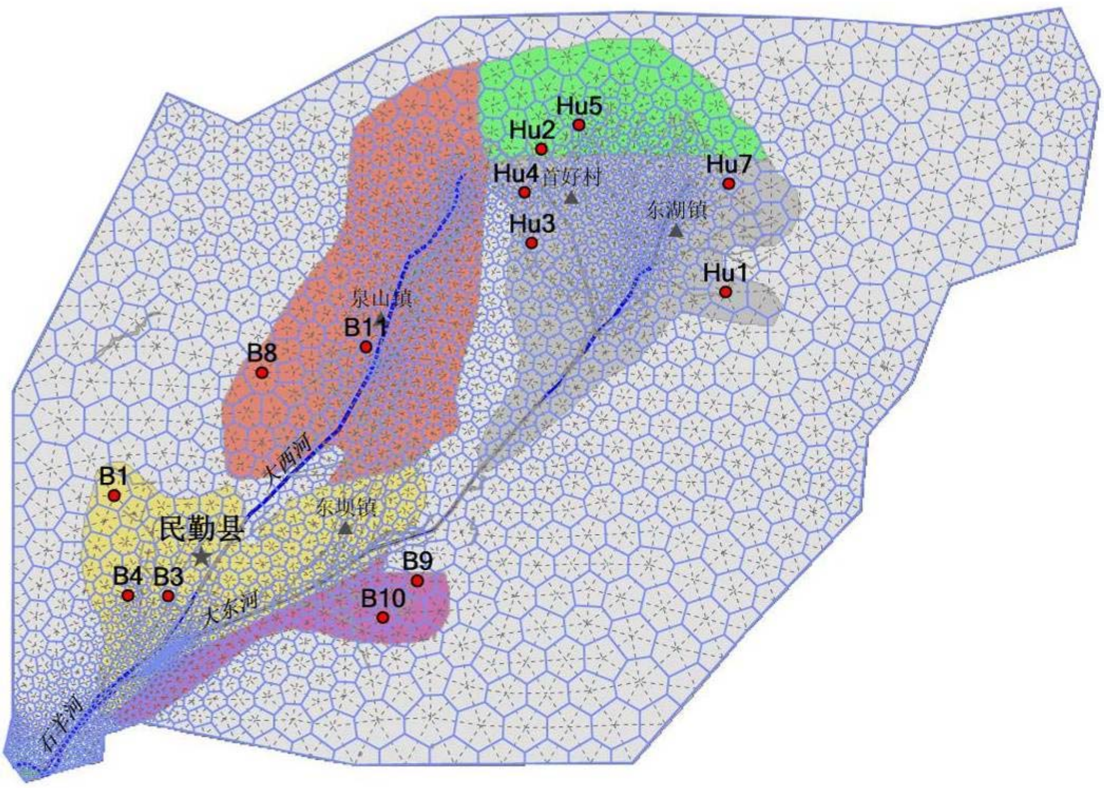
1.
WRA

China – UK, WRDMAP
Integrated Water Resources Management Document Series

Thematic Paper 1.1: Groundwater Flow Modelling

May 2010



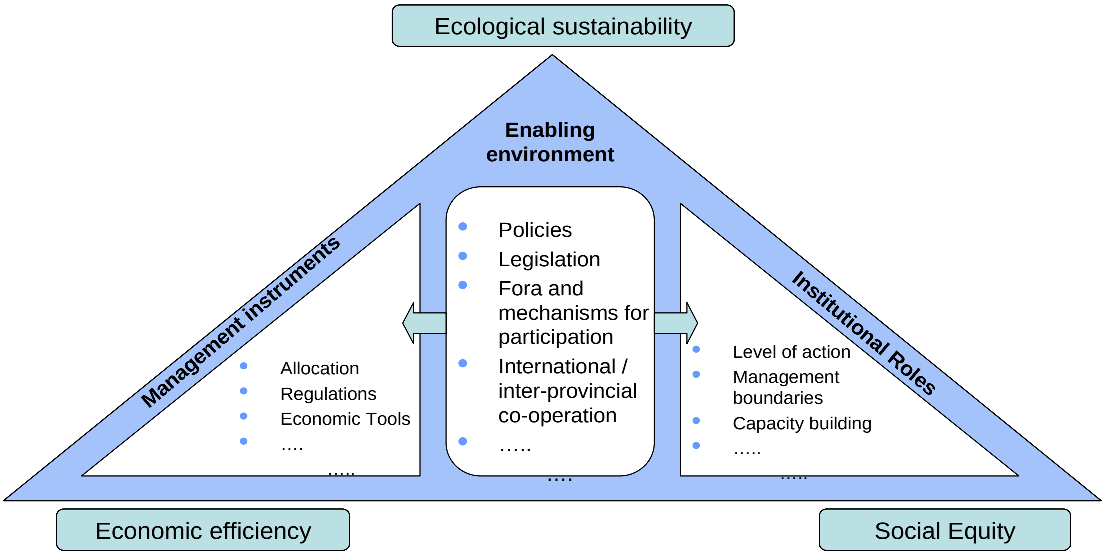
中国水利
CHINA WATER

DFID Department For International Development

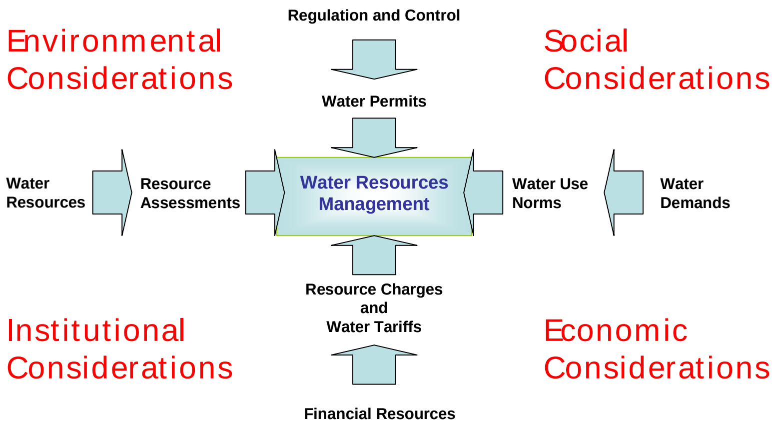
Mott MacDonald

Integrated Water Resources Management (IWRM)

(Basics after Global Water Partnership)



Driving Elements of Integrated Water Resources Management



(Second figure after WRDMAP)

Summary: This paper describes how groundwater models can be beneficial to groundwater management, and provides a technical framework for an effective groundwater modelling process. It also addresses some of the non-technical issues involved in groundwater management, such as ensuring effective use of model results amongst different stakeholders. Finally, a summary of recommendations for groundwater modelling is given

The paper is targeted at senior water resources specialists who require better appreciation of the power of groundwater models. It is also of benefit to groundwater modellers in obtaining a better appreciation of the broader aspects of groundwater models.

This Thematic Paper comprises the following sections:

1. Introduction
2. Use of groundwater models in groundwater management
3. Components of the modelling process
4. Non-technical issues
5. Recommendations

This document is one of a series covering topics on sustainable water resources planning, allocation and management. Details are given in the bibliography

The Ministry of Water Resources have supported the Water Resources Demand Management Assistance Project (WRDMAP) to develop this series to support WRD/WAB at provincial, municipal and county levels in their efforts to achieve sustainable water use.

1 Introduction

Regional-scale groundwater flow models are widely used throughout the world to aid in the management of groundwater resources and to increase understanding of the behaviour of the groundwater system and its interaction with the surface water system and the environment.

Past modelling practice in China has been largely case specific and little standardisation in terms of type of model code and model practice has been introduced. Modelling studies are commonly undertaken by specialists, often linked to universities. The studies are largely target orientated and do not involve significant stakeholder participation during the modelling study. The models generally suffer from a lack of comprehensive data, due to problems of access to historical data.

Thus many groundwater models have a research emphasis rather than a tool to facilitate groundwater management.

Completed models are generally not handed over to the institutions that are responsible for water resources management and are often, once completed, not used again. The models thus are static and are not subjected to gradual improvement as more data become available and understanding of the water resource system is enhanced.

Groundwater models are commonly recognised to be the best means of representing the processes operating in a groundwater system. However, they require considerable resources to develop, both financially and in commitment from those with specialist knowledge of water resources and related issues. Experience has shown that if these resources are not committed then the finished model may be inadequate for the tasks required.

A general modelling framework is proposed, which would include a process starting from an initial scoping study to completion and reporting and subsequent maintenance and updating of the model. Particular emphasis should be placed on adequate documentation, information/ knowledge management and dissemination.

A modelling framework is important in the context of IWRM.

To ensure that the models produced in future are developed to a consistently high standard, additional recommendations have been made regarding methodology, project management, the utilisation of staff resources and the continuing use of guidance notes to enable dissemination of knowledge.

This paper presents an outline framework for the development of regional distributed integrated surface water and groundwater resources models. Such models can become effective tools for groundwater resources management and resource utilisation planning. The framework methodology is largely based on that developed by the Environment Agency (EA) in the United Kingdom, who acts as regulator and guardian of the water environment. The EA in turn has drawn on experience from the USA, the Netherlands, Germany and Australia.

The significance of adopting a clear and comprehensive framework for future water resources modelling is in the use of the models in activities related to a large number of potential future business drivers. Model use could relate to sustainable resource utilisation, to assisting with water permitting, to environmental impact assessment, etc.

The framework also takes account of stakeholder involvement in modelling studies. Stakeholder involvement is essential for a number of reasons, most notably the following:

- Potential conflicts of interest can be avoided when the aim amongst all is to reach consensus on model findings.
- Large amounts of factual and tacit knowledge reside with stakeholders and it is in the interest of all to make use, as extensively as possible, of all available data and knowledge.
- Consensus on model findings will increase the chances that resource management decisions (based on model prediction scenarios) are acceptable to stakeholders.

Reference is made to the document reference sheet at the end of this paper. This contains a glossary of terms used in the paper and a list of references.

2 Modelling

2.1 What is Modelling?

Modelling is a process and not a computer application.

The process is sometimes termed the 'modelling cycle' and includes components such as:

- scoping,
- investigation and testing,
- monitoring,
- analysis,
- conceptualisation,
- use of evaluation tools such as analytical or numerical models, and
- documentation.

Such components are repeated on a regular basis. This multi-cyclical process is often referred to as the 'whole life' approach to investigations and modelling. It implies a continuing process of developing and enhancing the knowledge of groundwater systems and their inter-relationship with the surface water system and the water dependent environment. The multi-cyclical modelling process could cover a period of many years.

The first modelling cycle includes the initial scoping and the development and delivery of the model. This is then followed by regular updates and verification representing the subsequent cycles. The reason for starting a new cycle could be a mismatch between model performance and field observations found during the model verification. It could also be necessitated by the need for the model to address issues that were not included during the first cycle of model development.

Although often referred to as groundwater models, they should be seen as integrated surface water and groundwater models.

2.2 Why undertake modelling?

- Models provide a common management framework open to critical review.
- Conceptual and numerical models provide a high level of understanding of groundwater and surface water flow systems.
- The predictive capability of well constructed models is much better than traditional non-modelling approaches. A good model combined with good documentation and understandable output provides both confident and defensible decision making.

2.3 What is the purpose of modelling?

Groundwater modelling is used to quantify the water resource availability in complex, dynamic groundwater/surface water systems. Increasingly models are used to assess the environmental impacts of abstraction and climate variability/change.

A model must be technically sound and be an agreed representation of the combined groundwater and surface water system. It needs to be based on a sound and shared understanding (the conceptual model) of groundwater system behaviour and its interactions with the surface environment. A numerical model should adequately represent this conceptual understanding before it is used as a predictive tool for resources planning and management.

Distributed numerical models are not always required. It is not unusual that decisions on groundwater resources issues can be based on the conceptual model and possibly with the use of analytical or lumped parameter modelling tools.

The purpose of a groundwater model can be considered in the context of both 'tactical' and 'operational' water resources management.

The '**TACTICAL**' use of groundwater models relates to a holistic and basin-scale approach to understanding the role of groundwater systems and the influences exerted upon them (either natural or anthropogenic). This approach is described in Table 1. Tactical uses could also be seen as developing preparedness for adverse conditions.

The '**OPERATIONAL**' use of groundwater models relates to groundwater management functions. These are summarised and further clarified in Table 2.

These tables contain a list of possible drivers for modelling projects, but they are not inclusive of all possible uses of groundwater flow models.

Table 1 Tactical Use of Groundwater Flow Models

Use	**Clarification**
Review of water resources management plans	This relates largely to the evaluation of the limits of sustainable water resources development
Local impact assessment	This relates to use of the model to assess impacts of different groundwater management options on users, springs, river flows and wetlands
Forecast of water supply yield for prevailing groundwater conditions	To establish the current resource state and from that determine the optimum groundwater use for the immediate future
Forecast of response of groundwater to drought	The use of the model helps in drought forecasting and thus the development of appropriate drought plans
Forecast the need for mitigation measures	This is linked to the previous use and relates to the use of models in assessing mitigation needs such as use of river water and cutback/cessation of abstraction
Forecast operational yield of artificial groundwater storage and recovery (ASR) schemes	To assess the net gain in the short and long term
Assess the implications of climate change	This relates to assessing the impact of climate change on groundwater resource systems
Assess the implications of land use change	This relates to the impact of land use change on the groundwater resource system
Design of an 'optimum' groundwater monitoring network	Models allow for evaluation of the 'value' of monitoring facilities

Table 2 Operational Use of Groundwater Flow Models

Function	Drivers	Clarification
Strategic Water Resources Planning	River basin management plans	Models are essential to assist in river basin planning and are required wherever sustainability approaches (such as for example reduced groundwater abstraction) are likely to be contested.
	Environmental impact assessments	Groundwater models can be used to assess the impact of groundwater abstraction on environmentally sensitive areas such as rivers, wetlands and groundwater dependent terrestrial ecosystems. Such assessments often relate to small-scale areas and regional models can be used to set the boundary conditions for local-scale modelling. More refined modelling processes may be required to gain more confidence in impact assessments.
Operational Management of Groundwater	Abstraction permitting	Because of their regional coverage, models can play an important role in abstraction permitting. Better informed decision making will lead to improved acceptance of decisions made by the permitting authority.
	Water availability forecasts	Abstraction up to the full permitted rates is sometimes required under adverse climatic conditions, particularly drought periods when surface water is in short supply. As for permit limit determination, models can play an important role in this duty.
Monitoring	Asset management of monitoring network and design of monitoring networks	The cost of monitoring can be very high, yet monitoring data is essential to accurate groundwater resource evaluation and thus to effective resource management. Models are very useful in analysing how important certain data are to the accuracy of model predictions. Models therefore help to design monitoring systems that maximise model accuracy and minimise costs
Groundwater Quality	Framework for groundwater quality investigations	Groundwater quality is generally closely linked to groundwater flow and the input and output components of groundwater systems. Regional groundwater flow models can be seen as a first step in the evolution to more comprehensive flow and contaminant transport models.
	Groundwater protection zones	Time-variant groundwater models are reliable tools to asses the dynamic nature of groundwater protection zones.
	Diffuse pollution	Regional groundwater flow models are powerful tools to assess groundwater movement with time. They can form the basis for diffuse pollution modelling.
	Contaminated land	Regional groundwater models provide a good insight into the potential fate of pollutants originating from the contaminated land sites. More sophisticated modelling, probably at more localised scale, would be needed to obtain a more in-depth understanding of pollutant transport from localised contaminated land.

3 The Use of Groundwater Models in Groundwater Resources Management

3.1 Introduction

The sustainable development of water resources requires appropriate strategies with respect to surface water allocation and groundwater abstraction management. Optimal and yet sustainable development of groundwater (without compromising environmental needs and groundwater quality) is a major challenge. It requires a comprehensive understanding of the dynamics of the groundwater system and its relationship with the surface water environment.

This understanding can be adequately formulated as a quantitative conceptual model of the system and once embedded within an appropriate numerical model becomes the key to effective resource management.

Methods available for groundwater resources assessment can vary considerably in complexity. They may range from simple lumped water balance equations to complex distributed groundwater models integrated with surface water systems. Thematic Paper 1.2: 'Groundwater Resource Quantity Assessment' describes four levels of groundwater resource assessment and provides guidance on the choice of appropriate assessment methods.

Simple lumped water balance models are cheap, but often very approximate and do not always allow for a good understanding of the dynamic nature of groundwater system. Distributed groundwater models are expensive, require an accurate and comprehensive database and also require considerable expertise at all stages of model development. There are, however, considerable advantages of using complex distributed models:

- Groundwater systems are spatially variable and dynamic in their response to time-variant influences such as climate and human interventions (such as for example groundwater abstraction and use of river water for irrigation). Distributed numerical models allow for inclusion of both spatial and temporal variability and can thus most accurately approximate the real groundwater systems.
- A pre-requisite for the development of distributed groundwater models is an in-depth assessment of all available data and knowledge and the development of a comprehensive conceptual understanding of the behaviour of the groundwater system, both in space and time.
- In such models, data should be seen in a broad context and thus include all data of relevance to water balance components included in model simulation. Table 3, found below, provides an appreciation of the data needs.
- If used appropriately, distributed models allow for a systematic assessment of uncertainty and thus allow for more focused programmes of field investigations and monitoring aimed at reducing uncertainty. Understanding uncertainty will also lead to a better

appreciation of the reliability of model predictions.

- The models, although costly in developing, can reap substantial benefits through:
    - Significant improvement of the knowledge of the mechanics and dynamics of the groundwater system.
    - Rapid assessment of a large number of potential future resource development and management options.
    - Risk aversion, particularly when the models have been adequately calibrated and are based on an accurate and comprehensive database, and on a sound conceptual understanding of the groundwater system.
    - Contributing to water resources and environment functions of the regulator. For example, it could be used in the assessment of permit requests in relation to water resource availability, or to assess alternative abstraction and discharge scenarios.
    - When used as a tool to evaluate the need for field and monitoring data, it can result in considerable savings of time and cost related to field investigation and monitoring programmes.
    - The model can also be used as a tool for conflict resolution in relation to water resource or environmental issues and may thus avoid the need for costly litigation.

There is, however, a need for caution when deciding on the costly route of distributed model development. In particular:

- The phrase *‘a model is only as accurate as the data that feeds it’* holds true in many cases. It is essential to realise that the accuracy of a model relies heavily on the availability of a comprehensive database and availability of this database to the model developers.
- The development of a good model requires on the one hand a high degree of specialisation in hydrogeology and numerical modelling. On the other hand, it requires transparency and involvement of stakeholders in the development process is equally important.
- The model development should not be a one-off exercise; rather it should be seen as the start of a process of continued groundwater resource evaluation, which will result in a gradual strengthening of the model as a resource management tool.

Table 3: Components of groundwater resource assessment

Water balance/ resource component		Data requirements (monitoring data shown in bold)
Lateral flow across aquifer boundaries		• Elevations on base of layers • **Groundwater levels for layers** (spatial and temporal distribution) • Aquifer transmissivity
Leakage flows between aquifers		• Thickness of layers • **Groundwater levels for layers** (spatial and temporal distribution) • Vertical permeability
Storage changes		• Storage coefficients (unconfined & confined) • Groundwater levels for layers (spatial and temporal distribution)
Recharge	Natural (rainfall)	• Mapping of non-irrigated areas • Spatial and temporal distribution of **rainfall** • Soil classification and parameters (to assess soil moisture balance of root zone) • **Evapotranspiration** • Data from reports, climate stations and modelling studies
	Urban	• **Gross potable supply to urban areas** • "Return flow" factor (factor defining proportion of gross supply returning to groundwater)
	Irrigation	• **Gross irrigation supply and canal flows** • **Irrigated areas** • Irrigation efficiency factors including field application and distribution efficiencies
Surface water – ground water interaction	River/canal aquifer interaction	• **Groundwater levels** • **River levels** (together with groundwater this enables determination of surface water and groundwater interaction). • **River flows** at key gauging points • **Diversions** (together with river flows this enables carrying out a water balance for river reaches and determining whether the river is "gaining" or "loosing" water from/to the aquifer) • River surface area (could be time variant) • River bed conductance (together with river surface area enables estimation of possible seepage to the aquifer using analytical techniques)
	Reservoir aquifer interaction	• **Reservoir levels** • Surface water area (often directly related to reservoir level) • **Groundwater levels**
Discharge	Abstraction	• Well permit records • History of number and types of well • **Average daily abstraction** for irrigation, industry and domestic use • Irrigated areas, cropping calendar, crop demands, crop quotas and irrigation efficiency
	Capillary losses (only in shallow water table areas)	• Ground surface elevations • Soil types and their physical parameters • Rooting depths for various crops • **Groundwater levels**
Groundwater and Surface Water Salinity		• **Historical groundwater salinity data** • **Salinity of recharge components** • **Salinity of abstracted groundwater**

3.2 Choice of models

A large number of commercially and public domain groundwater modelling software is available. Such software ranges to just the model software to comprehensive packages including pre- and post-processing facilities and powerful graphics environments. Such packages aim at making operation of the model more 'user friendly' and also aim at enhancing the quality of visualisation of model results.

The notion that one model software package is better than another is misleading. Firstly, one has to consider the software package as a tool and this tool can only put to successful use when it is operated by an experienced modeller.

Secondly, people's preference for specific model software often stems from familiarity with a certain model.

Thirdly, commercial enterprise tends to rate models as being the best and most versatile, without revealing the true practicality of the use and operation of a model.

A list of groundwater modelling software is given in Table 4. The list is limited to software that allows for three-dimensional representation of aquifer systems and also includes some of the commonly used support packages.

The choice of modelling software is sometimes difficult and requires both knowledge of its capabilities and an understanding of the groundwater system it aims at simulating. Issues that need to be considered include:

- The choice of modelling software may be prescribed as the adopted standard within an organisation. For example, the Environment Agency in England and Wales has adopted a modified version of the USGS MODFLOW model (MODFLOW_VKD) as the standard for regional scale integrated groundwater and surface water modelling studies.
- If no modelling software is prescribed, then the choice should be based on the conceptual understanding of the integrated groundwater and surface water system, the purpose of the modelling study and, related to this, an understanding of the capabilities of available software packages.
- In general, the cost of groundwater modelling software is low and generally less than US$1000. All USGS software is public domain and thus freely available. Cost of related pre-and post-processing software can be high, generally ranging from US$1000 to 5000.
- Very important when choosing modelling software, is the availability of good and understandable user manuals. Such manuals should not only describe the operation procedures for the model, but also provide detail on its simulation procedures and limitations.
- Most importantly is that the choice of model is not led by glossy advertising, but by experienced modellers.
- As a final comment, it should be reiterated that the success of a modelling study does not depend on the model package, but rather of the people that use the model.

Table 4 Groundwater modelling and related software

Model name	Summary description	Supplier	Cost	Comments
Aqua3D	AQUA3D is a program developed to solve three-dimensional groundwater flow and transport problems using the Galerkin finite-element method. AQUA3D solves transient groundwater flow with inhomogeneous and anisotropic flow conditions. Boundary conditions.	Scientific Software Group http://www.scisoftware.com/	US$900	Links with surface water, but no flow routing
FEFLOW	FEFLOW is a finite element based model with a wide selection of numerical solvers for performing complex 2D and 3D steady-state or transient groundwater flow and contaminant transport modelling. FEFLOW's finite element approach allows the user to quickly build a model to accurately analyze groundwater flow and transport for complex 3D geology.	Scientific Software Group http://www.scisoftware.com/	US$3000+	No inclusion of surface water systems
MODFLOW	MODFLOW is the name that has been given the USGS Modular Three-Dimensional Ground-Water Flow Model. Because of its ability to simulate a wide variety of systems, its extensive publicly available documentation, and its rigorous USGS peer review.	Scientific Software Group http://www.scisoftware.com/ The software and associated manual can be freely downloaded from the USGS web site (http://water.usgs.gov/nrp/gwsoftware/modflow.html)	Free	Fully integrated groundwater and surface water model. Widely used as a standard throughout the world
MODPATH	MODPATH is linked to MODFLOW and used for simulation of groundwater flow paths and travel times,	Scientific Software Group http://www.scisoftware.com/ The software and associated manual can be freely downloaded from the USGS web site	Free	
MT3D	MT3D is linked to MODFLOW and used to simulate solute transport in aquifer systems.	Scientific Software Group http://www.scisoftware.com/ The software and associated manual can be freely downloaded from the USGS web site	Free	
MODFLOW-SURFACT	MODFLOW SURFACT is a comprehensive 3D finite-difference flow and contaminant transport model based on the USGS MODFLOW code, the most widely-used ground-water flow code in the world. Additional computational modules have been incorporated to enhance the simulation capabilities and robustness. MODFLOW SURFACT is a seamless integration of flow and transport modules.		US$ 2000 - 4000	Deal better with near surface processes in areas where the groundwater table is shallow
Visual MODFLOW	Visual MODFLOW for Windows 95/NT is the most complete and easy to use software package for practical applications in three-dimensional groundwater flow and contaminant transport modelling.	DataSurge	US$1490+ and US$300 annual maintenance	

4 Components of the Modelling Process

4.1 Overview

A groundwater modelling project should be preceded by project planning and scoping. The scoping study is the first step in getting the project started. Details of project planning and scoping are given in the following section.

First model cycle

During the first cycle of the groundwater model, the technical stages shown in Figure 1 are included.

Figure 1 shows the links between the different technical stages of the modelling process. The process of data review, model conceptualisation, model calibration and sensitivity analysis is iterative. The information gained from later stages is used to improve earlier steps and reduce uncertainties associated with the water balance components.

Subsequent modelling cycles

Modelling is a cyclic process, which could involve several stages of updating, verification and re-calibration Models should be **updated** regularly with time variant data, such as abstraction and recharge. The main objectives of the update are:

- To allow the model to be used as an up-to-date **forecasting tool**, which is particularly relevant to drought forecasting or seasonal water availability forecasting
- To **validate** the updated model. This involves assessing whether the updated model simulates the historical data to an agreed level of accuracy, and from this to judge the need for recalibration
- To **identify additional data requirements** and thus use the model in guiding field investigation and monitoring programmes

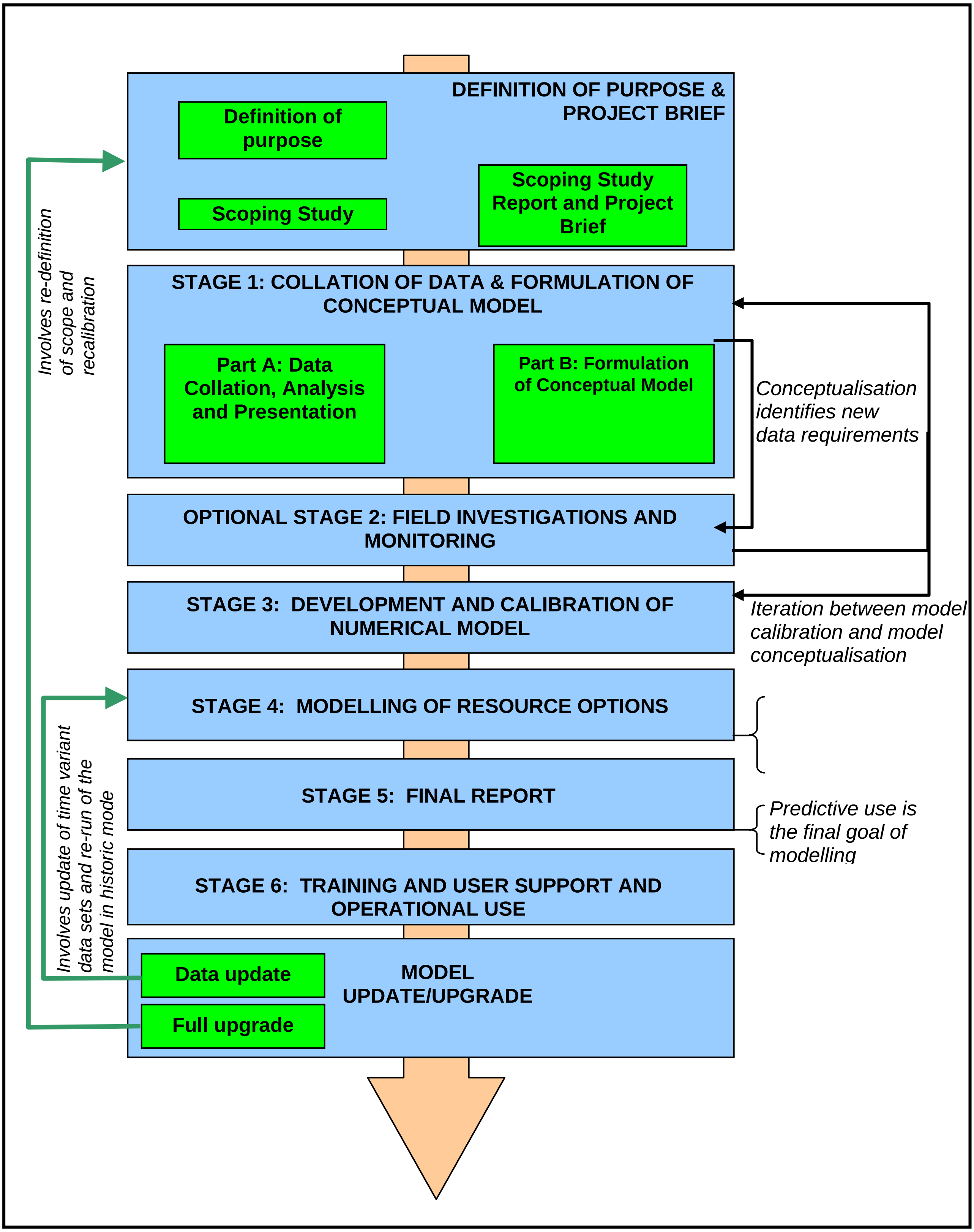
It is anticipated that recalibration of a regional model would be required on a 3 to 5 year cycle, obviously depending on the outcome of model validation undertaken during model updates. The need for model recalibration needs to be seen as a business case, and a cost-benefit analysis should be undertaken before embarking on recalibration. If a clear business case has been identified (Box 1), the process of approval and securing of funding would be put into motion.

Models are generally purpose built for specific reasons. If the scope for model use is to be changed, then it is important to re-scope and most likely recalibrate. Changes to the model may in this case be significant.

Box 1 Model re-calibration as a business case

If recent monitoring data has indicated that a model does not adequately represent the behaviour of the aquifer system, then the need for re-calibration needs to be considered. This requires an assessment of cost required for the recalibration process and the benefits that this may accrue. Benefits can be substantial a recalibrated model can avoid conflict (often resulting in costly litigation) between the resource management organisation and water users. It may also directly benefit the users within the organisation through time saving required to accommodate the uncertainties in the original model.

Figure 1: Phasing of groundwater modelling



4.2 Project planning and scoping

Planning and scoping of groundwater modelling projects should be in accordance with strategies developed at national and river basin levels.

Strong project planning and scoping is essential to the successful outcome of the modelling project. Project scoping serves to define clear objectives and deliverables. It defines the issues that are of importance to the different stakeholders. An important component in the scoping is the identification of the key interested parties, who can both benefit from the model deliverables and actively contribute to the model development. In this context, a clear communication and participation protocol needs to be established.

The scoping study components are listed below and discussed in subsequent sections:

- Purpose, scope and objectives, and identification of the main issues
- A clear idea of model detail is required since complexity determines the time and cost required to process data and construct and calibrate the model. Figure 2 illustrates appropriate detail related to data availability
- Cost-benefit analysis (Box 2) of model purpose and scope, with potential for scope enhancement, considered in the context of available time (deadlines) and budget
- Identification and assessment of data sources and data limitations, including availability
- Preliminary review of previous studies
- Preparation of a conceptual overview
- Definition of model and study area extent and detail (relates to purpose and scope) and possible limitations
- Initial conditions and time period for historical model
- Uncertainty in the context of the points listed above and model acceptance
- Good practice, related to Project Brief, project team, communication and participation, stakeholder participation, knowledge management and technical approach
- Benefits realisation, which is illustrated in Figure 3
- Work plan, an example of which is shown in Figure 4.
- Project Brief, which sets out in detail the modelling tasks related to the different modelling stages.

Box 2 Cost-benefit analysis

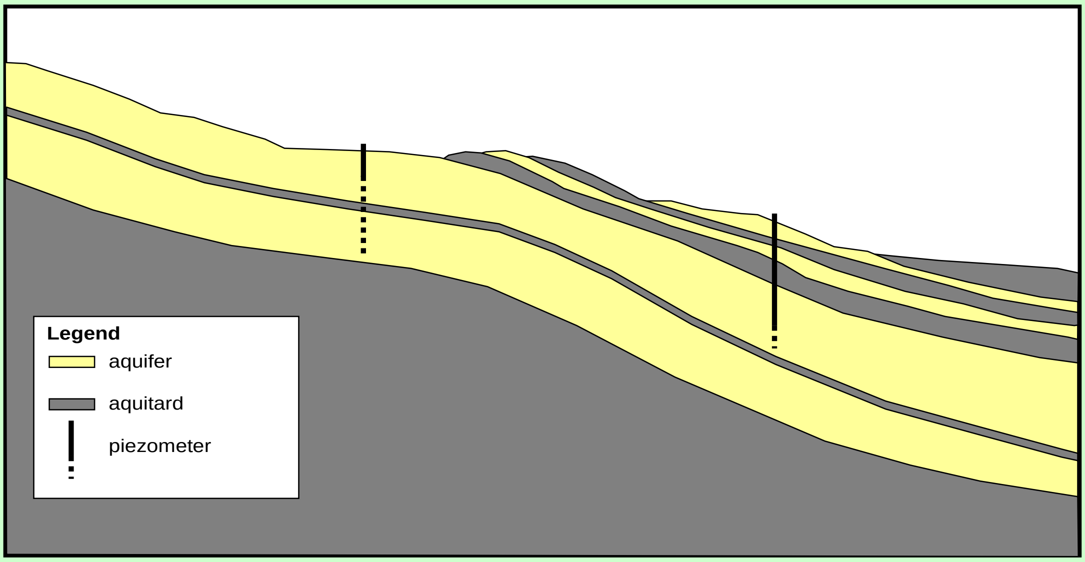
In the United Kingdom, cost benefit analysis is used to determine the value of the model to the end users. The analysis relates to the full cycle of model use, generally some 20 years.

Costs include the initial cost of model development and recurring costs for model updates (generally annual) and periodic re-calibration (every 3 to 5 years).

Benefits include both financial (tangible) and non financial (intangible) terms that cannot be easily presented in a financial context. Benefits are derived for the full period of the lifetime of the model, including the period of initial model development.

Figure 2: Model layering

The choice of layering depends on availability of groundwater level monitoring data for a sufficiently long period of time. Although the aquifer system may be well defined in terms of geological layering, monitoring data defining the groundwater levels in the aquifer layers may be limited. In this example a multi-layer aquifer system is known to exist. It comprises two main aquifers and two minor aquifers, with aquifers separated by low permeability aquitards. The monitoring data is limited to the main aquifers and at some locations the monitoring well covers two aquifers, thus not being able to distinguish between the individual aquifer layers. There is no monitoring data for the minor aquifers. Despite good knowledge of geological layering, the use of a multi-layer groundwater model would not result in accurate representation of groundwater levels and flows in individual layers, because of lack of model calibration data. In this case a 4-layer model comprising two aquifer and two aquitard layers would be appropriate.



The second situation shown below is identical to the first in terms of knowledge of geological layering. The difference is in the groundwater level monitoring, which is more detailed to the extent that knowledge is available on groundwater levels in the four aquifer layers. In this case an 8-layer model would be justified.

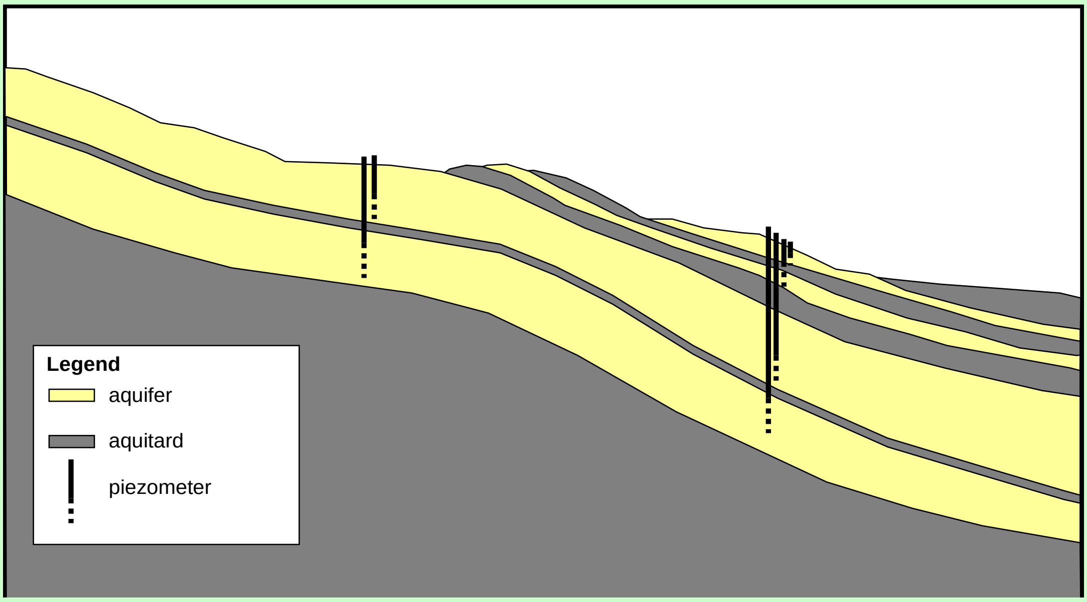


Figure 3: Benefits realisation related to modelling projects in the United Kingdom

Groundwater Modelling Stage		Benefits
Scoping		Establishment of stakeholder groups (including beneficiaries) will contribute to active participation from an early stage
		Identification of scope and objectives will provide clarity about project output and will thus avoid the raising of false expectations
		Details on knowledge/data exchange will clearly set out responsibilities for participants and will indicate the potential benefits of participation and collaboration
		The early assessment of benefits and the communication to the beneficiaries will ensure 'buy-in'
		Clarity about form of association/cooperation and associated responsibilities will enable better planning of activities
Stage 1, Part A	Data collection, analysis and presentation	A large amount of information arises from this stage of the project and will be of direct benefit to the beneficiaries. Information would be in the form of GIS maps describing the geological, hydrological, meteorological, hydrogeological, hydrochemical, soil and land use characterisation of the project region. It would also include databases and spreadsheets containing the data defining the characterisation of the project region both in terms of space and time. Furthermore it would provide documentation that would give a clear description of the project region in the context of past and current understanding and in the context of requirements of beneficiaries.
Stage 1, Part B	Formulation of conceptual model	The conceptual understanding of the project region, which includes a preliminary assessment of water balance for sub-areas of the project region is a valuable contribution to the understanding required by the team responsible for the various drivers. The conceptual model would also have addressed the uncertainties associated with the model and the associated data and provide recommendations for reducing this uncertainty. This assessment could be directly linked with the requirements and detail required by the different drivers.
Stage 2	Field investigations and monitoring (optional) (Address data storages)	This optional stage in the Strategy project could be of value if uncertainty could be reduced by undertaking additional field investigations and monitoring. Such tasks would have to be discussed with the tams responsible for the drivers and relate to the objectives of the Strategy project. There could be a clear mutual benefit.
Stage 3	Development and refinement of numerical model (historical model)	The conceptual model would form the basis for the historical numerical model. The refinement of the model would generally result in an enhanced conceptual understanding and a quantitative understanding of uncertainty. The Strategy project could significantly benefit from the local knowledge that resides with the drivers teams, while the enhanced conceptual understanding and the quantification of uncertainty will instill confidence in the value of the numerical model. Communication and participation of beneficiaries is essential at this stage.
Stage 4	Modelling of resource options (predictive simulations)	The modelling of resource option can be directly targeted to the needs of the beneficiaries. They thus gain significant benefit from the model results.
Stage 5	Operational tool	The model could be used at any time once completed to address the requirements of the various functions within the Agency and those of the stakeholders. For benefits to realise, the value and the possibilities the model can provide should be communicated to the potential beneficiaries.

Figure 4: Example of work plan for a regional groundwater modelling study

Project phase	Activities and output	Year 1	Year 2	Year 3	Year 4	Comments
Project scoping	Definition of purpose and preparation project *Scoping study report* *Project brief*					This scoping study is followed by a tendering process, which could take several months
Stage 1	1a: Collation of data *Database and GIS* *Data collation report* 1b: Formulation of conceptual model Data integration Recharge simulation Preparation of water balance Uncertainty analysis Conceptual model development *Stage 1 report*					The data collation report comprises sections related to specific data items. Reporting and reviewing is often done on an item by item basis Reporting involves submission of draft reports that will be subject to review by an external advisor and by the regulator and stakeholders. There can be a period of up to a month between submission of draft and final reports
Stage 2 (optional)	Field investigations and monitoring *Stage 2 report* *Updated database*					
Stage 3	3a: Development of groundwater model Model construction Model calibration Uncertainty analysis Preparation of development scenarios *Stage 3 report*					Stage 3 often overlaps with Stage 2, unless the conceptual understanding is insufficient to proceed with Stage 3 and additional data/knowledge is required from Stage 2
Stage 4	Modelling of resource development options *Stage 4 report*					The duration of this stage depends on the number of resource option evaluated using the model
Stage 5 & 6	Final Report and model handover Installation of model on NGMS *Final Report* *Operation and training manual*					The preparation of the final report depends on the detail required and the need to report for individual reporting areas

A model to which this workplan applies would be of a regional scale and be a detailed representation of the integrated groundwater and surface water system.
Models of this type have been developed in the Anglian Region of the Environment Agency of England and Wales. The models cover areas as large as 10,000 km^2, comprise over 200,000 model gird cells with a cell size of 200 x 200m. Such models are multi-layered and include up to 10 layers and fully integrate surface water systems, such as rivers and springs. The fine resolution of such models is their use as a tool to assess groundwater abstraction and climate impacts on groundwater dependent eco-systems of small size. The duration of such modelling studies can be from 3 to 5 years, while the cost of such large scale and detailed models can be as high as £1,000,000.
In other regions in England, models are of smaller size and comprise fewer layers. The duration of the modelling study would in this case cover a shorter period of time (from some 2.5 to 3 years). Model studies of this smaller size would generally require a budget of some £500,000.

4.3 Groundwater modelling process

Stage 1: Data collation and development of conceptual model

Stage 1 is split into two parts. Part A relates to the data collation while Part B includes the development of the conceptual model. Part B also includes recharge simulation and the preparation of water balances for selected model sub-domains.

The two parts of Stage 1 need to be closely linked. Groundwater modelling projects should place a lot of importance on the thoroughness of the data collation and model conceptualisation tasks.

Part A: Data collation

The data categories normally included in the data collation are listed below.

- Geology
- Hydrogeology
- Topography and drainage
- Soils and land use
- Rainfall
- Evaporation and evapotranspiration
- Abstraction and discharge related to both surface water and groundwater
- Locations and nature of water dependent features such as rivers and wetlands
- River flows
- Groundwater levels
- Hydrochemistry

The data collation should also include the review of literature and walkover surveys/site visits. The access to data should be pointed out in the project scoping document.

The data collation done in Part A should be factual and focus on completeness and accuracy of data sets, as well as developing databases for storage and retrieval of data, and data presentation formats. There is no need at the early stage of the data collation to analyse data in depth.

The processed data can be of immediate benefit to stakeholders. It is important that there is feedback of checked and processed data to the primary databases. This ensures that repetition of effort is avoided in the future and checked data have direct benefit to users.

To make processed data available and useful to the stakeholders, it is important that clarity in presentation is achieved. The use of advanced database and spreadsheet systems allows for rapid interrogation of data and for production of graphs and simple mapping. GIS is used for visualisation of spatial data and is a very powerful medium for results processing and presentation. Specific pre-and post processing facilities that are commercially available may be used. These are generally expensive and there is a tendency, for example in the United Kingdom, to use model specific GIS systems that allow for standardisation of results visualisation to suit specific purposes.

Part B: Development of the conceptual model

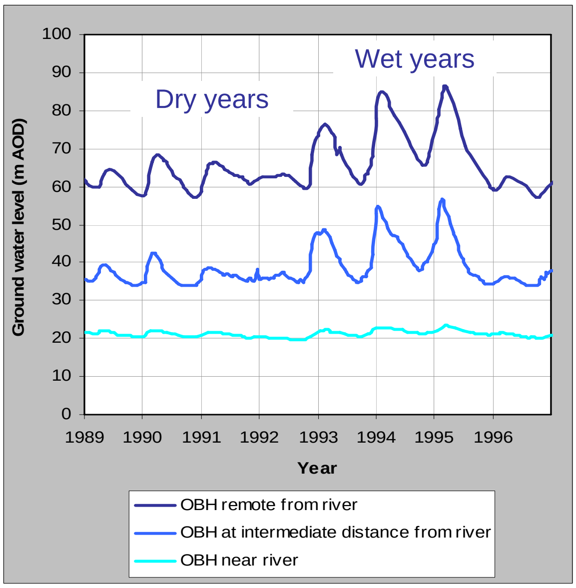
The conceptual understanding is developed using the components of conceptual model development described below. The development process normally starts from an initial understanding expressed in the Scoping

Study. The understanding is enhanced through an evolving and often iterative process until an agreed final conceptual model has been developed. The tasks included in the conceptual model development are summarised as follows:

Data integration. Data integration is the first task in the model conceptualisation. It is a very important task of Stage 1. The data integration includes the interpretation of all data with particular emphasis on data inter-dependencies, for example, the dependency of groundwater levels on geology, hydrogeological characterisation of the groundwater system, rainfall and river flows. The data integration allows for judgement of adequacy of data coverage and accuracy. It also allows for judgement of data interdependency as illustrated in Figure 5.

Recharge simulation. The initial derivation of spatially distributed recharge is done with recharge models or using other, proven recharge estimation methods (refer to Thematic Paper 1.2 'Groundwater Resource Quantity Assessment'). The recharge simulation is for the full duration of the historical model period. Preliminary recharge simulation aids the development of groundwater balances for selected sub-domains of the modelled area. Subsequent refinement of recharge assessment may be required during Stage 3. For recharge simulation modelling a time step of one day is common when recharge is strongly influence by variable rainfall. For situations where recharge from rainfall is less dominant, a longer time step would be used (one week to one month, in line with the time step duration used in the groundwater model).

Figure 5: Groundwater level dependency on recharge and proximity to a river



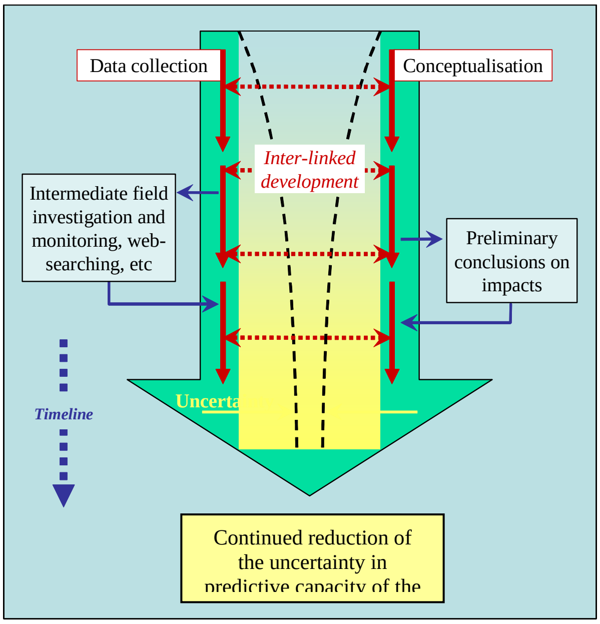
Preliminary water balances. Preliminary water balances are calculated for sub-domains of the modelled area (refer to Thematic Paper 1.2 'Groundwater Resource Quantity Assessment'). The derivation of water balances focuses attention on the adequateness of the data sources, both in terms of spatial and temporal distribution as well as their degree of accuracy. Quantification of water balance components (such as recharge, discharge, inflow-outflow to rivers, storage changes, etc) allows an appreciation to be gained of the significance of different data components to the model. This gives an indication of whether high data accuracy is necessary for each data component. For example, it may be that the groundwater lies below an impermeable surface, through which little recharge occurs. Thus rainfall data is not of great significance to the groundwater system, (unless river flows are an important part of the system).

Uncertainty analysis. Uncertainty can be both spatially and time variant. Gaining an understanding of uncertainty is important because it allows for better judgement of the predictive capability of the model.

Uncertainty analysis is an important part of the development of the conceptual model, and in Stage 1B of the modelling process one aims at gaining an understanding of the significance of parameter uncertainty on the components of the water balance. This initial analysis of uncertainty and its expression in quantitative terms will provide focus on additional data collection (during Stage 2) and model calibration (during Stage 3). The process of uncertainty analysis is illustrated in Figure 6 and reference is also made to Thematic Paper 1.2 ‘Groundwater Resource Quantity Assessment’.

It is also important to address conceptual uncertainty at this stage. Conceptual understanding is sometimes uncertain due to more than one explanation of system behaviour. Such uncertainty needs to be related to the uncertainty in data. It is beneficial to communicate this type of conceptual uncertainty to expert hydrogeologists/ modellers not associated with the project, as this often results in a reduction in the uncertainty. However, sometimes such uncertainty cannot be avoided and alternative conceptualisations need to be carried into the model calibration stage.

Figure 6: Process of uncertainty analysis



Conceptual model. The tasks described above allow for the development of a thorough conceptual understanding of the groundwater system and its interaction with the surface environment. This conceptual understanding forms the basis for numerical model development and calibration.

Preliminary design of the numerical model. One of the tasks for Part B is the preliminary design of the numerical model. This should be preceded by an assessment of the rationale for undertaking the numerical modelling stage. The following issues should be considered in the model design:

- The extent of the model
- The number of layers in the model
- The model grid resolution (grid cell size)
- Internal (rivers and main canals) and external boundaries

- The need for inclusion of drainage facilities and springs
- The need for simulation of shallow groundwater table conditions with possible use of an evaporation function
- The time frame for model simulation and the sub-division of the time domain. For regional groundwater models and time step ranging from third monthly to monthly are common. For local scale models of groundwater systems that show rapid changes in groundwater levels over short periods of time, a shorter time period ranging from one day to one week would be used.
- Acceptance criteria for model calibration, taking account of the uncertainties identified during model conceptualisation as well as the modelling scope and objectives
- Choice of model code, which may be pre-determined. It is important that the model code suits the purpose of the modelling studies and that not only any short-comings are identified, but that a clear indication is given as to who such short-comings can be overcome. Table 2 shows a summary of commonly used modelling software.

Identification of additional data needs. All the previous components of Part B allow for the identification of additional data needs, related to both groundwater system parameters and to monitoring data. Proper analysis of additional data needs allows for an effective programme of additional data collection during Stage 2 of the modelling project, with due consideration of cost and added value. This is further highlighted in the following section.

Reporting and benefits realisation. Comprehensive reporting is an essential component of Stage 1 and the report should represent a permanent record of all Stage 1 components. Benefits realisation (such as for example the provision of processed data to stakeholders) can be achieved throughout the course of Stage 1 and the opportunities for benefit realisation should be highlighted in the report with clear identification of beneficiaries and model components.

Account should be taken of reporting preferences of the key stakeholders. Thus an overview report should include the following topics:

- A clear introduction to the scope and objectives of the study and to the issues it aims to address.
- A summary of the data collation process with reference to the data collation report.
- A description of the final conceptual understanding of the integrated groundwater and surface water system and a clear statement on uncertainty.
- Water balances for the whole of the model area, with a breakdown into specific reporting units if necessary.
- A clear statement of benefits being accrued from Stage 1

More detailed reporting would be required to leave a permanent record of the Stage 1 development process. This could be on a model area basis, or in different reports describing selected reporting areas. Such reports would document in detail the conceptual development process from initial understanding to the final conceptual model described in the overview report. These reports will become the permanent records on the Stage 1 model development.

Stage 2: Field investigations and monitoring

This stage is optional and its need depends on the uncertainties associated with the conceptual understanding of the integrated groundwater/ surface system as identified during the Scoping Study and Stage 1. The early assessment of available data and understanding of groundwater system behaviour enables the identification of additional data needs and generally prompts the need for Stage 2 activities.

The additional data collection and field work is in addition to the routine monitoring that is undertaken by the different management levels. The value of the additional work needs to be carefully considered against the cost of undertaking the work. One should consider the value of the new data and focus the data collection on items that will be of direct value to reducing the uncertainties in the conceptual model.

Stage 2 could run fully or partially alongside Stage 3 and exchange of knowledge gained from each stage could be mutually beneficial.

Stage 3: Development and calibration of numerical model

Stage 3 comprises the following components:

Model construction

The model construction includes the preparation of all relevant model input files, the verification of the input files using an agreed protocol for data checking and visualisation, and the operational testing of the model operation.

Model calibration

The model calibration process includes the development of a historical model that simulates groundwater levels, river flows and other flow components (if relevant) such as drainage flows, spring flows. The aim is to achieve an acceptable match between simulated and observed groundwater levels and flows. The acceptance of model calibration is judged against acceptance criteria set initially during the model conceptualisation stage and agreed by the project team. Model calibration is done in a deterministic way and involves the adjustment of model parameter sets and the checking of simulated groundwater levels and river flows against observed data. The calibration process contains a number of components, including:

- **Initial model parameterisation** should be based on an understanding of the physical system gained through Stage 1. Parameters relate to the spatial and time variant data sets contained in the input files used by the model program. These include for example, the geometry of the aquifer system, its hydrogeological characterisation, the detail on surface water and groundwater interaction, location of wells and time series of abstraction, distributed and time variant recharge, boundary conditions, etc. If models exist for similar groundwater systems or if previous models exist for the same area, initial parameter setting could be based on such models if such models are believed to agree with the conceptual understanding.
- The data integration undertaken during Stage 1B will have resulted in an understanding of the relationships of the key model

calibration parameters and the physical characterisation of the model. Judgement of initial model response for the historical period against observations will indicate the **direction of parameter adjustment.**

- **Initial model calibration** can be carried out in steady state mode, in which case storage changes do not feature, or in a dynamic equilibrium mode, during which repetitive annual cycles of groundwater recharge and abstraction are put through the model. This latter mode allows for detection of possible trends in groundwater levels and for the establishment of initial conditions for the historical run.
- The **historical calibration** period depends on the availability of historical data related to climate and abstraction/discharge. It is advisable to start the historical calibration from pre-development conditions, for example before significant groundwater development started. In the United Kingdom, the duration of historical model runs is generally around 35 to 50 years and this duration is largely dictated by the availability of monitoring data and the knowledge that a dynamic equilibrium existed prior to the start of the historical period. In areas where falling groundwater level trends have been evident for a much longer time, long simulation periods are included. An example is shown in Box 3.

The actual model calibration could be preceded by exploratory modelling. An exploratory model could have the same resolution and extent as the final model, but could be simpler in set up, such as for example a reduced number of modelled layers. Exploratory models could also include separate models, for example two-dimensional vertical strip models to assess interactions between rivers and groundwater or to better understand the process of saline intrusion. Exploratory modelling is useful for testing the sensitivity of the model to changes in parameter settings. It helps gain an early understanding of how the model operates under certain conditions and aids in the subsequent model calibration process. It also allows for an initial exploration of the significance of uncertainty of model parameters on model simulation results (refer to Figure 6)

Box 3 Selection of calibration period

The Sherwood Sandstone Formation in northeast England is an aquifer of large extent and has been an important source for public water supply since the first half of the 19th century. The aquifer comprises unconsolidated or weekly cemented sands, which exhibit high porosity.

The abstraction pressure in the large urban areas has resulted in over-abstraction of groundwater and, because of the high storage capacity of the aquifer, in a gradual and slow decline in groundwater levels.

To capture this history of groundwater decline, the historical calibration period for a regional groundwater model (East Midlands-Yorkshire Sherwood Sandstone Groundwater Modelling Project, 2008) had to be extended back to 1839. Given that limited data were available, the time step was as follows:

- decade periods from October 1839 to Sept 1900 (inc); then
- annual periods to Sept 1963 (inc); and finally
- monthly periods to end Dec 2004

During model calibration, a continuous critical evaluation of the conceptual understanding is made. Thus an iterative process of model calibration and improvements to the conceptual understanding is undertaken, as illustrated in Figure 1.

Uncertainty analysis

Uncertainty analysis contributes to understanding the value of the model as a resources management tool. The output from the analysis should enable decision makers to obtain an appreciation of how accurate the model simulation results are and thus obtain a better idea of the risks involved with making decisions based on model results.

Sensitivity analysis is an important component of uncertainty analysis. It involves systematic changes to model input parameters within well-judged confidence limits. It allows for the development of an appreciation of the sensitivity of the model results to individual parameter changes. It thus highlights the relative importance of the accuracy of such parameters and can guide the efforts to improve the model data sets, for example through a field investigation and monitoring programme. The concept of sensitivity analysis is highlighted in Box 4.

Results processing and visualisation

The degree and format of processing and presentation of model simulation results can vary depending on modelling requirements. This is acceptable as long as the usefulness of model output to the groundwater managers and to the stakeholders (such as water users) is realised. The realisation of benefits that accrue from the historical model should thus be based on a well thought through communication and participation plan.

There is a growing tendency to use GIS as the main platform for presentation of model simulation results. This will, with participation of stakeholders, enable presentation to become more standardised.

Appropriate results processing also aids in the judgement of the model's 'fitness for purpose'.

Box 4 Sensitivity analysis

Model sensitivity runs may indicate that a systematic change in hydraulic conductivity has a significant impact on groundwater levels. Such change should be considered in the context of location of an observation borehole (for example little sensitivity may be observed when the borehole is close to a river). The sensitivity would allow for setting of uncertainty levels for the particular parameter. It should be noted that similar groundwater level changes may result from recharge variation.

When considering seasonal variation in groundwater levels, these may be influenced by a multitude of parameters, such as recharge, geology, hydraulic conductivity, and storage properties. It is important that sensitivity is assessed for one controlling parameter at the time and that parameter change is made within uncertainty bands considered realistic as evaluated during the conceptual model development.

It could also be that a water balance is so small compared to other components, that a change in the controlling parameters is of little significance and thus requires no further attention. An example is the allocation of confined storage coefficients to fully saturated aquifers.

The uncertainty bands of model input parameters, within which the sensitivity is undertaken, depend on the uncertainty attached to the base data that determines the model parameter settings and on the uncertainty in conceptual understanding.

Reporting and benefits realisation

Reporting should be clear and comprehensive so that it is easy for the reader to understand the model calibration process and the resulting output from the historical model. Although discussion of uncertainty is essential, the report should be positive so that it instils confidence in the users of model results.

It is clearly important that all beneficiaries are consulted regarding the presentation and the format of model output. For example, some groups of stakeholders may be satisfied with an overview report that brings out the final understanding of the integrated groundwater and surface water systems and the natural and anthropogenic influences. Thus different reports may be produced for different stakeholders.

More detailed reports that describe in detail the model calibration process, the changes made to achieve a final conceptual model and an associated numerical representation are required to leave a permanent record of work undertaken during Stage 3. Such reports could be on a sub-area basis if so required. These reports are for a more technical readership than the overview report.

The report should include a description of how the model outputs will be used by different stakeholders and management levels. The value of the model needs to be identified and recorded as this will provide evidence of the usefulness of the modelling studies.

A CD containing the report text, associated figures and other information should be included in the written report. The additional information relates to spreadsheets for interrogation of results and GIS viewers, which allow for drilling down into data and results.

Reporting may vary for different provinces and reporting preferences need to be appreciated. Consistency is, however, strongly recommended.

Scenario runs

The scenario runs are specified at this stage. Standard scenario runs include: (1) natural conditions with no abstraction and no discharges from for example sewage treatment works; (2) with actual recent abstractions and discharges; (3) with abstractions and discharges at the permit limit. Scenario runs for Stage 4 should be determined, in consultation with relevant stakeholders.

Stage 4: Modelling of resource options

Once the numerical model has been calibrated to an acceptable level of accuracy and uncertainty has been adequately understood and quantified, it can be used in predictive mode. The purpose of prediction runs is often pre-defined in the original objectives for the model, although additional scope may be identified during the modelling study.

Results from prediction runs can be used in the appraisal of resource management and development options.

The different modes of model predictions include:

- **Forecasting** models are used to predict the future response of a groundwater system to some future stresses. For example models used to assess the effect of climate change on groundwater resources.
- **Option appraisal** models are used to inform decisions requiring a choice between several options.

- **Control** models are actively used in groundwater management. Models are updated and run based on conceivable near future scenarios, such as the continuation of a current drought situation. Model results help to determine whether certain groundwater management actions need to be taken, particularly when trigger levels such as groundwater levels or river flows are exceeded.

Stage 5: Final report

The preparation of a final report is the conclusion of the model development and operation process. The final report should be a synopsis of the different stages of the modelling process and should focus on summarising the results and findings.

The conceptual model reports, prepared during Stage 1, need to be stand-alone (functioning as a principal guide to the groundwater system properties and status) and require possible updating in view of improved conceptual understanding derived from Stages 2 and 3.

Stage 6: Training and user support and operational use of the model

Stage 6 is the beginning of the operational use of the model as part of its 'life cycle'.

There is need for 'intelligent' interpretation of model prediction results. Results should be judged against the strengths and weaknesses of the model and should consider the original purpose of the model. Guidance on interpretation of model prediction results must be included in the user manual.

Operational use generally involves the regular update of the model and its use to satisfy the requirements of the various stakeholders.

4.4 Further operational use

The development of regional groundwater models incurs a high cost as has been illustrated in Figure 4. A model should therefore be considered as a valuable capital asset. Operational use of a model may be one of the objectives of a modelling project, but it may also be used again at a later date to address requirements of changes in resources management, or the availability of new data.

In either case, it is important to include regular evaluation and updating of both the conceptual and numerical model to ensure the model is usable years after the initial project completion.

As part of this regular updating, a model evaluation report should be produced which assesses whether the model still adequately represents the behaviour of the groundwater system as described by the new data. This report should provide documentary evidence that the model is still acceptable and will continue to assist in making resource management decisions based on the model.

The dynamic use of the model involves a number of modelling cycles repeated once every 3 to 5 years as illustrated in Figure 7.

5 Non-technical issues

5.1 Training needs and capacity building - who can build models?

The successful outcome of a modelling study does not only depend on the technical ability of the modellers. Equally important are aspects related to project management, stakeholder participation, communication, reporting and quality control, and knowledge management.

Barker and Kinniburgh (1995) quote from a US EPA report for groundwater modelling that states: *'if models are to be used effectively in water resources analysis, training in basic concepts of modelling and in proper interpretation of model results must be offered to decision makers at all levels of water resources management and environmental protection. Further, there is a need for specific training in the use of individual models, and a need for continuously informing and educating users and managers in research developments, new regulations and policies and field experience.'*

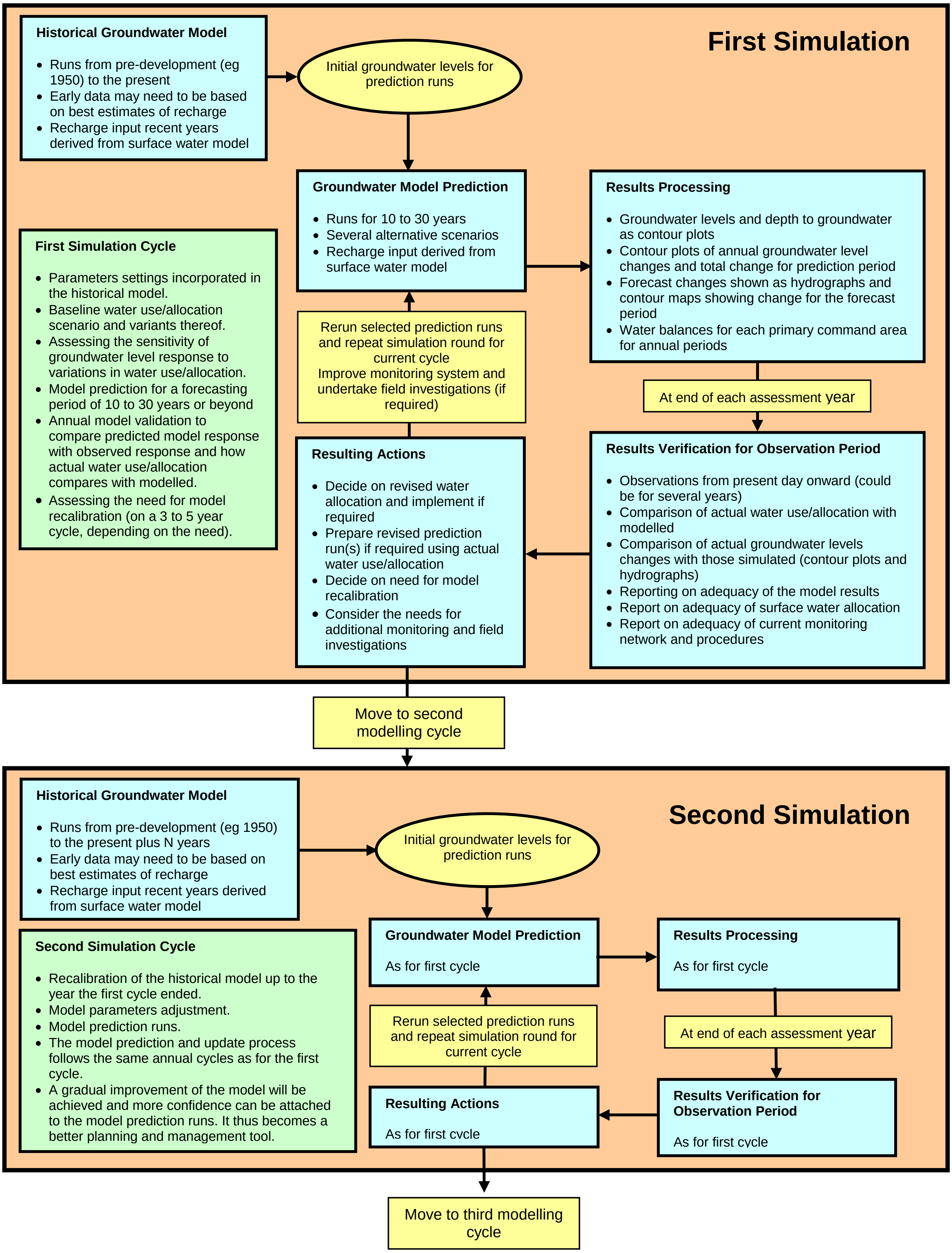
Capacity building and training needs are not, therefore, confined simply to modelling staff, but also to others involved in resource management (at different levels) who may not appreciate the advantages, and shortcomings, of distributed numerical models. It is suggested that on completion of a regional model, the results, conclusions and future use of the model are disseminated via seminars/ workshops and in the form of written documentation. Model results need to be understood. This requires not only clarity in model output, but also an understanding of the behaviour of the groundwater system. A model is a tool that aids decision making and is thus not an exact representation of reality.

Guidance notes on various aspects of model development and operation can help in communicating the capability of models to the stakeholders and to a wider audience. Guidance notes aid the reproducibility of groundwater models in other areas.

5.2 Project management

- The project management team should comprise senior staff from the local bureau that commissions the study and from the Consultant undertaking the study.
- Management roles and responsibilities should be clearly specified in the study's Terms of Reference.
- An independent expert, who should be part of the client's project management team, should review all procedures and results from a modelling project.
- Regular quality review group (QRG) meetings should be held to discuss project progress and issues.
- Maintaining issues and risks logs that document issues and risks, identify courses of action, allocate responsibility, and set a time scale for resolving the issues and risks.
- Throughout the model development process, monitoring and evaluation (M & E) should be undertaken according to pre-set standards. These are normally a component of standard quality assurance (QA) procedures, although more detail is required specific to the modelling study. The independent expert referred to earlier, plays an important role in M & E from a technical perspective.
- Quality Assurance is essential to ensuring a quality outcome of the modelling study and ensures both confidence in its use and continued use beyond the model development period. QA relates to all stages of the modelling process, both technical and non-technical.

Figure 7: Model simulation cycles



5.3 Stakeholder participation

- It is recommended that stakeholders are included in a project steering group to encourage a wider acceptance of the model.
- Regular steering group meetings should be held at key stages during the modelling study. Normally these key stages are at the start of the study and at the end of study phases.
- Participation of stakeholders may be important during the preparation of model prediction scenarios.
- If stakeholder representatives have the appropriate technical background in groundwater resources planning and modelling, these could participate in the review of the modelling work (a similar role as the independent expert).

5.4 Communication

- The project management team should be responsible for the development of a communication strategy and for the implementation of this strategy throughout the modelling study.
- Communication should occur both internally within the project management team and externally between the project team and the stakeholders.

5.5 Reporting and quality control

- Documentation relates to internal reporting (such as preparation of technical notes on adopted approach) and to the formal reporting on project findings.
- Interim reports should be issued upon completion of study stages, while a final report is prepared upon completion of the study.
- Reporting also includes documentation on the use of the model.
- Documentation of each phase of model development is important as it supports Quality Assurance/Quality Control and ensures a clear record of key activities and decisions taken. This is particularly important in a resource management and regulation environment where there must be a credible justification available to support decisions.
- Both the conceptual and numerical model reports are vital to ensure that the ideas leading to the development of the model are carried forward with the model so that it can be updated in the future.
- This documentation also has uses beyond just reporting the results of the modelling project itself and providing supporting evidence for the model design. Reports on the conceptual understanding of the groundwater system are important reference documents.

5.6 Data management and sharing

- An accessible information system should be prepared, containing all information used during the modelling study. This could take different forms, such as a reference library, a database containing both original and processed information, possibly linked with a GIS system, and model code and data files.

- The information system should be maintained and upgraded with new data/material, using appropriate quality assurance procedures.

6 Recommendations

In order to do ensure that groundwater models are developed to a consistently high standard, a number of recommendations have been made, outlined below.

Project methodology

Projects, including those carried out in-house, should generally follow the methodology outlined in Section 4, in particular:

- Scoping studies should be undertaken prior to the start of projects to ensure the purpose of the project is clearly defined, to evaluate the data requirements and estimate the resources and effort required.
- Models should be regarded as capital assets and be maintained and updated regularly so that they can be used operationally for resource management when necessary. Maintenance should be planned into the regional business plans or modelling strategies.
- Full and complete documentation of models is required to provide a comprehensive record that will give credible support to the models and decisions arising from their use.

Project management

- The responsibilities for project management and technical supervision should be separated.
- The objective and detailed specifications of the purpose, approach and output for each modelling task should be supplied to the contractor who will undertake the modelling study (this applies equally if the modelling study is done 'in-house'). It is recommended that this follows the staged approach as described in Section 4.
- An independent external expert should be included on the project management team to review procedures and results from the project.
- The project management team should include a representative from other stakeholders to widen 'ownership' of the models.
- Meetings with stakeholders should be held at key project stages.

Guidance notes

- It is recommended that Guidance Notes are prepared and regularly updated through contributions from experts and feedback from modelling projects.

Data

- Access to information and data, and maintenance of the database is crucially important to guarantee successful execution and completion of modelling studies.
- Access to data and data sharing should become a priority and no restrictions should be attached to the availability of data required for resource evaluation and modelling.

Document Reference Sheet

Glossary:

Analytical model	Exact mathematical solutions of the flow and/or transport equation for all points in time and space. In order to produce these exact solutions, the flow/transport equations have to be considerably simplified (e.g. very limited, if any, representation of the spatial and temporal variation of the real system).
Conceptual model	A simplified yet comprehensive representation or description of how the real hydrogeological system is believed to behave. A quantitative conceptual model includes preliminary calculations, for example, of vertical and horizontal flows and of water balances.
Calibration	The process of adjustment of model input parameters until an agreed match between the modelled and observed groundwater system responses is achieved. The comparison normally relates to groundwater levels and could also relate to river flows, spring flows and groundwater quality.
Distributed model	Model where the heterogeneity of the real system is represented by spatial variation in the inputs and outputs. Compare *lumped model.*
Distributed time-variant groundwater Model	A site specific numerical model, on the scale of a catchment, or larger, which simulates the behaviour of a hydrogeological system over a specified period of time (usually several decades). The parameters describing the system are varied according to their geographical and temporal distribution.
Groundwater protection zones	Zones defined around groundwater abstraction wells within which there is a significant risk of surface activities polluting the groundwater abstracted via the well. The closer the activity, the greater the risk of pollution; thus often a number of zones indicating different levels of risk are defined. Pollution prevention measures can then be set up in the zones of higher risk to protect groundwater from pollution.
Lumped model	Model within which each input parameter is represented by only one value over the whole model area or for specified sub-areas, e.g. a lumped water balance model for a catchment will use one value for recharge, one value for baseflow to rivers one value for abstraction etc. over the whole catchment. Compare to *distributed model*.

Mathematical model	Mathematical expression(s) or governing equations approximate the observed relationships between the input parameters (recharge, abstractions, transmissivity etc.) and the outputs (groundwater head, river flows, etc.). These governing equations may be solved using *analytical* or *numerical* techniques.
Model validation	Model validation involves operation of the model past its historical calibration period and checking model results for the extended period against real monitoring data. The validation is undertaken to check if the model still represents the real behaviour of the aquifer systems and triggers decisions to undertake re-calibration of the model.
Numerical model	In a numerical model the solution of the flow and/or transport equation using numerical approximations, i.e. inputs are specified at certain points in time and space which allows for a more realistic variation of parameters than in *analytical models.* However, outputs are also produced only at these same specified points in time and space.
Re-calibration	Re-calibration is required when model validation during model updates shows an inadequate match between observed and simulated groundwater system behaviour, again expressed through groundwater levels etc.
Sensitivity analysis	The testing of model sensitivity to the systematic change of model input parameters within pre-defined confidence limits. Changes should be made in only one parameter at a time.
Stakeholders	Individuals or organisations that are concerned with groundwater and related issues. They can contribute significantly to the model development process and/or benefit from the model findings/results. Stakeholder participation in modelling studies in the United Kingdom is standard practice.
Steady state model	Model where inputs and outputs do not vary with time. Thus recharge, abstraction and boundary conditions may vary spatially, but are constant. Storage changes do not feature in a steady state model
Time-variant model	Model where the inputs and outputs related to recharge, abstraction and boundary conditions do vary with time.

Uncertainty analysis	In Stage 1B (“Development of the Conceptual Model”) uncertainty analysis aims at gaining an understanding of the significance of parameter uncertainty on the components of the water balance. This understanding will contribute to the judgement of the adequacy of the conceptual model for continuation into the numerical modelling stage. Uncertainty in conceptual understanding should also be addressed in Stage 1B. Conceptual uncertainty arises when there is more than one plausible explanation for system behaviour. During Stage 3 (“Model Development and Calibration”) sensitivity analysis, which is a component of uncertainty analysis, is carried out.
USGS	United States Geological Survey

Document Reference Sheet

Bibliography:

Barker, J.A., Kinniburgh, D.G. and MacDonald, D.M.J. 1995. Groundwater Modelling and Modelling Methodology. R&D Project Record 295/20/A. NRA R&D Project 295.

Related materials from the MWR IWRM Document Series:

Thematic Paper 1.2	Groundwater Resources Quantity Assessment
Advisory Note 2.6/1	Groundwater Monitoring - River Basin to County Levels
Advisory Note 2.6/2	Groundwater Monitoring at Village Levels
Thematic Paper 2.6/1	Groundwater Management
Thematic Paper 2.6/2	Groundwater Monitoring and its Importance to IWRM

Where to find more information on IWRM – recommended websites:

Ministry of Water Resources: www.mwr.gov.cn

Global Water Partnership: www.gwpforum.org

WRDMAP Project Website: www.wrdmap.com

China – UK, WRDMAP

1. WRA

Integrated Water Resource Management Documents
Produced under the Central Case Study Documentation Programme of the GoC, DFID funded, Water Resources Demand Management Assistance Project, 2005-2010.

Documents will comprise of:

Thematic Papers

Advisory Notes

Manuals

Examples

Training Materials

IWRM Document Series materials, English and Chinese versions, are available on the following project website

WRDMAP Project Website: www.wrdmap.com

Advisory Services by : Mott MacDonald (UK) leading a consultancy team comprising DHI (Water and Environment), HTSPE (UK), IWHR, IECCO (Comprehensive Bureau), CIAD (China Agricultural University), Tsinghua University, CAAS-IEDA, CAS-CWRR, Gansu WRHB and Liaoning WRHB.

中国水利 CHINA WATER

DFID Department For International Development

Mott MacDonald