Historic England

Preserving Archaeological Remains

Appendix 4 – Water Monitoring for Archaeological Sites

Summary

This document is part of a suite of documents about the preservation of archaeological sites. It is a technical appendix to the main text (Preserving archaeological remains: Decision-taking for sites under development) and should be read in conjunction with that document, and where appropriate, the range of planning policy guidance detailed therein.

This appendix covers monitoring on archaeological sites. It begins with a more detailed consideration of why monitoring is carried out, and explains, based on past monitoring experiences those situations where it is considered best practice to monitor, and those where it is not. Practical advice on how monitoring projects should be undertaken is given, including a specific section dealing with project management and quality assurance of monitoring data.

The remaining sections of the guidance deal with the tools and techniques used for monitoring. This includes water level, water quality (redox and pH in particular) and soil moisture monitoring. A final section lists suppliers.

Additional methodological detail and technical advice is provided in the following appendices:

Appendix 1 – Case studies
Appendix 2 – Preservation assessment techniques
Appendix 3 - Water environment assessment techniques
Appendix 5 – Materials for use in the reburial of sites

This guidance note has been prepared by Jim Williams (Historic England), Claire Howarth (Nott MacDonald), Ian Panter (York Archaeological Trust) and Glyn Davies (ArcHeritage).

Please refer to this document as:
Historic England 2016 Preserving archaeological remains. Appendix 4 - Water monitoring for archaeological sites. Swindon. Historic England.

First published by Historic England October 2016.

HistoricEngland.org.uk/advice/technical-advice/archaeological-science/preservation-in-situ/

Front cover:
Monitoring redox at Brooksby Quarry in a flow-through cell.

Contents

1 Why Monitor?

There are two main reasons why monitoring might be undertaken on archaeological sites.

- To provide data for water environment studies (including where these data assist in the long-term management of known waterlogged archaeological sites unaffected by development or land-use change).
- As part of a mitigation strategy, to demonstrate whether viable preservation conditions are present during or after development or land-use change.

As was set out in the main document, within the context of development schemes or other land-use change projects, it is good practice for monitoring to only be undertaken to demonstrate whether a mitigation scheme is working as proposed, and only in those circumstances where it is possible to manipulate groundwater levels, or access the site for excavation, if data indicate optimum preservation conditions are not being met. The reasons why this is recommended are considered below with reference to past monitoring schemes.

1.1 Learning from past monitoring experience

Since 1990, a number of monitoring projects have been set up on mitigation schemes where archaeological remains have been retained *in situ* within a development. In many cases, no clear strategy was developed to identify an appropriate course of action if the monitoring data suggested that degradation might be taking place. Although such data could be used to study future redevelopment impacts on the site or adjacent / similar sites, if groundwater levels cannot be changed, or it is not possible to excavate the site (because it is under a building), then the value of collecting this information in the first place is questionable.

Additionally, experience suggests that *ad hoc* 'research' monitoring projects tied into development schemes are rarely successful and do not tend to produce the information in a format that provides additional clarity about the impact of any below-ground changes. Money would be better spent elsewhere, on better initial preservation assessment and water environment studies, or on a specifically designed research project to test particular key questions relating to a particular aspect of groundwater monitoring.

Away from development and land-use change, monitoring has also been undertaken to study the burial environment of known wetland / waterlogged archaeological sites over time. The purpose of monitoring has been to check that stable environmental conditions are present, usually in response to concerns that agricultural drainage or climate change was causing the site to dry out. However, such monitoring has often been carried out before preservation assessments were carried out and the data collected have not always been fully understood because the wider water environment has not been investigated. The Fiskerton case study in Appendix 1 demonstrates what can happen when monitoring is installed ahead of a thorough evaluation and preservation assessment. Equally, at Flag Fen, a number of different monitoring campaigns had been carried out over a ten year period, but the data were only really understood when integrated into a water environment study (*see* Appendix 1).

1.2 When to monitor

To avoid the unnecessary collection of monitoring data, the following rationale for monitoring archaeological sites is suggested.

The situations in which site monitoring for development or land-use change projects is most beneficial are:

- To observe whether a mitigation strategy is effective (only appropriate for sites where there are clear alternative measures in place if monitoring results demonstrate deteriorating conditions).
- To verify that short-term changes resulting occurring during the actual development period (that is temporary dewatering) do not have lasting effects.

In situations where it is possible to develop appropriate mitigation strategies for use if monitoring data indicate that environmental conditions are deteriorating, the *in situ* retention of the site and its monitoring may provide a cheaper option for the developer than excavation. There is a risk here though, because if additional monitoring data and further mitigation measures are needed, then the final costs to the developer (of monitoring, mitigation and potentially excavation) may be higher than the initial cost of excavation would have been.

On such schemes, those managing the planning process, that is planning archaeologists, planners, etc, need to be sure that any future mitigation that might arise as a result of the monitoring is enforceable, and that funds will be available in the future, particularly if the building or site changes ownership. This issue is discussed in the Guy's Hospital boat case study (*see* Appendix 1), where a legal agreement has been drawn up.

There are several good examples of where monitoring has been used alongside a development-led mitigation scheme, such as that at Shardlow, Derbyshire (case study in Appendix 1). More often than not, these examples are in open locations, ie gravel quarries or are set up in response to changes to agricultural land management (such as wetland habitat creation schemes). If monitoring data suggest a site is at risk, then it may be possible to manipulate local water tables to raise levels or improve water quality. Where these measures fail, the ultimate mitigation response is to excavate the archaeological site.

It is much harder to excavate a site at risk if it is underneath a large development, although access for future excavation can be designed into the building. This was advocated as a possible solution in the York development and archaeology study (Ove Arup 1991), and is the case for the Rose Theatre (Corfield 2012). It is also a key element of the Guy's Hospital boat mitigation scheme.

It therefore follows that there are few occasions when monitoring might be advocated on development-led mitigation schemes in the future. These situations would occur if:

- there was a desire to preserve a significant site;
- the appropriate assessments of preservation and water availability had been carried out, and that these demonstrated good levels of preservation;
- **but** there was concern about aspects of the site's future water availability or soil moisture levels,
- **and** it was be possible to design-in mitigation measures to the development (including access to make changes to the water environment or in the worse-case, for excavation).

For waterlogged archaeological sites outside of the development process or other programmes of land-use change, it is best practice for monitoring data to only be collected within a defined water environment study and once appropriate evaluation and assessment of the state of preservation of the site and its constituent parts has been carried out.

1.3 When monitoring is not recommended

Where preservation assessments and water environment studies have indicated that archaeological remains are well preserved, there is sufficient water available and development impacts are not assessed as harmful to this situation, monitoring would not normally be deemed necessary. Although there is a natural human reaction to want to check these prior assumptions, if the risk of impact is low, monitoring places an unnecessary and unreasonable additional burden on the developer.

Conversely, where there is a concern about water availability (or the risks of harm from construction are too high or unquantifiable), and no mitigation strategy exists to improve this situation, continued preservation and retention of the site within the development is not recommended. The site should either be excavated or not developed. There is little social or scientific value in monitoring a site if there is no option for doing anything, if the results indicate that environmental conditions are deteriorating and decay may be taking place.

1.4 Practical issues associated with monitoring projects

When monitoring is carried out it needs to be well planned, to an agreed set of objectives. If the goals of the monitoring work are not well thought out beforehand, the end result is often expensive schemes with unnecessary and unusable data.

There are several essential elements needed for a successful monitoring project:

- It is best practice for monitoring to have a fixed duration – it is impractical to monitor forever as a site will either be stable or it will be deteriorating and need some form of intervention.
    - Continued monitoring of stable sites once development or a land-use change has taken place and the burial environment has reached equilibrium is not best practice.
- There should be clarity about the purpose of the monitoring and its outcome. This should include optimum data ranges and trigger levels to identify when significant changes occur.
- Where significant changes are recorded, an appropriate first response might be to increase the frequency of monitoring and reviews, and bring in additional specialists, to ensure the situation is fully understood.
- Mitigation measures must be enforceable and financially viable (*see* Guy's boat case study).
- For any mitigation to be enforceable, observed changes in monitoring data which can be linked to the development are likely to be those that occur during, and in the immediate years following construction.
- It is unreasonable to place an open-ended commitment on the developer / owner for monitoring and/or mitigation which result from future climate changes or adjacent development.
- However, it is advisable to ensure that access for monitoring (assuming the equipment still functions) and potential future mitigation excavation is maintained if potential risks are identified at a later date.

- It is best practice for there to be a clear management structure outlined in the project design, with identified methods of data collection, data assurance and data management, including archiving.

- Water monitoring data, and in particular redox data, shows broad trends. These data should be viewed over time, in combination with other variables, such as pH and water level, to gain a general picture of whether the site or particular deposits are oxidising or reducing and whether these conditions are improving, stable or deteriorating.

- Data from any one monitoring visit should be treated with caution as the occasional inexplicably high or low figure, or outlier which doesn't match the rest of the data, should be expected. These occur on most monitoring projects and can be largely ignored; it is the general pattern that is important.

- Monitoring is not a fast process. It takes time to build up an understanding of water levels and quality on a site. This is why monitoring is not an effective method of deposit characterisation and why preservation assessment of artefacts and the deposits they are found within, and detailed water environment studies are recommended before any site-based monitoring is initiated.

1.5 Project management for monitoring projects

When a monitoring project is initiated it should be clear who will collect the data, and who has the responsibility for paying for the monitoring and making sure the data are collected. It is also important to set up some method of data assurance and review, particularly when data are collected by external contractors with little knowledge of the site or its archaeological significance. Finally, to ensure that data are available for future use and intra and inter-site comparison, consideration needs to be given to proper documentation of the work and archiving of the results with the relevant Local Authority Historic Environment Record (HER). Most monitoring projects that fail lack some or all of these elements (Williams 2012).

The best way to ensure a monitoring project goes smoothly and is properly documented is to produce a project design (for example Historic England 2015). This detailed plan should set out the following key points:

- Why you are monitoring
- Where you are monitoring
- What parameters you are going to monitor
- What the optimum data ranges and trigger levels are
- What mitigation measures are in place and how are they activated if trigger levels are breached
- Types of equipment and details of suppliers (for repairs / re-supply)
- Frequency of monitoring and review; duration of monitoring
- What you are going to do with the data you collect, including data storage and archiving.

The project design should also include information already assembled about the site (nature, significance and state of preservation of archaeological remains, water environment conceptual model) as well as details of available mitigation options if monitoring data breach agreed trigger levels. These levels need to be based on conditions on the ground, but for most sites, the optimum conditions given in the main document provide a good starting point.

The other key aspect of any monitoring project is that roles and responsibilities are clearly defined (and regularly updated if team members or site ownership changes). It is important to make sure that everyone on the project team (site owner / developer / consultant / local authority archaeologist / Inspector of Ancient Monuments / Science Advisor / monitoring contractor / hydrogeologist) takes an active part in data assurance / review meetings, and that it is clear who owns the project and is responsible for its ongoing success. Review meetings should take place on a regular basis to ensure that any changes can be quickly recognised and acted upon.

2 Water Monitoring Techniques

The following three sections cover techniques to monitor water level and quality, including:

- Water level
- Water quality – redox and pH in particular
- Soil moisture

The most critical variable to monitor is water level. If waterlogged / wetland archaeological sites remain sufficiently below the water table, year round, then oxygen will be excluded and conditions for preservation are likely to exist.

In terms of water quality the key variables to measure *in situ* are redox and pH. Additional parameters that are regularly recorded by water quality meters include temperate and electrical conductivity. Further chemical analysis of sampled water (that is *ex situ* in a laboratory) can be carried out to look at redox active species. These data can be compared with information collected at the site assessment phase, or used to investigate other changes seen in the water monitoring data. However, the experience of most monitoring projects conducted thus far in England is that the benefits of regular extensive water chemical analysis has yet to be demonstrated for all but the most complex of sites.

Finally, for those deposits that are above the water table but retain some degree of wetness (due to surface water infiltration and capillary rise), soil moisture monitoring may be needed to ensure that reducing conditions that have led to the site's survival are maintained. Soil moisture monitoring should always be initiated by measuring the porosity of the deposits, in order to be able to interpret the soil moisture monitoring results.

3 Monitoring Water Levels

Monitoring positions are known as boreholes, monitoring wells, dip wells and piezometers. Differences relate to construction and installation but their purpose is to measure groundwater through space and time.

Careful consideration should be given in the design stages in selecting the most appropriate type (or combination), and locations, to make the most effective use of budgets, together with operational considerations (for example staff availability / site security). Sharing data and incorporating third party networks (for example Environment Agency, private developer) can enhance the amount of field data available for a site and is to be encouraged wherever this is possible. This section is based primarily on information in Environment Agency (2003a and 2003b), and Brassington (2006).

3.1 Monitoring well – location selection and drilling practicalities

Boreholes for use on archaeological sites can be sunk in several ways, dependent upon the geology and site conditions:

- Hand / motor-driven augers – can be used to drill shallow boreholes (normally up to 3m) in stable, soft soils (for example clayey sands, silt or peat). Portable motor-driven augers are available that can reduce the time and physical effort of drilling compared to a hand auger.

- Cable-tool percussion (‘shell and auger’) – used to drill through relatively soft or granular soils. Drilling should always be undertaken by appropriately trained and experienced persons.

Where feasible monitoring boreholes should be placed on firm, dry ground. It makes installation and data gathering easier and reduces the risk of surface water leaking into the monitoring borehole (thereby giving misleading groundwater level readings).

Access must be considered, bearing in mind that materials to build the monitoring well will need to be transported and someone will need to make regular monitoring visits.

Figure 1
Installation of monitoring borehole at Fiskerton, Lincolnshire.

3.2 Monitoring well – design and installation

When designing a monitoring well consider where and how often you want to monitor and whether you want to collect samples.

Monitoring wells / piezometers vary in depths, diameters and installation materials. Some piezometers may be capable of being pushed into the ground, whilst others require borehole drilling prior to the installation of the monitoring pipework. The principal difference between monitoring wells and piezometers is that the latter are monitoring boreholes whose response zone represents only a small proportion of the total depth of the aquifer.

Table 1 provides an overview of various types for information, but broadly, monitoring boreholes fall into two main types:

- Dip well / monitoring well / 'standpipe' piezometer (Figure 2) – classic monitoring borehole (19mm, 50mm and 100mm common diameters) installed within a drilled borehole with a plain pipe and then a slotted (screen) across the 'response zone' of interest.

- A 'vibrating wire' piezometer tends be of a narrower diameter with a smaller response zone, enabling a larger number to be installed in a single borehole if required. They can be installed either with filter packs (separated by impermeable layers to prevent pressure bleed between units), or the whole borehole can be fully grouted (reducing the risk of pressure bleed between aquifer units).

Where it is important to measure different groundwater levels vertically at a particular location, it may be possible to install more than one pipe within the same borehole (Figure 3) provided an impermeable seal between the two filter packs (across the separating aquitard to prevent water leakage between layers through the borehole) can be ensured. Alternatively separate boreholes can be drilled (albeit to different depths).

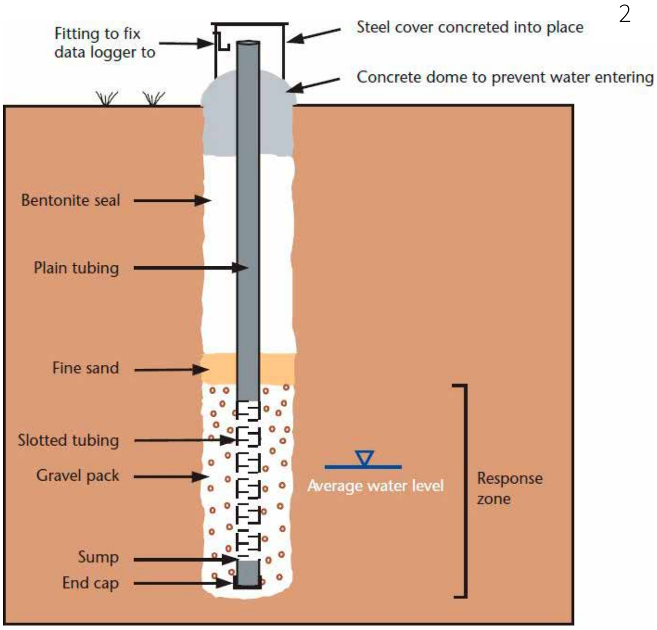
The depth of borehole will be dependent on the maximum depth of water table (if known as it may vary from season to season); the zone of interest within a particular aquifer / aquitard which most likely corresponds to the archaeological deposits being monitored ('the response zone'); and the number of monitoring pipes that will be installed in a single borehole.

Installation within a typical monitoring borehole (*as shown in* Figure 2) comprises:

Pipe - plastic pipe (uPVC or HDPE) placed in the drilled hole to prevent the sides collapsing. This is made up of:

- A slotted lower section ('the screen') of pipe that lies in the response zone to allow groundwater to flow freely into and out of the well.
- Non-slotted ('plain') pipe above the screen to surface to prevent groundwater from soils / higher aquifers or surface waters leaking into the well leading to misleading groundwater readings.
- It is good practice (where possible) to have a section of plain pipe, about 0.25-0.5m long below the screened section to act as a sump or sediment trap.

2



3

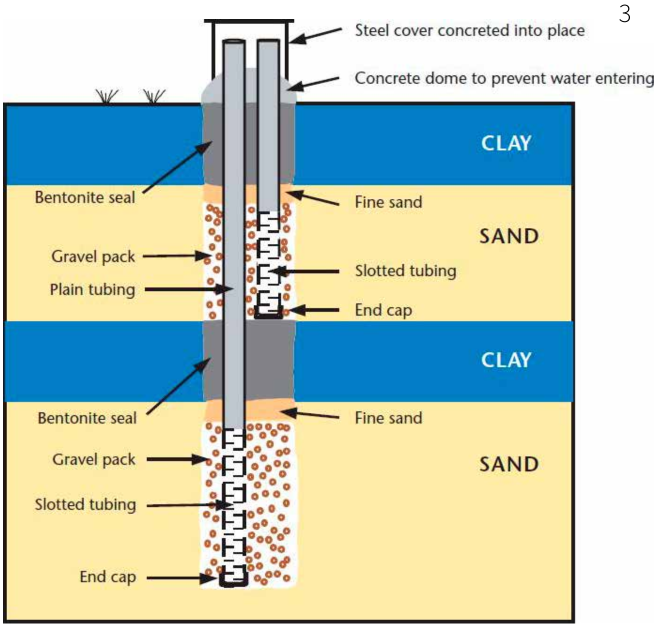


Figure 2
Typical monitoring borehole.

Figure 3
Nested monitoring borehole / piezometer.

Geomembrane wrap and end cap - The screen should be wrapped in a fine mesh or geomembrane wrap, with an end cap, to reduce the entry of silt or fine sand into the well. Purpose made screened tips are available.

Filter pack - The gap between the side of the borehole and the screened pipe should be filled with clean sand / gravel (a 'filter pack').

Sealing material - The gap between the side of the borehole and the plain section of pipe should be sealed with concrete or bentonite (a swelling clay).

Headworks and top cap - The top of the pipe itself should have a plastic cap attached (to minimise the risk of surface water or foreign objects entry), and then the whole borehole should be covered with secure headworks (for example metal cylinder / lockable cover). The cover should have some kind of air opening so that atmospheric pressure changes also happen in the standpipe.

The inside of a monitoring well should be cleaned after installation to remove any sediment introduced into the borehole during drilling.

A project design should be developed, which should include:

- The objectives of groundwater monitoring, linked to the best conceptual understanding of the water environment at that time.
- The function of each monitoring point and type of data collected should be clearly defined. This can be extended to include other pertinent types of water environment monitoring points (for example weirs, rain gauges) as appropriate.
- The construction of each monitoring point (for example screening depths, well diameters), together with location and measurement point elevation (mOD).
- How quality control measures will be incorporated into the monitoring plan, together with regular calibration of all monitoring instrumentation.

Monitoring point type	Depth limitations	Typical diameters	Borehole required	Filter pack required
Standard monitoring well	Only restricted by drilling capabilities and lift limitations for water sampling	50mm (but can be 19mm)	yes	yes
Standpipe piezometer - Casagrande tip	Only restricted by drilling capabilities and lift limitations for water sampling	12.7 mm, 19mm, 25.4mm	yes	yes
Standpipe piezometer - Wellpoint tip	Can be 'pushed' into soft soils (<5m)	tip - 19-40mm diameter, up to 600mm long	no - designed to be pushed into soft soils	no - designed to be pushed into soft soils
Vibrating wire piezometer - standard and specialist	Only restricted by drilling capabilities	standard = 19mm, low pressure = 29mm, push-in = 35mm	can be installed in borehole, embedded in fill or suspended in a standpipe	not necessarily, can be installed in grouted boreholes
Multi-level vibrating wire piezometer (as a single installed unit)	up to 45m	71mm diameter housing accommodates 6 vibrating wire piezometers	yes	not necessarily, can be installed in grouted boreholes
Vented vibrating wire piezometer	Designed for shallow wells / unsaturated zones	29mm	specifically designed for use in monitoring wells / surface water	suspended in monitoring / stilling well

Table 1 (part 1)
Typical monitoring point / piezometer overview.
Note: several other piezometer tips and designs are available for different water environment conditions (for example contaminated sites, aggressive saline environments). Specialist advice from piezometer suppliers should be sought in such circumstances.

Borehole outer diameter	Measurement point (tip / screen)	Groundwater level automatic recording	Advantages	Limitations
100 - 150mm (dependent on thickness of filter pack)	PVC or stainless steel screen of 1-2m+ lengths	separate data logger suspended down-hole	classic water quality monitoring well	can sample from smaller diameter piezometers (just restricted by size of sample tubing)
33.5mm (dictated by diameter of tip and filter pack thickness).	PVC filter tip (70 micron pore diameter, K=3x10-4m/s) joined to a riser pipe	separate logger suspended down-hole	simple and reliable, not electrical, no calibrated components	reading requires a person on-site, slower to show changes in water pressure
same as wellpoint diameter	stainless steel tip	separate logger suspended down-hole	simple, reliable, not electrical, no calibrated components	reading requires a person on-site, slower to show changes in water pressure; damaged in corrosive water environments
dependent on piezometer / riser pipe diameter and whether there is a need for filter pack	stainless steel	in-built transducer, connected at surface to recording unit	easy to read, accurate, good response time in soils, easy to automate	can be susceptible to electrical transients (energy spikes)
all piezometers installed in-line with PVC pipe, therefore diameter of borehole linked to diameter of PVC pipe - generally 70mm or larger borehole	PVC	in-built transducer, connected at surface to recording unit	easy to read, very accurate, good response time in all soils, easy to automate, reliable remote readings; all piezometers in-line with PVC pipe - able to place more accurately	can be susceptible to electrical transients
as per ‘standard monitoring well’	stainless steel	in-built transducer, connected at surface to recording unit	easy to read, accurate, can be connected to data loggers; requires no barometric compensation	electrical noise from pump in same well can interfere with operation

Table 1 (part 2)

3.3 Monitoring groundwater levels / pressures

An electronic contact dip-meter, comprises a length of wire inside a tape measure with a pair of electrodes at the end (Figure 4). When the electrodes touch the water an electric circuit activates a buzzer and / or light. The depth, relative to the measurement point, can then be read off from the integrated tape measure (Figure 5). Using a fixed measurement point for all readings, such as the lowest point of the rim of the monitoring well, reduces the chance of mistakes when the reference level is not documented and different people are responsible for taking readings.

4

5

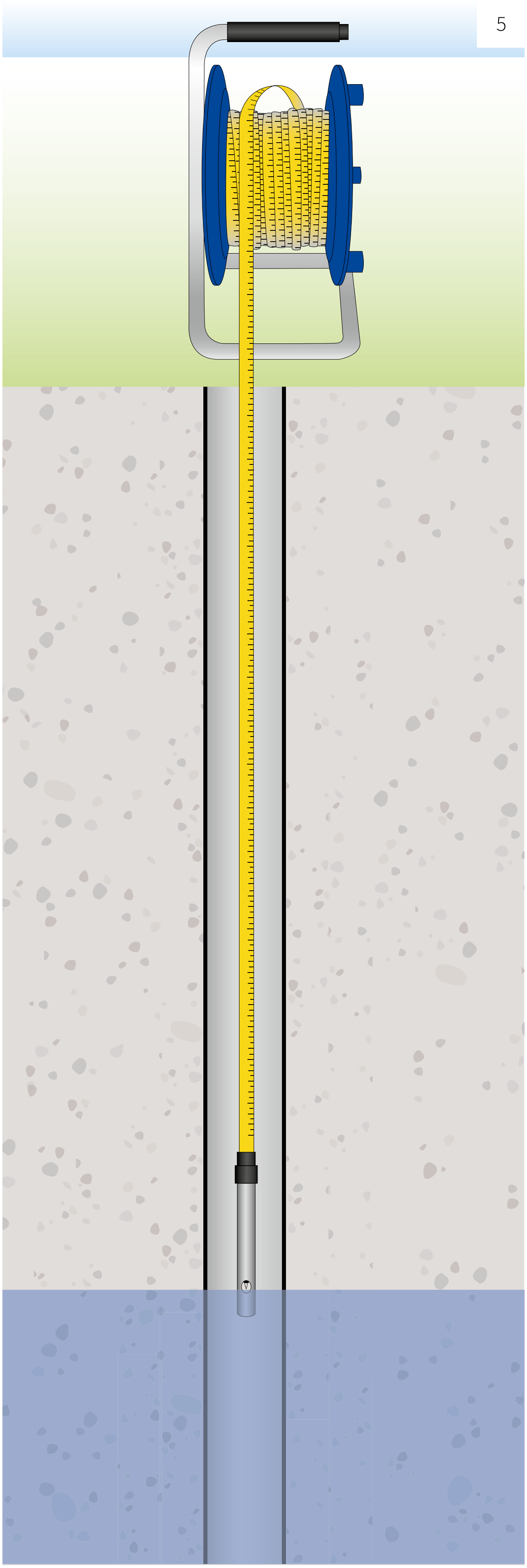


Figure 4
Typical Water level meter.

Figure 5
How a water level meter is used.

6

7

Automatic groundwater level / pressure recorders (commonly known as ‘data-loggers’) can be suspended in a monitoring borehole (Figure 6) automatically taking measurements at frequent intervals and recording the information digitally.

Several weeks, months or years worth of data (depending upon the frequency of reading set) can be stored in the instrument before it needs to be downloaded. In addition to data loggers suspended below the water table, a single (‘baro’) logger should be suspended above the water table / kept at ground surface, to record barometric pressure, which is used to correct for barometric variations. Although monitoring using data loggers is automated, regular manual measurements are still needed for calibration and quality assurance (to check for drift, instrumental errors etc).

Data can be downloaded in several ways:

- through removal of a down-hole suspended data logger and attachment to a PDA / laptop as in Figure 7 (in the case of a standpipe piezometer)
- straight from the data logger unit housed at surface without removing the pressure recording tip (as in the case of a vibrating wire piezometer)
- in some cases it may be possible to remotely download data without having to physically attach a PDA / laptop to the data logger.

Figure 6
Automatic data loggers are suspended in the water in a borehole. The one shown here is the Baro logger which sits above the water table.

Figure 7
The logger is connected to a computer to download the data.

Regardless of the method used, all monitoring equipment should be periodically checked and calibrated. Readings should be recorded in a consistent, systematic way that makes them easy to understand and interpret. Typical data gathered during a monitoring visit includes:

- Depth to water level – measured in metres below a fixed measurement point (that is 0.37m below measurement point).
- Total depth of borehole (m) – if the recorded depth is significantly less than the known depth it could be a sign of sediment accumulation, and potentially shortening of response zone.
- Weather – observations of weather on the day.
- Purge volumes – if groundwater samples are being taken for water quality analysis, the volume of water removed during purging (typically 3 well volumes) should be recorded.
- *In situ* water quality – if collecting groundwater samples for analysis, *in situ* water quality readings should be taken at several intervals during the purging process (noting the purge volumes removed at the time the *in situ* water quality readings are taken), together with a final *in situ* water quality reading when the sample is taken (following the recovery of groundwater in the monitoring well).

4 Measuring Water Quality

The main parameters measured in archaeological monitoring projects are redox, pH, conductivity and temperature.

4.1 Redox

Redox potential can only be measured in wet (or very moist) soils as it is hard to measure accurately in completely dry soils. If it is too dry, *in situ* redox probes do not function properly. Boreholes will be dry if their base is above the level of the water so redox measurement from water samples will not be possible. In this instance though it is also likely that the redox levels will be high (that is oxidising).

Redox potential	Redox state
> +400mV	Oxidising
+100 to +400 mV	Moderately reducing
-100 to +100 mV	Reducing
-400 to -100 mV	Highly reducing

Table 2
Classification of redox states based on recorded redox potentials, based on Patrick and Mahapatra (1968).

4.2 pH

pH is a critical variable in understanding site management and preservation because changes in pH can put archaeological materials and deposits at risk of deterioration (*see* Introduction to soil chemistry in Appendix 2). Any change in pH (to more acidic or more alkaline conditions) could damage those materials which are only preserved within certain pH ranges. pH is also measured because it is needed for the interpretation and calibration of redox data.

4.3 Temperature and electrical conductivity

Temperature should be collected because decay is temperature dependent and because pH and redox results are slightly temperature dependent. Temperature is also a key factor in bacterial reactions; these will take place at a faster rate in higher temperatures. Experiments have shown that a 10°C rise in temperature can produce an increase of 100-180% in decay rate (Matthiesen *et al* 2015a).

Electrical conductivity provides a measure of the ionic concentration of a liquid. For archaeological purposes it provides a useful indicator, in broad terms, of the sources of water entering deposits, for example fresh water, deeper aquifer waters, saline waters (Caple and Dungworth 1998). It can be very useful for differentiating between freshwater and sea water inputs in coastal contexts, or water influenced by natural rock salt deposits in parts of the North West such as Nantwich (Panter and Davies 2013). It may also indicate where a site has been subjected to high levels of agricultural waste or fertilisers. Conductivity is measured in microSiemens/cm, usually referred to as µS/cm. Environments which receive most or all of their water from rainfall have low conductivity levels, around 100µS/cm or less, while those fed by groundwater will have higher levels.

4.3 How to measure water quality

Water quality can be measured in several ways:

- Permanent probes
- Groundwater pumped from a borehole through a low-flow cell containing a range of monitoring probes
- Multi-probe units suspended in monitoring wells
- Extracted water samples sent to a laboratory for analysis.

4.4 Monitoring using permanent probes – Redox

Two types of bespoke *in situ* redox probes are currently in use in archaeology for monitoring redox in soils:

- Copper wire with a platinum tip - Cu/Pt
- A rigid resin (glass fibre epoxy) rod with platinum ring(s) - resin/Pt.

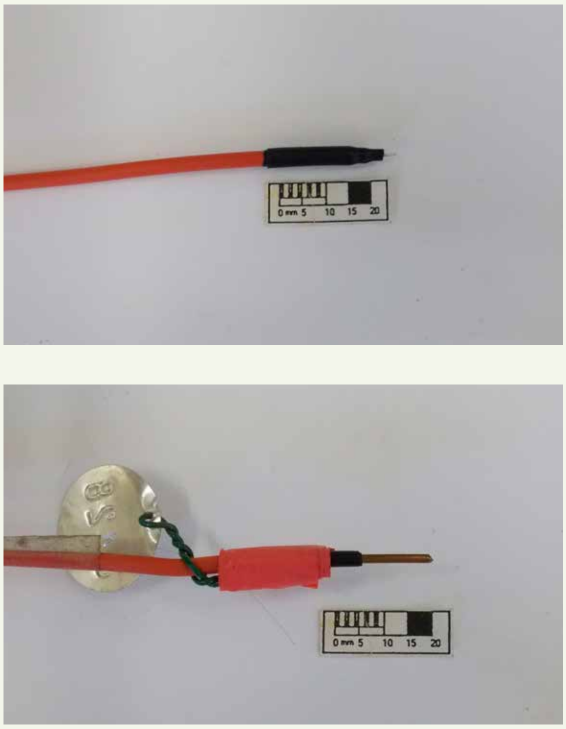


Figure 8a (top) shows the platinum tip (which is inserted into the deposit) and **Figure 8b** (below) shows the copper terminal. The copper has to be sheathed with heat-shrink sleeving to prevent current flow between the platinum and the copper producing erroneous results.

Since the 1970s researchers in wetlands and water environments have produced custom made electrodes, using thick copper wire with a platinum tip (Figure 8). The join between the copper and the platinum tip is shielded with heat-shrunk plastic to prevent any reactions taking place between these two metals (if this seal breaks it can affect the results). The manufacture process is described in a British Standard document BS ISO 11271 (2002). Cu/Pt electrodes have been successfully deployed on a large number of archaeological sites in a wide range of environments.

The Cu/Pt probes are installed by augering a small diameter hole to just above the deposits at which the monitoring is required, and then the probes are pushed in the final distance. This technique works well in soft organic deposits (like peat) but due to the flexible nature of the copper wires and the fragility of the platinum tip, these probes are harder to install in heavily consolidated deposits or urban environments full of solid inclusions.

These probes are often grouped in sets of three or more, as they do not always make good contact with the soil. This grouping of electrodes not only provides a back-up if one or more of the probes fails, but also allows individual redox readings to be averaged, since the tip of the electrode is only in contact with a very small part of the site (centimetres), and variations of +/- 100mV in the space of 20-30mm are not uncommon (*see* Panter and Davies 2013).

The other type of redox probes currently available have been developed by Dutch company Paleo Terra, and consist of thin bands of platinum, mounted on a resin rod (Vorenhout *et al* 2011). Up to nine redox sensors (bands) can be built into a single probe, allowing accurate measurement at different depths from the same probe. The rigidity of the rods also makes them easier to install than the more flexible Cu/Pt electrodes. As with the Cu/Pt probes, it is important to make sure that the Pt rings on the resin rods are in contact with the soil.

The two types of electrode were tested together at Nantwich (Panter and Davies 2013), and results from the resin rods were similar to those from Cu/Pt electrodes installed close by, and slightly more reducing than the water samples from adjacent boreholes. This would be expected as the response zone on these particular boreholes was much greater than the small area being measured by the *in situ* probes.

9

10

Figure 9
Reference electrode used in measuring redox from Cu/Pt or resin probes.

Figure 10
Multimeter to which redox and pH probes are connected.

4.5 The reference electrodes, meters and data loggers

When using permanent probes, the redox electrodes (either Cu/Pt or resin/Pt rods) are only part of the equipment needed to collect redox readings. A reference electrode is also required, as is a Millivolt meter on which the data are collected (*see* Figure 9 and 10). Any reliable pH meter with a mV setting would work well but it needs to have a sufficiently high impedance (input resistance of not less than 1 TOhm) or it will cause the electrode to produce unreliable results (Matthiesen *et al* 2004). The reference electrode is pushed into damp soil, and both electrodes are connected to the meter. If the soil surface is dry, the soil needs to be wetted with deionised water before the reference electrode is pushed into the ground and readings can be taken.

Readings from the meter will usually fluctuate and it is common practice to wait for the readings to stabilise, or if this rarely occurs, to have a fixed time at which the reading is recorded.

Collecting these data is often a manual process which requires someone to come to site with a meter and the reference electrode, connect the meter to each of the *in situ* electrodes individually, and the reference electrode, and take a reading. It is possible to automate the collection of redox data from *in situ* electrodes with a suitable data logger and permanently installed reference electrodes. The reference electrode would need to always be in contact with damp soil. Usually they contain a silver chloride (usually Ag/AgCl) solution which is deliberately leaked in very small amounts out of the base of the probe. This solution would need to be regularly topped up as part of the process of maintaining the probes.

The benefit of using a data logger is continuous monitoring of redox data without the need for regular site visits – data are stored on a SD card which is downloaded on monitoring visits. It also provides a much more detailed picture of cyclical changes than is provided by monthly or even weekly monitoring.

4.6 Redox monitoring using permanent probes – comparison with other methods

Redox can be measured in a number of ways, either using *in situ* probes as described above, or by analysing water in, or from, boreholes. Each approach has its benefits and drawbacks, and the selection of the right system for any given project will depend on the site, its deposits, issues of access and security, staff time and budget.

In situ probes often provide figures that are more reducing (that is more negative) than data from water retrieved from boreholes (*see* for example Williams *et al* 2008, Panter and Davies 2013; Matthiesen *et al* 2004; Smit 2002). This tends to be because the water in the boreholes is exposed to oxygen when the samples are taken or the boreholes are purged. However, although probes provide 'more accurate' results, they can give erroneous results unless they are in very close contact with the soil.

Figure 11
YSI Low-Flow through cell with redox sensor attached and mV meter.

4.7 Monitoring using water in or from boreholes

Water quality data can be acquired from water in boreholes, either *in situ* or *ex situ*. Results will be 'averaged' across the screened area of the borehole – the smaller the screened area, the more precisely the data will relate to a particular elevation. Where water samples are required from different depths, a number of boreholes / dip wells can be installed, with screened sections at the required heights (*see* Figure 3).

Water quality data (that is redox, pH, electrical conductivity etc) can be collected in three ways:

- *In situ* - Directly by lowering a probe (or multiprobe) into the water in the borehole.
- *Ex situ* - By testing water in a beaker which has been hand bailed out of the borehole. It should be noted that this sampling process can lead to the introduction of oxygen.
- *Ex situ* - Using a Low-Flow through cell where water is pumped from the borehole and into an airtight chamber containing the redox (or other) probe(s). The purpose of the Flow though cell is to reduce oxygen introduction during sampling.

It is standard monitoring practice to purge boreholes to remove stagnant water and allow the borehole to fill with fresh water from the deposits (for example BSI 2013; Smit *et al* 2006). Boreholes should be purged to 3 well volumes or until stabilisation of *in situ* water quality parameters is seen on the water meter (if less). Water quality data should be monitored and recorded at regular intervals during the purging process, as described above.

Where possible, it is recommended that when recording *in situ* water quality, data from boreholes samples should be collected through a Low-Flow through cell, or, failing that, probes should be inserted directly into the water in

Figure 12
Multi-parameter sonde.

the borehole (which has been purged). Testing of water in a beaker can be undertaken, but consideration of the potential for oxidation during the monitoring process should be borne in mind when assessing the data.

Probes used for *in situ* or *ex situ* water quality measurements are widely available, as they are used in a wide range of industries, both within laboratories and also for field survey and analysis; probes chosen for outdoor monitoring need to be sufficiently robust. Even so, these instruments are sensitive, and will need calibration at every site visit.

The types of probes used to monitor redox in water are usually described as ORP or combination ORP electrodes, the ORP standing for Oxidation Reduction Potential. These probes contain both the measurement probe and the reference electrode (usually Ag/AgCl) all within the same single piece of equipment.

Where low permeability deposits (those where water movement is slow) are being analysed, it may take some time – a day or more – for water to recharge into the borehole after purging. A large diameter borehole, or deeper response zone may improve recharge rates.

Equally, when water levels fall below the depth of the base of the dip well, no water quality data can be collected; it should also be noted that the performance of *in situ* probes above the water table is variable, and data in these instances may be unreliable (Mansfeldt 2003; Panter and Davies 2013).

4.8 Multi-parameter sonde

The multi-parameter sonde is a probe which has been designed for long-term unattended monitoring within boreholes (*see* Figure 12). It has been used in the contaminated land sector (Panter and Davies 2013) and has been installed on the site of a Roman boat at Guy's Hospital (*see* case study in Appendix 1). It can be a very expensive option and due to the large diameter will require large boreholes to be installed. Effective working depends on regular recharge of the monitoring well with 'new' water.

4.9 Results and calibration / display / interpretation

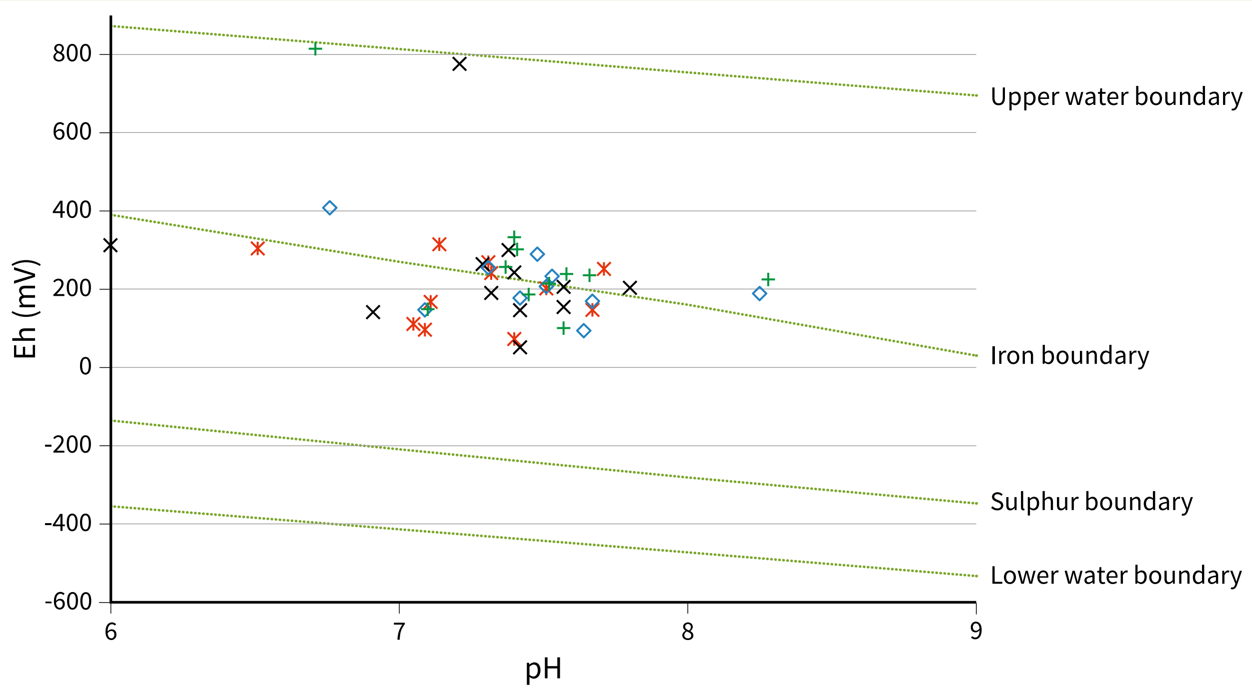
As noted above, probes used for water-based monitoring will usually require calibration in the lab or field before each use.

In addition, redox data need to be calibrated to the Standard Hydrogen Electrode (SHE); the required correction is dependent on the reference electrode that is used to take the measurement and the temperature of the reference electrode. The measured voltage (the redox figure from the meter) needs to be related to the voltage of the SHE electrode, by adding the potential of the reference electrode to the reading. The voltage obtained in this way is designated the redox potential (BSI 2002) and where it has been calibrated to the Standard Hydrogen Electrode, should be written as "mV vs SHE". Different reference electrodes have slightly different potentials at different temperatures and specific data supplied with the reference electrode should be used.

The need for correction is particularly the case for permanent redox probes, and may also be true of ORP electrodes. When purchasing ORP electrodes one should check with the supplier whether data from these require calibration; in some cases the probes and / or meters need to be calibrated using reference solutions prior to monitoring.

Where redox data from permanent redox probes are displayed and discussed against other redox data, for example showing a change in redox over time or from different parts of the site etc, data also need to be calibrated to standardise the result to pH 7 (neutral). In this case 59mV is subtracted for every pH number below 7 and added for every number above. So if the pH was 5.5, a correction factor of 88.5mV would be subtracted from the redox figure (7.0 – pH 5.5 x 59mV = 88.5mV). Again, this may not be the case with some ORP electrodes and this information should be checked when equipment is purchased or data provided by monitoring companies.

Where redox data are displayed on a graph against pH, a pH calibration / correction factor should not be used.



These graphs can be used to illustrate whether burial environments are static or fluctuate between reducing and oxidising conditions. Relevant boundary limits can be included on the chart, showing the theoretical stability limits for the oxidation and reduction of water, and the sulphur and iron boundaries which are usually used to define whether conditions are highly reducing (where sulphides exist) or whether mildly reducing (sulphates and ferric compounds exist) or oxidising (ferrous compounds exist).

5 Soil Moisture

Soil moisture need only be measured on sites where archaeological materials lie above the water table but are still well preserved by virtue of moisture retained within the soil, as a result of capillary rise or surface water infiltration. Thus the advice within this section relates solely to sites, or parts of site where this is the case. It is not necessary to monitor soil moisture for archaeological sites which are continuously below the water table because they would already be permanently saturated.

When measuring soil moisture, there are two ways in which the results can be used to understand and quantify changes taking place on site. Firstly, on sites (that are usually above the water table) where the state of preservation of artefacts and ecofacts is good, soil moisture monitoring data can be compared with initial soil moisture readings (calculated from weighed and dried soil samples). These figures can be used to see whether changes (for example from development or land-use change) cause soil moisture levels to rise or fall.

However, such an approach suggests that the soil moisture level measured when the deposits were first encountered was sufficiently high to ensure oxygen was not getting into deposits, which may not always be the case. Where it is perceived that oxygen may be getting into the deposits and soil moisture levels are not high enough, a different approach to interpreting the results is needed.

This second approach uses soil moisture data to determine air content within deposits, in order to predict the presence of oxygen. Field based research (Matthiesen *et al* 2015a) has shown that once air content in monitored archaeological deposits rises above 10-15%, oxygen is likely to be present. The precise amount will vary depending on the deposits (for example due to their clay or organic matter content), their reactivity in terms of oxygen consumption, and the capillary, molecular, and gravitational forces acting upon water within these different deposits.

Within this advice note, we therefore recommend the measurement of soil moisture, predominantly in order to understand oxygen dynamics of a given deposit. This is due to the high reactivity of oxygen in chemical reactions. When it is present in sufficient quantities it will also provide a suitable environment in which fungal growth can occur and soil fauna can be active, both of which can cause degradation to organic archaeological remains.

5.1 Methods of soil moisture measurement

Soil moisture content provides a quantitative measure of how much water is contained in the soil. It may be expressed by weight as the ratio of the mass of water present to the dry weight of the soil sample or by the volume as a ratio of volume of water to the total volume of the soil sample. Both measures are expressed as a percentage and it must be specified if the number is given as '% weight/dry weight' or as '% vol'.

Three main methods of soil moisture measurement are applicable to archaeological sites:

- Gravimetric – which calculates the difference between the weight of wet and dry soil samples
- Soil Dielectric – which is based on the soil's capacity to transmit electromagnetic waves
- Conductivity – which measures the soil's electrical conductivity.

Previously used methods based on radioactive neutron probes are not considered here as they are no longer used.

Table 3 provides further detail about these three methods of soil moisture measurement.

Technique	Description
Gravimetric	Simple technique measuring weight of water present. Sample weighed, dried and reweighed, moisture content determined as a % age of weight loss. It must be specified if the water content in % is given relative to the dry weight (% w/dw) or wet weight (% w/ww) of the sample. For soil samples of known volume the water content may also be given as %vol.
Soil Dielectric	Examples include Time-Domain Reflectrometry (TDR) and Frequency Domain Reflectrometry/ Capacitance (FDR). Techniques are based on the relationship between the dielectric properties of soil and their moisture content – the volume of water will influence the dielectric permittivity (a measure of the capacity of a non-conducting material to transmit electromagnetic waves or pulses) of the soil because the dielectric of water (81) is much greater than soil (4-5) and air (1). So when the volume of water changes in a soil, a probe will detect changes in the dielectric permittivity. For TDR, a probe or waveguide is inserted into a soil. The travel time for a TDR generated electromagnetic pulse (frequency up to 1GHz) to traverse the length of the probe is measured and analysed to determine the soil's bulk dielectric permittivity. From this the volumetric soil moisture content can be inferred. FDR/capacitance uses an oscillator to propagate an electromagnetic wave (at frequency up to 150 MHz) through a waveguide into the soil, and the difference between the output wave and the return wave frequency is used to determine the volumetric soil moisture content. Both TDR and FDR systems use either single sensors for spot readings at single locations, or multiple sensors combined in a single probe which is inserted into a permanently installed thin-walled access tube in the soil in order to generate moisture contents through the soil profile. Although both techniques have been used in archaeological monitoring programmes in the past, TDR performs more reliably when working with absolute measurements and in a wide range of sediment types.
Conductivity	Works on the principle that electrical conductivity decreases with decreasing soil moisture. Often referred to as electrical resistance blocks (or gypsum blocks), each block comprises two metal electrodes across which the electrical resistance is measured using a portable conductivity meter (Volumetric measurements).

Table 3 (part 1)
Summary of techniques used to measure soil moisture content.

More information and references for projects that have used these different techniques are given in Panter and Davies (2014) and Davies (2013).

Advantages	Disadvantages
Relatively cheap, requires no specialist equipment and provides reliable and accurate results.	Disturbance to deposits as samples must be extracted for processing in a laboratory. Time consuming if many samples require processing. Cannot show change over time without taking new samples.
High degree of accuracy of readings with TDR having a greater accuracy than FDR. Minimal calibration usually required, as the manufacturer provides different calibrations, but the results must be checked by gravimetric measurement. Soil with a high organic content, a high clay content, high salinity, or high water contents (>60%) can be problematic and require manual calibration. Lack of radiation hazards. Capable of providing continuous measurements. Works in all soil types and range of moisture contents.	Expensive, although FDR is cheaper than TDR. Limited range as readings taken from a small area adjacent to the waveguides and probes. Waveguides and access tubes must be in intimate contact with soil. Air pockets will produce erroneous measurements. Soil salinity will affect TDR greater than FDR.
Inexpensive and simple to use. Can quickly monitor soil moisture content at same location over time.	Requires permanent installation at a single location. Limited lifespan (1 year depending upon frequency of readings). Limited measurement range. Not as accurate as soil dialectic methods

Table 3 (part 2)

5.2 Sediment characterisation

Prior to designing and implementing a soil moisture monitoring programme, the nature of the soil/sediment type such as texture, water content, organic matter content and porosity requires quantification. This will involve the extraction of samples for laboratory processing. Soil porosity is the most critical variable here, as it is used to understand whether the soil moisture in any given deposit is sufficient to ensure oxygen is excluded.

To calculate porosity, you need a soil sample of known volume. This can be achieved by taking a sample from a section using a soil ring sampler. These are metal tins of exactly 100 cm^3 volume.

Water content is measured by oven drying at 105°C and comparing the dry weight with the original weight. Organic content is calculated from the weight loss when the sample is burned at 450°C. The remaining material in the sample is the inorganic content which should also be weighed.

To calculate porosity you need to work out the volume of the different components by using standard densities (1.5 g/cm^3 for organic material, 2.65 g/cm^3 for inorganic material, and 1 g/cm^3 for water). Methodology provided by Matthiesen (pers comm)

The porosity is then '100 cm^3 minus volume of organic material minus volume of inorganic material'. Finally, air content is 'porosity minus volume of water'

It is important to calculate porosity and not just work on the basis of average figures as soil porosity on archaeological sites can vary considerably between different contexts. In one test pit at Bryggen, Bergen, porosity of soil samples varied between 40% and 80%. This meant that some soil layers were fully saturated when they contained 40% vol water, whilst others needed 80% vol water to become water saturated (Matthiesen *et al* 2015a).

5.3 Equipment

Whilst the gravimetric method remains the simplest and most accurate method for measuring soil moisture content, the need to collect samples and process them off-site limits the usefulness of this technique for regular repeat monitoring. For *in situ* measurement, with minimal intervention (following installation), Time Domain Reflectometry (TDR), a technique based on the dielectric property of soil should be used. This system can be adapted to measure single-point, multi-point and soil profiles and can be set up to measure continuously in conjunction with a data logger. The addition of GPRS (mobile phone) modem technology allows for the transmission of real-time data, thereby enabling problems to be identified as soon as they develop (as long as the data are regularly reviewed) instead of waiting until readings have been collected manually.

The most appropriate way to monitor the dynamics and extent of the capillary zone above the water table, and especially where the stratigraphy is extensive and varied, is to use a profile probe, either permanently installed in the deposits, or manually inserted at regular intervals. Whilst the latter will be the cheaper option, the former will provide continuous data which can be real-time if necessary allowing for trouble-spotting at the earliest occasion. If using a data logger, the frequency of readings will depend on the questions that monitoring is addressing. If you wish to see the impact of rainfall on soil moisture, or study a highly fluctuating zone, more readings per day will be needed than if you were looking at soil moisture changes under a building where little variation was predicted.

The security of the equipment will need to be taken into consideration - there is no point installing expensive data loggers with telemetry in a public location if the equipment cannot be protected from vandalism or theft.

14

15

Figure 14
A TRIME T3P profile probe prior to installation in Nantwich.

Figure 15
Installation of the TDR access tube by Vincent Van Walt (Van Walt Ltd) in Nantwich.

5.4 Installation

Soil moisture probes should be installed close to where porosity measurements have been made, otherwise it will be difficult to interpret the results. This will be particularly challenging on sites with high levels of heterogeneity. Where it is not possible to access deposits during excavation to take samples to calculate porosity, it could potentially be calculated from material selected from core samples. However, additional provision would need to be made to ensure an accurate volume sample could be collected without soil moisture loss or significant sediment compression or disturbance during coring. The advice of geotechnical or soil science specialists should be sought in these instances.

All types of profile probes require the installation of purpose-built access tubes which must be in very close contact with the soil and must remain dry at all times. Keeping water out can be a problem, as was seen in trials at Nantwich where either the bung at the base of the tube failed to function correctly, or heavy rain conditions (which were experienced during the relatively dry summer of 2013) led to flooding of the well-head and water ingress from the top of the access tube. Similar problems of water ingress were encountered during research at Glastonbury Lake Village (Jones 2013). Whatever the reasons, the potential for flooding needs to be factored into the design of the installation. More information on the equipment installed in Nantwich and the results can be found in Panter and Davies (2014).

In some deposits it is difficult to obtain a sufficiently close contact between the access tubes and the surrounding soil, leading to erroneous results. Here it can be necessary to excavate a pit and manually install soil moisture probes (for example ML3 probes from Delta T) in individual soil layers. More details may be found in Matthiesen *et al* 2015b.

5.5 Calibration

As the dielectric property of the soil is dependent upon its composition, some calibration of the probe to reflect on site soil properties may be needed. Most systems come pre-calibrated for a universal mineral based soil, but users may wish to recalibrate for the specific soils under test, particularly if soils have a high organic content, clay content or saline concentration. Recalibration can be performed in the laboratory by inserting the probe into a wet sample of the deposit and recording the reading. The sample is then dried step-wise, taking readings with the probe and measuring the sample weight at intervals, according to the instructions by the manufacturer. These readings can be used to derive the dielectric constant of the wet and dry deposit which is then used to reprogramme the data logger software. Recalibration should be performed on each different sediment / soil / archaeological deposit being monitored.

Field-based recalibration involves installing the probe and performing gravimetric determinations on samples extracted during the installation process. Most data loggers have software which, when accessed with a laptop, enable the user to recalibrate.

Recalibration may not be necessary if overall trends or changes in soil moisture content are the principal driver for monitoring.

5.6 Making the most of specialist knowledge and experience

As soil moisture monitoring is an even more specialist field than water level or water quality monitoring, when setting up a soil moisture monitoring project it is advisable to discuss the exact requirements with equipment suppliers who will be able to advise on installation methods and the complex issue of calibration.

5.7 Results

As set out above, soil moisture data should be used to determine the air content within the deposit being measured. This is done by subtracting the water content (% volume) from porosity.

So for example, if the soil porosity is 62%, and water content is 55%, air content would be 7%. Previous studies have indicated that at this level of air content, the presence of oxygen would be limited. Conversely if water content dropped to 45%, the air content would rise to 17%, which is above the level at which previous studies have indicated that oxygen would be present within deposits.

Generally, it is recommended that to ensure the long-term preservation of archaeological remains within these unsaturated deposits, air content should not rise above 10-15%. The range given here reflects the fact that different soils / deposits will have different soil characteristics depending on their composition (clay / silt / organic matter) which affect water retention and oxygen transport. Further research to understand how these variables influence soil moisture and oxygen ingress would allow more deposits specific guidance to be given in the future.

6 Suppliers

There are a wide variety of supplies of water monitoring equipment, particularly in relation to water level measurement. Due to the large number their details are not provided here. A simple internet search for a 'water level dip meter', or a 'standpipe piezometer' will yield multiple returns. When purchasing any equipment, it is important to ensure it is suitable and rugged enough for use in the field.

Some items are less easy to acquire, in particular in relation to redox and soil moisture measurement so are included below.

6.1 Resin/platinum probes:

Made to customers' specification and available from:

Paleo Terra
Mariotteplein 41 - 1098 NX Amsterdam
email: paleoterra@xs4all.nl
Web: www.paleoterra.nl

6.2 Copper/Platinum probes

Currently commercially unavailable in the UK. May be available online from other countries. It is possible to manufacture these using the methodology set out in BS ISO 11271:2002, although significant post-manufacture testing is required to ensure they are suitable for long-term use

6.3 Data loggers

Hypnos III – designed to work with the resin probes from Paleo Terra but will also work (unsupported) with many other probes and sensors. Available from:

MVH Consult
Email: info@mvhconsult.nl
Web: www.mvhconsult.nl

A range of other data loggers for all types of water level and quality measurement are available from equipment suppliers, including those outlined in sections 6.4 and 6.5.

6.4 ORP Probes/mV Meters/Low Flow cells etc.

Van Walt Ltd
Web: www.vanwalt.com

Waterra
Now trading as *In situ* Europe
Web: www.in-situ-europe.com/

WTW
Web: www.wtw.de/en/products/lab.html

YSI
Web: www.ysi.com/
Trading via Xylem Analytics UK
email: adminuk@xyleminc.com
Web: www.xylemanalytics.co.uk

6.5 Soil moisture measurement

Van Walt Ltd
Web: www.vanwalt.com

Delta-T Devices Ltd
Web: www.delta-t.co.uk

RS Hydro
Web: www.rshydro.co.uk

ELE International
Web: www.ele.org.uk

Campbell Scientific
Web: www.campbellsci.co.uk

Streamline Measurement Ltd
Web: www.streamlinemeasurement.co.uk

7 Bibliography

Brassington, R 2006 *Field Hydrogeology*. Chichester: Wiley and Sons.

BSI - The British Standards Institution 2002 BS ISO 11271:2002 Soil quality. Determination of redox potential. Field method

Caple, C and Dungworth, D 1998 'Waterlogged Anoxic Archaeological Burial Environments'. Unpublished Ancient Monuments Laboratory Report 22/98. Historic Buildings and Monuments Commission: London. http://research.historicengland.org.uk/Report.aspx?i=4979&ru=%2FResults.aspx%3Fp%3D629

Corfield, M 2012 'The Rose Theatre. Twenty years of continuous monitoring, lessons and legacy' in Matthiesen, H and Gregory, D (eds) *Preserving Archaeological Remains* in situ*, proceedings of the fourth international conference. Special edition of Conservation and Management of Archaeological Sites*. **14** (1-4): 384-96

Davies, G 2013 'Preservation in situ guidance – soil moisture measurement. Desk based assessment'. Unpublished ArcHeritage report 2013/36

Environment Agency 2003a *A Guide to Monitoring Water Levels and Flows at Wetland Sites*. https://www.gov.uk/government/publications/a-guide-to-monitoring-water-levels-and-flows-at-wetland-sites-2nd-edition

Environment Agency 2003b *Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water*. https://www.gov.uk/government/publications/monitoring-of-landfill-leachate-groundwater-and-surface-water-lftgn-02

Historic England 2015 *Management of research projects in the historic environment. The MoRPHE project manager's guide*. Swindon: Historic England https://www.historicengland.org.uk/images-books/publications/morphe-project-managers-guide/

Jones, L 2013 'An evaluation of *in situ* preservation potential and monitoring strategies at the sites of the Sweet Track, and Glastonbury Lake Village, in the Somerset Levels, UK'. PhD Thesis. University of Reading

Mansfeldt, T 2003 '*In situ* long-term redox potential measurements in a dyked marsh soil'. *Journal of Plant Nutrition and Soil Science*. **166**:2 210–219

Matthiesen, H, Gregory, D, Jensen, P and Sørensen, B 2004 'Environmental monitoring at Nydam, a waterlogged site with weapon sacrifices from the Danish Iron Age. 1: A comparison of methods used and results from undisturbed conditions'. *Journal of Wetland Archaeology*. **4**: 55-74

Matthiesen, H, Hollesen, J and Gregory, D 2015a 'Preservation conditions and decay rates' *in* Rytter, J and Schonhowd, I (eds) *Monitoring, Mitigation and Management. The groundwater project – Safegaurding the World Heritage Site of Bryggen in Bergen*. Riksantikvaren: Oslo. 76-91

Matthiesen, H, Hollesen, J, Dunlop, R, Seither, A, and de Beer, J 2015b '*In situ* measurements of oxygen dynamics in unsaturated archaeological deposits'. *Archaeometry*. **57**: 1078–1094. doi: 10.1111/arcm.12148

Ove Arup and Partners and York University in association with Bernard Thorpe 1991 *York Development and Archaeology Study*.

Panter, I and Davies, G 2013 'Preservation *in situ* guidance - redox potential measurement.' Unpublished Final Report. English Heritage Project No 6524. YAT Conservation Department Report No 2013 /54

Panter, I and Davies, G 2014 'Preservation ***in situ*** guidance – soil moisture measurement'. Unpublished Final Report. English Heritage Project No 6523. YAT Conservation Department Report No 2014 /70

Patrick, W H and Mahapatra, I C 1968 'Transformation and availability to rice of nitrogen and phosphorous in waterlogged soils.' *Advances in Agronomy* **20**: 323-359.

Smit, A 2002 'The preservation potential of the burial environment' *in* van Heeringen, R M and Theunissen, E M (eds) *Desiccation of the archaeological landscape at Voorne-Putten*. Nederlandse Archeologische Rapporten (NAR) 25. Amersfoort: National service for archaeological heritage. 91-114

Vorenhout, M, and Hunting, E R 2011 'An improved datalogger and novel probes for continuous redox measurements in wetlands'. *International Journal of Environmental Analytical Chemistry* **91** (7): 801-810

Williams, J 2012 'Thirty years of monitoring in England – what have we learnt?' *in* Matthiesen, H and Gregory, D (eds) *Preserving Archaeological Remains* in situ, *proceedings of the fourth international conference. Special edition of Conservation and Management of Archaeological Sites*. 14 (1-4): 442-457

Williams, J, Fell, V, Graham, K, Simpson, P, Collins, M, Koon, H and Griffin, R 2008a 'Re-watering of the Iron Age causeway at Fiskerton, England' *in* Kars, H and van Heeringen, R M (eds) *Preserving Archaeological Remains* in situ, *proceedings of the third international conference*. Amsterdam: (Geoarchaeological and Bioarchaeological studies 10), Vrije Universiteit Amsterdam. 181-198

6 Acknowledgements

Images

Cover: © Jim Williams
Figure 2, 3: © Environment Agency
Figure 4, 5: © Soil Instruments
Figure 6, 7: © Van Walt Ltd
Figure 8, 9, 12, 13: © Ian Panter
Figure 10, 11: © Tim Malim
Figure 14, 15: © Michael Andrews

Every effort has been made to trace the copyright holders and we apologise in advance for any unintentional omissions, which we would be pleased to correct in any subsequent editions.

Historic England

We are the public body that looks after England's historic environment. We champion historic places, helping people understand, value and care for them.

Please contact
guidance@HistoricEngland.org.uk
with any questions about this document.

HistoricEngland.org.uk

If you would like this document in a different format, please contact our customer services department on:

Tel: 0370 333 0607
Fax: 01793 414926
Textphone: 0800 015 0174
Email: customers@HistoricEngland.org.uk

Please consider the environment before printing this document

HEAG100e
Publication date: v1.0 October 2016

Design: Historic England