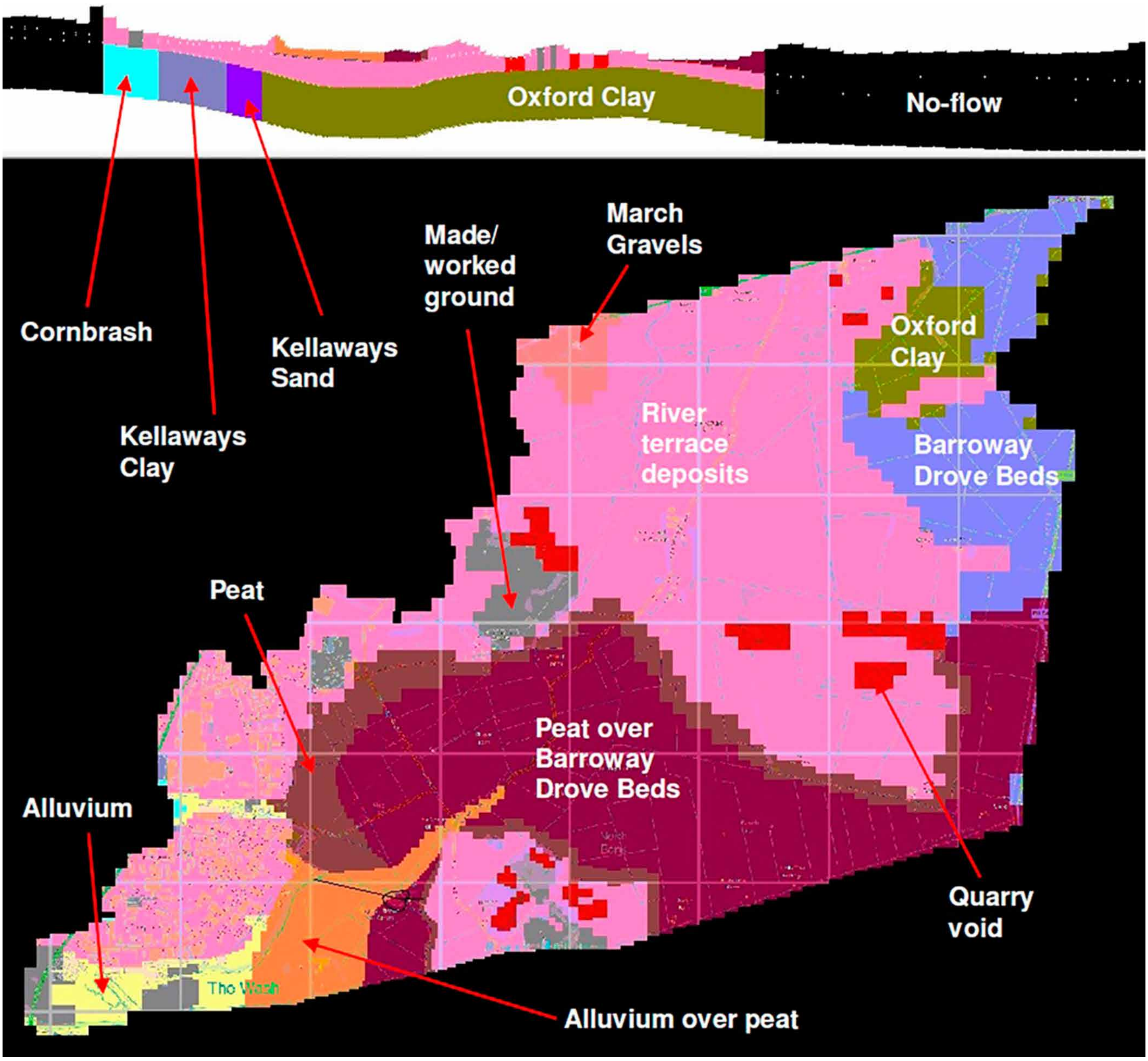
Historic England

Preserving Archaeological Remains

Appendix 3 – Water Environment Assessment Techniques



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 three areas. It begins with an introduction to hydrogeology setting out the concepts and terminology used within the rest of the document.

The next section contains a detailed description of the work involved in undertaking a water environment assessment, explaining what is done at each of the four 'Tiers'.

The final section of this appendix contains two case studies which provide worked examples of how these assessments are undertaken. The first is an extended case study from Nantwich exploring the water balance scenarios outlined in Appendix 1 in more detail. The second is a case study from Newington, Nottinghamshire, which covers Tiers 1-3 of a water environment assessment and makes suggestions for further Tier 4 work.

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

Appendix 1 – Case studies
Appendix 2 – Preservation assessment techniques
Appendix 4 – Water monitoring for archaeological sites
Appendix 5 – Materials for use in the reburial of sites

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Front cover:
Hydraulic property zones of the geological units around Flag Fen. Part of a Tier 4 numerical model, see Appendix 1.

Introduction

This document provides advice on water environment assessment techniques. It begins with an introduction to the concepts of hydrogeology and explains many of the terms and techniques used within the following sections. It is recommended reading for those unfamiliar with this subject area.

The next section outlines the methods used to undertake water environment assessments. It explains what sort of information is collected at each of the four 'Tiers' and how that information is used to gain an understanding of water availability and stresses around archaeological sites.

The final section of this appendix contains expanded discussion of two case studies. The first is an extended case study from Nantwich exploring the water balance scenarios outlined in Appendix 1 in more detail. The second is a case study from Newington, Nottinghamshire, which covers Tiers 1-3 of a water environment assessment.

1 Hydrogeological Concepts

1.1 Groundwater levels and flow directions

Groundwater levels are an expression of the pressure of water in the ground, with the level being the elevation to which groundwater rises when a monitoring borehole is installed into an aquifer. Monitoring borehole design can range from simple open wells to more complex installations with separate sealed piezometers to monitor groundwater levels at one or more specific depths (*see* Appendix 4 for more details on monitoring).

In an unconfined aquifer, where groundwater pressures are equal to atmospheric pressure, the groundwater level measured in a monitoring borehole will reflect the water table within the aquifer (Figure 1). The water table is free to fluctuate vertically under atmospheric pressure in response to any variation in recharge or discharge.

In the case of a confined aquifer, where groundwater is kept under greater than atmospheric pressure by an overlying aquitard, groundwater levels (referred to as 'hydraulic head') will rise until balanced by atmospheric pressure when a monitoring borehole is installed within the aquifer. As such levels may appear to lie above the upper surface of the confined aquifer (Figure 1). The imaginary surface connecting groundwater levels within a confined aquifer is known as the piezometric or 'potentiometric' surface.

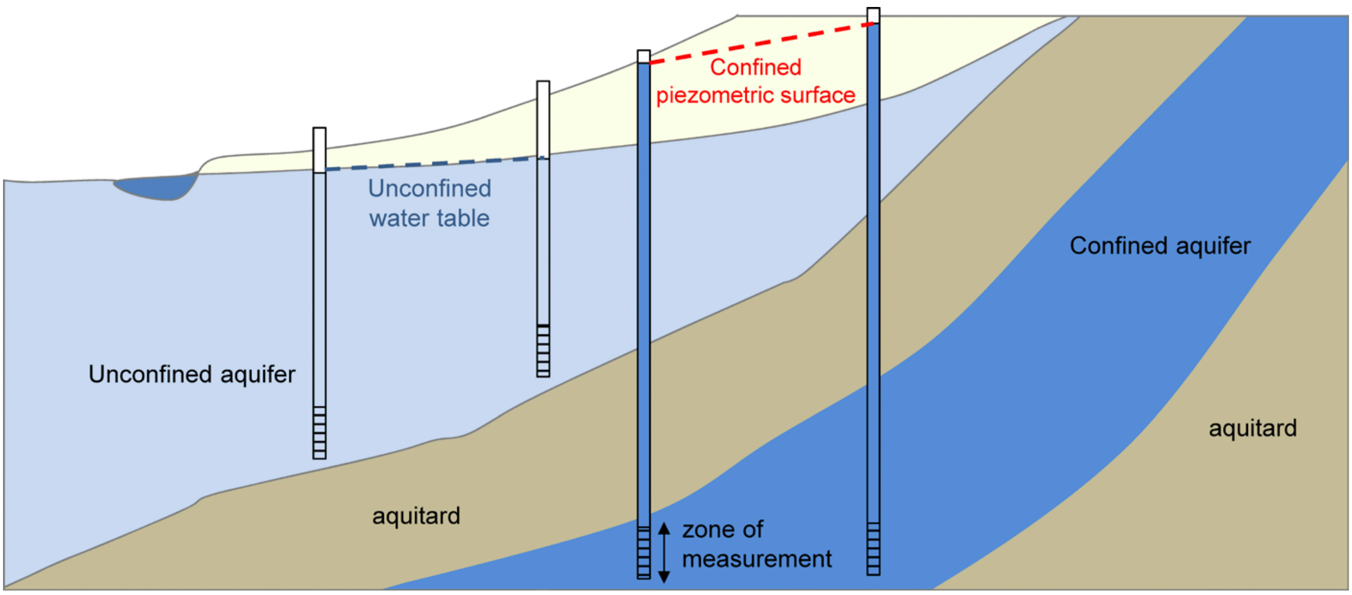


Figure 1
Groundwater levels in confined and unconfined aquifers.

Definitions

An aquifer is a body of saturated porous sediments or fractured rock through which groundwater can easily move. Conversely an aquitard is a geological formation (such as clay or non-porous / non-fractured rock) where groundwater flow is restricted, whilst an aquiclude is an impermeable body of rock or sediment that prevents groundwater flow between aquifers.

Aquifers may be described as unconfined, confined, or perched (*see* Figure 2). An unconfined, or 'water table' aquifer is partially saturated, exposed at ground surface or overlain by soils through which rainfall can easily infiltrate (recharge). A confined aquifer is bounded by aquitards, with the majority of recharge occurring at distance where the aquifer outcrops at surface. A perched groundwater table tends to be located above the main water table of an unconfined aquifer, occurring where local, laterally discontinuous aquitards are found.

Permeability is a measurable parameter representing the ease of flow of fluids through rock or sediments, reflecting the degree of connections between pores or fractures. Flow may be either 'intergranular' via pores in the sediments or rock (defined as primary permeability), and / or via fractures (defined as secondary permeability).

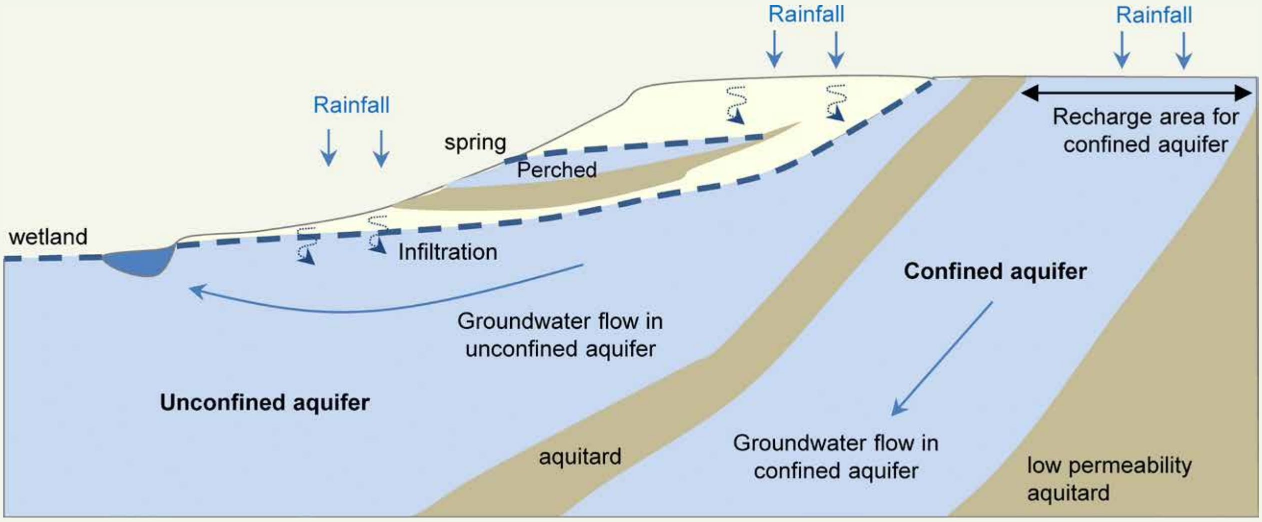


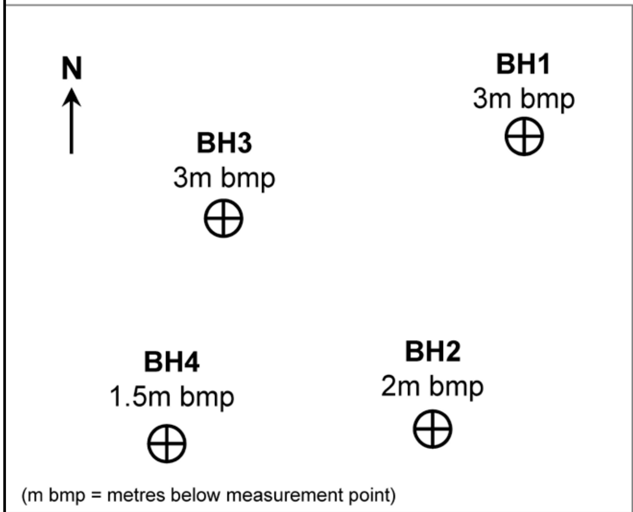
Figure 2
Aquifer types.

Groundwater levels are usually recorded with a hand-held electronic 'dip-tape' (Figure 3), with levels recorded as a depth below a fixed point of measurement, such as the top of the monitoring well. They can also be measured with *in situ* data loggers within a borehole.

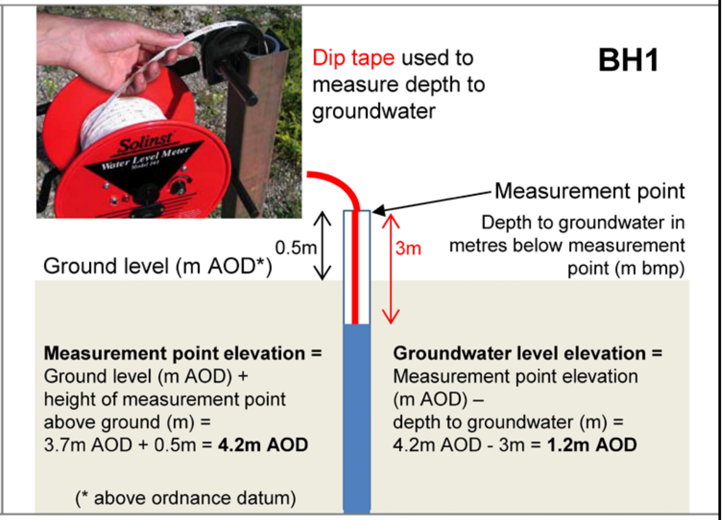
Because ground levels may vary between monitoring boreholes (as too can the selection of the point of measurement) groundwater depths should always be converted to groundwater elevations (eg m Above Ordnance Datum) before comparison between levels is undertaken. Figure 3 illustrates this concept.

Given the heterogeneous and laterally discontinuous nature of the geology associated with perched aquifers, groundwater levels monitored in such aquifers tend to be localised. To establish whether or not perched waters are hydraulically connected in a local area, a review of the distribution (spatial and vertical) of permeable deposits may be of benefit. This review should be undertaken in combination with a comparison of groundwater levels to assess their relative similarity.

***Step 1:** measure depth to groundwater*



***Step 2:** convert depth to groundwater elevation*



***Step 3:** convert all groundwater elevations*

Monitoring Well No.	Depth to groundwater (m bmp)	Measurement point elevation (m AOD)	Groundwater level (m AOD)
BH1	3m bmp	4.2m AOD	1.2m AOD
BH2	2m bmp	3.4m AOD	1.4m AOD
BH3	3m bmp	4.4m AOD	1.4m AOD
BH4	1.5m bmp	4.4m AOD	2.9m AOD

***Step 4:** plot groundwater elevations on map*

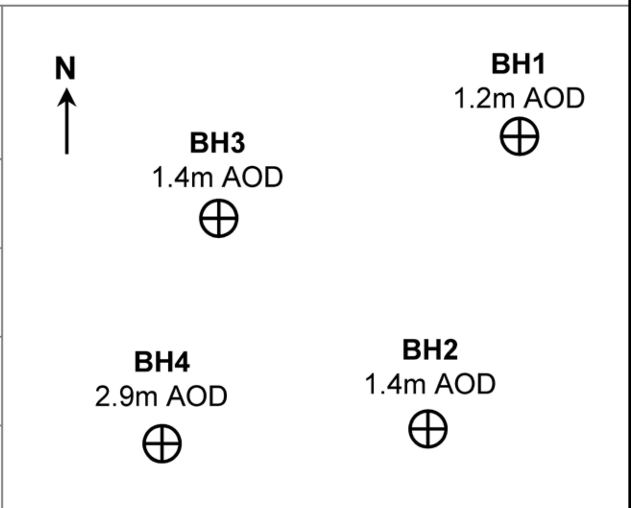


Figure 3
Groundwater depth measurement and conversion to elevation (m AOD).

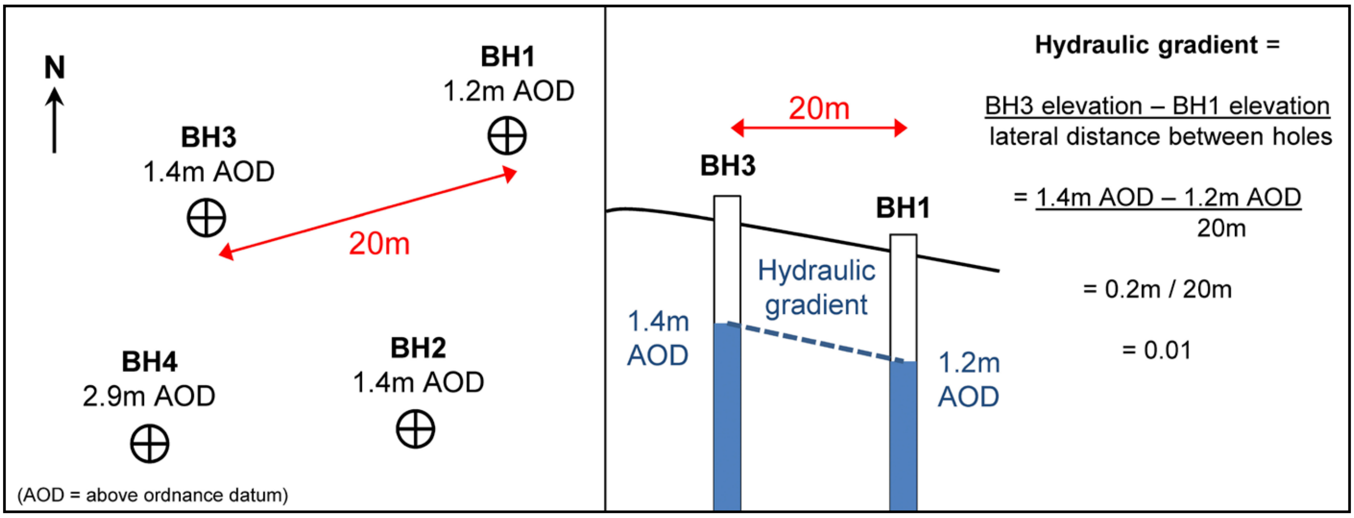


Figure 4
Hydraulic gradient estimation.

For example in Figure 3 groundwater elevations in monitoring boreholes BH1 to BH3 are similar, suggesting hydraulic continuity. However in the case of BH4, the groundwater elevation of 2.9m AOD is much higher than others in the monitoring network – possibly indicating a perched water table.

Groundwater flow is always from high to low groundwater level / hydraulic head (eg from BH3 to BH1 in Figure 3). Flow can be both horizontal and vertical (eg between shallow and deep aquifers) at the same time. The hydraulic gradient (or slope of the water table) is a key driver to groundwater flow and can be estimated using groundwater elevations in three (or more) monitoring boreholes and the measured distance between those boreholes. The hydraulic gradient calculation is illustrated in Figure 4.

Groundwater can flow in more than one direction, and as such it is important to have an appreciation of how groundwater levels may vary in the wider water environment. Groundwater contours represent lines of equal groundwater elevation / hydraulic head within the same aquifer.

Flow direction is at right angles to the contour. In areas where a plot of groundwater contour points shows water is moving in opposing directions, this would suggest a groundwater divide - indicating an area where some form of groundwater recharge is occurring.

If groundwater flow directions appear to be converging, either linearly or to a point, this would suggest a point of discharge from the groundwater system (eg a river or an abstraction point such as a quarry dewatering point or water supply well).

In order to draw a groundwater contour, and estimate a flow direction, a minimum of three monitoring boreholes in a triangular pattern is needed. Estimation of groundwater elevations between boreholes can be undertaken by triangulation of groundwater levels between monitoring boreholes.

With a greater number of monitoring boreholes and groundwater level data it is possible to estimate groundwater level variation (either locally or over a wider area) with more confidence.

Using all the information available on groundwater levels, hydraulic gradient and contouring it is possible to calculate groundwater flow directions. Groundwater flow rates can be calculated from permeability and hydraulic gradient (further reading: see Price 1996).

Useful tips when measuring groundwater:

- When reviewing groundwater levels only data from boreholes screened (see 'zone of measurement' in Figure 1) within the same hydraulically connected geological horizon should be compared

- Ensure data used for assessment are from the same date (or within a few days of each other). Groundwater level data from different weeks / months should not be directly compared to calculate hydraulic gradients or flow directions as levels within the water environment system may have changed during the intervening period

- If a site is close to a tidally controlled river, or estuary, there may be some tidal influence on groundwater levels (sometimes several hundred metres away from the river bank). As such careful note should be made of the timings of groundwater level dip readings to facilitate comparison

- Geological faults can be conduits or barriers to flow depending upon the permeability of juxtaposed rock, the openness of faults (tending to decline with depth and increasing pressure), and the potential permeability of material filling in the fault

- The presence of fractures and intervening low permeability areas can complicate water level measurement and estimation of aquifer properties. In sands and gravels in particular, flow is generally intergranular (although flow can be focused along lenses of more permeable gravels within heterogeneous deposits)

1.2 Hydraulic continuity between groundwater and surface water

In order for interaction to take place between groundwater and surface water (including surface water in drainage channels), there must be a degree of hydraulic continuity between the two systems (Figure 5). Where the surface geology is of low permeability (including any thicknesses of silt that may have accumulated on a riverbed) there may be limited connection. In these situations the surface water system is effectively isolated from any underlying aquifers, being solely supplied through rainfall and surface run-off from the surrounding catchment. Where the surface geology is more permeable, however, there will be a varying degree of hydraulic continuity between the two systems.

The scale of interaction also depends on the hydraulic gradient between the surface and groundwater systems. If the groundwater level is higher than the surface water level or ground surface, groundwater will tend to discharge via springs or seepages, and will provide a baseflow which helps to sustain surface water features during periods of dry weather.

If, however, the surface water level is higher than the surrounding groundwater, surface water will seep into the aquifer. This situation may occur following heavy rain when surface water levels increase rapidly before groundwater levels begin to respond. At different times of year, the same watercourse may be described as a 'gaining' or 'losing' stream, depending on whether it is being sustained by the aquifer or *vice versa*.

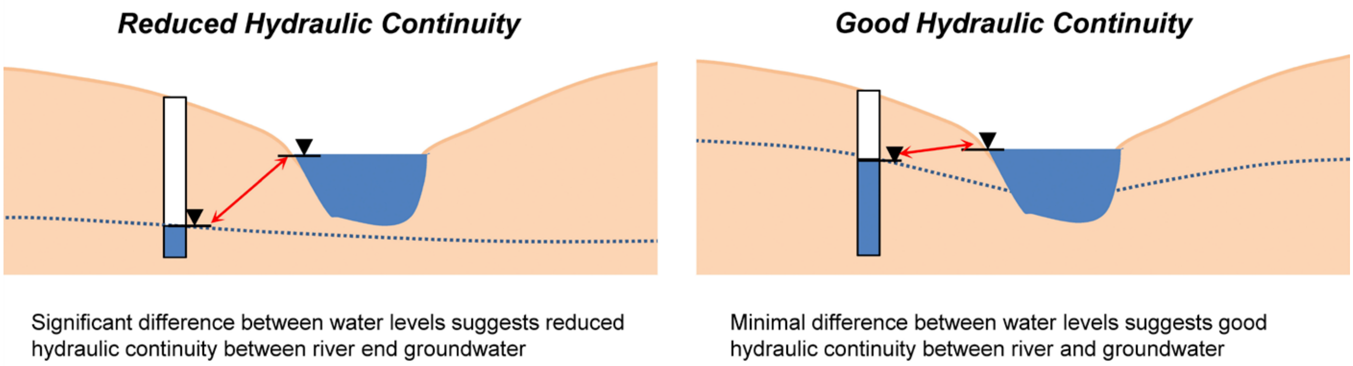


Figure 5
Groundwater-surface water hydraulic continuity.

Surface water courses (given that they represent a point of discharge from or recharge to the groundwater sub-system) often represent a useful boundary to define a local study area in terms of groundwater. The extent of their influence on local groundwater will depend upon whether they are a fully penetrating feature or a partially penetrating feature (Figure 6). A review of the vertical relationships between channel depths and the depths / thicknesses of the geological layers surrounding the channel will enable identification of the scale of penetration of the surface water feature.

A 'fully penetrating' surface water feature is as deep as the aquifer of interest and underlain by an aquitard. If a surface water course is not fully penetrating the potential exists for groundwater flow beneath and beyond the surface water course (either away from or towards the *in situ* asset of interest) – potentially exposing groundwater levels in the area of interest to changes / abstraction influences beyond the nearest surface water course.

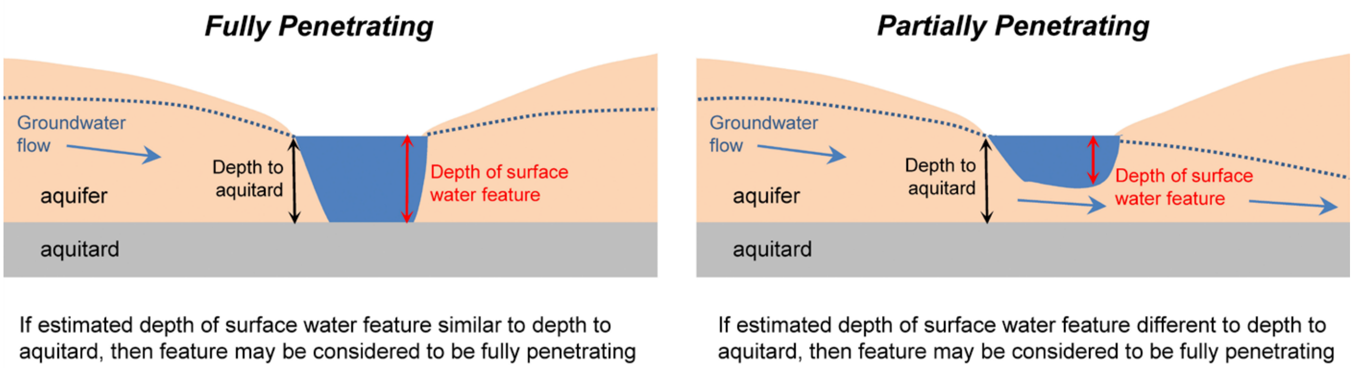


Figure 6
Surface water channel penetration.

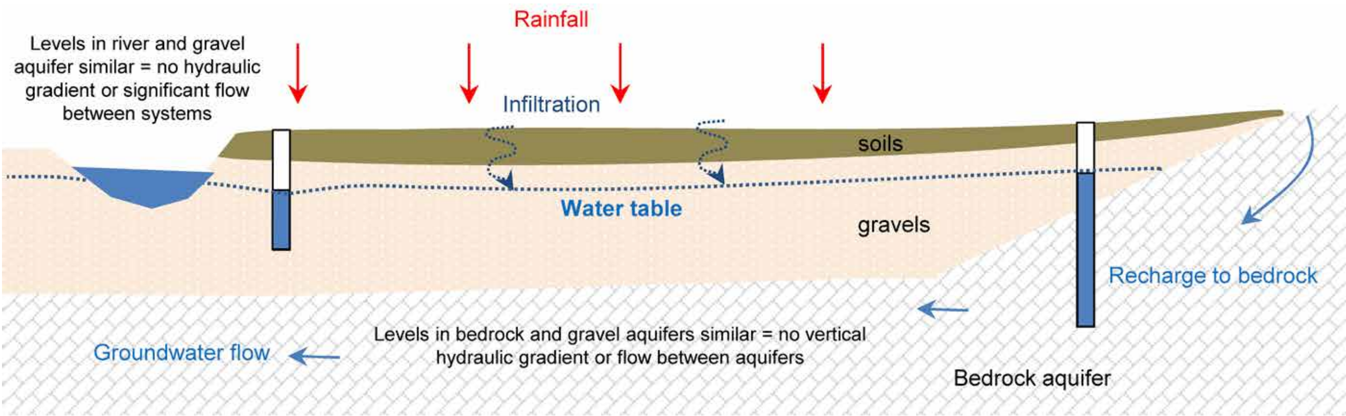


Figure 7
Baseline equilibrium.

1.3 How groundwater levels respond to change

The hydrological cycle can be represented as a system of inputs (eg seepage into ground from rainfall, re-injection of water, or groundwater inflow) and outputs (eg discharge to surface water, abstraction, groundwater flow out of study area) to the groundwater system. All natural systems strive to reach an equilibrium where the total inputs and outputs match (Figure 7).

If there is an imbalance between inputs and outputs, water must be taken from or added to storage (pores in soils or granular sediments, or fractures in rock) before equilibrium can be restored.

Where inputs exceed outputs additional water is taken into storage, observed as a rise in groundwater levels (Figure 8).

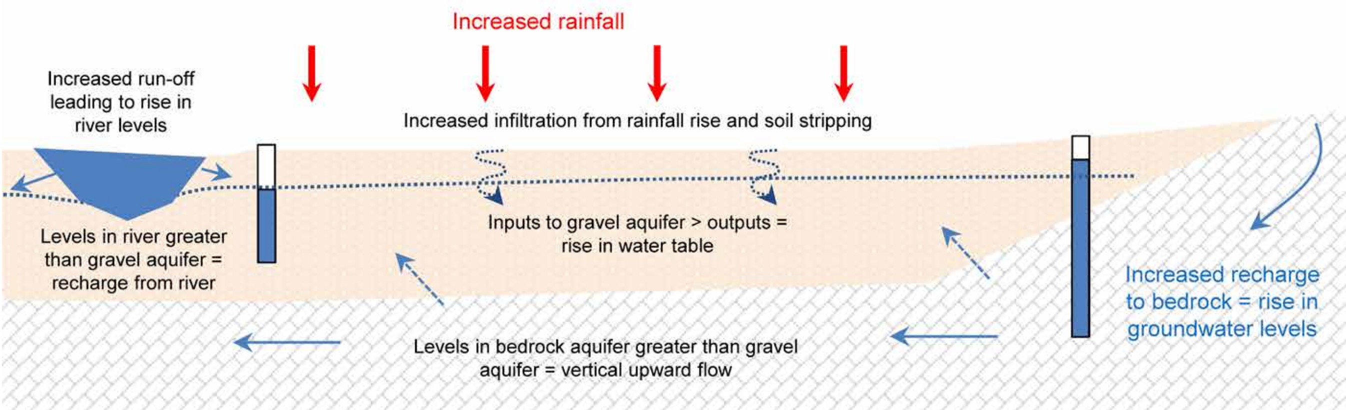
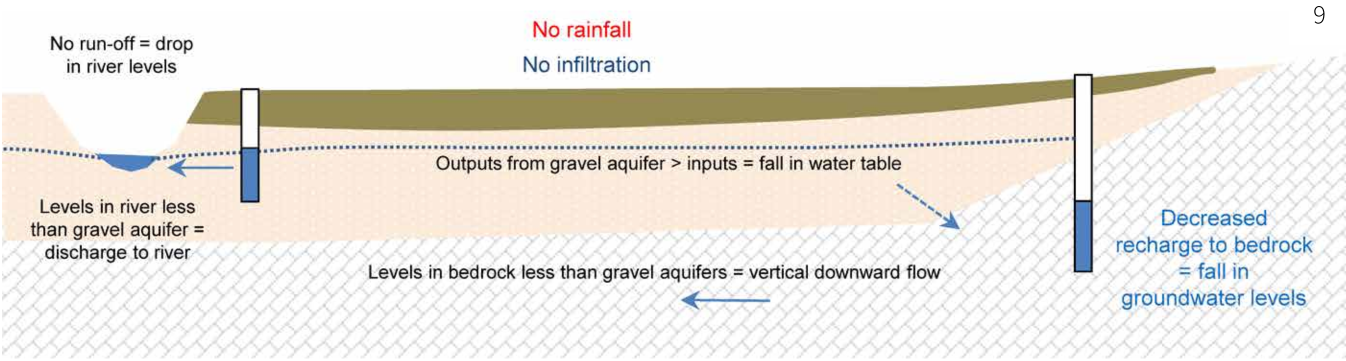


Figure 8
Increased recharge scenario.



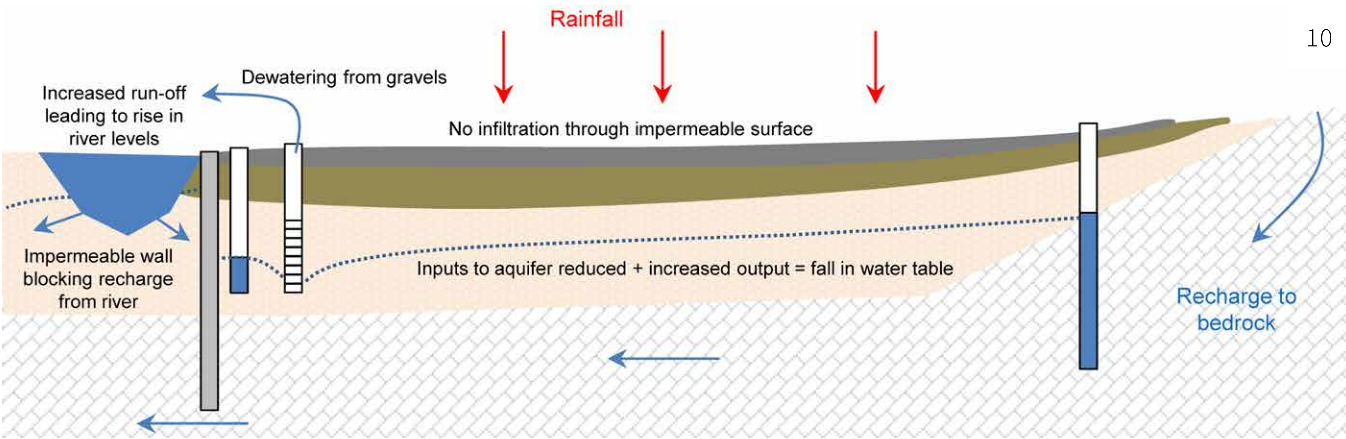


Figure 9
Increased recharge scenario.

Figure 10
Human influences on the hydrological cycle.

Equally, where outputs are greater than the inputs the system will try to compensate by removing water from storage, observed as a fall in groundwater levels over time and space until equilibrium is reached (Figures 9 and 10).

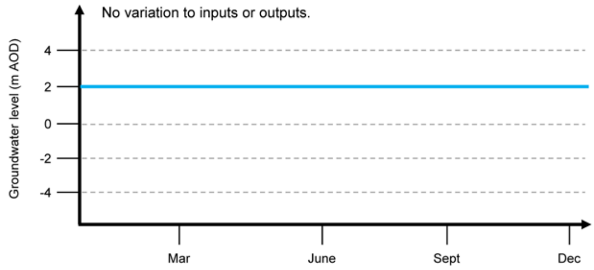
If there were no variation in inputs or outputs to the groundwater system, groundwater levels would remain constant throughout time (Figure 11).

In reality, the hydrological cycle is in a continual state of flux, with changes in storage taking place. Over a given period of time, if there are only minor fluctuations which balance out, the system may exhibit a 'dynamic equilibrium' or approximate steady state, but this may change if there is a sustained imbalance between inputs and outputs.

Groundwater levels recorded in the field reflect the combined influences of natural and anthropogenic inputs and outputs. The most basic input parameter variation is infiltration / recharge during the course of the year as a result of seasonal rainfall / evaporation patterns. At times when rainfall exceeds evaporation, increased recharge results in a rise in groundwater levels; when evaporation exceeds rainfall, decreased recharge results in a fall in groundwater levels.

If drawdown associated with periods of anthropogenic activity (eg abstraction) are superimposed on a background that is not impacted by seasonal variations, hydrographs similar to Figure 13 may be observed.

Combined influences of natural variation and man-made activities (such as abstraction), will lead to a change in the pattern of groundwater levels rise / fall (Figure 14). If abstraction periods continue for prolonged periods, then potentially annual average groundwater levels may be reduced.



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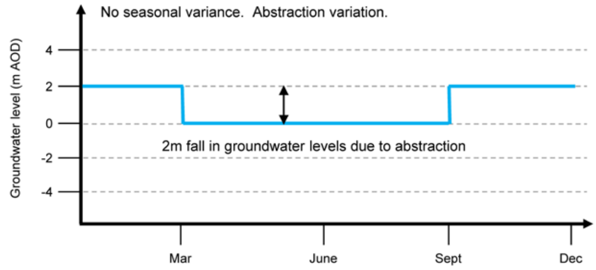

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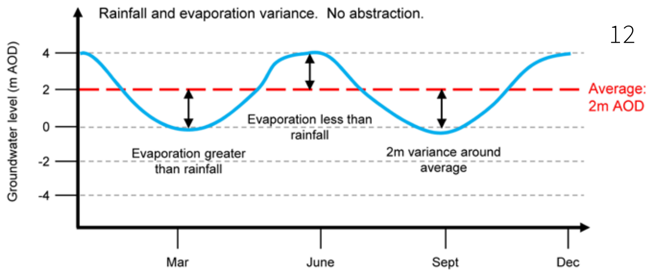

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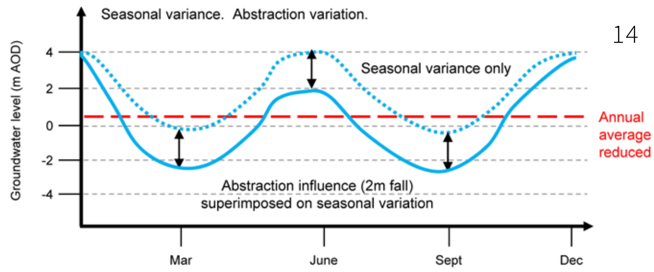

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Figure 11
No variation in inputs or outputs to the groundwater system.

Figure 12
Groundwater level responding to rainfall / evaporation variance (no abstraction).

Figure 13
Groundwater level responding to abstraction variance (no seasonal variation).

Figure 14
Groundwater level responding to seasonal and abstraction variance over time.

2 How to Undertake Water Environment Studies

Underpinning all water environment system assessments is the need for the development of a hydrogeological conceptual model. This is a written and / or diagrammatical explanation of the local geology and water cycle based upon the assessor's knowledge at that time. Consideration is given to the local groundwater and surface water regimes, their interactions with each other and with rainfall inputs, linkages to associated habitats, and other water dependent receptors (which may include designated and undesignated heritage assets) and users within an area.

Conceptualisation may be purely qualitative or partially quantified based upon the amount of information / data available for a site and surrounding area. The information that is required in order to form the conceptual model includes:

- the identification and hydrogeological characteristics of different aquifers, ie lithology, thickness, permeability and geological structure
- the principal groundwater flow mechanism in each aquifer unit, for example intergranular or fracture
- the extent to which groundwater is able to flow between the different aquifers; this may be influenced by intervening lower permeability strata or structural features such as faults
- the nature of interactions between groundwater and surface water, ie discharge points
- the identification of sources of recharge: rainfall infiltration, regional groundwater input, artificial infiltration sources or a combination of mechanisms

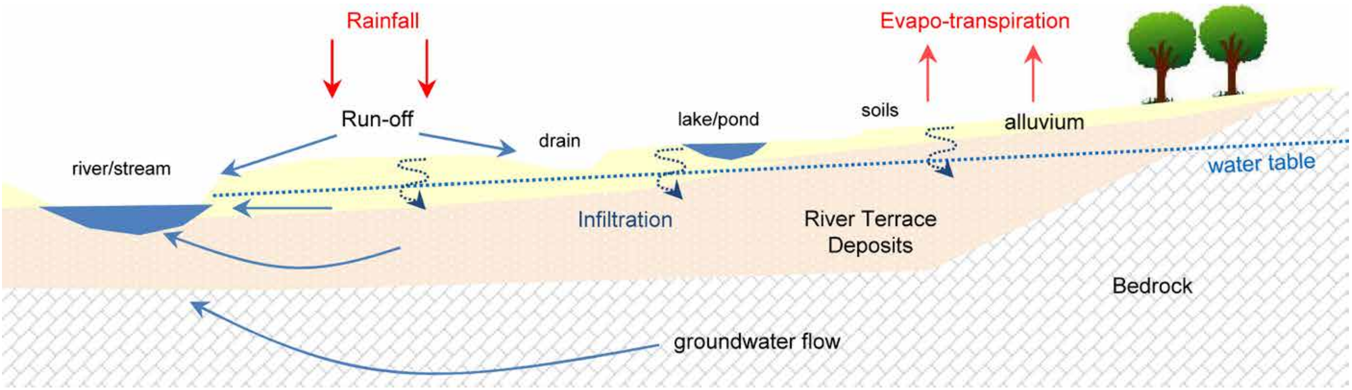

Figure 15
Simple hydrogeological conceptual model.

2.1 Assessing water environment systems

The investigation and assessment of a supporting water environment system is often a tiered and cyclical process. Selecting the most appropriate method of assessment, which in turn influences the methods by which groundwater data are collected, will be dependent not only on the amount of information / data available for a site, but also the budget available. A simple desk study with currently available information combined with a site walkover, can often yield useful appropriate assessments for a large number of sites, and be as valid an approach as the use of computer modelling at individual sites where the sensitivity / threat to archaeological remains is of critical importance.

An essential aspect of avoiding or minimising adverse effects to waterlogged archaeological remains is the use of appropriate and effective techniques to assess what may happen; monitor what actually happens; review / revise the assessment; and update / revise monitoring requirements. This reflects the development and progressive refinement of a hydrogeological conceptual model of a water environment system supporting the archaeological site of interest.

The reliability of a conceptual model is determined by the availability of data, and the sophistication of the tools that have been used to build the model. Depending on the likely scale and significance of the potential risks involved, and the complexity of the systems being 'modelled', the initial conceptual model may need to be progressively refined and improved through field tests and the acquisition of new data, in order to generate the level of confidence required to inform decisions on the potential for sustainable long-term preservation.

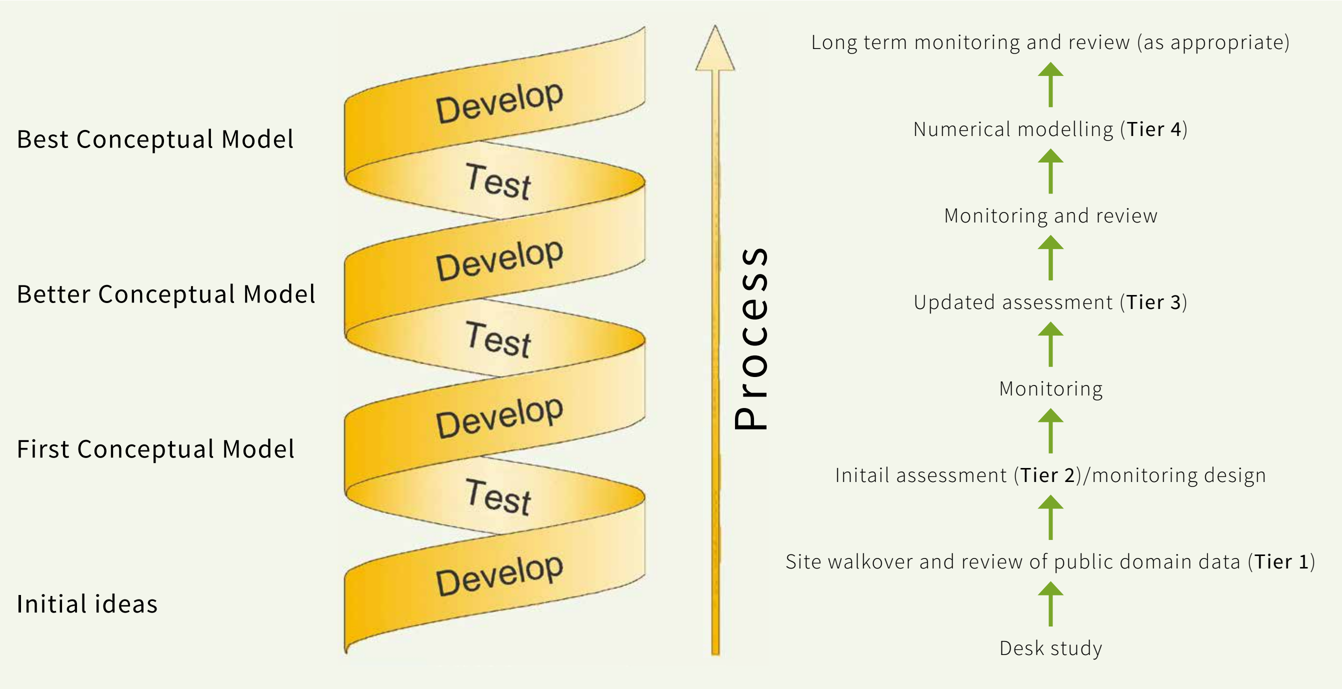

Figure 16
Assessment and monitoring cycle.

The different tiers of assessment include:

- **Tier 1**: Desk study and site walkover to derive 'first conceptual model'
- **Tier 2**: Basic qualitative assessment of water balance to identify groundwater levels, flow directions and identify key potential influences on the groundwater system
- **Tier 3**: Conceptual model tested using site-specific measurements, simple analytical equations and long-term average water balances, to arrive at a 'better conceptual model'
- **Tier 4**: Development of a numerical groundwater model, calibrated and validated against monitoring data from the site and surrounding area. Model is then tested using detailed data, such as time variant levels, and more sophisticated analytical tools

As the investigation progresses through the tiers, the cost increases, but so does the confidence in the model. As confidence increases, so the uncertainty decreases. From limited information gleaned from a desk study review of published information and site walkover, a first conceptual model can be developed within a day or so, identifying gaps in information that may necessitate monitoring and more assessment.

The investigation should continue up the tiers until the reliability of the conceptual model has reached an acceptable level. The level that is considered acceptable depends on what the conceptual model is being used for, although in practice it is also influenced by the funds and time available for further investigation and assessment. Common sense must be used, and in general, decisions should be made with the simplest model possible, with refinement of the model required only if a decision on the potential for long-term preservation cannot be made because the uncertainty is too great.

A summary of the assessment tiers is provided in this document to help archaeologists to have some knowledge of what may be undertaken at such assessment levels and be able to review what is proposed, having the confidence to pose questions to the specialist undertaking the assessment.

Whilst the assessment outlined here is a tiered process, it would be acceptable to identify at the outset of a project that you needed a Tier 3 or 4 product (without having to do Tiers 1 and 2 as separate pieces of work). However, in producing a Tier 3 or 4 product, all of the Tier 1 and 2 work would still be carried out, including data gathering, as a key part of work to build the conceptual model and populate a Tier 3 or 4 model.

2.2 Tier 1 Assessment

Where a waterlogged archaeological site is being considered for long-term retention within a development, the starting point for any investigation of its sustainability for future preservation is to undertake a Tier 1 assessment. This comprises a review of published maps / borehole logs, and a site walkover to record observations such as channel depths, vegetation growth etc. The questions that the assessment aims to address at this this first stage are:

- Are the deposits in which significant waterlogged archaeological remains are located, hydraulically connected to the wider groundwater system?
- Are these remains likely to be located under the water table or have been so in the past?

Initially this requires an identification of the three dimensional geometry of geology / soils, heritage asset boundaries (both vertical and lateral), water course elevations and drainage features in relation to the potential elevation of the archaeological remains, to build up a 3D picture of potential relationships prior to site walkover. Areas of uncertainty at the time of desk study (eg depths of features, vegetation) can then be explored at the time of site walkover to facilitate completion of the first conceptual model.

Estimating the depth to water in any streams / rivers from the bank will enable a rough estimate to be made of potential natural groundwater level locally, assuming there is a hydraulic connection and there are no anthropogenic influences. To extrapolate away from the river, consideration needs to be given to the geometrical relationship with other surface water features. For example if the drainage channel illustrated in Figure 17 has standing or flowing water in it during a dry weather period, then potentially it may have some connection to groundwater, enabling an estimate of groundwater level to be made based on the depth of the channel. If the channel has no signs of standing water, and it is silted and overgrown then it may be assumed that groundwater levels lie below the base of the channel. As such the base elevation of the channel could be considered to represent a limitation on maximum level. On the assumption that readings can be acquired safely, approximate depths of channels, streams and river beds can be taken using survey staffs.

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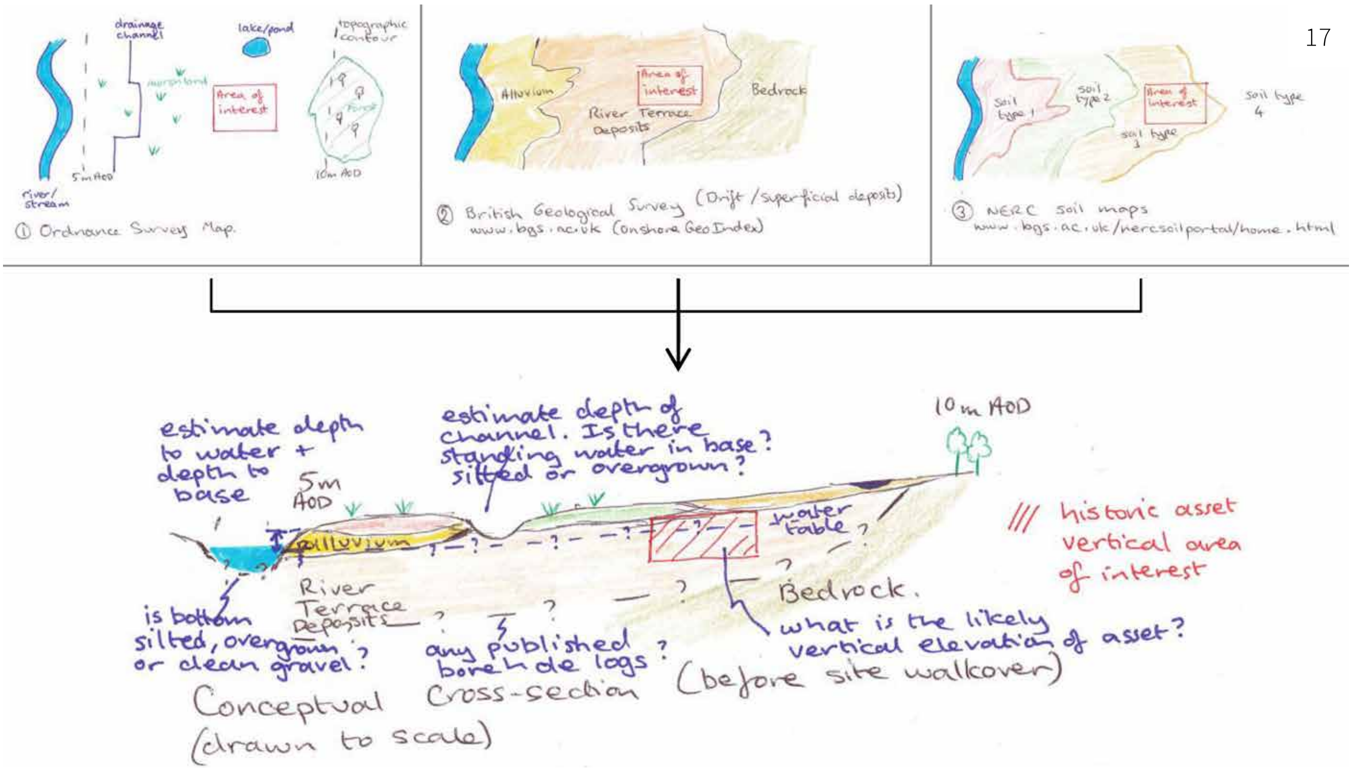

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Figure 17
Compiling a first conceptual model.

Figure 18
Vegetated channel, with plant growth visible throughout water column, North Delph, Fiskerton, Lincolnshire.

Figure 19
Gravel substrate, River Windrush, Naunton, Gloucestershire.

Observing the nature of the bed / channel substrates will give an indication of the potential for hydraulic continuity between surface water and groundwater. If there is a notable thickness of silt and vegetation (*see* Figure 18), then it is logical to conclude that the degree of hydraulic continuity between the two systems will have been reduced. Conversely if a clean gravel substrate can be seen (*see* Figure 19), then the likelihood of hydraulic connection between the systems may be high.

Depending upon the potential elevation of the archaeological remains of interest, in relation to strata and approximate natural groundwater levels, these remains may be marginal in terms of the likelihood of being naturally waterlogged. To appreciate whether such levels are likely to be sustained, an assessment of annual rainfall versus annual evaporation for the area is needed (data that are available on the Meteorological Office website). This indicates whether an area has a net positive effective rainfall that can infiltrate and feed into the local water system, or is an area of negative effective rainfall, where there is little water available to infiltrate into the local groundwater system.

At the end of Tier 1, representing less than 5 person days, a first conceptual model should be produced. At this time it should also be possible to decide whether more a detailed (Tier 2) assessment is needed to aid decision-making about long-term retention and preservation and to weigh up the pros and cons of installing site-specific monitoring to gather more data to assist in that assessment.

If it was decided that more data were required, the monitoring design (ie spatial location, depth and frequency of monitoring), would then focus on those areas of uncertainty highlighted in the first conceptual model. This collection of new data should aim to complement any existing monitoring networks already in place (owned by other parties).

2.3 Tier 2 Assessment

The aim of a Tier 2 assessment is to refine the first conceptual model with site-specific data, and to ask some more detailed assessment questions at minimal cost.

Through qualitatively considering the water inputs and outputs to the groundwater system (the water balance), at different times of year, and different locations across the site, it is possible to broadly understand when and where water systems may be likely to be under stress (either throughout the year, or during particular seasons / circumstances). This enables monitoring and any further investigation, to gather quantitative data for a Tier 3 assessment and design of potential mitigation measures, to be targeted.

This assessment can be undertaken after a month or two of monitoring over a summer period, when a system may be at a critical water stress, through to a year or more to gain a complete picture of the seasonal cycle. The Tier 1 assessment will have established whether the strata within which the relevant archaeological remains are located are hydraulically connected to the local groundwater system, and whether the elevation of these remains means that they are likely to be above or below water.

At the Tier 2 stage, questions asked include:

- Will the deposits in which significant waterlogged archaeological remains are located be underwater all year?
- If not, what variation can be expected and what is influencing the variation (anthropogenic or natural)? And are these variations short-term or long-term / permanent?

Groundwater and surface water levels from monitoring points installed post-Tier 1 assessment should be plotted as hydrographs against rainfall or effective rainfall from the time period. General values for 'effective rainfall' (rainfall minus evaporation) are available as a MORECS dataset from the Meterological Office, or can be collected from an automated rain gauge retained on site as part of the monitoring design. In addition spatial plots of groundwater elevations (m AOD) for defined dates should be drawn to explore flow direction changes over the course of the time period, and to establish any areas where groundwater levels may be impacted by abstractions or recharge. More information on monitoring and monitoring well design is given in Appendix 4.

At the end of the Tier 2 work, sufficient data should have been collected to allow a qualitative water balance review to be undertaken, as set out in the Nantwich case study in Appendix 1 (and expanded upon in the following section). This will in turn influence decisions to either continue to monitor and observe (subsequently updating the Tier 2 assessment with more data), or to move to a detailed Tier 3 assessment.

Any monitoring carried out to inform baseline assessment of hydrology and a site's water environment system is different to site monitoring for long-term management purposes. Baseline assessments should have a fixed, limited duration with clear purpose and most importantly, take place before decisions are made about the long-term retention of waterlogged archaeological sites. Site monitoring for management of waterlogged assets would only take place after such planning decisions had been taken. Even then, it should only occur where it is possible to alter water levels or access the site if the monitoring results demonstrate that assumptions made in the baseline assessment were not correct and suitable conditions for long-term preservation were not being maintained. This is explained in further detail in the main text.

2.4 Tier 3 Assessment

A Tier 3 analytical assessment can be undertaken by a hydrogeological specialist over a period of a no more than few weeks. Critical to the question of the water environment system's ability to support the long-term preservation of archaeological remains, is the issue of the water balance. Any differences in the water balance are seen as rises or falls in water levels. Table 1 outlines the types of data required to quantify the inputs and outputs to a water balance.

For defined snapshots in time and space, inputs and outputs to a water balance can be estimated to broadly understand whether groundwater needs to be taken into, or released from, storage, in order to balance the system. In most cases the inputs and outputs can be measured through relatively straightforward monitoring, or at least can be estimated to give a first approximation. This exercise / assessment can be repeated as more monitoring information becomes available, further enabling refinement of the conceptual model.

Estimating the changes to storage, particularly in relation to anthropogenic influences, is more difficult to predict, although there are simple empirical equations through to analytical equations that can be used (Smith and Howarth 2011a).

Although Tier 2 and Tier 3 assessments can be performed on the same amount of data, the difference between them is in the more detailed assessment of the data that takes place in Tier 3. As this analysis progresses, theoretical assumptions made in Tier 2 can be replaced by field data as/if more refined monitoring takes place.

	Local Scale (volume of strata surrounding asset of interest)	Regional Scale (surrounding area)
Inputs to the local system	▪ Rainfall over site area ▪ Groundwater input from up-gradient ▪ Groundwater input from below ▪ Surface water inflows from upstream	▪ Rainfall over catchment area ▪ Groundwater input from up-gradient boundary ▪ Surface water inflows from upstream
Storage within the local system	▪ Surface water storage (ponds / lakes) ▪ Soil moisture deficit within the unsaturated zone ▪ Groundwater storage in aquifers	▪ Surface water storage (lakes, ponds, reservoirs) ▪ Soil moisture deficit within the unsaturated zone ▪ Groundwater storage in aquifers
Movement of water within the local system	▪ Surface run-off to drainage channels ▪ Flow within drainage channels ▪ Infiltration ▪ Recharge ▪ Groundwater / surface water interactions	▪ Surface run-off to rivers and streams ▪ Flow within surface watercourses. ▪ Infiltration ▪ Recharge ▪ Groundwater / surface water interactions
Outputs from the local system	▪ Evapo-transpiration (site level) ▪ Site drainage ▪ Groundwater output down-gradient (horizontal or vertical) ▪ Surface water outputs downstream	▪ Evapo-transpiration (catchment). ▪ Local groundwater and surface water abstractions (Envirocheck search) ▪ Groundwater output down-gradient ▪ Surface water outputs downstream

Table 1
Water balance components.

2.5 Tier 4 Assessment

In some more complex water environment settings Tier 4 assessments are potentially worthwhile. These might include sites where mitigation is considered necessary to facilitate long-term preservation (eg through installation of low permeability barriers / recharge measures to isolate a system); or where there are concerns of water environment responses to development or changing climatic conditions in the future.

Generally such assessments are likely to require hydrogeological specialists and numerical modelling, which can take a number of months to complete. Ideally at least 1 – 2 years of site specific data, about the site and its surrounding area are needed to produce a robust model.

However, computer models can still be developed with more limited data, but the confidence of the model will be lower. Such modelling can often be useful as a 'sandpit' to explore potential system changes, and as a sensitivity check of the conceptual model. For further discussion on numerical modelling, see Smith and Howarth (2011a). A case study of a Tier 4 assessment is provided in Appendix 1 for Flag Fen and discussed for Newington below.

2.6 Summary of assessment process

Stage	Outputs	Information required / collected
Tier 1	First conceptual model	Desk study (of existing and publically available information) and walkover to undertake rapid review of geological and hydrological conditions.
Tier 2	Qualitative water balance review; Refined conceptual model	More detailed review of available data (ground / surface water levels; rainfall and effective rainfall; groundwater elevations and flow directions to estimate abstraction / recharge) and, where appropriate, time limited collection of new monitoring data.
Tier 2+	Additional refinement of conceptual model based on additional monitoring data	In some cases it may be necessary to collect more data to enhance a Tier 2 water balance review or conceptual model, which doesn't quite represent Tier 3 work, but involves more monitoring data than is needed for simpler Tier 2 outputs.
Tier 3	Analytical assessment to quantify inputs, storage, movements within system, outputs from system, to reach improved conceptual model	For data required, see Table 1. This differs from Tier 2 work, as more detail is needed, in terms of analysis and understanding of the deposits to determine where the water comes from, goes to and how it moves around the system. More refined and longer duration monitoring may be required.
Tier 4	Computer based spatial model to test implications of changes to existing system (ie from development) or as a sand-pit to address specific questions (for example in relation to mitigation options – see Flag Fen case study Appendix 1)	Builds on data gathered at Tier 3 but involves use of computer models to view and analyse data in 3D and predict potential future changes.

Table 2
Outputs at each stage of the assessment process and the information required.

3 Water Environment Tier 3 Case Study

3.1 Nantwich

This case study extends the example given in Appendix 1. In that document, the results of a Tier 2 ‘water balance quantitative review’ were discussed briefly. Figure 20 illustrates the three water balance scenario locations discussed below.

It shows qualitatively the water inputs and outputs to the perched groundwater system at different times of year, and different locations away from the River Weaver (Scenarios A to C).

Each of these scenarios is described below in more detail, providing a way to understand when and where water systems may be under stress (either throughout the year, or during particular seasons / circumstances). This enables additional monitoring and any further investigation (to gather quantitative data for a Tier 3 assessment and design of potential mitigation measures) to be targeted better.

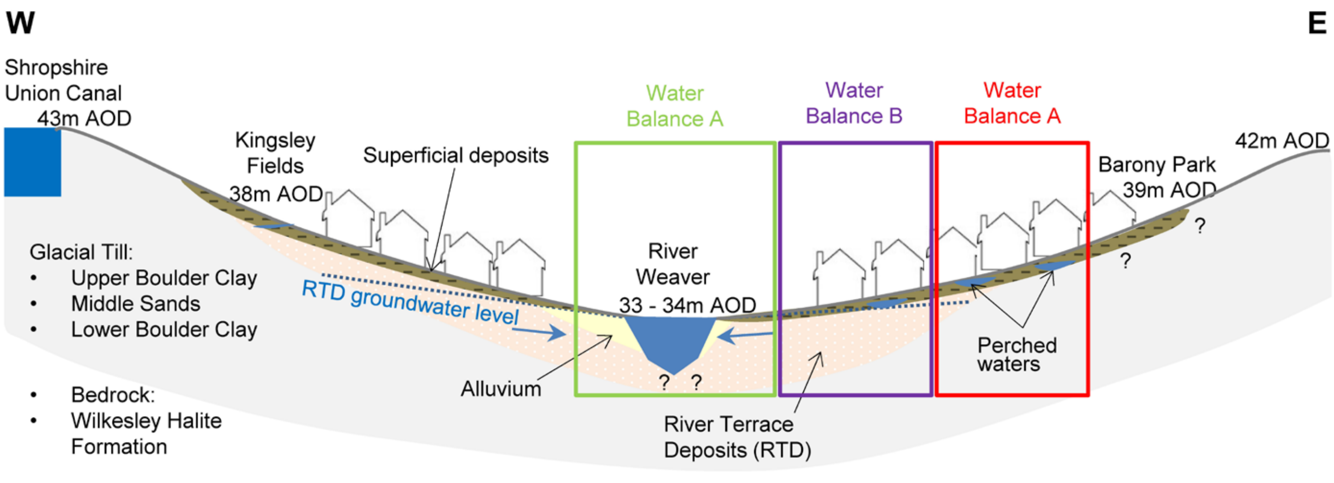


Figure 20
Water balance scenario locations.

3.2 Water Balance Scenario A

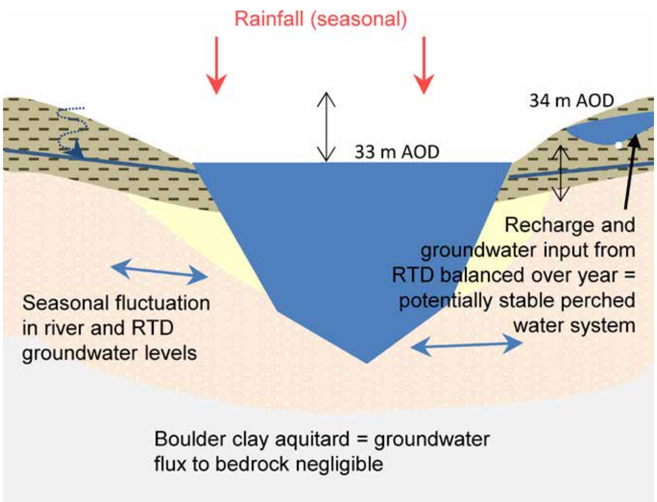


Figure 21
Water Balance Scenario A.

Winter

- RTD / alluvium – input from river (groundwater level rise)
- Recharge – overland flow to river (little direct infiltration to organic deposits)
- Perched waters in soils – inputs > outputs. Water levels in RTD likely to be close to ground surface (ie no separate perched waters), plus likelihood of flooding from the river
- Water balance in organic deposits – OK

Spring / Autumn

- RTD / alluvium – average groundwater levels (little hydraulic gradient between groundwater and river)
- Recharge – slow infiltration (due to waterlogged soils) through to overland flow
- Perched waters in soils – inputs = outputs (approx). Water levels in RTD falling, but some infiltration and drainage from previously water logged soils. Returning to perched water conditions
- Water balance in organic deposits – OK

Summer

- RTD / alluvium – output to river (groundwater level fall)
- Recharge – little to no direct infiltration through organic deposits
- Perched waters in soils – inputs < outputs. Water levels in RTD falling creating small downward gradient from perched waters (slow drainage to RTD). No inputs from recharge, may be slow development of Soil Moisture Deficit
- Water balance in organic deposits – limited temporary water stress

3.3 Water Balance Scenario B

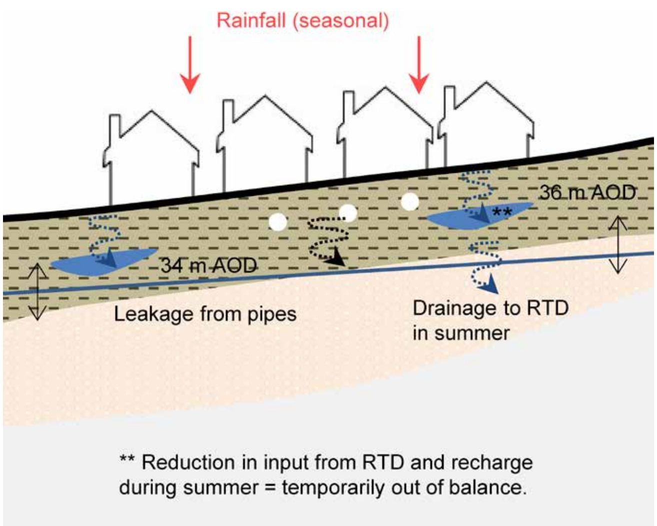


Figure 22
Water Balance Scenario B.

Winter

- RTD – groundwater level rise. May potentially rise above base of organic deposits
- Recharge – some rainfall infiltration (predominantly via open spaces) and leakage from pipes
- Perched waters in soils – potentially may have some input from RTD groundwater if levels rise high enough
- Water balance in organic deposits – may possibly be ok in some areas, under stress in other areas

Spring / Autumn

- RTD – average groundwater levels, likely to be falling below base of organic deposits
- Recharge – slow infiltration to little infiltration. May be some leakage from pipes
- Perched waters in soils – inputs < outputs. Water levels in RTD falling creating small downward gradient from perched waters (slow drainage to RTD). Returning to perched water conditions
- Water balance in organic deposits – likely to be under stress, particularly in dry winter years

Summer

- RTD – groundwater level fall below base of organic deposits
- Recharge – no direct infiltration through organic deposits. May be some limited leakage through pipes
- Perched waters in soils – inputs < outputs. Water levels in RTD falling creating larger downward gradient from perched waters (slow drainage to RTD). No inputs from recharge, development of Soil Moisture Deficit likely (particularly in drought years)
- Water balance in organic deposits – likely to be under stress for majority of summer period

3.4 Water Balance Scenario C

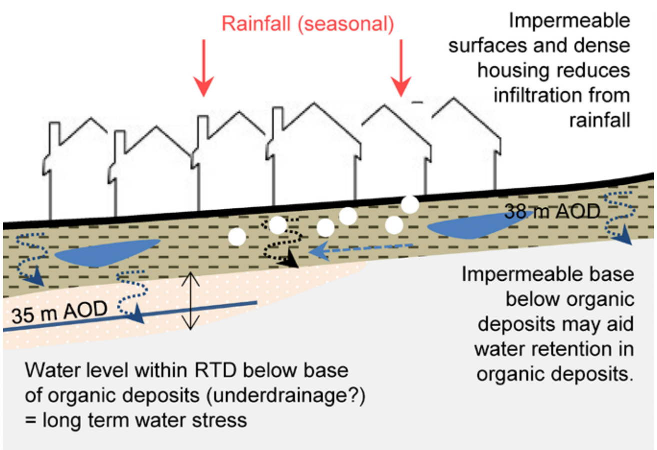


Figure 23
Water Balance Scenario C.

Winter

- RTD – groundwater level rise, but less likely to rise high enough in organic deposits to intersect perched waters
- Recharge – limited direct recharge due to impermeable surfacing and reduction in open space areas. Predominantly recharge from leakage from pipes
- Perched waters in soils – if underlain by RTD are likely to be underdrained. If underlain by lower permeability Boulder Clay then increased possibility that recharged water might be retained as perched in organic deposits
- Water balance in organic deposits – potentially in long term stress in areas underlain by RTD

Spring / Autumn

- RTD – average groundwater levels, below base of organic deposits
- Recharge – little infiltration to no infiltration (particularly in drought years). May be some leakage from pipes
- Perched waters in soils – inputs < outputs. Long term underdrainage if underlain by RTD. Improvements in utility pipework would reduce leakage, also putting perched waters underlain by Boulder Clay deposits at risk (particularly in drought years)
- Water balance in organic deposits – potentially in long term stress, particularly in dry winter years

Summer

- RTD – groundwater level at greatest depth below base of organic deposits
- Recharge – no direct infiltration through organic deposits. May be some limited leakage through pipes
- Perched waters in soils – inputs < outputs. Water levels in RTD falling creating larger downward gradient from perched waters (slow drainage to RTD). No inputs from recharge, development of Soil Moisture Deficit likely (particularly in drought years)
- Water balance in organic deposits – likely to be under stress for majority of summer period, but more severe stress in drought years

3.5 Next Steps – Developing and implementing a Tier 3 assessment

The Tier 1 and 2 assessments have confirmed the presence / distribution of waterlogged organic deposits across Nantwich. They have demonstrated that whilst some organic deposits are unlikely to be in a significant water stress situation, others (particularly at distance from the River Weaver) may potentially be experiencing significant water stress (at different times of year, or alternatively year round). Long-term water stress areas may be marginal in terms of a sustainable water balance to support the long term preservation of waterlogged archaeological remains (particularly if climate change is taken into account).

The assessment undertaken in the first two tiers has focused on higher level mapping, coring and a limited amount of monitoring data to identify the occurrence and potential origin of such deposits, as well as potential water levels within them.

For the future long-term management of these deposits, it is important to understand and quantify local water balances in areas where Tier 2 assessment suggests water balances are under significant stress throughout the year. Such information may aid in the design of mitigation measures, enable more focused comment on development proposals, or confirm any areas that have become marginal in terms of their ability to sustain waterlogged conditions.

To provide that information, a Tier 3 assessment could:

- Confirm the degree of underdrainage to the RTD from organic deposits – this can be identified through monitoring of fluctuations in RTD water levels against the elevation of perched waters / base of organic deposits. This may require additional monitoring and drilling.

- Compile a recharge map (for incorporation as a refinement to the GIS database of the distribution of organic deposits) – this would require consideration of the distribution of surfacing and utilities. Mapping could potentially comprise assignment of recharge as a percentage of effective rainfall based on land-use, then add in a % assumption on leakage to give an estimate of recharge (or purely rate as high, moderate, low recharge) to overlay as a map against waterlogged deposits.

- Consider of the effects that a management strategy or Sustainable Urban Drainage System (SUDS) might have – will it be any use in an area of underdrainage, such as where deposits are underlain by RTD? Might be more successful where deposits are underlain by Boulder Clay.

- Produce a quantification of water balances in identified areas with high risk of water stress.

What additional information may need to be gathered to inform such a Tier 3 assessment?

- Groundwater level monitoring in organic deposit dip wells over time.
- RTD monitoring wells measured over time / space.
- Water / sewer pipe plans – the local authority surface water management plan should have these aspects documented.
- Land use plans (particularly zones of impermeable surfacing) – Environment Agency flood risk studies should provide useful information in this regard.
- Effective rainfall data over the course of a year (min, max, average over a 10 year period or so) from the Meteorological Office.
- Soakaway tests – infiltration characteristics.

A lot of the information necessary to undertake Tier 3 assessments may be available from other third parties (such as the Local Authority and the Environment Agency), in conjunction with targeted monitoring.

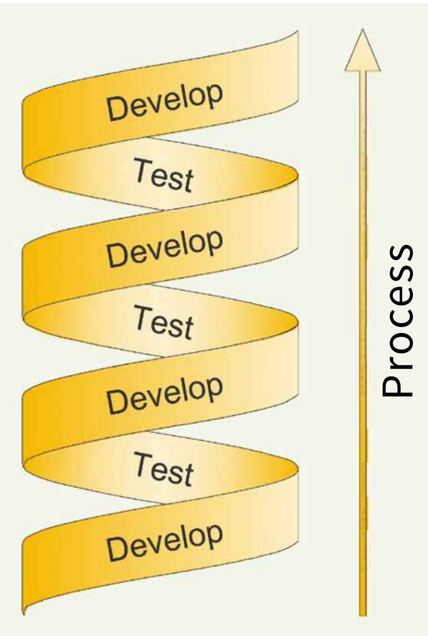
4 Water Environment Tiers 3 & 4 Case Study

4.1 Newington

The Newington case study area, located 2km east of Bawtry, in Nottinghamshire, is a site containing archaeological and palaeoenvironmental remains, preserved within peat and alluvial deposits of the River Idle floodplain. Beneath these deposits lie sands and gravels (old river terraces), and sandstone bedrock at depth.

In 2000, Hanson Aggregates began excavating the sands and gravels, dewatering the quarry to enable material to be worked dry. The potential impact of such dewatering (in combination with regional abstraction for public water supply from the bedrock aquifer) on water levels within the organic deposits was the subject of several research projects funded by the Aggregates Levy Sustainability Fund (ALSF) through English Heritage, in partnership with Hanson Aggregates, between 2006 and 2011.

The information gathered during the course of these projects falls into several tiers of assessment (as outlined above, and illustrated in Figure 24).



Updated Tier 4 assessment	See ‘Next Steps?’ section below
Updated Tier 3 assessment	As part of English Heritage research project 5792
Additional investigation and monitoring	Feb 2010 - Jan 2011: ▪ 64 piezometers (1-3m depth) in superficial soils ▪ 5 existing monitoring wells screened in sand and gravel ▪ Monthly groundwater level and *in-situ* water quality readings
Updated assessment (Tiers 3 and 4)	ALSF research project: ▪ Lillie (2007) report ▪ Golder Associates numerical model - sand and gravel aquifer focus
Initial assessment (Tier 2)	▪ Lakin (2000) report ▪ Leake (2000) report
Ground investigation	10 monitoring wells screened in sand and gravel
Desk study/Tier 1	Hanson Aggregates internal - pre 2000 (unreported)

Figure 24
Illustration of assessment tiers and previous studies at Newington Quarry.

This case study seeks to review earlier assessments and demonstrate what benefits further Tier 4 assessment could bring in terms of defining water table dynamics as part of enhancing our understanding of the potential for long-term preservation of the archaeological and palaeoenvironmental remains. As parts of the work were undertaken some years ago, this case study doesn't fit quite so precisely into definable Tiers, as set out in the guidance above, as not all work was undertaken in the order recommended. However, the concepts remain the same, and the final outputs do conform to the advice given.

4.2 Conceptual Model (Tiers 1 and 2)

The Newington site lies in the floodplain of the River Idle (Figure 25). It is a lowland river, approximately 2-3m deep, which flows roughly west to east, ultimately discharging to the River Trent. Historically flooding within the Idle catchment was exacerbated by high water regimes in the River Trent. Land drainage, regulated by the Idle and Ryton Internal Drainage Board (IDB) and Environment Agency, together with remedial works in the 1980s (comprising re-grading of the river channel and construction of a flood relief channel) have reduced the impact of flooding in the reach of the Idle's course near the site. Abstracted groundwater from the quarry site is pumped (via a lagoon) into the Slaynes Lane ditch, controlled at both ends by sluice gates that are only opened to discharge to the River Idle when additional storage capacity within the ditch is required.

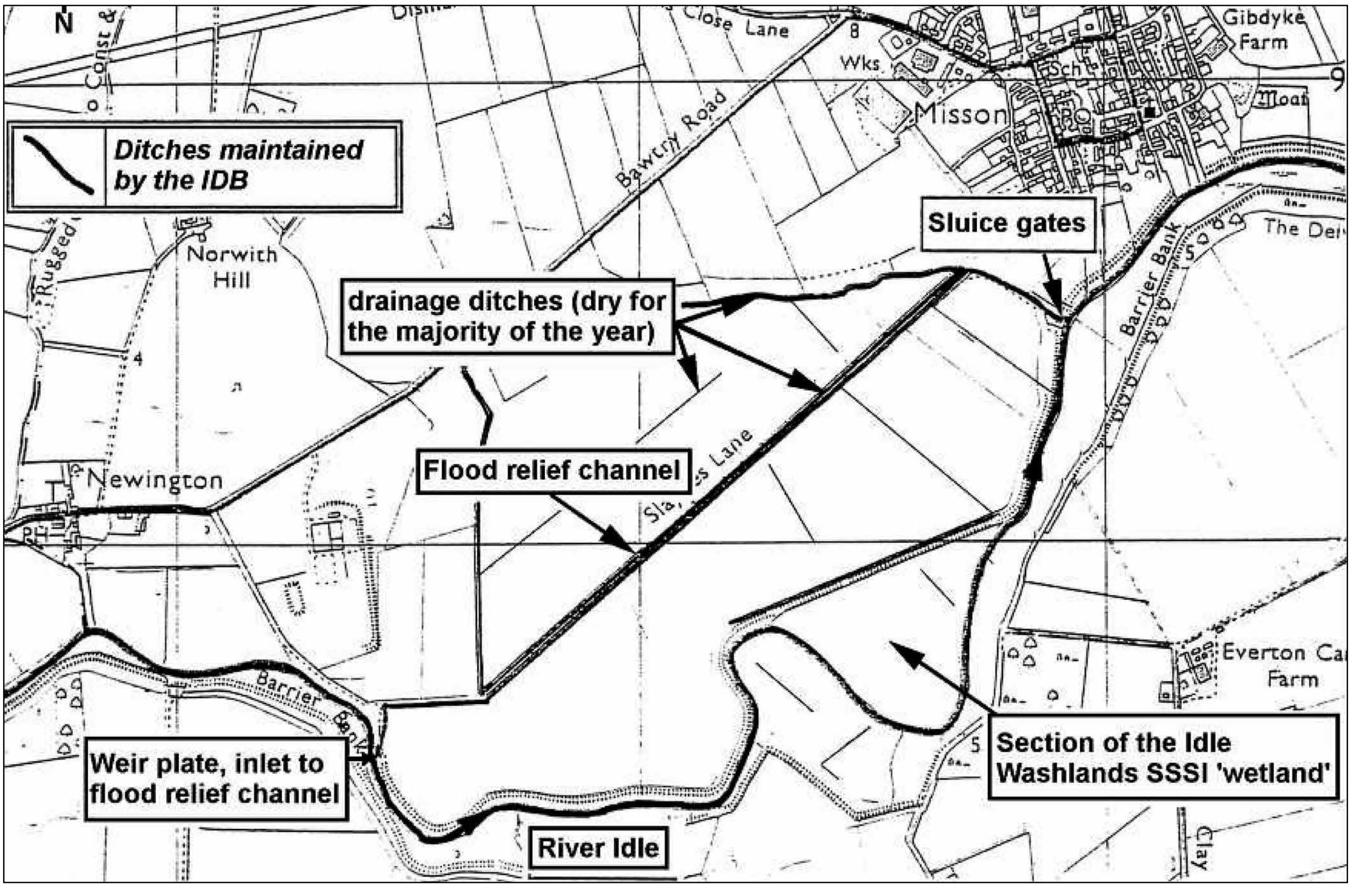


Figure 25
River Idle and drainage features in the vicinity of Newington Quarry.

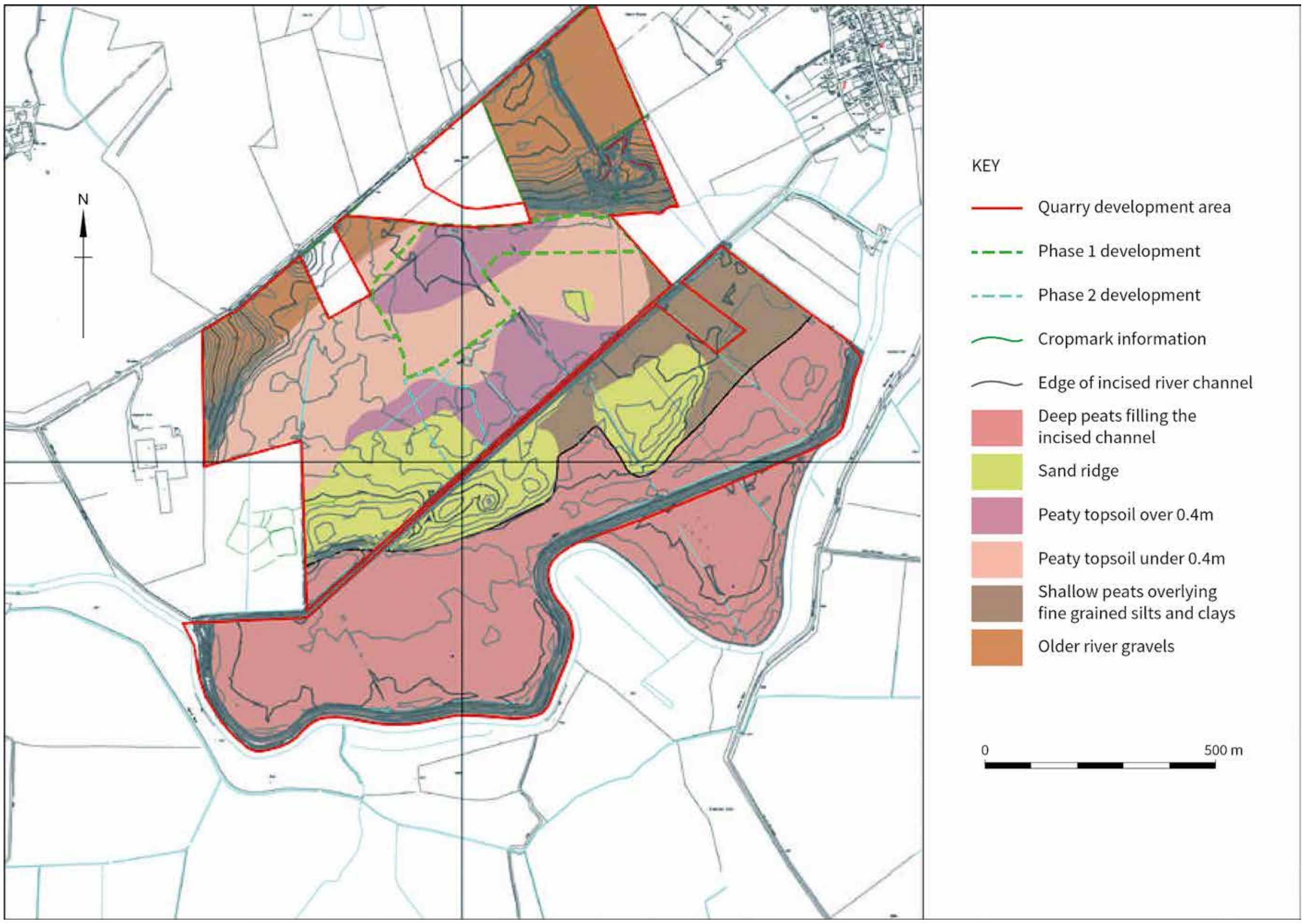


Figure 26
Superficial Devensian and Holocene units at the Newington site.

The geology underlying the Newington case study site comprises a bedrock of the Nottingham Castle Sandstone formation, overlain with Quaternary drift deposits (Older River Gravels and First Terrace deposits). Superficial deposits of the modern floodplain comprise sands, peats and alluvial deposits. The sand and gravel deposits form a ridge, upon which shallow peats and fine-grained silts and clays occur (Figure 26). Thicknesses of superficial peat and alluvial deposits recorded range from 0.6m (away from the floodplain) to 4m (within the floodplain itself).

Four broad categories of soil are found in the area:

- stony organic topsoil over sandy subsoils;
- deep, light-textured soils over the sandy ridge and terrace deposits;
- slightly stony peaty looms; and
- peaty soils associated with filled channels.

Recharge (via infiltration) from rainfall and flood inundations is likely to have led to the development of perched waters within the superficial deposits over time, creating waterlogged deposits that may have provided suitable anaerobic conditions for the preservation of waterlogged archaeological remains.

With a lack of aquitard between the Quaternary sands and gravels (RTD) and bedrock sandstone, the two aquifers would be expected to be in hydraulic continuity. The depth of the River Idle would suggest potential hydraulic connection between the river and groundwater within the sands and gravels – albeit historically the river may have been both a source of recharge or discharge from the RTD depending upon the season.

Figure 27 schematically illustrates potential 'historic' water environment conditions (prior to land drainage and abstraction from water wells), with groundwater flow within the RTD likely to be towards the river. In the past groundwater levels are expected to have been higher than observed currently. In some areas of the Newington site this may have potentially placed the water table within the overlying superficial deposits, aiding the saturation of the superficial deposits / maintenance of perched waters in combination with infiltration from ground level.

In 2000, prior to quarrying at Newington, groundwater levels within the sand and gravels at the site showed flow in a north-west direction, away from the River Idle, with levels ranging from -0.75m OD to +1.0m AOD across the site (Figure 28). Located a few kilometres north-west in the vicinity of Austerfield, two major public water supply wells drew approximately 10 million m^3/year (approximately 27,000 m^3/day) from the sandstone aquifer at depth (Figure 29).

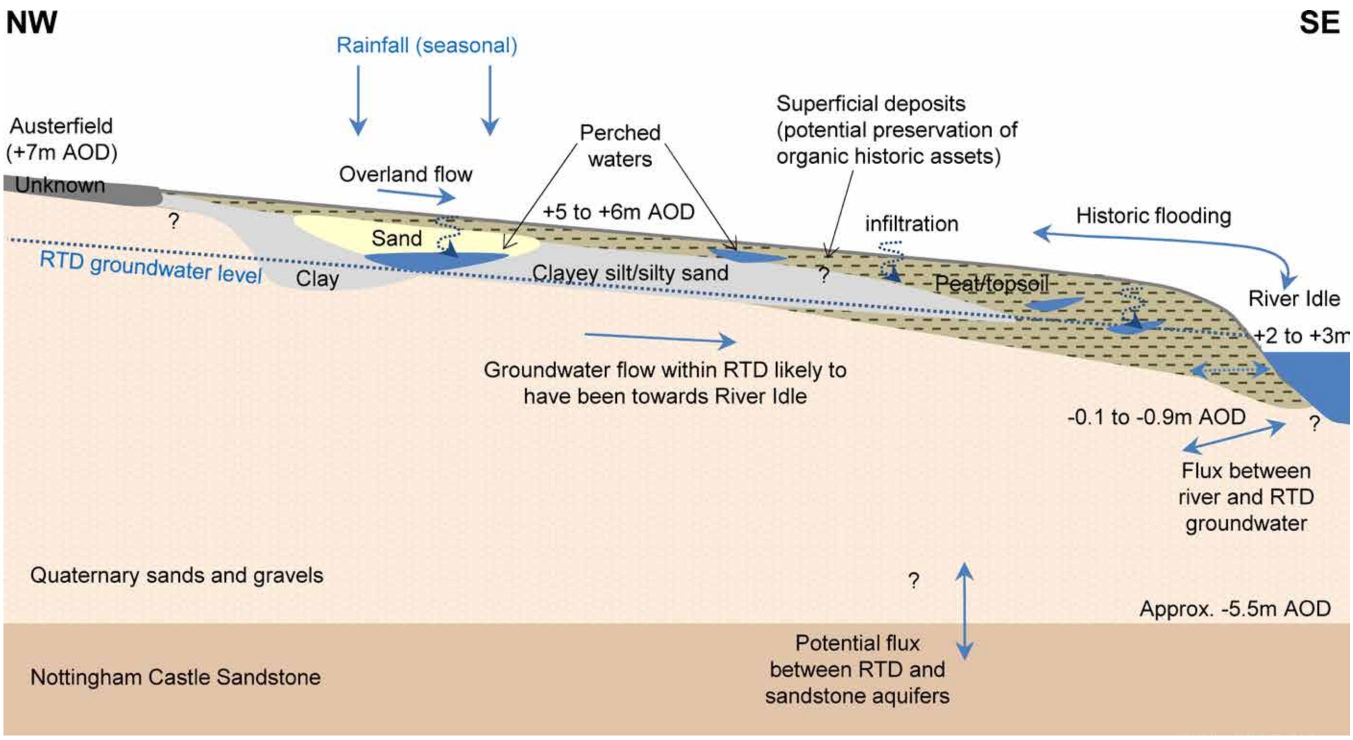


Figure 27
Conceptual model – potential historic water environment conditions.

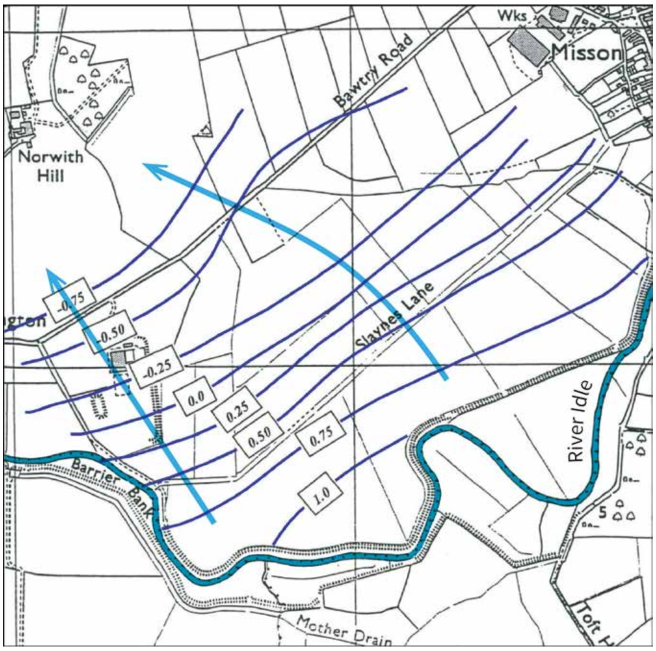


Figure 28
Sand and gravel groundwater level contours (m AOD).

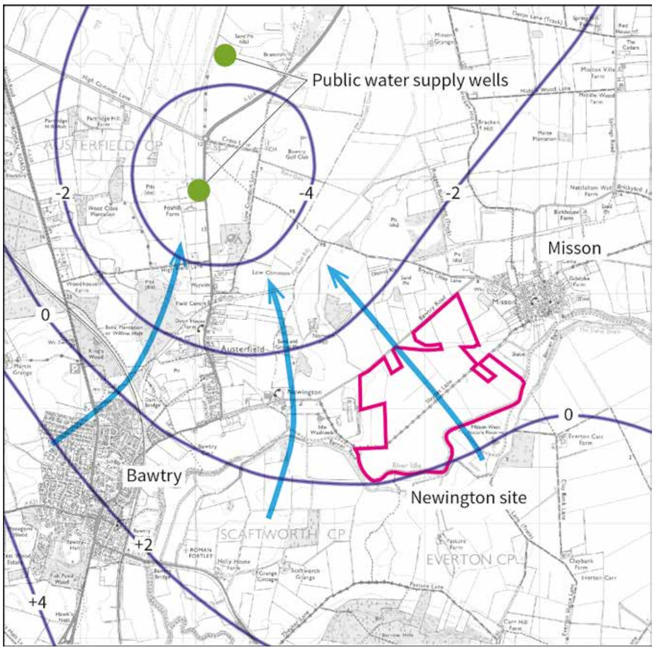


Figure 29
Sandstone groundwater level contours (m AOD).

The impact of abstraction from the public water supply wells led to depressed regional groundwater levels both in the sandstone and overlying RTD (as groundwater is drawn into the sandstone aquifer as a vertical downwards hydraulic gradient develops when groundwater is abstracted from the bedrock sandstone (Figure 30).

Conceptually water levels in the River Idle would remain higher than those in the RTD throughout the year, as such acting as a recharge source.

In terms of waters within the superficial deposits, the construction of drainage ditches and flood alleviation channels may enhance infiltration to deposits in close proximity to the ditches (and at greater depths) but the reduction in general flood inundation may potentially have reduced the amount of more widespread shallow infiltration that characterised 'historic' water environment conditions.

The drop in RTD groundwater levels to below the perched water within the superficial deposits is likely to have removed significant groundwater input (even if it was only a small component of support to the superficial deposits historically), plus the vertical gradient induced between waters within the RTD and waters within the superficial deposits may have led to a component of underdrainage from the superficial deposits.

Figure 31 schematically illustrates the potential conceptual model where water environment conditions are impacted by both abstraction from the public water supply wells and from quarry dewatering (to -3.5m AOD) at the Newington site.

Results of the numerical modelling of groundwater flow within the RTD aquifer (Figure 32), undertaken by Golders Associates (2006), suggest that the zone of dewatering influence associated with Newington Quarry is small when compared to the Austerfield wells (reflecting the smaller volumes of water abstracted at the quarry site).

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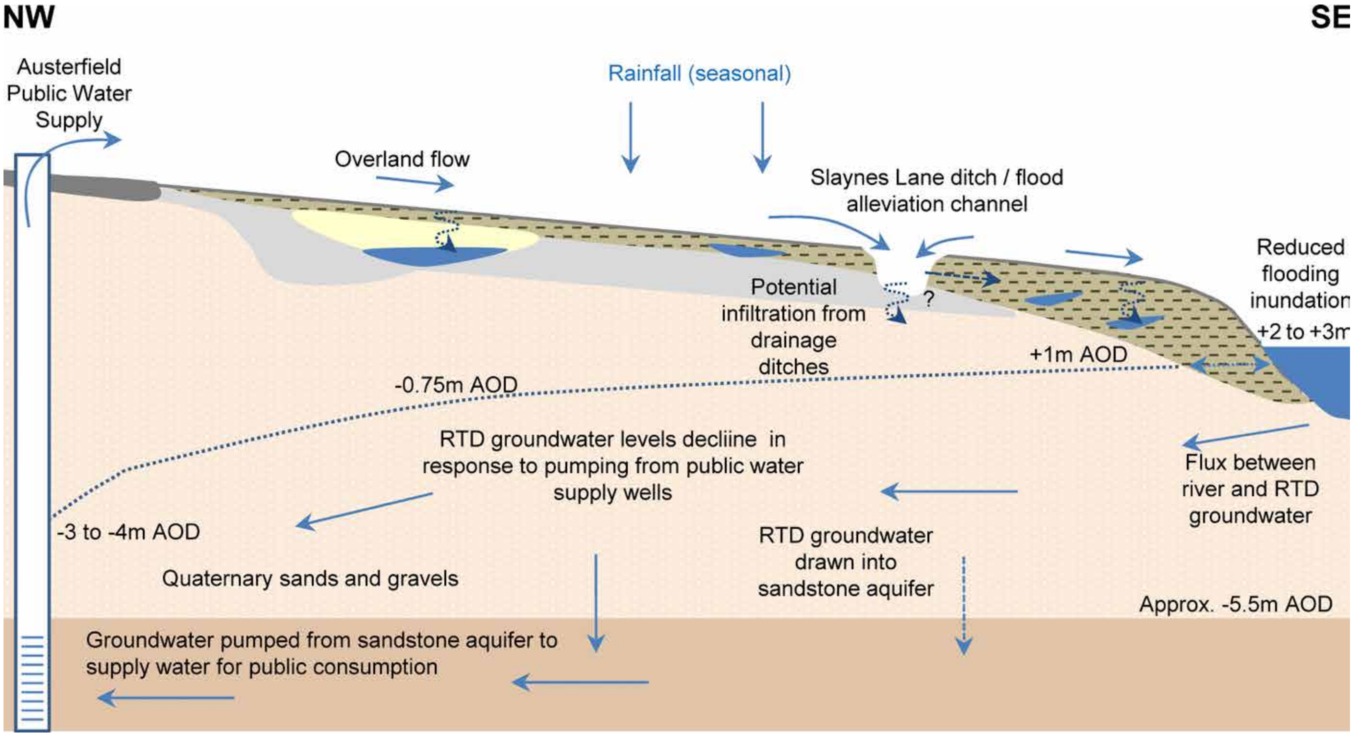

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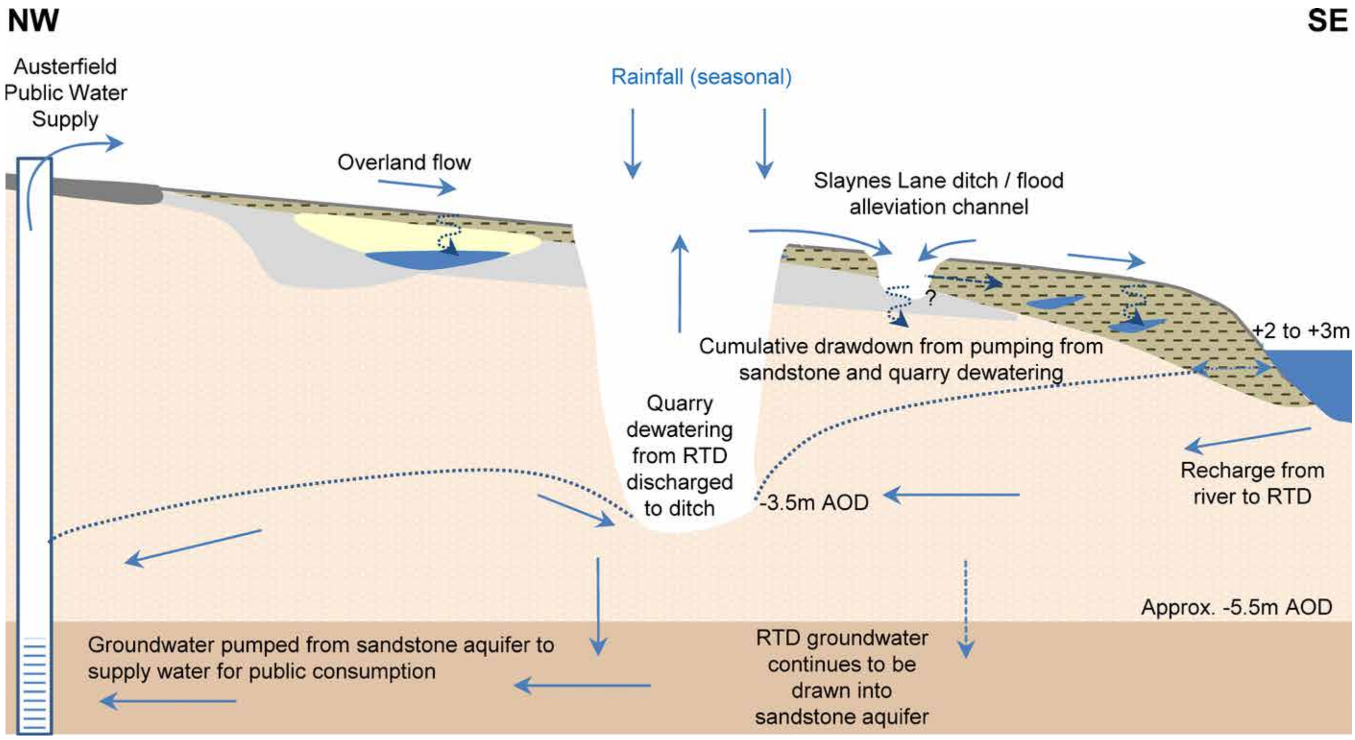

Figure 30
Conceptual model - Pre-quarrying, public water supply impact only (c 2000).

Figure 31
Conceptual model – Combined quarry dewatering and public water supply abstraction.

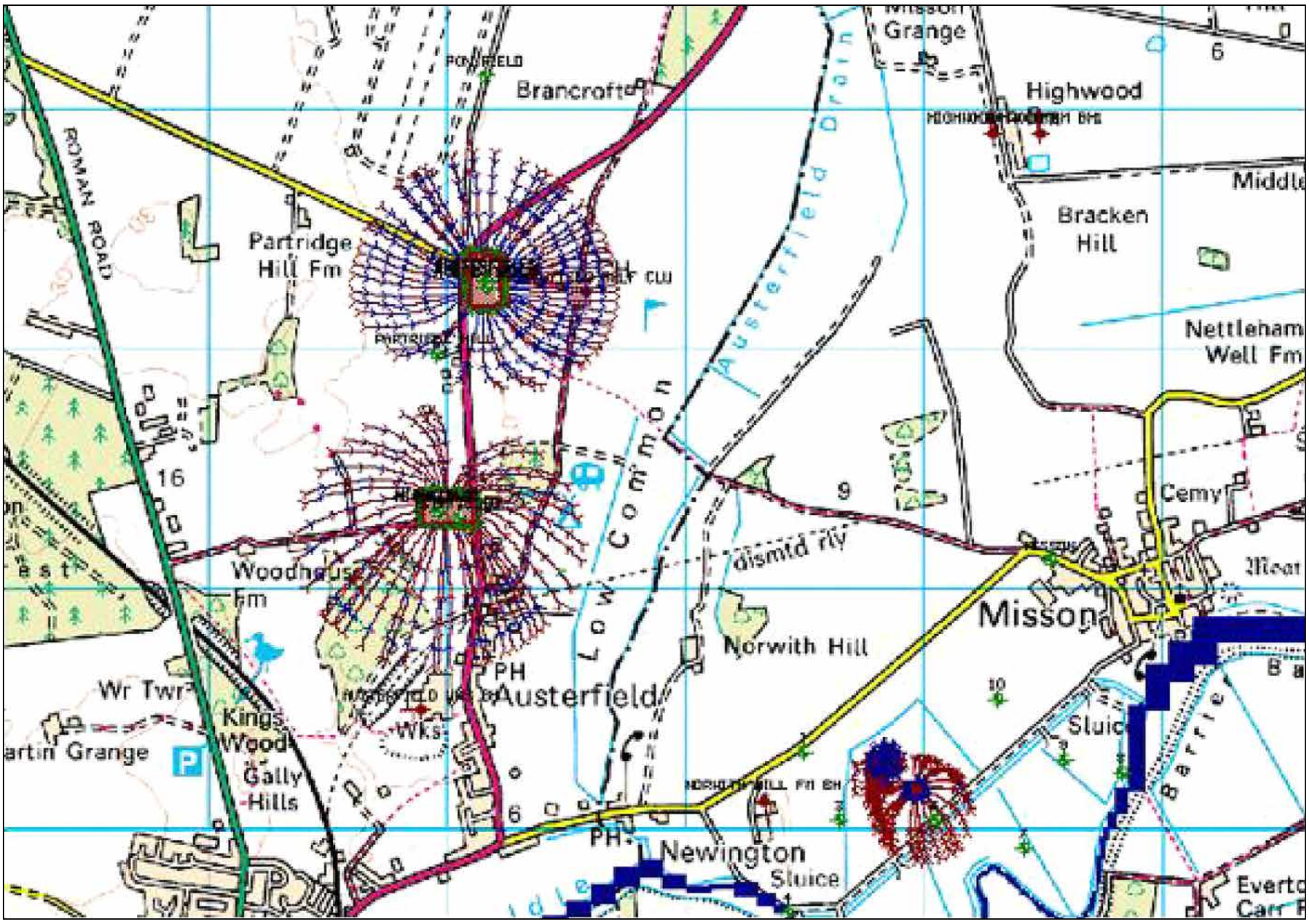

Figure 32
Predicted particle pathlines from ModFlow numerical model indicating influence of public water supply wells and Newington Quarry dewatering.

However, the drawdown from quarry dewatering at the Newington site superimposed upon the background depression in groundwater levels in the RTD due to public water supply abstraction, has potentially led to enhanced drawdown in groundwater levels in the RTD in close proximity to the quarry. Albeit the extent of such impact is likely to have been reduced due to presence of the River Idle as a source of recharge.

In terms of waters within the superficial deposits (the zone of primary interest with respect to the long-term preservation of waterlogged archaeological remains) theoretically groundwater inputs from the RTD may have been small historically, and since the commencement of abstraction from public water supply wells in the sandstone, groundwater input from the RTD to the superficial deposits is likely to have been even less. As such the enhanced local drawdown in the RTD due to quarry dewatering may potentially have had only a limited (to negligible) impact on the water balance within the superficial deposits prior to quarrying.

Discharge of dewatered groundwater from the quarry to Slaynes Lane ditch may potentially act as a local source of recharge to the superficial deposits, depending upon the degree of hydraulic connection between the ditch system and the peats / alluvial deposits. The degree to which this may, or may not, occur, and the relative contributions of RTD groundwater to rainfall infiltration in terms of water levels within the superficial deposits, was not explored in the 2006 / 2007 research undertaken by Lillie and Smith (2007).

To enhance the conceptual understanding of the water environment mechanisms influencing groundwater within the superficial deposits, in particular to record the relative variance in levels and water quality (key components in terms of understanding the future preservation potential of the superficial deposits), further investigation and assessment at the site was undertaken between 2010 and 2011. Details of the monitoring, and a brief summary of the assessment, are outlined in the next section.

4.3 Additional Ground Investigation and Review 2010 – 2011 (Tier 3)

In 2010 a network of 64 piezometers were installed within the superficial deposits (at 1m, 2m and 3m depths) to complement the five RTD monitoring wells of Newington Quarry (Figure 33). Groundwater levels in all monitoring points were recorded (by manual dipping) on a monthly basis between February 2010 and January 2011.

In addition, on each monitoring occasion *in situ* water quality measurements were recorded for pH, temperature, Oxygen Reduction Potential (ORP) and Electrical Conductivity (EC). Water quality results are not discussed within this case study. For further information the reader is referred to Smith and Howarth (2011b).

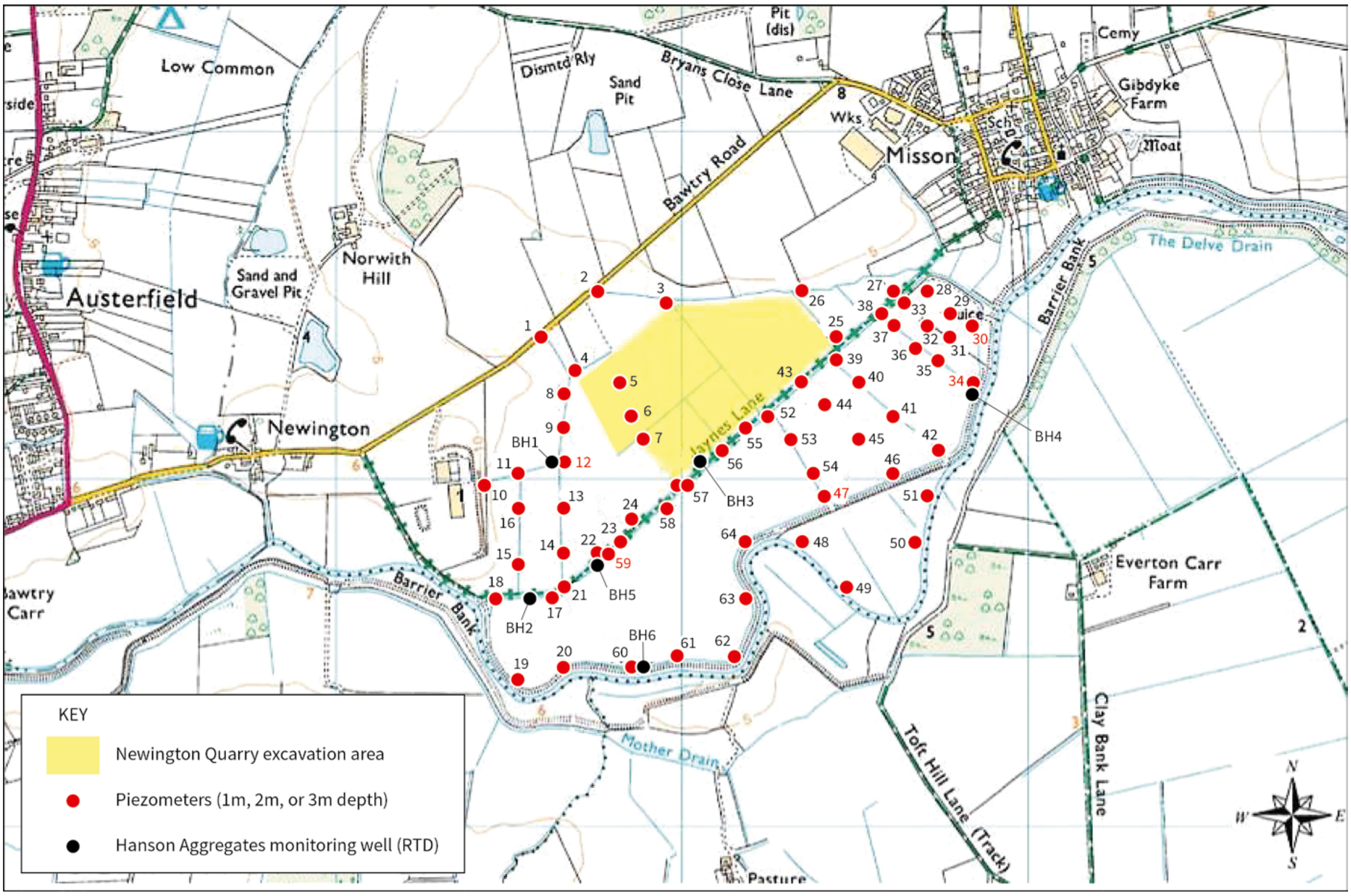

Figure 33
Newington Quarry monitoring network (2010 – 2011).

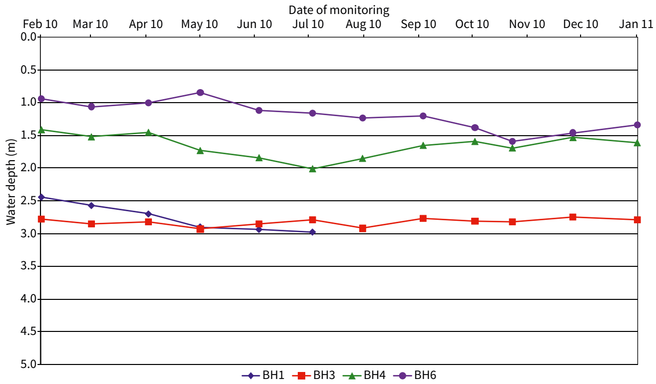

Figure 34
Sand and gravel aquifer groundwater depths (m) in piezometers 3 (red), 4 (green) and 6 (purple).

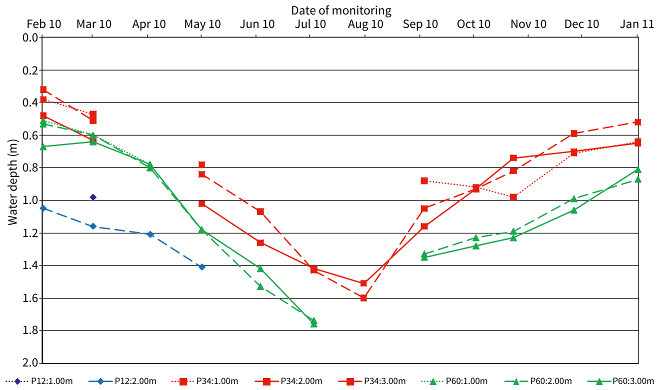

Figure 35
Superficial deposit groundwater depths (m) in piezometers 12 (blue), 34 (red) and 60 (green).

4.4 Sand and gravel groundwater depths

With respect to groundwater depths within the sand and gravel aquifer, underlying the superficial deposits, monitoring over the course of 12 months (Figure 34) indicates seasonal variation during the year limited to 0.5m in boreholes adjacent to the River Idle (BH4 and BH6).

In contrast depths in BH3 (located adjacent to the extraction area) remain relatively constant (c 2.75m depth), and between 1m to 1.5m lower than levels in boreholes BH4 and BH6.

The response in groundwater depths within the sand and gravel monitoring wells, combined with observations of the spatial variation in depths, would suggest that quarry dewatering may be having an impact close to the extraction site. However, further away from the extraction area seepage from the River Idle may be acting as a source of recharge tempering the potential extent of dewatering influence from the quarry. This would support the conceptual model schematically illustrated in Figure 31.

4.5 Superficial groundwater depths

Variation in groundwater levels in piezometers at 1m, 2m and 3m depths (at individual locations across the study area, Figure 35 and Figure 36) demonstrated seasonal variation in groundwater depths. In winter months groundwater depths were shallower, varying between 0.1m and 1.0m (depending upon location). Over spring and summer months groundwater depths increased to between 1.1m and 1.9m depth (depending upon monitoring point location).

A review of groundwater depths in piezometers at different depths shows trends in water levels are mirrored in each piezometer, with less than a 0.2m difference between water levels recorded at different depths (Figure 35). This could suggest an element of vertical hydraulic connection between the soil horizons. Groundwater depths in the deepest superficial deposit piezometers are generally lower than levels within the shallower piezometers, suggesting limited upward groundwater flux from the sand and gravel aquifer into the superficial deposits.

A comparison of the seasonal variation in groundwater depths recorded in the superficial deposits (~1m) versus that recorded in the sand and gravel aquifer (~0.5m), together with a comparison of groundwater depths in the sand and gravel aquifer (1m to 1.5m, similar to groundwater levels recorded during summer months in the superficial deposit) would suggest that the superficial deposits groundwater system is predominantly rainfall-fed.

Figure 35 presents groundwater depth results for piezometer P12 (located 200m west of the extraction), versus piezometers P34 and P60 (located adjacent to the River Idle). During winter months groundwater depths in the piezometers adjacent to the river are less than 1m, whilst depths away from the river (and closer to the excavation) are greater than 1m. This may potentially be indicative of underdrainage of the superficial deposits via the underlying RTD, local to the excavation area where quarry dwatering is taking place, and / or recharge influence of the River Idle locally elevating levels in close proximity to the river.

One aspect of uncertainty in the conceptual model illustrated in Figure 31, was with respect to the potential for recharge from the ditch / drainage system (in particularly the Slaynes Lane ditch that is used for discharge of groundwater from quarry dewatering operations). Figure 36 compares results from piezometers P30 (adjacent to the River Idle), P47 (adjacent to a ditch / flood alleviation channel), and P59 (adjacent to Slaynes Lane ditch). Quarry dewatering discharges are retained within the Slaynes Lane ditch, eventually soaking into the surrounding soils, unless additional storage capacity is required, necessitating the opening of the sluice gates and discharge to the River Idle.

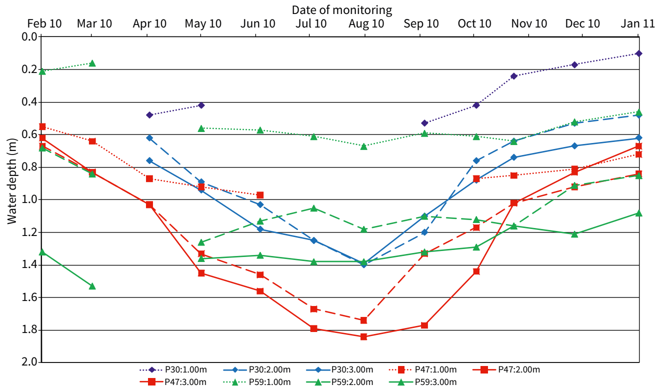

Figure 36
Superficial deposit groundwater depths (m) in piezometers 30 (blue), 47 (red) and 59 (green).

Groundwater depths within piezometer P30, adjacent to the river, reflect groundwater depths recorded at other parts of the site and the seasonal variation attributed to rainfall variation during the course of the year.

Within piezometer P47 (inland from the river but adjacent to a ditch), a similar seasonal pattern in groundwater depth is noted, albeit groundwater depths that are lower than those of P30. This may suggest that the recharge influence of the river does not stretch as far as this location, and that any seepage (from short-term periods of rainfall / overland flow) through the ditch does not significantly influence groundwater depths.

In the case of piezometer P59, adjacent to Slaynes Lane ditch, groundwater depths recorded are not demonstrating a strong seasonal influence. This could suggest that the relatively constant water level maintained in the Slaynes Lane ditch, through near-continuous discharge, is acting as a source of recharge locally, maintaining a shallow water table within the top 1m of the superficial deposits.

4.6 Next Steps – Further Tier 4 numerical modelling

Hydrogeological monitoring of the groundwater boreholes located within close proximity to the Newington Quarry site has indicated that groundwater depths within the sand and gravel aquifer close to the quarry are approximately 1m lower than those adjacent to the River Idle. Numerical modelling, in combination with monitoring, has demonstrated the influence abstraction (from both public water supply and local quarry dewatering) has had on such groundwater levels locally in the sand and gravel aquifer. As a result the water table within the superficial deposits is potentially separated from groundwater within the underlying sand and gravel aquifer for the majority of the year.

The results of monitoring groundwater depths within the superficial deposits would suggest that the system is predominantly rainfall-fed, as opposed to groundwater-fed. Water levels within the majority of the surface peat deposits are below 1m for most of the year, with the exception of an area near the Slaynes Lane ditch where near-continuous quarry dewatering discharge has potentially acted as a source of recharge.

In situ water quality results suggest potentially good conditions for the long-term preservation of archaeological and palaeoenvironmental material within the study area. However the fluctuations in the height of the water table (of nearly 1m in the peat deposits) between the summer and winter months have the potential to lead to a deterioration in conditions over time.

In terms of management of these waterlogged organic deposits in the longer term, further assessment could be undertaken to refine (and quantify) the understanding of water balances within the superficial deposits, and to explore the potential for passive / active mitigation measures that may minimise the fluctuation of groundwater levels during the course of the year.

This could include building upon the existing 2006 regional groundwater flow model (ModFlow), focusing on the superficial deposit layer (assuming a horizontal continuity within the superficial deposits is demonstrated). Alternatively (or in combination) it may be appropriate to build a 'superficial deposit' focussed groundwater model, utilising software appropriate to modelling wetlands on a local, smaller level (eg MIKE-SHE software) that may be possible / appropriate in the regional model.

As well as improving conceptual understanding of a groundwater system, numerical models can be used as 'sand-pits' to explore potential responses to changes in the water environment that may usefully inform the decision-making process with respect to the potential long-term preservation and management of the Newington site. For example:

- Will groundwater levels within the sand and gravel partially recover when quarry dewatering ceases? If so by how much, and how long will it take?
- If groundwater levels within the sand and gravel aquifer recover following the cessation of quarry dewatering, are they likely to rise high enough within the overlying superficial deposits to contribute significant quantities of groundwater?
- Modelling different mitigation measure options to assess the relative benefits in terms of water level response

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