soils and deposits have the ability to retain a large amount of water even when above the water table. Peats, for example, are typically 90 - 95 % water by volume when saturated, but about 85- 90 % water when above the water table (Ingram, 1983). Nevertheless, total saturation and lack of oxygen entry appear to be favourable in most *in situ* organic preservation cases.

2.2 Chemical balance

As noted above, the degree of waterlogging (e.g. the water table depth) is an insufficient indicator of preservation (Kenward and Hall, 2000; Van de Noort *et al.* 2001a). The chemical balance is crucial in determining the survival of waterlogged organic remains. In recent years major efforts have been made to define the chemical characteristics of the anoxic waterlogged burial environment. Caple (1994a) described some of the major chemical changes following waterlogging in organic archaeological environments. These included i) N_2O and N_2 increase since anaerobic bacteria (e.g. *Thiobacillus dinitrificans*) thrive (NO^{3-} declines); ii) S_2^- and H_2S increase since sulphate reducing bacteria (e.g. *Desulfovibrio disulfuricans*) thrives ($S0_4^{2-}$ declines); iii) redox reactions convert Fe^{3+} to Fe^{2+} and hence Fe^{3+} decreases; and iv) the changes to ion species are visually manifest in the mineral forms observed in these deposits; salts such as FeOOH are no longer observed but reduced salt forms are commonly found.

Redox potential is a measure of how oxidising or reducing the environment is in terms of electron occurrence. In deposits rich in organic matter, inundation with water (and the subsequent creation of a waterlogged environment) often results in a swift fall in the concentration of oxidising species present, as they are used up in redox reactions and no longer replaced by diffusion of oxygen from the atmosphere. Since many oxidising species are produced by aerobic micro-organisms which are inhibited, a lack of oxygen suppresses the further production of oxidising species. Consequently there is a rise in the reducing species present in the soil. Observed redox potentials have been a useful aid in distinguishing anoxic from aerobic environments (Stumm and Morgan, 1970) and low Eh environments (reducing environments) have been linked with apparently good survival conditions for archaeological organic material (French, 2004; Caple *et al.,* 1996).

The penetration of oxygenating species into anoxic waterlogged soil is limited not only by the oxygen diffusion rate, but also by the reaction of the oxygen or oxidising species with reducing species present within that deposit. High concentrations of reducing species will thus mop up oxidising species, ensuring the continuity of the anaerobic conditions. The incorporation of reducing species will more quickly establish and preserve anaerobic conditions (Caple, 1994a). The rate of dissolved chemical species entering the deposit depends on both the rate of transport of incorporation and the reducing capacity of the archaeological deposit (Welsh and Thomas, 1996). Certain individual bacteria play a key role such as those which reduce sulphate. These specialised converters (e.g. *Desulfovibrio disulfuricans*) will consume oxidised species that remain after the creation of anoxic conditions (often by products of the life cycles of micro-organisms). Their position is dependent on the location of a ready supply of oxidised sulphate species (to be converted to sulphide). Hence, they may play a very significant role in maintaining the anoxic environment beneath the oxic-anoxic interface. If they were not present, through high levels of toxins for example, it may not be possible to stop the diffusion of oxidised species and maintain anoxic conditions (Caple, 1994a). Therefore, chemical changes induced by alteration of water flowpaths or chemical inputs into the deposit (e.g. fertilisers, pesticides, construction chemicals) may have a major impact on archaeological preservation as they can alter the redox status of the deposit (Caple, 1996). Therefore data on the nature of baseline Eh values and the accompanying sediment chemistry would be useful when interpreting preservation risk. The extent of ion species present and their reducing capacity, either individually or collectively as Eh, are rarely recorded in archaeological site investigations (Caple, 1994a).

A number of factors will affect pH in an anoxic environment. Aluminium, and to a lesser extent iron, form complexes and provide buffering at pH values less than 5 (this may result in a lowering of pH around corroding iron objects); clay particles act as cation exchange sites, absorbing or emitting excess H^+ ions (particularly when inundated by other cations such as Fe^{2+}). The presence of these media can buffer pH, reducing the chances of extreme pH conditions and hydrolytic attack on (archaeological) organic materials. The pH that has been monitored at many well-preserved sites is often at nearly neutral levels (e.g. Coppergate, York, UK pH 7.0-7.6; and Piercebridge, UK, pH 6.6-7.8; Harry Kenward, pers com.).

2.3 Biological activity

Micro-organisms are recognised as the primary organic decay agents within the soil environment (Hopkins, 1996). Therefore it is desirable to account for this activity when considering *in situ* preservation (Van de Noort *et al.,* 2001b). Anaerobic conditions create a low energy environment that inhibits aerobic bacteria (e.g. brown rot and wet rot which cause the breakdown of wood). However, the tolerance range of fungi in terms of oxygen content, pH, Eh, chemical species (e.g. H_2S and ethylene), and temperature are relatively poorly understood. These limits need to be established to ascertain the biological diversity that a burial environment will tolerate (Caple, 1994a). The micro-organisms that operate within reducing conditions are responsible for initial fermentation and secondary breakdown products (e.g. pyruvic acid, lactic acid, methane, and ethane). The level of these organic products may subsequently limit bioactivity due to their toxicity. In high concentration they may lower pH and form complexes with metals which may have corrosive effects (Caple, 1994a). In low pH environments they may also act as electron acceptors, causing further chemical reactions. The potentially large range of effects has not been measured.

3. Rural research

Most research into *in situ* preservation has taken place at rural sites. This, in part, reflects the threat to rural landscapes though large scale development activity (e.g. quarrying, urbanisation) and hence the need to develop mitigation strategies; but also, that they are easier to investigate than more complex urban sites and also provide simpler case studies in which cause and effect can be more readily investigated (e.g. French, 2004). The following section therefore highlights examples of rural threats to archaeology and projects which have investigated processes involved with *in situ* preservation and degradation. These will then provide context for the subsequent section of this paper which will discuss urban preservation.

3.1 Rural threats

Agriculture poses a considerable threat to archaeological resources throughout the world today (Darvill and Fulton, 1998). Damage may be done through ploughing, fertiliser and pesticide inputs, changes to water abstraction rates and water chemistry, enhanced evapotranspiration and rooting, and improvements to subsurface and surface drainage. Van de

Noort *et al.* (2001b) summarised the risks posed to the wetland archaeological resource in England and Wales recognising seven key causes of destruction (Table 1). The greatest impact on this resource is from the drainage of land for agriculture and peat wastage. When wetlands are drained, oxygen is reintroduced into the burial environment and the microbial activity will commence. In addition the use of nitrate fertilisers alters the chemical balance of the site causing accelerated corrosion processes (English Heritage, 1996). There is therefore a land use conflict at many rural archaeological sites. At Sutton Common, UK, for example, the high water table required to achieve *in situ* preservation would result in widespread flooding of the surrounding agricultural land (Chapman and Cheetham, 2002).

3.2 Case studies

The discussion above highlighted the significance of moisture content, water chemistry and sediment type for the maintenance of anoxic conditions that preserve organic archaeological materials. Research into characterising water table behaviour was prompted in the UK when a number of important sites appeared to be threatened by dewatering. Monitoring programmes were initiated at these locations to ensure adequate hydrological conditions for preservation. A brief discussion of these projects, the characteristics of the sites, and the outcome of research is given below.

3.2.1 Somerset Wetlands and Cambridgeshire Fens

Wetlands have long been known for their role in preserving organic materials and acting as an archive of palaeoenvironmental information. Steenstrup (1830), for example, developed the concept of bog stratigraphy although it was not until the 1920s and 1930s that the survival of pollen in bogs and its role as a record of prehistoric vegetation was appreciated (e.g. Erdtman, 1924). In recognition of this asset, English Heritage has supported a long-term strategy of survey and research within the four main lowland wetland areas of England for over 30 years (Somerset Levels, the fenlands of East Anglia, the wetlands of North-West England, and the Humber wetlands; Darvill and Fulton, 1998). The primary aim was to identify and record the archaeological potential of each area. Throughout the survey period of the 1980s and 1990s, it became apparent that wetlands were under severe pressure of degradation and that reactive measures were required at many sites. It was estimated that 10,450 wetland monuments were destroyed by human impact between 1950 and 2000 amounting to 78 % of the total identified number in England (Van de Noort *et al.*, 2001b). For example, under immediate threat is the Flag Fen wooden palisade of 60,000 posts built up between 1350 and 950 BC where the water level is now below the upper parts of the late Bronze Age timber platform and avenue.

The Somerset Levels and Moors contain a mass of organic archaeological remains that have been preserved in waterlogged conditions, including numerous prehistoric trackways and the Iron-Age lake villages at Glastonbury and Meare. The density of archaeological sites in the Somerset peatlands has been estimated at 3.4 sites per km^2 (Van de Noort *et al.*, 2001b). The Iron-Age villages discovered in the 19th century still remain the best preserved in Britain, although they have suffered some damage (Coles and Coles, 1986). A comparison of ground surface heights and subsurface stratigraphy established that part of the former landscape must have existed to a height of at least +5.5 to +6 m above Ordnance Datum instead of the present day ground surface levels of +1.8 to + 2 m: a 4 m peat loss since the Medieval period (Housley *et al.,* 2000). This reduction in surface altitude due to peat shrinkage and desiccation has resulted in many of the archaeological remains being now very close to the ground surface and hence more prone to damage. A number of the waterlogged archaeological sites within the Somerset Levels and Moors, which are designated as Scheduled Ancient Monuments, exist within 90 cm of the ground surface. Predictions indicate that all known waterlogged sites of national importance in the area will be destroyed by desiccation and peat wastage by the end of the 21st century (Van de Noort *et al.*, 2001b).

Thus at many of these sites in Somerset, hard management solutions, some of which are extremely costly, are being proposed in order to try to maintain preservation. For example, in the area around the Sweet Track, a wooden trackway built across the wetlands around 3806 BC, has been affected by recent drainage, enhanced tree growth and associated dewatering (Brunning *et al.*, 2000). In an attempt to save the structure, water has been pumped onto a 500 m section of the track since 1983 and represents the longest running scheme for active preservation of waterlogged remains in the British Isles. Water levels, the movement of water through the peat and the degree of oxygen exclusion are monitored occasionally and this allows management refinement and determination of how much water table lowering is acceptable each summer to allow for harvesting of surrounding meadow grasslands. This monitoring suggests that occasional reduction of the water table below the Sweet Track is sustainable as there is sufficient moisture in the peat to maintain preservation for short drawdown periods. Recent keyhole excavations have confirmed that the trackway is in a good state of preservation (broadly comparable to those encountered during 1983 when the pumping started) and that the conditions are highly reduced. However, the Sweet Track is the only site in the Somerset wetlands that appears secure from the threat of desiccation and destruction, as a direct result of the pumping regime. The Sweet Track demonstrates the need for quantifiable baseline data on conditions of a site and its associated archaeology; this information needs to be collected at the earliest possible opportunity so that subsequent monitoring can confirm the success, or otherwise, of any *in situ* management practices.

The Abbots Way Track is another ancient Neolithic trackway in Somerset, where dewatering associated with tree planting and drainage has led to the desiccation of timbers and insect remains, although pollen and plant macrofossils had still survived when last examined (Cox *et al.*, 2001). Suggested changes to land management practices at this site, including tree felling and the introduction of grazing may result in a gradual rise in water levels, but associated nutrient enrichment may in itself affect preservation. Other alternative management intervention strategies include the use of plastic membrane at Corlea, Ireland, to maintain bog wetness and conserve a 6,000 year old timber trackway.

In 1982 a prehistoric causeway enclosure was discovered at Etton in floodplain wetlands of the River Welland, near Maxey Cambridgeshire, UK (Pryor, 1998). Due to the threat of dewatering caused by nearby gravel quarrying, French and Taylor (1985) undertook a study assessing the impact on the water table. This represents one of the first examples of a hydrological monitoring programme that assessed the impact of water table lowering on the archaeological resource. Structural degradation of the waterlogged wooden remains was observed to occur after just one month from the commencement of dewatering (French *et al.,* 1999). Similarly French (2004) initiated a hydrological monitoring programme at Willingham, Cambridgeshire, on the Great Ouse, in response to large scale gravel extraction. The significance of this project was the attempt to provide baseline data on the hydrological environment before the dewatering activity, during it and then following the dewatering. No other studies have yet been performed that have examined soil moisture, groundwater table and changes to the soil or groundwater chemistry, within a buried waterlogged archaeological landscape starting from an undisturbed state and progressing through the period of development.

Using a digital terrain model constructed from borehole and other stratigraphic data describing the present land surface, buried land surfaces and other sedimentary features, the research attempted to produce a three dimensional characterisation of the deposits and provide some indication of the nature, extent and timescale of dewatering and destruction of the organic deposits. The results followed basic hydrogeological theory; once large water storage areas are created below the water table, such as in a quarry, flow from the aquifer will fill the extra space lowering the groundwater table in the immediate vicinity. The dewatered zone of influence extended around 600 m away from the quarry (and more so downslope of the quarry). Archaeological sites within this zone experienced large reductions in soil moisture content and .both the pH and dissolved oxygen values rose appreciably. This research demonstrated that the good preservation of buried archaeology usually observed in this type of depositional environment can be undone in a matter of months through land management practises that occur some distance away from the site of interest. It led French and Heathcote (2003) to suggest that only hydrological monitoring and remediation schemes at each site where disturbance is planned can prevent wastage and partial destruction. However, predictive modelling before intervention occurs may be more cost effective.

3.2.2 Sutton Common

Research focused upon the *in situ* preservation of archaeological remains is still in its very formative stages and one of the earliest examples of such work is currently underway around the Iron-Age double enclosure at Sutton Common, South Yorkshire, UK. The excavation of deep dykes initially during the 1980s had lowered local water levels by approximately 2 m (Parker-Pearson and Sydes, 1997) and resulted in the installation of monitoring equipment to assess the burial environment, the position, shape and fluctuation of the water table (grid of 50 piezometers), the soil chemistry (automated redox probes) and microbiology (numbers of bacteria, presence of extra-cellular enzyme activity and measurement of microbial activity) (Van de Noort *et al*. 2001a, Chapman and Cheetham 2002). This monitoring programme has found that reduced conditions dominate when groundwater throughflow and regular vertical fluctuations of the water table which transport oxygen and nutrients are kept to a minimum. The preservation potential was found to be variable over different parts of the site dependent on the topography and morphology. For example, one palaeochannel intimately associated with the site displayed a water table consistently below the ground surface, but with a very stable and reducing environment with depth. In contrast, a second palaeochannel exhibited prolonged surface waterlogging, especially during the winter months, but had greatly fluctuating redox readings. This indicates that the former palaeochannel represented a more suitable location for long term preservation of organic materials. The variability of preservation potential was affected by the composition of the natural sediments: good preservation was associated with the 'water retentive' peat-filled palaeochannel, whereas poor preservation was associated with minerogenic sandy islands.

3.2.3 Wood Hall and Pict's Knowe

At Wood Hall, North Yorkshire, UK, elaborate Medieval bridges over a moat were perfectly preserved in saturated conditions. Minor variations in the local topography (such as a palaeochannel) were shown to result in exceptionally good preservation of organic remains. Similarly at Pict's Knowe, Dumfries and Galloway, southern Scotland a large henge monument is situated in a damp valley bottom. Extensive Iron-Age timbers are preserved in a waterlogged ditch where moisture retention is maintained despite the different sedimentological characteristics of surrounding deposits. In this case, a small part of the valley bottom was isolated to allow sufficient saturation for preservation. Such small pockets of preservation may respond differently to more general changes in external conditions.

Furthermore, these findings suggest that an understanding of the palaeolandscape will aid identification of the spatial distribution of preservation.

3.3 Summary of findings from rural sites

Rural studies have highlighted a number of important themes for understanding archaeological preservation. These are:

- *Impact of fluctuations in the water table*

An assessment of the risk posed at any site must consider the level to which the water table naturally fluctuates to allow a comparison to levels when damage to archaeology might occur. Thus water table time-series are needed from sites under investigation. However, the exact effect of water table fluctuations on the maintenance of the organic archaeological deposits remains difficult to infer. A fall in the water table below the level of the deposit may not necessarily lead to the destruction of the anoxic conditions and the onslaught of rapid decay processes provided that the organic remains can hold sufficient moisture (e.g. Sweet Track). Conversely, fluctuations in the water table may promote alterations between oxic and anoxic conditions leading to the generation of corrosive chemical species. In addition, water tables do not tend to be flat, and often do not even mirror the surface topography over a given site. There are much more complex patterns and often, water tables can dome over archaeological deposits.

- *The local hydrological regime must be placed in a wider context*

Processes and factors operating at considerable distances away from archaeological sites can affect groundwater systems and therefore impact on their well-being. Both the surface topographic context and the subsurface geology must be taken into account when investigating risk of archaeological destruction. It is important to understand the main sources and pathways of water for a given site and this necessarily requires an understanding of the environment that is of much greater spatial extent than the archaeological resource itself.

- *The nature of the water feeding into the deposit is important*

Efforts to manage threatened waterlogged environments must consider the chemical nature of the water input into the system. This is particularly the case of programmes that involve pumping to maintain a sufficient water table height. An activity that changes either the source pathways, or the dominant water input, may have an impact because the degree of oxygenation, ionic species and the redox potential which control the chemical environment are commonly determined by the nature of the water feeding into the deposits (Caple *et al.*, 1996; Caple, 1994b).

- *Timing of decay following desiccation is variable*

The length of time following a trigger of initial decay to total degradation of sites is variable. The relationships between the state of preservation and the period of drainage are often not linear. The saturated hydraulic conductivity and stratigraphy of the sediments are important factors in determining timing of decay; different soil types will respond differently to lowering of the water table. Coarser grained or fibrous deposits which drain quickly are likely to respond faster than finer grained sequences which may fail to drain significantly despite lower water table levels. This also emphasises the importance of site context for any assessment of the vulnerability to changing environmental conditions.

- *Interventive site management often required*

Many sites suffering degradation are in need of interventive management to preserve remains. This may involve water pumping, bunding (water damming) or tree-felling to maintain waterlogged conditions. However, care is needed when selecting the method of protection. For example, allowing an area to flood may inundate the landscape with heavily oxygenated waters that are also laden with agri-chemicals and this may have a deleterious impact upon the buried resource. Nevertheless the view that archaeological remains can be preserved *in situ* without any form of management is unsustainable (van de Noort *et al.*, 2001a, Kenward and Hall, 2000).

- *There is a high degree of spatial and temporal variability*

The important components of preservation are far from homogenous. At the site scale, *in situ* preservation may depend on small-scale features such as palaeochannels that influence the long-term preservation potential. A site may be good for preservation, but only because it has lots of smaller-scale features that allow preservation. At Willingham, UK, for example, susceptibility to changing environmental conditions was found to be dependent on the organic content, relative proximity to the groundwater table and alluvial ploughsoil, and altitude (French, 1999). Spatial heterogeneity causes difficulty when designing monitoring strategies because decisions over the most appropriate parameters to monitor and where to monitor them pre-supposes an awareness of the chemical, physical and biological variations within these environments. However, there is a greater need to understand the spatial and temporal variability of hydrological processes in preservation environments and how disturbance impacts on this variability and related decay. Small temporary fluctuations may result in substantial change in preservation status. Tipping *et al.* (2003) used numerical modelling of peat to show that periods of drying oxygenation can cause sulphur to be converted to sulphuric acid, consequently lowering the pH. Holden and Burt (2003) found permanent structural changes occurred to organic soils following droughts. This resulted in increased vertical macropore flow and, when it rained following the drought, deeper incursions of fresh rainwater into the ground. This was the case even several months after the drought had ended. Many organic soils undergo physico-chemical changes upon drying that are not reversible (Egglesmann *et al.*, 1993). Thus, one event can trigger a permanent change in site characteristics and provide a threat to long-term preservation potential. Welsh and Thomas (1996) argued that preservation depends on the maintenance of a stable chemical environment. However, the definition of 'stable' is far from clear. This is a problem because we do not yet understand the range over which conditions can fluctuate and yet maintain preservation (thresholds of response) nor understand the buffering capacity of different parameters.

4. Urban Research

Despite the potentially large archaeological resource under many urban areas (e.g. Carver, 1987), little has been done to investigate the influence of hydrological changes in these environments. There are a vast number of cities and towns across the world that have a potentially large archaeological resource beneath them. Important examples include Bergen, Dublin, London, Brussels, Paris, Florence, Rome, Rhodes, Milan, York, Cairo, Istanbul and Beijing to name but a few (Christensson *et al.*, 2004). Despite this, no major hydro-archaeological monitoring projects have been undertaken in urban environments. The urban cover can often act as protective barrier over archaeological deposits. Until modern times sequential developments were built over previous sites and this rarely resulted in total removal of the earlier deposits. At the same time, however, urban areas are sites of major activity and development and so the potential number of threats is great. This section of the paper describes what we know about urban archaeological deposits and their characterisation before describing the range of threats that urban change poses to the hydro-archaeological system. This part of the paper will show that an understanding of urban hydrology is crucial for archaeological risk assessment but that very few projects have combined hydrological and archaeological approaches in urban environments. In part this is because of the complexity of the urban environment, but in part, it is because the two types of specialist do not often work together; the scale of approach typically adopted by archaeologists is usually much finer than that of hydrologists.

4.1 Urban deposits and their characterisation

The natural processes of soil development are vastly altered in an urban setting. Indeed conventional soils tend not to form in urban areas, at least where the best waterlogged accumulations occur. Typically, over hundreds to thousands of years, wood and other materials are brought into urban areas for housing and are spread around creating a complex stratigraphy. Waste from habitation can generate large organic deposits within urban environments. Beneath parts of the City of York, UK, for example, there are up to 8 m of organic-rich archaeological deposits with a 2-5 m thickness below most of the city centre (Kenward and Hall, 2000).

Describing and appropriately classifying archaeological deposits for use in urban mapping exercises is important. However, there is a lack of archaeological protocols for the sort of data that should be routinely collected during surveys. It is certainly true that geotechnical projects (e.g. boreholes created for other reasons) could provide much useful information for archaeologists. At the same time archaeologists themselves could do much more during site investigations to collect useful contextual information on deposit characteristics. In most countries the archaeological and geotechnical classification of soil is very different to that used by a pedologist. The classification schemes also vary from country to country. Protocols need to be devised that specify recording, for example, core or pit location surveyed to within 50 cm in x and y co-ordinates and 10 cm in altitude, soil colour (from a Munsell colour chart), texture, inclusions, organic matter content, packing density and other geotechnical characteristics. In the longer term, national and worldwide standards for archaeological soil description at various kinds of sites are required. Furthermore there is a need for much better classification of the preservation status of many archaeological materials. Archaeologists have good preservation classification schemes for some types of material such as insects (Kenward and Large, 1998), and there have been some studies on the decay mechanisms of bone and metals (e.g. Kars and Kars, 2002; Schweizer, 1994; Mathias, 1996), but there is a dearth of appropriate classification schemes for materials such as leather and wood. Therefore it is difficult to assess the baseline condition for *in situ* preservation schemes never mind determine the success or need of protective measures.

Geological maps typically display a wide range of geoscientific information including bedrock geology and superficial geology, but engineering and environmental assessments require increased understanding of artificial ground (Price *et al.*, 2004). On British geological maps urban artificial deposits are usually simply termed ‘made ground’, ‘infilled ground’, ‘worked ground’, ‘landscaped ground’ and ‘disturbed ground’ and this only allows very limited information to be recorded. A new scheme has been developed by the British Geological Survey (BGS) that allows more meaningful information to be captured in a three-tiered classification based on the origins of a deposit or excavation (Price *et al.*, 2004). Two examples are given in Figure 1. As each level of the BGS hierarchy can be subdivided to give progressively more detail, either basic or detailed information can be captured as shown in Figure 1. This is more useful to archaeologists, but much further work is still required to align meaningful archaeological information to classifications of artificial ground. One of the main problems that will have to be overcome is one of scale. Sometimes archaeological investigations are carried out with attention to many layers that may be only a few mm thick. Pedologists and geologists are likely to collect data over a larger scale. Archaeologists will need to work with geologists and pedologists in order to devise appropriate data collection and classification protocols for archaeological sites.

Developing a more insightful classification of urban deposits and their characteristics as discussed above is a major first step for improving our ability to assess archaeological risk in urban environments. However, there is also a need to have a framework within which to visualise and interpret the stratigraphic record. Three-dimensional deposits models that place urban deposits into a spatial framework are an essential component for the interpretation of the archaeological record. Such models will also provide the basis for hydrological modelling approaches.

Hydrological data collected as part of routine archaeological work are often woefully inadequate. An example is shown in Figure 2. This map shows the distribution of ‘wet’ and ‘dry’ archaeological sites in the City of York, UK based on the York Archaeology and Development Database. This simply reports whether deposits excavated and recorded were ‘wet’ or ‘dry’, and hence a spatial distribution of apparently ‘waterlogged’ deposits can be mapped. Obviously a comparison of the spatial distribution of these deposits (i.e. whether wet or dry) with the topography or drift deposits of the city could help identify controls on the tendency for waterlogging, and indeed the figure illustrates the utility of using geographical information systems (GIS) to map such data. There does appear to be some clustering of wet and dry sites suggesting that local or perched water tables might be important. However, such qualitative reporting of wet and dry sites cannot be a truly reliable indicator of hydrological processes. It is not known whether a wet site indicates that the water table was reached and even if the water table was reached (unlikely in all cases) these data are useless because they were not i) tied in to a topographic datum and ii) there is no idea of the seasonal water table fluctuations at each site nor the date at which data were collected.

4.2 Urban threats

Studies evaluating the impact of hydrological changes on deposits in rural settings have involved highly controlled experiments in which there was a set of known variables. The influences on the hydrology of the site could be identified and measured (e.g. drainage, fertiliser input etc). However, for urban areas, identifying the hydrological influences on the site is a problem. Urban sites are primarily at risk of disturbance from redevelopment projects (Davis, 1996). In Europe a number of archaeological sites earlier affected by development in the 1960s have been re-examined, and there are concerns that engineering methods used have not been as effective in preventing damage as was expected (Tilly, 1996; English Heritage, 1996). The impact of construction is principally related to the size of the building, the type of foundation design and the methods of construction (Williams and Corfield, 2002; Ove Arup and Partners, 1991). Indeed there are often pre-construction impacts relating to boreholes and site investigation holes and site dewatering. Of particular concern is the potential for i) physical disturbance causing an increase in oxygen exposure, which in turn increases corrosion; ii) stimulation of biodegradation; iii) modification of the hydrological and geochemical regime; and iv) excavation of soil diminishing the amount of protective deposits (Sabbioni, 2002).

In York, UK, mitigation strategies to minimise the impacts on construction activities involve a 5 % rule, whereby the estimated damage to the archaeological resource caused by a building development cannot exceed 5 % (Oxley, 2002). However, the damage is usually defined by the superficial dimensions and does not take account of the surrounding disturbance (Tilly, 1996). A further problem with the 5 % rule is that repeated redevelopment or modification of a site will gradually reduce the amount of surviving archaeology unless foundations are re-used (Shilston and Fletcher, 1996). There is therefore a need for a more flexible approach aimed at lower disturbance levels.

4.2.1 Piling techniques

Piled foundations are often used on larger building developments since they enable tall and complex buildings to be constructed, particularly on weak and unconsolidated sediments. The York Development and Archaeology Study (Ove Arup and Partners, 1991) suggested that the archaeological deposits and soils in York are not suitable for carrying normal building loads and hence piling is an accepted method of building in the city. Piling was deemed the most appropriate foundation type for large buildings and mechanically loads the smallest plan area of any foundation type, so in theory, should cause the least damage below the building. The use of particular piling methods was therefore recommended for York to achieve minimal physical destruction of archaeological deposits. However, the validity of these assumptions has been called into question on a number of occasions and concerns include damage to archaeological deposits that may occur not only in the direct position of the pile, but in areas adjacent to the pile. Insertion of piles can cause changes to permeability around the pile-soil interface creating preferential pathways for dewatering and oxygen transport. Piling has been hypothesized to cause a permeable break in the confining layers causing drainage of perched aquifers or rising water under pressure. Although the exact nature and extent of piling damage remains unknown, it is clear that some methods are more damaging (e.g. displacement piles appear to do the greatest archaeological damage; Dalwood *et al.*, 1994). Sleeved continuous flight augured (CFA) piles are preferred on sensitive waterlogged archaeological sites. Overall, however, it would be beneficial for the archaeology if existing foundations were reused. This should always be the preferred option and has been used partially (and successfully) in Colchester, Lincoln, and York, UK (Williams and Chaddock, 2002). However, re-using existing foundations can be problematic if they have a small loading capacity or there is a lack of construction records (Shilston and Fletcher, 1996).

The impact of piling has been studied in relation to contaminants due to potential direct transfer of material by the pile tips, formation of preferential flow pathways by the pile and flow through the pile material. Campbell *et al.* (1984) examined such processes empirically while Boutwell *et al.* (2000) attempted to numerically simulate pile contaminant processes. The field observations implied that vertical migration of contaminants may occur with piled foundations, although the evidence was limited. Boutwell *et al.* (2000) used model studies and suggested i) there should be no increase in transmission of contaminants for displacement-type piles of low-permeability materials (e.g. treated wood and steel pipes); and ii) two pile types induced higher transmission and these were untreated wood and steel H pipes. It was concluded that piles of proper types driven through a contaminated zone did not create a significant problem. Further research on archaeological impacts of different piling methods is required.

4.2.2 Chemical influences

Concrete and grout are essential construction materials but they are considered to cause both physical and chemical damage to archaeological materials. Concrete and other construction materials may alter soil composition, acidity and electrical conductivity (due to dissolution of salts). Degradation of construction materials will also produce primary and secondary damage products that not only change the burial environment but interact with the material of archaeological interest itself (Sabbioni, 2002). The impacts of grout (this generic term includes bentonite and polymers used in construction processes to support pile walls or as ground improvement) is not well understood archaeologically. There are anecdotes concerning escaped grout appearing in archaeological sites such as the grout-filled skull and the collection of Bellarmine bottles filled with grout found under London Bridge railway station (Nixon, 1996). Grout can prevent the excavation of artefacts and restrict the amount of information available (e.g. bones covered in grout cannot be completely examined). Little is known about the chemical influence of these construction materials nor of how to quantify the extent of grout migration into archaeological deposits, and so further work is required, particularly where *in situ* preservation is a goal.

4.2.3 Compression

The effects of sediment compression via loading are poorly understood by archaeologists and difficult to measure. Archaeological deposits can contain remains which are incompressible and also voids which can form part of structures (e.g. drains, graves and hypocaust floors). The voids are prone to collapse under increased load (Shiltston, 1996). Furthermore, glass, ceramics and bone are fairly fragile and may be damaged under construction loads. Edwards (1996) also raised concerns over the impact of compression on metal artefacts. Loading may also squeeze moisture out of deposits. Shilston and Fletcher (1996) applied a 2-dimensional geotechnical model to different deposits and suggested that the surrounding accumulations control the ability of a particular deposit to be compressed. Hence it is again necessary to think about deposits outside the immediate building zone. Figure 3 shows the pressure distribution and settlement resulting from loading provided by a strip footing on a homogeneous soil. Given the nature of pressure shown, which may cause damage across and down to large areas, it may be beneficial to use raft footings for foundation support as these spread the load more. Calculating the pressure helps decisions to be made about whether to spread the compression (and archaeological damage) or confine it to a smaller area over which it will be more severe.

An archaeological deposit, or even an individual artefact can be considered as part of a geological or engineering deposit. The probability of a certain amount of damage will depend on a range of testable parameters. These values can be measured in the laboratory and can also be modelled. Adding real (or fake) artefacts to some compression experiments would help us obtain statistically robust data concerning the probability of damage survival. Some work is currently underway to assess the thresholds at which a range of sediment types and artefact class combinations deform, fail or are obliterated (Sidell *et al*., 2001), but there is a great need for more geotechnical data from archaeological deposits subject to laboratory and field testing.

4.2.4 Vibration

Intense levels of vibration during construction can distort sediment and damage artefacts, particularly if in a granular deposit. Most evidence is anecdotal, but suggests that vibration associated with vibro-compaction or vibro-replacement ground improvement can effectively cause ‘liquefaction’ of sediment, effectively destroying all archaeological integrity of a site. Research is urgently needed to identify the level of archaeological damage caused by different types of vibration associated with piling, tracking plant across sites, proximity to roads and so on.

4.2.5 Changes to vertical and lateral flow

An added dimension is the influence of artificial barriers to flow in the shallow deposit system. Insertion of piling, or digging of trenches and basements can alter not only the vertical flow of water but also the lateral flow. An urban environment is characterised by either underground constructions, such as basement car parking, or archaeological legacies of historic constructions. In York, for example, Roman walls at some distance beneath the surface may alter local flow between and within deposits. Such barriers may actually create conditions conducive to preservation by creating waterlogged zones. However, a new barrier to flow may cause some areas to get wetter and others to become drier (Figure 4). This is an important but often overlooked aspect of archaeological risk. Altering the subsurface flowpaths can result in changes to the hydrological status of a deposit at quite some distance away. Hence it may be that a new building development affects archaeological deposits many hundreds of metres away if the original flowpath to that point has been interrupted. Risk mapping will need to take account of such processes, but this will be aided by appropriate geoarchaeological deposit maps. Additionally, urban development may alter vertical and lateral flow of water not only through changes in infiltration, and subsurface flow redirection, but also through leakage from sewers and water supply pipes (see below).

4.2.6 Archaeology-engineering interface

Destruction of organic archaeological deposits through engineering methods has not been helped by a lack of dialogue between archaeologists and engineers. Sometimes if unexpected archaeological remains have been uncovered on construction sites, construction operations have been accelerated for fear of delays incurred while the archaeology was investigated (Tilly, 1996). Archaeologists are often faced with trying to explain the importance of sediments that seem of little interest to engineers and developers, and face resistance when discoveries are made after design, since implementing changes causes costly delays. In an urban circumstance, the development pressure is more severe since the cost of land is greater. Since the 1980s there have been positive moves to develop a greater mutual understanding. Increasing the degree of communication between different groups involved and better incorporation of archaeology in the design planning stage can allow successful mitigation of damage. The key to reducing this risk is to have sufficient information on hand to inform the design of the proposed structure and subsequent planning decisions (Oxley, 2002).

4.3 Urban water cycles

The nature of site hydrology is fundamental for the maintenance of anoxic conditions which facilitate preservation of archaeological remains. Construction-hydrology process interactions are the primary controls on changes to anoxic burial sites in an urban context. In order to assess the impact of changing groundwater and hydrological conditions it is important to first have an understanding of the nature of hydrological interactions. Shallow groundwater flow can be complicated within an urban environment. Site stratigraphy may result in discrete hydrological and redox conditions within different layers (for example coarse and finer grained alluvium). Shallow groundwater flows are also dependant on the characteristics of the ground surface, which controls effective rainfall recharge and runoff, and the distribution of surface water bodies. However, in urban environments the groundwater system may become disconnected from the ground surface. Rain water may be transported directly to streams, or out of the system by stormwater drainage systems, passing the groundwater zone. Furthermore, the primary source of shallow groundwater may change (e.g. from rainfall to leaking water mains and sewer pipes) leading to variations in saturation and redox state as a result of urbanisation. The nature of inputs to, flow pathways within, and outputs from shallow groundwater in an urban environment is illustrated schematically in Figure 5.

In trying to characterise a groundwater system, a hydrogeologist will start with a water budget approach (Brassington, 1998). This represents a useful way of evaluating the inputs and outputs of water and rough estimates of changes in storage through alterations in water levels (Price, 2002). Changes to the quantity of groundwater in storage and flow occur whenever discharge and recharge are unequal. In the long term, systems tend towards a steady state where recharge equals discharge, but perturbations to the system (for example due to construction) may change one or both variables, with resulting changes in saturation, redox and flow pathways. Water budget calculations thus require estimates of the inflow and outflow quantities illustrated in Figure 5.

4.3.1 Recharge sources

Groundwater recharge rates from precipitation are generally estimated from meteorological data and information on land surface type and gradient, but estimation is complicated by the spatial and temporal variability of surface and meteorological conditions; these complications are especially acute in urban areas. Impermeable surfaces (formed by buildings, roads and car parks) and channel precipitation into stormwater systems, reduce recharge and potentially lower the water table (Brassington, 1998). Soakaways and other infiltration devices also dispose of runoff and bypass the soil (Lerner, 2003). While it might be thought that urbanisation would tend to reduce groundwater recharge, in many areas (such as eastern and southern England where precipitation is 500 – 800 mm per year) the urban recharge is about the same as in the surrounding rural areas (Lerner, 2003). This is because recharge reductions due to impermeable surfaces are compensated for by recharge from leaking water systems. In areas of greater precipitation, however, it is likely that urban recharge will be lower than rural recharge. A reduction in any recharge source may cause a localised or a more generic reduction in the water table depending on the time scale of impact and the nature of the deposits.

The extensive network of water mains and sewers in urban zones provides a source of groundwater recharge. The leakage occurs at particular points on the system, but the large number of points can combine to have an important effect (Lerner, 2003). Water supply in the UK is typically 600 mm per year to a major city, and leakage rates have been found to add another 200 mm for some urban areas (Lerner and Yang, 2000). Even a relatively efficient mains water system will result in large quantities of water input into the groundwater; most urban water supply systems are based on a 15 % minimal acceptable leakage of overall water piped through the system. Below this level it is not economical to repair supply lines. Inputs to groundwater from the public supply also includes used water which is openly discarded such as watering of gardens, washing of outdoor facilities such as cars and driveways, or industrial machinery and construction sites. Additionally there can be spillages and leaks from industrial lagoons and tanks. Inputs from natural rivers and lakes can also be very important; these are discussed in section 4.3.4 below.

4.3.2 Discharges

If not balanced by recharge, outputs of groundwater will cause a lowering of the water table.. Abstraction from boreholes for either domestic or industrial use results in a loss of water from the groundwater system. Evapotranspiration from deep-rooted plants, or in areas of shallow groundwater, are also significant outflows, particularly during summer; there are often natural daily variations of evaporation rates that cause marked diurnal fluctuations of groundwater levels in such areas (Evans *et al.*, 1999). Loss of groundwater to surface streams or directly to the ocean may also represent an important component of the water budget (see section 4.3.4. below).

4.3.3 Flow within and between formations

Flow between the deposits and the ground surface depends on the surface characteristics and the hydraulic head within the deposit. A low permeability surface or geological confining layer may impede infiltration and evaporation, effectively disconnecting the aquifer unit from the surface (Welsh and Thomas, 1996). However, confined deposits may be brought in contact with the surface. Breaching of the overlying strata may be caused by construction activities for example. The sensitivity of the archaeological preservation environment to such disturbances is strongly dependent on the geological properties of surrounding deposits. A deposit lying close to high permeability strata will be highly sensitive to conditions within that formation (Welsh and Thomas, 1996). Conversely, if deposits of interest are surrounded by low permeability sediments these will effectively buffer the internal deposits from outside flow conditions. .

4.3.4 Groundwater-river water interactions

One important interaction that is often ignored in archaeological investigations concerns that between rivers and groundwater (Lamontagne *et al.*, 2003; Ellis *et al.,* 2003). On a simple level, rivers can either lose water to the surrounding areas or gain water (Figure 6). The direction of these flows depends on the difference between the stream stage level and the groundwater level (Price, 2002). During a flood period, increased stream stage induces infiltration of stream water into the aquifer; subsequent declines in stream stage cause a reverse motion of infiltrated water (Chen and Chen, 2003). These exchange processes have important implications on the water chemistry, since the alluvial aquifer is likely to display more reducing conditions than the stream itself (Lamontagne *et al.,* 2003). The interaction between groundwater and stream water during floods will be dependent on the geology and the topographic characteristics of the site (e.g. narrow V-shaped valley versus well developed floodplain) and includes both vertical diffuse recharge and bank recharge (Lamontagne *et al.,* 2003; Jolly *et al*., 1998). Piezometric monitoring is useful to help characterise groundwater–surface water dynamics during flood pulses (Burt *et al.* 1999; 2002). An increasing body of literature exists on methods of measuring exchange between streams and aquifers (e.g. Jones and Mulholland, 2003). Hydrograph separation techniques where river water is sampled for environmental tracers can be a useful tool to determine contributions from different sources at stages during a flood event and to calibrate numerical models (e.g. Kendall and McDonnell 1998; Cook and Herczeg, 1999).

Any changes in upstream management or climate may influence river levels in urban areas and therefore the groundwater-stream water interactions. Downstream management (such as the installation of tidal barriers) may also impact upstream processes. These management practices may not only influence the river water levels and their fluctuations but also the river water chemistry. In Bergen, Norway, for example, it has been shown that wood that is submerged in salt water may become resistant to microbial colonisation (Oyen et al., 2004). A reduction in salt concentrations (e.g. caused by a downstream tidal barrier) in local river waters may therefore alter the riverine preservation environment. At the same time, river bank flood piling is becoming more common in urban zones. This piling may reduce connectivity between the rivers and the local groundwater. Little is known about how riverbank piling influences the patterns of groundwater saturation or water chemistry in archaeological environments. Riverbank construction may reduce water flow from a river into the surrounding sediment during normal flow regimes. Indeed in some environments, todal barriers have not only altered the nature Given the importance of riverine zones for organic preservation of archaeology further work is urgently required**.**

4.4 Urban projects

Despite the complexity of the urban hydrological system a number of studies have attempted to define the urban water budget for practical purposes. These purposes include the renewed interest in the resource potential of urban supplies, contaminant hydrological investigation (e.g. horizontal and vertical plumes of hydrocarbons or nitrate pollution caused by sewage leaks) and problems of basement flooding, tunnel flooding and geotechnical engineering difficulties caused by high water tables. However, in terms of archaeological preservation only the Rose and Globe Theatres (London), the Marks and Spencer's Monitoring Project (York) and the EU Bergen (Norway) waterfront project represent *urban* monitoring programmes. These are highly cited examples; however, they are actually very basic investigations and lack the necessary detail required for understanding of hydrological processes operating at each site.

4.4.1 Rose and Globe Theatres in London

The Rose and Globe Theatres are famous 17th century playhouses. The investigations at these nearby sites located on the Thames floodplain represents the first example of a major hydrological monitoring programme in a complex urban environment. Following excavation in the late 1980s, prior to new building development, reburial and preservation *in situ* was planned. The presence of the archaeology had a substantial impact on the construction methodology and timetable (Corfield, 2004). The need to confirm that the hydrology and water chemistry remained in a state that would ensure the survival of the archaeological deposits demanded on-going monitoring of the burial conditions. Experiments were therefore set up at the Rose Theatre (English Heritage) and the Globe Theatre (Museum of London) to monitor the evolving soil environment (Caple, 1994a). The Globe Theatre monitoring sensors detected a significant change in moisture content and bacterial activity, while at the nearby Rose Theatre, site anoxia appears to have been maintained and adjacent structures are still well preserved. Caple (1994a) suggested that different sediment types were a factor resulting in such different responses between nearby sites. In other words the preservation conditions around each site seem to have been affected greatly by the precise sedimentary conditions, particularly the subsurface sediment architecture around each site. Therefore it should not be assumed that nearby or topographically similar environments will produce the same results. At the same time the Globe Theatre is also a case where hydrological monitoring has detected that *in situ* preservation is probably not being maintained and yet very little has been done about it.

4.4.2 Parliament Street, York

In November 1994 an archaeological evaluation was conducted during the redevelopment and expansion of a shop at 44/45 Parliament Street, York. A large void was discovered between an old concrete floor. There were also smaller voids within the underlying deposits and these voids had become filled with a calcium sulphate efflorescence precipitate.. It was presumed that dewatering had resulted in shrinkage of the organic-rich underlying deposits. The crystalline deposits are suggested to have resulted from water-laden with calcium (from a slab of poor concrete) interacting with dewatering sulphide-rich deposits which had until recently been anoxic (Kenward and Hall, 2000). In addition, the plant and insect remains of the archaeological layers displayed an unusual brown colouration that suggested post-depositional decay, especially since it was uniformly observed throughout 2 m of varied stratigraphy. Plant and insect remains were substantially less well preserved than in similar deposits excavated at nearby sites in earlier decades (e.g. at 6-8 Pavement, 16-22 Coppergate and a site in The Bedern, Hall *et al.*, 1993; Hall *et al.* 1983). A hydrological monitoring programme was carried out between June 1995 and April 1998; data from 30 visits was collected and presented in a report by Davis *et al* (2002). Data were collected using an electrical dip-meter (water level), a neutron probe (moisture content), portable dip-probes (water quality) and moisture cells (moisture content and deposit temperature). The water table and moisture content was found to be stable and there were very few fluctuations in the dataset. This appeared to be due to impedance by the relatively impermeable clay deposits underlying the highly organic archaeological remains. There were, however, seasonal fluctuations in water quality at the site with higher redox potential in autumn and winter and lower values in summer (Davis *et al.*, 2002). While these data provide baseline information for future studies, this investigation clearly suffered from having no data on conditions prior to building work. It is not known what hydrological changes had taken place at the site before and during construction nor how (or whether) these changes drove decomposition of the remains. The York Parliament Street monitoring project was conceived as a reactive response to an apparent decay and subsidence of organic matter. There is a real need for a project that monitors the hydrological conditions and preservation status of archaeological remains on a site before, during and after an urban development project, and across a wider distance beyond the archaeological site itself. Such work is planned in York, where there is to be a large building development on the Hungate archaeological site in the city.

4.4.3 Bergen, Norway

A three-pronged approach has been proposed for understanding the deterioration of deposits in Bergen (Matthiesen, 2004). This approach involves i) measuring the state of preservation of artefacts at different time intervals; ii) measuring experimental parameters (e.g. water table) and iii) burying test materials and studying how fast they decompose. Work began in 2002 to place test materials into different layers of the archaeological deposits in Bergen. These will be re-excavated and tested for decay. At the same time water samples were taken at monthly intervals from two dipwells at the site for chemical analysis. Results indicated that chemical applications of road salt during the winter are entering the sediments. Apart from this the two dipwells showed fairly stable conditions of a pH neutral, reducing, nutrient rich environment. While this may seem good, the high salt and nutrient content means that if the conditions were to become more oxidising then the environment would be very aggressive in terms of decay (Matthiesen, 2004).

4.4.4 Other studies

The urban hydrology studies described above were small-scale site-specific projects where drying out of the urban archaeology was an issue. However, this paper has demonstrated the need to evaluate the wider hydrological context of archaeological sites and also that changes in flowpaths and increased waterlogging can also cause archaeological loss and related problems. A number of ground collapses over 13th century basements (important historical monuments) connected by tunnels in Oppenheim, Germany, have been investigated (Cesano and Oloffson, 1997). Analysis of water chemistry from groundwater observation wells, the River Rhine, water in the cellars, surface water, and samples from screened wells surrounding Oppenheim suggested that leakage from underground drainage pipes was causing enhanced subsurface flow. Leakage from the urban sewage system led to water penetration into the 13th century cellar systems resulting in subsurface erosion and the creation of cavities and caverns that caused structural subsidence problems for buildings on the surface. Hence the problem was not one related to large changes in water volumes. Rather the problem was caused by changes to the routing of water along preferential flow pathways.

The recent rise in groundwater conditions has threatened the antiquities of the West Bank of the Nile around Cairo. The geology of the city of Cairo, is complicated by centuries of accumulated anthropogenic fill. The bed of decayed buildings interspersed with silt and clay from the Nile floodplain reaches 20 m deep. The hydrogeology was found to be very complex with individual soil layers within a complex stratigraphy only laterally persistent over a few metres. Groundwater levels were encountered at very deep levels in some borings at one site whereas another within the same site showed water at the surface. This demonstrates the clear need to ensure that groundwater measurements are keyed into appropriate fine scale geological deposit maps. For archaeological purposes, any boreholes we wish to sample must be made with reference to a geological model of the shallow deposits. In summary the Cairo monitoring showed that additional water table recharge was due to i) seepage from the irrigation channel network, ii) infiltration of surplus irrigation water, iii) leakage from the sewer network embedded in the strata, iv) losses from potable water supply network, and v) local upward flux from the aquifer. Overuse (above design capacity) of the water supply and sewerage system has lead to severe leakage. Harmful effects have been observed on a number of outstanding architectural and historic antiquities including the foundations and masonry of the Qalawun Complex (1284-1285 A.D., Balhri Mamluk period) and the surrounding soil geotechnical properties have been affected too.

While much of this paper has focussed on the need to maintain waterlogging to encourage archaeological preservation the examples of Cairo and Oppenheim demonstrate that this is not always the case. Rather, it is the alteration of subsurface hydrology and the interlinked chemical properties from the status under which preservation was originally maintained, that is the key. In order to assess risk of degradation it is necessary to determine what magnitude of change an archaeological deposit may be able to withstand.

5. Monitoring and modelling needs

The complexity of the anoxic burial environment has led Caple (1994a) to argue the need for better monitoring of the chemical balance of deposits. This, he argued, was the key to establishing whether anoxic conditions are being maintained. However, Pollard (1995) argued that because it was not possible to monitor all sites, it was important to develop modelling approaches. French (2004) suggested that each threatened landscape should be associated with both hydrological monitoring schemes, and the application of hydrological and groundwater models such as those used by Welch and Thomas (1996) at Cricklade Road, Gloucester, UK, and Van de Noort *et al.* (2001) and Chapman and Cheetham (2002) at Sutton Common, South Yorkshire, UK. However, Caple (1994a) felt that the relationships were too dynamic and too poorly understood to be able to adequately modelled. We suggest that there is a role for modelling as a tool for investigating processes, rather than for making hard predictions about hydraulic head and other parameters as is done in resource studies (e.g. Weiler and McDonnell, 2004). Models can be used in order to test linkages between process components, or the sensitivity of certain parameters to perturbations to the system.

5.1 Monitoring

In situ monitoring for archaeological purposes is a very young discipline, with only a handful of current projects. Hydrological and chemical data are required as well as data about preservation status and shallow and deep geology. A number of carefully chosen and well-designed intensive urban monitoring programmes (monitoring over space and time) coupled with laboratory and modelling analysis are required. These would have a significant ability to increase our understanding of the behaviour of the preservation environment and how it responds to change. However, Caple (1994b) noted that there were a range of inherent difficulties in designing and interpreting measurements from such environments including:

1. The problems with accurately analysing these environments without upsetting the chemical, biological and physical balances which maintain them (e.g. accurate pH determination within an anoxic deposit without disturbing the CO_2 and NH_3 equilibria).
2. Selecting the scale on which sampling should occur; there will be variations at many levels (e.g. site-wide macro changes in geology and water sources, interfaces between deposits, zonation around objects).
3. Determining the history of the deposit and the rate of decay at the start of the monitoring programme (e.g. decay state may have resulted from the occurrence of very dry periods in the past, rather than gradual decay in waterlogged conditions).
4. Selecting the characteristics to monitor: pH, Eh, and dissolved oxygen have been emphasised. However, other parameters such as pressure and conductivity may also be useful, as well as analyses for selective redox-determining species.

There is a shortage of consistent recordings of the anoxic preservation environment. While considerable resources may be required for major monitoring programmes, advantage could be taken of opportunities that arise from development work. For example, during the Jubilee Line underground extension in London, Sidell *et al.* (2001) undertook a geoarchaeological analysis of the deposits that were unearthed during shaft construction. Monitoring of preservation conditions could also have been incorporated into such a study had resources been available. A bank of data could be generated during standard site investigations by emphasising the necessity for characterisation of site conditions and comparison with the preservation of archaeological remains (e.g. recording the decay status of insect remains). This bank of data would help confirm the nature of relationships between key environmental variables and preservation, and will help develop a clearer process understanding. Work is required to publicise the significance of defining and monitoring the burial environment that maintains the archaeological resource.

In addition to monitoring programmes there is a need for further laboratory-based analogue studies of the effect of changes in the chemical, biological and physical aspects of the burial environment on the preservation of archaeological artefacts and ecofacts. The characteristics of anoxic archaeological burial environments are controlled by a range of interlinked factors. However, the studies that have been carried out rely on the use of indicators of the environmental conditions as a proxy with which to infer the level of preservation. There is a lack of real process understanding. This hampers implementation of more effective management of site conditions in order to maximise preservation. There is a danger that people may monitor changes in ‘prime’ parameters without due consideration of the site and process interactions. That is to say that the monitoring of changes in given ‘indicators’ is only useful if there is some idea of the meaning of these changes. For instance, we do not really know what a 1 % change in redox potential mean in terms of future decay.

We need clearer methods of assessing the degree to which archaeological burial sites can withstand changing hydrological conditions. Davis (1996) argued that a major justification for the increased emphasis on hydrological *monitoring* of ‘wet’ archaeological remains that are under threat, is the fact that excavation is often not appropriate. Monitoring can therefore form an important part of the management strategy at the same time as increasing the knowledge base while also being useful to assess the success of a particular protection scheme. Too often, however, monitoring is not adopted because it is seen as costly and unnecessary. The problem is not helped by those cases such as the Globe Theatre where monitoring has identified a problem and yet nothing has been done about potential archaeological loss.

5.2 Modelling

5.2.1 Model utility and coupling

Models can be used to help us understand hydro-archaeological systems, identify which parameters and stresses are most important, and predict impacts of landscape or climate change (Holden, 2005). In the past few decades, dramatic improvements in computer hardware (notably in storage capacity, processing speed, and graphic handling ability), and software (GIS, database, programming environments), have led to the development of more sophisticated hydrological codes capable of solving increasingly complex problems. At the simplest level models of hydrological processes are assumed to be steady-state, such that input and output are equal. The time dimension is not considered explicitly; average values for water levels, for example, over the simulation period are used. This type of model is useful for identifying the relative magnitudes of the input and outputs and the main subsurface flow pathways. However, such models can also be used to make predictions about the effects of changing the stresses (e.g. recharge rates, pumping rates, river levels) on the system; what is not predicted is the timescale over which these changes will take effect. At the next level of complexity, transient model codes treat the time dimension explicitly such that changes in water levels and hence changes in the amount of water stored are simulated. The explicit modelling of the time dimension allows seasonal fluctuations in water levels, for example, to be modelled, or they can be used to provide information on the timescale of impacts due to climate or land-use change. However, such models require much more data in order to be calibrated properly; monthly water level measurements and recharge estimates are required to model seasonal fluctuations. The production and calibration of a steady state model is usually appropriate before a transient model is used; the water levels produced by the steady state model are then used as the starting point for the transient simulation (Anderson and Woessner, 1992).

Groundwater and surface water flow modelling have historically developed as two separate disciplines. Groundwater flow models do not explicitly model surface water flows; surface water bodies are typically simulated as boundary conditions (i.e. specified head boundaries). Similarly, surface water flow models do not explicitly model subsurface flows. Surface water flow models commonly lack rigour in the physical treatment of flow processes seen in groundwater flow models; groundwater models on the other hand typically ignore dynamics of overland and stream flow processes. More recently, attempts have been made to develop coupled ground and surface water flow models, especially for large scale catchment studies (e.g. Henriksen *et al*, 2003). Integration of ground and surface water flows is done in either tightly or loosely coupled manners. Tightly coupled models simulate different hydrological processes using one integrated set of computational procedures (one source code). However, few large tightly coupled models are developed since they are rather inflexible for problems other than those for which they were originally generated. Loosely coupled models describe different hydrological processes in separate source codes with communication facilitated by a data server (Ryan and Sieh, 1993). Surface water movement is first calculated followed by the groundwater flow, which uses values produced by the surface water model.

Coupling of ground and surface water flow models needs to consider the huge differences in spatial and temporal scales of the hydrological processes between systems. It is often suggested that the area of interest should be split into several sub-areas; each of these sub-areas will have its own spatial grid and time step related to the scales of the underlying hydrological processes. For example, timescales of groundwater and surface water flow often differ by a few orders of magnitude and it is generally not feasible, due to constraints on computing time, to study the groundwater flow with the same time step as is used for surface water flow. Hence, linking the different sub-domains involves averaging variables in time and space (Haadsma and Johanns, 1998). The use of an integrated surface water - groundwater model might not be appropriate in many archaeological projects; in many cases development of separate but parameter-linked ground and surface water flow models may be more appropriate.

5.2.2 Urban hydrology models

Urban hydrology models can involve a very different approach from classic groundwater and catchment models. In an urban context the hydraulic characteristics of the drainage system is more important than the hydrological characteristics of the whole basin. This has given rise to a remarkable growth of complex hydraulic models for urban drainage design in the past few decades. Hydraulic models for surface runoff and flooded surfaces, and sewer flow have been established (Herath, 2001). However, the various anthropogenic and natural systems (e.g. natural rivers and aquifers) that are connected to urban drainage systems have yet not been integrated in these models.

For successful application of distributed hydrological models in urban catchments a good spatial description of elevation, land cover, soil data and geology is required. For model validation and calibration hydrological variables such as rainfall, runoff, and water levels must be recorded. However, urban hydrological modelling faces challenging problems since data are very sparse, due to monitoring difficulties. Even the simpler task of evaluation of the urban water budget requires many direct and indirect estimation techniques.

5.2.3 Existing numerical modelling packages

A number of numerical modelling packages are available; the modelling package that is most appropriate will depend on project objectives, data quality and quantity, the nature of the site conceptual model, project constraints. MODFLOW, originally developed by the United States Geological Survey, is probably the most commonly used standard groundwater modelling programme in the world. The original code for MODFLOW is a relatively simple, 3D cell centred, finite difference saturated groundwater flow model. The orginal MODFLOW did not model flow in the unsaturated zone and the nature of the surface water-groundwater interactions were relatively simple. However, MODFLOW has developed in recent years and new versions hold a range of more sophisticated abilities (nonetheless the basic code remains the same). Features include: complete desaturation and resaturation of grid cells, delineation and tracking of water table position (taking into account flow in the unsaturated zone, delayed yield, and vertical flow components), automatic redistribution of the total flow rate of a well screened through multiple model layers due to dewatering, prevention of water table build up beyond a specified recharge-ponding elevation, handling of seepage face boundary conditions, and capabilities of modelling unsaturated water or air movement. Most other groundwater modelling packages are based on MODFLOW but incorporate a greater number of modules. The advantage of its very large number of users is that most of the errors in the code have been discovered. MODFLOW works alongside sub-modules which facilitate various hydrological calculations based on the cell-by-cell flows it produces. These modules include MODPATH, which permits forward and backward particle tracking, in order to identify the routes taken by chemical species carried by the groundwater. Other modules such as ZONEBUDGET uses the cell-by-cell flow results created by MODFLOW to construct the water budgets of individual zones (Harbaugh, 1990). Various software packages have been developed that incorporate different module codes with a user interface that allow MODFLOW to be easily applied (e.g. Groundwater Vistas, Environmental Simulations Ltd., Shrewsbury, UK).

There are a limited number of widely used groundwater models that are not based on MODFLOW, such as NAMMU (developed at the Harwell institute of the UK Atomic Energy Authority). NAMMU has gained some popularity and is a finite-element software package for modelling groundwater flow and transport in porous media, capable of modelling saturated and unsaturated conditions. The physically-based, distributed, integrated hydrological and water quality modelling system developed by the Danish Hydraulic Institute (DHI), the British Institute of Hydrology, and the French consulting company SOGREAH, known as MIKE SHE simulates the hydrological cycle including evapotranspiration, overland flow, channel flow, soil water and ground water movement. This system is able to simulate surface and ground water movement and the interactions between the surface water and ground water systems (e.g. see Henriksen *et al.*, 2003). Some of the applications of the software include surface water impact from groundwater withdrawal, conjunctive use of groundwater and surface water, wetland management and restoration, aquifer vulnerability mapping with dynamic recharge and surface water boundaries, groundwater management, impact studies for changes in land use and climate and impact studies of agricultural practices including irrigation and drainage. This model is rapidly growing in use within the sectors of water management and environmental protection, and may be applicable to prediction of catchment-wide impacts on archaeological preservation potential within river basins.

5.2.4 Risk mapping

Archaeological managers are in desperate need of tools to help them with *in situ* preservation plans and risk assessment. They require models that will provide spatial data about which deposits are at risk and predict outcomes from environmental changes (including building development, climate, flood defence etc). Unfortunately, there have been few real attempts to map archaeological risk other than the report by Van de Noort (2001a), which was based on rural wetlands and that by Masgrau *et al.* (2002) which assessed risk from flooding using qualitative assessments. However, characterising the "intrinsic vulnerability" of archaeological remains preserved in anoxic conditions requires a much more integrated and quantitative approach. The spatial variation in the state of the anoxic environment and its vulnerability needs to be identified; the geological environment needs to be well-characterised so that a ground model of the site and its environs can be developed. Preferential flow pathways, perched water tables, zones of high hydraulic conductivity and areas most susceptible to groundwater fluctuations need to be identified using appropriate hydrological measurements. A spatial representation of these features would provide the basis of any further risk assessment. This sort of work would not only allow us to identify deposits at risk from schemes while incorporating spatial and geological context into the model, but also tell us which deposits are not at risk and thereby save developers money where archaeological expenditure is not required.

6. Conclusion

This paper has outlined our current knowledge base on *in situ* preservation from a hydrological perspective and pointed to a series of future research needs. We are still not in a position to suggest which archaeological sites would suffer minimal damage and which would be far more threatened by any given development. Clearly, we need a better understanding of how individual construction or land usage activities impact on specific types of archaeological deposits. It is usually not possible to piece together the dynamics of the groundwater system in urban areas from available archaeological site accounts; the piecemeal nature of hydro-archaeological data collection currently makes it impossible. Improvements in routine data collection from archaeological sites on soil and water parameters are needed. More intensive experimental monitoring schemes are also required. This will allow observations to be placed within their geographic and seasonal context, for processes to be understood in more detail and for model development to occur that will allow more generic risk mapping tools to be developed. Detailed data analysis and hydrological modelling to clarify the underlying processes at key sites would then be well-placed, and a cost-effective alternative to simply amassing more data and waiting for a greater number of examples to illustrate a trend. There is also a need for a structured programme of research to quantify decay in different soil and water environments on a range of key organic materials such as bone, pollen, plant macro-fossils, insects, wood and shell. This research should be linked to the types of information extracted from the archaeological materials so that we can know at what state of decay an organic material becomes useless for the purposes of specific archaeological analysis and interpretation. This will allow us to more adequately assess when sites can be preserved or need to be prioritised for excavation. In spite of the long history of study of archaeological burial environments, the scientific study of *in situ* preservation is in fact a relatively new one and is a discipline that will require significant scientific investment in the coming years. There will, however, be plenty of opportunities for archaeologists to work in collaboration with others in order to help develop the newly emerging field of *in situ* preservation archaeology.

Acknowledgements

This work was jointly funded by English Heritage (Project 3670 MAIN) and the UK Natural Environment Research Council (NER/E/S/2003/00712). The research was carried out while JH was in receipt of a Natural Environment Research Council Fellowship (NER/I/S/2001/00712). The support of City of York Council is also appreciated. The comments of two anonymous reviewers were also appreciated.

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Table 1. Key threats to wetland archaeology in England and Wales described by Van de Noort *et al,* (2001b)

Drainage	Arterial drainage systems and underdrainage for agricultural purposes results in accelerated runoff. Environment Agency data shows a general lowering of the groundwater table by 2-3 m in alluvial lowland landscapes of Yorkshire, East Midlands and the East of England, and between 1 and 2 m in the alluvial lowlands of the North West and South West of England. Virtually no lowland peatlands or alluvial lowlands remain completely free from the effects of drainage.
Water abstraction	This has caused significant lowering of groundwater tables, affecting the resource much the same as drainage. Archaeological needs are not considered in the allocation of abstraction licenses. Groundwater abstraction constitutes 30 % of the overall supply of public freshwater for England and Wales. Water abstraction is far greater in the South and East of England. The European Union's Water Framework Directive, requiring sustainability of surface and groundwater use by 2015, will provide opportunities to address this threat.
Conversion of pasture into arable land	As much as 165 000 ha of pasture land in England's wetlands may have been converted into arable land over the last 50 years. The majority of these areas lie in the alluvial lowlands and peatlands in the North West, Yorkshire, East Midlands, East of England and the alluvial lowlands of the South West.
Peat wastage	When peat humifies it becomes a structure-less dust-like substance that is easily blown away by wind (Holden and Burt, 2003). Peat wastage occurs as a result of drainage, desiccation, oxidation and increased micro-biological action.
Peat erosion in uplands	50 % of UK England and Wales upland wetlands can be described as degraded due to grazing and game (which involves moorland burning), and small-scale peat extraction.
Peat extraction	Peat extraction was widespread until the 1980s. In some places it is still ongoing, although there has been a considerable reduction in extraction licensing.
Urban/industrial expansion onto wetlands	From data available, the total loss of wetlands to urban and industrial land between 1950-2000 was around 5 % of the total wetland (55,000 ha).

Figure captions

Figure 1. Examples of the artificial ground classification scheme developed by the British Geological Survey and the potential for branching to provide detail (after Price *et al*., 2004)

Figure 2. Location of 'wet' and 'dry' archaeological sites in York, according the York Development and Archaeology database; a) for the whole of the City of York; b) for central York.

Figure 3. Typical contour bulbs beneath a strip footing; a) bulbs of pressure; b) settlement in a cohesive sediment.

Figure 4. A simple theoretical diagram of groundwater flow impeded by an inserted engineering structure. If lateral flow is impeded then both wetting or drying of different parts of the deposit may occur. Note that i) groundwater flow can sometimes occur in the opposite direction to surface topography depending on the deposits and ii) there will be more complex three-dimensional changes in flow direction related to obstacles.

Figure 5. Typical inputs and outputs from a groundwater system in urban areas.

Figure 6. Schematic diagram of river-groundwater interactions; a) a river losing water; b) a river gaining water and c) a river losing water with flood piling preventing connectivity. The situation for (c) could vary depending on the river flow and nature of piling. If the river is gaining water from the local ground then piling may reduce the amount of water provided and enhanced saturation behind the piling may occur. Flood defence will reduce the risk of surface inundation too which may influence the archaeological deposits.