

# A proposed framework for hydrogeological conceptual modelling

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## Keywords

conceptual model; environmental assessment; groundwater; hydrogeology; impact assessment; risk.

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doi:10.1111/j.1747-6593.2009.00173.x

## Abstract

The process whereby hydrogeologists interpret the available information to produce a justifiable set of simplifying assumptions to describe a groundwater system is called *conceptual modelling*. Although this process is inherent in all hydrogeological assessments and can therefore be regarded as synonymous with hydrogeological practice there are no standard specifications for it. A framework for conceptual modelling has been designed to both assist in the planning and process of the work and to provide an audit trail to facilitate independent scrutiny. The application of this framework is illustrated by two case histories, one of a small-scale investigation for a proposed cemetery and the other of an investigation of the migration of a large-scale sulphate plume in a public supply aquifer. This framework is applicable across the full range of scales of hydrogeological systems, and indeed is readily extendable to other analogous areas of endeavour in the management of natural resources.

## Introduction

The requirement by UK environmental regulators for auditable risk assessments has continued to increase across a wide range of activities that have potential environmental impacts (Anon 2000). Examples where hydrogeological assessments are needed include applications to the Environment Agency for new abstraction licences, waste management licences to operate landfills or discharge consents for an effluent to go to a soakaway. The natural mineral water regulations specifically require a hydrogeological assessment to be completed to identify the catchment for the source. Planning applications for quarrying and mining need to be supported by hydrogeological assessments to define the potential impacts. Hydrogeological evaluations are also often required to demonstrate the sustainability of any private water supply before planning consent is given for new properties in areas where mains water supplies are not available. Such evaluations are also used by developers, industry and many others to help locate new water supply boreholes, for example, or to assess the feasibility of a geothermal energy scheme for a new building.

The present national shortage of qualified hydrogeologists (Brassington 2004) means that many of the straightforward hydrogeological assessments are undertaken by scientists from other branches of geology or even from

related environmental sciences. Whereas any practice of hydrogeological judgements being made by those without adequate training is not condoned, this common practice cannot be ignored and emphasizes the need for a standard and auditable method to make these assessments as suggested here. The framework will also provide guidance for those with limited practical experience in this field and may also act as an aide-mémoire for more experienced hydrogeologists. An essential element is an audit trail that allows a third party to undertake an independent review. Such audits may be part of the appraisal undertaken by a regulator of an application and are also part of the scrutiny carried out at a public inquiry or even a court case.

## Conceptual modelling

Models are of fundamental importance in most scientific investigations and have become one of the principal tools of modern applied science (Silvert 2001). Models range from physical or imaginary objects to three-dimensional structures, descriptions, equations or combinations of several of these groups. In order to develop any of these models it is necessary to create a theory-based description that represents the phenomena being studied founded on a set of variables with logical and quantitative

relationships. Such a theory-based description is termed a *conceptual model*.

The procedure whereby hydrogeologists interpret the available information to produce an adequate description of a groundwater system is called *conceptual modelling* (e.g. Rushton 2003) and applies to all scales of hydrogeological work. A conceptual model will comprise an assemblage of justifiable, simplifying assumptions which summarize the principal characteristics of the real system so that its behaviour may be more clearly understood. The model should be developed so that it represents the current consensus on system behaviour, whether this is informed by direct interpretation of published information with or without field and laboratory data, or whether further understanding has been extracted from these data by mathematical modelling. In most cases, the purpose of developing a conceptual model is to arrive at a sufficient understanding of the relationships between the principal characteristics of a system so that deductive and/or mathematical methods can be used to evaluate possible outcomes of changes within the system for a range of feasible situations. An example of such changes is variations in abstraction patterns within a wellfield and the possible outcomes may be the potential impacts on surface water flows and wetlands resulting from the associated changes in groundwater levels.

Conceptual modelling should always precede any attempt to mathematically model a groundwater system (Environment Agency 2001, 2002; Rushton 2003; Younger 2007). However, conceptual modelling does not necessarily have to be followed by mathematical modelling at all (Brassington 2006; Younger 2007). Rather, the development of conceptual models of groundwater systems is frequently an end in itself, as it forms the basis for the majority of hydrogeological projects where the understanding of the system provided by the conceptual model allows decisions to be made and the risks associated with new developments to be evaluated to a satisfactory level of accuracy.

The scale of hydrogeological assessments and investigations is very variable. At one extreme, a desktop study using published data to locate a new borehole site may take an experienced hydrogeologist less than half a day. This contrasts with the effort required in a major investigation such as that by UK-Nirex (Chaplow 1996) for the proposed deep repository for radioactive waste at Sellafield that took a large multidisciplinary team of geologists, hydrogeologists and many other specialists most of a decade to complete. Most groundwater studies fall between these extremes involving some fieldwork in addition to the collection and interpretation of the available information.

Data acquisition is key to the conceptual modelling process with the relationship between obtaining data and

the process itself being shown in Fig. 1. The assumptions made about each predominant characteristic of a groundwater system are repeatedly re-evaluated to further develop understanding as new evidence is acquired and tested against the evolving conceptual model, frequently taking a number of iterations to accomplish. Figure 2 represents this process as an upward flowing spiral.

This iterative process of development by testing each aspect forms the structure for all hydrogeological projects, even those that are limited to a desk study using only published information. It can identify the need for new fundamental information as is illustrated by a study of the Sherwood Sandstone aquifer in the Lancashire Fylde by the Environment Agency (Seymour *et al.* 2006). When numerical methods were used to simulate groundwater fluctuations predicted groundwater levels in the Preston area did not match the historical records unless the aquifer thickness was significantly reduced. A borehole was drilled that showed significant thinning of the aquifer beneath the centre of Preston possibly resulting from a previously unknown horst structure.

### Available guidelines

Some form of structured approach to system interpretation based on scientific reasoning and an understanding of geology has been used since the earliest days of applied hydrogeology (Mather 2004). However, formal 'conceptual modelling' as such has only begun to be discussed in hydrogeological textbooks relatively recently, with many standard works including little or no mention of conceptual modelling as illustrated by Table 1.

A number of textbooks provide some guidance (e.g. Bear & Verruijt 1987; Rushton 2003; Younger 2007) although none is in sufficient detail to act as an instruction manual. Several guidance manuals have been produced although they generally focus on large-scale and often, specialized investigations. Guidance on conceptual modelling as a precursor to a large-scale mathematical model-based study is provided in Environment Agency publications (2001, 2002), written primarily as a guide for regional-scale investigations and would be difficult to apply to smaller-scale projects. More recent Environment Agency publications (2003a, b) include advice and guidance on undertaking hydrogeological assessments specifically in relation to landfills with similar advice relating to new groundwater abstractions in a more recent Environment Agency document (2007). These three later publications refer to the importance of creating an audit trail in this process. The Institute of Geologists of Ireland (Anon 2002) provides useful information for the geological and hydrogeological aspects of environmental impact assessments. The same organization has also published a

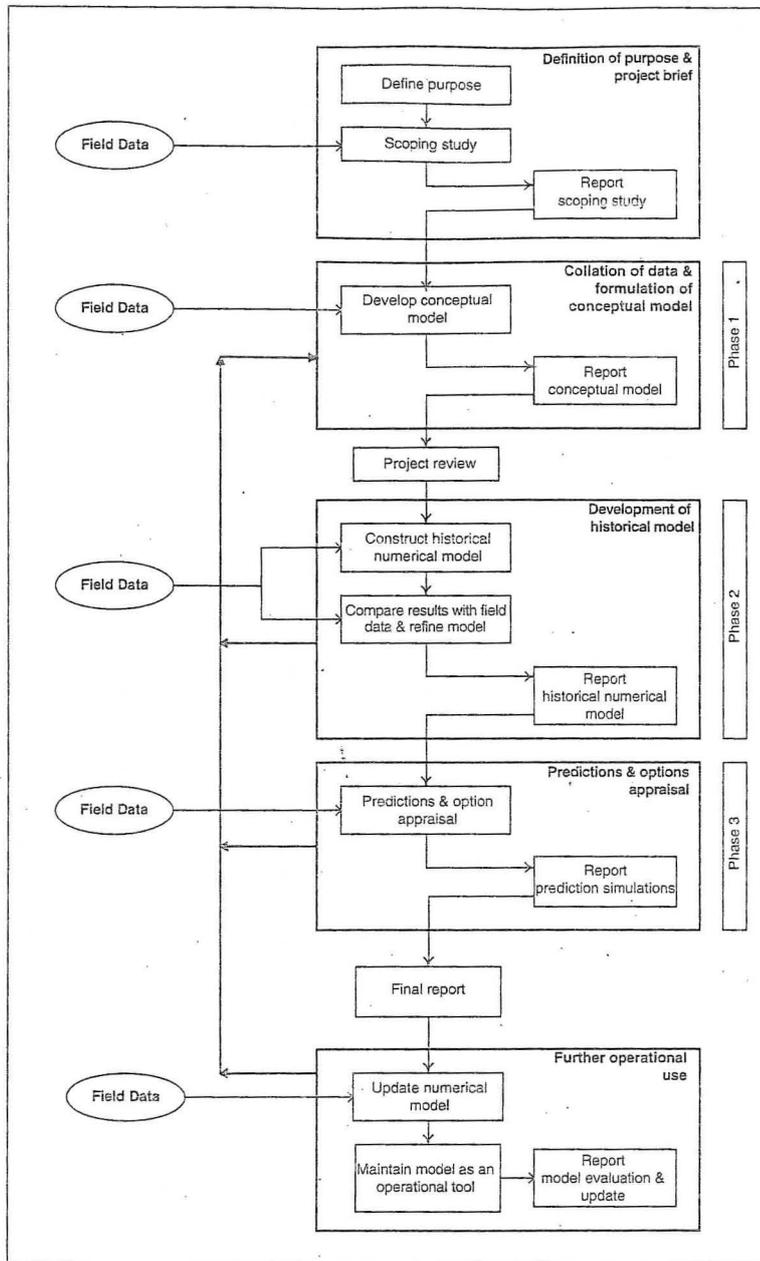


Fig. 1. Flow chart for developing a conceptual model in large-scale investigations (after Environment Agency 2002. © Environment Agency copyright. All rights reserved).

checklist of data types required for the assessment of new quarries (Anon 2007) that has a wider application. Most of the documents mentioned here are available on-line in electronic format.

Cashman & Preene (2001) discuss the development of conceptual models as the first step in designing dewatering schemes in civil engineering construction. They list geological parameters that must be considered as well as the features of the potential dewatering system and provide an example set out as a proforma that could be used as a template for similar assessments. Bedient *et al.*

(2000) advocate the development of a conceptual model to aid planning a groundwater contamination study. El-Ghonemy *et al.* (2004) describe a conceptual modelling methodology for assessing radioactive contaminated land for BNFL using the low-level radioactive waste disposal site at Drigg Cumbria as an example. The method lends itself to detailed investigations of complex contaminated sites rather than a more general application. Examples of conceptual models are given in some text books (e.g. Rushton 2003; Younger 2007). Other examples are included in papers on specific hydrogeological topics, and

occasionally are found as the main subject, such as Black & Brightman (1996), Burgess *et al.* (2002) and Brassington (2007).

Although these various publications provide advice on the overall process of conceptual modelling, as well as the individual considerations that are necessary to achieve it, no overall framework has been provided for this activity that is generally accepted as a standard approach. The auditable framework for completing hydrogeological assessments that is described below is put forward as such a standard procedure that can be used in investigations on all scales.

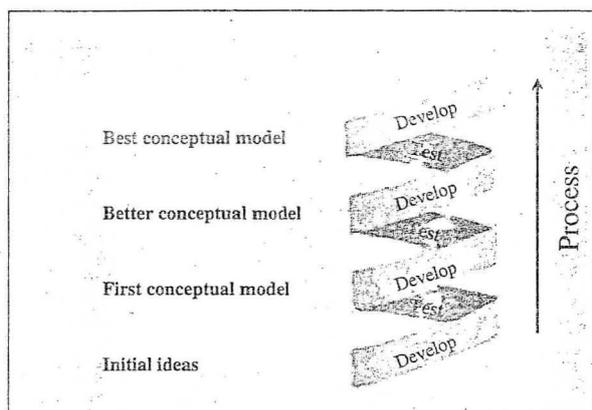


Fig. 2. Diagram of the conceptual modelling process (after Environment Agency 2002. © Environment Agency copyright. All rights reserved).

### Proposed framework

Although inexorably linked, the activities necessary to complete a hydrogeological investigation and the methodology of developing a conceptual model are not exactly the same. The actions at each stage of a hydrogeological investigation are generally focused on collecting information whereas the emphasis in developing a conceptual model is the interpretation of data as they are collected and identifying additional information needed to complete the conceptual understanding. A typical hydrogeological investigation can be divided into a number of separate parts, each building on the previous one so that eventually an adequate understanding of the system being studied may be achieved. It will always be necessary to tailor the details of the investigation to the needs of each particular study; however, the essential elements or phases that would be expected to be included in the majority of investigations are as set out below (adapted from Brassington 2006):

- Desk study
- Walkover survey
- Exploration
- Monitoring programme
- Data management
- Water balance
- Completion of the conceptual model.

The various steps in the proposed framework for developing a conceptual model as proposed here, are set out in Fig. 3. The order follows the logical sequence taken to

Table 1 Summary of comments on conceptual modelling in selected hydrogeology publications

Publication	Comments
<i>Text books</i>	
Bear & Verruijt (1987)	Provides definition and list of contents for a conceptual model
Bedient <i>et al.</i> (2000)	Discusses conceptual modelling in planning groundwater contamination studies
Brassington (2006)	Discusses the use of a conceptual model in planning field work and suggests outline procedure
Cashman & Preene (2001)	Provide proforma method for use in design of dewatering schemes
Domenico & Schwartz (1997)	Not mentioned
Fetter (2001)	Conceptual modelling seen as part of mathematical modelling
Rushton (2003)	Strongly advocates conceptual modelling as basis of more detailed analysis and gives examples
Todd & Hayes (2005)	Not mentioned
Younger (2007)	Includes guidance and an example of a conceptual model
<i>Reports and papers</i>	
Anon (2002)	General information in relation to environmental impact assess
Anon (2007)	Useful check-list for planning data collection
El-Ghonemy <i>et al.</i> (2004)	Provide method for large-scale nuclear waste related investigations
Environment Agency (2001)	Guidance provided – only applies to large-scale investigations
Environment Agency (2002)	Guidance provided – only applies to large-scale investigations
Environment Agency (2003a)	Guidance provided – concentrates on monitoring around landfills
Environment Agency (2003b)	Guidance provided – concentrates on landfill
Environment Agency (2004)	No mention of conceptual modelling, outline advice on hydrogeological assessment
Environment Agency (2007)	Guidance provided – concentrates on proposed new abstractions
Neuman & Wierenga (2003)	Guidance provided in the context of investigations of nuclear installations

Step	Primary sources of information	Activity	Other sources of information	Review process	Audit trail (examples)
1 Define objectives	Client's needs. Regulator's requirements Research objectives	Define elements of study needed to provide the required information	Regulator's policy documents, laws and regulations	Review with regulator and/or client before starting project	Minutes of meetings; letters/emails with client/regulator; agreed statement with client
2 Topography and surface water	Published topographical maps	Identify water features, estimate catchment boundary	Walk over survey	Compare field observations with map information	List of maps used. Copy of field notes
3 Geology	Published topographical maps, geological maps, reports and borehole records	Interpret data. Identify gaps in information	Additional mapping and new boreholes and geophysical surveys	Start to develop conceptual model	List of maps and reports; boreholes records; logs for boreholes drilled during the study; geophysical surveys
4 Aquifer framework	The results from Steps 2 and 3, reports of pumping tests and other published data	Determine need for field tests and/or laboratory measurements	Site specific information from pumping tests or falling head tests	Continue developing conceptual model using new data	List of aquifers; records of pumping tests and other field tests; copies of lab test certificates; copies of data analysis and interpretation reports
5 Groundwater flow	The results from Steps 2, 3 and 4 using published topography maps, borehole records	Identify need for more data points and levelling in to common datum	Measurements taken in new piezometers and/or boreholes	Review conceptual model using new data. Use computer model to test ideas	List of observation boreholes; copies of groundwater level measurements
6 Aquifer relationships	Information from Steps 2, 3, 4 and 5. Preliminary results of computer model if used	Assess relationships between groundwater levels, other aquifers and surface water bodies	Data from new pumping tests, water chemistry and spring/stream flow measurements	Review conceptual model using new data. Use developing computer model to test ideas	Copies of data collected/used in this step; copies of calculations, flow nets etc; records of outputs of each numerical model run in summary form; list of assumptions tested in each model run
7 Water balance	Long-term records of hydrogeologically effective precipitation	Assess available groundwater resources using water balance	Use rainfall, evaporation and stream flow data to refine estimates	Review conceptual model using new data. Use computer model to test ideas	Copies of data used for water balance calculation
8 Description of model	Apply conceptual model to assess environmental impacts or further refine computer model to make predictions of potential impacts. Any new data and the results of the computer modelling should be reviewed against the conceptual model and the assumptions on which it is based				Written description of the conceptual model illustrated by diagrams and supplemented by the records from Steps 1 – 8

Fig. 3. Outline of the proposed framework for conceptual modelling.

develop a conceptual model and defines the information sources, activities, review process and audit trail at each step. The repeated reviews are an essential element of the process and may require earlier stages to be developed further.

### Step 1 – defining the objectives

The objectives for the investigation must be defined before the commencement of data acquisition and should be set out in writing and agreed with the client, regulator or other persons or organizations with interests in the outcomes of the project. It is important to ensure the objectives focus attention on all the key questions that need answering to ensure that the field investigations will provide all necessary data.

### Step 2 – defining the topography and surface water drainage

Groundwater systems are usually closely linked to surface water catchments and in order to understand the hydrogeology of an area it is essential that this is undertaken in the context of both the surface and groundwater catchment areas. Key surface water features such as water-courses, springs and ponds should be identified, initially

using topographical maps that also have contour information that will allow the elevation of each feature to be determined. The contours are also used to define the surface water catchment areas for comparison with the geological information in the next step and for subsequent interpretation. Flow data for springs, streams and rivers may already be available otherwise it will be necessary to take field measurements.

### Step 3 – defining the geology

The geology of an area controls its hydrogeology; hence, it is essential to understand the types of rocks present in the area of interest, their lithologies and their structural inter-relationships. This is key to defining the three-dimensional variations in permeability and storage properties (Younger 1993) and how these influence groundwater flow directions and rates, and recharge processes. The information can be derived from existing geological maps and reports that are interpreted within the framework of elevations provided by the topographical maps and may also include records from boreholes drilled for the study or for other purposes and geophysical surveys. The geology also enables the relationship between the groundwater and surface water systems to be understood.

The review of the available geological information may show that more data are needed, possibly involving

additional field mapping, drilling exploratory boreholes or geophysical surveys. Such additional field work should be planned using the results of the desk study with each element of the new work testing specific aspects of the developing conceptual model.

#### **Step 4 – defining the aquifer framework and boundaries**

The aquifer or aquifers being studied exist as three-dimensional bodies and consequently the aquifer boundaries need to be defined on the top, bottom and all sides. This information is often most easily understood as a series of maps and cross sections.

The geological information derived from Step 3 should be used to identify the aquifers and to estimate the possible values for the aquifer properties. Two major reports (Allen *et al.* 1997; Jones *et al.* 2000) of the hydraulic properties of aquifers in England and Wales provide a good starting point in these countries. Robins (1990, 1996) provides information on the major aquifers in Scotland and Northern Ireland. More detailed local information may be available in published reports such as Plant *et al.* (1999) and from data held by regulators such as the Environment Agency and Scottish Environment Protection Agency (SEPA).

Pumping tests may be required to provide data from which the hydraulic properties can be calculated and should be conducted carefully to provide reliable data following the procedures described by Brassington (2006) and the British Standards Institute (2003). The data should be analysed following appropriate methods (e.g. Kruseman & de Ridder 1990) and details of these calculations kept as part of the audit trail.

Groundwater is part of the hydrological cycle and the potential links between surface and groundwater systems in the study area must be identified. A comparison of information from the geological maps and watercourses shown on topographical maps will allow an initial assessment of these relationships and provides a first approximation of the most appropriate aquifer catchment area to be studied. As more detailed information is accumulated these boundaries may well be refined. This exercise is important to the next step by providing clues to where aquifer recharge occurs, the discharge areas and groundwater flow paths. Defining the groundwater catchment boundaries based on an interpretation of the available data is far better practice than the common use of a fixed radius from the point of interest (e.g. proposed new borehole). Such an oversimplified approach may miss identifying key water features at risk from the proposal or equally, can imply threats to water features

that are not at any risk or may not be relevant to the assessment.

#### **Step 5 – defining groundwater flow directions**

Groundwater flow directions are best defined using rest groundwater levels measured in nonpumping boreholes interpreted using the geological information and information on the aquifers taken from Step 4. Information taken from topographical maps on the location and elevation of springs and surface watercourses is also used.

Groundwater flow is driven by a three-dimensional field of hydraulic heads from which it follows that the vertical component of head is likely to drive flow along boreholes, even where these penetrate an apparently single aquifer unit (Fetter 2001). Measurements of both groundwater levels and water chemistry are likely to be altered by such intraborehole flow, and the interpretation of field data must take this possibility into account (Brassington 1992).

It is likely that the desk study phase of the investigation will comprise the initial appraisal of the data used in Steps 1–4 of the conceptual modelling process. A walkover survey will then help further develop understanding and should be planned in advance from the information collated during the desk study bearing in mind that for large study areas several such surveys may be needed. Such first-hand observations are important as they allow the hydrogeologist to picture the geology and envisage how groundwater is flowing through the rocks, using the information assembled in the desk study. Groundwater flow is usually controlled by lithology and secondary structural features, such as joints, cracks and fissures. Flow generally converges on natural discharge zones, which typically correspond to the lines of streams and rivers running along valley bottoms. Bearing these generalizations in mind it is possible to envisage the overall groundwater flow system.

#### **Step 6 – defining the aquifer relationships**

This step follows naturally from Steps 4 and 5 and involves considering the flow rates and volumes of groundwater flowing through the system from one part of an aquifer to another, between aquifers and between the aquifers and the surface water system. Such flow should be quantified and will usually involve calculations based on the Darcy equation or the Dupuit assumption. This is the point to decide on the need for a numerical model to assist in the development of the conceptual

understanding and/or to make predictions on aspects of the system when part of it is stressed (e.g. by new or increased abstraction).

New data are likely to be gathered during this step and should be compared with existing data sets by repeating earlier steps of the framework. The new data may confirm existing ideas, expand on developing concepts or even challenge them. This is also the point in the process where the current understanding of the system should be critically evaluated to identify any gaps in the available evidence which could be addressed by field investigations. As financial budgets are always critical, the cost-benefits need to be taken into account before any decisions are made on this additional work.

### Step 7 – water balance

A water balance involves the calculation of the volume of water both entering and leaving the aquifer system being studied and incorporates the elements shown in Table 2. This is an important factor in all groundwater assessments as it defines the resources available to support wetlands and provide dilution factors in contamination studies. Where numerical models are being developed, a water balance may be used to gauge the accuracy of the model in replicating the hydrogeological processes involved.

### Step 8 – describing the conceptual model

The continual review of the available information and collection of necessary data will eventually result in the development of a conceptual model that is adequate for the purposes set out in the objectives (Step 1). When that point is reached the conceptual model should be set out in a written description that is illustrated by maps and diagrams as necessary. It is then used to answer the questions posed in the objectives. In small-scale studies the description of the conceptual model is likely to be brief and may be simply presented as the conclusions of the report. In larger projects it is likely to be a separate section of the report.

### Audit trail

An essential feature of the conceptual modelling process is that it should be auditable and is a requirement in all

applications of the conceptual modelling process ranging from simple desk studies to complex regional studies. The purpose of the audit trail is to record the sources of data that have been used and the reasons for the way that the data have been interpreted. An audit trail simply comprises copies of the correspondence relating to the project and a list of all the information sources (possibly including actual records of field measurements) that have been used and will enable a third party to follow the logic steps used throughout the conceptual modelling process. A record of the changing and evolving understanding should be included with brief notes on what changes were made and why. Figure 3 includes examples of the documents and records that will constitute the audit trail in most groundwater investigations.

The report for a small-scale study should contain this information as a list of reports and maps used and the explanation of the logic behind the hydrogeological interpretation. The key assumptions made and their justifications should be summarized in a table. Larger studies may involve meetings to discuss progress at which aspects of the hydrogeological interpretation may be discussed and agreed with notes kept as part of the audit trail. Large projects may require small associated studies to reviews aspects of the hydrogeological system with the reports on such studies forming part of the audit trail. Where a numerical model is developed it is standard practice to keep a record of all model runs including the aspects of the system being tested by that run and the conclusions drawn from the exercise. These records should form part of the project reports although they are often kept as reference documents and not part of the main report or its appendices.

### Example application of the conceptual modelling framework

The application of this proposed framework to real cases is illustrated using two examples: the first is an assessment of the potential impact on groundwater sources from a proposed new cemetery; and the second is a more complex investigation of the migration of a contaminant plume through a major aquifer.

The potential for water contamination has to be identified before a new cemetery can receive the necessary permissions. Brassington (2006) provides an example of

Table 2 Water-balance equation

Inflows	Outflows	
Rainfall+recharge from surface water+seawater intrusion+inflow from other Aquifers+leakage+artificial discharge	=Abstraction+spring flow+base flow in rivers+discharge to sea+flows to other aquifers+evapotranspiration	± Change in aquifer storage

Adapted from Brassington (2006) with permission from John Wiley & Sons.

Step	Primary sources of information	Activity	Other sources of information	Review process	Audit trail
1 Define objectives	Environment Agency's policy. Need to avoid water contamination	To define hydrogeology, groundwater flow directions and identify risk using source, flow path, receptor model	Environment Agency's policies and guidelines	Discussions with Environment Agency and client	Records of correspondence (including emails) with the Environment Agency and client
2 Topography and surface water	Published 1:25 000 scale Ordnance Survey map	Identify water features. Define topography of area	Walk over survey confirmed water features on map	Compares field and map data	Name of map used and copy of field notes/photographs
3 Geology	Published OS maps and BGS maps, reports (Rees & Wilson 1998)	Define drift and solid geology of area	Geological information from piezometer construction	Compare field data with map and report	List of BGS maps and report; piezometer details
4 Aquifer framework	The geological information was used to delineate the extent of the aquifer	Aquifer boundaries derived from geology. Need for flow line information identified	Information on aquifer properties in Jones <i>et al.</i> (2000)	The conceptual model now defined the three-dimensional aquifer. No additional information needed.	List of data sources used.
5 Groundwater flow	Piezometer data interpreted using results from Steps 2, 3 and 4.	Interpret groundwater contours, flow directions. Flow lines used as boundaries	Water level data from pumping station boreholes.	Compare all water level data and review against developing conceptual model	Piezometer records; copies of maps
6 Aquifer relationships	Information from Steps 2, 3 and 4.	Re-examine geological information to consider inter-aquifer flow	No requirements for additional information were identified.	Review conceptual model using new data.	Copies of data used in this Step
7 Water balance	Long-term average monthly MORECS data used to quantify groundwater flux	Calculate inputs and outputs of water balance	Licensed quantities for pumping station.	Compare flux with abstraction figures	Copies of data used. Consultancy report
8 Description of model	The conceptual model was described in consultancy report.				

Fig. 4. Development of the conceptual model for a cemetery study.

such an investigation that led to a successful application for permission to construct the cemetery. Figure 4 shows the steps taken in developing the conceptual model and lists sources of information used in completing each step in this process.

The site lies on the north-west side of the Potteries where a sheet of glacial sand overlies Upper Carboniferous mudstones directly beneath the site and extends westwards over part of the Sherwood Sandstone aquifer located on the eastern edge of the Cheshire Basin with a faulted boundary separating the solid formations. The geology of the area is shown on published British Geological Survey maps and is described by Rees & Wilson (1998). In Fig. 5 the proposed cemetery is the field immediately to the east of the cricket ground. It is located on a watershed between two minor watercourses. The closest surface water feature lies about 100 m to the south and comprises a small spring forming the head of a minor watercourse. A preliminary conceptual model supposed that the groundwater flow from the site would be to the south in the direction of this spring.

Groundwater levels were monitored using a series of six purpose drilled standpipe piezometers installed round the periphery of the site that also provided information on the sand thickness. Measurements were taken over a 12-month period to identify the seasonal variation in groundwater levels with the highest recorded levels (March 2004) used to construct groundwater contours

(Fig. 5). These show that the groundwater flow is towards the north-west and not towards the spring as was initially assumed from the topographical information. Flow lines were used to define lateral boundaries for the study area.

Records show that groundwater levels at a major groundwater source in the sandstone aquifer some 2 km from the proposed cemetery have fallen by about 30 m since the wells were constructed some 70 years earlier. This implies that groundwater levels have declined across the sandstone aquifer thereby encouraging groundwater in the sands to drain into the sandstone and changing its flow direction away from the spring.

The resulting conceptual model was used to assess the potential impact from the anticipated number of burials using data published by the Environment Agency (2004). It was concluded that the available dilution in the groundwater flow means that the source would not be impacted by the additional loading. The relatively simple hydrogeological system and limited groundwater abstractions meant that it was not necessary to develop a numerical model to assess the potential impacts.

The second example is an investigation of the migration of a plume of contaminated groundwater originating from abandoned coal workings below the Magnesian Limestone aquifer in North-east England. This project led to the successful application of a numerical model based on a conceptual model derived in accordance with the proposed framework. Although a summary of the project

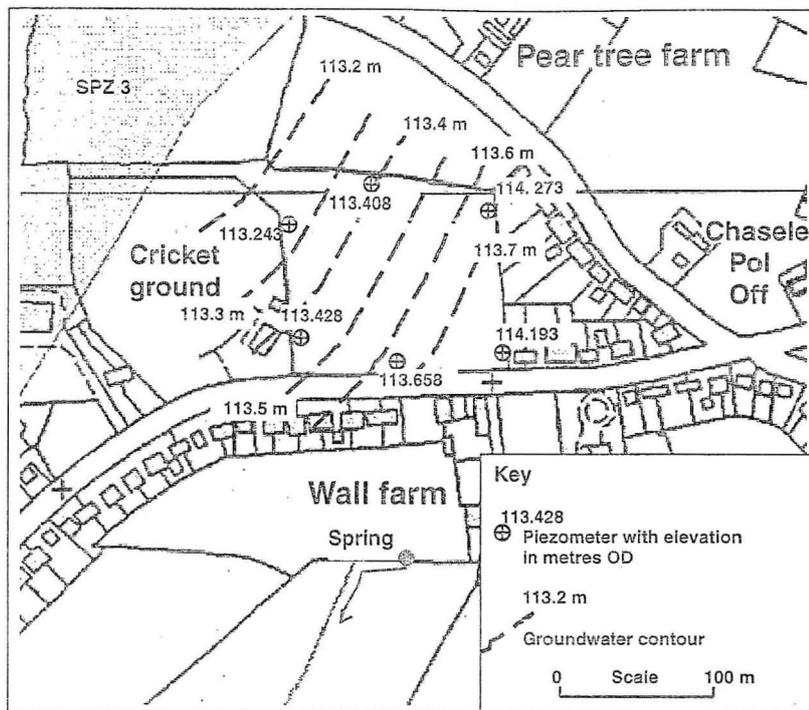


Fig. 5. The proposed cemetery is the field to the east of the cricket ground. Groundwater contours have been constructed from measurements made on the six piezometers shown (after Brassington 2006 with permission of John Wiley & Sons. Map © Crown Copyright. All rights reserved).

as a whole has been presented by Neymeyer *et al.* (2007), the detailed explanation of the application of the conceptual modelling framework has not yet been published.

The steps taken in developing the conceptual model are set out in Fig. 6 and details the sources of information used in completing each step in the conceptual modelling process. The conceptual model described by Neymeyer *et al.* (2007) defined the aquifer boundaries using published geological mapping supplemented by borehole logs to define the top and bottom of the limestone aquifer. Mine records were used to define the extent of the deep coal mining beneath the limestone and the west to east groundwater flow direction was defined from observation borehole water level measurements. Figure 7 shows the aquifer boundaries and groundwater flow directions as well as the location of the study area in relation to local towns and the coast. Figure 8 shows an east-west cross section that illustrates the geology and the major features identified in the conceptual model.

To the west of the limestone outcrop, hydraulic heads in the worked Coal Measures is effectively maintained at a relatively constant elevation by the decanting of 'excess recharge' (i.e. recharge over and above that which makes its way into the limestone across the unconformity) through several prolific surface mine water outflows to the River Wear to the west of Bishop Auckland. Prior modelling of the Coal Measures in this area revealed that the high permeability of flow path connections to these surface outflows results in an extremely subdued re-

sponse to annual recharge events (Parkin & Adams 1998). It was therefore concluded that, for purposes of modelling plume migration in the limestone aquifer, it could be safely assumed that flow in the coal workings would be accounted for adequately by representing them with a head-dependent flow boundary condition applied across the Carboniferous–Permian unconformity. There was no need on this occasion to increase model complexity and run times by explicitly simulating heads and flows in the network of flooded mine voids.

The lateral boundaries of the model domain (Fig. 7) comprise:

- (1) a fault to the north (the Butterknowle Fault), which is known to be associated with a discontinuity in groundwater levels in the limestone of several metres (assumed to be a zero-flow boundary);
- (2) the westward limit of the limestone outcrop (also assumed to be a zero-flow boundary);
- (3) the River Tees in the south-east (assumed to be a head-dependent outflow boundary);
- (4) a groundwater flow divide in the south-west (zero flow boundary);
- (5) the coast line between the city of Hartlepool and the River Tees (specified head boundary).

Mine water migrating into the limestone aquifer from the Coal Measures is joined by natural recharge. In areas where glacial deposits are thin or absent, so that the limestone aquifer is present immediately below the soil surface, recharge rates were estimated from MORECS

Step	Primary sources of information	Activity	Other sources of information	Review process	Audit trail
1 Define objectives	Environment Agency's policy. Need to maintain public water supplies	The main objective: to quantify the flow of polluted mine water into the aquifer and predict its migration	Environment Agency's policy; water quality standards set by the Water Framework Directive	Discussions with Environment Agency and Hartlepool Water Company	Records of correspondence (and emails) with EA and Hartlepool Water Company
2 Topography & surface water	Ordnance survey maps	Topography of area described from map	None required	Not needed at this stage	List published maps
3 Geology	There are published topographical maps & BGS maps, reports (Smith & Francis 1967) & borehole records	Smith and Francis (1967) contains many borehole logs and no insurmountable data gaps were identified	No other sources of information were needed	The geological information covers the full extent of the study area	Record of published geological maps & reports, mainly Smith & Francis (1967)
4 Aquifer framework	The geological information was used to delineate the extent of the aquifer	Boundary conditions were derived using methods described by Anderson and Woessner (1997) & Rushton (2003)	The aquifer properties from Cairney (1972) and Younger (1995). Coal Authority records used to identify areas where up flow from flooded mines could occur	The conceptual model now defined the three-dimensional aquifer. No additional geological information was required	List of data sources used
5 Groundwater flow	Environment Agency observation borehole data interpreted using results from Steps 2 and 3	Interpret groundwater contours and flow directions	Water level data from water company boreholes	Once the conceptual model development was relatively mature MODFLOW was used to refine it and calculate flow rates	Observation borehole records; copies of maps; copies of results from computer runs
6 Aquifer relationships	Information from Steps 2, 3 and 4. First results of computer model. Borehole groundwater chemistry data used to define pollution plume	Evaluate results of model runs against the conceptual model as developed at this stage	No requirements identified for additional information were identified	Review conceptual model using new data. Use developing computer model to test ideas	Copies of data used in this Step; copies of results from computer runs
7 Water balance	Abstraction data from water companies and other abstractors. Used MORECS methodology (Hough and Jones 1997)	Calculate inputs and outputs of water balance	Geological records to identify areas covered with thick clayey drift	Identify areas with reduced recharge. Modify conceptual model	Copies of data used. Printouts and results of early simulation runs. Unpublished MSC report
8 Description of model	The conceptual model is described in words by Neymeyer <i>et al.</i> (2007) & in the text. It was used as the basis of the numerical simulations using MT3D (Zheng & Wang 1999) that were carried out to predict the migration of the polluted mine water				

Fig. 6. Development of the conceptual model in a polluted limestone aquifer.

data (Hough & Jones 1997) to average around 0.77 mm/day. In areas with thick (> 1 m) mantles of glacial deposits, recharge rates were assumed to be considerably less. Application to the local setting of reasoning suggested by Brassington (2006) resulted in reductions in estimated infiltration rates to an average of only 0.22 mm/day in these areas.

The culmination of the mathematical modelling of flow, and then of solute transport, amounted to refinements in the understanding enshrined in the conceptual model. As such, the entire process of numerical modelling is essentially an exercise in assessing the consistency between the conceptual model and the data upon which the derivation of the conceptual model was based (Konikow 1981). It is only when satisfaction has been reached that such consistency exists and it becomes justifiable to use a mathematical model to ask specific questions by means of exploratory forecasting runs. In this case the questions which were addressed related to the likely time period before water supply boreholes might be expected to be producing water with sulphate

concentrations in excess of the drinking water limit (Neymeyer *et al.* 2007).

## Conclusions

(1) The development of a conceptual model is the fundamental approach used in all hydrogeological assessments ranging from simple desk studies to complex large-scale investigations. It is an iterative process involving the re-evaluation of the interpretation as new information is obtained until an adequate understanding of the system has been developed to meet the needs of the task in hand.

(2) No widely accepted methodology that defines this process exists, possibly because the process is necessarily iterative and therefore complicated to describe. A number of guidelines have been published that are appropriate for large-scale studies and consequently are too complicated to be easily adopted for more routine projects. Other guidelines are also available for specific types of investigations.

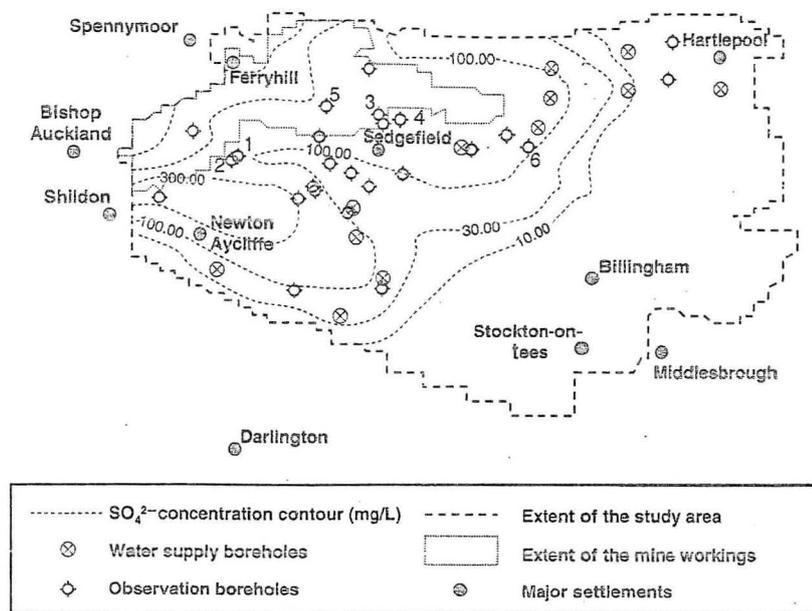


Fig. 7. The map shows the location of the study area in relation to towns in North-east England. The contours show the extent of the migration of a plume of high sulphate groundwater as defined by the observation borehole data. See Fig. 8 for cross section that gives geological detail. [Reproduced from Neymeyer *et al.* (2007) with permission of the Geological Society.]

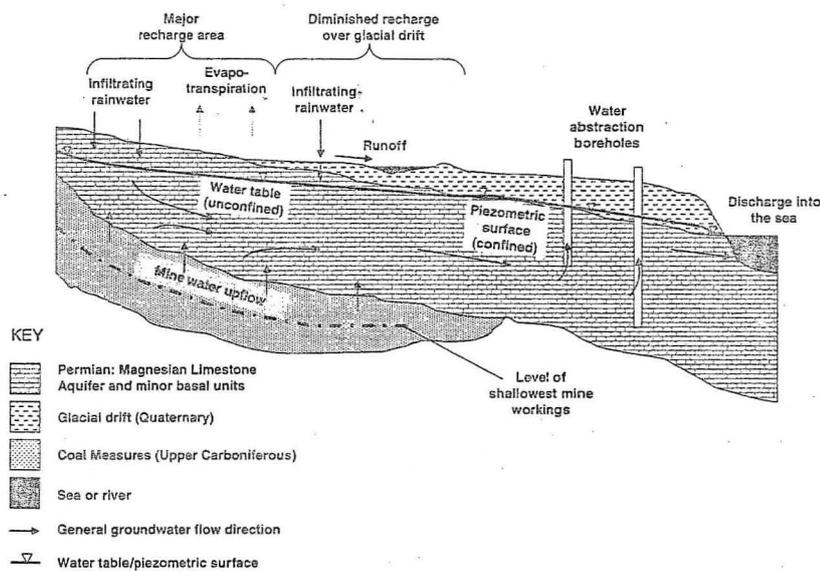


Fig. 8. Diagrammatic cross section summarizing the key features of the conceptual model for groundwater flow through the magnesian limestone aquifer including mine water upflow from the underlying flooded mine workings. [Reproduced from Neymeyer *et al.* (2007) with permission of the Geological Society.]

(3) As hydrogeological assessments are becoming increasingly required for a wide range of environmental impact assessments it is important for the process to be standardized and auditable. This will ensure that high standards of assessments are maintained with the consequential advantages of environmental protection.

(4) The framework proposed in this paper is designed to be used for all scales of hydrogeological investigations and includes an audit trail. The two examples used to illustrate the process have been chosen from either end of the scale in terms of extent and detail of investigation. The audit trail comprises a complete record of the documents that

record the purpose of the study, the logic processes involved in the development of the conceptual understanding sources of information and may include copies of data records. This audit trail will allow an independent third part to make a comprehensive evaluation of the work carried out. Such assessments are important in reviews of applications by regulators and in the scrutiny carried out during a public inquiry.

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