Quantifying Dynamic Baseline Water Environment Conditions in Sand and Gravel Extraction Areas in order to Assess the Potential Impact of Water Drawdown upon Historic Environment Assets

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Volume 2 Case Studies of Newington and Over Quarries

(Separately reported)

1. TERMS OF REFERENCE

1.1 The concept of a 'dynamic baseline' was identified originally in Capita Symonds' 2007 report[1] to the Department of Communities and Local Government (DCLG) which outlined policy recommendations for a water environment annex to Minerals Planning Statement (MPS) 2[2]. The report recommended that 'environmental effects, mitigation measures and opportunities for improvement should all be judged against the backdrop of changing environmental conditions brought about by the variety of land use and climatic changes within the area concerned'.

1.2 The purpose of the recommendation was to make sure that:

1) Regulators (including English Heritage Case Officers and Local Authority Archaeological Officers) and land-use planners are able to gain an improved understanding of the dynamic nature of the baseline conditions of the water environment against which applications are assessed;

2) Mineral operators are not unreasonably held to account for environmental changes for which they are not responsible; and

3) That the effects which quarrying may have upon the water system are considered in combination with the likely impacts from other water environment users (e.g. Public Water Supply [PWS] wells, engineering works, underground mining, etc.), when proposals for future mineral extraction are first being considered.

1.3 This is further highlighted by the emphasis that the European Union Water Framework Directive (WFD)[3] places on a more holistic and integrated catchment management approach of our water resources. In order to meet the aims of the WFD, land use planning and management decisions need to be based upon sound scientific understanding at both a local and catchment-wide level.

1.4 Regulators, land use planners and developers (including mineral operators) are increasingly being confronted with the need to understand the likely changes in background water environment conditions in advance (or constraints in predictions) when assessing the potential future effects of mineral extraction and / or associated restoration schemes on groundwater and surface water flow regimes (and associated receptors who may be sensitive to changes in the water environment).

1.5 This understanding needs to take account, not only of the latest available climate change scenarios (both natural and anthropogenically induced), but also of other known land use and development proposals (e.g. PWS wells, engineering works, underground mining, etc.) within the surrounding area that may contribute to changes in water environment baseline conditions.

1.6 Before predictions of likely change in water environment conditions can be made, however, it is important to both determine and understand the recent dynamics of these conditions within the local catchment. In particular, it is important to differentiate between natural and anthropogenic influences in order to appreciate the type of background changes that might occur, irrespective of a proposed (or existing) quarrying operation.

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[1] Thompson et al., 2007

[2] DCLG, 2006

[3] European Commission, 2000

Requirement for Research

1.7 The number (and, in some cases, complexity) of many assessment tools and hydrological models can often distract from the primary aim of assessing any development-led operation in terms of the significance of the impact upon the water resource within a particular catchment.

1.8 It was therefore felt that there is a need to develop a simple but reliable 'user-friendly' methodology that assists in the basic interpretation of water environment monitoring data (and facilitates communication of such information) without the immediate requirement for complex analysis or numerical modelling. Such a methodology should be aimed at providing results which can be understood by a non-specialist target audience (including English Heritage case officers, land use planners, elected members and the general public).

1.9 It is considered that a draft methodology to quantify dynamic baseline water environment conditions may provide a useful tool for screening sites, providing an initial assessment of potential impacts, and / or indicating where additional analysis and / or monitoring data may be needed.

1.10 The following issues need to be better understood by all parties and in order to evaluate more complex groundwater / surface water impacts (and the need for additional analysis):

- Highlight the primary water balance impacts associated with different anthropogenic influences;
- Indicate areas of conceptual uncertainty within a water environment system that may require further investigation / study; and / or
- Prompt more targeted assessment / numerical modelling where it is considered necessary and appropriate to do so (based on a cost-benefit assessment).

1.11 There is also a need to better understand how water environment baseline conditions might broadly be expected to change in the future, and inform the development of a framework against which this 'dynamic baseline' can be monitored.

1.12 It was felt that the development of a Dynamic Baseline Methodology (DBM) that is designed with the foregoing points in mind, may assist in improving communication of our understanding of fluctuations within baseline water environment conditions and their subsequent impact upon both the historic and environmental resource, enabling proportionate response and targeted monitoring / modelling where it is necessary.

Project Aim

1.13 Bearing in mind the research requirements outlined above, the over-arching aim of this research project was to develop a draft DBM that assists in the basic interpretation of water environment monitoring data in order to differentiate background changes (both natural and anthropogenic) in the water environment within sand and gravel deposit areas.

1.14 Such a methodology would aim to be simple but reliable, 'user-friendly', and without the immediate requirement for complex analysis or numerical modelling. It was hoped that such a methodology would aid the assessment of the extent to which such changes in the water environment may impact upon the historic environment resource located within these areas.

Project Objectives

1.15 The initial objectives of the project (as outlined in the original research proposal) fell into three main stages of work, which are summarised as follows:

Stage 1 - Development of a draft generic DBM

Existing water balance / level spreadsheet models would be reviewed in order to identify their ability to be tailored for use in determining water environment baseline conditions; historic case studies would be looked at to try to determine the relative influence of natural (climatic and seasonal) variations and anthropogenic controls on the surface and sub-surface water environment, and a draft methodology would be produced for defining the dynamic baseline of the water environment within an area that is currently being actively quarried, or an area of preferred mineral working.

Stage 2 - Undertake high-resolution, baseline hydrological and water chemistry monitoring programmes at two case study sites

These would be where proven historical environment assets are located in close proximity to areas of current / future mineral working and would contribute to understanding how a draft DBM might be developed by collecting data.

Stage 3 - Refine the water balance components of the draft DBM

This would be done by utilizing the data collected during Stage 2, to produce technical and non-technical reports which set out the major findings of the work and recommendations for how this methodology might be tested in different hydrogeological settings in the future.

1.16 During development of the project, these objectives naturally evolved in order to accommodate the findings from the various stages of the work. As a result, the revised objectives (which link to the major sections of this report) are:

Stage 1 - Defining the requirement of a draft generic DBM

Review the existing water balance / level spreadsheet models to identify their ability to be tailored for use in determining water environment baseline conditions; work towards a draft methodology for defining the dynamic baseline of the water environment within an area that is currently being actively quarried, or an area of preferred mineral working.

Stage 2 - Undertake high-resolution, baseline hydrological, hydrogeological and water chemistry monitoring programmes at two case study sites

Perform a background study and carry out the monitoring at sites where proven historical environment assets are located in close proximity to areas of current / future mineral working and that would contribute to understanding how a draft DBM might be developed by collecting data.

Stage 3 - Developing the requirements of a DBM

This would be done by utilizing the data collected during the previous stages (including input from stakeholder consultees at a research workshop held on 28th January 2011), to produce a report which sets out the major findings of the work and makes recommendations for how a methodology might be further developed and employed.

1.17 The change in emphasis of some of the original objectives, where prompted by the nature of the research, is supported by text in the main body of this report.

Scope of Report

1.18 With respect to the aim and objectives (above), this report summarises the research and findings from all stages of the project as follows.

1.19 For the benefit of the reader, Section 2 (in combination with Appendix 1) expands on some of the background water environment concepts (e.g. conceptual models, water balances, dynamic baseline, etc.) by way of introduction to later chapters.

1.20 Section 3 summarises the tasks and findings from Stage 1 of the research, focussing on the review water balance / level spreadsheet models and their ability to be tailored for use in determining water environment baseline conditions (-the full review is held within Appendix 2 for information).

1.21 Section 3 also presents the results of an inter-programme review (November 2010) of what could be achieved within the project, and better define the nature of the development of the DBM, based upon the outcomes of the research undertaken during Stages 1 and 2 of the project at that time.

1.22 Section 4 then outlines the philosophy and evolution of the draft Dynamic Water Environment Baseline Assessment Toolkit (DWEBAT), comments / views raised at the research workshop, and resultant changes to the draft DWEBAT.

1.23 Section 5, which relates to the original Stage 2 of the work, provides a summary overview of the background changes in the water environment that have taken place in the recent past around the two chosen case study sites where sand and gravel quarrying operations are ongoing. It describes the methods used during the installation of a hydrological and water chemistry monitoring grid at the sites and the subsequent monitoring to support the development of a DBM. The case studies are presented in detail in Volume 2 of this report series. Lessons learnt from the case studies in relation to the evolution of the DWEBAT (or in respect of the wider water environment in general) are also highlighted.

1.24 In concluding this report, Section 6 provides a summary and recommendations for future research (both in relation to knowledge gaps, evolution of the DWEBAT, and in respect of the monitoring dataset gathered from the two case study sites).

Research Limits and Considerations

1.25 In working towards the project objectives, there are a number of restrictions that have been placed on the scope of the research. These, as a result of the heterogeneous nature of geological deposits and hydrogeological systems, are as follows:

- Only intergranular flow systems are discussed (i.e. there is no consideration of fracture flow systems).
- Only sand and gravel deposits are considered.
- Only surface quarries are discussed (i.e. there is no consideration of underground mining).
- Although the research is primarily focused on drawdown impacts, there are other hydrological / hydrogeological impacts to be considered that are associated with quarrying operations[4], in addition to the activities of other third parties within sand and gravel deposit areas.

[4] Thompson et al., 2008

- Only heritage receptors are considered as potential targets that may be impacted upon by changes to the water environment. In reality far more receptors (including ecological, water resources, etc.) may potentially be impacted, but consideration of a greater number of receptors is beyond the scope of this research.

2. BACKGROUND CONCEPTS

Understanding the Aquifer System as Part of the Wider Water Environment

2.1 Developing a good understanding of the local aquifer system, including its relationship to surface hydrology, local hydrogeology and larger (regional) scale aquifer systems is an essential requirement for the creation of any conceptual model of the water environment[5].

2.2 A conceptual model is a written and / or diagrammatical explanation of the local water cycle based upon the assessor's knowledge to date (Figure 2.1). This includes the local groundwater and surface water regimes, their interactions with each other and with rainfall inputs, linkages to associated habitats, ecosystems and other water dependent receptors (which may include designated and undesignated historic environment assets) and users within an area.

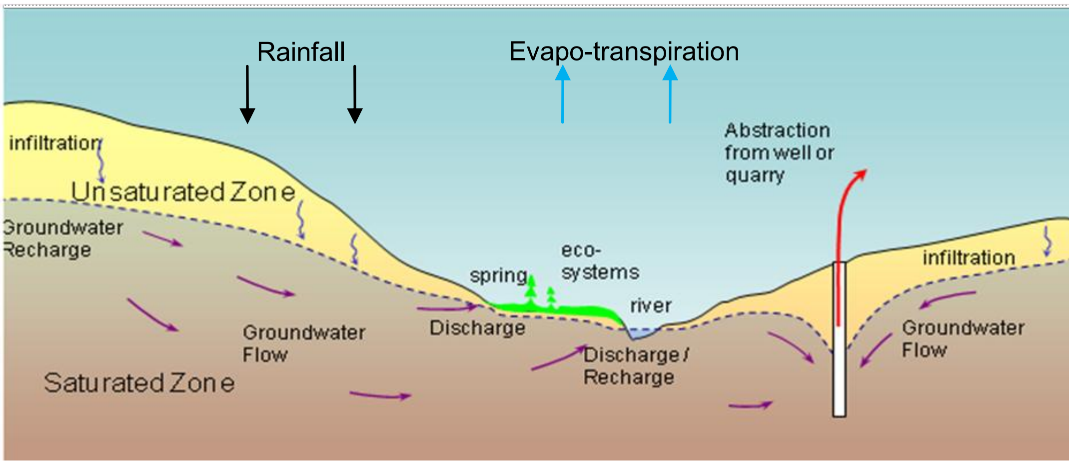


Figure 2.1 Simple conceptualisation of the local water cycle.

2.3 Conceptualisation may be purely qualitative or partially quantified based upon the amount of information / data available for a site and surrounding area. The creation of a conceptual model requires the collation of geological, hydrogeological and hydrological information, in order to provide a basic understanding of the water environment. In particular, this may enable the identification of the hydrological / hydrogeological conditions and processes in operation within and surrounding the area of interest. The degree of complexity of the system is an important consideration for the assessment of impacts.

2.4 The information that is required in order to form the conceptual model includes the following:

- The identification and hydrogeological characteristics of the different aquifer units (i.e. lithology, thickness, permeability and geological structure);
- The principal mechanism for groundwater flow in each aquifer unit (whether intergranular or fracture flow). The presence of fractures and intervening low permeability areas can also complicate water level measurement and estimation of aquifer properties. In sands and gravels in particular (which are considered within this project), flow is generally intergranular (although flow can be focused along lenses of more permeable gravels within heterogeneous deposits);

[5] Gill et al., 2008

- The extent to which groundwater is able to flow between the different units (which may be influenced by intervening geological strata of lower permeability or structural geology, such as faults); and
- The nature of interactions between groundwater and surface water bodies (including the principal areas of groundwater recharge and discharge).

2.5 Depending on the likely scale and significance of the potential risks involved, and the complexity of the systems being assessed, 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 (which may in some cases require numerical modelling). Conceptualisation is thus an iterative and cyclic process, where several iterations may potentially be necessary before sufficient confidence has been gained in order to justify planning permission being given, or precautionary mitigation measures agreed to.

Key Hydrological / Hydrogeological Concepts

2.6 Appendix 1 provides a useful reference tool to some of the basic hydrogeological and hydrological concepts referred to throughout this report. For a fuller description of water hydrological and hydrogeological processes the reader is referred to Part 1 of *Good Practice Guidance on Controlling the Effects of Surface Mineral Working on the Water Environment*[6]. Highlighted below are a few areas of error that are often commonly made by non-specialists that can have a significant impact on interpretation of monitoring data.

Groundwater elevations and hydraulic gradients

2.7 Groundwater levels (recorded as a depth below a point of measurement, e.g. ground level and top of casing) should always be converted to groundwater elevations above a common datum (often Ordnance Datum [OD]). As illustrated in Figure 2.2, depths of groundwater levels below the point of measurement are similar in boreholes 1 and 2 which (if not converted to elevations) you would think may mean levels were the same in both boreholes.

2.8 However, upon conversion to groundwater elevations (metres above OD [mAOD]) it becomes clear that groundwater levels in borehole 2 are higher than those in borehole 1, thus indicating a hydraulic gradient and flow between the two locations.

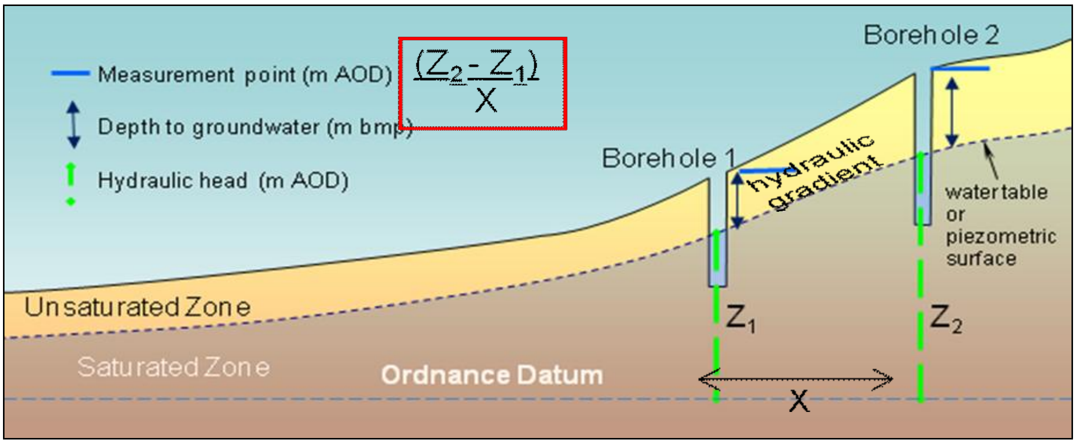


Figure 2.2 Groundwater level and hydraulic gradient estimation.

[6] Thompson et al., 2008

2.9 Groundwater levels are an expression of the pressure of water in the ground, with the hydraulic head being the level to which groundwater rises when a borehole is put into the ground settling at the point where atmospheric pressure counter-balances groundwater pressure. Flow is always from high hydraulic head to low hydraulic head, and can be both horizontal and vertical (either up or down depending upon the pressures) at the same time.

2.10 When comparing groundwater levels, only data from boreholes screened[7] within the same hydraulically connected geological horizon should be compared. For example in Figure 2.3, comparison of all groundwater elevations (without consideration of geological units) would have suggested a much steeper hydraulic gradient than the actual reality. However a brief review of the vertical relationship of screened borehole lengths, in combination with geological review, indicates the presence of a perched groundwater system in the vicinity BH4 disconnected from the main groundwater system).

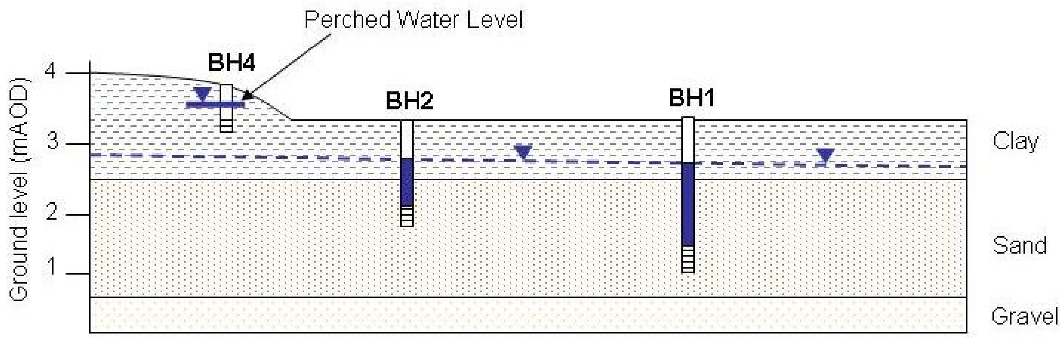


Figure 2.3 Perched versus continuous groundwater bodies.

2.11 Other points to be aware of when comparing groundwater levels include the following:

1) Ensure data used is 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 significantly during the intervening period.

2) 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 back). As such, careful note should be made of the timings of groundwater level dip readings to facilitate comparison.

<u>Groundwater Contours and Flow Directions</u>

2.12 Groundwater contours represent lines of equal hydraulic head within the same aquifer unit, with groundwater flow direction generally at right angles to the contour. Triangulation of multiple sets of monitoring points to estimate groundwater elevations between boreholes[8] is required to enable extrapolation of groundwater contours (Figure 2.4). Contouring software packages (such as Surfer) are available to enable contouring of multiple

[7] Assuming the rest of the monitoring point is screened with solid casing, the screened length of the borehole is the only part of the borehole which will allow water to enter. As such the groundwater level monitored is unique to that location at that screened depth.

[8]

$$\text{Contour distance from borehole (m)} = \frac{\text{Borehole groundwater level (mAOD)} - \text{contour level (mAOD)}}{\text{Hydraulic gradient between the two boreholes}}$$

groundwater levels; however, being based on pure mathematical extrapolation (rather than tied into the reality of the natural water environment), they should be used with caution.

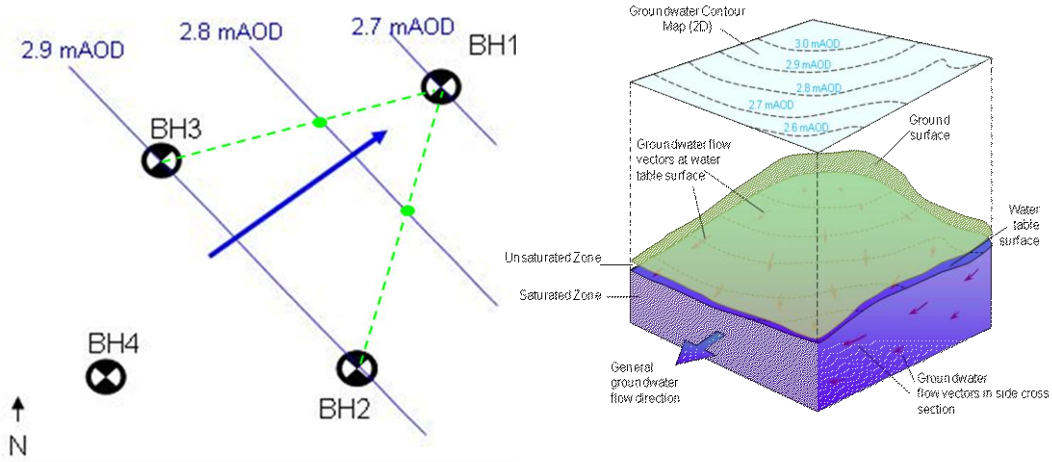


Figure 2.4 Groundwater contouring and flow direction calculation.

2.13 Groundwater will 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 (Figure 2.4). In areas where a plot of groundwater contour points would suggest water is moving in opposing directions, this would suggest a groundwater divide indicating an area where some form of groundwater recharge is occurring. Surface water divides (based on topographical elevations) do not necessarily coincide with groundwater divides.

2.14 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 (e.g. a river or an abstraction point such as a quarry dewatering point or water supply well).

Confined versus Unconfined Aquifers

2.15 Aquifers can either be ‘confined’ by an overlying layer of low permeability material such as mudstone or clay; or they can be ‘unconfined’, i.e. exposed at the ground surface or overlain only by soils and rocks through which water can easily flow (Figure 2.5). The two types behave differently in the way they yield water and in the way they respond to the effects of mineral extraction and associated dewatering.

2.16 For an ‘unconfined’ (or water table) aquifer, piezometer water levels are equal to the actual water level within the aquifer. In this situation the water table is the surface connecting all such water levels, and the slope of this surface is equal to the hydraulic gradient.

2.17 In ‘confined’ aquifers, groundwater is kept under pressure by a confining layer of lower permeability strata. Within such aquifers, the hydraulic head can be (and generally is) above the upper surface of the aquifer unit. Where the pressure is sufficient to cause the piezometer water level to rise above the ground surface, such that water would overflow without pumping, the conditions are described as ‘artesian'. The imaginary surface connecting the piezometer water levels within a confined aquifer is known as the piezometric surface (or ‘potentiometric’ surface), and the slope of this surface equates to the hydraulic gradient of the aquifer.

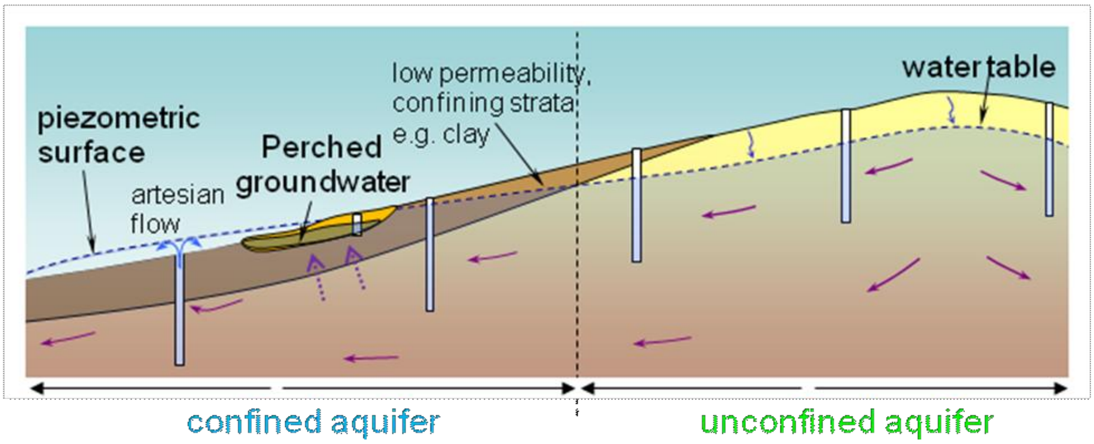


Figure 2.5 Confined and unconfined aquifers.

2.18 'Perched' groundwater tends to be shallow groundwater bodies (laterally discontinuous) within a superficial deposit underlain by low permeability material. Given the heterogeneities of perched water bodies, comparison of groundwater elevations should be restricted to those screened within the same geological unit (as determined by field investigation), and / or monitoring wells in close proximity to the receptor of interest or the development of concern.

Hydraulic Continuity between Groundwater and Surface Water

2.19 In order for interaction to take place between groundwater and surface water, there must be a degree of hydraulic continuity between the two systems. Where the surface geology is of very low permeability, there may be little or no connection, and the surface water system is then effectively isolated from any underlying, deeper aquifers. Where the surface geology is more permeable, however, there will be a varying degree of hydraulic continuity between the two systems.

2.20 The geology and sedimentology of the river bed, including the thickness of any silt that may temporarily accumulate on the bed of a sand- or gravel-bed river before being disturbed by subsequent high flow events, determines how easily water can flow from the groundwater to the river and vice versa. In large, slow moving rivers, the thickness of silty alluvium can form an aquitard between the aquifer and the surface water; whereas in faster, gravel bedded rivers (or where dredging has taken place to provide a navigable channel), there can be total hydraulic continuity between the surface and groundwater systems.

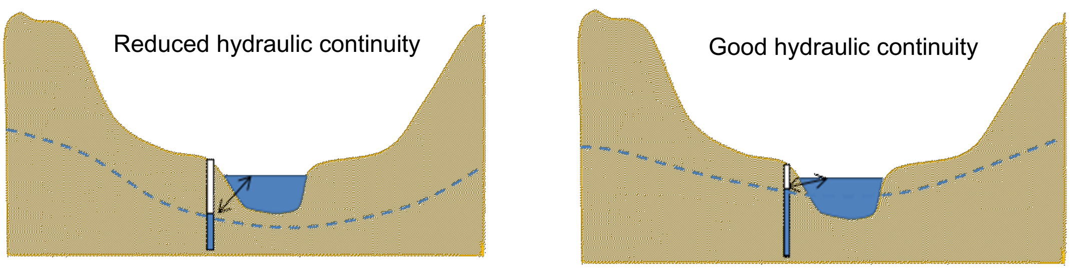


Figure 2.6 Groundwater - surface water hydraulic continuity.

2.21 The nature of this 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 the baseflow component which helps to sustain surface water features during periods of dry weather.

2.22 If, however, the surface water level is higher than the surrounding groundwater, surface water will seep (recharge) 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 therefore be described as a ‘gaining’ or ‘losing’ stream, depending on whether it is being sustained by the aquifer or vice-versa.

Partially Penetrating versus Fully Penetrating Surface Water Courses

2.23 If a surface water course is fully penetrating (i.e. as deep as the aquifer of interest and underlain by a low permeability base) it is likely to act as a discharge or recharge point to the groundwater sub-system (Figure 2.7). If, however, a surface water course is not fully penetrating the potential exists for groundwater flow (and the impacts of dewatering on groundwater levels) beneath and beyond the surface water course (Figure 2.7).

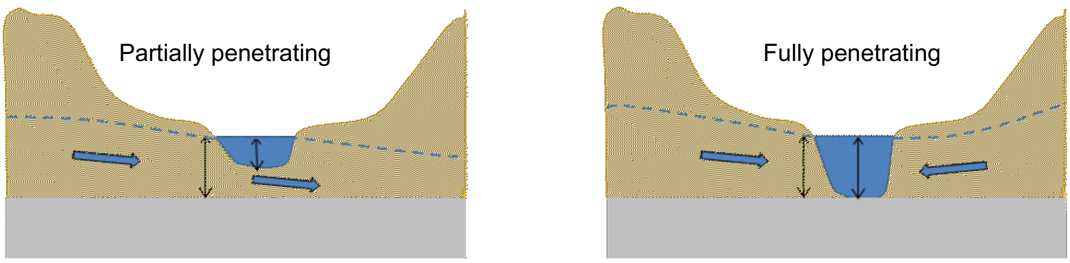


Figure 2.7 Partially and fully penetrating surface water courses.

2.24 To assess which category a surface water course may fall into a review of vertical relationships between channel depths and the depths / thicknesses of the geological layers would be required.

How a groundwater system responds to change

2.25 As illustrated in Figure 2.1, the hydrological cycle can be represented as a system of inputs (e.g. infiltration, re-injection of water, discharge from surface water or groundwater inflow) and outputs (e.g. discharge to surface water, abstraction and groundwater flow out of study area). All natural systems strive to reach an equilibrium (or ‘steady state’) where the total inputs and outputs balance. If there is an imbalance between inputs and outputs, water must be taken from or added to storage within that sub-system before equilibrium can be restored. Whilst changes in storage are taking place, the conditions are described as ‘unsteady state’. For any given sub-system, this concept can be described in terms of a simple water balance:

(Total Inputs = Total Outputs + Change in Storage)

2.26 Where inputs exceed outputs additional water is taken into storage, observed as a rise in groundwater levels. Vice versa, 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 (Figure 2.8).

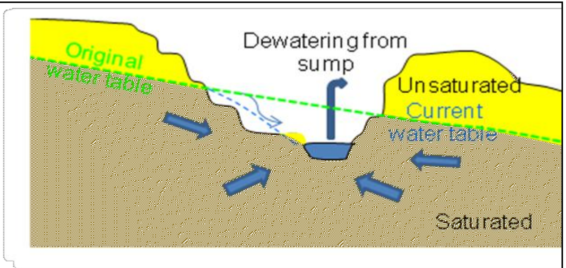
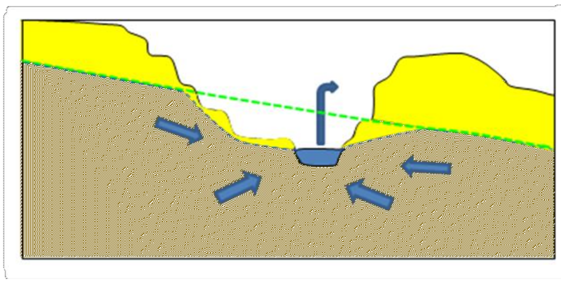
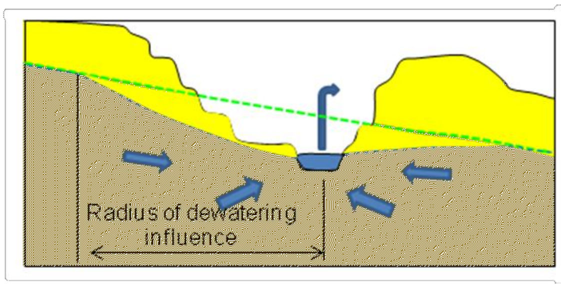
Early time (hours)	*Unsteady State* Dewatering leads to an increase in outputs. Water is taken out of storage resulting in groundwater levels starting to drop locally.	
Short term (hours, days)	*Unsteady State* Groundwater will continue to be taken from storage until such time as inputs and outputs balance again. The cone of depression will continue to develop expanding laterally until either: • Inputs and outputs balance; or • The cone of depression encounters a hydraulic barrier (e.g. recharge boundary, fault, low permeability barrier etc).	
Long term (days, weeks)	*Steady State* Inputs = outputs, therefore no further changes in storage (or groundwater level). Maximum radius of dewatering influence, and predictions of groundwater level drawdown at specific distances, can be calculated	

Figure 2.8 Steady and Unsteady State.

2.27 For defined snapshots of 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 reality, the hydrological cycle is in a constant state of flux, as a consequence of natural variations (e.g. seasonality) and external anthropogenic influences (e.g. quarrying). Changes in storage are therefore constantly 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.

Dynamic Baseline Concept

2.28 Groundwater levels recorded in the field reflect the combined influences of natural and anthropogenic inputs and outputs. If there were no variation in inputs or outputs to the water balance, groundwater levels would remain constant throughout time. The most basic input parameter variation is infiltration / recharge during the course of the year as a result of seasonal rainfall / evaporation patterns. As illustrated in Figure 2.9, adding on increases in rainfall contribution to a static baseline generates a resultant groundwater hydrograph (in blue) similar in profile to what you would expect for baseline water levels in an area with no anthropogenic influences.

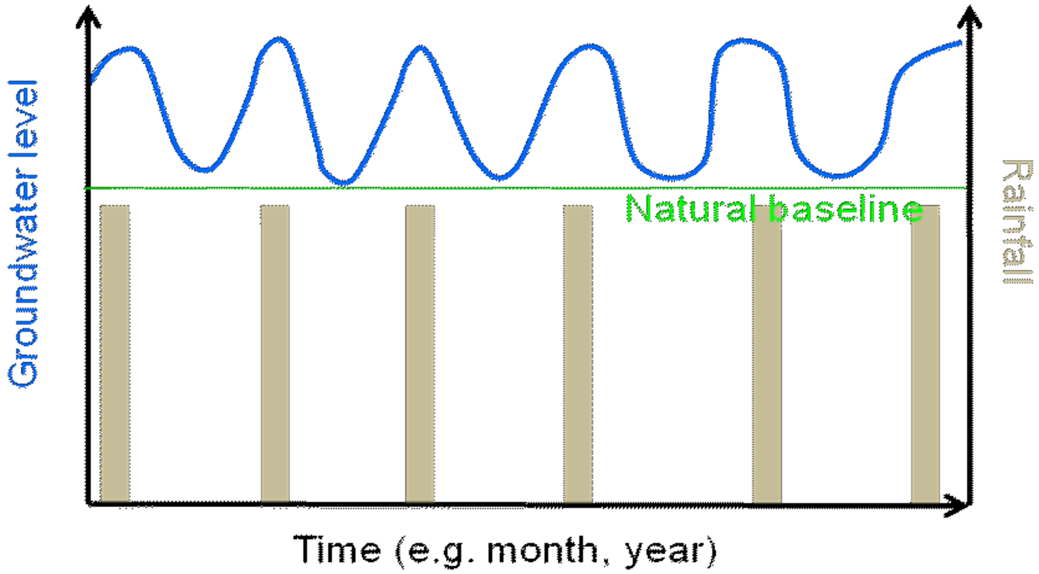


Figure 2.9 Natural input variation - resultant groundwater levels.

2.29 Vice versa, if inputs are kept constant and outputs are varied (e.g. during periods of quarry dewatering), estimation of the potential groundwater hydrograph profile would involve calculation of groundwater drawdown at a measurement point and super-position of that amount of drawdown upon the natural baseline profile (as illustrated in Figure 2.10).

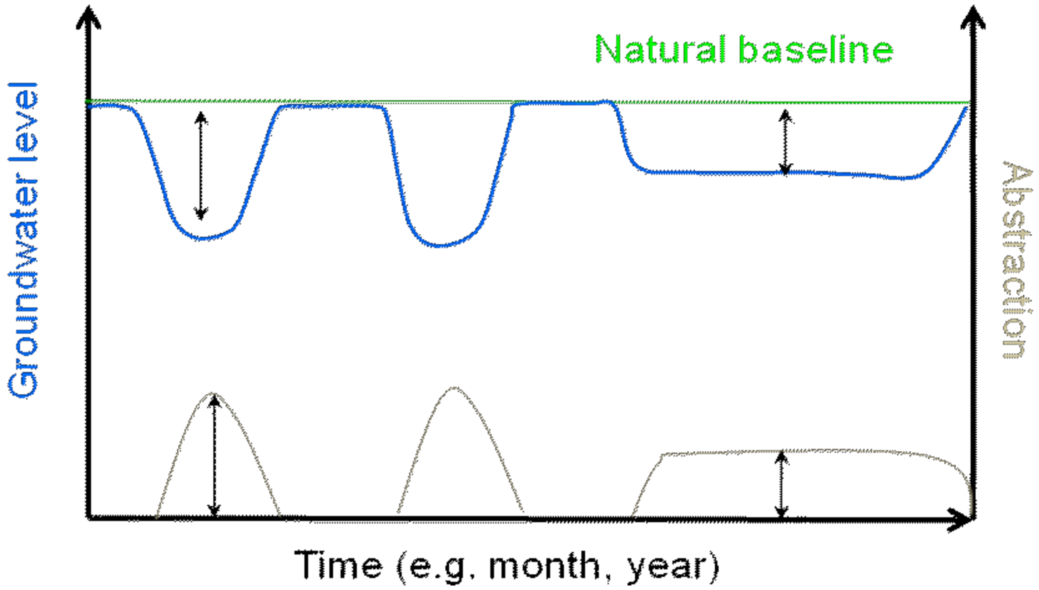


Figure 2.10 Anthropogenic output variation - resultant groundwater levels.

2.30 In practice only an approximate steady state condition can ever be achieved, since the rate of natural recharge is constantly changing. The rate of pumping therefore also tends to be variable and is usually intermittent, being adjusted as necessary to keep pace with seasonal changes in inputs from groundwater and surface run-off so as to maintain groundwater levels just below the base of the excavation. This variability of pumping rate, reducing to a minimum during the summer months when recharge is low, is a characteristic feature of quarry dewatering and distinguishes it from other forms of abstraction, where the requirement is usually for a reliable rate of supply that either remains constant throughout the year or has increased demands.

2.31 Input and output variation will be super-imposed upon the natural fluctuating baseline delivering potentially a very different hydrograph to what may be expected (as illustrated in Figure 2.11 below).

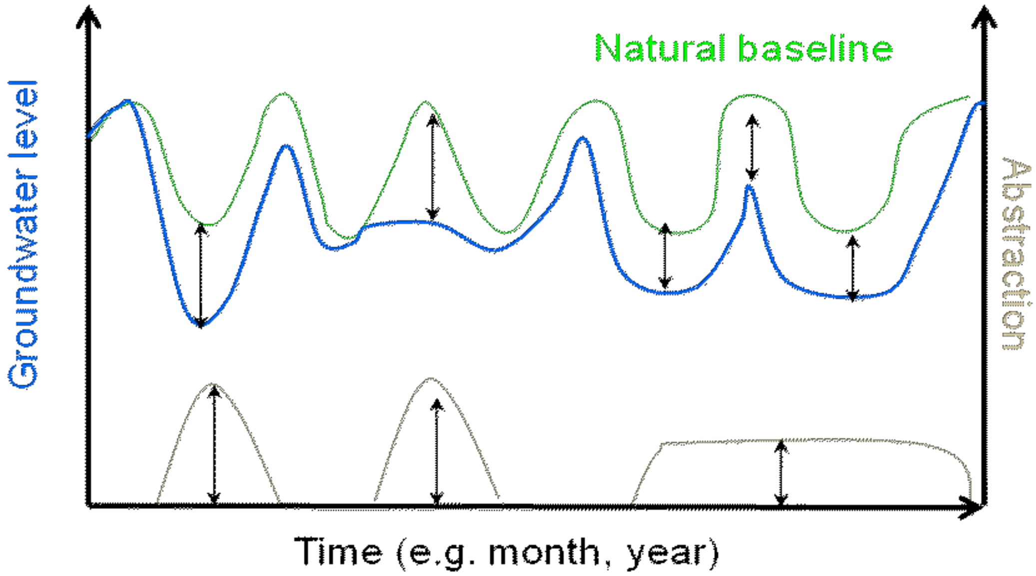


Figure 2.11 Combined input and output variation - resultant groundwater levels.

Assessment Approaches

2.32 In most cases the inputs and outputs to a water balance can be measured through relatively straightforward monitoring, or can at least be estimated, to give a first approximation. The changes in storage, which are critical to understanding the way in which the system responds to an imposed change (such as dewatering) are more difficult to predict, however, and there are many different methods available (as discussed further in Section 3 and Appendix 2).

2.33 These methods range from simple empirical equations (which may be adequate for very simple hydrogeological situations where there is also little or no other anthropogenic influence); analytical solutions for one-dimensional scenarios (Figure 2.12); combining analytical solutions for one- or two-dimensional scenarios where there is more than one anthropogenic influence on the water environment (Figure 2.13); through to ultimately numerical groundwater flow modelling (illustrated in Figure 2.14).

2.34 Depending upon the likely scale and significance of the potential risks involved, and the complexity of the systems being assessed, 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 degree of confidence required. In some cases, the production of more detailed analytical equations / spreadsheets or numerical models may be required, but only where this is justified by the level of risk involved and where there is adequate and reliable data to feed into such models[9].

[9] Gill et al., 2008

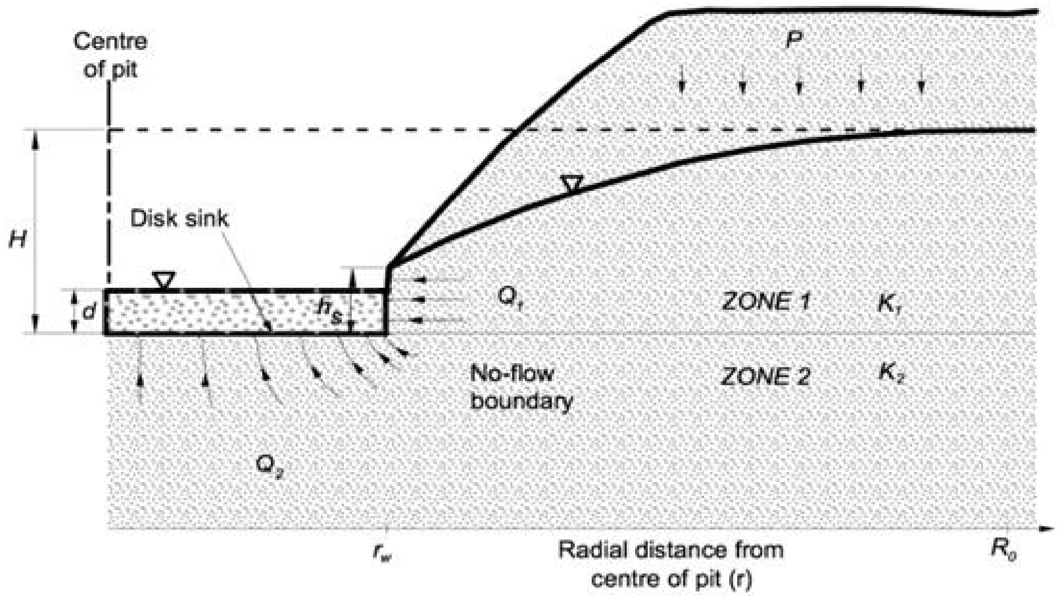


Figure 2.12 Example of a one-dimensional analytical solution.

2.35 The decision to model the impacts of water abstraction / extraction upon the water environment needs to be based upon an objective review of the facts relating to, for example, the complexity of the situation, the requirement of a sophisticated solution, the availability and quality of field data, and the constraints of the budget relative to costs and schedule[10].

2.36 This research focuses on the basic initial assessment end of the spectrum of available tools which are available, in order to develop a methodology / tool for navigating the assessment choices and helping to identify where further data may be required. The findings of the research review (Section 3) and the evolution of the Draft Dynamic Baseline Assessment Water Environment Toolkit (DWEBAT) (Section 4) follow in their relative sections.

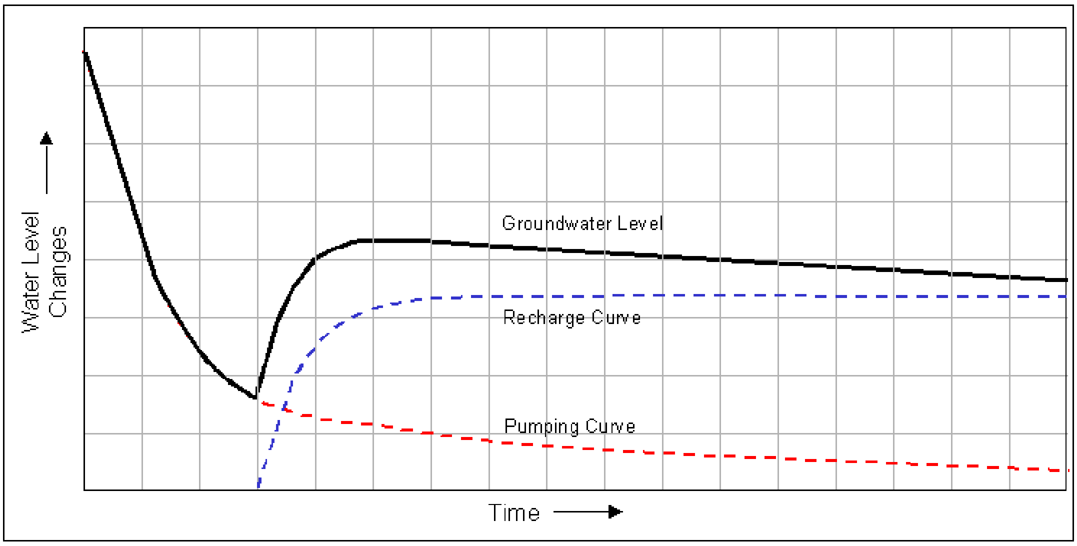


Figure 2.13 Super-position of two analytical solutions to predict resultant mitigated groundwater level profile as a result of recharging to ground whilst the quarry continues to operate.

[10] Watson and Burnett, 1995

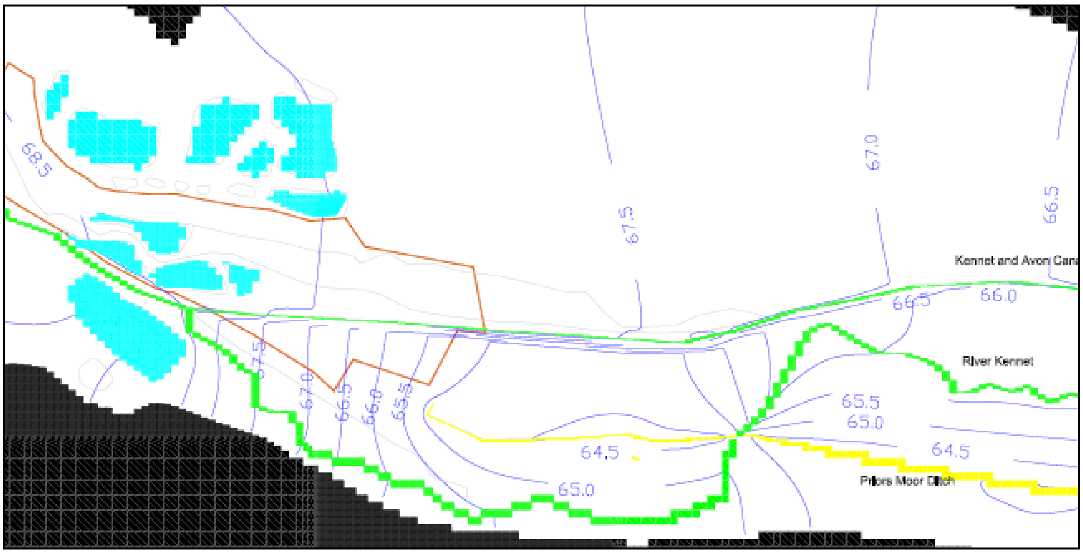


Figure 2.14 Example of a 3-D numerical model.

3. REQUIREMENTS OF A DESK BASED METHODODOLOGY

3.1 As noted in Section 2, the differentiation of changes in the water environment (whether natural or anthropogenic in origin) naturally requires a good understanding of the local aquifer system in question. This understanding should include the local system's relationship to surface hydrology and to larger (regional) scale systems. As discussed in the previous section, a combination of information on geology, hydrogeology, climatic influences, hydrology and rational assumptions can be brought together to create a 'conceptual model' that provides a general (i.e. basic) representation of the water environment and the processes in operation. A conceptual model can therefore be used to understand a system's influence on receptors such as habitats and the species that depend on them, features of cultural and heritage value, and the availability of water for supply.

3.2 While not all aspects of a conceptual model are described numerically, some numerical data is usually employed alongside other means of explaining the real-world situation. This section therefore describes the main types of modelling with numerical data (used within conceptual models) and which might therefore be used as a basis for the development of a Desk Based Methodology (DBM). A review of the available water balance and water level models has been conducted and a summary of the findings of the full review (detailed in Appendix 2) is presented within this chapter.

Approaches to Modelling

3.3 There are two main approaches to modelling the potential impacts of water abstraction and / or mineral extraction upon the water environment. These are relatively simple analytical models or more detailed numerical models. With both types of model, the approach can be 'lumped' (for example, where the system properties are averaged over the whole area under study) or carried out in a more distributed manner (where the system properties are varied spatially). The way in which calculations are undertaken may also vary from being done manually, within a spreadsheet or via a bespoke computer programme. The two main types of model are summarised in turn below and specific models are reviewed in Appendix 2.

Analytical Models

3.4 Analytical models are generally quick to use and involve a mathematical equation (or equations) to assess the water environment conditions. The analytical equations, which are presented in Appendix 2, are used to represent how water moves at a general level, both on an inter- and intra-site basis. More simply, they may calculate groundwater flow (or other properties) for a given set of input data.

3.5 While they provide an exact mathematical solution, analytical equations are usually based on a number of assumptions for the system being modelled (such as simple geometry and uniform properties) and thus can only be solved for particular (i.e. simple) situations. Analytical models are usually two-dimensional and steady-state.

3.6 The user of analytical models needs to be able to decide how the system being investigated can be simplified in order to satisfy the requirements of the model, without compromising the representation the main features of the system and reducing the level of resolution to below that which is appropriate for the investigation.

3.7 Outputs of computer-aided analytical modelling (for example, in spreadsheets) generally include graphs (such as for drawdown against distance, or time; and monthly recharge) or a single value (such as a transmissivity value or a dewatering rate).

Numerical Models

3.8 Numerical models have the capacity to deal with a greater degree of complexity than analytical models as they generate an approximate solution for groundwater flow based on a number of user-entered ‘parameters’. These parameters may be based on physical processes or can be derived from empirical relationships. Values are assigned to levels, flows, and properties within a conceptual model and these are used within the numerical modelling framework (i.e. several types of data for locations across an area are inputted to a computer programme that generates a modelled output). Numerical models are thus spatially-distributed. They are also time-variant, usually three-dimensional and are calibrated and validated against historical data.

3.9 As a result, appropriate use of the model is essential in order to minimise numerical error; and successful numerical modelling relies somewhat upon the skills of the user / developer.

3.10 These models come in a range of sophistications to match the available data, relevant scale (i.e. regional, catchment and local), budget and time associated with an investigation. As with analytical models, the required confidence in results and the significance of the system being investigated (in terms or potential impacts) may influence the type of model selected.

3.11 Outputs from numerical modelling typically include groundwater levels, contours and monitoring targets; flow lines and drawdown from a baseline water level; contoured plot plans (water chemistry data); and flow nets (e.g. for seepage into a tunnel).

3.12 Examples of numerical models include MODFLOW (the Modular Finite-Difference Flow model) and pre- and post-processing packages (such as Groundwater Vistas, or Visual MODFLOW). Modelling packages may also interface with Geographical Information System (GIS) packages such as ArcGIS, MapInfo and Surfer.

Summary of the Review

3.13 Common to both types of model are that the degree of complexity of the system and the desired level of sophistication of understanding are important considerations, and will influence the type of model used and the level of detail of the data that is needed to inform it[11].

3.14 Depending upon the likely scale and significance of the potential risks involved, and the complexity of the systems being assessed, 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 degree of confidence required.

3.15 The review identified a number of one-dimensional analytical equations, two-dimensional steady-state / transient analytical models and three-dimensional steady state / transient computer-generated groundwater models that are all currently available. While there are many analytical and numerical tools and techniques, there is no single tool or technique that covers all aspects of the water environment under different environmental conditions and contexts (including sand and gravel deposit areas) in a simple manner. As such, it may be necessary to utilise a number of modelling approaches (i.e. a combination of analytical equations and a water balance spreadsheet methodology) in order to understand water movement within a sand and gravel producing area.

[11] Gill et al., 2008

Conclusions

3.16 A best-fit model may be chosen depending on the availability and quality of data. The principle of a tiered risk assessment is appropriate here, in which the level of assessment (and thus understanding) required is dictated by the nature and scale of the development and the sensitivity of the potential receptors (including designated and undesignated historic environment assets).

- Tier 1 risk assessments determine issues; derive questions to be investigated, formulate hypotheses and test with basic / best basic models (lumped long-term average water balances).
- Tier 2 risk assessments revise Tier 1 conceptual model hypotheses and test with intermediate / best intermediate models (more detailed data [time variant heads and flows]) or more sophisticated tools (spatially lumped seasonal water balances) or analytical solutions for impacts).
- Tier 3 risk assessments revise Tier 2 conceptual model hypotheses and test with detailed / best detailed model (spatially distributed and time variant numerical model).

3.17 The wide range of different tools and models led to difficulties and confusion in deciding which tool was most appropriate to deal with a particular aspect of the water environment system.

3.18 The cumulative nature of numerous natural and anthropogenic factors that contribute to recorded groundwater levels mean that attempting to ‘unravel’ complex water environment changes (to apportion natural versus anthropogenic change) without using a numerical model is considered to be not appropriate.

3.19 However, the Stage 1 review did demonstrate that a tool to aid regulators / non-hydrogeologists conceptualise a water environment system, and to be able select (with increased confidence) appropriate one-dimensional analytical equations for simple water environment settings.

3.20 Thus, such a toolkit needs to be simple to use, aimed at a non-hydrogeologically trained user and combine consideration of water environment date, heritage asset information and assessment tools to provide a central knowledge base.

4. DEVELOPING THE DBM TOOLKIT

Philosophy and Initial Development

4.1 Building upon the outcomes of the Stage 1 review (as discussed in Section 3), the initial research aim of development of a DBM (that did not use a numerical model) which could potentially be used to 'unravel' a complex water environment in order to differentiate proportionate natural influences versus those of anthropogenic origin, was deemed to be unattainable.

4.2 As such, instead of a specific methodology, the project was re-focused upon developing a tool for non-hydrogeologically trained users that would aid conceptualisation of the dynamic water environment baseline and enable a selection of appropriate one-dimensional analytical equations based upon that conceptualisation.

4.3 Given the broad range of tools and sources of data that are used to characterise a conceptual model, a primary aim of the toolkit was to try and gather relevant data and tools within a single place in order to build up a consolidated picture, and to better enable identification of potential data gaps that may require more monitoring or field investigation. This concept is graphically illustrated in Figure 4.1.

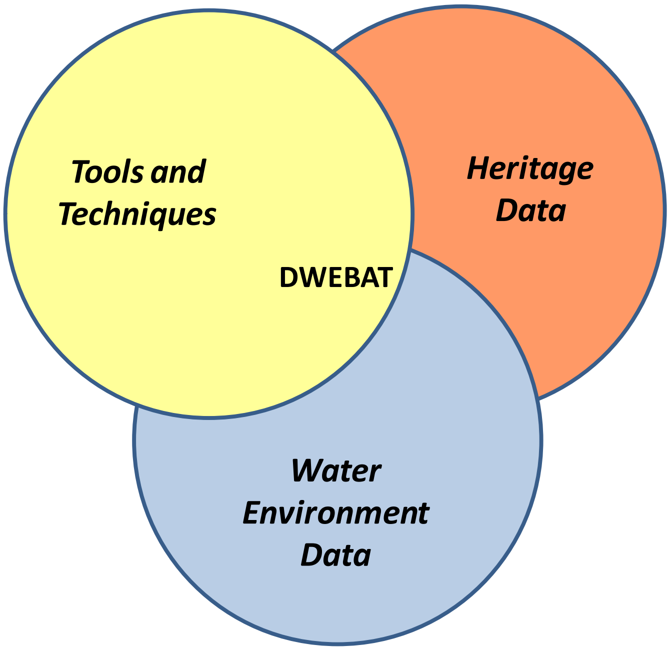


Figure 4.1 Dynamic Water Environment Baseline Assessment Toolkit concept diagram.

4.4 In terms of the needs of the user, our initial remit was to develop a toolkit that is:

1) Simple to use, by making use of graphics to explain basic concepts;
2) Will help in the estimation of hydraulic gradients, groundwater contouring, etc;
3) Will provide step by step conceptualisation; and
4) Will help to identify gaps in data / conceptualisation that may necessitate further work (e.g. monitoring, field investigations or more detailed assessments [such as numerical modelling]).

4.5 In order to aid step-by-step conceptualisation, whilst also focusing on keeping the overall approach simple to understand, it was decided that a series of targeted questions relating to the water environment and sensitive heritage features would be most appropriate.

4.6 The pros and cons of a database (such as Access) versus a spreadsheet approach were considered. Given that the majority of users will already be familiar with Excel (the worksheet layout enables improved navigation and there is greater flexibility for numerical calculation), it was decided that this type of spreadsheet workbook would be appropriate.

4.7 Given that the premise of this research is to facilitate quantification of groundwater drawdown in areas where dewatering of sand and gravel quarries is proposed / takes place, the DWEBAT search area was defined based upon a rough estimate of the maximum radius of dewatering influence (using the Sichardt empirical equation [which can be found on the *Abstractions* worksheet of the DWEBAT]).

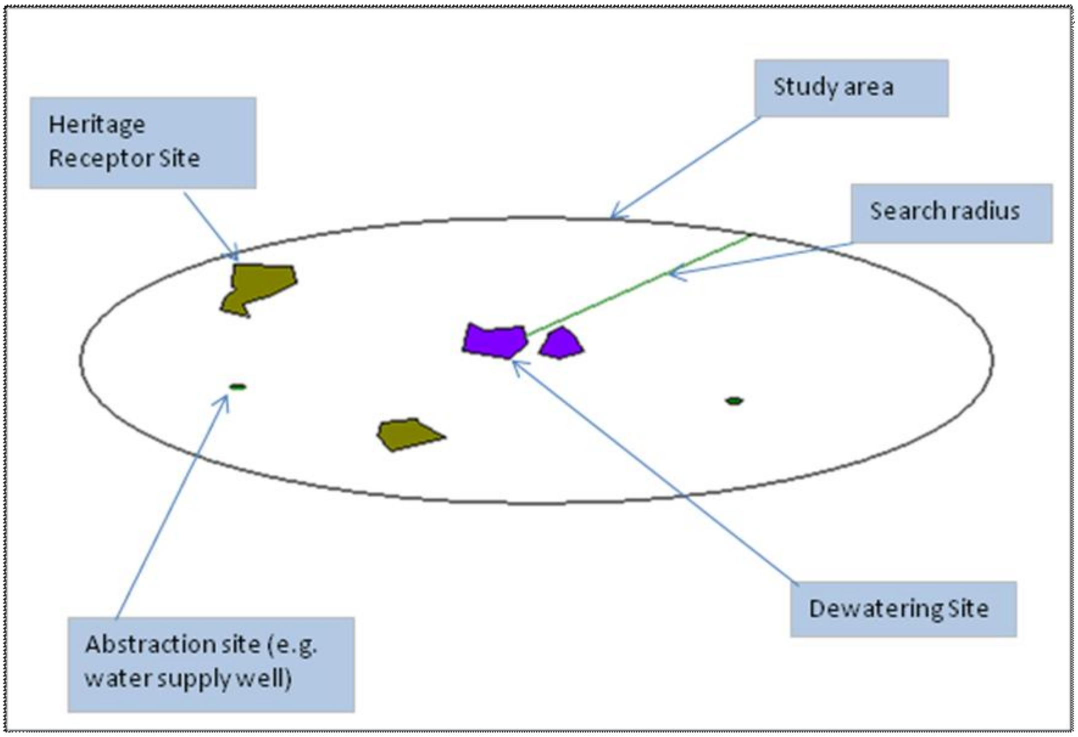


Figure 4.2 DWEBAT search area definition.

4.8 In characterising the natural water environment baseline, individual worksheets with targeted questions include those relating to:

1) Topography and land use;
2) Geology;
3) Surface water (including run-off and drainage);
4) Groundwater (including consideration of infiltration and groundwater flow); and
5) Climatic conditions.

4.9 Whilst in respect of anthropogenic receptors and influences, the following worksheets were included, each containing relevant targeted questions:

1) Heritage receptor sites (location, layer of interest, sensitivity to change, etc.);
2) Abstractions (groundwater and surface water); and
3) Discharges (groundwater and surface water).

4.10 Each of the worksheets followed a similar pattern of questioning that aimed to compartmentalise the study area into a number of different layers / blocks (as illustrated in Figure 4.3)

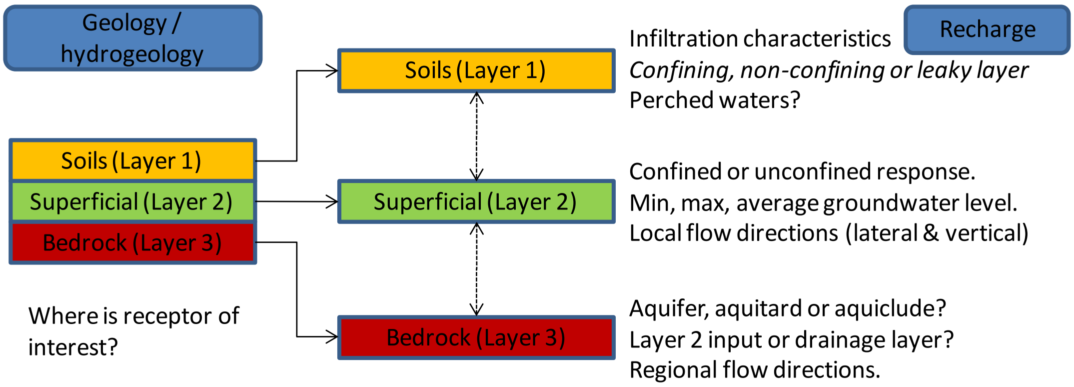


Figure 4.3 Typical compartmentalised approach to DWEBAT targeted questioning.

4.11 Where the answer to a question may not be obvious, guidance notes and links to useful information are included as an aid.

4.12 During the development of the initial DWEBAT it became clear that there was potential for the toolkit to become bigger and more technically complex than it had originally intended to be, particularly given the non-specialist target audience. As such holding a research workshop with interested users from English Heritage and local authority archaeological officers was vital to steering the DWEBAT in the most appropriate direction for the audience.

Workshop Review

4.13 A project workshop was held on 28th January 2011and was attended by Jen Heathcote (English Heritage), Helen Chappell (English Heritage) and Kasia Gdaniec (Cambridgeshire County Council). Prior to looking at the working copy of the draft DWEBAT, brief background presentations were given on basic hydrogeological concepts and the dynamic baseline concept.

4.14 Key feedback on the DWEBAT (version dated 26th January 2011) included the following:

- Development Control archaeologists would not have the time to complete such an extensive workbook, and it would require more water environment technical knowledge to be able to select the most appropriate answer.
- The developer's archaeological consultant / contractor and / or hydrologist / hydrogeologist could use the toolkit in order to enhance the understanding and appreciation of the archaeology / heritage in question.
- The DWEBAT would benefit from a summary section in order to act as a checklist and provide a narrative.
- The DWEBAT has the potential to be marketed as a useful 'knowledge to date' tool whose potential for development is beyond the realms of English Heritage; but into the wider market place with expansion in order to consider other receptors.
- The DWEBAT needs to be refined to present boxes where consultants using the tool have to present their workings (maintaining a transparency of approach).

- The DWEBAT needs discussion and conclusion sections that relate to archaeology / heritage (especially Historic Environment Records and in-situ preservation considerations).
- There needs to be an option on the spreadsheet to press a button and generate a graph which can give a more visual representation of the data.
- It would be useful for the DWEBAT to have water quality components and a sedimentary analysis of the area in question (although it was agreed that this did not have to be addressed prior to completion of the project).
- The DWEBAT could promote discussion regarding the mitigation of heritage assets and the issues associated in these mitigations.

Changes to the Draft DWEBAT

4.15 The results of the project workshop have been fed back into the continued development of the DWEBAT (Appendix 3).

4.16 As well as completing the outstanding questions on the draft DWEBAT, the key change to the spreadsheet following the project workshop, is the inclusion of a summary worksheet that links to all other worksheets within the workbook together.

4.17 Rather than a repeat of the questions, the summary page tabulates against each defined conceptual model layer (the details of data entered for each of the worksheets are listed in paragraphs 4.8 and 4.9).

4.18 As well as providing a summary narrative, the DWEBAT will also aid an appreciation of data gaps (based on empty cells or 'unknown' text). In addition, an 'if' formula statement has been incorporated, whereby if there is more than one abstractor within a search area that may affect a historic environment asset, it will immediately flag up a recommendation to bring in a specialist hydrogeologist in order to tackle assessment of the cumulative impact.

Have the Original Aims of the Development of the DBM been met?

4.19 The current version of the DWEBAT has encouraged the gathering of data on both aspects of the water and historic environment (in the context of a radius of dewatering influence associated with a quarry) which, in combination with the recently incorporated summary worksheet, will help in the conceptualisation of the system. It will also aid in the identification of data gaps.

4.20 The development of a tool which produces a bespoke graphic output based upon the data entered requires specialist programming and is beyond the realms of this project.

4.21 Nevertheless, the DWEBAT does guide users into employing appropriate one-dimensional analytical equations (with references and links to other sources of information being listed within the resources worksheet). Given the challenges experienced with even basic hydrogeological concepts (see discussion below), it was considered that including all the tools themselves within the workbook (in addition to the rest of the data) would have been too overwhelming for the identified user audience.

4.22 In terms of the initial remit for the development of a DBM, with some background knowledge of basic water environment principles, it was possible for the non-specialist workshop attendees to follow the questions. However, without the half-day training on the basic principles of the water environment system, workshop attendees did not think they would have been comfortable completing the workbook.

4.23 It was not possible to achieve the estimation of hydraulic gradients, groundwater contouring, etc. within the current version of the DWEBAT. This is primarily related to the number of permutations of the different boreholes over different sedimentological horizons. Generally, it is easier to sketch out by hand or use a contouring package such as Surfer; this encourages the assessor to look at borehole screening depths in order to make sure the correct groundwater level information is being used for interpretation purposes within the right layer.

5. CASE STUDIES SUMMARY

5.1 This section provides a brief summary of the investigations undertaken at the two case study sites (Newington Quarry in Nottinghamshire and Over Quarry in Cambridgeshire). The information is presented in the context of the headings associated with the *Summary* worksheet of the DWEBAT, and the following questions asked:

1) Is the information presented sufficient to adequately characterise the water environment surrounding the quarry, and in the vicinity of historic environment receptors of concern?
2) If no, what data gaps are there and is it essential to fill them before a judgement can be made upon the impact of dewatering operations on the surrounding water environment?
3) Are key heritage environment receptors sensitive to short term or long term change in surrounding water environment conditions?
4) Given the information presented what 'next step'[12] in terms of assessment would use of the DWEBAT have prompted?

5.2 For more detailed information on the case study sites, monitoring installed and discussion of the results, the reader is referred to Volume 2 of this report series.

Newington Quarry, Bawtry, Nottinghamshire

5.3 Hanson Aggregates' Newington Quarry site is located approximately 2km to the east of the town of Bawtry (National Grid Reference: SK675943) within the floodplain of the River Idle (Figure 5.1). The 40.75ha site is bounded by Bawtry Road to the north and the River Idle to the south, and is dissected by Slaynes Lane. Several drains and a flood relief channel cut across the site, which are dry for the majority of the year.

5.4 Key historic environment receptors of interest within the area surrounding the quarry include two Scheduled Ancient Monuments (Misson village 'Moated Site and Fishpond'[13], labelled as 1 on Figure 5.1, and Scaftworth Roman Fort and Road[14], marked as 2 on Figure 5.1). In addition, the natural wetland environments of the River Idle Washlands Sites of Special Scientific Interest are marked as 3a, 3b and 3c on Figure 5.1.

[12] Gather more monitoring data; 1-D analytical solution assessment; or involvement of hydrogeologist to consider cumulative impacts and advice on need for more complex assessment (e.g. numerical modelling).

[13] Scheduled Monument No: 23217, Grid Reference SK69299497.

[14] Scheduled Monument No: 29923, Grid Reference SK65939274.

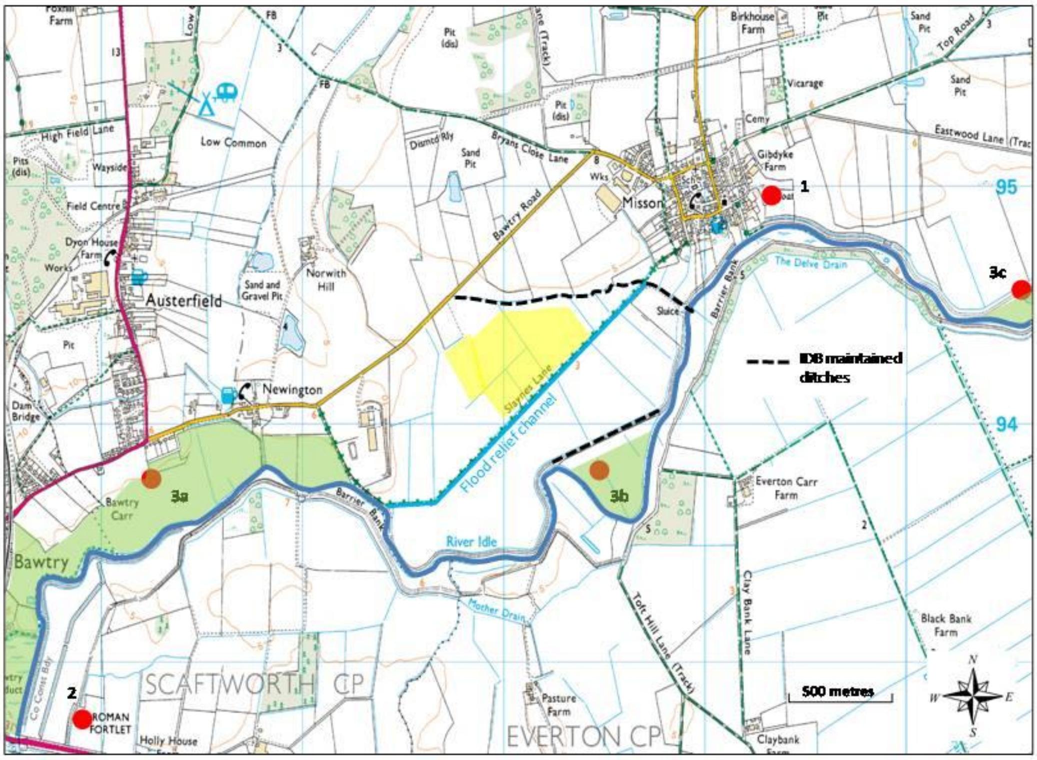


Figure 5.1 Newington Quarry (yellow) location plan and key receptors of interest.

5.5 Underlain by peat superficial deposits, terrace sand and gravels, and ultimately the principal water resource aquifer of the Sherwood Sandstone, groundwater levels within the sand and gravel have experienced the cumulative impact of drawdown both from PWS abstraction in the Sherwood Sandstone and dewatering from Newington Quarry. This has been well documented, and been the subject of numerical modelling in previous assessment work[15]. Conceptual hydrogeological cross-sections and numerical modelling results of that work are presented in Figures 5.2 and 5.3 for information.

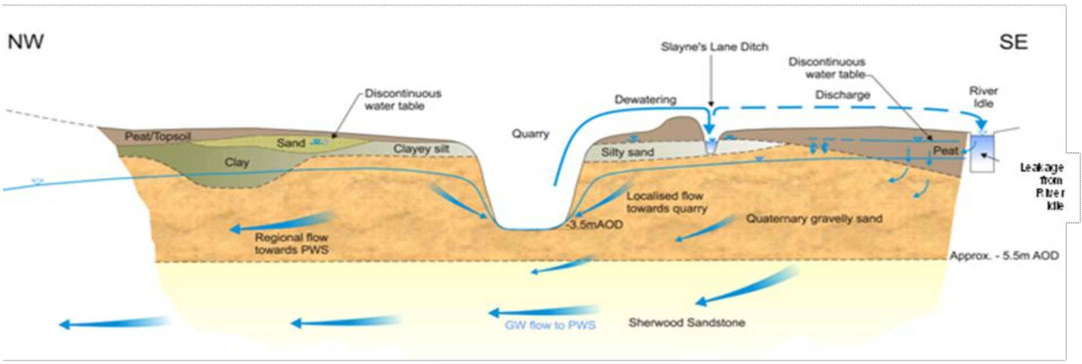


Figure 5.2 Schematic hydrogeological cross-section (modified from Golder Associates Ltd, 2006 [in Lillie and Smith, 2007]).

15 Lillie and Smith, 2007, 2008

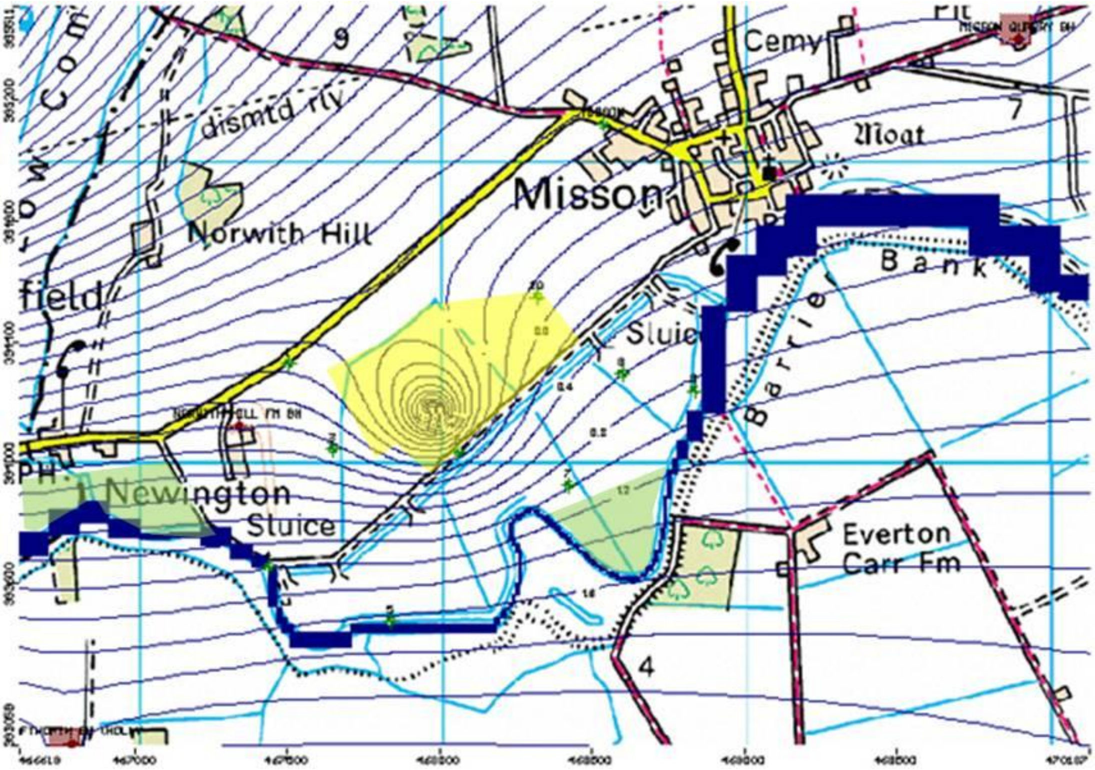


Figure 5.3 Newington Quarry numerical model groundwater contours (Nov 2003[16]) showing circular cone of depression associated with sand and gravel dewatering at Newington superimposed on regional drawdown to north-west towards the Austerfield PWS (abstracting from the Sherwood Sandstone).

5.6 Previous assessment work did not, however, focus on changes within the peat superficial deposits as a result of lowering groundwater levels in the sand and gravel (through combination of dewatering and PWS abstraction) in order to identify whether such changes had potential implications to the historic environment in-situ preservation potential. Nor did the previous work differentiate the scale of impacts purely associated with quarry dewatering (i.e. the impacts that would still remain if the PWS was no longer abstracting).

5.7 1m, 2m and 3m deep piezometers were installed in c. 66 locations across the site and surrounding area (complementing the 10-12 sand and gravel monitoring wells, and two Environment Agency Sherwood Sandstone monitoring wells in the surrounding area). All piezometers and sand / gravel monitoring wells were monitored monthly for water level and limited in-situ water quality parameters between February 2010 and January 2011.

5.8 A summary of DWEBAT data, based upon the information reported in Volume 2, is provided in Table 5.1 below.

[16] Modified from Golder Associates Ltd, 2006 [in Lillie and Smith, 2007] to show quarry area (yellow) and water environment receptors of interest (green)

Table 5.1 Newington Quarry summary conceptualisation.

Natural Environment					
1	Topography	Low lying floodplain: 2-3 mAOD in south. 6-8m AOD in north.			
2	Geology	*Layer No:*	*Lithology:*	*Depth of base (thickness, m)*	*Aquifer Designation?*
		1 (soils)	Alluvium	Not defined individually, approximately 3m combined	Secondary?
		2 (drift 1)	Peat		Secondary?
		3 (drift 2)	River Terrace sand and gravels	Not defined (5-6m?)	Secondary
		4 (bedrock)	Sherwood Sandstone	Not defined	Principal
3	Land use cover	Predominantly agricultural.			
4	Climatic conditions	Rainfall:	Not defined	Evaporation:	Not defined
5	Surface water	*Name / type*	*Depth (m)*	*Hydraulic continuity?*	*Partially / fully penetrating*
		River Idle	Not defined	Yes (presumed, river level data to enable analysis)	Assumed fully, but no depth data to confirm.
		Flood relief channel	Not defined	Possibly (no details of channel nature / sedimentation / vegetation to define).	Assumed partially within Layer 1 to 2, but no depth data to confirm.
		Drainage ditches	Not defined	Possibly (no details of channel nature / sedimentation / vegetation to define). Dry for majority of year.	Assumed partially within Layer 1 to 2, but no depth data to confirm.
6	Drainage	Run-off:	Not defined		
		Ditches:	Potential channel flow not defined.		
7	Recharge	Potential infiltration rates are not defined.			
8	Aquifer	*Layer No:*	*Confined / unconfined / perched?*	*Groundwater level range (m AOD)*	*Permeability estimate (m/d)*
		1 alluvium	Perched	Groundwater levels need to be converted to m AOD. 0.4m – 1.6m variation in water levels over year.	Not defined
		2 peat	Perched / unconfined		Not defined
		3 sand and gravel	Unconfined	Groundwater levels need to be converted to m AOD. 0.5m variation in water levels over year. 1m difference in groundwater at quarry and below River Idle (~1km east).	Not defined.
		4 sandstone	Confined	2000 data: 0.5m AOD in south to -0.75m AOD in north.	Not defined

Table 5.1 (continued) Newington Quarry summary conceptualisation.

9	Groundwater gradient and flow directions	*Layer No:*	*Hydraulic gradient:*	*Flow direction:*	
		1 alluvium	Not defined	Perched waters assumed to be disconnected, therefore not overall flow direction.	
		2 peat	Not defined	Some discussion of waters in superficial deposits being connected, but based on piezometers at a significant distance from one another.	
		3 sand and gravel	Not defined	Regional – north west towards public water supply. Local – superimposed flow towards quarry dewatering. Cone of depression lateral spread possibly mitigated by recharge from River Idle.	
		4 sandstone	Not defined	Not assessed, but presumably north west towards Austerfield public water supply.	
10	Hydraulic boundaries?	Low flow:	None		
		Recharge:	River Idle possibly acting as a recharge boundary. River water levels (compared to groundwater levels) would be need to confirm.		
Anthropogenic Environment					
11	Key heritage receptors	*Name:*	*Layer?*	*Distance from dewatering?*	*Predicted drawdown from quarry dewatering?*
		River Idle Washlands SSSI	Layers 1-2 (possibly fed by Layer 3)	~ 500m south east	Not calculated.
		Moated site & fish pond	Layers 1-2	Over 1km north east	Beyond likely quarry zone of dewatering influence.
		Roman fortlet	Layer 1	Over 1.5km to south west.	Beyond radius of dewatering influence, plus River Idle likely to provide mitigation.
12	Abstractions - Groundwater	*Name (type & quantity):*	*Layer of abstraction?*	*Continuous / variable?*	*Drawdown & radius of influence.*
		Newington Quarry (<300,000 m^3/year)	Layer 3 (sand and gravel)_	Not defined, but likely to be variable depending on quarry needs.	4-5m drawdown at quarry. Modelled radius of influence 400m after 5 years.
		Austerfield (public water supply. 9,955,740 m^3/year)	Not defined, but presume Layer 4 (sandstone)	Not defined, but presumed to be continuous.	Not defined, but presumed to have a large regional impact.
		Lovershall Farm (water supply. 1,137 m^3/year)	Not defined, but presume Layer 4 (sandstone)	Not defined, but from volume assumed to be variable depending upon demand.	Not defined, but likely to be significantly less than that associated with Austerfield PWS

Table 5.1 (continued) Newington Quarry summary conceptualisation.

13	Abstractions - surface water	*Name:*	*Surface water abstracted from?*	*Continuous / variable?*	*Quantity.*
		None			
14	Discharges - groundwater	*Name:*	*Groundwater discharge point?*	*Continuous / variable?*	*Quantity.*
		None			
15	Discharges - surface water	*Name:*	*Surface water discharge point?*	*Continuous / variable?*	*Quantity.*
		Newington Quarry	Not defined	Not defined	Not defined

5.9 The results of the case study investigations have been reviewed in the context of questions raised at the start of this chapter; these are as follows:

Is the information presented sufficient to adequately characterise the water environment surrounding the quarry, and in the vicinity of historic environment receptors of concern?

5.10 From Table 5.1 it can be seen that there are a number of components of the site conceptualisation that have not been defined, calculated, or require further data to fully confirm that a particular process is occurring (e.g. the recharge influence of the River Idle, the infiltration characteristics of the drainage network across the site, or comparison to groundwater levels from the Sherwood Sandstone as well to fully appreciate the links between the sand and gravels and underlying sandstone).

If no, what data gaps are there and is it essential to fill them before a judgement can be made upon the impact of dewatering operations on the surrounding water environment?

5.11 To determine whether or not data is sufficient to deliver a judgement upon the impacts of dewatering, it is important to consider what the key area of interest is. In this way it is possible to ascertain whether or not a situation requires full conceptualisation / quantification or a focused assessment. In the case of this investigation, the key areas of interest were firstly upon how much the dewatering of Newington Quarry may be cumulatively adding to the regional abstraction impact, and secondly what the impacts at the key heritage environment receptors may be.

5.12 In relation to the first question of quantifying additional dewatering drawdown associated with Newington Quarry, insufficient information has been presented with respect to the nature of dewatering operations (location, dewatering volumes, discharge locations, etc.) to enable a full answer to the question of how much the dewatering of Newington Quarry might add to the regional picture. However previous numerical modelling work, which presumably did take account of such information, demonstrates that the zone of dewatering influence associated with Newington Quarry is no more than 400m.

5.13 In relation to the second question of impacts at the identified receptors, however, full conceptualisation of the whole water environment system may not be necessary. In the case of the Roman Fort and the Fish pond Scheduled Ancient Monument, both receptors lie at a significant distance beyond the zone of dewatering influence and conceptually lie within the potentially perched waters of the shallower superficial deposits. As such they are less likely to be impacted by drawdown in the sand and gravel deposits associated with the quarry dewatering.

5.14 In the case of the River Idle Washland SSSI, lying the closest to the point of dewatering, groundwater levels potentially have a component of recharge from the River Idle. Potential infiltration through the Slaynes Lane ditch may also minimise potential drawdown. With the new monitoring information gathered as part of this investigation within this area, there is the data available to enable some more informed judgements upon the potential impacts of drawdown within the wetland without the need for modelling.

Are key heritage environment receptors sensitive to short term or long term change in surrounding water environment conditions?

5.15 In the absence of review of historic groundwater level data (compared to that gathered during the course of this investigation) in combination with a review of dewatering practices during that time, it is not possible to comment upon whether the fluctuations in water levels observed within piezometers within the shallow superficial deposits are short-term or long-term in nature.

5.16 As highlighted in Volume 2, whilst groundwater fluctuations within the sand and gravel deposits are limited to around 0.5 m over the course of the year, in the case of shallow deposits water level fluctuations are more significant (ranging from 0.4 m to 1.6 m fluctuation). This would suggest that even in the short term, significant changes to saturation conditions within the peat can occur. Even though water quality conditions appear to remain conducive to preservation, these fluctuation in saturation conditions could be of concern if there were to be a buried archaeo-organic / palaeoenvironmental remains that were dependent upon consistent saturation conditions for their preservation.

Given the information presented what 'next step' in terms of assessment would use of the DWEBAT have prompted?

5.17 The case study investigation has added significantly to the monitoring network in the vicinity of Newington Quarry, particularly in respect of the superficial soil deposits that are of importance to the water environment system of the River Idle Washlands SSSI.

5.18 Given that there is now a good data set for water levels within this deposit, but gaps in climatic data and drainage information to enable accurate review of infiltration into the soils (and ultimately partially recharged to sand and gravel groundwater). Use of the DWEBAT, and the review prompted by its use, would suggest that the next step in understanding of this system would be to gather site specific climate data, elevation data for the drainage network, and to focus on developing a water balance focused on the peat system to ascertain the amount of infiltration lost to groundwater (and whether there has been a significant increase in the amount lost as a result of quarry dewatering). This could be constrained to looking at the SSSI management unit 3b, or be expanded to consider the area between 3b and the Newington site.

Over Quarry, Earith, Cambridgeshire

5.19 Hanson Aggregates' Over Quarry site is located approximately 0.5 km south of the village of Earith in the Fens of Cambridgeshire and covers an area of 350 ha in the floodplain of the River Great Ouse. In keeping with the wider Fens area, the site and surrounds is characterised by a number of artificial channels (e.g. Old West River to the north east of the site) and a series of smaller land drains (Figure 5.4).

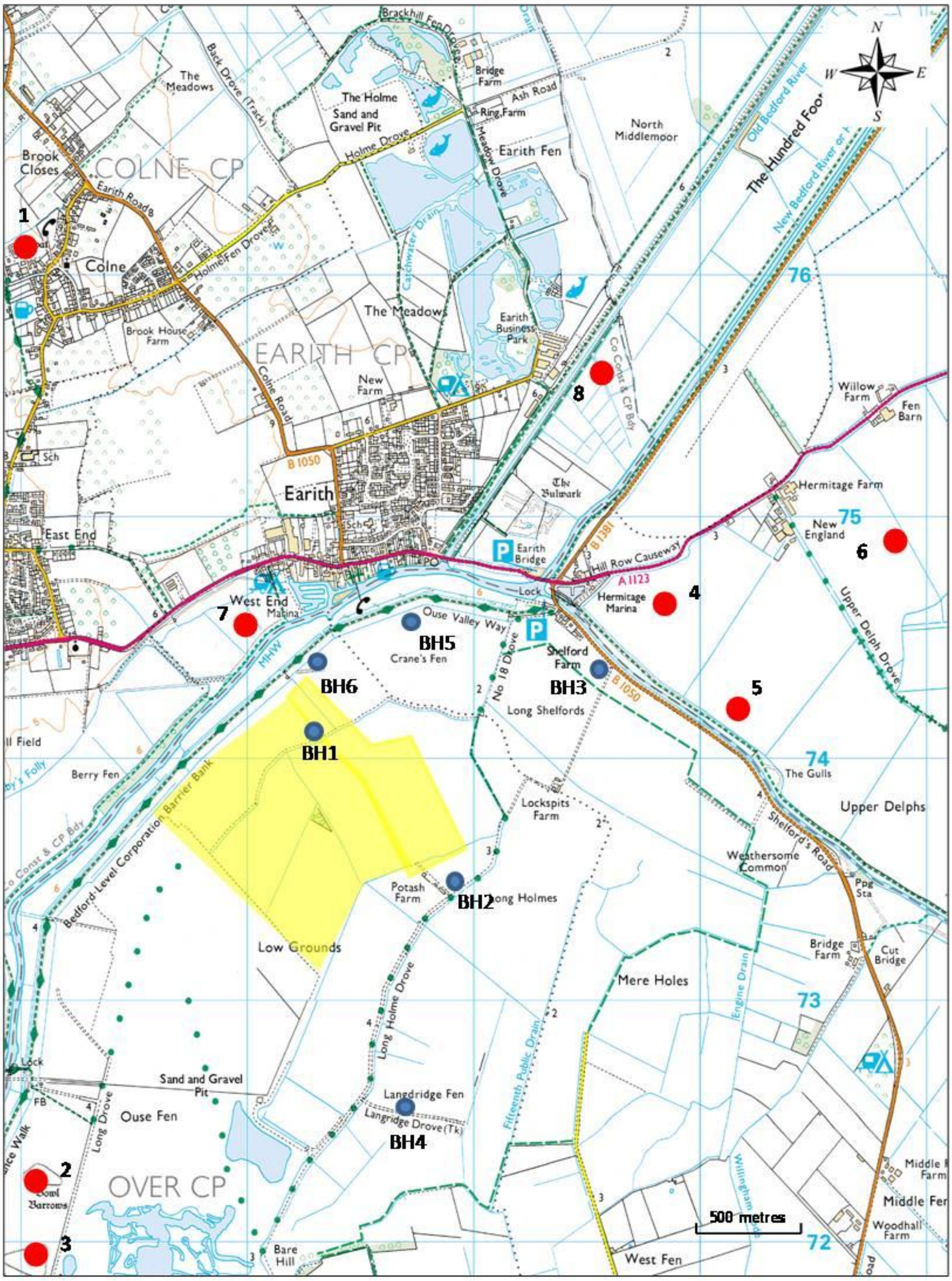


Figure 5.4 Over Quarry (yellow) location plan, key receptors of interest (red) and sand / gravel groundwater monitoring well locations (blue).

5.20 Key historic environment receptors of interest within the area include a number of bowl barrows surrounding the quarry (marked as 1 to 6 on Figure 5.4). In addition, the natural wetland environments of the Barry Fen and Ouse Washes Sites of Special Scientific Interest are marked as 7, and 8 respectively on Figure 5.4.

5.21 Superficial deposits comprise 0.5 - 2.5 m thickness of alluvium over 60 % of the site area, with the remainder comprising up to 2 m thick peat and silt deposits. Underlying the superficial deposits are river and fen sand and gravels of the Goodwin Ridge, through which palaeochannels of the River Great Ouse have been recorded (Figure 5.5). Ultimately, at depth, beneath the gravels, lie the consolidated low permeability clays of the Corallian Clays.

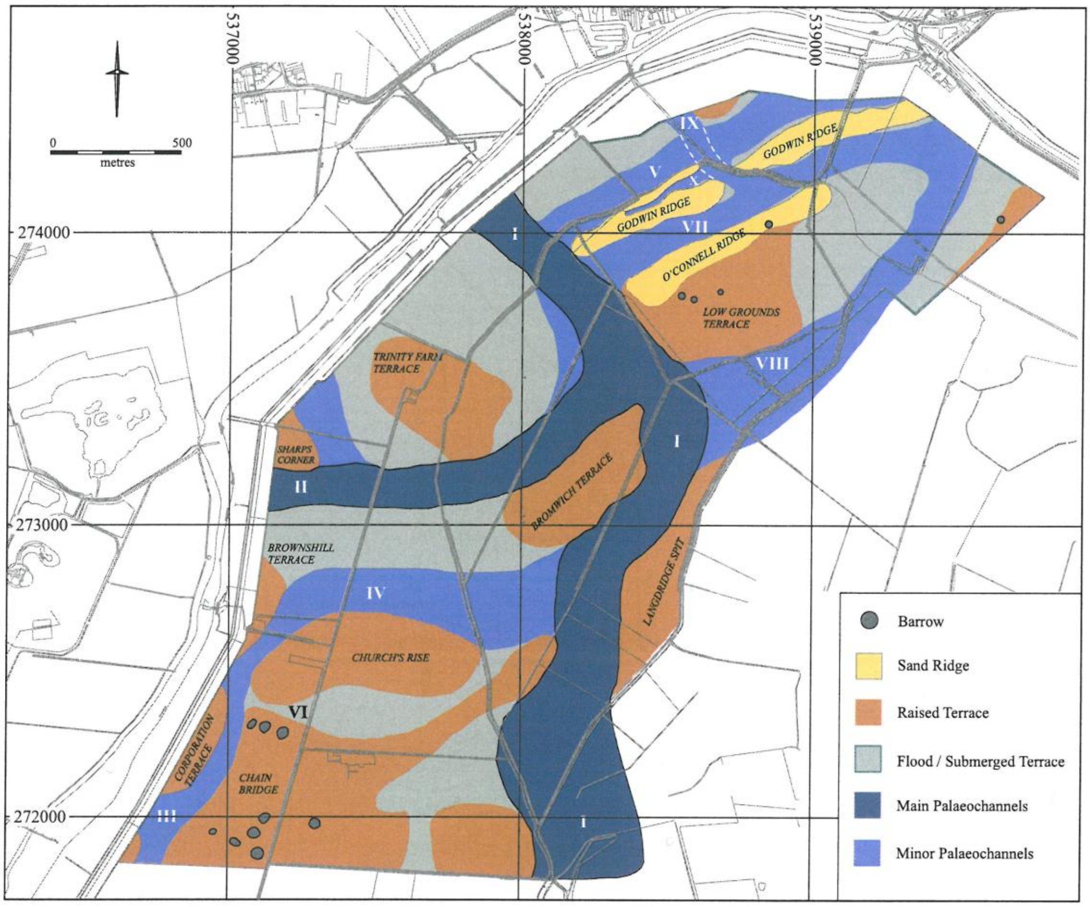


Figure 5.4 Sedimentary units associated with the north-eastern part of the Over site (from Evans and Vander Linden, 2009).

5.22 Previous assessment work[17] at the site has noted that groundwater levels within the sand and gravel deposits had been drawn down to around 5 m below ground level, with a radius of dewatering influence of approximately 500 m.

5.23 These previous investigations did not focus on changes within the alluvium / peat superficial deposits as a result of lowering groundwater levels in the sand and gravel in order to identify whether such changes had potential implications to its archaeo-organic in-situ preservation potential. 1m, 2m and 3m deep piezometers were installed in 66 locations across the site and surrounding area (complementing the 6 sand and gravel monitoring wells). All piezometers and sand / gravel monitoring wells were monitored monthly for water level and in-situ water quality parameters between Feb 2010 and Jan 2011.

5.24 A summary of DWEBAT data, based upon the information reported in Volume 2, is provided in Table 5.2 below.

[17] French et al., 2004

Table 5.2 Over Quarry summary conceptualisation.

Natural Environment					
1	Topography	Low lying floodplain: 1-3 mAOD.			
2	Geology	*Layer No:*	*Lithology:*	*Depth of base (thickness, m)*	*Aquifer Designation?*
		1 (soils)	Alluvium (60% of area) Peat / silts (40% of area)	Alluvium 0.5 – 2.5m thick. Peats / silts 2m thick	Secondary?
		2 (drift 1)	Palaeochannel infill	Not defined	Secondary?
		3 (drift 2)	River Terrace and Fen sand and gravels (Goodwin Ridge)	Not defined (5-6m?)	Secondary
		4 (bedrock)	Corallian Clays	Not defined	Non-Productive
3	Land use cover	Predominantly arable cultivation.			
4	Climatic conditions	Rainfall:	Not defined	Evaporation:	Not defined
5	Surface water	*Name / type*	*Depth (m)*	*Hydraulic continuity?*	*Partially / fully penetrating*
		River Great Ouse	Not defined	Yes (requires, river level data to enable analysis)	Assumed fully, but no depth data to confirm.
		Flood relief channel (running parallel to Great Ouse) and Old West River (north east)	Not defined	Artificial channel, possible disconnection.	Assumed partially within Layer 1 to 2, but no depth data to confirm.
		Drainage ditches	Not defined	Possibly (no details of channel nature / sedimentation / vegetation to define). Dry for most of year.	Assumed partially within Layer 1 to 2, but no depth data to confirm.
6	Drainage	Run-off:	Not defined		
		Ditches:	Anecdotal evidence to suggest water levels remain constant throughout year (possible sign of slow infiltration).		
7	Recharge	Potential infiltration rates are not defined.			
8	Aquifer	*Layer No:*	*Confined / unconfined / perched?*	*Groundwater level range (m AOD)*	*Permeability estimate (m/d)*
		1 alluvium / peat	Perched	Majority of piezometers dry throughout year. Water levels >1m bgl, only found in piezometers close to ditches. 0.2m – 0.6m variation in water levels over year.	Not defined
		2 Palaeochannel	Unconfined?	Not defined	Not defined
		3 sand and gravel	Unconfined	0.5m reduction in water levels over year in BH4. BH5 and BH6 level decline of 1-2m (no mitigation from River Great Ouse), whilst BH3 <0.25m variation (possible mitigation from river)	Not defined.
9	Groundwater	*Layer No:*	*Hydraulic gradient:*	*Flow direction:*	

	gradient and flow directions	1 alluvium / peat	Not defined	Perched waters assumed to be disconnected, therefore no overall flow direction.	
		2 palaeochannels	Not defined	Not defined	
		3 sand and gravel	Not defined	locallly south west towards point of dewatering	
10	Hydraulic boundaries?	Low flow:	Corallian Clays provide low permeability base. Clay walls installed to south of site to act as mitigation to spreading of cone of depression associated with quarry dewatering.		
		Recharge:	River Great Ouse possibly acting as a recharge boundary to north east, but no evidence of recharge along its course to the north west of the site (possibly blocked by flood relief channel ?).		
Anthropogenic Environment					
11	Key heritage receptors	*Name:*	*Layer?*	*Distance from dewatering?*	*Predicted drawdown from quarry dewatering?*
		Bowl Barrows 2 and 3	Layers 1-2	> 1km south west	Beyond radius of influence, and clay walls to south would limit cone of depression.
		Bowl Barrows 1, 4 to 6	Layers 1-2	>1km and on opposite side of River Great Ouse	Beyond likely quarry zone of dewatering influence, and river acts as recharge boundary..
		SSSIs	Layers 1-2 (possibly fed by 3)	<500m to north west	Not calculated, but SSSIs are on opposite bank of River Great Ouse (possible recharge boundary
12	Abstractions - Groundwater	*Name (type & quantity):*	*Layer of abstraction?*	*Continuous / variable?*	*Drawdown & radius of influence.*
		Over Quarry (unknown quantity)	Layer 3 (sand and gravel)_	Not defined, but likely to be variable depending on quarry needs.	3m drawdown at quarry. radius of influence 500m (French, 2004).
13	Abstractions - surface water	*Name:*	*Surface water abstracted from?*	*Continuous / variable?*	*Quantity.*
		None			
14	Discharges - groundwater	*Name:*	*Groundwater discharge point?*	*Continuous / variable?*	*Quantity.*
		None			
15	Discharges - surface water	*Name:*	*Surface water discharge point?*	*Continuous / variable?*	*Quantity.*
		Over Quarry	Not defined	Not defined	Not defined

5.25 The results of the case study investigations have been reviewed in the context of questions raised at the start of this chapter as follows:

Is the information presented sufficient to adequately characterise the water environment surrounding the quarry, and in the vicinity of historic environment receptors of concern?

5.26 From Table 5.1 it can be seen that there are a number of components of the site conceptualisation that have not been defined, calculated, or require further data to fully confirm that a particular process is occurring (e.g. the recharge influence of the River Great Ouse, the infiltration characteristics of the drainage network across the site, or comparison of groundwater levels from the sand / gravel to water levels in the alluvium / peat as well to fully appreciate the links between the two systems).

If no, what data gaps are there and is it essential to fill them before a judgement can be made upon the impact of dewatering operations on the surrounding water environment?

5.27 To determine whether or not data is sufficient to deliver a judgement upon the impacts of dewatering, it is important to consider what the key area of interest is. In this way it is possible to ascertain whether or not a situation requires full conceptualisation / quantification or a focused assessment. In the case of this investigation, the key area of interest was in respect of the potential impacts to both historic and environmental receptors.

5.28 In respect of the identified historic and environment receptors, all lie outside the identified radius of dewatering influence (potentially minimised by the presence of clay walls to the south west) or beyond the River Great Ouse. In the case of the wetland SSSIs, however, which lie within the radius of dewatering influence, groundwater levels recorded within boreholes 5 and 6 do not suggest that the river is acting as a recharge boundary in the local vicinity. As such more monitoring information, particularly in terms of groundwater levels to the north-west of the site and on the nature of the River Great Ouse (depths, elevations, etc.) would need to be gathered before it would possible to make a judgement upon whether or not the wetland SSSIs are at risk of significant drawdown in groundwater levels as a result of quarry dewatering.

Are key heritage environment receptors sensitive to short term or long term change in surrounding water environment conditions?

5.29 In the absence of review of historic groundwater level data (compared to that gathered during the course of this investigation) in combination with a review of dewatering practices during that time, it is not possible to comment upon whether the fluctuations in water levels observed within piezometers within the shallow superficial deposits are short-term or long-term in nature.

5.30 As highlighted in Volume 2, shallow deposits water level fluctuations range from 0.2 m to 0.6 m during the course of the year. This is less than observed in groundwater levels within the underlying sand and gravel deposits, possibly suggesting slow infiltration from drainage ditches combined with water retention in perched systems act to minimise the amount of potential impact. However even though water quality conditions appear to remain conducive to preservation, these fluctuations in saturation conditions could be of concern if there were to be a buried archaeo-organic features of interest that were dependent upon consistent saturation conditions for their preservation.

Given the information presented what 'next step' in terms of assessment would use of the DWEBAT have prompted?

5.31 The case study investigation has added significantly to the monitoring network in the vicinity of Over Quarry. One-dimensional assessment could be undertaken based upon the information collected.

5.32 Although there is now a good data set for water levels within this deposit, gaps in climatic data and drainage information to enable accurate review of infiltration into the soils still exist (and ultimately partially recharged to sand and gravel groundwater). Use of the DWEBAT, and the review prompted by its use, would suggest that the next step in understanding this system would be to gather site specific climate data, elevation data for the drainage network, and to focus on developing a water balance focused on the alluvium / peat system to ascertain the amount of infiltration lost to groundwater (and whether there has been a significant increase in the amount lost as a result of quarry dewatering).

5.33 In addition, as highlighted above, more monitoring information, particularly in terms of groundwater levels to the north-west of the site and on the nature of the River Great Ouse (depths, elevations, etc.) would need to be gathered before it would possible to make a judgement upon whether or not the wetland SSSIs are at risk of significant drawdown in groundwater levels as a result of quarry dewatering.

6. SUMMARY AND RECOMMENDATIONS

6.1 Increasingly, the complexities of water environment analysis and monitoring data are being presented (to inform judgement upon development applications) to non-hydrogeologists (such as development control officers, archaeological stakeholder consultees, etc.) as part of the planning process. Set against an ever-changing background of natural and anthropogenic influences (a dynamic water environment baseline), differentiating natural variation from that associated with human activities within an area and being able to communicate such variation clearly was a prime driver to this research.

6.2 It was felt that there was a need to develop a simple but reliable 'user-friendly' methodology that assists in the basic interpretation of water environment monitoring data (and facilitates communication of such information) without the immediate requirement for complex analysis or numerical modelling. This would aim to at provide results which can be understood by a non-specialist target audience (including English Heritage case officers, land use planners, elected members and the general public).

6.3 During the course of this research it has been found that to robustly differentiate natural impacts from anthropogenic impacts within an area affected by more than one groundwater abstraction could not be easily undertaken in the absence of a numerical model.

6.4 A draft Dynamic Water Environment Baseline Toolkit (DWEBAT) has been developed during the course of this project that aimed to bring together information on both the water and historic environment, in combination with tools / techniques to facilitate assessment. Whilst the toolkit has been found to usefully bring together data in a simple to follow format, highlighting gaps in the conceptualisation of the water environment, it was found that without additional guidance in some of the basic hydrogeological concepts, non-specialist users found the technical assessment side difficult to follow easily. As such, they felt that in more complex settings (e.g. where there is more than one abstractor in an area, or consideration of dewatering and mitigation influences is required) a trained hydrogeologist would be called upon to undertake the assessment.

6.5 As it stands, the draft DWEBAT provides a useful checklist for conceptualisation (providing a user with direction as to when more monitoring data may be needed, when to undertake a one-dimensional assessment, or when to refer to an experienced hydrogeologist); highlights the importance of considering water and historic environment changes together; and promote transparency in assessment calculations (a clear audit trail) for assessment provided in support of planning applications.

6.6 The concept of the DWEBAT, and its potential for evolution to meet the wider aim of facilitating assessment for non-specialists, could be of interest to stakeholder groups beyond English Heritage (e.g. Natural England, mineral operators, development control planners, etc.). With increasing amounts of monitoring information being gathered by a large number of stakeholders across the country, the evolution of joint conceptualisations and datasets (potentially centred around a GIS front end database linked to the Excel based DWEBAT) would represent good practice and shared knowledge amongst the wider scientific community.

6.7 If the DWEBAT were to be taken forward for development as a concept within English Heritage, in order to bridge the gap in terms of knowledge and to help the user make the most out of the toolkit, there is the need for brief non-technical guidance to be developed on some of the basic water environment concepts and assessment techniques (e.g. hydraulic gradient calculations, groundwater level contouring, etc.).

6.8 The two case study investigations undertaken as part of this research have significantly added to the monitoring networks at the two sites. Review of the data collected has identified that any future research associated with the two sites should focus predominantly upon quantification of the water balances within the superficial deposits that are of most interest from an in-situ preservation point of view.

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8. APPENDIX 1 - GLOSSARY OF TERMS

Abstraction: The removal of water from a 'source of supply', such as a river, lake or groundwater. More specifically, abstraction is defined by Section 221(i) of the Water Resources Act 1991 as "*the doing of anything whereby any of that water is removed from that source of supply, whether temporarily or permanently, including anything whereby the water is so removed for the purpose of being transferred to another source of supply.*"

Areal (extent): Is the magnitude of an area.

Aggregate: Crushed rock, natural sand and gravel or artificial material that is used as a construction material, usually in conjunction with a suitable binder such as cement or bitumen.

Analytical models: Analytical models are mathematical models that have an exact solution, i.e. the solution to the equations used to describe changes in a system can be expressed as a mathematical analytic function.

Aquifer: Defined in the Water Framework Directive (WFD) as *"a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater"*.

Aquitard: A subsurface layer or layers of rock or other geological strata which have low permeability and which may thereby impede the flow of water between adjoining aquifers (see also Minor Aquifer).

Archaeology: The study of ancient cultures by the scientific analysis of physical remains.

Axial flow: The flow rate of water along an axis (i.e. radial flow towards an abstraction).

Axially symmetric: is symmetry around an axis; an object is axially symmetric if its appearance is unchanged if rotated around an axis.

Baseflow: That component of surface water flow in streams and rivers that is sustained purely by the discharge of groundwater within the surface water catchment.

Baseline monitoring / characterisation: Measurement and monitoring of the physical, chemical and / or biological parameters which characterise a system or sub-system (such as a local water catchment), undertaken before the commencement of any development or operations (e.g. quarrying or water abstraction) which could give rise to changes in one or more of those parameters. Some of the parameters (e.g. topographic features) may be relatively static, prior to development, whilst others (e.g. streamflow) may be dynamic, necessitating a programme of monitoring over time in order to establish both 'average' conditions and the 'typical' range of variation. The 'baseline conditions' assessed by such monitoring form a basis for assessing the nature and magnitude of any subsequent changes, as revealed by further operational (or post-operational) monitoring data.

Borehole: Is the generalised term for any narrow shaft drilled in the ground.

Cartesian co-ordinates: Specify each point uniquely in a plane by a pair of numerical coordinates, which are the signed distances from the point to two fixed perpendicular directed lines, measured in the same unit of length.

Catchment: The area from which water drains towards a specified point. The surface water catchment and groundwater catchment relating to the same point may encompass different areas.

Catchment Abstraction Management Strategy (CAMS): A policy mechanism used by the Environment Agency in England and Wales in order to determine whether the water resource situation within a particular catchment is deemed to be sustainable ('fully licensed' or 'under licensed') or unsustainable ('over licensed' or 'over abstracted').

Chemical kinetics: (Also known as reaction kinetics) is the study of rates of chemical processes.

Chemical status: A measure of water quality, required to be assessed under the WFD. WFD Article 2 (Definitions), No. 24 defines 'Good surface water chemical status' as *"the chemical status required to meet the environmental objectives for surface waters established in Article 4(1)(a), that is the chemical status achieved by a body of surface water in which concentrations of pollutants do not exceed the environmental quality standards established in Annex IX and under Article 16(7), and under other relevant Community legislation setting environmental quality standards at Community level"*. WFD Article 2(No. 25) defines 'Good groundwater chemical status' as *"the chemical status of a groundwater body, which meets all the conditions set out in table 2.3.2 of Annex V"*.

Channel bed conductance: The rate at which a channel bed can transmit fluids.

Conceptual model: A written and / or diagrammatic explanation or representation of a system based on a synthesis of available information. It may be purely qualitative or partly quantified. In the context of this report a quantitative conceptual model of the local water cycle is an essential starting point for the assessment of potential impacts of quarrying on the local groundwater and surface water regimes, water features and associated ecosystems. It should form the basis of more sophisticated analytical solutions or numerical models where these are appropriate and necessary (which will not always be the case) and may be used in the design of both quarrying proposals and mitigation measures to ensure that potential impacts are minimised and / or adequately controlled.

Confined (aquifer): A saturated aquifer that is isolated from the atmosphere by an overlying layer or layers of low permeability strata.

Contaminant: A substance that is either present in an environment where it does not belong or is present at levels that might cause harmful effects to humans or the environment.

Dewatering: The localised lowering of groundwater levels, usually by means of groundwater abstraction, in order to enable activities such as construction and mineral extraction to continue below the level of the natural water table.

Discharge: Is the volume rate of water flow, including any suspended solids (i.e. sediment), dissolved chemical species (i.e. $CaCO_{3(aq)}$) and / or biologic material (i.e. diatoms), which is transported through a given cross-sectional area.

Drawdown: The extent to which the water table has been lowered by dewatering (i.e. the vertical distance between the original water table or piezometric surface and the surface of the cone of depression at a given point).

Dynamic equilibrium: The state of a system or sub-system in which time-averaged inputs equal time averaged outputs and in which, as a consequence, the average levels of storage within the system (e.g. groundwater levels within an aquifer) remain constant with time. See also **steady state**.

Empirical (equations): Derived from or guided by experience or results from an experiment.

Environment: The external conditions, resources, stimuli, etc. with which a living organism interacts. Except where otherwise stated, the term is generally used in this report to encompass not only the natural environment but also the built environment and the **historic environment**.

Equilibrium: Is the condition of a system in which competing influences are balanced.

Evapotranspiration: The combination of evaporation and transpiration.

Finite-element simulator: Is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations.

Finite difference model: Is a numerical method for approximating the solutions to differential equations using finite difference equations to approximate derivatives.

Floodplain: Generally flat surface alongside a stream or river that (in most cases) has been created by the deposition of river-borne sediments and over which water flows in times of flood (or would do so but for the presence of flood defences, where these exist).

Geology: The scientific study of the physical and chemical composition of the Earth, its origin and evolution over time, and the processes involved.

Geometry: Is a part of mathematics concerned with questions of size, shape, relative position of figures, and the properties of space.

Groundwater: Defined in the WFD as *"all water below the surface of the ground in the saturated zone and in direct contact with the ground or subsoil"*. The term is also legally defined in Section 104(d) of the Water Resources Act (WRA) 1991 as *"any waters contained in underground strata"*. Technically, the WFD definition, which specifically excludes water in the unsaturated zone (i.e. 'soil moisture') is more accurate, but the WRA definition becomes important in relation to the abstraction licensing regime.

Groundwater contours: Lines joining points of equal **hydraulic head**.

Head: (See **Hydraulic head**).

Heterogeneous: Heterogeneous sediment is one which has variable properties (e.g. permeability and storage) as a result of variable sedimentary composition.

Historic environment: Aspects of the environment which relate to historical land use and development, including (but not limited to) ancient monuments, listed buildings and archaeological remains.

Hydraulic conductivity: A measure of the rate at which water can move through pore spaces of fractures in rock or sediment.

Hydraulic head: A measurement of water pressure within an aquifer or surface water body, usually expressed in terms of height above a specified datum level (e.g. sea level). Defined as the sum of the elevation head, pressure head, and the velocity head at a given point (the latter usually being negligible in the case of groundwater).

Hydrogeology: A specialised branch of geology concerned with the scientific study of water within the Earth's crust, including its physics, dynamics, chemistry and relationships to geological and environmental factors.

Hydrologic cycle: is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and the hydrosphere.

Hydrology: The scientific study of the properties, distribution and circulation of water. The term is normally used specifically in relation to surface water but sometimes may refer also to groundwater.

Hydrostratigraphy: A geologic framework consisting of a body of rock having considerable lateral extent and composing a reasonably distinct hydrologic system.

Infiltration: The process by which water on the ground surface enters the soil.

Image well: Is a hypothetical well that simulates recharge or discharge at the same distance from the hydraulic boundary as the real production well.

Impermeable: Not permeable, not permitting fluids to pass through it.

Injection well: Is a vertical pipe in the ground into which water, other liquids, or gases are pumped or allowed to flow.

Intergranular flow: The flow of groundwater through pore spaces (e.g. between individual grains of sediment) within an aquifer.

Isotropic: Having physical properties, as hydraulic conductivity, elasticity, etc., that are the same regardless of the direction of measurement.

Lacustrine: Means of a lake, or relating to a lake.

Leaky aquifer: When a well in a leaky aquifer is pumped, it pulls water from the leaky aquifer, and from the aquifers above and / or below.

Line sources: Is a source of water, air, noise, water contamination or electromagnetic radiation that emanates from a linear (one-dimensional) geometry. A river could be line source of either recharge or discharge to an aquifer.

Lumped models: Simplify the description of the behaviour of spatially distributed physical systems (e.g. the environmental processes / interactions occurring within a catchment).

Major aquifer: A term previously used by the Environment Agency to describe aquifers which are of major strategic importance for the public supply of groundwater. Major aquifers are now reclassified as principal aquifers in the Environment Agency’s revised classification system.

Mass balance: Is an application of conservation of mass to the analysis of physical systems. By accounting for material entering and leaving a system, mass flows can be identified which might have been unknown, or difficult to measure without this technique.

Mitigation: Taking actions to reduce adverse effects (e.g. to reduce the potential impacts of quarrying on the environment).

Mitigation strategy: A planned sequence of actions, typically designed to provide successively more robust levels of mitigation as and when specified conditions are identified.

Nutrients: Is a chemical that an organism needs to live and grow or a substance used in an organism's metabolism which must be taken in from its environment.

One-dimensional: The dimension of a space or object is informally defined as the minimum number of coordinates needed to specify each point within it. Thus a line has a dimension of one because only one coordinate is needed to specify a point on it.

Outflow: The act or process of flowing out.

Overburden: Is the material that lies above the area of economic or scientific interest.

Partial differential equations: Ordinary differential equations (ODEs) arise naturally whenever a rate of change of some entity is known. ODEs describe such changes of discrete entities. Partial differential equations (PDEs) are analogous to ODEs in that they involve rates of change; however, they differ in that they treat continuous media.

Particle pathlines: The trajectories that individual fluid particles follow. These can be thought of as a "recording" of the path a fluid element in the flow takes over a certain period. The direction the path takes will be determined by the streamlines of the fluid at each moment in time.

Permeability: A measure of the ability of a material (such as rocks) to transmit fluids.

Piezometer: An instrument for measuring hydraulic pressure - commonly a tube installed in the ground to allow the measurement of water level in a specific unit of the sub-strata.

Piezometric surface: The level at which the hydrostatic water pressure in an aquifer will stand if it is free to seek equilibrium with the atmosphere. For artesian wells, this is above the ground surface.

Pit: Is a hole in a surface.

Porosity: Is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume, between 0-1, or as a percentage between 0-100%. Not all porosity is drainable.

Precipitation: Water which falls to earth from the atmosphere in the form of rain, hail, sleet, snow or dew.

Pumping test (also known as aquifer testing): A method of hydrogeological investigation designed to enable *in-situ* calculations of aquifer properties such as permeability and to allow field observations of the way in which a particular groundwater system responds to the changes induced by groundwater abstraction. In England and Wales, such tests should be undertaken in accordance with BS 6316 *Code of Practice for Test Pumping of Water Wells* (1992), and will require Section 32 'pump test' consent from the Environment Agency.

Pumping well: A well produced by use of some kind of downhole pump.

Purging: The process of removing "stale" groundwater from a borehole or well prior to sampling for water quality, to ensure that the sample is representative of the surrounding groundwater. Purging three times the borehole's volume is a commonly accepted procedure.

Radial flow: Is flow converging to a well.

Radius of influence: The radial distance from the centre of a wellbore to the point where there is no lowering of the water table or potentiometric surface (the edge of the cone of depression).

Receptor: In the context of environmental impact assessment, a receptor is anything that might be affected by environmental changes that are induced by the proposed development.

Recharge: The process by which water is added to groundwater storage within an aquifer (e.g. by natural precipitation or by artificial recharge), or the amount of water added to groundwater in a given period.

Recharge features: Generally man-made excavations that allow water abstracted from a quarry to be recharged back into the aquifer by means of infiltration. Such features could include abandoned former quarries that have not been backfilled but, more commonly, they are purpose-designed trenches or lagoons which have been excavated through any overburden material and into the underlying aquifer.

Redox reaction: The process by which a substance is ‘oxidised’ or ‘reduced’ by the process of electron transfer. A substance may acquire electrons and thereby become reduced (if the redox potential is positive) or it may lose electrons and thereby become oxidised (if the redox potential is negative).

River discharge: The amount of water that flows down a river channel.

River flow gauging: Refers to a site along a river where measurements of water surface elevation (stage) and / or volumetric discharge (flow) are made.

River reach: A river segment of a particular length.

River roughness coefficient: The roughness coefficient is often used as the main calibration parameter in river models, although previous research has shown that the uncertainty in the hydraulic roughness of the river bed is one of the main sources of uncertainty in the computed water levels.

Sediment: Particles of material, such as clay, silt, sand, gravel, boulders or organic fragments which are either carried by flowing water, ice, wind or mass movement; or which have previously been carried by such processes and subsequently deposited.

Sedimentary: Geological deposits and rocks that are composed of **sediment**.

Seepage face: A belt on a slope, such as the bank of a stream, along which water emerges at atmospheric pressure and flows down the slope.

Semi-logarithmic graph: Is a way of visualizing data that are changing with an exponential relationship. One axis is plotted on a logarithmic scale. This kind of plot is useful when one of the variables being plotted covers a large range of values and the other has only a restricted range – the advantage being that it can bring out features in the data that would not easily be seen if both variables had been plotted linearly.

Site investigation: A term used to encompass all aspects of the investigation of the physical and geological characteristics of a site, prior to proposed development. It includes initial desk studies and walk-over surveys, together with all aspects of ground investigation, analysis, interpretation and reporting that are needed in order to determine the suitability of the site for the proposed development and / or any ground improvement or other engineering measures, including foundation design, that may be necessary.

Soil moisture: Is the quantity of water contained in a soil.

Soil moisture deficit: Is the amount of rain needed to bring the soil moisture content back to field capacity.

Solute (transport): The transportation of a substance that is dissolved in a fluid, forming a solution.

Specific yield: Is a material physical property that characterizes the capacity of an aquifer to release groundwater from storage in response to a decline in hydraulic head.

Steady state: The state of a system or sub-system in which inputs equal outputs and in which, as a consequence, there are no changes in storage (e.g. groundwater levels within an aquifer) with time and no changes in the magnitude and directions of flow (e.g. groundwater flow). In practice, all natural systems are constantly in a state of flux, with temporary adjustments in both storage and flows to accommodate natural variations in inputs (e.g. rainfall). Conditions of approximate steady state can, however, be said to obtain where the average inputs and outputs remain reasonably constant over time. With regard to groundwater modelling, a steady-state model calculates one set of head levels for an infinite time step, when all boundary conditions, inputs / outputs and properties are constant.

Storage coefficient: The volume of water released from storage in a confined aquifer per unit surface area per unit decrease in the hydraulic head. The storage coefficient is the product of the specific storage and the aquifer thickness.

Storativity: See **storage coefficient**.

Streamline: Refers to fluid flows (see particle **pathlines**).

Structure (geology): The physical characteristics of a geological feature (e.g. bedding, jointing, folds, faults, etc.) which are related to and therefore help to deduce its geological history.

Sub-catchment: is a discrete self-contained part of a catchment (groundwater or surface water) where all the water from this area drains through a single location. It is used to model run-off from a given area of land.

Sump: Is a low space that collects any often-undesirable liquids such as water or chemicals.

Surface water: General term encompassing all water on the surface of the land, within streams, rivers, springs, lakes, ponds, canals, ditches, wetlands and surface reservoirs.

Three-dimensional: The inside of a cube, a cylinder or a sphere is three-dimensional because three co-ordinates are needed to locate a point within these spaces.

Timestep: A particular interval of time (e.g. a day, week, year, etc.).

Time variant system: Is a system that is not time invariant (TIV). Roughly speaking, characteristics of its output depend explicitly upon time (e.g. daily, seasonally, etc).

Transient: A term used in groundwater modelling for simulations that analyse time-dependent problems. The model calculates head levels for a number of time steps over a specified period of time.

Transmissivity: A term which describes the ease of flow of water through the aquifer as a whole. It is the mathematical product of the **hydraulic conductivity** and the thickness of the aquifer unit, and is measured in units of m^2 / day.

Trench: Is a type of excavation or depression in the ground.

Two-dimensional: A surface such as a plane or the surface of a cylinder or sphere has a dimension of two because two coordinates are needed to specify a point on it (for example, to locate a point on the surface of a sphere you need both its latitude and its longitude).

Unconfined (aquifer): An aquifer where the water table is exposed to the atmosphere through unsaturated overlying material.

Unsaturated zone: The unsaturated zone (also known as the vadose zone) is the portion of the subsurface above the water table. At least some of the time, it contains air as well as moisture in the pores.

Water balance: Quantification of all the inputs to, outputs from, and storage changes within, a given water system.

Water environment: Defined for the purposes of this report as comprising "*groundwater and surface water bodies and the water resources within them, together with the ecosystems, habitats, species, water users, existing land use and development, and archaeological features that are either dependent on those resources or sensitive to changes in their conditions".*

Water run-off: Water flow that occurs when soil is infiltrated to full capacity and excess water from rain, meltwater, or other sources flows over the land.

Water table: The upper surface of the saturated zone within an unconfined aquifer, where the upward hydrostatic pressure is equal to the downward atmospheric pressure.

Well (wellpoint): An artificial excavation or structure put down by any method such as digging, driving, boring, or drilling for the purposes of withdrawing water from underground aquifers.

Zone of (dewatering) influence: The surface area over which drawdown as a result of dewatering has an effect.

9. APPENDIX 2 - REVIEW OF WATER BALANCE SPREASHEET MODELS

This appendix explains the main analytical equations that are used as the basis for analytical and numerical models. The models themselves are subsequently reviewed.

Hydrogeological Equations Modelling

The primary analytical equations that are considered to be the most useful in terms of assessing the water environment within and surrounding sand and gravel quarries, are highlighted in Table 3.1 and discussed in the sections below. They have been sub-divided as follows:

- Measurement of water transfer and consumption in an open void (water balance equation);
- Assessment of the radius of influence of a well / pit and flow to a pit (radius of influence equations);
- Measurement of drawdown and steady state flow from wells associated with differential on-site pumping regimes (abstraction equations); and
- Assessment of single or multiple flows into a trench or wellpoint (construction dewatering equations).

Equations which are time dependant are only really relevant for impacts which do not reach steady-state (for instance very short duration activities, or for monitoring of time dependant water levels to obtain aquifer properties). Generally, for assessing the impact of dewatering activities or long-term pumping, an assumption that the pumping reaches steady-state would be conservative. It would normally be reasonable to assume that quarry dewatering and water resource pumping reach steady-state during the typical duration of either a quarry, or abstraction licence, which is a number of years. Steady-state impacts in terms of overall drawdown levels and extents will be greater than transient impacts before steady state is reached. Nevertheless, for practical management of dewatering it can be useful to estimate the volume of water pumped over time.

As is demonstrated in Table 1 (below) there are a number of analytical solutions that can be utilised in order to assess water movement within a site or an aquifer unit. However, a number of these equations are for use within a confined aquifer setting. In most geological settings sand and gravel aquifers are likely to be unconfined as they are superficial deposits that are located near to the surface. Hence confined analysis is likely to have only a limited application both within and surrounding typical aggregate quarry sites.

In some geological environments a low permeability surface deposit (e.g. a lacustrine-lake-clay) can provide a confining layer over sands and gravels. However, once the overburden is removed for mineral extraction the area of the actual quarry would be unconfined. Analysis of both unconfined (in the quarry) and confined conditions (elsewhere) would generally be beyond analytical solutions and require a numerical modelling approach.

The most suitable analytical equations for assessing the water environment in an unconfined aquifer setting are discussed below.

Table 1 Main analytical equations used to assess water movement (based on Water Management Consultants, 2006**).**

	Aquifer setting	Description / typical application
Water balance equation		
Water balance	Confined / Unconfined	Tool to account for water transfer and consumption in an open void
Radius of influence equations		
Radius of influence (Niccoli et al., 1998)	Unconfined	Method to estimate radius of influence of dewatering upon an unconfined aquifer
Flow to a pit (Marinelle and Niccoli, 2000)	Unconfined	Flow into a pit using separate solutions for the sides and the base
Radius of influence (Sichardt and Kyrieleis, 1930)	Unconfined	Empirical equation based on drawdown and permeability
Radius of influence (Bear, 1979)	Confined	Radius of influence for a pumping well in an infinite confined aquifer
Abstraction equations		
Thiem (1906)	Confined	Steady-state flow to a well in a confined aquifer
Dupuit-Thiem (combination of Dupuit [1863] and Thiem [1930])	Unconfined	Steady-state flow to a well in an unconfined aquifer
Theis (1935) -Time Variant	Confined	For assessing drawdown at a distance, r, from a pumping well at a time, t, from the start of pumping
Cooper-Jacob (1946) - Time Variant	Confined	For assessing drawdown at a distance, r, from a pumping well at a time, t, from the start of pumping
Cooper-Jacob (1946) - Time Variant	Unconfined	For assessing drawdown at a distance, r, from a pumping well at a time, t, from the start of pumping
Dupuit-Forchheimer (combination of Dupuit [1863] and Forchheimer [1930])	Unconfined	Steady flow in an unconfined aquifer, used to determine seepage
Leaky aquifer - De Glee (1930)	Leaky	Steady-state flow to a well with leakage flow across an aquitard
Construction dewatering equations		
Trench with flow from one side (Mansur and Kaufman, 1962)	Unconfined	Partial penetration by a single row of wellpoints of an unconfined aquifer fed from a single line source
Trench with flow from one side (Mansur and Kaufman, 1962)	Confined	Partial penetration by a single row of wellpoints of an unconfined aquifer fed from a single line source
Trench with flow from two sides (Mansur and Kaufman, 1962)	Unconfined	Partial penetration by a single row of wellpoints of an unconfined aquifer midway between two equidistant and parallel lines sources
Trench with flow from two sides (Mansur and Kaufman, 1962)	Confined	Partial penetration by a single row of wellpoints of an unconfined aquifer midway between two equidistant and parallel lines sources
Partial penetration by a double row of wellpoints (Mansur and Kaufman, 1962)	Unconfined	Partial penetration by a double row of wellpoints of an unconfined aquifer midway between two equidistant and parallel lines sources
Partial penetration by a double row of wellpoints (Mansur and Kaufman, 1962)	Confined	Partial penetration by a double row of wellpoints of an unconfined aquifer midway between two equidistant and parallel lines sources
Single well with image well (Ferris, 1969)	Unconfined	Full penetration by single well of unconfined aquifer fed by single line source
Single well with image well (Ferris, 1969)	Confined	Full penetration by single well of unconfined aquifer fed by single line source

Water balance equation

For the water environment to be in equilibrium the total inputs to, and outputs from, a system need to be in balance[18]. If there is an imbalance between the inputs and outputs, water must either be taken from or added to storage within that system (which is observed as a change in water level). The concept of a water balance, when considered over a defined spatial area and a set moment in time, can be represented simply by a number of

[18] Thompson et al., 2008

individual components (i.e. 'building blocks'); and is illustrated in Table 2 (below). In general, inputs and outputs (for a snapshot in time and space) can be estimated through the application of standard hydrogeological and hydrological analytical equations using collected monitoring data. By constructing a water balance from each of its component parts, it is possible to start to estimate the potential changes in storage (translating to potential water flow and level changes) in very broad terms (given that 'total inputs = total outputs +/- storage').

Vice versa, from a review of how water flows and levels have varied over time (using available monitoring information), it is possible to approximate the potential storage changes within a water environment system (which ultimately reflect changes in either total inputs or total outputs [and therefore those that may be natural or anthropogenic in nature]). However, this theoretical approach may require the simplification of the water environment system and its component parts.

Some of the information required to construct a detailed water balance may be obtained from publicly available sources, such as river flow gauging, groundwater levels, rainfall (as the principal input to the system) and evaporation records, and details of groundwater and surface water abstractions. The rainfall must subsequently be apportioned between *infiltration*, *evaporation* and *surface run-off*, according to local catchment characteristics (such as slope, infiltration capacity, soil moisture deficit, vegetation and land use), using the methods described in *SNIFFER: Derivation of a Methodology for Groundwater Recharge Assessment in Scotland and Northern Ireland* (Entec UK Limited, 2003).

Table 2 Water balance components (after Gill et al., 2008).

	Basic background water balance	Potential additional quarry water balance
Inputs to the local system	1) Rainfall 2) Groundwater input from up-gradient 3) Surface water inflows from upstream	1) Reduced groundwater input from up-gradient due to use of low permeability barrier 2) Reduced or increased recharge depending upon site situation.
Storage within the local system	1) Surface water storage (lakes, ponds and reservoirs) 2) Soil Moisture Deficit within the unsaturated zone 3) Groundwater storage in aquifers	1) Surface water storage in attenuation ponds and silt lagoons 2) Changes in storage in the unsaturated zone (e.g. though removal by quarrying) 3) Changes in aquifer storage (e.g. through removal by quarrying or drawdown of groundwater levels)
Movement of water within the local system	1) Groundwater flow 2) Surface runoff 3) Flow within surface watercourses 4) Infiltration 5) Recharge 6) Other interactions between groundwater and surface water	1) Changes in rainfall / runoff relationships induced by quarrying 2) Control of surface water movement *within* the local system including diversion of watercourses, drainage systems, surface water abstractions and discharges 3) Dewatering transfers *within* the local system (rates of abstraction and rates of discharge or recharge) 4) Artificial disruption of groundwater flow (e.g. by the use of low permeability barriers) 5) Localised readjustment of groundwater flows induced by dewatering or other operations
Outputs from the local system	1) Evapo-transpiration 2) Local groundwater and surface water abstractions 3) Seepages 4) Groundwater output down-gradient 5) Surface water outputs downstream	1) Changes in evapo-transpiration induced by quarrying and / or reclamation scheme 2) Discharges from groundwater and surface water abstractions associated with quarrying which are not balanced by recharge or discharge within the local system 3) Water content of products transported off-site

Similarly baseflow (groundwater discharge) needs to be estimated from river or stream flow data (if available). Often only level gauging data is available. However, flow gauging does not indicate baseflow and further analysis to separate the baseflow component (which will vary over time) from the flow record will be required.

In addition to the parameters outlined above, further baseline monitoring of local and hydrogeological systems is also likely to be required in order to provide more specific data. For the background water balance, this may comprise the collation of more detailed and localised data than can be obtained from publicly available sources (such as rainfall at the quarry and its immediate surroundings, groundwater levels, surface water levels and flows, local abstractions and discharges). Some of these will require the installation of suitable monitoring equipment. Groundwater flow rates and directions can be estimated by analysing groundwater levels (using empirical equations), while the interaction (inflow / outflow) between groundwater and surface watercourses can be assessed by using groundwater level data and surface water levels and flows. However, some of these estimations may be fairly approximate if extensive, on-site data are not available.

<u>Radius of influence equation</u>

Most natural aquifers have a natural though flow of groundwater, which varies seasonally with recharge. This may result in an increase in recharge, if prior to dewatering potential recharge was unable to enter the aquifer (e.g. due to a high level of runoff, or no available storage [i.e. the aquifer is fully saturated]) and following dewatering additional recharge can be accepted by the aquifer. When dewatering begins, natural discharge from the aquifer diminishes (as shown in Figure 1 below). The sources of recharge include the following (Powers et al., 2007):

- Surface infiltration from rainfall or surface inundation;
- Seepage from lakes, ponds, influent streams or the sea;
- Horizontal connection with other aquifers; and
- Vertical leakage through upper or lower confining beds (aquitards).

Where an excavation is undertaken either at or in close proximity to a river which is in contact with the aquifer that is to be dewatered, it is frequently more convenient to simulate the total recharge as an equivalent line source (a vertical plane that is offset from the centre of pumping). A line source is said to have an effect on dewatering volume similar to a circular source at twice the distance (Powers et al., 2007).

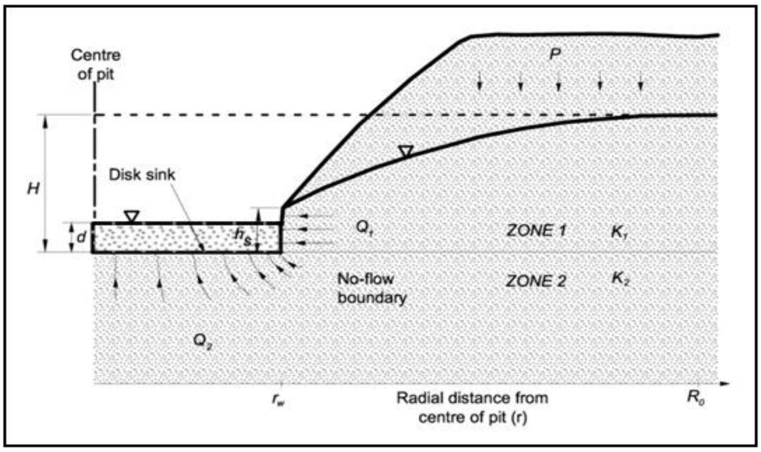

Figure 1 Diagrammatical representation of radius of influence (from Nicolli et al., 1998).

The equation used to measure the radius of influence from the example presented in Figure 1 above is as follows:

$$H = \sqrt{h_s^{\,2} + \frac{P}{K_{h1}}\left[R_0^{\,2}\ln\left(\frac{R_0}{r_w}\right) - \frac{R_0^{\,2} - r_w^{\,2}}{2}\right]}$$

Where:

- H - Height of water table at radius of influence
- P - Recharge
- H_s - Saturated thickness to seepage face
- r_w - Radius of quarry
- s - Drawdown (H-h_p)
- R_0 - Effective radius
- K_{h1} - Layer 1 horizontal hydraulic conductivity

The conditions and assumptions underlying this equation are as follows (Niccoli et al., 1998):

- There is steady-state, unconfined, horizontal radial flow towards the pit;
- There is uniformly distributed recharge at the water table;
- Pit walls are approximated as an upright circular cylinder;
- The static water table is horizontal;
- Groundwater flow is horizontal; and
- Groundwater flow to the pit is axially symmetric.

Abstraction Equations

Dupuit-Thiem Method

The Dupuit-Thiem Method is a combination of steady-state equations (i.e. when the magnitude and direction of water flow is constant with time throughout the entire system) for a well fully penetrating and screened in an unconfined aquifer (as shown in Figure 2 below) (obtained from Dupuit [1863] and Thiem [1930]). Aquifer hydraulic conductivity can be determined by using the Dupuit-Thiem Method if the rate of discharge of a production well and the drawdown in each of two wells at a known distance from the pumped well can be determined (Kasenow, 2001). Transmissivity can be calculated if the aquifer thickness is known (Kruseman and de Ridder, 1994).

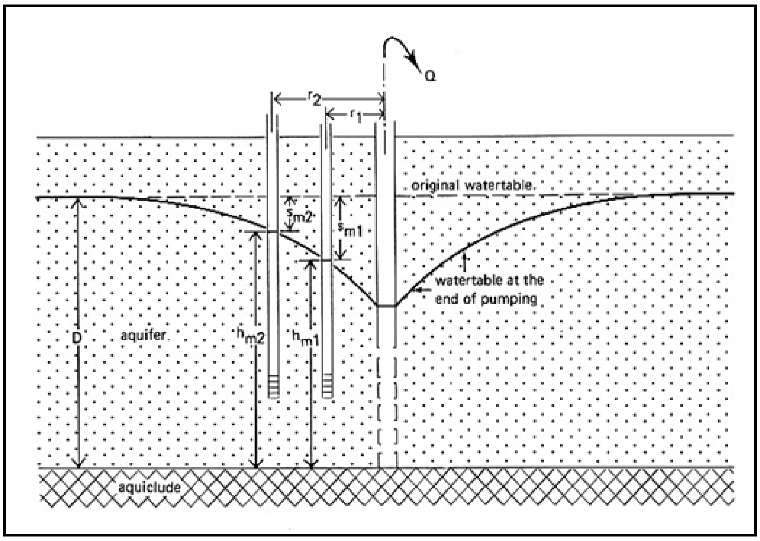

Figure 2 Diagrammatical representation of the Dupuit-Thiem Method (from Kruseman and de Ridder, 1994).

The equation used to measure the steady-state flow to a well in a confined aquifer (Dupuit-Thiem Method) from the example presented in Figure B.2 above is as follows:

$$Q = \Pi K \frac{(h_2^{\ 2} - h_1^{\ 2})}{2.3\log(\frac{r_2}{r_1})}$$

Where:

- h_1 - Height of water table at observation well 1
- r_2 - Distance to observation well 2
- r_1 - Distance to observation well 1
- K - Hydraulic conductivity of aquifer
- h_2 - Height of water table at observation well 2
- Q - Total discharge from well

To find the drawdown at a given radius from the well:

- Q - Discharge
- h - Water table height at radius of interest
- r_2 - Radius of interest
- s_r - Drawdown at radius

To find the radius of a specific water level:

- Q - Discharge
- r_2 - radius of required drawdown
- h_2 - Water table height at radius of interest

However, steady-state conditions do not consider time; and therefore this equation cannot be solved for the storage coefficient. All groundwater is assumed to originate beyond the limits of the zone of water table depression. In addition, the Dupuit-Thiem Method assumes the following (Kruseman and de Ridder, 1994; Kasenow, 2001):

- The aquifer is homogenous, isotropic, of equal thickness, and infinite in areal extent;

- The production well penetrates and receives water from the entire aquifer thickness;
- The transmissive property of the aquifer is constant at all times and at all locations in the aquifer;
- Rate of discharge is constant and has occurred for a sufficient time in order to allow for a steady-state hydraulic system (i.e. no change in rate of drawdown); and
- Flow to the well is horizontal, radial and laminar.

The assumptions outlined above cannot easily be applied to either quarry dewatering or assessing other possible impacts upon the water environment baseline. This is primarily due to the fact that these assumptions ignore the existence of seepage faces at the well point (which in the case of quarries comprise large surface areas). However, it may be possible to use this method in order to estimate permeability which could subsequently be used in an (other) modelling tool.

In addition to the assumptions above which limit the validity of using the Dupuit-Thiem Method in the setting of a sand and gravel quarry, the vertical components of water flow and the curvature of flowlines are also ignored. As such, the equation should therefore be used with caution where the curvature of water flow is accentuated >15 degrees. Nevertheless, this method does correct for dewatering and is valid when drawdown due to dewatering is ≤25% of the aquifer's thickness (Kasenow, 2001).

Cooper-Jacob Method

The Cooper-Jacob Method (1946) permits an approximate solution to the Theis (Time Variant) non-equilibrium equation (1935) (see Table 2 for details) using a straight-line (semi-logarithmic) approach (as presented below in Figure 3). If other terms, including pumping rate and distance from pumping well to observation wells are known, it is possible to estimate transmissivity and storativity of the aquifer from values read from the semi-logarithmic graph (Fletcher, 1997).

However, one must be aware that whilst the Theis equation (1935) applies at all times and places (if the assumptions are met); the Cooper-Jacob Method applies only under certain additional conditions (see below). These conditions must also be satisfied in order to obtain reliable answers (Heath, 1987:38).

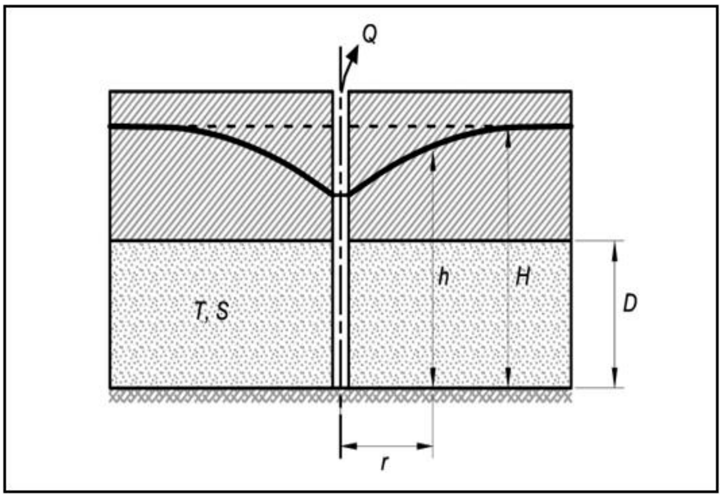

Figure 3 Diagrammatical representation of the Cooper-Jacob Method (from Kruseman and de Ridder, 1994).

The equation used to assess drawdown, *s*, at a distance, *r*, from a pumping well and a time, *t* (Cooper-Jacob Method) from the example presented in Figure B.2 above is as follows:

$$Q = \frac{4\pi Ts}{2.3\log\left(\frac{2.25Tt}{r^2 S}\right)}$$

Where:

- *T* - Transmissivity of aquifer
- *S* - Storage coefficient
- *t* - Time from start of abstraction

To find Q if s is known:

- *H* - Height of water table at radius of influence
- *r* - Distance from centre of well at *r*
- *h* - Height of water table at radius r
- *Q* - Total discharge from well
- *s* - Drawdown (*H*-*h*)

To find s if Q is known:

- *Q* - Total discharge from well
- *s* - Drawdown at distance *r*
- *r* - Distance from centre of well at *r*

The assumptions and conditions underlying the Cooper-Jacob Method are as follows (Kruseman and de Ridder, 1994):

- The aquifer is confined;
- The aquifer has a seemingly infinite areal extent;
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area;
- Prior to pumping, the piezometric surface is horizontal (or nearly so) over the area;
- The aquifer is pumped at a constant discharge rate; and
- The well penetrates the entire thickness of the aquifer and thus receives water by influenced by horizontal flow.

Two basic types of flow conditions have already been defined during this report: transient and steady-state. A third type of flow condition can be termed ‘steady-rate’. Transient flow analysis considers drawdown that changes with time and involves storage. Steady-state analysis considers drawdown that does not change with time, because equilibrium exists between the rates of discharge and recharge (McWorter and Sunada, 1977). Steady-rate is a type of transient flow where no change in rate of drawdown occurs as a function of time (Kasenow, 1997).

The Cooper-Jacob Method utilises drawdown that occurs under steady-rate conditions. This limitation is important, but is sometimes ignored, because this solution is much easier to use when compared to the Theis-type curve solution. When aquifer test data are analysed without considering this limitation the transmissivity can be inflated (Kasenow, 1997:112-113).

Dupuit-Forchheimer Method

The Dupuit-Forchheimer Method is an analytical solution using a combination of equations from Dupuit (1863) and Forchheimer (1930) which can be applied to the estimation of recharge and to the radial flow to a well in an unconfined aquifer (as shown in Figure 4 below). This method allows a two-dimensional flow problem to be reduced to one dimension (Misstear et al., 2006).

The Dupuit-Forchheimer theory states that in a system of shallow gravity flow to a well when the flow is approximately horizontal, the lines of equal hydraulic head or potential are vertical, and the gradient of hydraulic head is given by the slope of the water table. This assertion, in effect, means that this methodology neglects the vertical flow components of the system (Schwartz, 2005). However, the Dupuit-Forchheimer Method can provide an accurate description of groundwater flow in environments that are underlain by relatively impermeable materials (Baird et al., 1998; Raubenheimer et al., 1999).

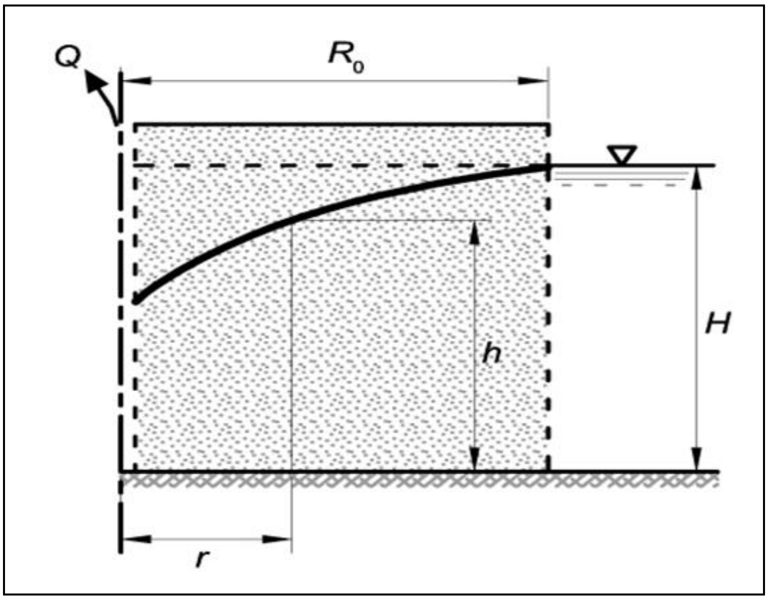

Figure 4 Diagrammatical representation of the Dupuit-Forchheimer Method (from Misstear et al., 2006).

The equation used to assess steady-flow in an unconfined aquifer per unit face (Dupuit-Forchheimer Method) from the example presented in Figure B.4 above is as follows:

$$q = \frac{K\left(H^2 - h^2\right)}{2L}$$

Where:

- *H* - Height of water table at radius of influence *R*
- *r* - Height of water table at radius *r*
- *sr* - Drawdown at radius *r*
- R_0 - Radius of influence
- *r* - Radius of interest
- *L* - Distance between *R* and *r*
- *K* - Hydraulic conductivity
- *q* - Inflow per metre of open face
- *w*- Length of face for which flow occurs
- *Q* - Total inflow into pit from face

To find the radius of a specific drawdown:

- *Q* - Discharge
- *h* - Water table height at radius of interest
- *sr* - Required drawdown
- *r* - Radius of required drawdown

To find the drawdown at a specific distance:

- Q - Discharge
- h - Water level at radius of interest
- r - Radius of interest

The assumptions and conditions associated with the Dupuit-Forchheimer Method are as follows (Misstear et al., 2006):

- The aquifer is unconfined;
- The aquifer as an infinite areal extent;
- The aquifer is homogenous and of uniform thickness;
- There is only a small water table gradient; and
- Groundwater flow is horizontal.

Although these assumptions highlighted above can solve a variety of groundwater flow problems with satisfactory accuracy, many of these assumptions are contradictory (e.g. soils are usually stratified and generally exhibit horizontal permeabilities in excess of those in the vertical direction [often by more than one order of magnitude], and groundwater flow to the well is horizontal, which is invalid in unconfined aquifers, or if the well is only partially penetrating [Cashman and Preene, 2001). Calculations that incorporate these assumptions will therefore indicate a lower water table in the vicinity of the wellpoint and when a seepage surface can be expected (i.e. in open voids such as quarry faces).

Construction dewatering equations

The construction dewatering equations presented below are based upon the basic equilibrium relationships developed by Muskat (1935) and Thiem (1906); these are as follows:

- The aquifer is confined;
- The aquifer has a seemingly infinite areal extent;
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test;
- Prior to pumping, the piezometric surface is horizontal (or nearly so) over the area that will be influenced by the test;
- The aquifer is pumped at a constant discharge rate;
- The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow; and
- The flow to the well is in a steady-state.

They have subsequently been adapted by many investigators since their original formulation. A principal benefit of these formulas is the understanding that they give as to how each variable enters into the determination of the rate of total discharge from a wellpoint / pit (Patrick, 1992).

The analytical construction dewatering equations shown in Table 1 have been used for decades in order to estimate the performance of dewatering systems. When they have been applied, and when the values assumed were appropriate, the estimates of water movement have been reliable. However, the mathematical analysis is, by its very nature, extremely simplified.

In complex aquifer situations or with dewatering systems of complex geometry, numerical solutions using steady-state or transient (i.e. when the magnitude and direction of water flow changes with time) groundwater models may be more useful and provide a more accurate interpretation of the water environment system (Patrick, 1992). As such, the following discussion relating to several of the most appropriate construction dewatering equations, must only be utilised in the interpretation of less complex water environment systems.

Trench with flow from one / two sides

Mansur and Kaufman (1962) estimated discharge and drawdown associated with the partial penetration of an unconfined aquifer by a single row of wellpoints of an unconfined aquifer fed from a single line source (as presented in Figures 5 and 6 below). The applications for these equations include narrow trench work, wellpoints to a single side, an unconfined aquifer, river or similar line source.

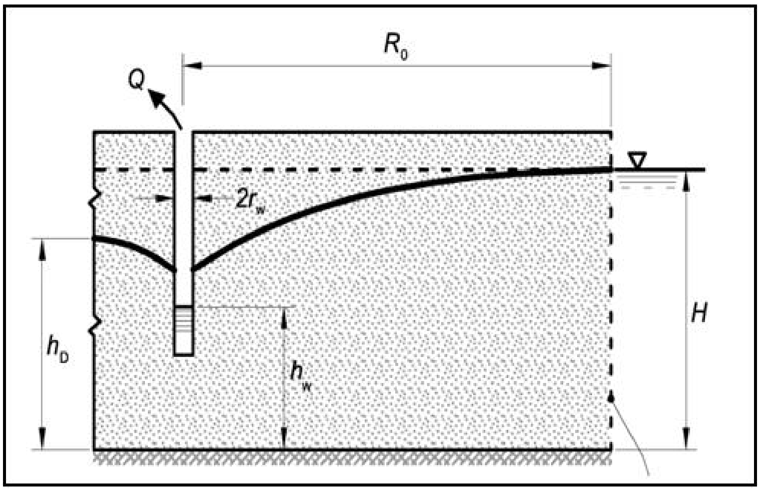

Figure 3 Diagrammatical representation of the trench with flow from one side (from Mansur and Kaufman, 1962).

The equation used to assess a trench with flow from one side (Mansur and Kaufman, 1962) from the example presented in Figure 5 above is as follows:

$$Q = \frac{KDx(H - h_w)}{R_0 + E_A}$$

Where:

- *H* - Height of water table at radius of influence
- *hw* - Height of water table at well
- *K* - Hydraulic conductivity of aquifer
- *D* - Thickness of confined aquifer
- *W* - Length of well in permeable aquifer
- *Q* - Total discharge from wellpoints

- *x* - Length of trench
- *w*- Length of face for which flow occurs
- R_0 - Distance to line source, equal to radius of influence
- *Q* - Total inflow into pit from face

To find the height of the water table downstream of slot:

$$h_D = \frac{E_A(H - h_0)}{R_0 + E_A} + h_0$$

Where:

- h_d - Height of water table downstream of slot

The equation used to assess a trench with flow from two sides (Mansur and Kaufman, 1962) from the example presented in Figure 6 below is as follows:

$$Q = \left[\left(0.73 + 0.27\frac{(H - h_w)}{H}\right)\frac{Kx}{R_0}(H^2 - h_w^{\ 2})\right]$$

Where:

- *H* - Height of water table at radius of influence
- *x* - Length of trench
- h_w - Height of water table at well
- R_0 - Distance to line source, equal to radius of influence
- *K* - Hydraulic conductivity of aquifer

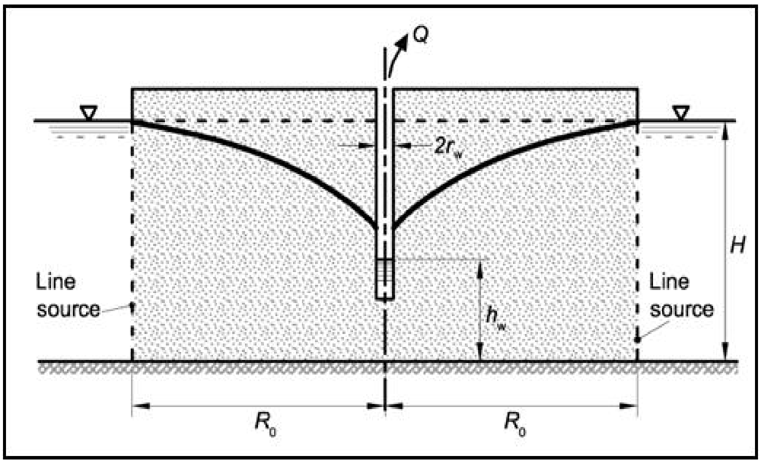

Figure 6 Diagrammatical representation of the trench with flow from two sides (from Mansur and Kaufman, 1962).

The conditions and assumptions underlying this method are as follows (Mansur and Kauffman, 1962):

- The wellpoint is infinite in length;
- The distance between the wellpoint and the height of the water table (R_0), and the height of the water table (*H*) before pumping commences is greater than or equal to 3;

- The aquifer is unconfined;
- The aquifer is homogenous, isotropic and of uniform thickness;
- The Dupuit-Forchheimer Method (see above) is valid;
- The aquifer has reached steady state conditions; and
- The initial water table is horizontal.

However, many of the assumptions highlighted above are based upon those originally outlined by the Dupuit-Forchheimer Method, and as discussed previously; this approach contains a number of assumptions which may not always be valid. Therefore, caution must be shown in assessing the water environment system using this type of approach.

Partial penetration of an aquifer by a double row of wellpoints

Mansur and Kaufman (1962) estimated the partial penetration of an unconfined aquifer by a double row of wellpoints with gravity flow midway between two parallel line sources. The applications for this equation includes wide trench works with a double row of wellpoints, an unconfined aquifer, and two line sources with a trench midway between them.

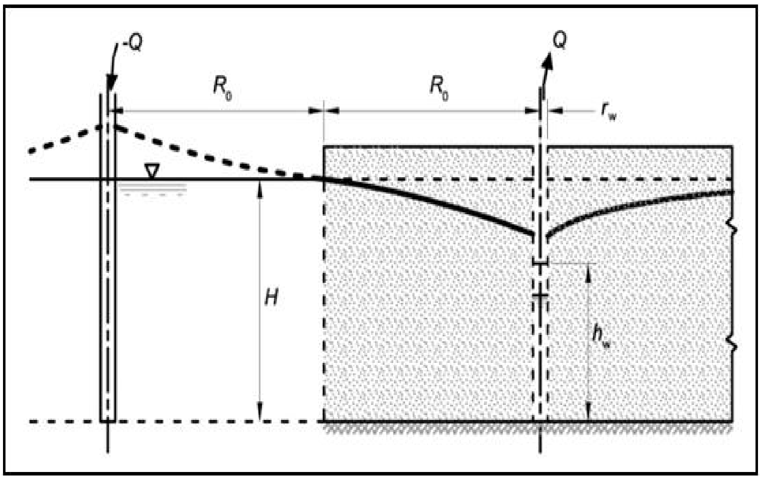

Figure 4 Diagrammatical representation of a single well with recharge image well (from Mansur and Kaufman, 1962).

The equation used to assess the partial penetration by a double row of wellpoints of an unconfined aquifer midway between two equidistant and parallel line sources (Mansur and Kaufman, 1962) from the example presented in Figure 7 above is as follows:

$$Q = \left[\left(0.73 + 0.27 \frac{(H - h_w)}{H} \right) \frac{Kx}{R_0} (H^2 - h_w^2) \right]$$

Where:

- H - Height of water table at radius of influence
- x - Length of trench
- h_w - Height of water table at well
- R_0 - Distance to line source, equal to radius of influence
- K - Hydraulic conductivity of aquifer
- Q - Total discharge from wellpoints

To find the height of the water table at centre of dewatered area:

$$h_D = h\left[\frac{C_1 C_2}{R_0}\left(H - h) + 1\right)\right]$$

Where:

- *l* - Distance to centre of dewatered area
- C_1 - Coefficient 1 (l/h)
- R_w - radius of each well
- C_2 - Coefficient 2 (*rw*/*H*)
- H_D - height of water table at centre of dewatered area

The assumptions and conditions associated with the above equation are as follows (Mansur and Kaufman, 1962):

- The wellpoint is infinite in length;
- The distance between the wellpoint and the height of the water table (R_0), and the height of the water table (*H*) before pumping commences is greater than or equal to 3;
- The aquifer is unconfined;
- The aquifer is homogenous, isotropic and of uniform thickness;
- The Dupuit-Forchheimer Method (see section above) is valid;
- The aquifer has reached steady state conditions; and
- The initial water table is horizontal

Single well with image well

Ferris (1959) describes image well theory by which the influence of hydrogeologic boundaries in aquifer tests can be determined. An image well is a hypothetical well that simulates recharge or discharge at the same distance from the hydraulic boundary as the real production well (i.e. the geologic boundary is replaced by an imaginary well for analytical purposes). Both the real production well and the image well are considered to be operating simultaneously (as presented in Figure 8 below).

The drawdown caused by real wells and image wells are additive, resulting in an effective discharge position of no flow in cases of image abstraction wells. The times of equal drawdowns of both real and image wells are located on a pumping test graph for an observation well. The distance from the observation well to the image well can be determined if all required determinants are known.

The equation used to assess the full penetration by a single well of an unconfined aquifer fed by a single line source (Mansur and Kaufman, 1962) from the example presented in Figure B.9 below is as follows:

$$Q = \pi K \frac{(H^2 - h_w^{\ 2})}{\ln \frac{(2R_0)}{(r_w)}}$$

Where:

- H - Height of water table at radius of-influence
- R_0 - Distance to line source, equal to radius of influence
- h_w - Height of water table at well
- R_w - Radius of well
- K - Hydraulic conductivity of aquifer
- Q - Total discharge from wellpoints
- x - Length of trench

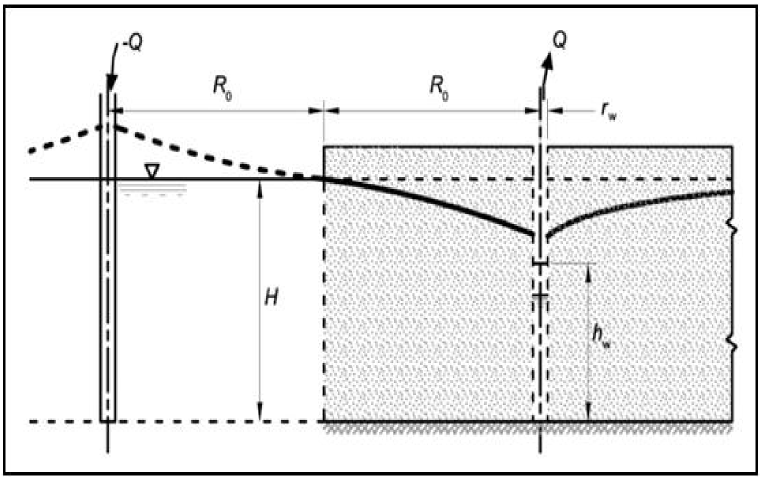

Figure 5 Diagrammatical representation of a single well with recharge image well (from Mansur and Kaufman, 1962).

The conditions and assumptions underlying the single well with image well methodology are as follows (Mansur and Kauffman, 1962):

- The aquifer is homogeneous, isotropic and of uniform thickness;
- The aquifer is of an infinite areal extent;
- The aquifer is unconfined;
- The abstraction well fully penetrates the aquifer;
- The water body fully penetrates the aquifer; and
- The water body is replaced by a recharge image well.

Analytical and Numerical Models

There are many analytical and numerical tools and techniques that are available and which can be used in order to assess the water environment. The merits and limitations of each of the main analytical and numerical solutions are now described. A summary of each modelling approach (including their associated limitations) is highlighted in Table 3 at the end of this Appendix.

<u>Spreadsheet Models</u>

Spreadsheets can be a useful means of linking equations and calculations in order to help represent a groundwater system. A variety of equations can be used within a spreadsheet environment.

Impact of Groundwater Abstractions on River Flows (IGARF) / Flows in Multiple Rivers (SPIGARF) are spreadsheet-based tools that were developed by Environmental Simulation International Limited (ESI) (2004), on behalf of the Environment Agency, for estimating the impact of groundwater abstraction on river flows (IGARF), or flow in multiple rivers or multiple reaches of a river (SPIGARF). The analytical solutions in the most recent versions are based on the methods of Theis (1941), Hantush (1965) and Hunt (1999).

A key problem of using the IGARF and SPIGARF spreadsheet methodology, which reduces the resolution of the estimation of the impact of groundwater, is the approximation that the transmissivity is independent of head which is not strictly valid in shallow aquifers. Other limitations include the following (Huxley and Thompson, 2004):

- The analytical solutions for a confined setting will not necessarily apply to quarry sites;
- The spreadsheet tool focuses on water flows rather than levels; and
- The analytical solutions rely on knowing the abstraction rate to predict drawdown at distance and that the abstraction rate is constant, something that is not necessarily the case in quarries.

Nevertheless, improvements on these spreadsheet models can be made by using numerical modelling techniques (Parkin et al., 2002).

<u>Lumped Models</u>

'Lumped' models can provide a simple assessment of the water environment. These may be undertaken within a spreadsheet. In lumped models, a region is specified (usually a catchment or sub-catchment), and a water balance assessment is undertaken, generally at either annual or monthly timescales, involving the calculation of all inflows (e.g. precipitation), outflows (e.g. river discharge, evapotranspiration, abstractions), and changes in (primarily) groundwater storage (Boak and Johnson, 2007).

Resource Assessment Methodology

Lumped models are a useful first step in a tiered risk-based approach to represent river-aquifer interactions. For example, a simple lumped model of an aquifer can be used to assess the annual contribution of groundwater flow to a river; or a more complex lumped model (e.g. Resource Assessment Methodology [RAM] [Environment Agency, 2002]) can be used to help manage groundwater systems, with abstracted quantities being allocated to more than one river (Buss et al., 2008). The CAMS process uses the RAM tool, enabling the Environment Agency to assess whether a catchment is 'over' or 'under' abstracted, based upon the acceptable water availability within it (Boak and Johnson, 2007).

The RAM is based on catchment flow accumulation and surface water-groundwater interaction. There are five main stages in the RAM process, all of which are supported by spreadsheets. However, the RAM is not intended for local scale licensing impact assessments (such as those found in quarrying scenarios) or local scale flow improvement schemes (e.g. wetland environments), and assumes that there is a connection between surface water and groundwater (Huxley and Thompson, 2004).

In addition, lumped models do not provide any representation of how water moves within catchments or aquifers. As many water management questions need to take into consideration the relative positions of abstractions and discharges, and the timing of impacts over shorter timescales, it may be necessary to use spatially-distributed models (Buss et al., 2008).

Analytical Models

There are certain simplifying conditions (typically including homogeneity and uniform thickness of aquifer), where it is possible to use an analytical solution in order to assess the water environment (i.e. one in which the hydraulic head can be written as a mathematical function of all other variables) (Buss et al., 2008). The main analytical models are discussed in the sub-sections below.

Spatially Distributed Models

Spatially distributed models can vary in complexity and are based on mathematical (partial differential) equations describing processes as a function of hydraulic head distributed in space; in one, two or three dimensions (x, y, z), and time (t). The equations represent water movement at a general location; and as such, it is necessary to define the geometry of the region over which the equations apply (i.e. the location of the boundaries, aquifer thicknesses, etc.), the boundary conditions (e.g. river or lake levels), physical properties and how they vary over space (e.g. hydraulic conductivities, river roughness coefficients, etc.), inputs and outputs (including precipitation, potential evapotranspiration, abstractions, etc.), and initial conditions for a transient model (e.g. groundwater levels at the start of a period of time for which predictions of water level changes are required) (Buss *et al.*, 2008).

WinFlow and WinTran

WinFlow is an interactive, analytical model that simulates two-dimensional steady-state and transient groundwater flow (both in confined and unconfined aquifers) with wells, uniform recharge, circular recharge / discharge areas and line sources or sinks. The model depicts the flow field using streamlines, particle traces and water-level contours (Huxley and Thompson, 2004). The steady-state module simulates groundwater flow in a horizontal plane using analytical functions developed by Strack (1989). The transient module uses equations developed by Theis (1935), and Hantush and Jacob (1955) for confined and leaky aquifers, respectively.

WinTran couples the steady-state groundwater flow model from WinFlow with a contaminant transport model. The transport module has the feel of an analytic model but is actually an embedded finite-element simulator. The finite-element transport model is constructed automatically by the software but displays numerical criteria (Peclet and Courant numbers) to allow the user to avoid numerical or mass balance problems (Huxley and Thompson, 2004).

Radial Flow Models

Some analytical models (such as RADFLOW) consider radial flow to a borehole or well in a variety of aquifer configurations by using radial instead of Cartesian co-ordinates (Boak and Johnson, 2007). RADFLOW is a two-dimensional, axial-flow (vertical and radial dimensions) finite-difference model. The axial-flow nature of RADFLOW means that it is capable of representing a multi-layer system, composed of aquifers and aquitards; however, each layer must be treated as internally homogeneous (ibid, 2007).

AquiferWin32

AquiferWin32 is a Windows program that supports the analysis of aquifer tests, slug tests, and step tests. Multiple observation wells can be analyzed individually or as a group. The programme also evaluates test data using the derivative method and can be used to simulate aquifer tests.

AquiferWin32 Modelling extends many of the pump test solutions into a modelling environment supporting any number of pumping wells with variable pumping rates. Output includes contour maps of hydraulic head or drawdown, colour floods, particle traces, and graphs of draw-down versus time, at any number of monitoring wells (Parkin et al., 2002)

Numerical Models

The main modelling codes that are used by hydrogeologists are presented in the sub-sections below. The choice of an appropriate model for a given application depends upon a range of factors, including purpose, data availability, level of conceptual understanding, and time / resources available to complete the assessment process. In general, the more complex spatially-distributed models require substantial amounts of effort and data and should be developed only after concluding initial scoping calculations using simpler models. However, for any of these models, questions of model calibration and validation, and estimations of predictive uncertainty need to be addressed (Buss *et al.*, 2008).

Modular Finite-Difference Flow Model

The industry standard groundwater flow model that has been developed by the United States Geographical Survey is the Modular Finite-difference Flow Model (MODFLOW) (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). MODFLOW models two or three dimensional groundwater flow using a finite-difference representation of the equations governing flow in confined or unconfined multi-aquifer systems. Timesteps of days and months can be inputted to generate transient models and the spatial data is also flexible. MDOFLOW does not have a Graphical User Interface (GUI) so additional pre- and post- processor software is normally used to facilitate input of data to the model and presentation and interpretation of the output. The interface can also aid with processes such as calibration, by facilitating multiple runs and linking to other models (such as chemical transport models). The Groundwater Vistas interface is a commonly used GUI by industry and is the primary choice of the Environment Agency; visual MODFLOW is also used widely.

Many MODFLOW models use a grid or mesh size that is appropriate to represent the water environment system studied. These scales are adequate to model exchange flows between groundwater and surface water (i.e. representing base flow contributions to run off), and to characterise their regional scale variations; but do not usually include river flow dynamics at the timescale of storm events and their feedbacks (Buss et al., 2008).

To simulate river-aquifer interactions, add-on modules have been developed to complement the basic MODFLOW model. In the RIVER module, the flow between the surface water and groundwater is always vertical and depends upon a channel bed conductance, and the head difference between the aquifer and river.

In addition to the simplifications involving the river aquifer interactions, MODFLOW does not explicitly calculate evapotranspiration (although this can be accounted for within the Groundwater Vistas interface), infiltration, flow or recharge. However, some of these processes can be accounted for within models or tool used on the data prior to its input into MODFLOW.

Grid Refinement for Site Specific Studies

There are two approaches that can be used to refine the spatial scale of model calculations. Firstly, nested models can be used for the data (e.g. groundwater levels); these are taken from the outputs of a regional model in order to produce a smaller scale local model using this data as the boundary conditions. Some software interfaces are designed to allow appropriate boundary conditions for local models to be set up automatically.

A more refined solution is to improve the grid within a regional scale model around the area of interest (Buss et al., 2008). Traditionally, most finite-difference models allowed a limited degree of grid refinement across the whole grid, but more recently software has been developed which allows localised grid refinement anywhere within a groundwater model, although these are not yet in common use. This approach is used in the ZOOMQ3D model (Buss et al., 2008).

ZOOMQ3D is a numerical groundwater flow model that has similar advantages as MODFLOW. It allows rapid grid refinement where detailed assessment is required. However, ZOOMQ3D is not currently used within the industry and is very data and staff resource intensive (Huxley and Thompson, 2004).

SEEP/W is a finite element flow model for analyzing groundwater seepage and excess pore-water pressure dissipation problems within porous materials such as soil and rock. It is used in order to assess the ground-water table beneath water retention structures such as lagoons and tailings ponds, the effect of subsurface drains and injection wells, seepage flow quantities into excavations and the drawdown of a water table due to pumping from an aquifer.

The Finite Element subsurface FLOW system (FEFLOW) is a computer program for simulating groundwater flow, mass transfer and heat transfer in porous media. It can be used under similar conditions as MODFLOW. The program uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems. It is used to assess groundwater drawdown and rise in mining areas, mine dewatering studies and construction site dewatering processes.

Integrated Modelling Systems

There are a number of integrated modelling systems which have been designed to represent groundwater and surface water flows and their interactions at local and catchment scales, including the Systeme Hydrologique Europeen (SHE) model (Ewen et al., 2000). This typically works at an hourly timescale (although time-steps may vary from minutes to days, depending on hydrological conditions) (Buss et al., 2008).

SHEs successors are MIKE SHE and SHETRAN. MIKE SHE is an integrated hydrological modelling system for building and simulating surface and groundwater flow. MIKE SHE can simulate the entire land phase of the hydrologic cycle and allows components to be used independently and customized to local needs. SHETRAN is a hydrological modelling system for water flow, solute and sediment transport in river catchments. It is a physically-based, distributed model that can also simulate the entire land phase of the hydrologic cycle. The plan area of the catchment in SHETRAN is usually in the range of one to a few thousand square kilometers and the horizontal depth of the sub-surface is usually less than 100 m. SHETRAN also provides the facility to simulate unsaturated conditions under the stream channels and to include data for layered porous media beneath the channel (Parkin et al., 2002).

Table 1 The most commonly used tools and procedures for assessing the water environment**.**

	Description	Analytical method	Advantages	Disadvantages
Spreadsheet models				
Impact of Groundwater Abstractions on River Flows (IGARF) / Impact of Groundwater Abstractions on Flows in Multiple Rivers (SPIGARF)	Local and regional impacts assessment spreadsheet package designed to distribute stream flow depletion due to abstractions, both spatially and in time SIGARF apportions local and regional impacts of abstraction to several river reaches	Analytical solutions: Theim (steady state in a confined aquifer) Theis (representing a fully penetrating river bed) Hantush (representing a fully penetrating river with semi-permeable river bed sediments Stang (representing a partially penetrating river with semi-permeable river bed sediments)	Standard analytical equations for borehole abstractions Simplified spreadsheet approach	Not readily available to the public. Analytical solutions for a confined setting will not necessarily apply to a quarry Focuses on flows rather than levels Abstraction well geometry / analysis rather than open void (confined versus unconfined analysis) Analytical solutions rely on knowing abstraction rates in order to predict water drawdown at a distance, and that abstraction rate is constant; something which is not necessarily the case in quarry situations which are level rather than flow driven
Lumped models				
Lumped models (e.g. Resource Assessment Methodology [RAM])	Empirical formulas with physical parameters for representing river-aquifer interactions	Need to define the area of interest for the lumped model (e.g. the area for the water balance)	Inexpensive Models are analytically flexible Minimal computational requirements Good within the range of calibration Calibration involves matching model output with catchment output to an acceptable level of accuracy; whilst preserving physical realism as far as possible	Parameters cannot be physically interpreted Needs calibration from records No allowance for spatial variation Often linear, so should not be extrapolated outside the range of calibration All models are characterised by parameters, the values of which must be specified for a particular catchment
Analytical models				
Radial flow models (e.g. RADFLOW)	Considers radial flow to a borehole or well in a variety of aquifer configurations by using radial instead of Cartesian co-ordinates	Two-dimensional, axial-flow (vertical and radial dimensions) finite-difference models	The axial-flow means that they are capable of representing a multi-layer system, composed of aquifers and aquitards	Each layer must be treated as internally homogeneous ordinates No lateral heterogeneities or boundaries can be represented
WinFlow	2D analytical model used for local and regional impact prediction	Simulates two-dimensional steady-state flow in a horizontal plane (Strack) and transient groundwater flow for both confined and leaky aquifers (Theis and Hantush, and Jacob, respectively)	Simulates wells, uniform recharge, circular recharge / discharge areas and line sources or sinks Depicts the flow field using streamlines, particle traces and water-level contours	Representation of aquifer settings is fairly simplistic (one value for most parameters etc.) Can be useful for simple situations or quick estimates

	Description	Analytical method	Advantages	Disadvantages
WinTran	Groundwater flow model from WinFlow plus additional transport capacity	Has the feel of an analytical model, but is embedded in a finite element simulation	Steady-state and transient flow conditions Constructed automatically by the software but displays numerical criteria to allow the user to avoid numerical or mass balance problems	Not designed to calculate ecological objectives
AquiferWin32	Software package for analysis of pump test data	Performs analytical groundwater flow modelling and pumping test simulations	May be used to run virtual pump tests in order to predict potential drawdown at selected distances	
Numerical models				
MODFLOW (- a spatially distributed model)	Numerical groundwater flow modelling - flow equations solved numerically (approximately) rather than analytically	Industry standard computer code for numerical modelling	Used when analytical models do not sufficiently represent reality, or the decision is too important to be undertaken by analytical methods Can be used to represent abstraction well or open void (with a set groundwater head) Can model a heterogeneous system Can model abstraction well or open void, in a confined or unconfined setting	Date intensive and staff resource intensive The flow between surface water and groundwater is always vertical and depends upon a channel bed conductance, and the head difference between the aquifer and river Questions arise concerning the accuracy of using MODFLOW to model localised impact on a smaller scale unless the model is set up to do this.
Grid refinement for site-specific studies (e.g. ZOOMQ3D)	Non-industry standard, but more advanced object orientated code being used by the British Geological Society for the development of numerical models	Numerical local and regional modelling solution	Same advantages as MODFLOW Allows rapid grid refinement where detailed assessment is required Can model abstraction well or open void, in a confined or unconfined setting	Data intensive and staff resource intensive Not widely used within industry at present
Finite Element subsurface FLOW system (FEFLOW)	A computer program for simulating groundwater flow, mass transfer and heat transfer in porous media	Uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems	The features of the package even allow very complex and large problems to be solved where other programs fail	Requires more resources and computational power from the hardware to profit from the implemented features of the software
Integrated modelling systems (e.g. Systeme Hydrologique Europeen [SHE], MIKE SHE and SHETRAN)	Represent groundwater and surface water flows and their interactions at local and catchment scales	Three-dimensional surface groundwater coupling is also included in some models by including the rivers and narrow bank elements along the boundary of grid elements	Work at an hourly timescale (although time-steps may vary from minutes to days, depending on hydrological conditions)	Very data intensive and resource intensive

	Description	Analytical method	Advantages	Disadvantages
Analytical equations				
Measurement of water transfer and consumption in an open void (water balance equation) Assessment of the radius of influence of a well / flow to a pit (radius of influence equations) Measurement of drawdown and steady state flow from wells associated with differential on-site pumping regimes (abstraction equations) Assessment of single or multiple flows into a trench or wellpoint (construction dewatering equations) Measurement of recharge rate / river-aquifer leakage (recharge equations)	Representations of how to assess water movement at both the inter- and intra-site level on a generic basis		Analytic solutions are simple equation that can give a quick answer based on a few basic parameters	The required derivation for all but the simplest systems can be quite complex Analytical solutions are difficult to apply to geometrically complex situations They all have a number of assumptions which are only valid in particular circumstances - the validity of each equation needs to be checked before its use at a particular site.

10. APPENDIX 3 - DRAFT 'DYNAMIC WATER ENVIRONMENT BASELINE ASSESSMENT TOOLKIT' (DWEBAT)

(See separate Excel spreadsheet)