

Environment Agency Framework for Groundwater Resources. Conceptual & Numerical Modelling

R&D Technical Report W214

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This report describes a project to improve the use of regional groundwater models within the Environment Agency based on an evaluation of the past use of these models. A framework has been produced outlining a programme of conceptual and numerical models and how these may be delivered. The information contained is for use by Environment Agency staff and others involved in water resources management and groundwater modelling.

Key words: Groundwater, water resources, groundwater model

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GLOSSARY

This glossary defines terms as they are used in this document.

ALF	Alleviation of low flows. The strategy for resolving environmental problems in certain catchments.
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).
CAMS	Catchment Abstraction Management Strategy.
Conceptual Model	A simplified representation or working description of how the real hydrogeological system is believed to behave. A <u>quantitative</u> conceptual model includes preliminary calculations, for example, of vertical and horizontal flows and of water balances.
DETR	Department of the Environment, Transport and the Regions.
Distributed model	Model where the heterogeneity of the real system is represented by spatial variation in the inputs and outputs. Compare <i>lumped model</i> .
Grid	Network of points in space (nodes) for which a <i>numerical model</i> requires inputs and produces outputs.
Integrated Catchment Model	A <i>numerical model</i> in which surface and subsurface flow equations are coupled and solved simultaneously.
LEAP	Local Environment Agency Plan. The process by which the Agency plans to respond to the environmental issues in a catchment. A consultation plan is published followed by an action plan, which is reviewed every five years.
Lumped Model	Model where the each input parameter is represented by only one value over the whole model area, 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.
Mathematical Model	Mathematical expression(s) or governing equations which 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 <i>analytical</i> or <i>numerical</i> techniques.
Numerical Model	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 <i>analytical models</i> . However, outputs are also produced only at these same specified points in time and space.
Regional Distributed Time-	A site specific numerical model, on the scale of a catchment, or

Variant Groundwater Model	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.
Regional Model	In the context of this report, a regional model is synonymous with a regional distributed time-variant groundwater model.
SAC	Special Area of Conservation. An area classified under the EC Habitats Directive and agreed with the EC to contribute to biodiversity by maintaining and restoring habitats and species.
SPA	Special Protection Area. An area classified as such under the EC Birds Directive by the Secretary of State, following submission by English Nature, to provide protection to birds, their nests, eggs and habitats.
SHE	Système Hydrologique Européen. A numerical model code representing the entire land phase of the hydrological cycle (<i>integrated catchment model</i>) developed by the Danish Hydraulic Institute, Sogreah of France and the Institute of Hydrology.
Time-variant model	Model where the inputs and outputs vary in time.
Total catchment model	Model which represents both the groundwater and the surface water components of the flow behaviour of the catchment. The mathematical representation of the groundwater and surface water flow need not necessarily be coupled and so a total catchment model is not synonymous with an <i>integrated catchment model</i> .
USGS MODFLOW	A numerical groundwater model code developed by the United States Geological Survey (McDonald and Harbaugh, 1988).

EXECUTIVE SUMMARY

Background

Regional-scale groundwater flow models have been used since the 1970s as tools to aid in the management of groundwater resources and to increase understanding of the behaviour of groundwater systems. By the mid-1990s over 30 such models were held by the Agency's predecessor, the National Rivers Authority (NRA) and concerns had arisen over the absence of a long-term nationally coordinated programme for groundwater modelling and the poor quality of some of the more recent models developed in the early 1990s.

Objectives

To address these concerns, this R&D project was initiated with the overall objective of promoting a nationally consistent framework for the use of groundwater modelling as a tool for groundwater resources management.

Results

Past modelling practice was evaluated during an internal survey of regional groundwater models held by the Agency and discussions with the Agency's modelling staff. The Survey, undertaken in 1998, indicated that most of the groundwater models had met their original development objectives and had also been successfully used to underpin resource management decisions. However, it was also apparent that many had not been updated or maintained since completion of the original project objectives. This was considered to be a serious under-utilisation of a valuable capital resource. Other issues highlighted by the survey included the need for guidance to both modellers and project managers and for a more standardised methodology for modelling projects.

The Environment Agency has a statutory duty to protect and improve the water environment through effective management of water resources and by reductions in pollution. The need for reliable, consistent and accurate tools to aid water resource management is becoming increasingly important as the pressures on these resources increases. Within a regulatory agency, the tools used to arrive at decisions need to be scientifically sound and the methods well documented so as to permit external scrutiny when required. The need for this openness is emphasised in the plans for Catchment Abstraction Management Strategies, which are to be developed from 2001 onwards.

Groundwater models are generally recognised to be the best means of representing the crucial processes operating in a groundwater system. However, they require considerable resources to develop, both financially and in commitment from Agency staff. Past experience has shown that if these resources are not committed then the finished model may be inadequate for the task required. The lack of a methodology, appropriately applied, for all modelling projects has also led to a variable quality of models, particularly in regard to documentation.

A general modelling methodology has been proposed, based on a combination of existing published guidance and the lessons learned from past regional modelling projects undertaken by the Agency's predecessors. This methodology outlines the process starting from an initial scoping study to completion and reporting and subsequent maintenance and updating of the model. Particular emphasis was placed on producing full documentation of all aspects of the development of a model.

As part of these guidelines, a set of Guidance Notes have been produced, covering the conceptual and numerical modelling stages of a modelling project. These Notes are based on

modelling experience in England and Wales and are intended for use by modellers and project managers. They will be published as the second output from this R&D project.

The need for a nationally coordinated approach to modelling has been addressed by proposing a programme of modelling projects covering all the major aquifers in England and Wales. The primary aim of the programme is to develop well-documented conceptual models of these aquifers and initial planning suggests that over 60 such projects may be initiated over the next 10 to 15 years. Numerical models will only be developed where these are considered appropriate and subject to the financial constraints and priorities in individual Regions. Nevertheless, the proposed programme provides an outline indication of future demands on Agency personnel and financial resources.

Some of the potential implications of this proposed programme on the staff resources of the Agency are considered as these are critical to the success of any modelling projects. Recommendations have been made on the organisation of a project, in particular the need not to underestimate the staff time required, and the requirement for strong technical supervision. The importance of developing and retaining a strong modelling expertise within the Agency is emphasised, particularly in regions where groundwater models form the main groundwater resource management tool.

Recommendations

The major recommendations of the report are that

- a quantitative conceptual understanding of all the major aquifers in England and Wales is developed.
- where appropriate, groundwater models are developed based on this understanding
- the modelling programme proposed by the R&D project is taken forward by the Regions and used as the basis for a better coordination of modelling projects in the future.
- it is essential to ensure that sufficient staff with suitable expertise are available in order to carry out the programme and that a certain number of staff will be required to have an in-depth knowledge of numerical modelling techniques.

To ensure that the models produced in future are developed to a consistently high standard, additional recommendations have been made regarding project methodology, project management, the utilisation of staff resources and the continuing use of the Guidance Notes to pass knowledge around the Agency.

1. INTRODUCTION

1.1 Purpose of this Document

This report presents a framework within which the Environment Agency ('the Agency') can develop regional distributed groundwater resources models to provide effective tools for groundwater resources management.

This report is directed towards water and groundwater resources managers within the Agency. It is also intended to inform interested external organisations how the Agency intends to take regional groundwater modelling forward in the future.

This Chapter (Chapter 1) describes the background to the project and its objectives together with the outputs from the project.

Chapter 2 deals with the Agency's statutory role in groundwater resources management. Chapter 3 defines groundwater modelling and provides an overview of the main components in the process. Chapter 4 summarises the Agency's past experience of groundwater modelling. Chapter 5 discusses the guidance prepared by the Agency in the light of that from other countries and outlines the Agency's modelling methodology. The proposed future modelling programme is laid out in Chapter 6. The implications of fulfilling this programme on the Agency's resources are discussed in Chapter 7. The recommendations made as a result of the project are summarised in Chapter 8.

1.2 Background

The Agency and its predecessors, the Water Authorities and the National Rivers Authority (NRA), have developed spatially distributed time-variant groundwater flow models to simulate and predict the flow behaviour of aquifers at a regional scale since the 1970s. A large proportion of these models were developed at the University of Birmingham. In the late 1980s, with the increased availability of model codes and hydrogeologists trained in the use and theory of numerical modelling, an increasing number of the regional models were developed by consulting engineers. By the mid 1990s the NRA held over 30 regional time-variant numerical models. During the 1990s, groundwater resources managers began to question the quality of some of these numerical models and whether enough were being used effectively as operational tools

In 1995 a Research and Development project 'A Strategic Review of Groundwater Modelling' was initiated to review the NRA's use of regional groundwater flow modelling and to recommend how this should be utilised in the future. Two major areas of concern were identified in the original 1995 Project Initiation Document (PID):

1. There was no long-term nationally co-ordinated programme for groundwater modelling. This had resulted in:
 - NRA Regional offices developing models whilst being unaware of the activities or approaches taken in other Regions.
 - The absence of systematic collaboration between water companies and the NRA leading to duplication of effort and the potential for conflicting models. For example two different models were produced for the Lower Greensand of the Upper Stour in Kent and used by opposing sides during a public inquiry over an abstraction licence.

- The development of local-scale models without reference being made to the flow behaviour represented in the regional scale models, where these existed. This was identified during the Agency's development of models for defining Source Protection Zones for the major groundwater sources.
2. Groundwater models developed by consulting engineers were felt to be less than adequate. The reasons for this were thought to be:
- Inadequate terms of reference provided by the NRA.
 - Insufficient time and money allocated by consultants as a result of the fierce competitive tendering process.
 - A shortage of modelling expertise primarily within the NRA but also in the consulting organisations.

Two further issues were also identified. Firstly, there was a proliferation of groundwater modelling techniques and software in the 1990s. The NRA had little experience of these and there was a perceived need for them to be properly evaluated so the NRA hydrogeologists could take a view on their use. Secondly, some groundwater models had been used to support regulatory decisions at public inquiries, with varying success. The appropriate use of models at public inquiries and the confidence that could be placed in model results was questioned.

To address these issues the following tasks were proposed for the project:

- A survey and review of existing regional groundwater models
- The benchmarking of modelling software packages
- The development of a standard terms of reference and modelling methodology
- The development of a groundwater modelling strategy
- A review of the NRA/Environment Agency use of models at public inquiries

1.3 Objectives

The first task, an internal review of previous regional groundwater models, was carried out during 1998. The feedback from Regional Agency staff that this prompted led the project board to review the original objectives of the project. The objectives agreed in 1998 are given below.

The overall objective of the project is:

To promote a nationally consistent framework for the use of groundwater modelling as a tool for groundwater resources management.

The specific objectives are:

1. To complete a survey and review of the spatially distributed time-variant regional groundwater models that have been developed for catchments across England and Wales within the Agency or its predecessor bodies.
2. To produce a document which sets out the essential strands of a nationally consistent framework for regional groundwater modelling studies. This will provide the guidance for each Region to produce its own Regional Strategy. It will also consider the role of groundwater flow modelling in contaminant transport investigations.

3. To consider previous modelling studies and to identify best practice and quality control procedures resulting in the production of Guidance Notes to provide insights on technical and project management topics based on the Agency's past experience. These will also include a standard Terms of Reference, or Project Brief.
4. To identify what capabilities the Agency requires from its groundwater modelling software and to review the capabilities and limitations of the packages which the Agency has already used for water resources investigations.

The Project Board came to the decision that benchmarking of software as included in the original objectives was a misnomer and was replaced by objective 4 (above) which was considered to be better fitted to the requirements of Agency modelling staff. It was also decided that information on the role of models in public inquiries would be gathered by the National Groundwater and Contaminated Land Centre in an independent project.

1.4 Outputs

In order to fulfil the objectives outlined above, two outputs have been produced.

1. **R&D Technical Report W214** – Environment Agency Framework for Groundwater Resources Modelling (this document). The report summarises results of an internal review of existing groundwater models and the Agency's experience of modelling in general (Objective 1). It outlines the Agency's preferred modelling methodology and a proposed national programme of work over the next 10 to 15 years (Objective 2).
2. **R&D Technical Report W213** – Groundwater Resources Modelling: Guidance Notes and Template Project Brief. These Guidance Notes are based on the Agency's experience over 20 years of regional groundwater flow modelling for resource assessment. They are intended to complement existing textbooks and be directly relevant to the operational use of groundwater models by the Agency (Objectives 3 and 4). The intended readership is Agency staff involved in modelling, both specialist modellers and modelling project managers. At a later stage this document will also be made available externally.

1.5 Related Projects

A number of other Environment Agency R&D projects are related to this project. These are described briefly below and mentioned where relevant in subsequent sections.

R&D Project W6D(96)01: Groundwater Recharge Assessment. The objective of this project is to develop a scientifically sound and nationally consistent method for estimating mean annual groundwater recharge for aquifers in England and Wales. This project is ongoing.

National Centre Project NC/06/01: A Framework for Assessing Water Resource Availability and Acceptable Abstraction Impacts. The project seeks to develop a nationally consistent method for resource assessment in order to be able to compare sustainability and manage resources more equitably. An assessment framework supported by a spreadsheet tool has been produced which can be applied across a variety of hydrogeological conditions and catchments. Trialing studies

were undertaken during the 1999/2000 financial year.

National Centre Project
NC/99/67:

Hydraulic conductivity variation with depth in MODFLOW. The objective of the project is to find a means of representing the non-linear variation of hydraulic conductivity with saturated depth which occurs in the Chalk and Limestone aquifers throughout southern and eastern England. The mechanism has been incorporated into the USGS MODFLOW code, which is widely used in the UK and has also been selected as the best interim solution for in-house groundwater flow modelling within the Agency.

National Centre Project
NC/069/28:

Estimating the Impacts of Groundwater Abstraction on River Flows (IGARF). The development of a reasoned, robust and technically supportable rationale for the initial evaluation of the effects of groundwater abstraction on river/groundwater interaction when assessing groundwater abstraction licence applications.

National Centre Project
NC/99/38:

Strategy for the development of an improved Agency capability in decision-making involving modelling of contaminant fate and transport.

2 GROUNDWATER RESOURCES MANAGEMENT

2.1 Statutory Position for Groundwater Resources

The Environment Agency (the Agency) has a statutory duty under the Water Resources Act 1991 and the Environment Act 1995 to protect and improve the water environment through effective management of water resources and by reductions in pollution.

In addition to UK environmental legislation, membership of the European Union (EU) has added to the regulatory framework through the adoption of EU Directives which impose a duty on member states to comply with these directives within a given time limit. Particularly relevant to water resources management is EU Directive 92/43/EEC (Habitats Directive). This Directive requires the designation of Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) and places a statutory duty on the Agency to protect these sites from damage by surface water or groundwater abstraction. It is proposed that all the sites designated under this directive will be assessed by 2005. The new Water Framework Directive (EU Directive 2000/60/EC) came into force on 22 December 2000. This Directive focuses on integrated water management and planning on a river basin scale; consideration of the natural qualitative and quantitative interaction between surface and groundwater and achieving a “good status” of surface and groundwater.

International Conventions to which the UK is a signatory have also imposed obligations for managing particular habitats. These include the Ramsar Convention on Wetlands of International Importance (1976) and the Convention on Biological Diversity (1992) both of which include habitats that may be sensitive to groundwater abstraction.

The Environment Agency controls the use of water resources through the abstraction licensing system. The current system has been in place, more or less unchanged, since the 1963 Water Resources Act. By the late 1990s the government had taken the view that revision was needed to ensure the sustainable use of water resources in the future and issued a consultation paper in June 1998. In the light of the responses received, the government published ‘Taking Water Responsibly’ (DETR, 1999) outlining the intended modifications to the abstraction licensing system. Some of these modifications require changes to the legislative system, while others can be implemented by the Agency using powers already available. Of these, the most significant is the proposal to develop Catchment Abstraction Management Strategies.

2.2 The Environment Agency’s Strategies for Groundwater Resources

The Agency published *An Environmental Strategy for the Millennium and Beyond* in 1997 which laid out the issues facing the Agency and the strategy to be adopted in tackling these issues. This strategy was supported by the publication in 1998 of eleven Action Plans for each of the Agency’s Functions. The principle aim of the Water Resources Function was stated as being:

‘To ensure that existing management and future development of our water resources is carried out in an environmentally sustainable manner through balancing the needs of abstractors with those of the environment’ (Environment Agency, 1998a).

2.2.1 The Agency's Water Resources Strategy

The Agency's national water resources strategy for England and Wales has been addressed in

'Water Resources for the Future' (Environment Agency, 2001a) which deals with overarching policy, approaches and techniques and provides an overview for regional water resources strategies. This document and the supporting regional water resources strategies replace earlier documents produced by the Agency's predecessor, the NRA, in the early 1990s. They are intended to provide a framework for managing water resources over the next 25 years and consider the water needs of both the environment and society. The strategies build on the latest resource estimates from the water companies completed as part of the AMPIII periodic review and examine the uncertainties about future water demand and availability.

2.2.2 Catchment Abstraction Management Strategies

In 1999, following a review and public consultation, the Government published its decisions on changes to the abstraction licensing system (DETR, 1999). One of these was the proposal to develop Catchment Abstraction Management Strategies (CAMS). Public consultation on the Agency's proposals for CAMS was undertaken during 2000 and a national supporting document setting out how the process will operate was produced in 2001 (Environment Agency, 2001b). The development of individual CAMS will begin in June 2001.

Each CAMS will outline the status of water resources within a particular catchment and outline a strategy to deal with the pressures on these resources. The Strategies will be used to inform and support the new licensing process with its emphasis on time limited licences. They will provide the opportunity for open consultation and demonstrate the transparency of licensing policies.

The Catchment Abstraction Management Strategies must be based on a sound knowledge of the interaction between groundwater and surface water and the behaviour of the surface and groundwater system. Where knowledge of a particular matter is incomplete, the Agency will apply the precautionary principle, in which decisions made and measures implemented err on the side of environmental protection. However, the use of the precautionary principle may not always be acceptable. There is therefore likely to be an increasing need for water resources management tools to support CAMS and reduce uncertainty so that decisions can be made defensibly and with more confidence.

2.2.3 Local Environment Agency Plans

The water resources strategies inform the local objectives set in river catchments by Local Environment Agency Plans (LEAPS). These plans identify, assess and prioritise local issues related to the Agency's objective of protecting and enhancing the environment while taking into account views of industry, local communities and government. The LEAPS process is currently under review.

2.3 Groundwater Resources Management and Modelling

Through its Abstraction Management Strategies, the Agency aims to secure the sustainable development of water resources. Where demands are high this requires a good understanding of how to achieve optimal development of local groundwater resources for abstraction uses, but without compromising the environmental water needs of wetlands, springs and rivers or to manage groundwater quality.

To achieve this optimal development of resources, a good understanding of the behaviour of

the groundwater system and its interaction with surface water environments must be achieved. This understanding is formulated as a quantitative conceptual model of the system and this model is the key to effective resource management.

To ensure protection of the environmental requirements or groundwater outflow requirements, abstractions and discharges are subject to licensing controls. Abstraction licences are determined by considering both local impacts and the acceptability of cumulative impacts from many abstractions on the regional groundwater/surface water system. In the past a variety of methods (or tools) have been used to assess these impacts. This variety reflects differing hydrological and hydrogeological conditions across England and Wales and the significance of abstraction impacts (Environment Agency, 1999a).

2.3.1 Regional Variation in Groundwater Resources

Groundwater is an important source of water for public supply. In England and Wales approximately 35% of the public water supplies are provided from groundwater (Downing, 1993). However, this usage is not spread evenly over this area. In parts of southern England 70% of supplies depend on groundwater sources, while in the north and west it may be as low as 10%.

This variation in the use of groundwater is a result of a number of other factors, including the high (and increasing) concentration of population in the south, lower rainfall in south east England and East Anglia and the unsuitability of land in the south for the development of surface water resources. The drier conditions in the east of England also give rise to demands on groundwater from agriculture, which often requires water in the summer when aquifers are under additional pressure from low recharge and increased domestic water consumption.

The physical properties of the aquifers have an additional impact on the resources. In the south and east where demand is highest, the main aquifer is the Chalk, which has low storage. Downing (1993) reported that in the Thames Valley the aquifer may only store the equivalent of twice the average annual recharge. In contrast, the Sherwood Sandstone may store 20 times the average annual recharge. The effective thickness of the Chalk aquifer is not great and seasonal fluctuations in water level may be very large, a factor which will affect the resources available for abstraction and surface water support.

The environmental demands on groundwater may also vary geographically. Downing (1993) pointed out that rivers in eastern and southern England often depend on the baseflow from a single aquifer, the Chalk. Changes in the groundwater flow regime may therefore have a greater influence on the river flow than in other areas where rivers may be supported by more than one aquifer. River flows in Chalk catchments are also more sensitive to changes in groundwater level due to the physical properties of the Chalk, which can cause large changes in baseflow from small rises or falls in groundwater level.

The importance given to the protection of wetlands has also increased in recent years and this places additional demands on resource management, particularly in stressed aquifers, for example the Chalk in East Anglia. In some parts of East Anglia up to 75% of the gross resource available may be allocated for environmental support.

These regional variations suggest that in order to effectively manage resources in a highly abstracted Chalk catchment, a more thorough understanding of the time-dependent flow behaviour of the system is required compared to a sandstone catchment with low demand. In the latter there is more tolerance for error. This in turn has implications for the tools used to

manage these resources.

2.3.2 Tools for Groundwater Resource Management

The tools used in the past for resource assessment have been reviewed as part of a recent Agency R&D project (Environment Agency, 1999a). These range from methods based on a simple comparison of steady state recharge against abstraction quantities, to complex distributed numerical groundwater models. The simpler methods require less time and effort to complete and have more limited data requirements than a distributed numerical model (Figure 2.1). However, they also over-simplify the actual flow system and this reduces the confidence in the assessment. Nevertheless where this is not critical, one of the quicker, simpler methods will be the appropriate tool.

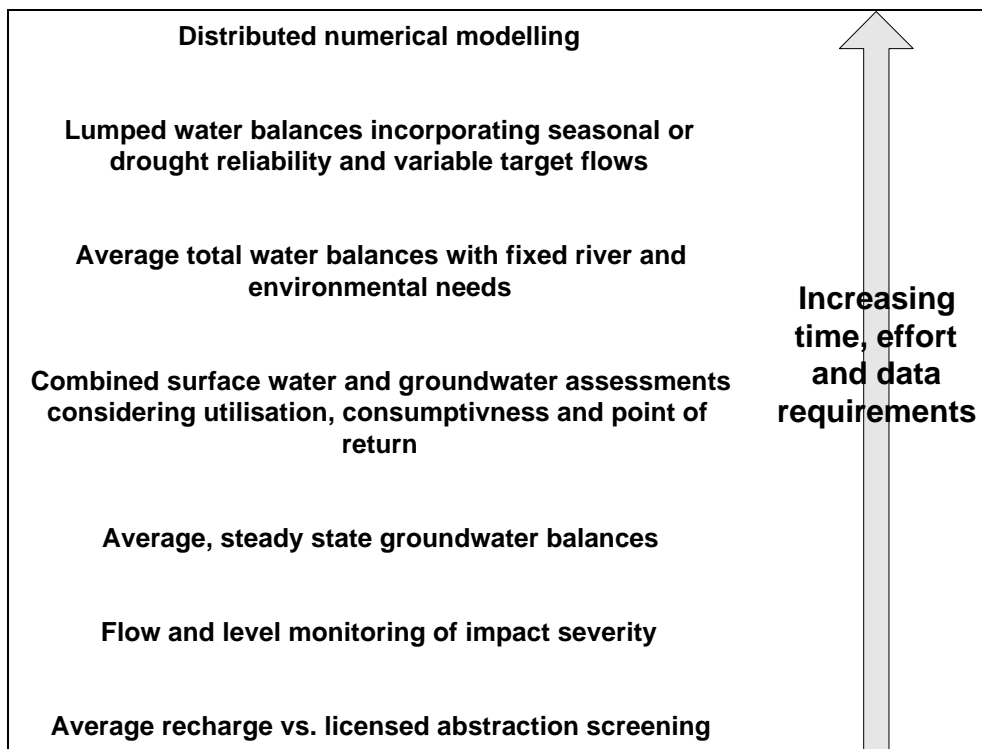


Figure 2.1 Groundwater Resource Assessment Tools (Environment Agency, 1999a)

What, then, are the benefits of using a distributed numerical model?

Firstly, there is considerable uncertainty inherent in dealing with groundwater systems since, unlike surface water systems, flows in to and out of aquifers cannot be directly measured, but in most cases can only be inferred indirectly from other measurements such as groundwater levels and river hydrographs. As more data are collected, they can be more readily incorporated into a numerical model compared to a simpler tool and therefore increase the confidence in the assessment.

Secondly, all aquifer systems vary spatially (e.g. aquifer properties, recharge) and temporally (e.g. recharge) and this affects the balance between abstraction and environmental needs. Many of the simpler tools do not take this spatial and temporal variation into account. For this

reason, distributed numerical models are often seen as the best way to provide an assessment of abstraction impacts and to understand the aquifer flow system and its interaction with rivers and wetlands. This is particularly the case in groundwater systems that are over-stretched due to abstraction demands or have particularly sensitive environmental water needs, for example parts of East Anglia.

A framework methodology for resource assessments has been developed in a recent Agency R&D project (Environment Agency, 1999a). The Available Resource Methodology (ARM) considers groundwater and surface water together and introduces a consideration of temporal variation into the assessment. ARM provides a framework within which various tools can be used for estimating, for example, water balances or acceptable river flows. Any of the tools shown in Figure 2.1 may be used as part of a water resources assessment within the ARM framework. A numerical model could be used to provide input to the methodology as equally as one of the simpler methods. ARM has since been incorporated into a Resource Assessment and Management Framework as part of an Agency Research and Development project (Project W6-066M).

Although a numerical model would potentially give the most accurate information for input to a resource assessment, it may not always be appropriate. Care must be taken that the effort involved in developing a numerical model will actually deliver a tool that will support better quality decision-making than one of the simpler methods. It may be that the effort required to develop a satisfactory model is not justified by the end result.

3 GROUNDWATER RESOURCES MODELLING

3.1 Introduction

This chapter deals with the definition of models in the context of water resources management and outlines the processes involved. The costs and potential benefits of modelling are also considered.

3.2 Definition of Groundwater Resources Modelling

In this document, groundwater modelling is taken to be the process which yields a quantitative understanding of a groundwater flow system in order to support decisions required in the management of groundwater resources. This does not, therefore, imply that a numerical model is always required or is the most appropriate tool. A quantitative conceptual model, a lumped model or an analytical model may be sufficient to underpin the decision.

3.3 The Groundwater Modelling Process

The scope of this project focuses on the whole modelling process leading to the development of a numerical model. This section briefly describes the main components of that process as shown on Figure 3.1.

The process consists of three main activities, collation of the available data, formulation of a conceptual model and construction of a numerical model. The important point to note from the diagram is that the process is an iterative one, more akin to a research project where a set of hypotheses are repeatedly tested against field data.

The initial stage in the development of a groundwater model requires the collation and evaluation of all available data. Data originates either from within the Agency (for example, from hydrometric monitoring and field investigations) or from external sources such as the British Geological Survey and the Meteorological Office.

Using this information, a quantitative understanding of the groundwater system is developed (the conceptual model). This stage is fundamental to any assessment of the water resources of a groundwater system regardless of whether a distributed numerical model is being developed or not. The processes identified in the conceptual model may then be represented mathematically.

Analytical models (e.g. Theis) solve the mathematical equations exactly, but require the conceptual model to be considerably simplified. For example, they generally assume an homogeneous aquifer of uniform thickness with an infinite extent (etc.). Numerical models use linear approximations to solve the mathematical equations at different points in time and space.

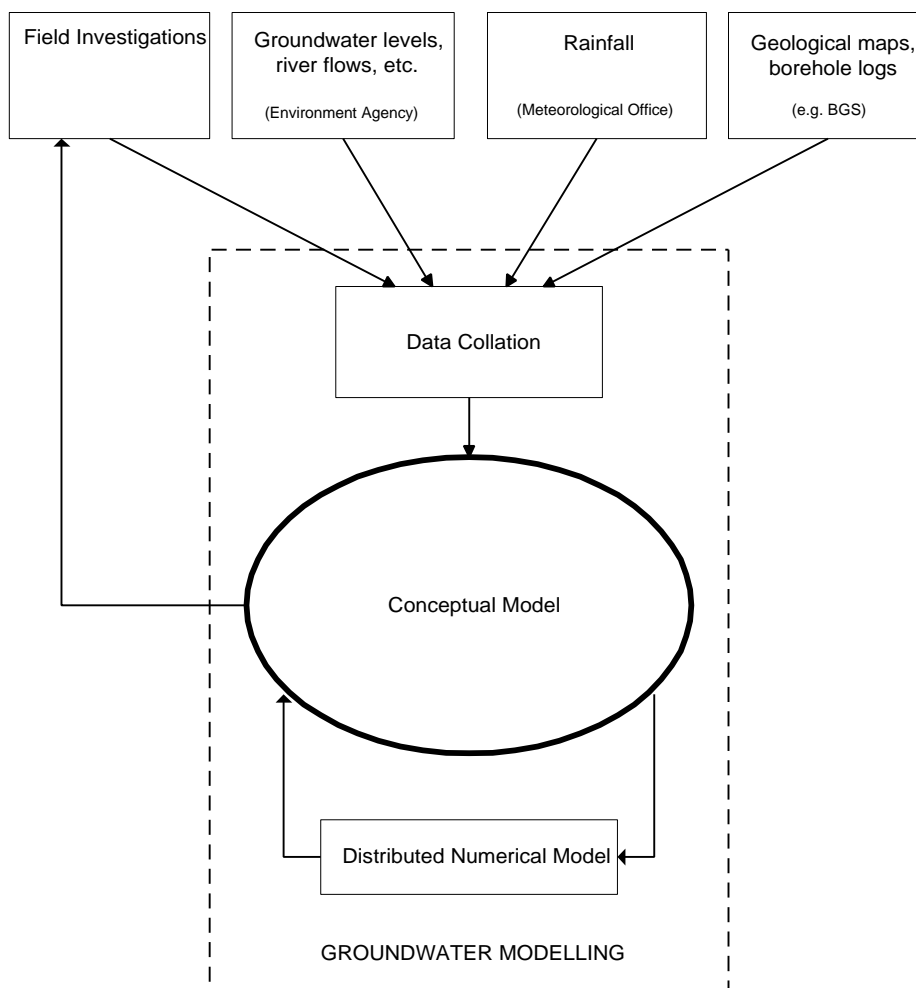


Figure 3.1 An overview of the groundwater modelling process

3.4 Costs and Benefits of Numerical Groundwater Modelling

3.4.1 Costs

The development of a numerical model requires the investment of considerably more time and money to complete than simpler methods. A conceptual model is required for any mathematical tool, but if a numerical model is selected, the underlying conceptual model will be of necessity more complex than that required to support a simpler tool. Recent regional modelling contracts have taken over two years to complete at a cost in excess of £200k. The final cost will depend on the size and the data requirements of a numerical model. Larger models and those requiring major hydrogeological investigations to support them, may well cost over £500k. Consequently, the role and cost-effectiveness of such tools within water resource management needs to be carefully considered.

3.4.2 Benefits

The benefits of developing conceptual and numerical models are

- Synthesis of the available data. The numerical model integrates temporally and spatially

variable data from a wide variety of sources into a single representation (the model).

- Improving the conceptual and quantitative understanding of the study area. A numerical model simulates the processes identified in the conceptual model quantitatively. Comparison of the simulation with measured historical behaviour can challenge this understanding and help us focus on where it is deficient.
- Predicting the future behaviour of an aquifer system. This application of a numerical model can be subdivided into three groups: forecasting, planning and control models (Barker, et al, 1994).
 - *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 (Chichester model, Southern Region and Southern Limestone model, Anglian Region).
 - *Option appraisal* models are used to support decisions requiring a choice between several options. These may be, for example, the siting of river support boreholes or the modification of abstraction licences to alleviate low river flows. Examples from the UK include West Midlands Trias (Midlands Region) and Kennet Valley (Thames Region).
 - *Control* models are actively used in aquifer management where a particular action depends on recent updated data on the system behaviour prior to the decision being made. The only example of this type of use in this country is the Lincolnshire Chalk model (Anglian Region) which is used to control abstraction rates to prevent the intrusion of saline water.
- Documentation of the conceptual understanding of a groundwater system will be in one place.
- Regional models act as a foundation for local scale modelling (for example, impact on wetlands and contaminant transport models). A large regional model will provide a framework within which local scale models can be constructed ensuring consistent groundwater flow behaviour at the different scales.
- Numerical models take into account the spatial variation in aquifer parameters and recharge and can therefore simulate variations across an area that a simpler lumped parameter type model cannot.
- Planning monitoring networks. A conceptual model will indicate areas where additional data is required to provide a better understanding of the groundwater system behaviour. If a numerical model is completed, it may not adequately simulate the behaviour of the aquifer, particularly when the aquifer is under stress (e.g. drought conditions) and this can indicate further areas where additional monitoring is required.
- A numerical model provides a means of analysing the resources of a large area rather than a piecemeal approach of considering resources in individual catchments in isolation.
- A numerical model can provide an agreed common technical basis for groundwater resources management for use by both the Agency and groundwater abstractors.
- Numerical models can provide improved effectiveness in the determination of abstraction licence applications. A study undertaken in Anglian Region suggested that there were significant financial benefits in the form of reduced costs due to more effective and less

contentious resource allocation (Environment Agency, 1999b).

- Numerical models can provide a greater certainty with regard to resource availability with the result that the abstraction licence review period could be extended, resulting in financial savings.

4 AGENCY'S EXPERIENCE OF DISTRIBUTED GROUNDWATER MODELLING

4.1 Introduction

This chapter deals with the background to and the outcomes from an internal survey of existing distributed groundwater flow models undertaken in 1998. In addition it also deals with aspects of local scale modelling, which arose as a result of the survey and subsequent discussions with Regional staff.

4.2 Survey and Review of Existing Regional Models

4.2.1 Background to the Survey

During the review of the models held by the Agency, it was important to appreciate that numerical modelling as a tool for understanding and managing groundwater systems dates back to the early 1970s. Over this 30-year period modelling techniques, best practice standards, model codes and computer hardware have changed significantly.

In the mid 1970s the use of numerical techniques to simulate groundwater flow was still largely a research activity. In the United Kingdom, the Civil Engineering Department at the University of Birmingham took a particular lead in developing computer codes at this time and some of these were used in groundwater models developed by the Water Authorities. This early involvement by the University of Birmingham is highlighted by the fact that nearly half the regional flow models currently held by the Agency were originally developed at Birmingham.

From the late 1980s numerical codes, both public domain and proprietary, became more widely available. A significant influence in this was the development of the United States Geological Survey (USGS) public domain code MODFLOW which encouraged the wider use of numerical modelling. Together with these code developments, computer power was also increasing dramatically and codes previously run on mainframes could be migrated to personal computers, further widening the availability of modelling as a hydrogeological tool. Towards the end of the 1980s, in addition to the well-established team at the University of Birmingham, the capability to undertake groundwater modelling was also being offered by a number of consulting organisations.

This expansion of modelling emphasised the need to develop an accepted development methodology, particularly in the United States where studies undertaken on behalf of US Environmental Protection Agency (EPA) highlighted issues of quality control in model development (de Heidje, 1992). These issues were taken up by the American Society for Testing and Materials (ASTM) which published a series of guidance notes on groundwater modelling in the early 1990s (ASTM, 1999).

4.2.2 Objectives of the Survey

For the purposes of the survey, only regional time-variant groundwater flow models fully or partly financed by the Environment Agency, or its predecessor organisations were considered.

The overall objective of the Survey was to review the present situation regarding these regional flow models and provide feedback into a modelling framework for the Agency. Specific objectives were:

- To establish the number of regional groundwater/catchment models that are currently available and in use nationally, and to establish the present model coverage.
- To briefly document details of the models
- To summarise aspects of the modelling contracts and any problems encountered.
- To document the status of the models and their use since project completion
- To make recommendations on future modelling practice.

4.2.3 Recommendations from the Survey

The survey showed that in July 1998 the Agency held 34 completed models covering approximately 30% of the major aquifers in England and Wales. Figure 4.1 shows the locations of these models.

The survey confirmed the concerns raised at the beginning of this project from the absence of a long-term nationally co-ordinated programme for modelling and the shortcomings of recent models (1990-95) produced by some consultants.

A number of recommendations were made in the survey to ensure that, in the future, distributed groundwater models are fully and effectively utilised in water resources management. These are briefly noted below.

Model use.

- Updating and maintenance of models should be planned into each Region's Modelling Strategy so that sufficient personnel and time resources are allocated to this task

Procurement.

- Tenders should be assessed on the basis of at least an equal evaluation of both quality and cost. An unrealistically low bid may not allow for sufficient time to formulate a clear understanding of an aquifer system or for a proper documentation of the results.

Project Specification.

- A standard template project brief should be produced which details the objective of the modelling project and the purpose, approach and output for each task within the project.
- The standard template should also be used for modelling projects which are carried out in-house to ensure they are completed to the same standard as external contracts.

Project Management.

- Sufficient Agency staff time must be allocated at the planning stage for both project management and technical input to the project to ensure adequate supervision of the modelling team.

Project Team.

- Representation from appropriate external bodies should be included as part of the project steering group to encourage a wider acceptance of the model.
- Where a model is being developed adjacent to another Region, it is essential that the project team includes a representative from the adjacent Region to ensure a consistent conceptual understanding and representation of the boundary.
- An independent expert, who should be part of the Agency project management team, should review all procedures and results from a modelling project.

Staffing.

- The Agency must ensure that there are sufficient experienced groundwater modellers available at a Regional level to carry out its modelling programme.
- A forum for groundwater modelling staff should be set up to enable them to share experiences and make recommendations to the Groundwater Resources Group.

Documentation.

- The requirements for reporting and documentation should be clearly stated in the specifications and identified as separate tasks.
- Documentation of in-house models should be to the same standard as that required for externally developed models.

Boundary conditions.

- Numerical model boundary conditions should be located far enough from the area of interest so as not to affect the model results.

Databases.

- It is recommended that the use of the Agency databases in modelling projects is investigated with a view to improving ease of access to the data and its integrity.

As a consequence of this R&D project and the issues it has highlighted, shortcomings in modelling practice have been recognised within the Agency. As a direct result of this project and the work of the senior modeller at the National Groundwater & Contaminated Land Centre alongside Regional modelling staff, a number of the recommendations are now being implemented.

4.3 Local Scale Modelling

Local-scale models are generally developed as part of the investigation of contaminant transport issues, including the definition of source protection zones (SPZ), or the management of low flow rivers. A detailed assessment of local-scale flow and/or contaminant transport models was not part of this project. However, a local-scale model must be consistent with the flow pattern and conceptual understanding of the catchment(s) within which it falls. If the local model does not take into account the regional context it is likely to produce misleading results.

Some early SPZ models produced conflicting flow patterns because they ignored the regional flow pattern shown on the existing regional flow model. In this situation the boundary conditions specified on the local model may be inappropriate. In other cases adjacent SPZ

models have had inconsistent flows at their adjoining boundaries due to the lack of a regional model as a reference framework. There are tangible benefits from good communication between those using water resources and water quality models.

For water quality studies it is important to recognise that any transport modelling depends on a good understanding of the aquifer flow system. If this understanding is lacking then any conclusions regarding contaminant transport will be unreliable. Zheng and Bennett (1995) state "... the first task in transport simulation is the development of a reasonable flow model, at the appropriate scale, on the basis of existing hydrogeologic data and interpretations. It should be stressed that the velocity distribution as determined by the flow model is by far the most important factor in controlling solute transport under most circumstances." Even though a good flow model does not guarantee an accurate flow velocity distribution, a knowledge of the documented conceptual understanding and the results of any regional flow model would be valuable to water quality staff developing transport models.

One method to ensure a consistent flow pattern at all scales is to use the technique of Telescopic Mesh Refinement (TMR). In this method the local model is defined as a sub-region of a larger (regional) model. However this requires that a regional model framework is already in place. An example of projects where this has been done are the Wylde catchment in Hampshire, modelled as a sub-region within the regional Upper Hampshire-Avon model, and the Helpston contaminant transport model, developed as a sub-region of the Southern Limestone model in Anglian Region.

It is also worth pointing out that the investigation and modelling of groundwater pollution incidents can provide useful information on the local flow regime that can be fed back into the conceptual model of the regional model. This has occurred during the investigations and modelling at Helpston.

Several recommendations can be made in the light of the above issues.

- When local-scale models are to be developed, the Agency staff involved should consult reports from and staff involved with regional modelling to ensure that the local-scale model reflects the flow pattern and conceptual understanding of any regional model in which it falls. The boundary conditions and assumptions of local-scale models are most reliably determined from the flow pattern of regional-scale models.
- In order to ensure consistent flows at a regional and local scale, the conceptual understanding of the flows in the major aquifers needs to be documented and available to the Water Quality staff within the Agency.
- The requirements of water quality modelling and resource modelling should be coordinated so that the transport models are based on the latest understanding of the aquifer flow behaviour.
- Water resource and water quality staff should keep each other informed of the results of modelling projects or pollution incidents. This could be done during a project or at post project seminars given to the relevant staff.
- The use of Telescopic Mesh Refinement (TMR) for defining a local model as a subset of a large regional model should be investigated further.

4.4 Essential Mechanisms and Software Needs

4.4.1 Essential Aquifer Mechanisms

There are a number of important mechanisms within groundwater systems which are not yet fully understood. These mechanisms are often critical in determining the effect groundwater abstraction has on the environment. A number of these are identified below. This list will be used to direct Agency R&D projects in support of groundwater modelling software development.

River/aquifer interactions. This area is the subject of current research programmes that will be investigating these mechanisms (e.g. CHASM and LOCAR).

Wetlands. There is considerable uncertainty concerning how groundwater interacts with the variety of wetland types that exist in England and Wales. Because of the potential complexity of the relationship it may be that this interaction can only be modelled with detailed local models. However, regional time-variant models must take into account the inflows and outflows of local wetland models if resources are to be assessed accurately.

Mechanisms operating in wetland sites need to be studied using relatively dense monitoring networks to establish groundwater and surface water flows. Site investigations of this nature will probably be undertaken as one of the requirements of other initiatives, such as the Habitats Directive.

Drift. Drift deposits significantly complicate the modelling of groundwater systems due to the variability of the sediments within them. These sediments may act to delay recharge to the aquifer or they can act to route precipitation away to recharge the aquifer elsewhere.

Recharge. This is the subject of an ongoing research project that is aimed at developing a consistent methodology for estimating recharge (Section 1.5). Recharge is the largest part of the water balance and the input to which groundwater models are most sensitive. It is therefore critical that mechanisms in a catchment are recognised and quantities accurately estimated. The inherent problem with recharge is that it cannot be measured, only estimated from calculations using areal rainfall, evapotranspiration, soil and crop parameters, etc.

4.4.2 Software Development

It is important that the Agency has access to numerical codes that are able to represent the crucial hydrogeological mechanisms operating within British aquifers. The Agency has chosen the public domain code USGS MODFLOW as the preferred code for model development within the Agency until 2002 (NOTE. This does not necessarily preclude the use of other codes provided this can be justified). It is recommended that the Agency encourages and funds the development of additional code packages to enhance MODFLOW and improve its applicability to conditions present in the UK. There are also enhancements to MODFLOW published in scientific journals and these should be evaluated where they might be applicable to conditions in England and Wales.

Recently, the first stage to develop code to simulate the variation of hydraulic conductivity with saturated depth in the chalk was completed (Environment Agency, 1999c). Further development is planned in 2000/01. This project has also highlighted other issues with the MODFLOW code that have proved beneficial to Agency modellers.

Other code developments may be required as research into the aquifer mechanisms noted in Section 4.4.1 produce results. Code developments are likely to be promoted by the experience of Agency modelling teams when developing distributed regional groundwater models. An internal Agency group composed of modelling practitioners would provide a valuable forum for discussing such developments and promoting new R&D projects focussed on the Agency's requirements.

Code development must be completed and rigorously tested before it is needed, otherwise projects may be delayed, or forced to use different, less satisfactory, methods for representing aquifer mechanisms.

Integrated Surface/Groundwater Models

Integrated catchment models attempt to combine the simulation of surface water flows with groundwater flow simulation. For example, the SHE (System Hydrologique European) family of model codes are designed to simulate the complete land-based hydrological cycle, including that of unsaturated groundwater flow. The strengths and limitations of this type of model need to be investigated further.

A few groundwater model codes have been modified to include surface water components, for example the Intergrated Catchment Management Model developed by Mott MacDonald.

A discussion of integrated surface/groundwater models can be found in a scoping study report from the Institute of Hydrology (Naden, et al, 1996).

New Model Codes

There is also the potential to develop new codes based on the latest software development techniques (e.g. Object Orientated Code). The Agency should take an interest in such developments. However, it is recommended that this is done on the condition that these new codes will be made public domain code, rather than proprietary. The advantage of the code being public domain is that it can be investigated and tested by a large number of experts. This can increase the confidence in the code by making all its features, including the negative ones, public knowledge. Models used to back up regulatory decisions which use such a code may therefore have some advantage over models developed using a proprietary code.

5 GUIDANCE ON GROUNDWATER MODELLING

The process of developing a groundwater model requires an iterative multi-disciplinary approach within which there is a continual testing of the conceptual understanding of an aquifer's flow behaviour and of the numerical model against field data.

To aid a systematic approach to developing a model, the tasks required within the process can be outlined in a generic fashion applicable to any modelling project. This systematic approach helps to ensure that important tasks are completed and will aid in the project management by setting targets to be attained.

The generic procedure for developing a numerical groundwater model is widely recognised and published in textbooks on groundwater modelling (for example, Anderson & Woessner, 1992) and as a series of ASTM (American Society for Testing and Materials) standard guides dating back to 1993 (ASTM, 1999). This generic guidance can be applied to flow modelling or contaminant transport modelling.

This chapter provides a brief summary of modelling guidelines produced in other countries and goes on to describe the Agency's methodology for developing time-variant resource models and the available guidance to aid staff in this process.

5.1 International Guidance

A number of guidelines for groundwater modelling have been written, or are currently under development in other parts of the world. These are briefly reviewed below.

5.1.1 USA

The United States has a long and well documented record of groundwater flow modelling. During the late 1980s and early 1990s issues regarding the quality control of numerical models and experiences of modelling practitioners were documented in studies undertaken on behalf of the US EPA, some of which were reviewed as part of an NRA R&D project (Barker et al., 1995). The information from these studies suggested that there was a need for groundwater modelling standards. The American Society for Testing and Materials (ASTM) was funded by, among others, the US EPA and the USGS, in order to develop these standards.

There has been some controversy over the use of the word 'standard'. However, the authors' intention has been that these documents are for guidance only and do not represent procedures to be followed blindly. Professional judgement is always required in applying the advice contained in these 'standards'.

The ASTM standard guides on modelling (ASTM, 1999) cover topics such as:

- The main steps in developing and applying a groundwater model (D5447-93)
- Testing a model against historical data (D5490-93 and D5981--96)
- Definition of boundary conditions (D5609-94)
- Defining the initial conditions (D5718-95)
- Documentation (D5719-95)

A number of regulatory bodies within the USA have produced their own guidelines and recommended procedures. However they tend to deal with contaminant transport, rather than time-variant flow models. For example the California EPA (1995) has produced guidelines for the application of groundwater and contaminant transport models to the characterisation of hazardous waste sites.

5.1.2 The Netherlands

A Handbook of Good Modelling Practice (GMP) has recently been issued in Holland (STOWA, 1999). The Handbook forms one output of a project to develop a standard framework for the use of models in the control of water in Holland. Other activities of this project included completing an inventory of modelling tools available (already completed) and developing links between different models. The Handbook is designed as a resource to support modellers and project managers and is not intended to be prescriptive. The main objectives of the Handbook are stated to be:

- To develop guidelines for model use which can be supported by all parties involved in water management
- To initiate more careful use of water control models
- To improve the reproducibility and transferability of model studies

The Handbook consists of two sections.

Section 1 describes each step in a (generic) modelling process which covers all types of models involved in water control. The Handbook suggests that these steps can be used as a checklist when developing a model or undertaking a QA check to ensure that the correct steps have been included.

Section 2 gives an overview of pitfalls and sensitivities of models. Thirteen different application domains are reviewed, from groundwater quality models to surface water resources models, ecological models and economic models.

5.1.3 Germany

In 1999 the Hydrogeology Group of the German Geological Society (FH-DGG) published the document 'Hydrogeological Models. Guidelines for Clients, Consultants and Regulatory Officers'. These guidelines were the product of a committee formed following a workshop in 1995 entitled 'Hydrogeological models as a foundation for numerical groundwater models'. The guidelines have been presented at workshops in Munich (October 1999) and Cottbus (March 2000).

The guidelines focus on the 'hydrogeological model' which is synonymous with the term conceptual model as used in the UK. Numerical models are viewed as tools for testing and applying the hydrogeological model.

The guidelines discuss the development of the hydrogeological model and cover the following topics:

- Defining the objectives of the model, outputs required, definition of the area of investigation and the choice and commissioning of a consultant to undertake the work. The amount of work required prior to commissioning a project is emphasised, as is the need to clearly define objectives. The importance of choosing a suitable consultant is

noted, as is the advice that this choice should not be based on the cheapest price.

- Data requirements, evaluation of the data and documentation. There is some emphasis on separate reporting of the hydrogeological model and its supporting data from any mathematical modelling.
- Development of the hydrogeological model and requirements for a numerical model.
- Testing and application of the hydrogeological model. Model testing using field data and mathematical models is discussed. The guidelines emphasise that this testing is of the aquifer behaviour rather than against individual parameters.
- Quality assurance (QA). The procedure and basic steps necessary to develop and apply a hydrogeological model are discussed. The importance of presenting reports at intervals in the process is noted as an important part of the QA procedure.

There are parallels in these guidelines to the discussions within the Agency.

5.1.4 Australia

A project is currently underway to develop guidelines for modelling studies on behalf of the MDBC, the body responsible for the management of water resources in the Murray Darling Basin, eastern Australia. The project was initiated because of concerns that modelling standards in use were not appropriate to the specific situation in the Murray Darling Basin.

The objectives of the project are:

- To develop guidelines on methodologies and standards for groundwater model calibration which will be applied to new modelling studies and reviews of existing models (flow models only).
- To seek agreement for the approach and content of the guidelines from model developers and users at the federal, state and private industry level.

It is intended that the guidelines develop performance indicators through which the quality of the calibration can be assessed.

5.2 Environment Agency Guidelines

The basic steps required when developing a numerical model are well recognised and all the guidelines and methodologies mentioned above follow the same general pattern. The Environment Agency's methodology aims to address the specific requirements of groundwater modelling for water resources assessments (Section 5.2.1).

This methodology is incorporated into a set of Guidance Notes which have been produced as an output of this R&D project, based on the experience of Agency staff. These Guidance Notes also include a template project brief (terms of reference) for groundwater modelling projects. The content and philosophy behind these Guidance Notes are discussed in Section 5.2.3.

The data requirements for a modelling project are crucial. Two sources of data that are under the control of the Agency, hydrometric monitoring and field investigations, are discussed in Section 5.2.2.

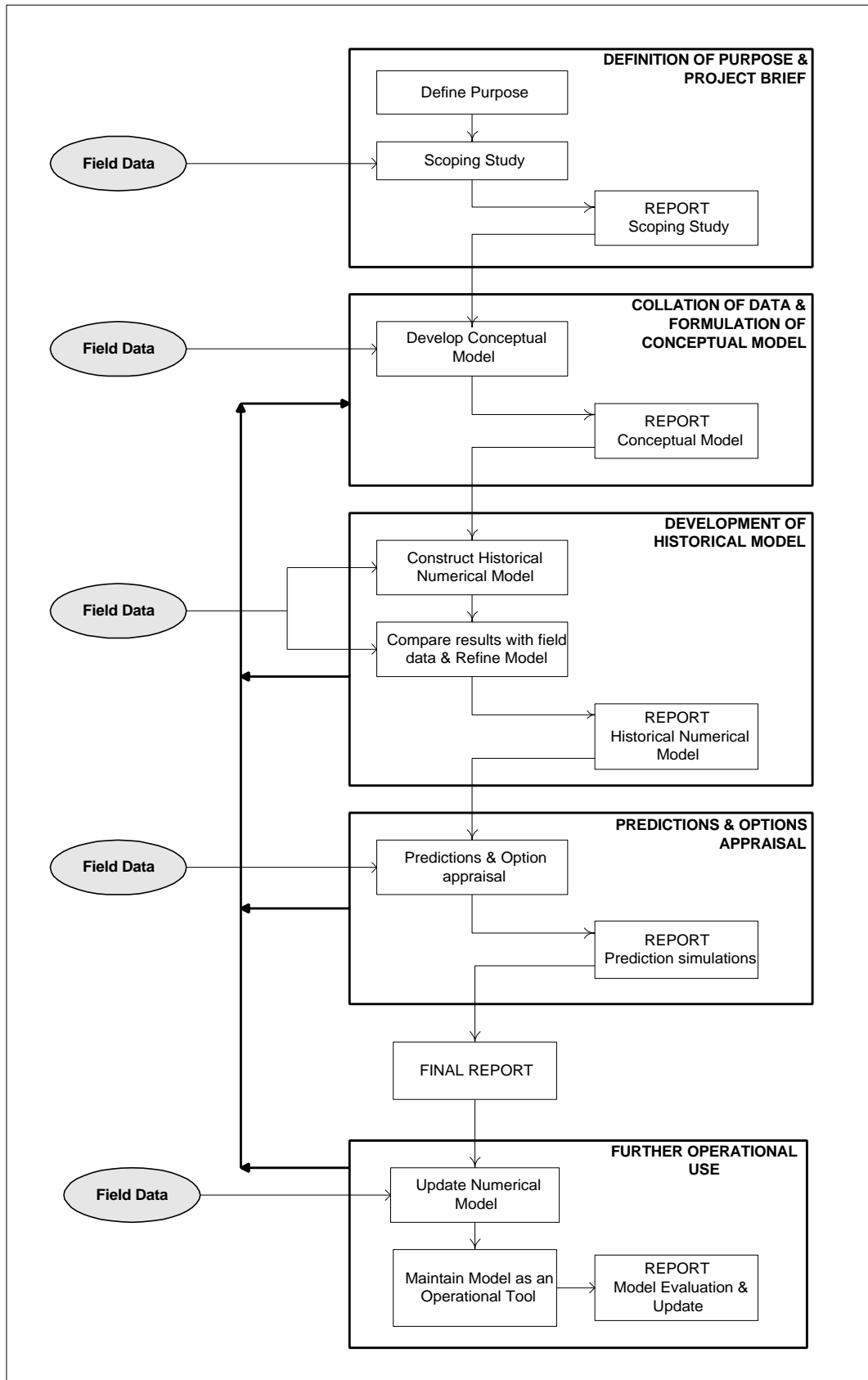


Figure 5.1 Modelling methodology for Agency projects

5.2.1 Modelling Methodology

A summary of the Agency's modelling methodology is shown on Figure 5.1. Each of the five main activities are discussed in more detail below.

Documentation of each stage of this methodology is emphasised as it supports QA/QC and ensures a clear 'audit trail'. This is particularly important in a regulatory 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. The Agency staff updating the model may not have had any involvement in the original development and the documentation is therefore critical in allowing the model to be understood and used at a later date.

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 aquifer are an important reference document, which can provide support to operational staff within the Agency. For example, they can be used to back up licensing decisions or to provide a conceptual framework against which land and groundwater contamination issues can be considered.

Definition of purpose and scope of work

A clearly defined purpose for a modelling study will focus the project on the questions that need to be answered and the resources and effort likely to be required. To aid this a scoping study is recommended for most projects. Among other objectives, this study should define the scope of work by

- presenting clear objectives for the project
- defining the regulatory and corporate drivers for the project (CAMS, LEAPS, ALF, etc.)
- listing available data and recommending additional work where necessary
- indicating the geographical extent of the study area
- providing budgets and timescale
- defining specifications for the modelling phase

It may prove advantageous to undertake the scoping study well in advance of an intended project start in order to identify any need for long-term monitoring data.

Collation of data and formulation of the conceptual model

This task is the key component in the development of a numerical model and will probably take up most of the project time. This applies at any scale of study from a local abstraction licensing issue to a regional groundwater resource assessment. In all cases the conceptual understanding is the key to making the correct management decision. The tasks leading to the development of the conceptual model are given in more detail in R&D Report W213 (EA, *In prep*).

The crucial processes operating in the aquifer must be identified in the conceptual model. In his paper on Groundwater at Risk, Rushton (1998) states: "Aquifer systems are so complex that it is not possible to study every detail. This leads to the question of what needs to be to be

included in an aquifer study and what can be ignored. For most aquifer systems there are a small number of crucial factors which must be examined in detail; if only one of these is ignored the conclusions may be seriously in error.”

During the development of the conceptual model, the understanding of the groundwater system will be continually tested using field data and quantitative methods such as analytical models and water balances. This testing may identify gaps in the conceptual understanding that cannot be resolved without recourse to additional data collection from field investigations.

Development of historical numerical model

The processes identified in the conceptual model are represented mathematically using the selected model code. The results from this mathematical representation are then tested against observed data. This is referred to here as model ‘refinement’ rather than ‘calibration’. This is because in the United Kingdom, considerably more thought and effort is expended in producing a model which best represents the long-term, seasonal and short term flow behaviour of the spatially distributed groundwater and surface water system than merely the best fit implied by the term ‘calibration’.

Where the model output differs from the observed data the conceptual and the numerical model are revised. It is important that all modifications made to the model during refinement, including reasons and outcomes, are fully reported. This should include those modifications that are rejected. The results should be reported as a stand-alone document.

Prediction and option appraisal

Predictive runs can be carried out once the historical model has been sufficiently refined so as to adequately represent the past behaviour of the aquifer. The purpose of these model runs will have been defined in the original objectives for the model, such as considering the various options available to alleviate low river flows.

Further operational use

Regional groundwater models can cost between £100,000 and £300,000 to develop over two years, or more. They therefore constitute a valuable capital asset, if they are kept up to date. Operational use of a model may be one of the objectives of a modelling project, but it may also become a necessity at a later date due to some change in the requirement of the aquifer management.

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 aquifer as described by the new data. This report should provide documentary evidence that the model is still acceptable and will back up regulatory decisions based on the model.

5.2.2 Data Collection

Although data acquisition is generally not considered to be part of a modelling project, Discharge and abstraction data, hydrometric monitoring and site investigations are mentioned here as they involve expenditure by the Agency and require some forward planning.

Discharge/abstraction data

The quantification of abstractions from rivers and aquifers and discharges to rivers is an important component in the understanding of a groundwater system. Unfortunately, they are not always measured and where they are, there may be gaps in the data. A current Agency R&D project (W6-042) is investigating methods with which to estimate this missing data.

In the case of small groundwater sources, where abstraction returns are not required, the sources are often assumed to abstract at their full licensed rate for resource estimation purposes. This is probably unlikely and adds additional uncertainty to the quantification of the flows in the system.

Hydrometric Monitoring

Hydrometric monitoring is undertaken routinely as part of the Agency's general duty to monitor the condition of the environment and forms one of the basic inputs to a groundwater resource assessment. It includes river gauging, spring flow measurements, recording the rates of abstraction from groundwater and surface waters and the recording of groundwater levels.

The need for planning the collection of monitoring data was recognised by Barker et al. (1994) in their review of groundwater modelling and modelling methodology. One of the recommendations of the review was that the NRA needed to take a long term strategic view of the need to collect data for modelling.

For use with a time-variant numerical groundwater flow model, river flow and water level data need to be collected over a long period of time. The longer the record against which the numerical model is tested, the more confidence there will be in the model. It follows that the numerical model will only be as good as the data on which it is based and if, for example, there is no record of aquifer behaviour during drought conditions, the model should not be expected to simulate such conditions with any confidence.

Agency models are generally set up with 25 to 30 years of historical data with which to test and build up confidence in the model. Some sandstone models have used initial conditions set 20 to 30 years earlier to ensure that the initial conditions do not influence the period of interest.

It is important, therefore, to ensure that the Agency has a regional strategy for hydrometric monitoring so that some of the needs of groundwater modelling can be anticipated. This strategy should also include surface water monitoring such as spring flows.

The importance of the scoping study in highlighting data shortages must be reiterated here. An early indication of additional data requirements may allow several years worth of data to be collected prior to modelling proper beginning.

Field Investigations

Field investigation may be initiated specifically as a result of data deficiencies or problems identified during the modelling study.

In the process of developing the conceptual model it may become apparent that there is a lack of data which prevents an adequate understanding being developed. As the numerical model integrates such a large amount of spatially variable data, some problems may not become apparent until the development of the numerical model has started. In both cases it will be

necessary to collect additional data through field investigations which may include installing monitoring wells, designing and carrying out pumping tests, assessing drift deposits, gauging streams and spring flows, monitoring of water levels and hydrochemistry and geological mapping. Consequently, a modelling contract will often not proceed in a linear fashion from start to finish, but will have to run through several feedback loops resulting in the project extending beyond the initial estimate.

5.2.3 Agency Guidance Notes

As a response to the issues raised during the survey of groundwater models and subsequent discussions with Agency staff, it was decided to write a set of Guidance Notes covering the conceptual and numerical modelling stages of regional groundwater resource assessments.

The Guidance Notes are specifically directed towards the development of large time-variant models used to aid in the management of groundwater resources. They are intended primarily for Agency staff involved in modelling projects, both specialist modellers and project managers. The objective is to provide assistance in the development of these models to a common standard across the Agency.

The Guidance Notes aim to meet this objective by :

1. Distilling the Agency's experience with the conceptual and numerical modelling components of groundwater resources studies into a working document
2. Setting out the principles which guide the Agency's approach to conceptual and numerical modelling
3. Raising awareness and understanding of the Agency's approach and providing a focus for discussion within the Agency
4. Making the tendering process easier for both Agency staff and contractors
5. Providing a working document which can be updated as the Agency's experience grows
6. Being one of the tools to help build the Agency's community of groundwater modellers by sharing their experience and contributing to and updating the Guidance Notes
7. Providing a template project brief for groundwater resource modelling projects with details of the purpose, approach and outputs for each task.

The Guidance Notes are intended to be modified regularly, based on the experience of the Agency as models continue to be developed. They will be produced in a format to allow regular updating. It is suggested that the maintenance of the Guidance Notes is co-ordinated through a forum made up of representatives of the Agency's groundwater modelling staff.

Initially the Guidance Notes will be issued internally for evaluation by Agency staff, after which they will be released to the public domain.

6 AGENCY MODELLING PROGRAMME

6.1 Introduction

The need for a national framework within which regional groundwater flow modelling could be undertaken was one of the objectives of the R&D project. In the past, model development was not co-ordinated across England and Wales and there was no overview of how model development was proceeding.

Outlining a programme to develop distributed groundwater models over the major aquifers of England and Wales would only partially develop this framework because the production of such models would not be appropriate, or technically possible, for all these aquifers. The framework recommends, therefore, that the primary aim should be to produce a well-documented conceptual understanding for all the major aquifers. Where appropriate this conceptual understanding will be developed into a distributed numerical model.

This framework outlines a proposed modelling programme, the details of which will be finalised within each Region's modelling strategy or business plan.

6.2 Proposed Modelling Programme

The proposed modelling programme is laid out in the following section. It is intended that the programme will:

- provide a planning tool for managing future groundwater modelling projects. It will lay out a programme for both conceptual and numerical modelling studies over the next 10 to 15 years, as currently proposed by each Region. The programme will indicate the number of projects and their anticipated duration, but excluding time that may be necessary for additional site investigations (which cannot be estimated at this stage). This will enable water resource managers to view future demands on Agency personnel and financial resources.
- provide a national framework within which detailed regional plans can be developed and co-ordinated. This should ensure that the development of new models takes into account existing models
- increase awareness of the gaps in understanding of some aquifers and ensure that all the regionally important aquifers are covered by well documented conceptual models. This will improve the information base and understanding required to provide a robust and defensible abstraction licensing policy.
- provide a means of planning future investment in field investigations and hydrometric monitoring. It should therefore encourage the Agency to be proactive in the collection of data required for model refinement.
- promote models at an appropriate scale defined, where possible, by static physical boundaries in order to minimise water balance errors introduced by assuming hydrogeological boundaries, such as groundwater divides and faults, are no-flow boundaries.
- provide a framework of time-variant models within which detailed catchment scale or local contaminant transport models can be developed. This will ensure a consistent

modelled flow pattern at all scales.

- facilitate the co-ordination of effort in groundwater investigations and modelling across Agency functions and with interested parties. In particular, water companies involved in developing groundwater models will be able view the Agency's priorities in regard to their own strategy which would encourage collaborative action and the development of a consistent and agreed set of models which could reduce the likelihood of conflict at public inquiries.

6.2.1 Approach to Defining the Modelling Programme

For this National Framework, the major aquifers have been divided up into Groundwater Resource Investigation Areas. The Investigation Areas define an area of aquifer within which certain identified issues need to be addressed and which is bounded by physical and/or hydrogeological boundaries. It should be emphasised that the definition of these investigation areas does not imply that the development of a numerical model is the final end product of a particular study, nor are they intended to show the location of the boundaries of a potential numerical model.

A scoping study will be undertaken for each Investigation Area and this will define the area to be included in a detailed study leading to the formulation of a conceptual model. A conceptual model will be developed for all the Investigation Areas identified, however this may not necessarily be carried forward into a numerical representation of the aquifer. In some cases the conceptual modelling may indicate that the development of a numerical model is not appropriate. However, the conceptual model can still be used to support other mathematical tools (such as lumped or analytical models) for solving resource, licensing or environmental problems.

This study area for the conceptual model may be larger than the original Investigation Area depending on the results of the scoping study. The boundaries of any numerical model will only be defined following the formulation of a conceptual model.

The provisional Investigation Areas, defined in this document, will be refined and developed further in Regional Strategies.

6.2.2 Proposed Groundwater Resource Investigation Areas

The Groundwater Resource Investigation Areas proposed in this report cover all the major aquifers in England and Wales, shown on Figure 6.1. In addition some regionally important minor aquifers have been included from North-east England and Wales.

The Groundwater Resource Investigation Areas are discussed below under the heading of the aquifer in which they are located. Maps showing the details of the location of the Groundwater Resource Investigation Areas can be found in Appendix A, together with indicative timescales for the work to be undertaken.

It is important to recognise that these programmes will be altered subject to each Region completing its own Modelling Strategy, or Business Plan, and subject to priority planning within each Region. They are shown here to illustrate the potential workload required and should not be taken to imply that numerical models will be developed, or that there are any deadlines by which to complete any modelling.

Chalk

The Groundwater Resource Investigation Areas cover the Chalk outcrop and the area where it is concealed beneath younger deposits. The locations of the Investigation Areas are shown on Figure A1.1. The Spilsby Sandstone and Sandringham Sands are included within Chalk Investigation Areas because an effective water balance can only be achieved by including both the Chalk and sandstone aquifers.

A total of twenty-five Groundwater Resource Investigation Areas have been defined, of which nine already have operational groundwater flow models (Figure A1.1). The provisional programme for developing models in these Investigation Areas is shown on Figure A1.2.

Lower Greensand

The locations of the proposed Investigation Areas are shown on Figure A2.1. Seven areas have been defined. An operational model is already available for one Area in a combined Chalk and Greensand model.

The proposed development programme is shown on Figure A2.2.

Jurassic Limestones

Groundwater Resource Investigation Areas proposed for these aquifers cover the Corallian Limestones in Yorkshire, the Great and Inferior Oolites of Lincolnshire and the Oolites in the Cotswolds. Detailed locations are shown on Figure A3.1.

Seven Investigation Areas are proposed, of which four already have groundwater models developed. The Southern and Northern Lincolnshire Limestone Areas may be combined at some future date to form a single Lincolnshire Limestone model. The outline programme is shown on Table A3.2.

Permo-Triassic Sandstone

Nineteen Groundwater Resource Investigation Areas have been proposed for the Permo-Triassic sandstones, shown on Figures A4.1, A4.2 and A4.3. Five groundwater flow models have already been completed in the sandstones, as indicated.

Figure A4.4 shows the proposed timings of these projects.

Magnesian Limestone

Five Groundwater Resource Investigation Areas are shown on Figure A4.1. It is likely that only quantitative conceptual models for these areas will be developed.

Carboniferous Limestone

Seven Groundwater Resource Investigation Areas have been proposed for Carboniferous limestones in South Wales, the Mendips and the Pennines (Figure A5.1). No numerical models are planned for any of these areas and the programme involves completing quantitative conceptual models for the aquifer.

A preliminary timescale for these projects is shown on Figure A5.2.

Minor Aquifers

The locations of these Groundwater Resource Investigation Areas are shown on Figure A6.1. They include five areas of river gravels, one of which has already had a model developed, and two areas of Old Red Sandstone.

6.3 Regional Implementation

The programme outlined in the preceding Section is a provisional plan and its implementation will be subject to each Region developing its own strategy for modelling. The detailed implementation of the proposed programme will be defined in the form of a Regional Modelling Strategy, or as part of a Regions business plan. Anglian Region have already issued their modelling strategy and its implementation is currently underway (Environment Agency, 1998c).

Some guidelines on the contents of a Regional Modelling Strategy, or the modelling section of the Regional business plan, are given in Appendix B.

7 AGENCY RESOURCES

One of the recommendations from the Survey of models (Section 4.2.3) was that the Agency should ensure that there are sufficient experienced groundwater modellers available at a Regional level to enable the proposed and existing modelling programme to be carried out effectively.

Implementation of the provisional modelling programme outlined in Section 6 will potentially commit the Agency to developing more than 60 modelling projects over the next 10 years. After their development, these models will require regular updating to ensure that they are available operationally for resource management.

The implication of this potential workload is that significant demands will be placed on the financial and staff resources of the Agency. Financial resources are not considered here as they are dealt with through the business plans within each Region. The demands from other modelling activities within the Agency also need to be considered, in particular from requirements to maintain the steady-state source protection zone models, although this will vary depending on how modelling work is organised within different Regions.

The Agency must therefore consider the following:

- how to staff modelling activities in the Regions
- the training and development needs of modelling staff
- how to co-ordinate modelling activities so the proposed programme is kept on track and knowledge and experience is transmitted around the Agency.

7.1 Staffing of Modelling Activities

The resources required within each Region and EA Wales will be assessed in detail as part of either Regional business plans, or a specific Regional groundwater modelling strategy. These plans, or strategies, will need to consider the requirements of modelling projects developed as part of the proposed programme and those of updating models to keep them available operationally.

7.1.1 Modelling Projects

There are a number of options for resourcing groundwater modelling projects and these can be evaluated by considering the four main areas of responsibility (Table 7.1).

- **Project Management:** Managing contractual aspects of the project, budgeting and programming of activities.
- **Technical Management/Supervision:** Ensuring that the technical work being undertaken by the modelling team is to best practice standards, addresses the objectives of the project. Ensuring that the technical work is kept on-track and meets the specifications in the Project Brief.
- **Modelling Team:** Undertaking the model development work as specified in the Project Brief and delivering the required outputs.
- **Technical Review:** Providing technical QA/QC on the project and support and advice

when necessary.

Table 7.1 Organisation and resourcing of projects

Function	Responsibility	Staffing	
		Option ①	Option ②
1 Project Management	<ul style="list-style-type: none"> Ensuring that the project is running to programme and budget Resolving contractual and liaison difficulties Providing ongoing review of progress 	Agency (or Contractor)	Agency
2 Technical Supervision	<ul style="list-style-type: none"> Ensuring that the technical team undertakes the work in accordance with best practice standards Ensuring the work meets the Agency's objectives 	Agency	
3 Modelling Team			
3a Supervision	<ul style="list-style-type: none"> Management of the modelling team Ensuring outputs meet the objectives of the Project Brief 	Contractor	Agency
3b Technical Team	<ul style="list-style-type: none"> Delivering the outputs required by the Project Brief 	Contractor	Agency (+ Contractor)
4 Technical Review	<ul style="list-style-type: none"> Independent review of project QA/QC of outputs Technical advice and backup 	Agency (NGWCLC) External advisor	

The two main options used by the Agency in the past have been:

1. Model development carried out by an external contractor under the supervision of Agency staff.
2. Model development undertaken in-house by Agency staff, supervised by Agency staff.

These are considered in more detail below.

Modelling team made up of an external contractor. In this situation it is important that the responsibilities for project management and technical supervision are separated. Where they have been combined in a single individual, the tendency is for the technical supervision to be reduced due to the heavy workload required for the project management. Some modelling teams may require more supervision than others to ensure objectives are being met and

reducing time spent on this will affect the quality of the work.

The technical supervision is considered to be a vital component in a successful project and if it is absent the project is most unlikely to meet the high standard required.

It is recommended that Agency personnel always undertake the technical supervision of an external contractor. When a numerical model is being produced, this person should be a modeller with 5 years or more of practical modelling experience with abilities in the maths and physics of groundwater flow, programming and familiarity with applying a range of modelling packages.

The project management need not be undertaken by someone with modelling experience and there could be an option for using a contractor in this position rather than Agency staff.

Modelling team formed in-house. Project management and technical supervision should be undertaken by different people for in-house projects for the same reasons as they are for a team of contractors. However, it *is* possible to combine the technical supervision with the supervision of the modelling team (3a on figure 7.1) in a single individual.

The resources necessary for an in-house project should not be underestimated, particularly as Agency staff will have other operational commitments. Possible options for increasing resources in the short-term are to bring in contract staff for particular project tasks, or to temporarily replace Agency staff with a contractor while they are assigned to the modelling project.

Where the Region does not have an experienced groundwater modeller, consideration could be given to the temporary transfer of a modeller from another Region.

7.1.2 Model Maintenance

It is important to ensure that models are regularly updated for the reasons discussed in Section 5.2.1. There are two options to resource this task:

- Use Agency modelling staff
- Contract the work to an external contractor.

If Agency staff are used, it will be important to ensure that time for this task is allocated in Regional planning. In Regions where there are many models, the task of regular updating may occupy a significant portion of time over a year and this may influence the size of the specialist modelling support team in the Region.

The second option is to contract the updating of models to an external contractor, possibly the same one that developed the model. The disadvantage of using a contractor is that it may reduce the Agency's involvement with the models to that of a management role, with no hands-on use of the models. The Agency would become entirely dependent on consultants to undertake model runs for groundwater management purposes. It would result in de-skilling rather than developing capability of the Agency's staff to manage water resources and regulate the users of those resources.

7.2 Training and Development

Barker and Kinniburgh (1994) quote from a USEPA report on 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."

The Agency's training needs and development are not, therefore, confined simply to modelling staff, but also to others involved in resource management 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 around the Regional and Area staff concerned via seminars.

Barker and Kinniburgh (1994) also note a danger that managers may expect staff to become competent in modelling after attending a short course. This is even more likely with the advent of user friendly graphical interfaces. It is important to realise that the view on the screen may not represent what is actually in the input files and the modeller must have familiarity with the file structure and review these prior to running the programme (Arnold, F.D., 1998). These comments were made in reference to the public domain MODFLOW code, they are equally valid for proprietary codes.

In addition, it is worth reiterating that understanding is everything. What is seen on a computer screen can aid understanding when coupled with sound hydrogeological thinking, but if taken at face value, it will only mislead. A model is a tool, not a substitute for reality.

The Guidance Notes to be produced as one of the outputs from the project are intended to communicate the Agency's modelling experience to a wider audience, both within the Agency and to consulting organisations. They will provide one of the means for developing groundwater modelling staff within the Agency.

7.3 Co-ordination of Modelling

During this R&D project there have been a number of developments which have improved communication and collaboration within the Agency. These have been:

- The appointment of a Senior Groundwater Modeller at the National Groundwater and Contaminated Land Centre. This position has acted as a national co-ordination point for modelling work in the Agency and the provision of advice to Regional offices.
- The formation of the project Technical Working Group has led to increased contacts between modelling staff within the Regions.

From this recent experience, it is suggested that there would be advantages in developing a forum, or group, for groundwater modelling staff within the Agency. This would act as a focal point for reviewing and discussing the proposed groundwater modelling programme, the development of groundwater modelling staff and wider issues within the Agency that relate to the requirements of model development, for example the use of the Agency's databases.

8 RECOMMENDATIONS

This report recommends that to fully support the decision-making process in water resource management, the Agency should:

- Develop a well-documented and quantitative conceptual understanding of all the major aquifers in England and Wales.
- Develop large-scale distributed time-variant groundwater flow models based on this understanding, where this is appropriate. The development of relatively small single-catchment resource models should not be encouraged due to the potential for problems with hydrogeological boundaries.
- Undertake these developments by implementing the modelling programme outlined in Section 6.

In order to do this and ensure that groundwater models are developed to a consistently high standard across the Agency, a number of further recommendations have been made. These are:

1. **Project Methodology.** Projects, including those carried out in-house, should generally follow the methodology outlined in Section 5.2. 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 an audit trail that will give credible support to the models and decisions arising from their use.
2. **Project Management.**
 - The responsibilities for project management and technical supervision should be separated.
 - In-house project teams should be managed as if consultants were undertaking the work. This should include the use of a detailed project brief.
 - The project objective and detailed specifications of the purpose, approach and output for each task should be supplied to the contractor. It is recommended that this is based on the template project brief included as an appendix to the Guidance Notes.
 - 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 interested parties to widen 'ownership' of the models.
3. **Agency Staff Resources.** To utilise resources more effectively, the Agency should:
 - ensure that there are sufficient experienced groundwater modellers available to carry out its modelling programme effectively.

- Develop a forum for groundwater modelling staff within the Agency that will enable them to present and discuss lessons learned from their own modelling projects and make recommendations related to hands-on modelling practice to the Groundwater Resources Group.
 - Disseminate the results of modelling projects more widely within the Agency by means of internal reports and seminars.
 - Ensure that the conceptual models developed from modelling projects are readily available to Area teams.
 - Consider alternative ways of forming modelling teams to encourage the transfer of skills between consultants and the Agency.
4. **Guidance Notes.** It is recommended that the Guidance Notes are regularly updated by contributions from Agency staff and feedback from modelling projects.
5. **Data**
- In co-ordination with the modelling programme laid out in section 6, it is recommended that the Agency Regions should develop a programme of field data collection and review their hydrometric monitoring in advance of the modelling projects defined in the modelling programme.
 - The ease of use of the Agency's databases should be investigated. Particular concerns are accessibility of data required for model input (improved query tools) and the integrity of information that may be duplicated on several databases.
6. **Water Quality Models.** There should be closer co-ordination between the Water Quality and Water Resource Functions to ensure that:
- local-scale contaminant transport, flow and SPZ models are developed within a consistent regional conceptual model.
 - Regional time-variant models support future developments in Source Protection Zone Modelling.

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Appendix A

Proposed Groundwater Resource Investigation Areas

Table A. Summary of Proposed groundwater Resources Investigation Areas

Aquifer	Groundwater System	Groundwater Resource Investigation Area
Chalk	Southern Chalk	North West Norfolk (inc. Sandringham sands) North Norfolk/Yare Ely Ouse Yare South East Suffolk North South Essex* Cam/Bedford Ouse* Upper Lee Valley* LONDON BASIN* Colne Valley SW CHILTERN KENNET Hampshire Avon* Wessex Basin* Test Itchen* EAST HAMPSHIRE CHICHESTER Brighton/Worthing Seaford/Eastbourne East Kent/Thanet North Kent DARENT* Isle of Wight Central Chalk
	Northern Chalk	YORKSHIRE CHALK* Lincolnshire Chalk (inc. Spilsby Sandstone)*
Lower Greensand		Upper Stour Medway DARENT* Lower Greensand* Western Rother* Isle of Wight Lower Greensand
	Woburn Sands	Woburn Sands
Permo-Triassic sandstone	Midlands & NW England	FYLDE Merseyside & Mersey Basin Manchester & East Cheshire Wirral/West Cheshire* Shropshire* West Midlands (KIDDERMINSTER-WORFE) Birmingham Lichfield Burton-Coventry
	Eastern England Permo-Triassic (including Magnesian Limestone)	NOTTS DONCASTER* Maltby-Hucknall Magnesian Limestone SELBY* Southern Magnesian Limestone* York Central Mag Limestone Northallerton Northern Mag Limestone Hartlepool

Table A. Contd.

Aquifer	Groundwater System	Groundwater Resource Investigation Area
Perno-Triassic sandstone	Stoke-Derby	Stoke Derby
	Leek	Leek
	Newent	Newent
	Otter Valley	OTTER VALLEY
	Carlisle Basin/Eden Valley	Carlisle Basin/Eden Valley
	Vale of Clwyd	Vale of Clwyd
	Furness	Furness
Jurassic Limestones	Great Oolite	MALMESBURY-AVON COTSWOLDS
	Lincolnshire Limestone	SOUTHERN LIMESTONE Northern Limestone
	Yorkshire Corallian	Derwent Corallian (SCARBOROUGH CORALLIAN) Rye Corallian
	Malton-Norton Corallian	Malton-Norton Corallian
Carboniferous Limestone	Buxton-Matlock	Buxton-Matlock
	South Pembrokeshire	Northern Pendine Central Southern
	Gower	Gower
	Northern Outcrop	Northern Outcrop
	Vale of Glamorgan	Porthcawl-Schwyll Cowbridge Llanharry-Machen
	Chepstow	Caerwent Penhow Shirenewton Itton St Arvans Tidenham
	Mendips	Mendips
Minor Aquifers	Herefordshire Old Red Sandstone	Ross South Hereford
	Upper Lugg	Upper Lugg
	Lower Lugg	Lower Lugg
	Golden Valley	Golden Valley
	Rheidol Valley	Rheidol Valley
	Yazor Gravel	YAZOR GRAVEL

Notes:

1. CAPITAL LETTERS indicate that a numerical model has already been completed and is available for use.
2. * indicates Groundwater Resource Investigation Areas where inter-Regional consultation will be necessary.

Appendix A.1

Chalk

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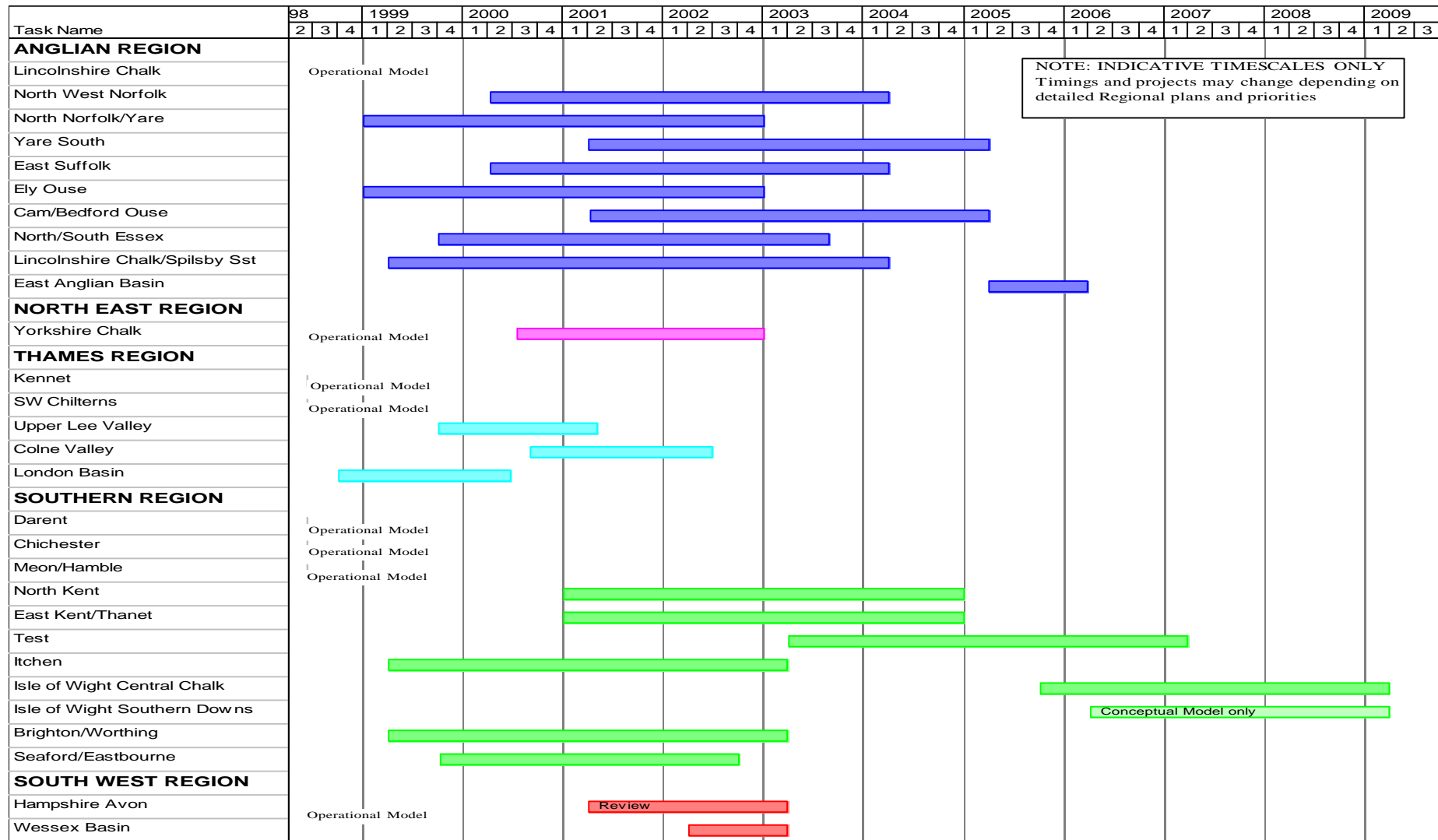
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Figure A1.2. Chalk: Project timescales



Appendix A.2

Lower Greensand

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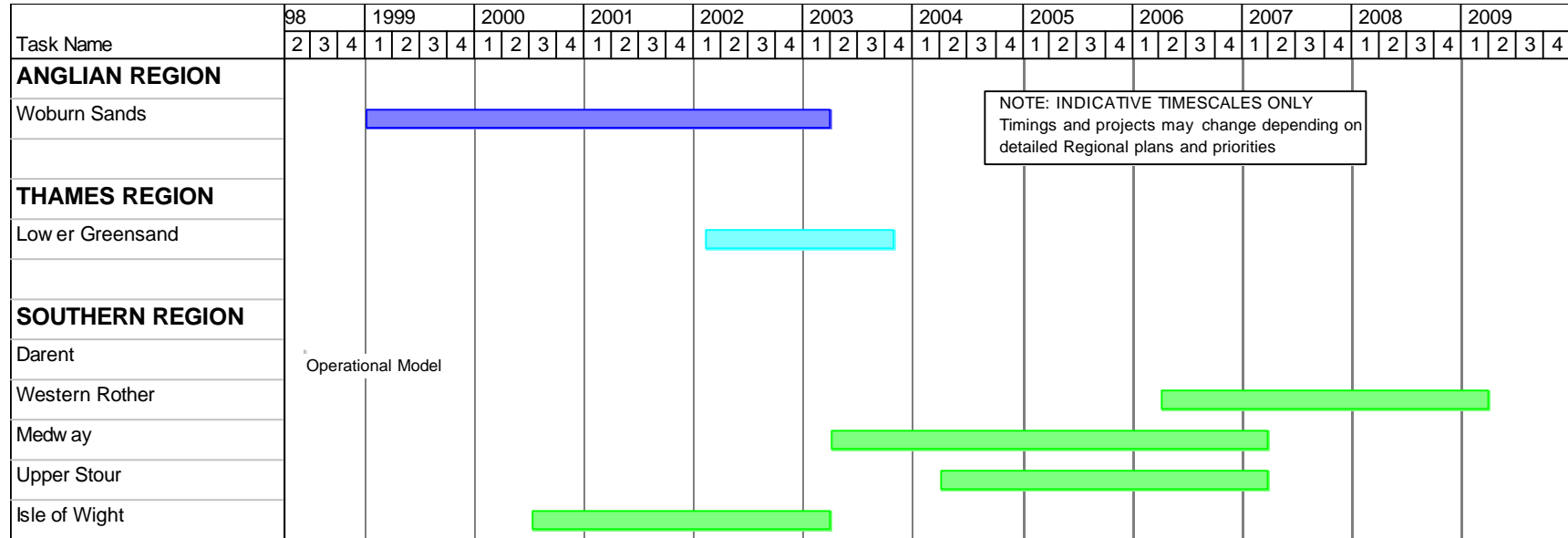
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Figure A2.2 Lower Greensand: Project timescales



Appendix A.3

Jurassic Limestones

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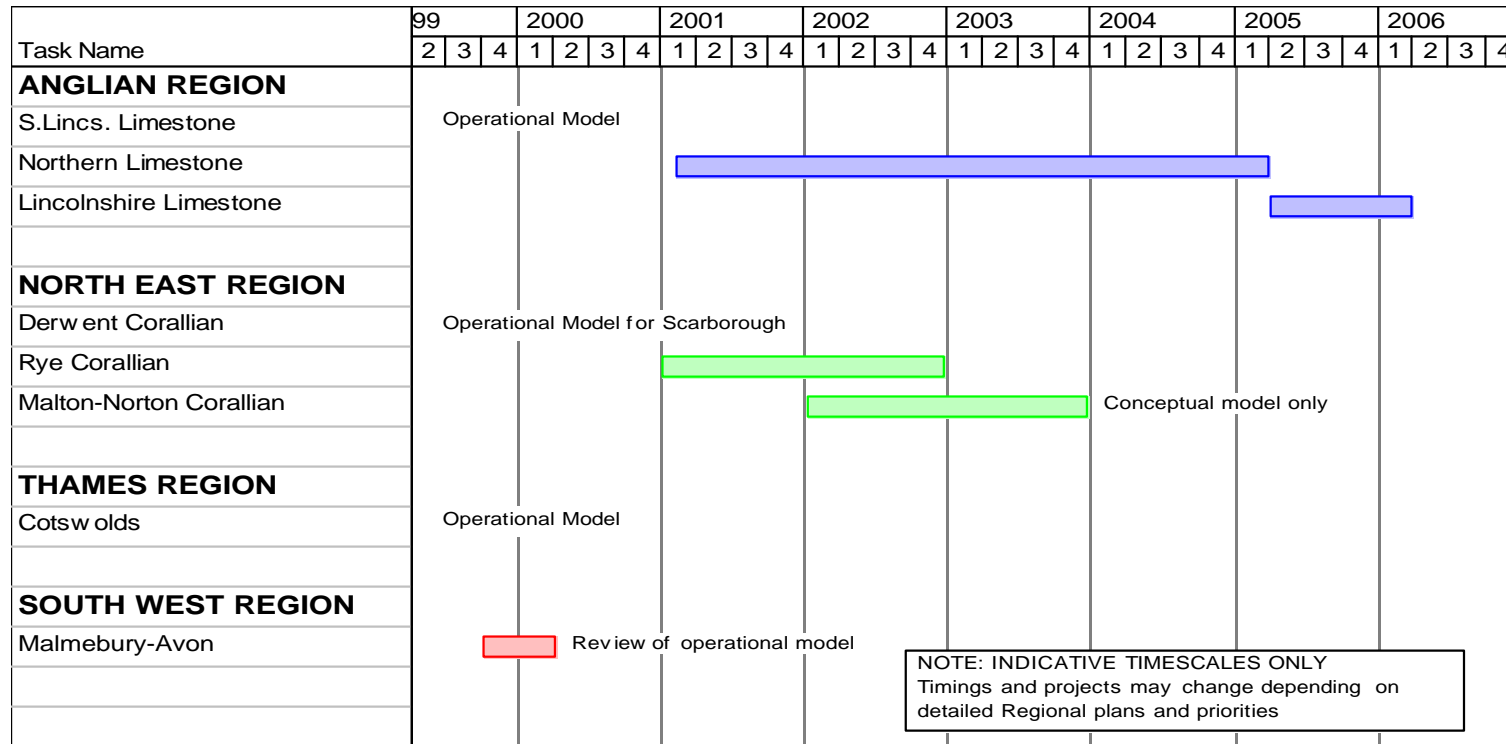
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Figure A3.2 Jurassic Limestones: Project timescales



Appendix A.4

Permo-Triassic sandstones and
Magnesian Limestone

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Appendix A.5

Carboniferous Limestone

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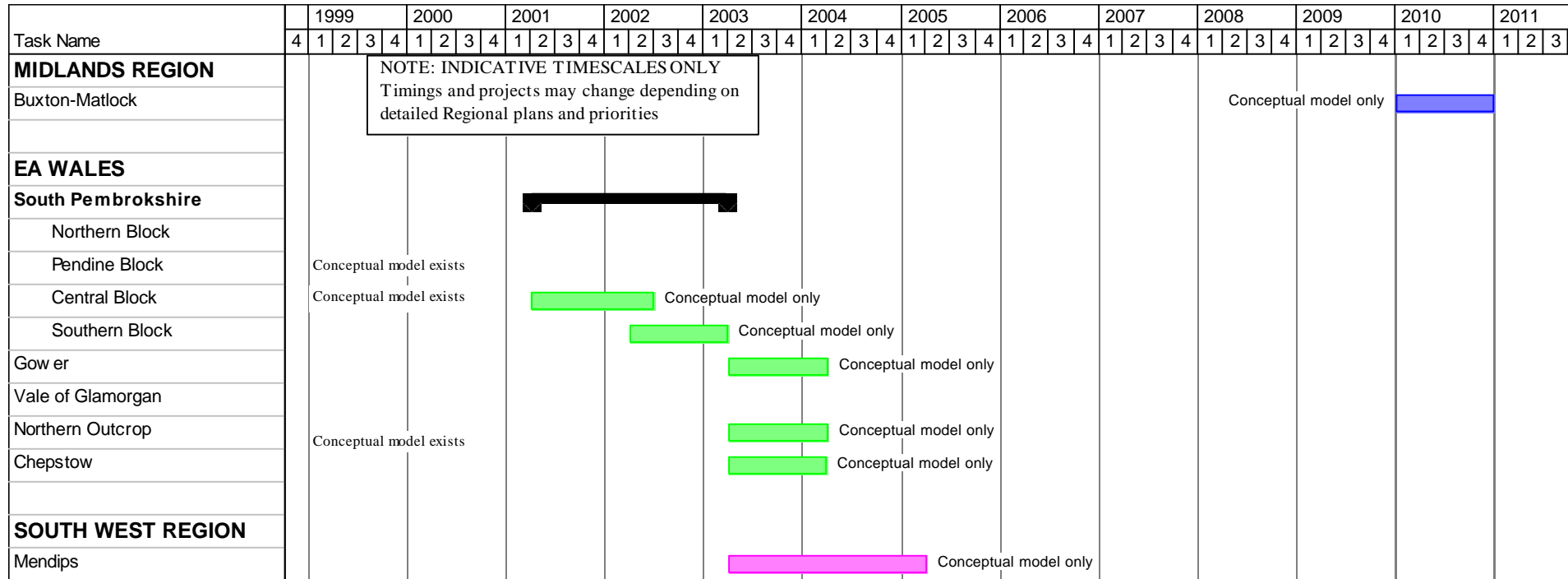
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Figure A5.1. Carboniferous Limestone: Project timescales



Appendix A.6

Minor Aquifers

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