Numerical Modelling of the Impact of Groundwater Abstraction on River Flows

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This report describes the research into the impact of groundwater abstraction on river flows using numerical flow models. An approach for investigating such impacts is presented. The information within this document is for use by Environment Agency staff and others involved in managing water resources.

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EXECUTIVE SUMMARY

This is a proof of concept project carried out within the Environment Agency's Science Department, funded collaboratively by the Environment Agency and the British Geological Survey (BGS).

The aim of the project was to test the capability of the existing object-oriented model, ZOOMQ3D, for estimating the impacts of groundwater abstraction on river flows. The driver for this work has been the lack of tools the Environment Agency has for representing some of the complexity of aquifers that can be developed in a short period of time i.e. hours or days rather than the months or years it takes to develop a regional groundwater model. Currently, the Environment Agency has the IGARF 1 & SPIGARF analytical tools for assess river impacts. These are quick to use but contain a number of limiting assumptions. Regional groundwater models will give better estimates of river impacts but these have not been developed for all aquifers and take several years to build and test.

The overall objective of the project has been fulfilled by dividing the study into three components. The first involved an investigation to decide which features of an aquifer need to be simulated when quantifying the impact of abstraction on river flows. This work, referred to in this report as "impact modelling", examined the need to represent accurately features such as catchment size, aquifer boundaries, recharge, transmissivity variations, unconfined conditions and ephemeral rivers.

The second component of the work involved undertaking an assessment of groundwater abstraction impacts on river flows for a real catchment. The River Candover augmentation scheme (Southern Water Authority, 1979), developed in the mid-1970s, formed the basis of this work and provided observed river flow data during an extended pumping test. Models of different levels of complexity were developed and used to calculate the impact of the augmentation scheme pumping test on the Candover Stream. These results were then compared to depletion rates estimated from observed river flow data.

The final component of this study involved the development of a prototype modelling tool so that hydrogeologists who are involved in abstraction licensing can develop ZOOMQ3D models and use them to assess groundwater abstraction impacts. This was achieved by developing a simple Microsoft Excel tool to prepare input for, run and examine the output from the groundwater flow model.

In addition to these main components, which are summarised below, a number of other tasks have been undertaken including:

- a review of the current tools used by the Environment Agency for the assessment of groundwater abstraction impacts;
- a short review of other commercial modelling codes which could be used to simulate river-aquifer interaction;
- a review of the literature about the use of object-oriented modelling techniques in water resources and groundwater modelling;

- a brief description of the LOCAR and CHASM thematic catchment research programmes.

Software development

The tools currently available to the Environment Agency to assess the impact of groundwater abstraction on river flows fall into two categories. First, spreadsheet models, which use analytical solutions to assess impacts. These are simple, quick to use and help to develop understanding, but are subject to a significant number of assumptions and provide only a general indication of the likely spatial and temporal distribution of the impacts of abstraction. In contrast to these 'simple' approaches, the Environment Agency has developed a number of numerical regional groundwater flow models of many, but not all, UK aquifers and these are also used to investigate the impacts of groundwater abstraction on river flows. However, regional groundwater models are not used routinely to assess abstraction impacts. This is because the hydrogeologist assessing the abstraction license does not often have 'ownership' of the model and has to ask the consultant who developed the model or sometimes another member of Environment Agency staff to perform a simulation. This obviously incurs a cost and therefore regional models do not tend to be used to assess licence applications for small supplies. For larger, and therefore more valuable supplies it is likely that a regional groundwater model would be used in conjunction with a detailed hydrogeological investigation.

Because of the limitations of current modelling approaches available to the Environment Agency, the ZOOM_IGARF tool has been developed to assess the impact of groundwater abstraction on river flows. This tool has been developed to be relatively easy and quick to use whilst enabling the incorporation of some of the complex features that can be simulated by regional groundwater models. Perhaps the most significant advantage of the model over the simpler analytical spreadsheet tools is the ability to represent multiple, non-linear and dendritic river catchments. The correct representation of the rivers is important because this is one of the few 'knowns' within a system.

The ZOOM_IGARF tool uses a Microsoft Excel spreadsheet interface to set up and run the regional groundwater model ZOOMQ3D (Jackson and Spink, 2004) and analyse its results. The Excel spreadsheet, ZOOM_IGARF, is used as a pre- and post-processor for the groundwater flow model. It is then possible to run the model and analyse the impact of an abstraction borehole on one or more reaches of a river within a catchment. The benefit of the use of Excel is that its application requires little prior knowledge of the structure of the input and output of the flow model, ZOOMQ3D. A full description of the ZOOM_IGARF spreadsheet is given in the user manual (Mansour and Jackson, in press), which has been produced as part of this project.

In addition to the creation of the Excel tool, two Windows applications have been developed to assist the user when constructing models containing complex river catchments. The first of these simplifies the process of transferring river geometry and elevation data from a GIS into the ZOOM_IGARF model and the second simplifies the adjustment of the model parameters values relating to the rivers e.g. river-bed conductances. These applications serve to demonstrate within this 'proof of concept' project that the transfer and manipulation of data from a GIS can be relatively simple. However, a better solution would be to incorporate the functionality of these Windows applications into ArcGIS and this could be achieved in a future project. This task was not undertaken as part of this project due to cost constraints and because of the change from the use of ArcView to ArcMap that occurred during the life of the project.

Impact modelling

As it was first envisaged, the objective of the impact modelling exercise was to examine whether recharge could be ignored when calculating the impacts of abstraction on river flows. However, during the project the purpose of the impact modelling was broadened to consider which features of a groundwater system are important in this context. Consequently, instead of focusing predominantly on the importance of aquifer recharge in impact assessment, models were developed to investigate the effect of incorporating a number of different hydrogeological features.

The impacts of abstraction were calculated by examining the difference between the results of two simulations; one in which the abstraction borehole under assessment is pumped and one in which it is switched off. Numerous impact models have been presented and conclusions drawn relating to the hydrogeological features that must be represented in numerical models if satisfactory predictions of groundwater abstraction impacts are to be derived. The impact modelling has highlighted that the following points are important and should be considered when using a numerical model to assess impacts of groundwater abstraction on river flows:

- It is important to include all of the rivers that could be affected by pumping and good practice to define the boundaries of a model using the physical extent of the aquifer if possible. It is not acceptable to select a stable groundwater divide between two catchments as a model boundary when assessing the impact of abstraction on river flows.

- If a sub-catchment model must be developed then it is likely that a better estimate of the depletion rate will be derived if the average is taken of the depletion rates calculated using two models: (i) the sub-catchment model in which the boundaries are defined as no-flow and (ii) the sub-catchment model in which the boundaries are defined as fixed heads. By taking this average, the effect of the poorly defined boundary conditions can be reduced.

- The application of recharge to a model which is used to calculate differences in river flow, that is depletion rates, only affects the results when (i) transmissivity depends on groundwater head, (ii) when the introduction of recharge affects the timing of when parts of the river become perched or sections of the channel become dry, or (iii) when the introduction of recharge causes another flow mechanism to exhibit non-linear behaviour.

- If the length of the river being modelled changes during a simulation then the impact that an abstraction borehole has on its discharge will change. Care must then be taken to represent the changing length of the river if depletion rates are to be calculated accurately.

Modelling of the River Candover augmentation scheme

In the mid-1970s the Southern Water Authority (1979) developed a river flow augmentation scheme in the Candover catchment on the Chalk in Hampshire. During testing of the three boreholes constructed as part of the scheme, groundwater abstraction rates and river flows were monitored. These data were used to compare simulated river baseflow depletion rates with those observed. The Candover modelling study fulfilled the objective to investigate a real catchment for which estimates of groundwater abstraction effects on river flows have been made using observed data. The availability of observed data of this type is limited and the Candover study proved to be the only easily accessible source of data.

A series of numerical models of the Chalk aquifer around Candover were developed with increasing levels of complexity. The results of the numerical models were compared with the field data with the aim of determining which features of the system have to be represented accurately in order to obtain adequate modelled depletion rates. The Candover data were collected during trial pumping of three augmentation boreholes carried out during the summer of 1976, in the middle of a severe drought period. Groundwater levels were very low at this time and this complicates the interpretation of the impact of abstraction on river flows. However, a number of conclusions are drawn from the Candover modelling exercise, which relate to the required complexity of a numerical model and to the confidence with which its results can be regarded.

The simulation of the impact of abstraction on river baseflows in this Chalk aquifer during the 1976 drought is a difficult task and probably requires the incorporation of some complex hydrogeological features in the model. Consequently, it has not been possible within this project to develop a numerical model that can reproduce the impact of groundwater abstraction on river flows as calculated using the observed data. However, there is also some uncertainty associated with calculation of 'observed' river baseflows depletion rates.

The model has shown which features of a system need to be represented in order to make a better assessment of the impacts. A numerical model can represent the correct geometry of the river network and this is a significant advantage over analytical solutions. Whilst it has been difficult to simulate the Candover pumping test accurately, the development of a model provides a framework with which to formalise the understanding of an aquifer and test ideas about how it may behave. For these reasons, the development and application of an appropriate model during the assessment of a groundwater abstraction licence should be promoted. Hence hydrogeologists who are unfamiliar with the use of models will need to be made aware of their benefits and how they can be used.

A hydrogeologist who is assessing an abstraction license will rarely have enough time to develop a model that contains all the important features of an aquifer. However, the process of building even a simple model increases the hydrogeologist's understanding of the system and this leads to better decision making.

1 INTRODUCTION

1.1 Background

This is a proof of concept project carried out by the Environment Agency's Science Department and funded collaboratively by the Environment Agency and the British Geological Survey (BGS). It aims to investigate whether a tool for estimating the impact of groundwater abstraction on river flows can be developed which is more accurate than current analytical tools and yet quicker than building a fully distributed groundwater model such as MODFLOW.

New statutory requirements such as Catchment Abstraction Management Strategies (CAMS) and the Habitats Directive mean that the Environment Agency will need to estimate the spatial and temporal distribution of the impacts of groundwater abstraction on river reaches and wetlands more accurately.

The existing tools developed by the Environment Agency as part of the Impacts of Groundwater Abstraction on River Flows (IGARF) project (NC/00/28) are adequate for about 50% of abstraction licence assessments. However, it is recognised by the developers that the existing IGARF analytical models do not produce results with sufficient confidence where:

- a groundwater abstraction has a significant impact on more than two rivers;
- the particular hydrogeological setting significantly influences the impact of an abstraction and generic tools such as IGARF 1 are inadequate;
- the groundwater level falls below the bed of the river and away from hydraulic contact with the river;
- a more accurate spatial or seasonal distribution of the impacts on both flow and groundwater level is important, for example when the effects of several abstractions must be considered;
- there is a variation of hydraulic conductivity with depth as in most Chalk and Limestone catchments;
- the regional context is important for estimating the local impact, which is often true for wetland sites.

There is a larger risk of appeal for cases associated with the above conditions if the assessment relies only on the generic analytical tools where impacts could be seriously wrong. This risk could be reduced by using estimating tools which incorporate the hydrogeological influence of the above conditions and hence can produce more accurate results. The USGS code MODFLOW (McDonald and Harbaugh, 1988) is currently the only tool readily available to the Environment Agency which takes some of these conditions into account. The Environment Agency has several regional MODFLOW models but these are inappropriate for the rapid assessment of impacts since they take two to three years to produce at a cost of £200k to £300k each.

The relationship between the cost of producing groundwater models and the required results from the study is illustrated by Figure 1. In theory as more money is spent on an investigation, the accuracy of the results should increase. Presently the only tools available are either low cost and low accuracy or high cost and high accuracy. This project aims to provide groundwater modelling tools that fill the gap in between low accuracy solutions such as IGARF and regional groundwater modelling.

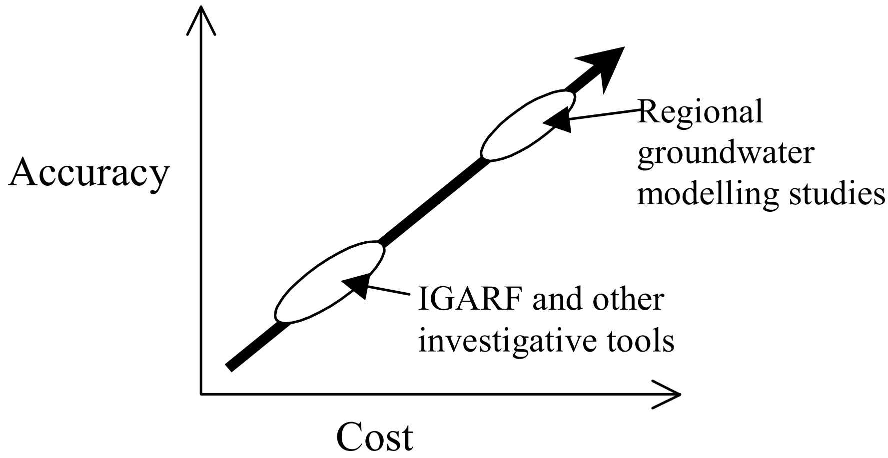

Figure 1 Relationship between cost of investigation and accuracy of results

An intermediate tool is sought which removes some of the limiting assumptions associated with the current low cost modelling tools (e.g. aquifer homogeneity or geometric simplicity) but which can be set up in a few hours. Operational hydrogeologists could then increase the confidence of their impact assessments and test the uncertainty associated with the key hydrogeological conditions which prevail for a particular site. The groundwater flow model ZOOMQ3D provides the opportunity to develop such a tool.

ZOOMQ3D is an object-oriented groundwater flow model which has been developed by a partnership of the University of Birmingham, the Environment Agency and the British Geological Survey. The model code has all the functionality of MODFLOW, but with additional features. These features include local grid refinement, the ability to represent rivers independently of the grid and a variable hydraulic conductivity with depth mechanism (VKD). A recharge model has also been developed that is compatible with ZOOMQ3D and uses GIS based data directly. Both models have been applied by the BGS to a variety of regional groundwater flow studies on both Chalk and Permo-Triassic aquifers.

Because of the object-oriented design of the model and its capability to modify the model grid and rivers rapidly, ZOOMQ3D provides the basis for a tool that can be used to investigate the effects of groundwater abstraction on rivers relatively quickly whilst representing aquifers more accurately than existing modelling tools.

In broader terms, the object-oriented (OO) approach is rapidly becoming popular for hydrological simulation because it enables applications to be developed that incorporate a high degree of complexity but which are accurate, easily modifiable, and easy to use (for example Bauer et al., 2004; Jansson and Moon, 2001). This approach offers the potential to solve many of the problems associated with existing modelling tools, which are used for the assessment and management of the water environment.

The major benefit of the approach is that it enables applications to be developed which focus on physical processes and mechanisms. That is, it is now realistic to envisage the development of models that are constructed around hydrological or hydrogeological features. It should no longer be considered acceptable to 'fit' engineering problems into the fixed frameworks of current models. Tools can now be developed that enable users to investigate processes rather than just being able to define parameter values. The core principle of object-oriented model development is the reproduction of real-world features as computational equivalents.

For example, when considering a number of scales, aquifers, river catchments, wetlands or pumped wells, each could be defined as objects containing a complex but well defined behaviour. Wetlands in particular are generally simulated inadequately in existing models. Compared with current techniques it would be relatively straightforward to incorporate a number of different conceptual models of wetlands and detailed wetland processes in an object-oriented model.

1.2 Overall objectives

The overall objectives of the project, as they were defined in the Project Specification, are reproduced below. These objectives have been fulfilled. However, the approach to fulfilling them, envisaged at the start of the project, has altered slightly during the investigation. Both the original and final objectives are reproduced below.

1.2.1 Original objectives

The original overall objectives were defined as follows:

This project aims to test the capability of the existing object-oriented model, ZOOMQ3D, as a means of estimating the impacts of groundwater abstraction on river flows. Can models be developed with ZOOMQ3D which produce more accurate estimates than the analytical tools IGARF 1 & SPIGARF but which can be set up in days rather than the years it takes to develop a full regional model?

Two methods are to be investigated:

1) *Producing an impact model with no recharge.*

2) *Applying a generic model to a catchment which is refined as knowledge or time available increases.*

The existing object-oriented (OO) groundwater model will be tested on a series of hydrogeological settings.

The project must deliver tools that [Environment] Agency scientists can use for estimating the impacts of groundwater abstraction and for investigating the importance and influence of groundwater mechanisms on stream flows and groundwater heads.

The development of the impact model (point 1 above) has involved the investigation of how the inclusion of different groundwater flow processes in a numerical model affect the simulated impacts of abstraction. In particular, the question that has been addressed is whether, and when, it is necessary to include recharge in models used to assess impacts.

The second method of assessing groundwater abstraction impacts was to involve the application of a generic model to a real catchment or perhaps more than one catchment. These models were to increase in complexity from initially relatively simple representations of the aquifers. The models were to be tested on a series of hydrogeological settings previously defined by the Environment Agency (2002b). These settings represented different hydraulic parameter distributions within river valleys e.g. high conductivity valley gravels within a low transmissivity aquifer. However, it was considered by the project board during the investigation that the representation of aquifer systems with different parameter distributions was of lesser importance than the investigation of aquifers that incorporate different processes. Consequently, much of the work has focused on assessing which features of an aquifer must be represented in a model, if groundwater abstraction impacts are to be determined with any degree of accuracy.

1.2.2 Final objectives

Given the considerations above (Section 1.2.1), the final overall objectives developed during the project and were described as follows:

This project aims to test the capability of the existing object-oriented model, ZOOMQ3D, as a means of estimating the impacts of groundwater abstraction on river flows. One aim of the investigation is to address the question whether models can be developed using ZOOMQ3D which produce more accurate estimates than the [Environment] Agency's existing IGARF 1 & SPIGARF analytical tools but which can be set up in days rather than the years it takes to develop a full regional model. This will involve the investigation of which processes need to be simulated when quantifying the impacts of groundwater abstraction on river flows. For example, in some hydrogeological settings it may be possible to gain accurate estimates using simple models. The project seeks to address under what conditions the use of such simple models is valid.

The overall objectives of the project are separated into the following three components:

1. *Investigate which features of an aquifer system need to be simulated when quantifying the impact of abstraction on river flows.*

   In this report the impact of an abstraction borehole on a section of river is termed the depletion rate. This is a function of the time since the start of pumping and can be calculated by comparing the difference in river flow between two simulations; one in which an abstraction borehole pumps and one in which it does not. The investigation will address whether features such as aquifer recharge, transmissivity variations (both spatially and over time), ephemeral rivers or river geometry need to be represented accurately in order to obtain reasonable estimates of river flow depletions rates.

   This section of the work is referred to as ***impact modelling*** *in this report.*

2. *Based on a real catchment study of the impacts on groundwater abstraction on river flow, for which river flow depletion rates have been calculated, undertake an assessment using numerical models.*

   The numerical modelling starts by applying the simplest approach to assessing abstraction impacts. It is then made to represent the aquifer more closely by incorporating additional hydrogeological features in a step-wise manner and the changes in the predicted results noted.. It is possible that the final model may resemble a regional groundwater model.

   This section of the work is referred to as ***investigative modelling*** *in this report.*

3. *Develop a modelling system that can be used to assess the impacts of groundwater abstraction on river flows within the timescales of an [Environment] Agency abstraction licensing assessment, i.e. one to two man-days, but that can incorporate some of the features in regional groundwater models to enable more accurate results to be obtained. The tool should be able to assess the spatial distribution of impacts in catchments with multiple river channels.*

   The project must deliver tools that [Environment] Agency scientists use for estimating the impacts of groundwater abstraction and for investigating the importance and influence of groundwater mechanisms on stream flows and groundwater heads.

1.3 Specific objectives

The specific objectives of the project, as they were defined in the Project Specification, are reproduced below. The fulfilment of all of these was viewed by the project board as a significant undertaking at the start of the project. Most of these objectives have been fulfilled. However, it has not been possible to fulfil some due to time constraints or because of slight changes to the emphasis of the work which occurred during the project. All changes to the objectives of the project were agreed by the Project Board. The original specific objectives are listed below and each of these is considered in turn. Reasons are presented if they have been modified or not fulfilled during the project.

1) **Review previous work on estimating the impacts of groundwater abstraction on river flows and the use of the OO approach in groundwater modelling.**

   This specific objective has been fulfilled. A discussion of previous tools used to estimate the impacts of abstraction on river flows is presented in this document. The literature relating to the use of object-oriented approaches in groundwater modelling has been reviewed and is also documented in Section 2.

2) **Define a range of hydrogeological settings for which the estimates of the impacts of groundwater abstraction produced by IGARF 1 may not be accurate enough.**

   The definition of these hydrogeological settings was to be based on those produced as part of the Environment Agency's IGARF II project (Environment Agency, 2002b). These specific settings represented different hydraulic parameter distributions within river valleys. For example, one of the settings represents high conductivity valley gravels within a low transmissivity aquifer system. An investigation of these settings would have provided some information on the different levels of impact that can be expected in systems with different hydraulic properties. However, after consideration, the Project Board deemed that it would be more useful to investigate which processes need to be included in a numerical model if groundwater abstraction impacts are to be determined with any degree of accuracy. Consequently, the investigation of 'typical' settings has not been undertaken.

3) **Assess whether ZOOMQ3D can be used without recharge for rapidly estimating the impacts of groundwater abstraction on rivers in the above hydrogeological settings.**

   This specific objective has been fulfilled, though it has not focussed on hydrogeological settings but rather on aquifers in which different processes operate.

4) **Devise a method for processing input and output data using existing standard software such as Excel, Surfer, ArcView.**

   This has been achieved and a suite of simple software has been developed that allows a user to use ZOOMQ3D to assess the impacts of abstraction on river flows in a timely manner.

5) **Investigate whether the OO approach can help with:**

   a) **The testing of conceptual understanding via introducing new mechanisms rather than merely changing parameters.**

b) **The estimation of predictive uncertainty via systematic sensitivity analysis.**

At the start of the project it was envisaged that there may be sufficient time to make alterations to the ZOOMQ3D code, for example to introduce a new process. However, this has not been the case. Similarly, it has not been possible to apply the parameter estimation software, PEST, to investigate the predictive uncertainty associated with model simulations, within the given time-scale of the project.

6) **Assess whether ZOOMQ3D can be applied as a generic model to a catchment and produce useful impact estimates.**

This specific objective has been fulfilled through the application of ZOOMQ3D to a number of conceptual aquifer systems, as part of the impact modelling discussed in Section 3, and the investigative modelling of a real system discussed in Section 5.

7) **Carry out case studies on actual sites covering a range of hydrogeological settings for which there are good data and an existing numerical model.**

This task has depended on the identification of field data relating to the impact of groundwater abstraction on river flow. Such data was produced during the development of the Candover river flow augmentation scheme by the Southern Water Authority (1979). This has been used as the basis by which to assess the accuracy of numerical modelling of impacts using models that incorporate different levels of complexity. The work has focused on this one catchment because its was considered that this approach provided the best means of validating the usefulness of the different modelling methods. Consequently, rather than attempting to simulate multiple different hydrogeological settings for which observed data was not available, the Candover scheme has formed the basis of the 'investigative' modelling described in Section 5.

8) **Define whether new river/aquifer mechanisms should be represented as objects to improve impact estimates.**

This specific objective has not been fulfilled due to time and cost constraints. The Project Board agreed that this was a significant task and not possible within this project.

1.4 Target Audience

A modelling tool which produces estimates of impacts on rivers and which reflects the key processes better than IGARF 1 & SPIGARF would be useful within the Environment Agency for the following staff and their consultants:

- Environment Agency scientists;
- Area hydrogeologists working on resources assessments for the Water Framework Directive;

- Area hydrogeologists reviewing consents for the Habitats Directive;
- CAMS officers and their teams for impacts on rivers;
- Regional hydrogeologists & groundwater modellers as an investigative tool;
- Water Resources Policy and Process teams;
- Water Framework Directive Programme Board.

1.5 Report Structure

This report is divided into six sections. After this first introductory section a review of the literature that has been published on the use of object-oriented techniques in hydrological modelling is presented in Section 2.

Section 3 describes the development of the various *impact models*, as they are referred to in this report. This numerical modelling seeks to fulfil the first overall objective, which is to investigate which features of an aquifer system need to be simulated in order to quantify the impacts of abstraction on river flows accurately.

In Section 4 the modelling tools that have been developed to enable a user to run ZOOMQ3D and analyse its results are described.

In Section 5, numerical models of the River Candover catchment in Hampshire are developed. In the mid-1970s a river flow augmentation scheme was developed to maintain the flows in the Candover Stream during low flow periods. Data from this project provides the basis for the investigative modelling work which is described in Section 5. This investigative modelling addresses the second overall objective of the study, which is described in Section 1.2.

In the final section of the report, Section 6, the conclusions from the study are synthesised and recommendations arising from the project made.

2 LITERATURE REVIEW

2.1 Introduction

This literature review provides a background to the work undertaken as part of this project. It summarises the current state of the use of object-oriented (OO) techniques in surface water and groundwater modelling, examines the latest technology in terms of linking groundwater and surface water models, and provides a short description of the NERC thematic programmes examining groundwater-surface interaction. The review is not comprehensive, but is intended to provide the reader with background for the work reported below. The review begins with a discussion of the tools currently used by the Environment Agency for the assessment of the impact of abstraction on river flows.

2.2 Review of tools used by the Environment Agency for the assessment of impacts due to groundwater abstraction

The Environment Agency Area hydrogeologists provide estimates of the impacts of groundwater abstraction pressures as part of the abstraction licensing process. This section considers the estimates that the hydrogeologists make and the methods that are currently being used.

2.2.1 Impacts estimates required for licensing decisions

Environment Agency regulatory staff make the decision whether to issue a groundwater abstraction license or to allow quarry dewatering. They are supported by hydrogeologists from the Environment Agency Area team, who will consider the potential impacts of the new abstraction or quarry dewatering a) on surface water features, for example rivers, springs, wetlands, lakes and pools, and b) on other abstractors. The impacts considered include the following.

Impacts of groundwater abstraction

- Depletion on rivers.
- Drawdown beneath wetlands.
- Estimating change in groundwater flow to & from wetlands as a result of groundwater abstraction.
- On water features other boreholes, springs, pools.

Impacts of quarry dewatering

- Drawdown & flow depletion from rivers & wetlands.
- Change in flow patterns after backfilling quarry with landfill.

Role of guidance on Hydrological Impact Assessment (HIA)

The Environment Agency Science Department is currently working with Area hydrogeologists to produce guidance on methods for estimating the impacts of groundwater abstraction or quarry dewatering (Environment Agency, 2007 a and b). The guidance recommends using a tiered approach so that the simplest, quickest (Tier 1) methods are used if they can provide an impact estimate in which we have sufficient confidence to make a decision. If not, more complex and expensive (Tier 2) methods are used if it is thought they can provide better impact estimates.

However, it is sensible to use the best tool available. That is, if a simple (Tier 1) assessment is being undertaken and a good regional numerical groundwater model is already available, then it would be sensible to use it, although it should be recognised that there might be significant costs associated with this.

2.2.2 Methods used for estimating impacts due to groundwater abstraction

The Environment Agency currently uses a range of methods for estimating the impacts of abstraction and quarry dewatering. These methods are described below in order of increasing complexity.

Manual methods

If no suitable data are available, or a high degree of uncertainty is acceptable, then the flow impacts can be allocated manually, using professional judgement. For example, for an abstraction close to a spring or a chalk stream, it might be decided to allocate 100% of the flow impact to the spring or stream. Some simple calculations can be performed, based on the estimated hydraulic resistance between the abstraction and each feature in turn, and then apportioning the impact in proportion to these resistances.

For estimates of the drawdown beneath wetlands there may be monitoring data that can be inspected to identify any change in groundwater levels near the wetland when the abstraction pattern was changed.

Analytical tools

At an intermediate level, the IGARF spreadsheet model (see Section 2.2.3) may be useful for estimating the impacts on river flows. The spreadsheet requires estimates of: radial distance of the river from the abstraction, aquifer hydraulic conductivity and storage coefficient, and river bed thickness and conductivity.

For estimates of the drawdown beneath wetlands the Theis equation has been used to estimate the drawdown due to a) abstracting the maximum daily rate over a period until the annual licensed quantity is reached or b) at the average daily rate for 365 days.

Regional numerical groundwater model

If a suitable model is already available, or if a high degree of confidence is essential, then a numerical groundwater model can be used to apportion the flow impacts. This is achieved by performing prediction runs with the proposed abstraction included in the model with all the existing abstractions, and will probably require help from a specialist groundwater modeller

2.2.3 The Environment Agency's analytical spreadsheet tool for estimating the impact of groundwater abstraction on river flows (IGARF)

IGARF is a spreadsheet-based tool developed for estimating the impact of groundwater abstraction on river flows. The analytical solutions in the most recent version (IGARF1 v4) are for two infinite straight line rivers in an infinite homogeneous aquifer system and are based on work by: Theis (1941), Hantush (1965) and Hunt (1999) as described in the review by Jackson (2004).

IGARF1v4 allows the user to:

- consider the impact of a groundwater abstraction on one or two infinite rivers;
- specify the relative positions of the river(s), boundary and well;
- consider continuous and periodic pumping regimes;
- obtain river flow depletion predictions in time and space;
- provide an audit trail for their model.

2.2.4 The Environment Agency's analytical spreadsheet tool for estimating the impact of groundwater abstraction on flows in multiple rivers (SPIGARF)

This tool estimates the impact of a groundwater abstraction in terms of the depletion in river flow multiple rivers or multiple reaches of a river. The impact is calculated for a specific time. SPIGARF has only been released as a beta version and is not in general operational use (Environment Agency, 2002a).

2.3 General description of the use of OO techniques in engineering applications

The current known developers of OO applications in environmental modelling are summarised in Table 1. The table shows that the majority of developers are based in universities and are developing a range of OO applications. A literature review of the use of OO techniques has been undertaken and is summarised in Appendix A. Again, the use of OO techniques is varied, covering a number of different fields, with no one type of application predominating.

The following sections describe the application of OO techniques to both surface water and groundwater flow modelling.

Table 1 Summary of OO code development

Organisation	Description	Contact
Centre for Computational Fluid Dynamics (CFD) studies/Earth Sciences University of Leeds, Leeds, UK	Generalised FEM model to solve PDE of a "diffusion" type	S D Harris
Dept of Computational Science/Civil and Mechanical Engineering, Queens University, Belfast, UK	Applying OO techniques to Engineering Design	Prof. Stan Scott
Dept of Civil Engineering, University of Newcastle-Upon-Tyne, UK	NOAH-1D Hydraulic network modelling (http://www.ncl.ac.uk/noah/)	Dr V Kutija
Manchester School of Engineering, Manchester, UK	River Water Quality Modelling	Dr D Chen, Dr M Cotton
Colorado Advanced Software Institute/Dept of Geology and Engineering Geology, Colorado School of Mines, Golden, CO, USA	Development of OO reactive transport model	Prof W Hanson
Tessella, Abingdon, Oxon, UK	Time dependent Probabilistic Safety Assessment System, developed for AEAT. Modelling system for assessment of nuclear repositories	Via website: http://www.tessella.org/
Vector space programming, Fremont, CA, USA	OO-based FEM modelling library	Via website: http://www.vector-space.com/
Eco-metrics Inc., University of Montana, USA	RIFLS-2 model of floodplain hydrology, hydrogeology and biocomplexity	Geoffrey Poole
University of North Carolina, USA	Surface Water OO Modelling system (SWOOMS) for Neuse River Estuary, NC	R Luettich et al.
University of Georgia, USA	Tim, an OO Analytical Element groundwater flow and transport model	Mark Bakker
University of Illinois, USA	Pattern language for developing OO Frameworks	D Roberts and R Johnsen
South Florida Water Management District	OO replacement for the South Florida Water Management Model (SFWMM), which is know as the South Florida Regional Simulation Model (SFRSM). Currently under development, the SFRSM is capable of modelling runoff-routing and groundwater flow in combination	Via website: http://www.sfwmd.gov/

2.4 Use of OO techniques in water resources modelling

The use of OO techniques within surface water, groundwater and GIS is extensive. Whilst the wider computing community have been using OO techniques commonly since the 1980s, the potential for water resources applications was recognised in the mid-1990s (e.g. Larsen and Gavarnovic, 1994; Wurbs, 1994). Since then, in terms of user interfaces, relational databases and GIS systems, OO techniques have been widely adopted (Murray, 2003). However the use of OO techniques in the solution of the partial differential equations (PDEs), i.e. the model code itself, has been more limited. This is probably because of the legacy effect whereby developers are tied to a particular software because of the large amount of time and effort invested in developing the model code.

2.4.1 Surface water modelling

Hydroinformatics is defined as 'the handling of the flow of information and knowledge within hydrology and hydraulics for all its aspects'. OO techniques have been used in this subject area since the mid-1990s. The application of OO techniques to hydroinformatics can be divided into three types:

1. Treating models as complete objects.

2. Data manipulation tools.

3. Model engine/solution methods.

Examples of treating models as complete objects include Alfredsen (2000) who based a system of linked river models on COM[1] and Cate et al. (1998) who used CORBA[2] technology to provide a framework for linking models. Various user interfaces and data manipulation tools have been written in OO codes. Examples include Deckers (1994) who uses a proprietary GIS system to couple user interface, GIS and databases into a single application and McKinney and Cai (2002) who linked water resources models with GIS using OO techniques. The more recently developed, and less widespread use of OO techniques is for the solution of the PDEs themselves. A good example of the use of OO techniques in river modelling is NOAH (Kutija, 1998), which is a 1-D river model developed at Newcastle University.

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[1] COM (Component Object Model) is a standard by which applications can expose objects to the system for use by other applications and, conversely, by which applications can use objects that have been exposed by other applications. COM is Microsoft's object-oriented programming model that defines how objects interact within a single application or between applications.

[2] The Common Object Request Broker Architecture (CORBA) is a set of specifications designed to support platform and language-independent, object-oriented distributed computing. It is similar in purpose to Microsoft's Distributed Component Object Model (DCOM). While DCOM is a proprietary technology, CORBA was devised by an assembly of over 800 corporations in the computing industry known collectively as the Object Management Group (OMG).

2.4.2 Groundwater modelling

Various organisations have expressed a wish to develop OO groundwater flow and solute transport models but, with few notable exceptions, there has been very little development. For example, Havnø et al. (2001) express an interest on behalf of DHI in developing an object-oriented groundwater model. Whilst no models have yet been released, DHI have been working on MIKE-Objects, which is a COM based set of objects. The current (February 2005) set of MIKE-Objects are for time series plotting.

The main exception to this is the Tim project, which is driven by Mark Bakker (see Table 1). The Tim project is an open-source, analytical elements based OO groundwater modelling system written in the OO programming language Python. It has a large degree of functionality and can model wells, line sinks and ponds. Currently two versions of Tim exist; a single layer, steady-state and time-variant version, called TimSL, and a multi-layer, steady-state version, called TimML. TimSL is no longer supported. All of these codes are available from the Tim website (www.engr.uga.edu/~mbakker/tim.html).

The South Florida Regional Simulation Model (SFRSM) is currently being developed as a replacement of the South Florida Water Management Model (SFWMM). The SFRSM aims to exploit the most recent advances in computing, including OO techniques. It is stated (www.sfwmd.gov/org/pld/hsm/hsm.html) that the OO based SFRSM will only replace the SFWMM after "years of development and testing". The current version of the SFRSM is a finite-element groundwater flow model and uses a triangular mesh. Runoff routing is incorporated into the model (Wasantha Lal et al., 1998).

Work on the SFRSM started in 1994 (Larrendo-Petrie and France, 1995) when the OO framework for the model was defined using domain analysis. Development of the model code has continued and functionality has been added to the model in stages. The most current status of the model is summarised in Brion et al. (2001), which describes the application of the model to the Southern Everglades.

2.5 Linking surface water and groundwater models

Linking surface water and groundwater models falls into two categories: fixed, hard coded systems and flexible systems that allow different models to interface with each other. Fixed systems can consist of models "hard-wired" together or single codes, such as MIKE-SHE. The OpenMI interface standard developed by the HarmonIT project (www.harmonit.org) is an example of a flexible system, which enables run-time linking of different simulation models.

Object-orientation offers the potential to allow the linking of surface water objects with groundwater objects more readily than other techniques. Examples of converting existing code into objects by "wrapping" an existing procedural code in an OO code exist in Hydroinformatics (Alfredsen, 2000) and are being developed in the HarmonIT project (see below). However, one of the real benefits of objects could be realised by providing a hydrological framework within which models of different parts of the hydrological system could be linked. As in the OpenMI standard, a suitable interface can be defined for the linking of each object.

2.5.1 Integrated groundwater surface water models

The vast majority of commonly used integrated groundwater surface water models are produced by either writing model codes, which have all the required features (e.g. MIKE-SHE) or by linking existing models, e.g. IHM (www.intera.com) which couples MODFLOW and HSP-F. Table 2 summarises the most commonly used types of integrated surface water-groundwater models. Of those models listed, two are based on MODFLOW; MODHMS which derives from MODFLOW-SURFACT, and IHM which couples MODFLOW and HSP-F (http://water.usgs.gov/software/hspf.html). Wash123D, developed by Professor Yeh at the University of Central Florida, is a Finite Element code and builds on FEMWATER (http://dino.wiz.uni-kassel.de/model_db/mdb/femwater.html). IHSim (http://www.modhms.com/software/IHSim.html) is another finite element code, which has the equivalent features of MODHMS. MIKE-SHE has been developed by the Danish Hydrological Institute (DHI) and uses MIKE-11 to model river flow in combination with a bespoke groundwater flow model. The complexity of the model representing each component of the hydrological cycle can be chosen depending on the understanding of the system and the demands of the modelling study. A short description of some of the codes used to simulate river-aquifer interaction is presented in Appendix B

Table 2 Summary of combined surface water and groundwater models

Model	Developer	Description	Website
MIKE-SHE	DHI	Fully featured code that models rainfall-runoff, unsaturated zone, saturated zone and river flow (MIKE11)	www.dhisoftware.com/mikeshe
MODHMS	Hydrogeologic	Based on MODFLOW-SURFACT, but includes 2-D overland flow and 1-D channel flow	www.modhms.com/software.htm
IHSim	Hydrogeologic	Finite Element version of MODHMS	www.modhms.com/software.htm
IHM	Intera, AQUATERRA and the University of South Florida	Couples MODFLOW with the surface water code Hydrologic Simulated Program (Fortran) or HSP-F	www.intera.com/techology_ihm.php
SFWMD & SFHSM	South Florida Water Management District	See description above	www.sfwmd.gov/org/pld/hsm/hsm.html
Wash123D	Professor George Yeh, Uni of Central Florida	FEM model (based on FEMWATER) coupled with 1-D river and 2-D overland surface flow models	http://people.cecs.ucf.edu/yeh/

2.5.2 HarmonIT

HarmonIT is an EU funded project (www.harmonit.org) whose goal has been "to develop, implement and prove a European Open Modelling Interface and Environment (OpenMI) that will simplify the linking of models and hence allow catchment managers to explore the likely outcomes of different policies". The project has provided a common interface between models of different types that is specified by the OpenMI standard (www.openmi.org). Prototype OpenMI compliant models have been produced and linked river flow and groundwater model demonstrations have been undertaken.

The OpenMI standard defines a series of protocols that enable models to pass data in the correct format and to allow the control of models' time stepping (Gijsbers et al., 2005). The system is set up as a cascade of models with one "master" model controlling the simulation process. For a model of any description to be OpenMI compliant it requires an interface written in C# or Java. This interface handles the passing of data to and from the model and their run-time control.

2.6 Research catchments improving the understanding of river-aquifer interaction

Two NERC programmes exist under the National Infrastructure for Catchment Hydrological Experiments (NICHE) umbrella: Catchment Hydrology and Sustainable management (CHASM) and LOwland CAtchment Research (LOCAR). Both are funded through the NERC Joint Infrastructure Fund (JIF), but LOCAR is a NERC thematic programme and research grants have been awarded. CHASM investigates features of upland catchments whilst LOCAR compliments this by studying lowland catchments.

2.6.1 LOCAR thematic programme

The major objective of LOCAR is stated as "to undertake detailed, interdisciplinary programmes of integrated hydro-environmental research relating to the input-storage-discharge cycle and in-stream, riparian and wetland habitats within groundwater dominated systems." (www.nerc.ac.uk/LOCAR). One of the main aims is to determine the key hydrological processes controlling surface water-groundwater interactions, the movement of groundwater, and material fluxes in lowland permeable catchments. There are two parts to LOCAR, the instrumentation of the research catchments, funded by JIF, and the research grants distributed by NERC.

As the foundation for the research three catchments have been instrumented:

1. Pang and Lambourn, Berkshire.
2. Frome-Piddle, Dorset.
3. Tern, Shropshire.

The monitoring infrastructure in the LOCAR catchments includes facilities to study river-aquifer interaction, for example arrays of boreholes in close proximity to rivers.

Of the LOCAR projects commissioned by NERC, two have direct significance to this work. These are entitled "Hydrogeochemical functioning of lowland permeable catchments: from process understanding to environmental management", led by Professor Wheater at Imperial College and, "Investigating stream-groundwater interactions in lowland chalk catchments using hydrogeophysical characterisation of the riparian zone", led by Dr Binley at Lancaster University. The findings of the LOCAR research projects have been published in a special edition of the Journal of Hydrology (2006, Vol 330, Issue 1-2).

2.6.2 CHASM

CHASM is a framework with which to undertake research on hydrological processes operating within a catchment (wrsrl.ncl.ac.uk/chasm/WEB/). Unlike LOCAR no funding for research projects has been provided by NERC, so funding is achieved through piecemeal bidding into existing research programmes. The stated aims are to undertake experiments at a scale between the normal experimental scale and the catchment scale. CHASM also aims to promote hydroecological research. To fulfil the research aims, four upland catchments were chosen:

1. Oona, Northern Ireland.
2. Feshie, Eastern Scotland.
3. Eden valley, Cumbria.
4. Upper Severn, Wales.

2.7 Summary

Since the mid-1990s, OO techniques have been recognised as providing significant benefits to hydrological modelling. OO techniques have been applied in many different environmental modelling fields. In hydroinformatics, the discipline that covers surface water modelling, the use of OO techniques is widespread, but predominantly for data preparation and visualisation and linking models rather than for the simulation. However, NOAH 1D is a good example of an OO river modelling system. There has been a limited uptake of OO techniques into groundwater flow modelling, ZOOMQ3D (Jackson and Spink, 2004) excepted. The best examples are the Tim project, an OO analytical element code and the South Florida District model development.

In terms of modelling river-aquifer interactions, integrated groundwater-surface water models exist, both as bespoke code, e.g. MIKE-SHE and linked models e.g. IHM, which combines MODFLOW and HSP-F. HarmonIT is a EU funded project, which has developed a flexible system for linking existing models together. Work, however, has to be undertaken in developing the interface for the particular model. HarmonIT offers the opportunity to investigate the problems that occur when models of different types interact.

Finally, the research catchments instrumented as part of the LOCAR and CHASM programmes and the associated research offer the opportunity to advance the understanding of river-groundwater interaction. The findings of the LOCAR research projects have been published in a special edition of the Journal of Hydrology (2006, Vol 330, Issue 1-2).

3 IMPACT MODELLING

3.1 Purpose of impact modelling

At the outset of the project the term *impact modelling* was considered to refer to the development of numerical models to assess the impact of abstraction on river flows which *did not* incorporate recharge. The description of this task relating to impact modelling as defined in the project specification is reproduced in the following box:

Project specification: Task 4 – ZOOMQ3D as an impact model

During this task ZOOM impact models will be developed with and without recharge to test how well the "no recharge" model predicts impacts. The estimates of the impacts of abstraction will be compared to existing methods.

The details of the approach for developing a "no recharge" ZOOMQ3D model will be agreed at the start up meeting but it will be based on the initial model having the following characteristics:

- Time-variant.
- No recharge.
- Horizontal steady-state initial heads.
- Uniform river stage and river bed elevation.
- Uniform hydraulic properties.
- Abstractions will be added and the difference in heads and river flows from the model without abstraction will be calculated.

The current analytical tools IGARF 1 (Environment Agency, 2001) and SPIGARF (Environment Agency, 2002a), developed by the Environment Agency, estimate impacts by calculating differences in groundwater levels (drawdown) and river flows. IGARF 1 distributes the timing of the impact but assumes that the whole impact is on a single stream. SPIGARF estimates the spatial distribution of the impacts. The EA/BGS technical team will set up ZOOMQ3D as an impact predictive tool by estimating these same differences. For example, starting heads would be flat, there would be no recharge and boundary conditions would be no flow. Best estimates of river coefficients will be used for river/aquifer interaction. These can be based on field observations (accretion profiles), experience of similar rivers elsewhere or values used in regional models.

Cross-boundary flows cannot be represented with flat heads since there is no gradient. If ignoring regional groundwater flow is significant, we will investigate how the error can be minimised, e.g. by extending the impact model to the real physical boundaries. Although for some aquifer systems, e.g. the southern Chalk, the models could then be as large as a river basin district.

The intention was to use these impact models to calculate river flow depletion rates and then compare the results with those calculated using models incorporating recharge. In this manner it was planned to investigate the situations in which it is necessary to include aquifer recharge when calculating the impacts of groundwater abstraction on river flows if adequate results are to be produced. The impacts of abstraction are calculated by examining the difference between the results of two simulations; one in which the abstraction borehole, for which the impact is to be quantified, pumps and one in which it is switched off.

Whilst the aims of impact modelling task, as it was first construed, were worthwhile, the scope of the *impact modelling* was modified slightly during the project. Instead of focusing predominantly on the importance of the representation of aquifer recharge in impact assessment, models have been developed to investigate the effect of incorporating, or not, a number of different hydrogeological features. These features are frequently encountered during groundwater modelling investigations.

In this section the results of the numerous impact models are presented and conclusions drawn relating to the hydrogeological features that must be represented in numerical models if satisfactory predictions of groundwater abstraction impacts are to be derived. The development and application of the models must be considered within the constraints of time generally imposed when, for example, hydrogeologists use numerical models to assess the impacts of abstraction on river flows. In the following sub-sections of Section 3, the following features are considered with the aim of assessing whether it is important to incorporate them in numerical models used for impact assessment:

- number of surface water catchments;
- spatial and temporal variation of aquifer recharge;
- accurate river elevations;
- transmissivity varying with saturated aquifer thickness;
- cross-boundary flows and model boundary conditions;
- vertical variations of horizontal hydraulic conductivity;
- catchment size.

3.2 Structure of impact models

During this impact modelling exercise, several simple but different models (named A1, A2, A3, A4, B1, C1 and C2) are used to assess the impacts of groundwater abstraction on river baseflow under a number of different conditions. These models are used to assess the importance of including, or correctly representing, different aquifer features when they are to be used for prediction. The structure of each model is described below. The values assigned to the hydraulic parameters in each model are described when the individual simulations are discussed. In Figure 2 to Figure 8 the blue lines represent rivers or streams and the red dots abstraction boreholes.

3.2.1 Model A1

A plan view of model A1 is shown in Figure 2. The details of the model are listed below.

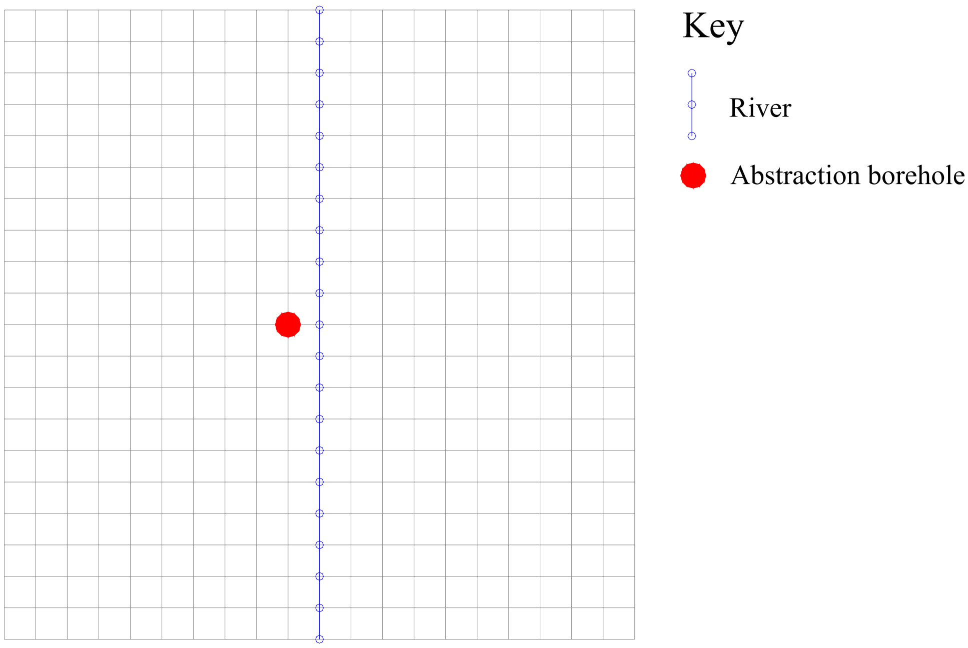


Figure 2 Structure of model A1

Model A1 details

- Width and length: 5 km by 5 km.
- Mesh size: 250 m square.
- Number of layers: 1.
- Abstraction borehole at (2250 m, 2500 m) i.e. 250 m from river.
- Flat river profile.
- River stage 100 m above datum (base of aquifer).
- Bed elevation = 99 m above datum.
- River flows from north to south along x = 2500 m.
- Boundary conditions: all no-flow.

3.2.2 Model A2

A plan view of model A2 is shown in Figure 3. The details of the model are listed below.

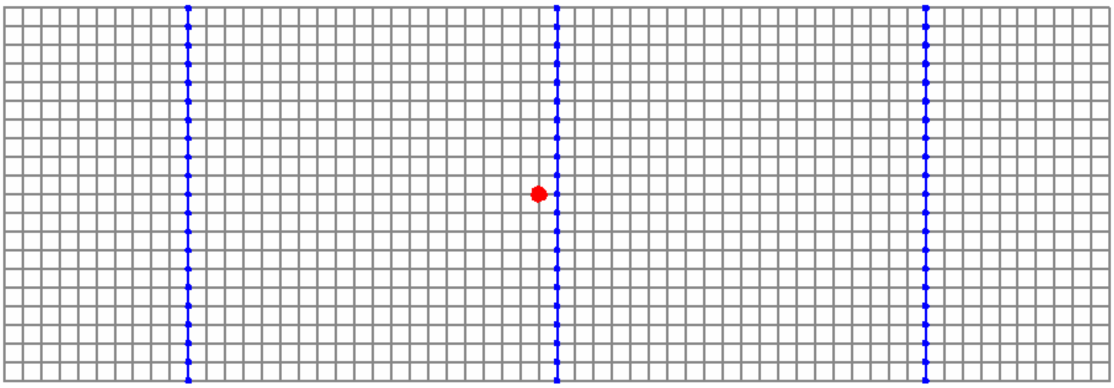


Figure 3 Structure of model A2

Model A2 details

- Width and length: 15 km by 5 km.
- Mesh size: 250 m square.
- Number of layers: 1.
- Abstraction borehole at (7250 m, 2500 m) i.e. 250 m from the central river.
- Rivers flow north to south along x = 2500 m, x = 7500 m, x = 12500 m.
- Flat river profiles.
- River stage 100 m above datum (base of aquifer).
- Bed elevation = 99 m above datum.
- Boundary conditions: all no-flow.

3.2.3 Model A3

A plan view of model A3 is shown in Figure 4. The details of the model are listed below.

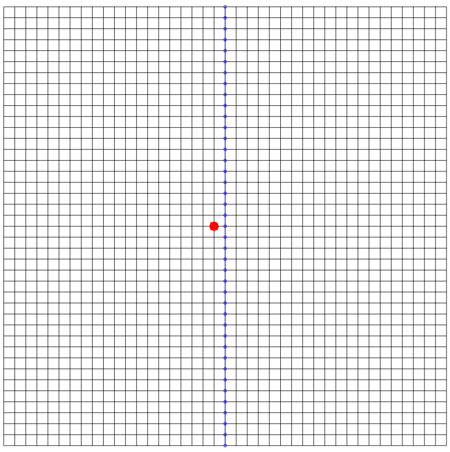


Figure 4 Structure of model A3

Model A3 details

- Width and length: 10 km by 10 km.
- Mesh size: 250 m square.
- Number of layers: 1.
- Abstraction borehole at (4750 m, 5,000 m) i.e. 250 m from river.
- Flat river profile.
- River stage 100 m above datum (base of aquifer).
- Bed elevation = 99 m above datum.
- River flows from north to south along x = 5,000 m.
- Boundary conditions: all no-flow.

3.2.4 Model A4

A plan view of Model A4 is shown in Figure 5. The details of the model are listed below.

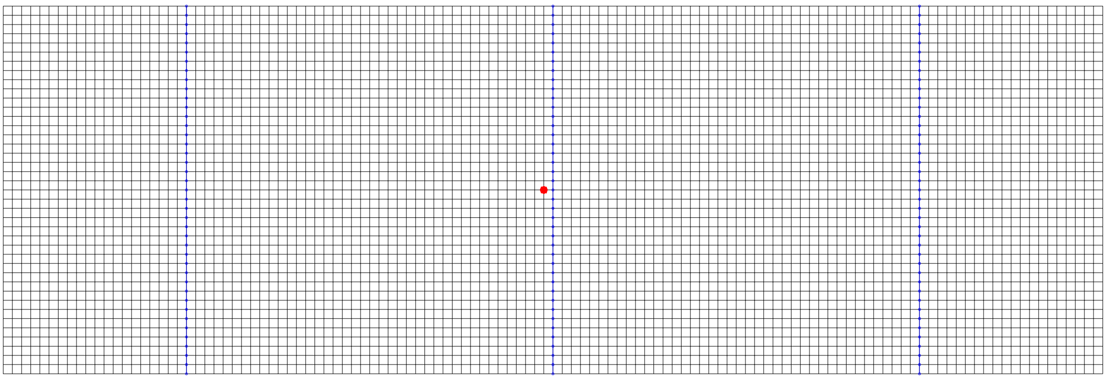


Figure 5 Structure of model A4

Model A4 details

- Width and length: 30 km by 10 km.
- Mesh size: 250 m square.
- Number of layers: 1.
- Abstraction borehole at (14750 m, 5,000 m) i.e. 250 m from the central river.
- Rivers flow north to south along x = 5000 m, x = 1500 m, x = 25,000 m.
- Flat river profiles.
- River stage 100 m above datum (base of aquifer).
- Bed elevation = 99 m above datum.
- Boundary conditions: all no-flow.

3.2.5 Model B1

A plan view of Model B1 is shown in Figure 6. The details of the model are listed below.

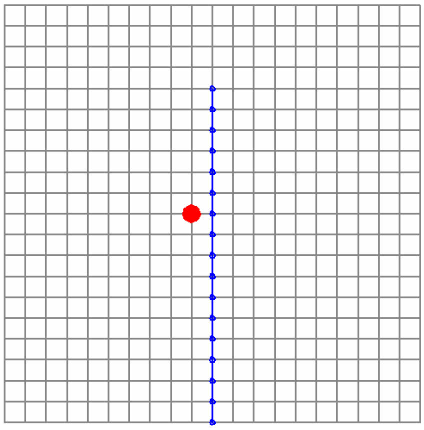


Figure 6 Structure of model B1

Model B1 details

- Width and length: 5 km by 5 km.
- Mesh size: 250 m square.
- Number of layers: 1.
- Abstraction borehole at (2250 m, 2500 m) i.e. 250 m from river.
- Flat river profile.
- River stage 100 m above datum (base of aquifer).
- Bed elevation = 99 m above datum.
- River rises at (2500 m, 4000 m) i.e. within the model domain.
- River flows from north to south along x = 2500 m.
- Boundary conditions: all no-flow.

3.2.6 Model C1

A plan view of model C1 is shown in Figure 7. The details of the model are listed below. The red line illustrates the boundary of the sub-model C2, which represents this central area of the larger model C1.

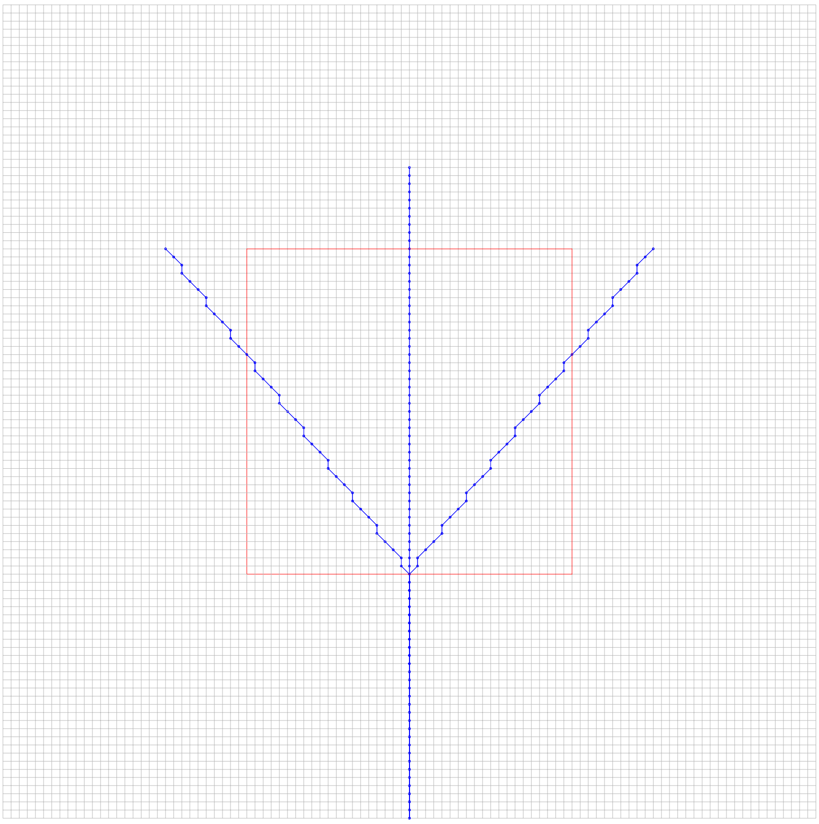


Figure 7 Structure of model C1

Model C1 details

- Width and length: 10 km by 10 km.
- Co-ordinate of south west corner: (0 m, 0 m).
- Mesh size: 100 m square.
- Number of layers: 1.
- Boundary conditions: Impermeable except along the bottom boundary where fixed heads of 100 m are specified and along the top boundary where a specified flow into the model is defined. This specified flow is distributed uniformly along the boundary and is equivalent to 2 m^3day^{-1} per metre length of the top boundary. Therefore, the total flow across this boundary is 20,000 m^3day^{-1}.
- Abstraction borehole at (4500 m, 5500 m) i.e. 500 m from central river.
- Flat river profile with river stage 100 m above datum (base of aquifer) and bed

elevation 99 m above datum.

3.2.7 Model C2

A plan view of model C2 is shown in Figure 8. The details of the model are listed below.

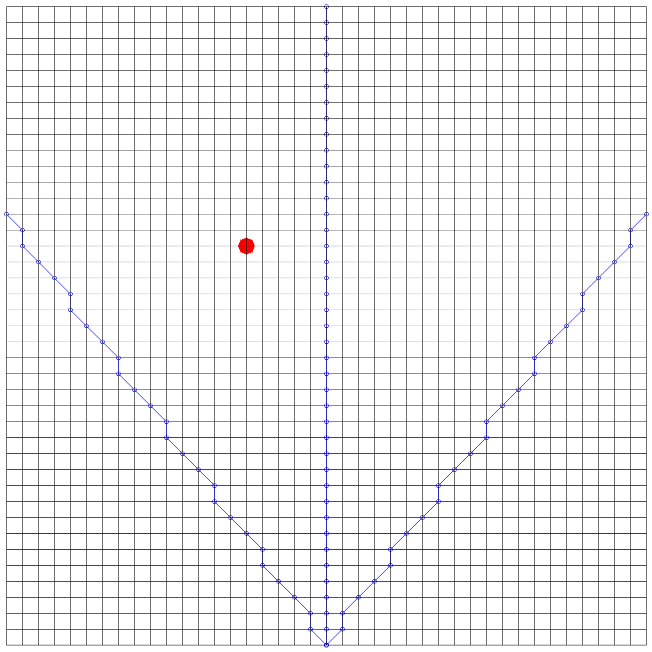


Figure 8 Structure of model C2

Model C2 details

- Width and length: 4 km by 4 km.
- Co-ordinate of south west corner: (3000 m, 3000 m).
- Mesh size: 100 m square.
- Number of layers: 1.
- Abstraction borehole at (4500 m, 5500 m) i.e. 500 m from central river.
- Flat river profile with river stage 100 m above datum (base of aquifer) and bed elevation 99 m above datum.
- Boundary conditions: dependent on model simulation.

3.3 The representation of river-aquifer interaction in ZOOMQ3D

In ZOOMQ3D river-aquifer interaction is represented as a linear head-dependent leakage mechanism. The rate of leakage depends on the difference between groundwater head and river stage and is expressed by

$$Q_z = \frac{K_z}{B} \cdot W \cdot L \cdot (h_a - h_r)$$

where

Q_z is the leakage rate ($m^3 day^{-1}$)

K_z is the vertical hydraulic conductivity of the river bed ($m\ day^{-1}$)

B is the thickness of the river bed (m)

W is the width of the river (m)

L is the length of the river reach (m)

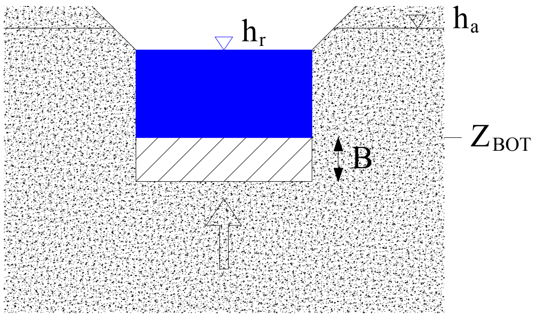
h_a is the head in the aquifer (m)

h_r is the river stage (m)

This equation is modified when the head in the aquifer falls below the base of the river bed, $(Z_{BOT} - B)$, where Z_{BOT} is the elevation of the bed of the river. Under these conditions, the driving head is equal to the difference between the river stage and the base of the river bed, $(Z_{BOT} - B)$. The leakage from the river under perched conditions is therefore defined as

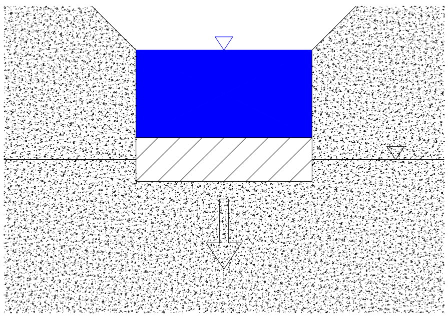
$$Q_z = \frac{K_Z}{B} \cdot W \cdot L \cdot [(Z_{BOT} - B) - h_r]$$

In addition to limiting the flow between the aquifer and the river when the groundwater head falls below the river-bed, different hydraulic conductivity values are applied between influent and effluent conditions. The difference reflects the seepage force applied to the bed material and the associated increase in permeability when groundwater is discharging to the river. However, in the Excel spreadsheet developed to run the ZOOMQ3D model and calculate depletion rates (described in Section 4), a single vertical hydraulic conductivity value is applied under both influent and effluent river leakage conditions. The different relative positions of the river stage and groundwater head are shown in Figure 9. The appropriate vertical flow equation representing the interaction is presented next to each scenario.



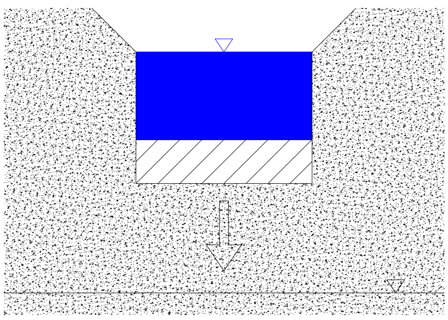
a) Influent river.

$$Q_z = \frac{K_Z^I}{B} \cdot W \cdot L \cdot (h_a - h_r)$$



b) Effluent river. Groundwater head above the base of the river bed, $(Z_{BOT} - B)$, but below river stage

$$Q_z = \frac{K_Z^E}{B} \cdot W \cdot L \cdot (h_a - h_r)$$



c) Effluent river. Groundwater head below base of the river bed, $(Z_{BOT} - B)$

$$Q_z = \frac{K_Z^E}{B} \cdot W \cdot L \cdot [(Z_{BOT} - B) - h_r]$$

Q_z	is the flow rate ($m^3 day^{-1}$) from the aquifer to the river
K_Z^E	is the vertical hydraulic conductivity of the river bed ($m\ day^{-1}$) under effluent river conditions
K_Z^I	is the vertical hydraulic conductivity of the river bed ($m\ day^{-1}$) under influent river conditions
Z_{BOT}	is the elevation of the bed of the river
B	is the thickness of the river bed (m)
W	is the width of the river (m)
L	is the length of the river reach (m)
h_a	is the head in the aquifer (m)
h_r	is the river stage (m)

Figure 9 Formulation of river-aquifer interaction under influent and effluent conditions

3.4 Impact model runs

In this section a number of different numerical groundwater flow models are used to examine the effect of varying different aquifer parameters on the impact of groundwater abstraction on river baseflow over time. The series of simulations are listed in Table 3. Each of these series of runs is used to investigate the influence of changes to a particular model feature on the impact of a borehole. For example, in one of the series of simulations the effect of varying the value assigned to the hydraulic conductivity of an unconfined aquifer is examined. Table 3 lists the number of the report section in which each series of simulations is discussed.

Table 3 Summary of impact model runs

Series	Purpose of series of model runs	Report section
1	To examine the effect of modelling single or multiple river catchments	3.4.2
2	To examine the effect of applying or not applying recharge	3.4.3
3	To examine the impact of different representations of rivers rising within the groundwater model domain	3.4.4
4	To examine the effect of the different elevations of multiple rivers	3.4.5
5	To examine the effect of simulating unconfined aquifer conditions	3.4.6
6	To examine the effect of the different representation of boundary conditions	3.4.7
7	To examine the effect of different VKD profiles on depletion rates	3.4.8
8	To examine the effect of different VKD profiles on depletion rates	3.4.9
9	To examine the effect of the spatial variation of recharge	3.4.10
10	To examine the effect of the temporal variation of recharge	3.4.11
11	To examine the effect of the size of the catchment modelled	3.4.12

3.4.1 Method of calculating river depletion caused by groundwater abstraction

The impact of an abstraction borehole on a section of river is termed the *depletion rate* in this report and is a function of time since the start of pumping. This depletion rate is calculated by comparing the difference in river leakage between two simulations; one in which an abstraction borehole pumps and one in which it does not. The procedure for calculating the depletion rate is as follows:

1. Run a simulation in which the abstraction borehole for which the impact is to be quantified does not pump during the simulation period.

2. For each time step of this simulation, record the leakage rate between the aquifer and the river at each finite difference node along the section of river for which the impact is to be quantified. The sign of these nodal leakage rates will differ between effluent and influent river conditions.

3. Sum these leakage rates to obtain a total leakage rate for the section of the river for each time step of the simulation.

4. Re-run the model with the abstraction borehole pumping at a constant rate from the start of the simulation period.

5. Perform steps 2 and 3 for this simulation run.

6. Subtract the total leakage rate for the simulation in which the borehole does not pump from that when it pumps, for each time step of the simulation.

7. The difference between the two total leakage rates is the depletion rate. The depletion rate is plotted against time as illustrated in Figure 10.

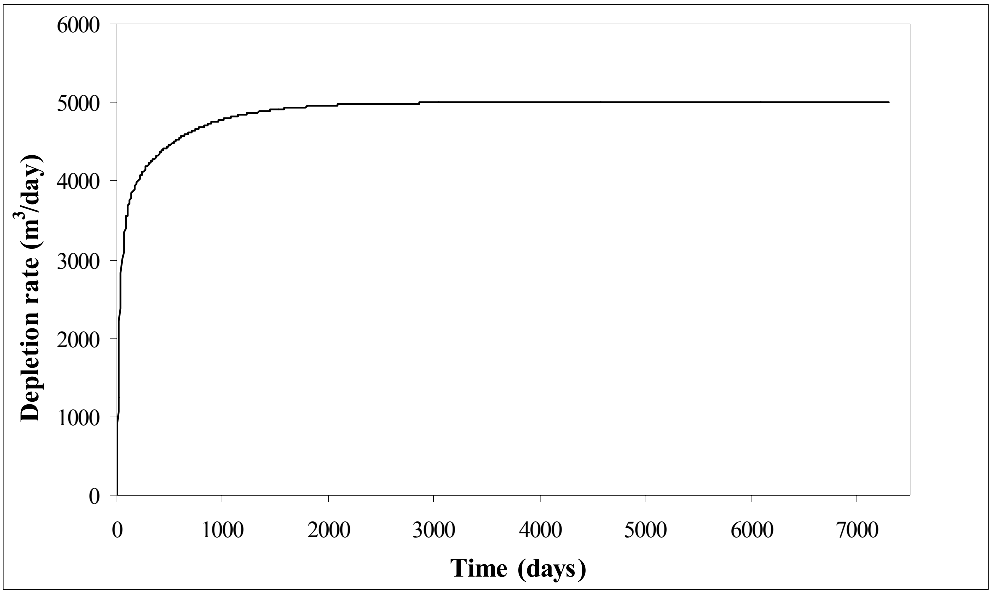


Figure 10 Example plot of river depletion rate against time

3.4.2 Impact modelling: Series 1. How many catchments should be modelled

Models used in this series

The two models used in this series of runs are A1 and A2, which are described in Section 3.2. Model A1 contains a single flat straight-line river running from north to south through its centre. Model A2 includes two additional and identical river catchments to the west and east of this central river catchment.

Purpose of this series of simulations

In this first series of simulations, the two models are used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. The effect of representing either a single or multiple river catchments is investigated. This is performed to assess the magnitude of the errors that may be produced by a numerical model that considers that all the water pumped from a borehole derives from the nearest river. This will be the case if the numerical model only includes a single river catchment as in model A1. In reality, abstraction from a pumped well can reduce the flow of groundwater to rivers in other surface water catchments, which may also be located within other groundwater catchments. This is possible because abstraction from the pumping well will cause a cone of depression to continue to spread until it has stopped an equal amount of water from leaving the aquifer. Hence the drawdown frequently spreads into adjacent groundwater catchments so that the groundwater heads are depressed and the flows to the rivers are reduced. An explanation of this is given in the conclusions for this series of runs.

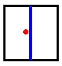
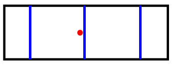
Summary of the model runs

The only difference between the two models in this series of simulations is that model A2 incorporates two additional river catchments. The following parameters are the same in the models A1 and A2.

- no recharge;
- elevation of base of aquifer: 0 m;
- flat river with elevation: 100 m;
- constant transmissivity of aquifer: 500 m^2day^{-1};
- homogeneous aquifer with storage coefficient of 10%;
- initial groundwater head: 110 m throughout model domain;
- initial flow along each river and inflow at top of each river: 50,000 $m^3day^{-1;}$
- depletion rates are calculated over the full length of river closest to the abstraction borehole i.e. the central river in model A2.

Five simulations are performed using model A1 and five using model A2. In each set of five, abstraction is increased from zero to 40,000 m^3day^{-1} between the runs. The impact of abstraction on river baseflow is calculated by comparing the simulation with abstraction with that without abstraction. The simulation runs performed in this series are summarised in Table 4.

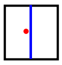
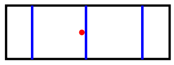
Table 4 Summary of Series 1 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	Recharge rate ($mmday^{-1}$)
S1_1	A1		0	0
S1_2	A1		5,000	0
S1_3	A1		10,000	0
S1_4	A1		25,000	0
S1_5	A1		40,000	0
S1_6	A2		0	0
S1_7	A2		5,000	0
S1_8	A2		10,000	0
S1_9	A2		25,000	0
S1_10	A2		40,000	0

Results from this series of simulations

Comparison 1.1

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 m^3day^{-1}.

		
Run	S1_2	S1_7
Abstraction rate	5,000 m^3day^{-1}	5,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

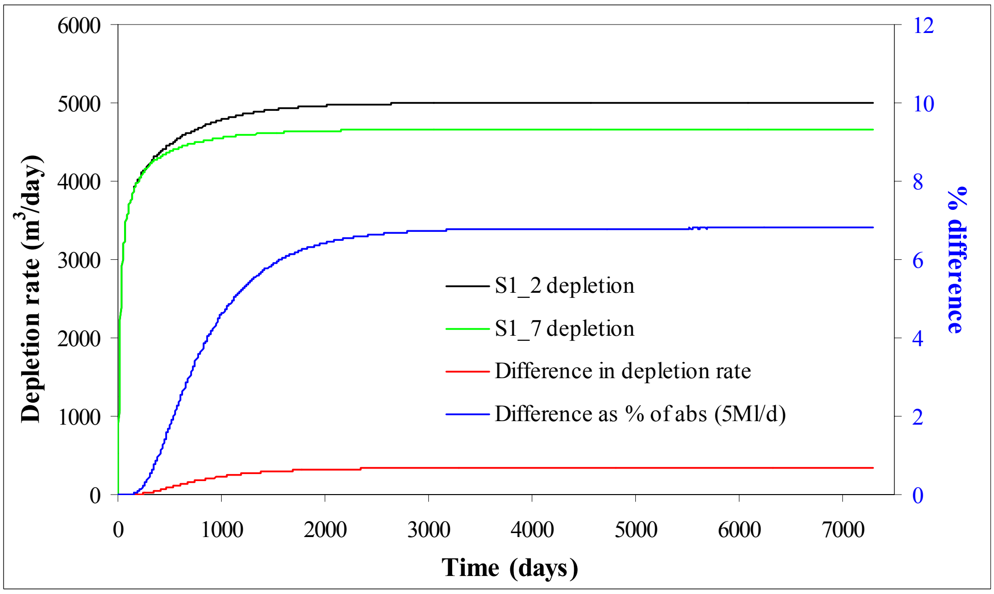


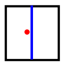
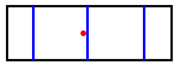
Figure 11 Depletion rates for Series 1 - Comparison 1.1

In model A1 (Run S1_2) the total river depletion increases until a steady-state is reached after approximately 2,800 days of pumping (Figure 11). At later times the abstraction borehole receives all of its water from the river as opposed to some from the river and some from aquifer storage. In the larger model, A2 (Run S1_7), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After steady-state conditions have been reached in the larger model, the abstraction borehole receives only 4,660 m^3day^{-1} of groundwater from the river nearest to it.

Consequently, the depletion rate for the central river in the large model is 340 m^3day^{-1} less than for the single river in the small model, which is equivalent to 6.8% of the pumping rate.

Comparison 1.2

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 10,000 m^3day^{-1}.

		
Run	S1_3	S1_8
Abstraction rate	10,000 m^3day^{-1}	10,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

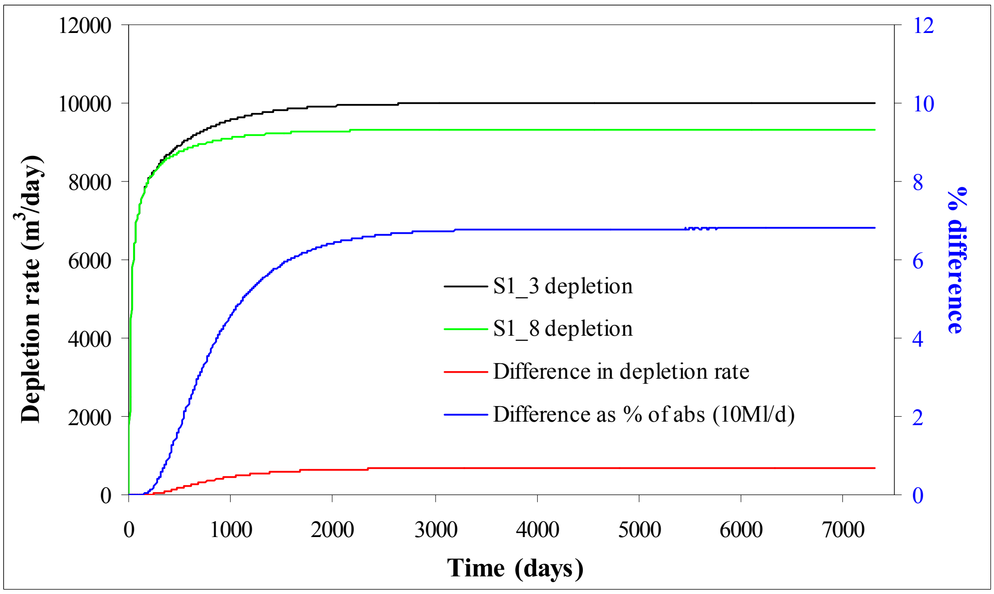


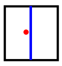
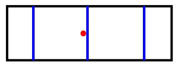
Figure 12 Depletion rates for Series 1 - Comparison 1.2

In model A1 (Run S1_3) the total river depletion increases until a steady-state is reached after approximately 2,800 days of pumping (Figure 12). At later times the abstraction borehole receives all of its water from the river as opposed to some from the river and some from aquifer storage. In the larger model, A2 (Run S1_8), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After steady-state conditions have been reached in the larger model, the abstraction borehole receives only 9,320 m^3day^{-1} of groundwater from the river nearest to it.

Consequently, the depletion rate for the central river in the large model is 680 m^3day^{-1} less than for the single river in the small model, which is equivalent to 6.8% of the pumping rate.

Comparison 1.3

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 25,000 m^3day^{-1}.

		
Run	S1_4	S1_9
Abstraction rate	25,000 m^3day^{-1}	25,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

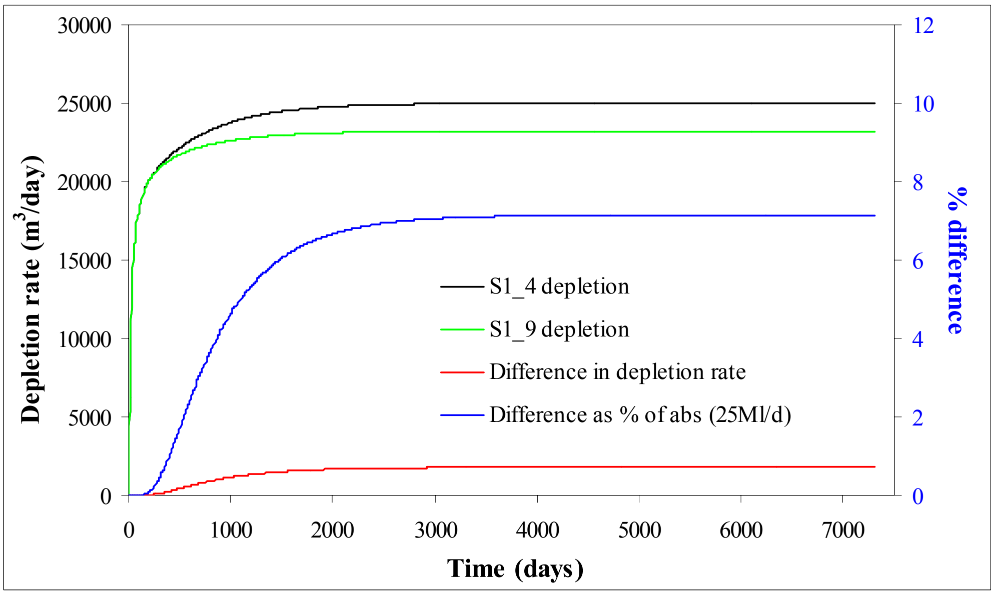


Figure 13 Depletion rates for Series 1 - Comparison 1.3

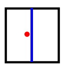
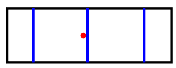
In model A1 (Run S1_4) the total river depletion increases until a steady-state is reached after approximately 2,800 days of pumping (Figure 13). At later times the abstraction borehole receives all of its water from the river as opposed to some from the river and some from aquifer storage. In the larger model, A2 (Run S1_9), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After steady-state conditions have been reached in the larger model, the abstraction borehole receives only 23,210 m^3day^{-1} of groundwater from the river nearest to it.

Consequently, the depletion rate for the central river in the large model is 1,790 m^3day^{-1} less than for the single river in the small model, which is equivalent to 7.1% of the pumping rate.

The increase in the percentage of water that the borehole derives from the peripheral rivers in this simulation, with respect to the previous two comparisons in which the pumping rates were lower, is due to one node of the central river becoming “perched”. With a pumping rate of 25,000 m^3day^{-1} the groundwater head beneath the river, at its nearest point to the borehole, falls below the base of the river. In this case, the leakage from the central river is limited and more water is sourced from the peripheral catchments in model A2. It is shown in the next comparison that with a pumping rate of 40,000 m^3day^{-1} the three central nodes on the central river become perched causing even more water to be sourced from the peripheral catchments due to the limiting of leakage from the central river.

Comparison 1.4

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 40,000 m^3day^{-1}.

		
Run	S1_5	S1_10
Abstraction rate	40,000 m^3day^{-1}	40,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

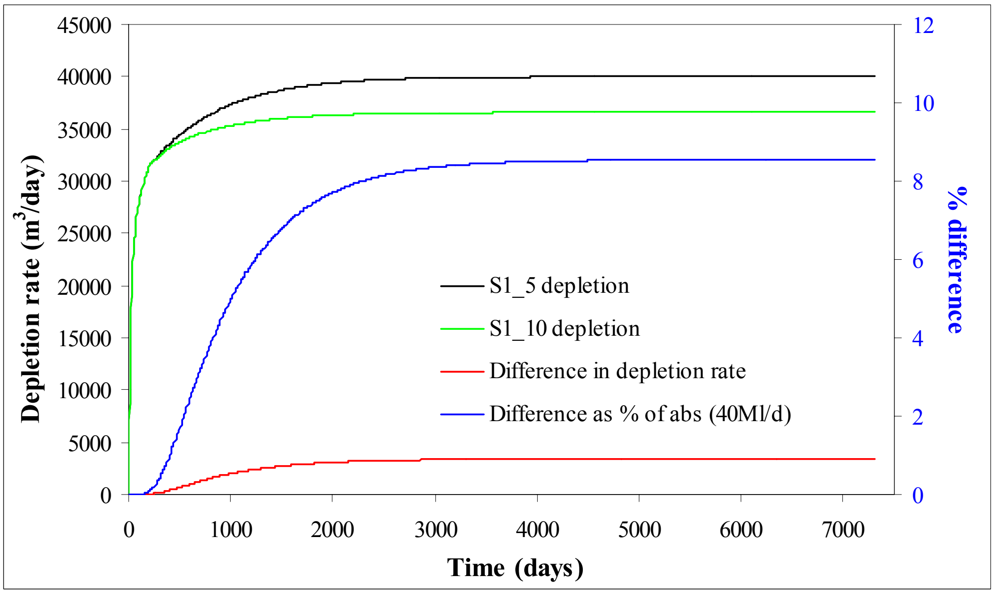


Figure 14 Depletion rates for Series 1 - Comparison 1.4

In model A1 (Run S1_5) the total river depletion increases until a steady-state is reached after approximately 2,600 days of pumping (Figure 14). At later times the abstraction borehole receives all of its water from the river as opposed to some from the river and some from aquifer storage. In the larger model, A2 (Run S1_10), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After steady-state conditions have been reached in the larger model, the abstraction borehole receives only 36,580 m^3day^{-1} of groundwater from the river nearest to it.

Consequently, the depletion rate for the central river in the large model is 3,420 m^3day^{-1} less than for the single river in the small model, which is equivalent to 8.5% of the pumping rate.

As with the previous comparison the increase in the pumping rate to 40,000 m^3day^{-1} causes the groundwater head beneath the river, at its nearest point to the borehole, to fall below the base of the river. In this case, the leakage from the central river is limited and more water is sourced from the peripheral catchments in model A2. In this model the three central nodes on the central river become perched causing more water to be sourced from the peripheral catchments due to the partial limiting of leakage the central river.

Conclusions from Series 1 runs

This first series of simulations has been performed to investigate the magnitude of the errors that could be involved in the calculation of river flow depletion rates if peripheral river catchments are not represented in a model. In each of the comparisons made in this series, the calculated depletion rates are the same in both models until the effects of pumping reach the boundary of the single catchment model. After this time, less water is sourced from the central river by the abstraction borehole in the models containing three rivers.

The magnitude of the difference in depletion rate calculated by the two models, expressed as a percentage of the pumping rate, depends on the rate of abstraction. In the first two comparisons, in which the borehole pumps 5,000 m^3day^{-1} or 10,000 m^3day^{-1}, 6.8% of the water abstracted by the well is drawn from the two outer rivers when steady conditions have been reached. When the abstraction rate is increased to 25,000 m^3 day^{-1} the borehole derives 7.1% of its water from the peripheral river catchments. When the abstraction rate is set to 40,000 m^3day^{-1} the borehole derives 8.5% of its water from the peripheral river catchments.

In the first two models containing three river catchments, in which the borehole pumps at a rate of 5,000 or 10,000 m^3day^{-1}, none of the river nodes become perched. In this case the amount of water that the well derives from the peripheral catchments is the same in both of these models when expressed as a percentage of the pumping rate. In the second two models with three river catchments, in which the borehole is pumped at a rate of 25,000 or 40,000 m^3 day^{-1}, the groundwater level falls below the river bed along a central section of the central river. This results in more water being derived from the peripheral river catchments as a percentage of the pumping rate.

These results are in keeping with the principle in Section 2.4 of the Environment Agency's guidance on how to assess the hydrogeological impact of groundwater abstractions (Environment Agency, 2007 a), which states that *"the effect of the abstraction will spread until it has stopped an equal amount of water from leaving the aquifer (in both confined and unconfined aquifers)"*. This will usually be in the form of reduced discharges (reduced spring flow, reduced baseflow, or reduced seepage).

This subject was addressed 65 years ago by Theis (1940), who stated, "Under natural conditions…previous to development by wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system, and it must be balanced by an increase in the recharge of the aquifer, or by a decrease in the old natural discharge, or by loss of storage in the aquifer, or by a combination of these."

When assessing the impact of abstraction on rivers it is important to include all of the rivers that could be affected by the pumping. However, in practice, knowing which rivers these are *a priori* may be difficult. When using a numerical model to quantify the impacts of abstraction, it is good practice to define its boundaries using the physical extent of the aquifer. It is not acceptable to select a stable groundwater divide between two catchments as a numerical model boundary when assessing the impact of abstraction on river flows.

As a guide to how rapidly a cone of depression spreads radially outwards from an abstraction borehole, the following equations can be applied:

$$t_{point} = \frac{r^2 S}{4T}, \qquad r_{circle} = \sqrt{\frac{2\,T\,t}{S}}$$

where:

t_{point} is the time (days) when the *rate* of drawdown at a *point* at radius, r, (m) from the well is a maximum

r_{circle} is the radius (m) of the *circle* around which the rate of drawdown is integrated and found to be a maximum at time t (days)

T is the transmissivity of the aquifer ($m^2 day^{-1}$)

S is the aquifer storage coefficient (dimensionless)

These expressions are derived from the Theis (1935) equation and are thus subject to the assumptions on which this solution is based; it supposes that the aquifer is confined, homogeneous, isotropic and of infinite extent and, that groundwater is pumped at constant rate from a well with an infinitely small radius. A full derivation of these expressions is presented in Appendix C.

3.4.3 Impact modelling: Series 2. Including recharge

Models used in this series

The two models used in this series of runs are A1 and A2, which are described in Section 3.2. Model A1 contains a single flat straight-line river running from north to south through its centre. Model A2 includes two additional and identical river catchments to the west and east of this central river catchment.

Purpose of this series of simulations

As in the first series of simulations, in this series, the two models are used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. This series of runs differs from the first in that recharge is applied to the aquifer at a constant rate during the simulation period. The effect of representing either a single or multiple river catchments is investigated. Again, this is performed to assess the magnitude of the errors that may be produced by a numerical model that considers that all the water pumped from a borehole derives from the nearest river. This will be the case if the numerical model only includes a single river catchment as in model A1. In reality, abstraction from a pumped well can reduce the flow of groundwater to rivers in other surface water catchments, which may also be located within other groundwater catchments. This is possible because abstraction from the pumping well will cause the position of the groundwater divide to move and thus capture recharge from a larger area. Recharge is introduced to illustrate the effect it has on the calculation of river baseflow depletion rates.

Summary of the model runs

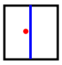
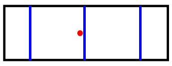
The only difference between the two models in this series of simulations is that model A2 incorporates two additional river catchments. The following parameters are the same in the models A1 and A2.

- recharge of 0.5 mm day^{-1}
- elevation of base of aquifer: 0 m
- flat river with elevation: 100 m
- constant transmissivity of aquifer: 500 m^2day^{-1}
- homogeneous aquifer with storage coefficient of 10%
- initial groundwater head: 110 m throughout model domain
- initial flow along each river and inflow at top of each river: 50,000 m^3day^{-1}
- depletion rates are calculated over the full length of river closest to the abstraction borehole i.e. central river in model A2.

The recharge rate is specified as 0.5 mm day^{-1}, then five simulations are performed using model A1 and five using model A2. In each set of five, abstraction is increased from zero to 40,000 m^3day^{-1} between the runs.

The impact of abstraction on river baseflow is calculated by comparing the simulation with abstraction with that without abstraction for models with the same recharge rate. The simulation runs performed in this series are summarised in Table 5.

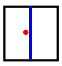
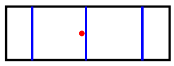
Table 5 Summary of Series 2 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	Recharge rate ($mmday^{-1}$)
S2_1	A1		0	0.5
S2_2	A1		5,000	0.5
S2_3	A1		10,000	0.5
S2_4	A1		25,000	0.5
S2_5	A1		40,000	0.5
S2_6	A2		0	0.5
S2_7	A2		5,000	0.5
S2_8	A2		10,000	0.5
S2_9	A2		25,000	0.5
S2_10	A2		40,000	0.5

Results from this series of simulations

Comparison 2.1

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 m^3day^{-1}. Recharge is applied to the aquifer at a rate of 0.5 mm day^{-1}.

		
Run	S2_2	S2_7
Abstraction rate	5,000 m^3day^{-1}	5,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river
Recharge rate (mm day^{-1})	0.5	0.5

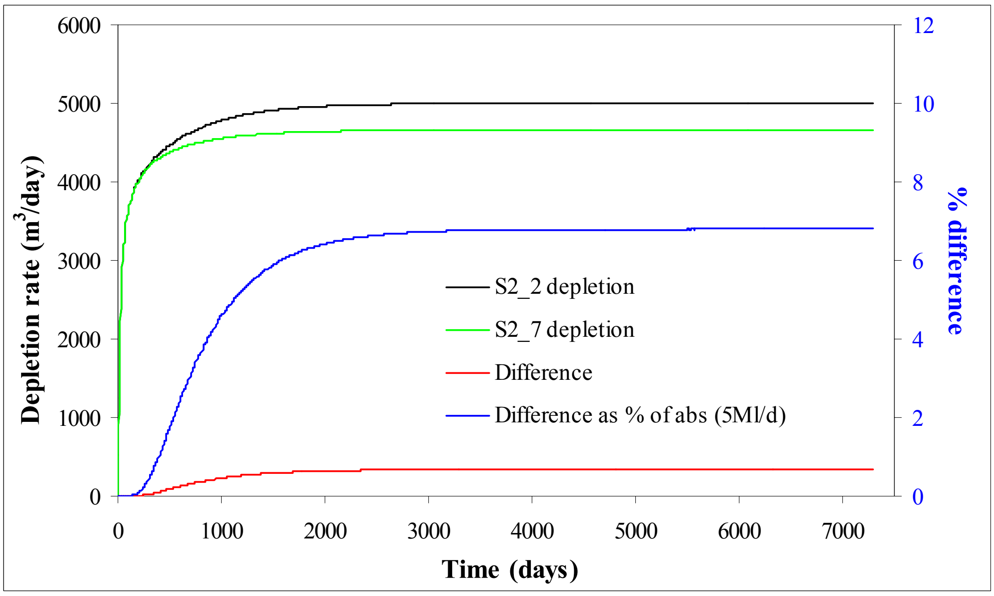


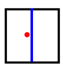
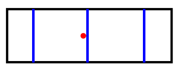
Figure 15 Depletion rates for Series 2 - Comparison 2.1

In model A1 (Run S2_2) the total river depletion increases until a steady conditions is reached after approximately 2,800 days of pumping (Figure 15). At later times the abstraction borehole depletes the river at the same rate as it pumps and no water is derived from aquifer storage. In the larger model, A2 (Run S2_7), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After a steady condition has been reached in the larger model, the abstraction borehole receives only 4,660 $m^3 day^{-1}$ of groundwater from the river nearest to it. Consequently, the depletion rate for the central river in the large model is 340 $m^3 day^{-1}$ less than for the single river in the small model, which is equivalent to 6.8% of the pumping rate.

These depletion rates are the same as those calculated using the models in Series 1, in which no recharge was applied to the aquifer.

Comparison 2.2

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 10,000 $m^3 day^{-1}$. Recharge is applied to the aquifer at a rate of 0.5 mm day^{-1}.

		
Run	S2_3	S2_8
Abstraction rate	10,000 $m^3 day^{-1}$	10,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$ per river
Recharge rate (mm day^{-1})	0.5	0.5

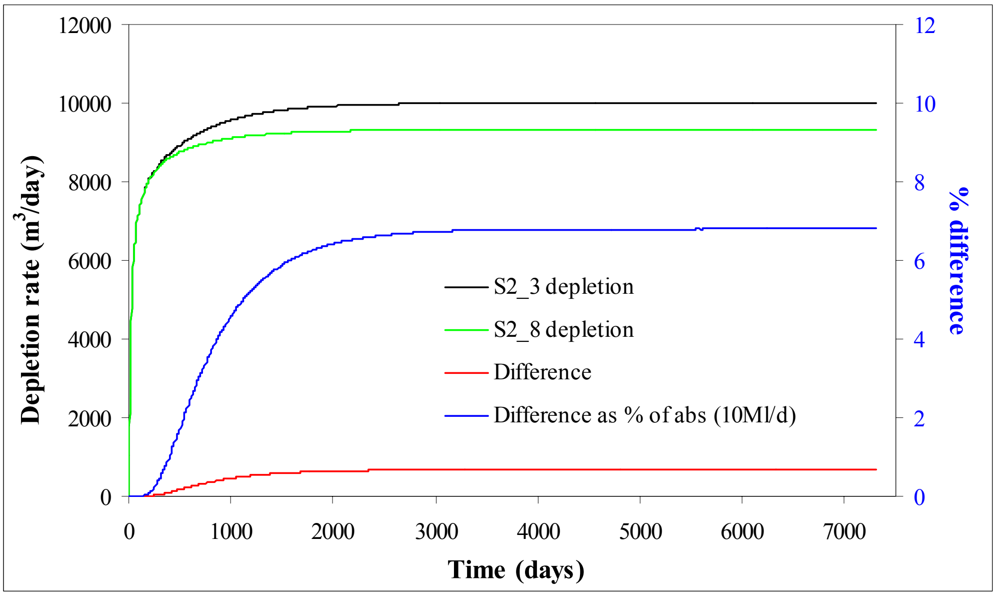


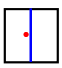
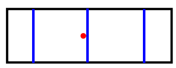
Figure 16 Depletion rates for Series 2 - Comparison 2.2

In model A1 (Run S2_3) the total river depletion increases until a steady condition is reached after approximately 2,800 days of pumping (Figure 16). At later times the abstraction borehole depletes the river at the same rate as it pumps and no water is derived from aquifer storage. In the larger model, A2 (Run S2_8), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After a steady condition has been reached in the larger model, the abstraction borehole receives only 9,320 $m^3 day^{-1}$ of groundwater from the river nearest to it. Consequently, the depletion rate for the central river in the large model is 680 $m^3 day^{-1}$ less than for the single river in the small model, which is equivalent to 6.8% of the pumping rate.

These depletion rates are the same as those calculated using the models in Series 1, in which no recharge was applied to the aquifer.

Comparison 2.3

In this comparison, the total depletion rates along the full length of the river closest to the abstraction borehole are calculated for the two simulations in which the abstraction borehole pumps at a rate of 25,000 $m^3 day^{-1}$. Recharge is applied to the aquifer at a rate of 0.5 mm day^{-1}.

		
Run	S2_4	S2_9
Abstraction rate	25,000 $m^3 day^{-1}$	25,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$ per river
Recharge rate (mm day^{-1})	0.5	0.5

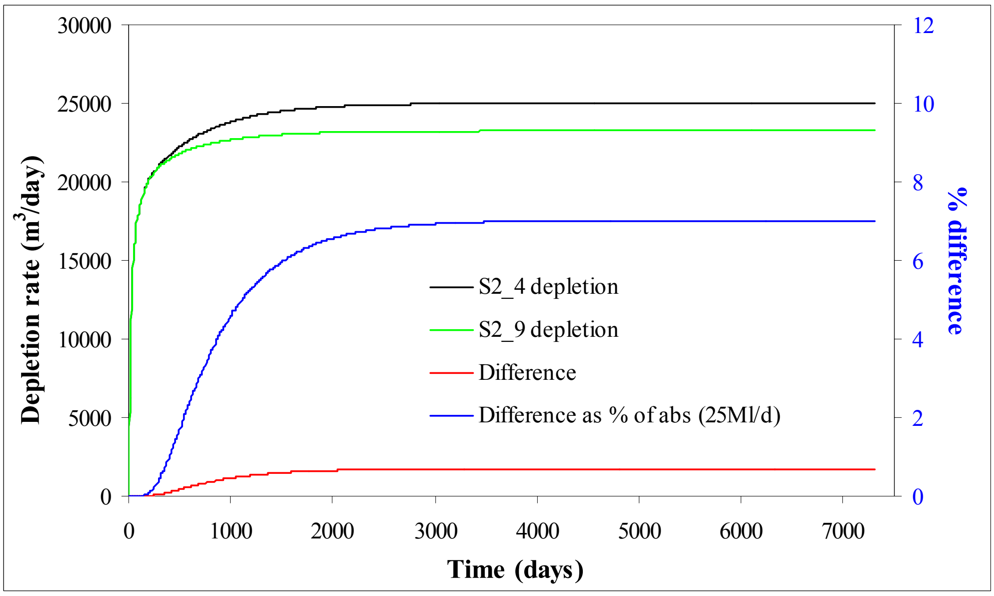
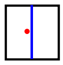
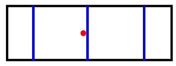


Figure 17 Depletion rates for Series 2 - Comparison 2.3

In model A1 (Run S2_4) the total river depletion increases until a steady-state is reached after approximately 2,800 days of pumping (Figure 17). At later times the abstraction borehole depletes the river at the same rate as it pumps and no water is derived from aquifer storage. In the larger model, A2 (Run S2_9), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After a steady condition has been reached in the larger model, the abstraction borehole receives only 23,247 m^3day^{-1} of groundwater from the river nearest to it. Consequently, the depletion rate for the central river in the large model is 1,753 m^3day^{-1} less than for the single river in the small model, which is equivalent to 7.0% of the pumping rate. The increase in the proportion of the abstraction contributed by leakage from the outer rivers, when compared to Comparison 2.1 and 2.2, is caused by the river node nearest to the abstraction borehole becoming perched in each of the models. This results in slight changes to the cones of depression around the boreholes.

Comparison 2.4

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 40,000 m^{3}day^{-1}. Recharge is applied to the aquifer at a rate of 0.5 mm day^{-1}.

		
Run	S2_5	S2_10
Abstraction rate	40,000 m^{3}day^{-1}	40,000 m^{3}day^{-1}
Upstream river inflow	50,000 m^{3}day^{-1}	50,000 m^{3}day^{-1} per river
Recharge rate (mm day^{-1})	0.5	0.5

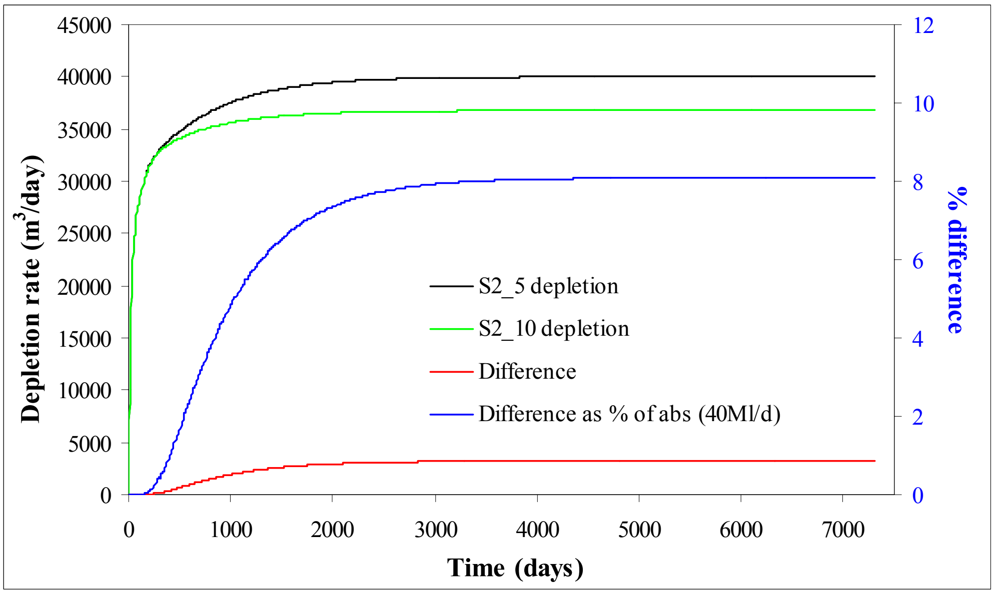


Figure 18 Depletion rates for Series 2 - Comparison 2.4

In model A1 (Run S2_5) the total river depletion increases until a steady condition is reached after approximately 2,800 days of pumping (Figure 18). At later times the abstraction borehole depletes the river at the same rate as it pumps and no water is derived from aquifer storage. In the larger model, A2 (Run S2_10), the total depletion rate for the central river increases in the same way as that of the river in model A1 for approximately 200 days. After this time the cone of depression around the abstraction borehole extends beyond the area equivalent to that of the smaller model. After a steady condition has been reached in the larger model, the abstraction borehole receives only 36,765 m^{3}day^{-1} of groundwater from the river nearest to it. Consequently, the depletion rate for the central river in the large model is 3,235 m^{3}day^{-1} less than for the single river in the small model, which is equivalent to 8.1% of the pumping rate. A larger proportion of the abstracted water is sourced from the outer rivers in this example (8.1%) than in Comparison 2.1 and 2.2 (both 6.8%)

because the three river nodes nearest to the abstraction borehole become perched in both models (A1 & A2). This is illustrated in Figure 19 which shows the leakage rates and groundwater head along the central rivers at the end of the twenty-year simulation period. This perching of the central river limits the leakage and results in more water being derived from the peripheral river catchments in model A2. In model A1 this perching results in more water being derived from the far ends of the single river.

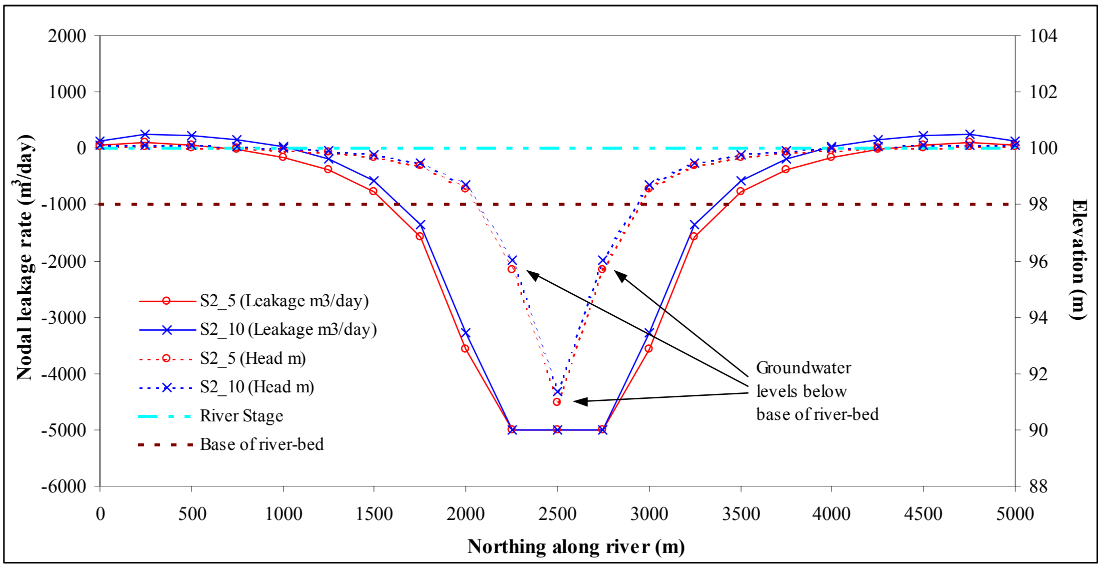
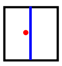
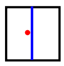


Figure 19 Groundwater head and river leakage profile along the rivers for Comparison 2.4

Comparison 2.5

In this comparison, model A1 is used to examine the total depletion rates, along the full length of the river, induced by the abstraction borehole, which pumps at a rate of 5000 $m^3 day^{-1}$. In the first simulation recharge is not applied. In the second simulation a uniform recharge of 0.5 mm day^{-1} is applied across the aquifer.

		
Run	S1_2	S2_2
Abstraction rate	5,000 $m^3 day^{-1}$	5,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$
Recharge rate (mm day^{-1})	0.0	0.5

The results of the two simulations are shown in Figure 20. This shows that the introduction of recharge into the model has no effect on the calculation of the depletion rate as the two models produce identical results. The curve of the difference between the two depletion rates shows that the differences are very small (less than 0.005% of the abstraction rate) and of the order of the accuracy of the numerical solution.

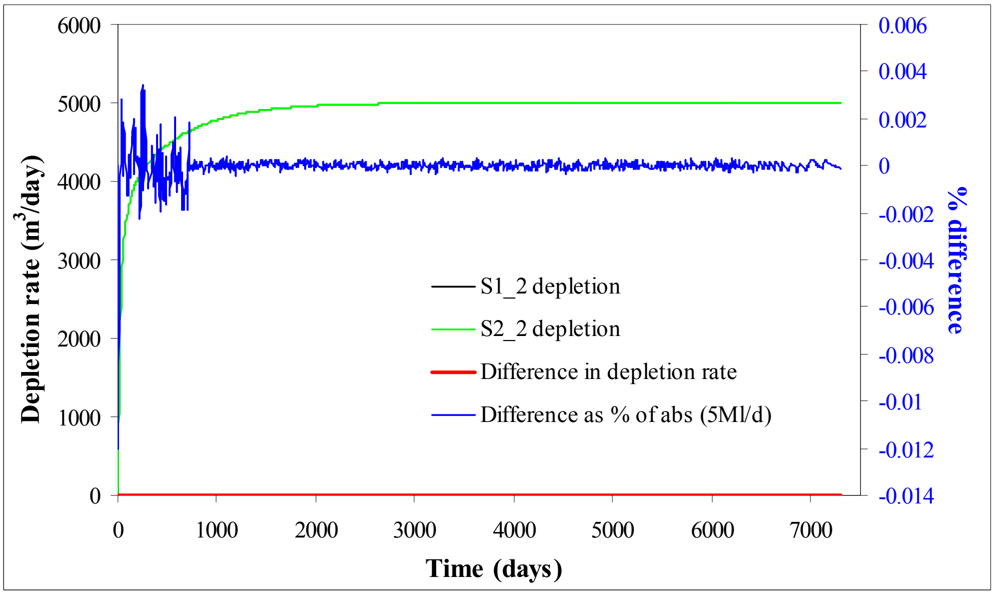
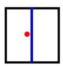
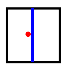


Figure 20 Depletion rates for Series 2 - Comparison 2.5

Comparison 2.6

In this comparison, model A1 is again used to examine the total depletion rates, along the full length of the river, induced by the abstraction borehole, which pumps at a rate of 10,000 $m^3 day^{-1}$. In the first simulation recharge is not applied. In the second simulation a uniform recharge of 0.5 mm day^{-1} is applied across the aquifer.

		
Run	S1_3	S2_3
Abstraction rate	10,000 $m^3 day^{-1}$	10,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$
Recharge rate (mm day^{-1})	0.0	0.5

The results of the two simulations are shown in Figure 21. Again, this shows that the introduction of recharge into the model has no effect on the calculation of the depletion rate as the two models produce identical results.

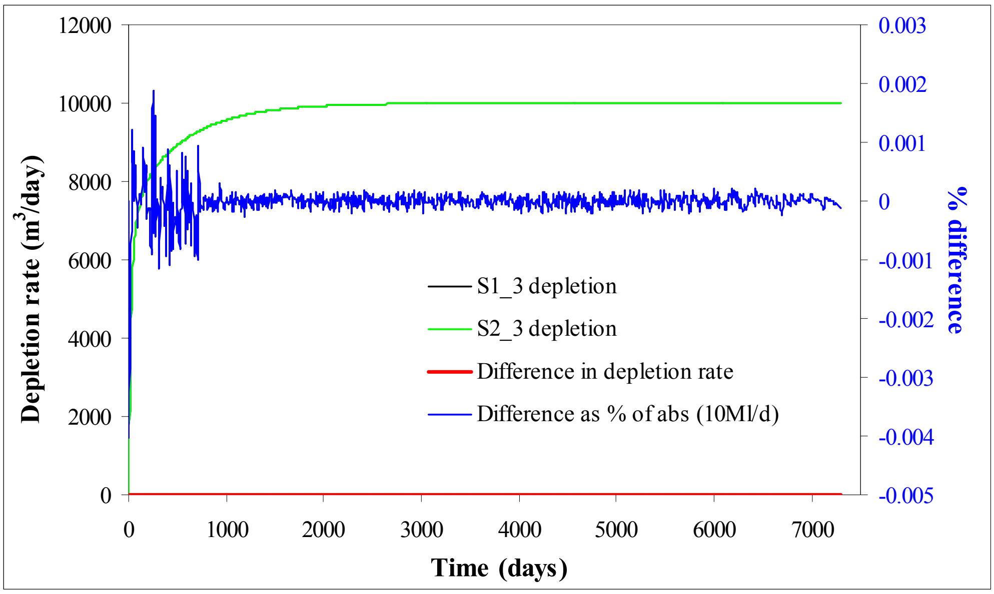
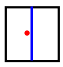
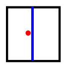


Figure 21 Depletion rates for Series 2 - Comparison 2.6

Comparison 2.7

In this comparison, model A1 is used to examine the total depletion rates, along the full length of the river, induced by the abstraction borehole, which pumps at a rate of 25,000 m^3day^{-1}. In the first simulation recharge is not applied. In the second simulation a uniform recharge of 0.5 mm day^{-1} is applied across the aquifer.

		
Run	S1_4	S2_4
Abstraction rate	25,000 m^3day^{-1}	25,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1}
Recharge rate (mm day^{-1})	0.0	0.5

The results of the two simulations are shown in Figure 22. In this case small differences are observed between the depletion rates for the two models (about 0.5% of the abstraction rate). The differences are caused by the river becoming perched at different times in model S1_4 and S2_4 due to the difference in recharge. The introduction of recharge to the model (S2_4) results in groundwater heads being maintained above the base of the river for longer at the river node nearest to the abstraction borehole. The time at which the central river node becomes perched is shown in Figure 23 for the two models. This result illustrates that the inclusion of recharge could be important when there are sections of the river where the groundwater head falls below its base.

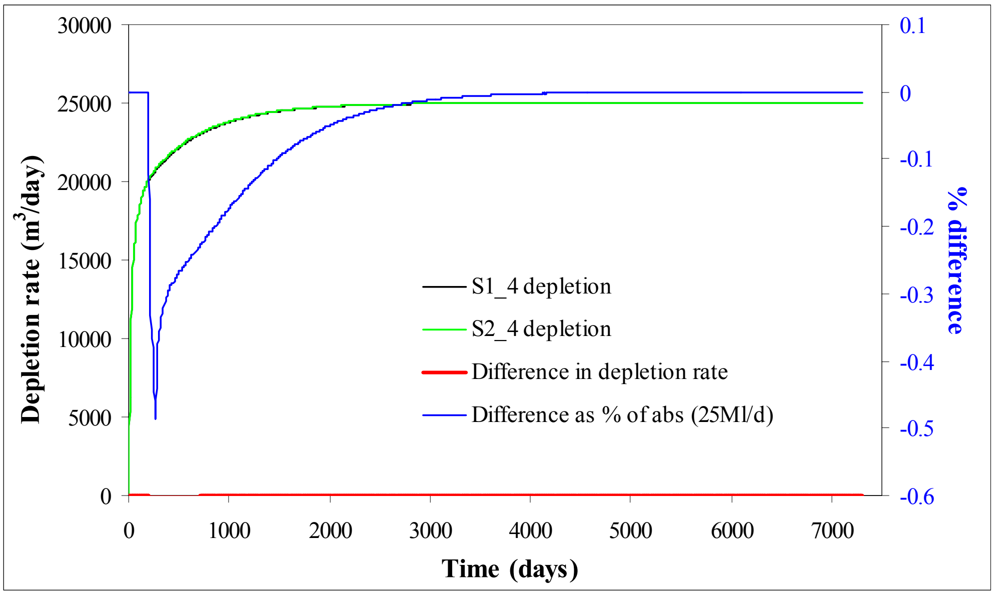


Figure 22 Depletion rates for Series 2 - Comparison 2.7

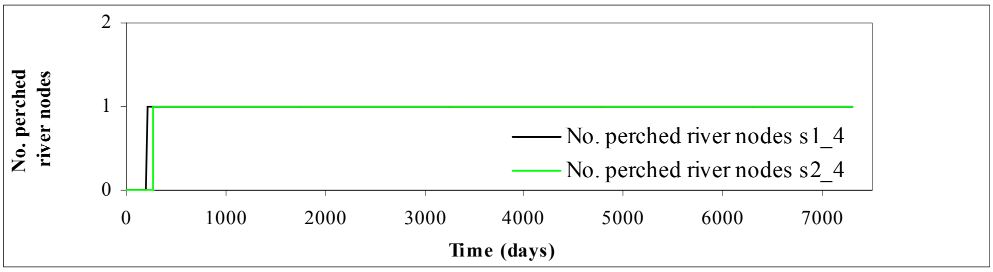
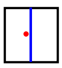
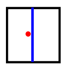


Figure 23 Number of perched river nodes over time – Comparison 2.7

Comparison 2.8

In this comparison, model A1 is used to examine the total depletion rates, along the full length of the river, induced by the abstraction borehole, which pumps at a rate of 40,000 $m^3 day^{-1}$. In the first simulation recharge is not applied. In the second simulation a uniform recharge of 0.5 mm day^{-1} is applied across the aquifer.

		
Run	S1_5	S2_5
Abstraction rate	40,000 $m^3 day^{-1}$	40,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$
Recharge rate (mm day^{-1})	0.0	0.5

The results of the two simulations are shown in Figure 24. As in the previous comparison, differences are observed between the depletion rates calculated using the two models. Again, the differences are caused by the river becoming perched at different times in model S1_5 and S2_5 due to the difference in recharge. The introduction of recharge to the model (S2_4) results in groundwater heads being maintained above the base of the river for longer along the reach of the river near to the pumping well. As shown in Figure 25, in these model runs three river nodes become perched during the simulation period; the central river node nearest to the abstraction borehole and its two adjacent nodes. As in the previous example, this result illustrates that the inclusion of recharge in the model is important when there are sections of the river where the groundwater head falls below its base.

For these models, there is a small difference between the calculated depletion rates (about 1.5% of the abstraction rate) as the groundwater level falls below the base of the river. At later times the modelled systems behave in the same manner and the depletion rates are the same.

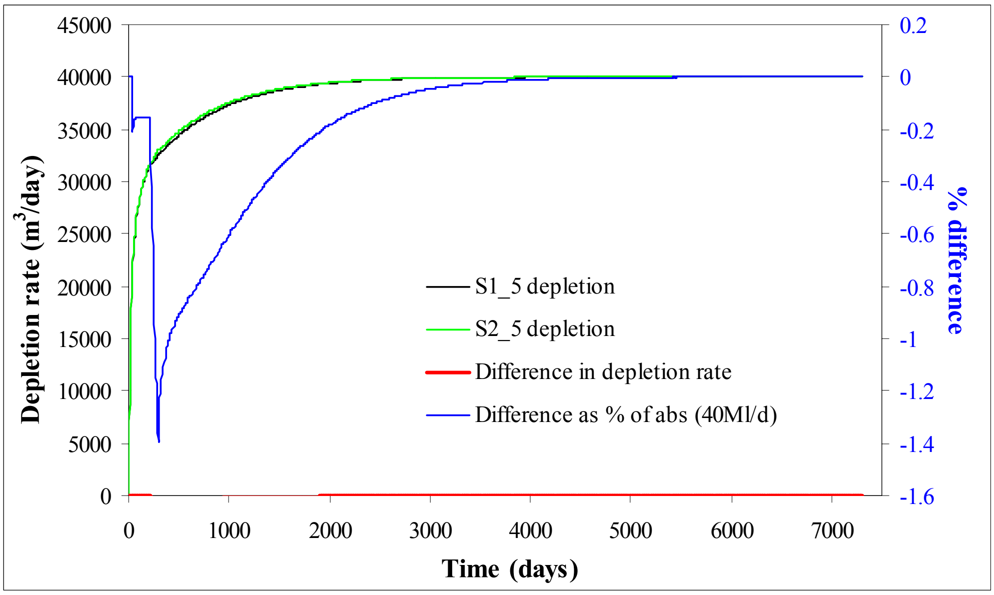


Figure 24 Depletion rates for Series 2 - Comparison 2.8

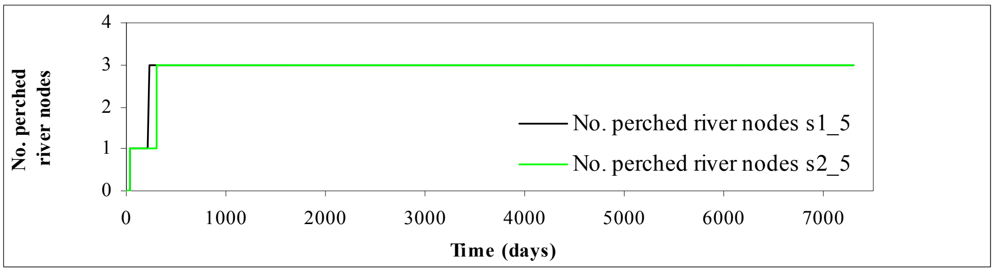


Figure 25 Number of perched river nodes over time – Comparison 2.8

Conclusions from Series 2 runs

The introduction of recharge to a model which is being used to assess the impact of abstraction on river flow does not necessarily affect the calculated depletion rates. If the model does not represent the variation of transmissivity with saturated aquifer thickness, then the governing groundwater flow equation is a linear equation. The introduction of recharge does not result in the system behaving non-linearly. It is this linearity of the system that means that the depletion rates calculated using a model without recharge are the same as those calculated when recharge is applied. The comparisons shown in this series illustrate that this is the case.

Whilst in many of the simulations shown in this series, the inclusion of recharge results in no change in the rates of depletion that are calculated, its application can affect other mechanisms, which in turn affect the impact of abstraction. It was observed in Comparisons 2.7 and 2.8 that the inclusion of recharge in the model resulted in a delay in the time when sections of the river near to the borehole became perched. The process of a model river node becoming perched, as the groundwater level falls below its river bed, results in a change in the system behaviour. When this occurs different depletion rates are calculated by the models with and without recharge.

3.4.4 Impact modelling: Series 3. Rivers rising within the catchment

Models used in this series

The model used in this series of runs is B1, which is described in Section 3.2. This contains a single flat straight-line river running from north to south through its centre. The upstream end of the river is located inside the boundary of the model, one kilometre from the northern boundary.

Purpose of this series of simulations

The model is used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. Simulations are performed to investigate the errors produced when the flow in a river, which rises within the region being modelled, is represented incorrectly. In general, rivers begin to flow on unconfined aquifers where the groundwater table rises to intersect the ground surface, the position of which is controlled, in part, by the amount of recharge. Consequently, the question arises of whether it is necessary to include recharge in a numerical model that is to be used to quantify the impact of abstraction on ephemeral sections of a river. If recharge is not applied to the aquifer then the correct location of the source of a stream could be represented by applying a specified discharge in the model at its upstream end. These issues are considered in this series of simulations.

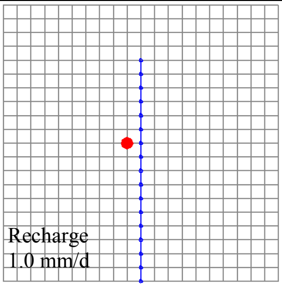
Summary of the model runs

The five simulations performed using model B1 in this series of runs are summarised in Table 6. In the first simulation (S3_1) recharge is applied to the aquifer at a constant rate of 1 mm day^{-1}. The pumping well is switched off and steady conditions are simulated by running the model time-variantly for a sufficiently long period of time. A groundwater head pattern is produced that reflects the uniform distribution of recharge and the shape of the river channel. The flow in the river increases downstream as it collects recharge but the flow does not vary in time at the end of the simulation.

The second run (S3_2) uses the groundwater head profile and river baseflows simulated in S3_1 as initial conditions. Again, recharge is applied to the aquifer at a constant rate of 1 mm day^{-1} but in this case the abstraction borehole starts to pump at a constant rate of 5,000 m^{3}day^{-1} from the start of the simulation period. By comparing the results of these first two runs, the rate of depletion rate due to pumping can be calculated for the full length of the river.

In the third and fourth simulations (S3_3 and S3_4) recharge is switched off. Their initial conditions are based on those simulated at the end of the S3_1 run. Setting the recharge to zero would result in the river drying up from its upstream end, however, in these two simulations a constant discharge is applied at the river source to prevent this from occurring. The impact of the abstraction borehole is then calculated by comparing the simulation in which the abstraction borehole is switched off (S3_3) with that in which it pumps at a constant rate of 5,000 m^3 day^{-1} (S3_4).

Table 6 Summary of Series 3 simulations

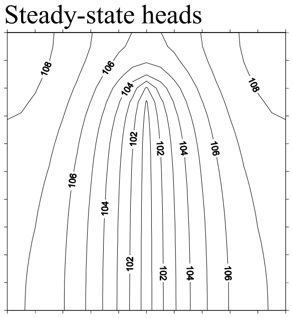


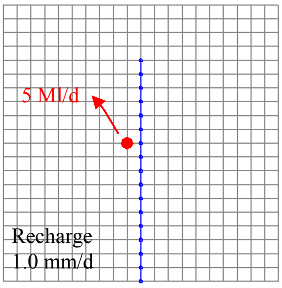
Run S3_1

Steady-state.
No abstraction.
Recharge = 1.0 mm/day.

➨ *Steady-state groundwater heads and river flows.*

Steady-state heads

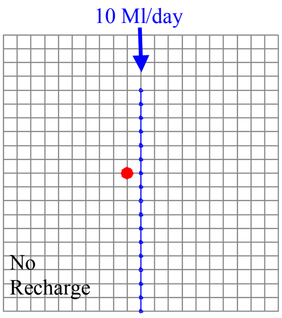




Run S3_2

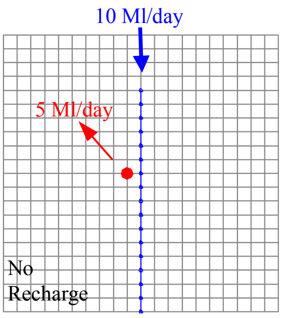
Use steady-state groundwater heads and river flows as initial conditions.
Pump at 5,000 $m^3 day^{-1}$ (Time-variant run - S_c = 10%).
Recharge = 1.0 mm/day.

➨ *Calculate depletion by comparison with no abstraction run (S3_1).*



Run S3_3

Use steady-state groundwater heads and river flows as initial conditions.
No abstraction.
No recharge.
Specify a 10,000 $m^3 day^{-1}$ constant discharge at the top of the river.

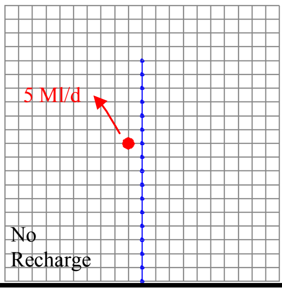


Run S3_4

Use steady-state groundwater heads and river flows as initial conditions.
Pump at 5,000 $m^3 day^{-1}$.
No recharge.
Specify a 10,000 $m^3 day^{-1}$ constant discharge at the top of the river.

➨ *Calculate depletion by comparison with no abstraction run (S3_3).*

➨ **Compare depletion rates calculated using first two models with second two models**



Run S3_5 (no abstraction) and S3_6 (abstract at 5,000 $m^3 day^{-1}$)

Use steady-state groundwater heads and river flows as initial conditions.
No recharge.
Do not include 10,000 $m^3 day^{-1}$ constant discharge at the top of the river.

➨ *Calculate depletion by comparing S3_5 and S3_6.*

In the final two simulations of the series (S3_5 and S3_6) recharge is switched off and the constant discharge to the top of the river is removed. The depletion rate for the river is calculated by comparing the results of S3_5 in which the pumping well is switched off with those of simulation S3_6 in which the well abstracts at a rate of 5,000 m^3 day^{-1}.

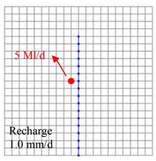
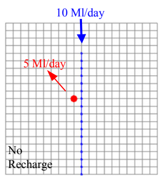
The following parameters are the same in all the simulations performed in this series.

- elevation of base of aquifer: 0 m;
- flat river with elevation: 100 m;
- constant transmissivity of aquifer: 500 $m^2 day^{-1}$;
- homogeneous aquifer with storage coefficient of 10%;
- depletion rates are calculated over the full length of river.

Results from this series of simulations

Comparison 3.1

In this comparison the depletion rates are shown for the models in which (i) recharge is applied to the aquifer and (ii) recharge is switched off but the river is sustained by a constant discharge

		
Run	S3_2	S3_4
Abstraction rate	5,000 $m^3 day^{-1}$	5,000 $m^3 day^{-1}$
Upstream river inflow	0 $m^3 day^{-1}$	10,000 $m^3 day^{-1}$
Recharge rate (mm day^{-1})	1.0	0.0

The depletion rates for the two models are plotted in Figure 26, which show that they produce identical results to within the accuracy of the computed solution. The results of the two models are the same because in neither case does the linear behaviour of the system break down. If a section of the river was to become perched or the length of river was to change, by its upstream end drying up in one of the simulations, then different results would be expected. However, this does not occur.

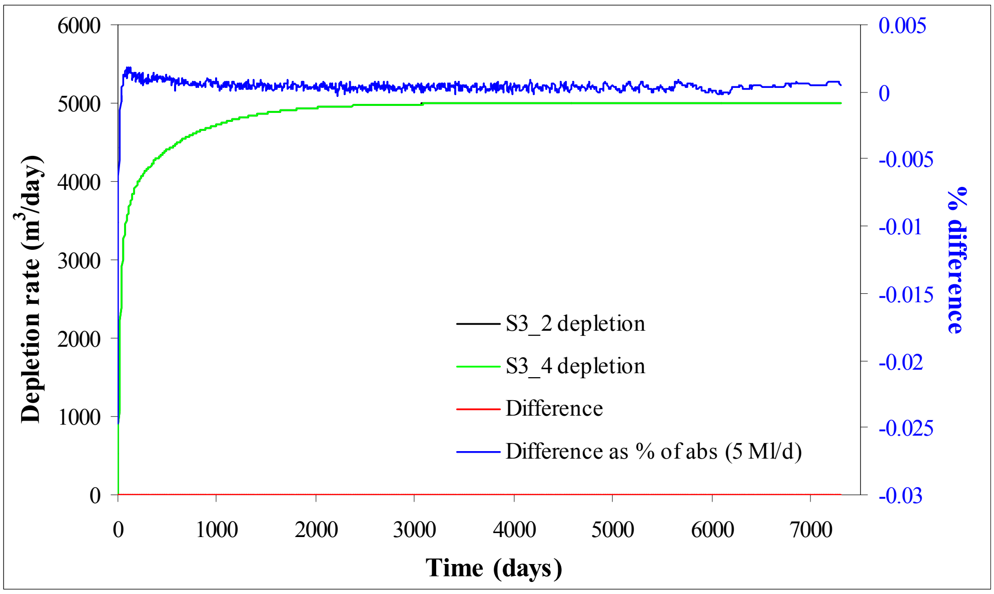
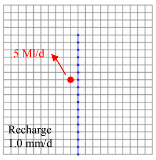
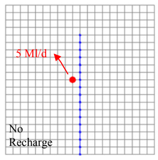


Figure 26　　Depletion rates for Series 3 - Comparison 3.1

Comparison 3.2

The additional simulations, S3_5/6, are used to illustrate the effect of not applying recharge when a river rises within the model area. In neither simulation is a discharge applied to the top of the river. The comparison is summarised below. In S3_2 recharge is applied to the aquifer at a rate of 1 mm day^{-1}. In S3_6 recharge is not applied to the system.

		
Run	S3_2	S3_6
Abstraction rate	5,000 m^{3}day^{-1}	5,000 m^{3}day^{-1}
Upstream river inflow	0 m^{3}day^{-1}	0 m^{3}day^{-1}
Recharge rate (mm day^{-1})	1.0	0.0

The depletion rates calculated using the two models are shown in Figure 27. The calculated depletion rates are the same for approximately 800 days until the river in model S3_6 starts to dry up from its upstream end. Consequently, after this time, the depletion rate calculated using this model, in which recharge is not applied to the aquifer, reduces because of the shorter length of flowing river. After approximately 5,000 days, the depletion rate calculated using the pair of models S3_5/6 falls to zero. The variations of the total leakage rate along the river in simulation S3_5 and S3_6 are shown in Figure 28. The difference between the two leakage curves is the depletion rate. None of the river nodes dry up in simulation S3_5 as the flow at all of these is maintained by releases of groundwater storage in the aquifer, though towards the end of the simulation these releases are minimal.

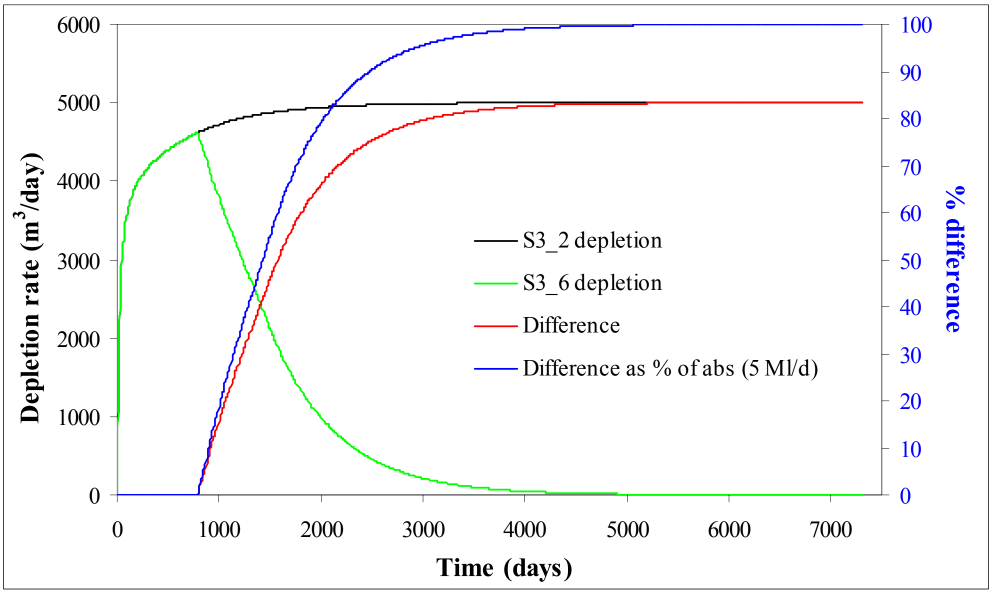


Figure 27 Depletion rates for Series 3 - Comparison 3.2

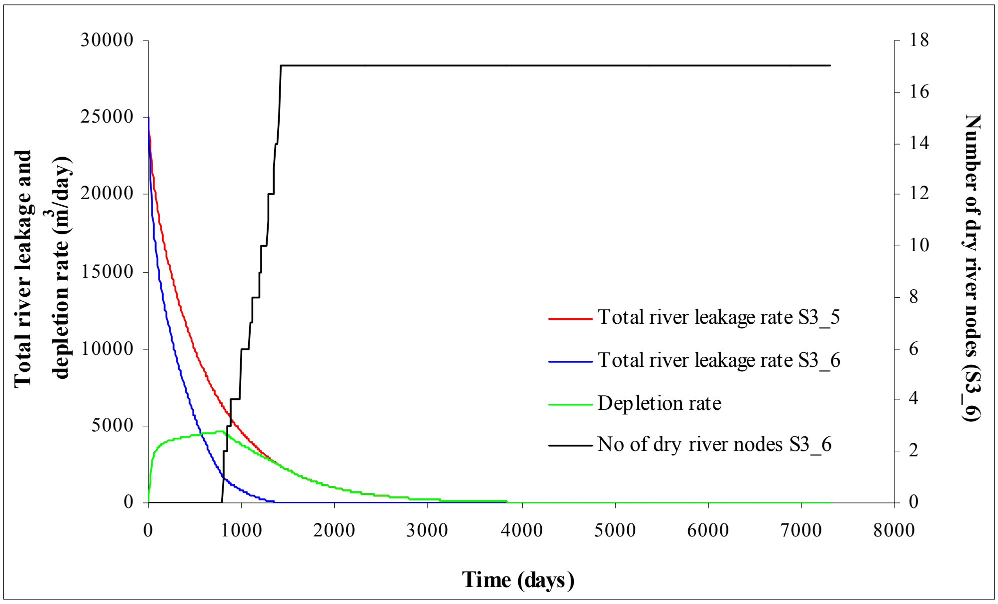


Figure 28 Total leakage rates for simulations S3_5 and S3_6

Conclusions from Series 3 runs

If the length of the river being modelled changes during a simulation due to sections drying out then the impact that an abstraction borehole has on its discharge will change. In Comparison 3.2 it was observed that the depletion rate decreased as the river dried up from its upstream end. At the end of the simulation S3_6 the river stops flowing and the borehole can only mine aquifer storage.

A change in the length of the river results in a breakdown in the linear behaviour of the aquifer. In such a case, care must be taken to represent the changing length of the river if depletion rates are to be calculated accurately.

3.4.5 Impact modelling: Series 4. Rivers with different elevations

Models used in this series

The model used in this series of runs is A2, which is described in Section 3.2. Model A2 contains three flat straight-line rivers running from north to south. One of the rivers runs through the centre of the model. The two rivers to the west and east are equidistant from the central river.

Purpose of this series of simulations

In this series of simulations, the model is used to calculate baseflow depletion rates along the rivers due to pumping from an adjacent abstraction well. The effect of setting the rivers at different elevations is illustrated with a number of different models in which the configuration of the catchment elevations is modified.

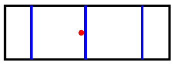
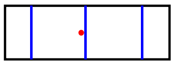
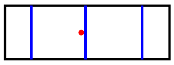
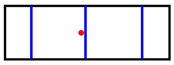
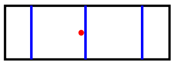
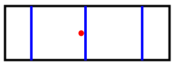
Summary of the model runs

The only difference between the models in this series of simulations is the elevations of the river catchments. The following parameters are the same in all the models.

- no recharge
- elevation of base of aquifer: 0 m
- constant transmissivity of aquifer: 500 $m^2 day^{-1}$
- homogeneous aquifer with storage coefficient of 10%
- initial groundwater head: 150 m throughout model domain
- initial flow along each river and inflow at top of each river: 50,000 m^3 day^{-1}
- depletion rates are calculated over the full length of the central river

Six simulations are performed using the model with are grouped into three pairs. The two simulations in each pair of simulations are identical except for the abstraction rate. This is set to zero in the first run and 5,000 m^3 day^{-1} in the second run. The impact of abstraction on river baseflow is calculated by comparing the simulation with abstraction with that without abstraction. The simulation runs performed in this series are summarised in Table 7.

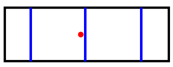
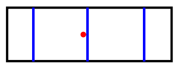
Table 7 Summary of Series 4 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	River elevations
S4_1	A2		0	100m 100m 100m
S4_2	A2		5,000	100m 100m 100m
S4_3	A2		0	110m 100m 110m
S4_4	A2		5,000	110m 100m 110m
S4_5	A2		0	90m 100m 90m
S4_6	A2		5,000	90m 100m 90m

Results from this series of simulations

Comparison 4.1

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 m^3day^{-1}. In simulations S4_3 and S4_4 the elevation of the two peripheral rivers is raised 10 m to 110 m above datum, which is the base of the aquifer.

		
Run	S4_2	S4_4
River configuration	100m 100m 100m	110m 100m 110m
Abstraction rate	5,000 m^3day^{-1}	5,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

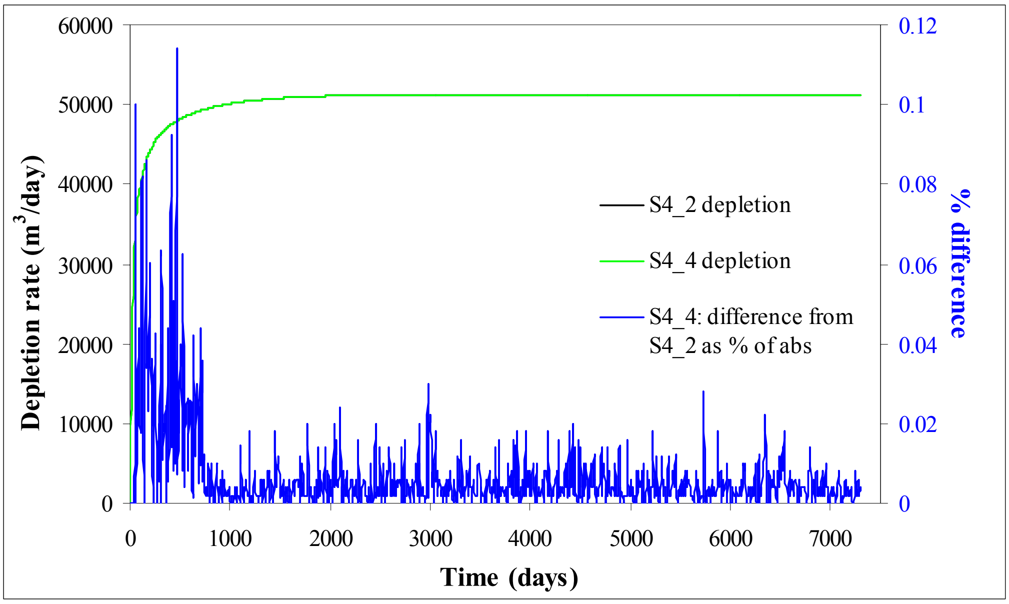
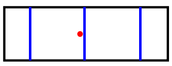
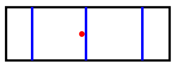


Figure 29 Depletion rates for Series 4 - Comparison 4.1

Figure 29 shows the comparison between the depletion rate calculated using the pair of simulations S4_1/2 and the pair S4_3/4. The results are identical to within the accuracy of the computed solution and the difference in the elevation of the rivers does not result in different depletion rates.

Comparison 4.2

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 $m^3 day^{-1}$. In simulations S4_5 and S4_6 the elevation of the two peripheral rivers is lowered 10 m to 90 m above datum, which is the base of the aquifer.

		
Run	S4_2	S4_6
River configuration	100m 100m 100m	90m 100m 90m
Abstraction rate	5,000 $m^3 day^{-1}$	5,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$ per river

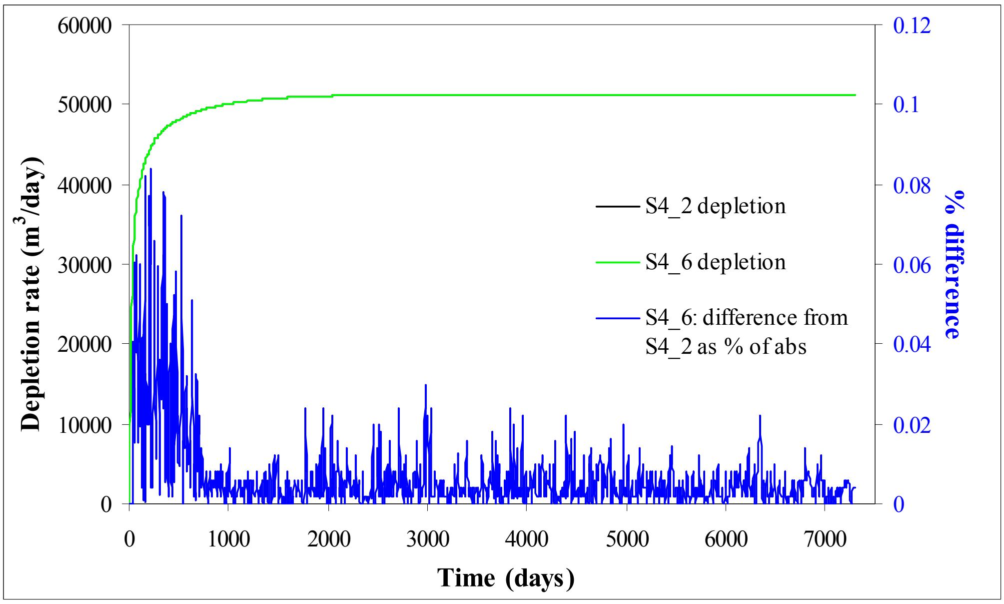


Figure 30 Depletion rates for Series 4 - Comparison 4.2

The comparison between the depletion rates calculated using the pair of simulations S4_1/2 and the pair S4_5/6 is shown in Figure 30. As in Comparison 4.1 identical results are produced, which illustrates that the elevation of the river does not affect the impact that an abstraction borehole has on its discharge, *if* the behaviour of no other mechanisms operating in the system is altered.

Conclusions from Series 4 runs

The elevation of a river does not directly affect the impact that an abstraction borehole has on it when this is calculated using a numerical model. In a linear aquifer system, i.e. one in which the transmissivity does not vary with saturated aquifer thickness and other constraints apply, the elevation of the river will not affect the calculated depletion. However, rivers at different elevations will experience different impacts if their position affects other features of the system. For example, the saturated aquifer thickness and transmissivity may be different in catchments at different heights or, different sections of the river may be perched. In these cases the system will not exhibit a linear response to pumping and different depletion rates will be calculated for the different rivers when such features are included in a numerical model.

3.4.6 Impact modelling: Series 5. Unconfined aquifers

Models used in this series

The model used in this series of runs is A1, which is described in Section 3.2. This contains a single flat straight-line river running from north to south through its centre.

Purpose of this series of simulations

In this series of simulations the variations in the values calculated for depletion rate are examined for unconfined aquifers. A number of models are constructed which have different saturated thickness and hydraulic conductivity. In each model the initial transmissivity is 400 m^2day^{-1}. The saturated thickness is adjusted by raising the base of the model. Depletion rates are calculated by comparing a run in which an abstraction borehole pumps at a constant rate with one in which it is switched off.

Summary of the model runs

All of the simulations run in this series have the following characteristics. The parameters which vary between simulations are listed in Table 8. The model is illustrated in Figure 31.

- initially flat head profile at 150 m above the model datum
- initial flow in river uniformly 50,000 m^3day^{-1}
- flat river with a uniform stage 100 m above the model datum
- no recharge
- specific storage = 0
- specific yield = 10%.

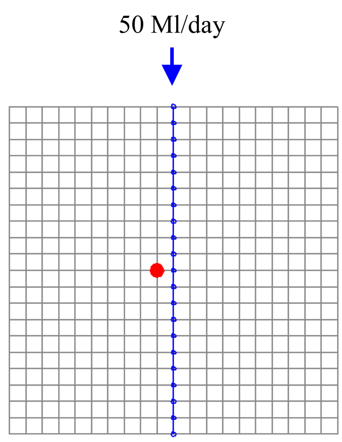


Figure 31 Model A1 used in Series 5 simulations

Table 8 Variation of parameters in Series 5 simulations

Run	Abstraction (m^3day^{-1})	Elevation of aquifer base (m)	Initial saturated thickness (m)	K_h	Initial transmissivity (m^2day^{-1})
S5_1	0	-250	400	1	400
S5_2	5,000	-250	400	1	400
S5_3	0	-150	300	1.3333	400
S5_4	5,000	-150	300	1.3333	400
S5_5	0	-50	200	2	400
S5_6	5,000	-50	200	2	400
S5_7	0	50	100	4	400
S5_8	5,000	50	100	4	400

Results from this series of simulations

Four depletion rates are calculated from these eight simulations; one from each pair with and without abstraction. For each pair, the hydraulic conductivity is increased by one-third, by two and then by four when compared to the first two simulations. The initial transmissivity is maintained at 400 m^2day^{-1} by raising the elevation of the base of the aquifer appropriately. The four depletion rates are shown in Figure 32 and at first inspection the differences between the curves do not seem very significant.

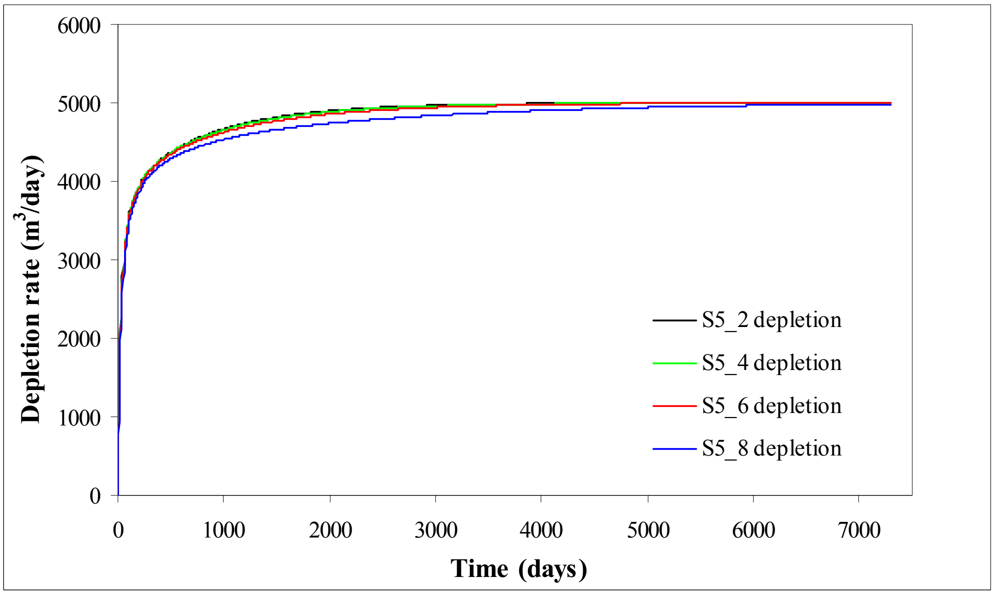


Figure 32 Series 5 simulated depletion rates

The differences between the depletion rates are plotted in Figure 33 and Figure 34. In Figure 34 they are plotted as a percentage of the abstraction rate (5,000 m^3day^{-1}). The maximum difference in depletion rate compared to the first two simulations in which hydraulic conductivity is set to 1 m day^{-1} is, as expected, observed in model S5_7/8 which has the highest hydraulic conductivity (4 m day^{-1}) and lowest saturated thickness (50 m). This is approximately 160 m^3day^{-1} or 3.3% of the abstraction.

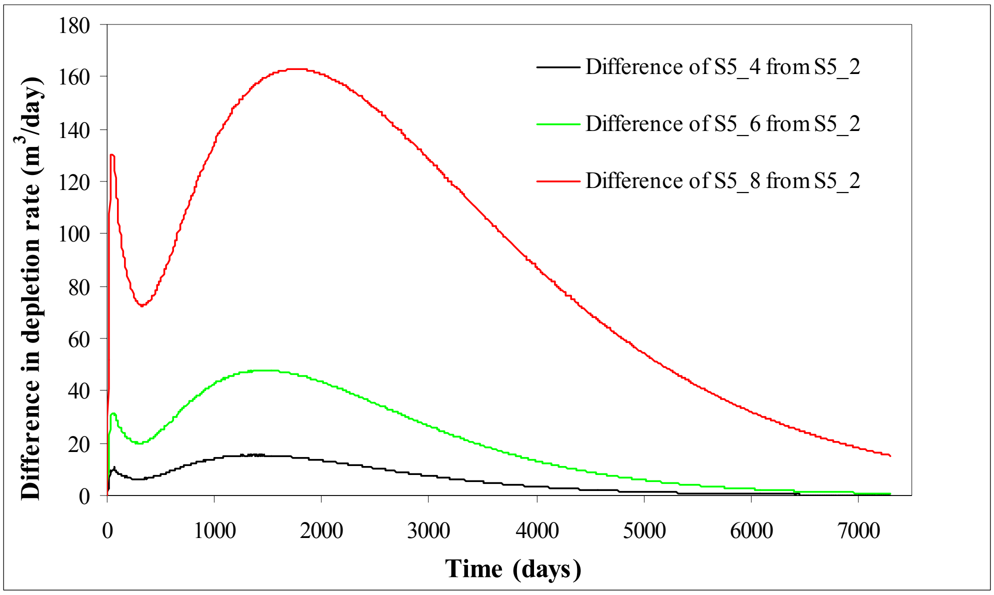


Figure 33 Difference between depletion rates (Series 5)

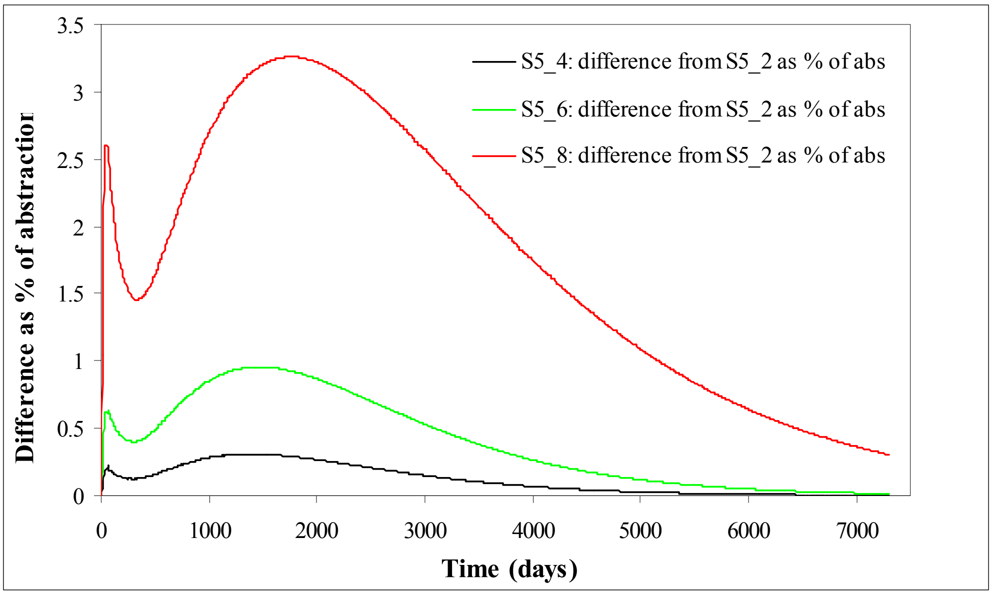


Figure 34 Difference between depletion rates as a percentage of abstraction (Series 5)

Conclusions from Series 5 runs

Differences between the depletion rates calculated in this series of simulations are apparent but are not as significant as those produced when varying other model parameters, for example catchment size. The variation of saturated thickness modelled in this series of simulations is likely to be significantly greater than in a real aquifer. Because of this, other features of a model are likely to introduce more error to the calculated depletion rate. The representation in the model of the variation of horizontal conductivity with depth, for example in a Chalk aquifer, will also affect the simulated depletion rate (see Section 3.4.8).

Comment about the behaviour of unconfined aquifers

The governing equation of groundwater flow in a confined aquifer can be expressed as:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} - N \qquad \text{Equation 3.1}$$

where:

h is the groundwater head [L]

T_x and T_y are the transmissivity in the x and y directions, respectively $[L^2T^{-1}]$

S is the storage coefficient

N is a source flow term per unit area of aquifer.

This equation, which is derived by integration of the general three-dimensional groundwater flow equation over the saturated aquifer thickness, is a linear equation as discussed in Appendix D. The linearity of the system represented by Equation 3.1 means that modelled depletion rates are not affected by the rate of recharge for example. However, in an unconfined aquifer the transmissivity depends on the groundwater head. In this case the governing flow equation is expressed as:

$$\frac{\partial}{\partial x}\left(k_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y h \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} - N \qquad \text{Equation 3.2}$$

where k_x and k_y are the hydraulic conductivity in the x and y directions, respectively $[LT^{-1}]$. This is a non-linear equation. The non-linearity of the system represented by Equation 3.2 means that recharge and other aquifer processes must be represented properly if accurate depletion rates are to be calculated using a numerical model. Because transmissivity depends on groundwater level in an unconfined aquifer, the impact of an abstraction borehole on river flow also depends on the groundwater level. Consequently, the loss of river water to the aquifer, which is induced by pumping, will be different if recharge occurs during the pumping period or not. This is not due to the difference in recharge but to the resulting difference in the transmissivity.

3.4.7 Impact modelling: Series 6. Selection of boundary conditions

Models used in this series

The two models used in this series of runs are C1 and C2, which are described in Section 3.2. Model C1 contains a flat river which is composed of a main channel, running from north to south through its centre, and two tributaries. Model C2 represents the central region of model C1. It can be viewed as having been cut out from the centre of the larger model. Consequently, the smaller model only includes the central section of the three-channel river catchment.

Purpose of the series runs

This series of runs is undertaken to examine the importance of defining boundary conditions accurately when only a part of a river catchment is modelled to assess the impact of groundwater abstraction on river baseflow. When no-flow conditions are defined around the boundary of a model containing a pumping well and a river, the only sources of water for the borehole are recharge, aquifer storage and river baseflow. Such models, based on no-flow boundary conditions, are difficult to construct in reality when the real physical no-flow boundaries are a long distance away, for example in the southern Chalk, because the models must then be large. Groundwater divides should not be used to define no-flow boundary conditions when assessing the impact of abstraction of river baseflow because the cone of depression due to abstraction from a pumping well will continue spreading until it has stopped an equal amount of water from leaving the aquifer. Hence the drawdown frequently spreads into adjacent groundwater catchments so that the groundwater heads are depressed and the flows to the rivers are reduced. An explanation of this is given in the conclusions for the Series 1 runs (Section 3.4.2).

Out of these considerations arise the following two related questions:

1. Is it possible to calculate the impact of an abstraction on a river accurately if only a part of the catchment is modelled?

2. If a model of part of a catchment is constructed how should the boundary conditions be defined i.e. does the use of no-flow boundaries enable the impacts to be calculated accurately or is it necessary to define more realistic boundary conditions?

These questions are considered by running the models C1 and C2. The process used to examine the validity of using sub-catchment models is as follows:

1. Model C1, the full catchment model, is run to steady-state. In this steady-state simulation no recharge is applied over the aquifer and there is no abstraction. Along the top boundary of the model a specified flow into the model is defined. This is distributed uniformly along the boundary and is equivalent to 2 m^3day^{-1} per metre length of the boundary. The resulting head profile shows that groundwater flows from the top boundary towards the river channels and the bottom model boundary, along which a fixed head condition is defined (Figure 35).

2. This steady-state head profile is taken as the initial condition for two time-variant simulations using model C1. In the first, nothing is modified and the model continues to simulate the steady conditions of groundwater flow to the rivers and fixed head boundary. In the second, an abstraction borehole pumps at a rate of 5,000 $m^3 day^{-1}$ from the start of the simulation. The impact of the abstraction on each of the sections of the three river channels, which are located within the sub-model area, is calculated over time by comparing the two simulations.

3. These model runs provide two sets of time-variant specified flow boundary conditions for the smaller model, model C2; a steady condition and a condition including the effects of abstraction. The model C1 runs provide flows at each boundary node of the smaller model for each time-step of the simulation.

4. The smaller model is then run a number of times with different boundary conditions. The initial condition for each run is defined by the steady-state groundwater head profile of model C1, the larger model (Figure 36). The baseflow in each river channel as it flows onto the model is specified as that produced by the steady-state model C1 simulation at the same location. These flows rates are held constant over time.

5. Seven pairs of simulations are performed using the sub-model, model C2. In each pair a different boundary condition is defined. In the first simulation of each pair the abstraction borehole does not pump. In the second simulation of each pair the abstraction borehole is switched on at the start of the simulation period and pumps at a constant rate of 5,000 $m^3 day^{-1}$. No recharge is applied to the aquifer in each case. The impact of the abstraction on baseflow in each of the three channels of the sub-model is calculated by comparing the 'no abstraction' and 'abstraction' runs. These three depletion rates are then compared to the three depletion rates calculated using the large model containing the full river catchment.

6. The conditions specified around the boundary of the sub-model in each of the seven pairs of simulations are listed in Table 9. A depletion rate is calculated for each of the three river channels for each of the seven model scenarios. The comparisons of the results of each of these seven scenarios with the full catchment model are described below.

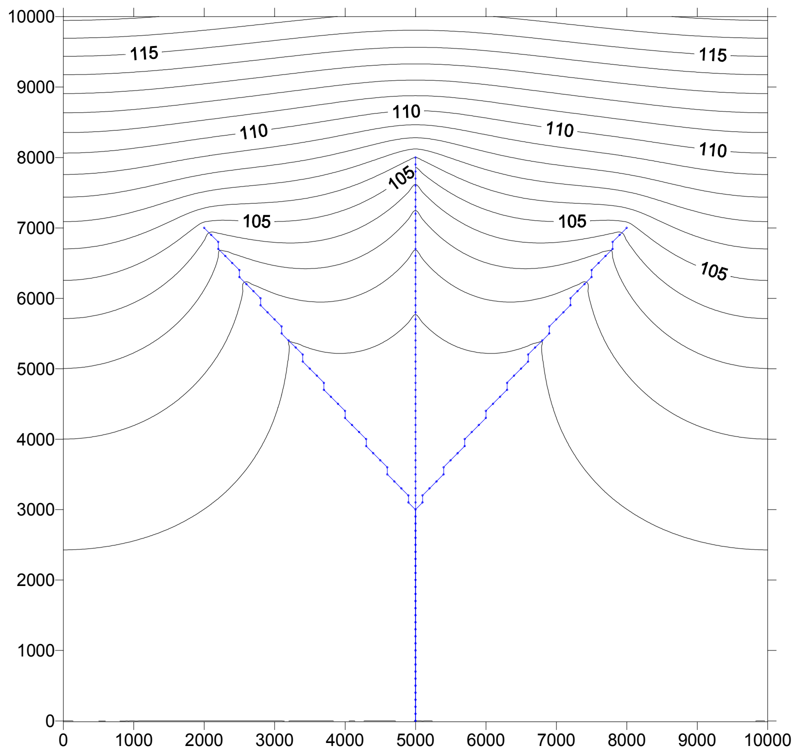


Figure 35 Groundwater head profile for steady-state model C1 simulation (recharge but no abstraction)

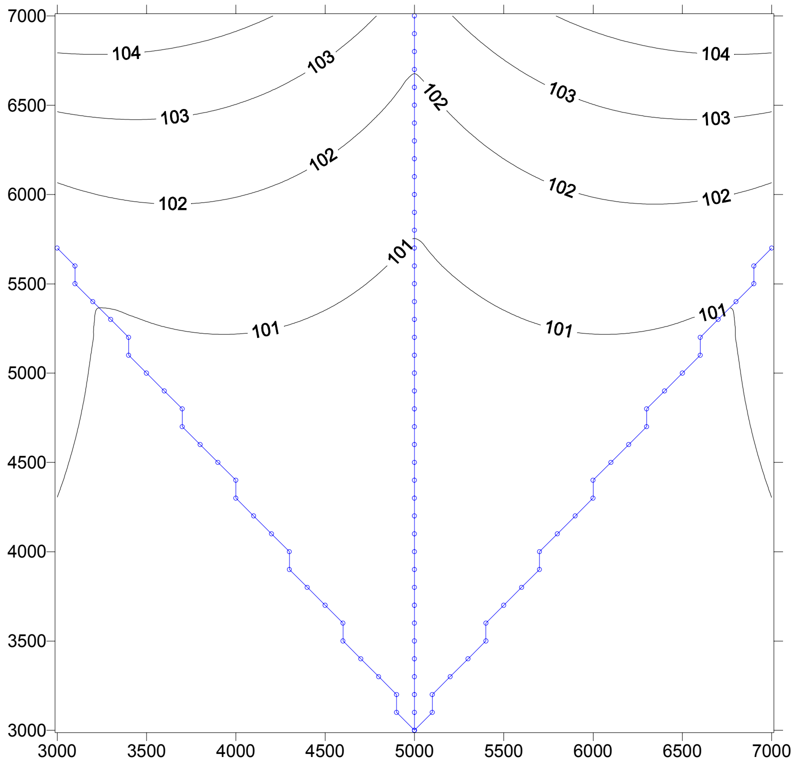


Figure 36 Initial groundwater head profile for model C2 simulations

Summary of model runs

As described above, seven pairs of simulations are performed using model C2, which use different boundary conditions. The depletion rates calculated for each of the three river channels, for each of the seven boundary types are compared to those calculated using the larger model C2, which incorporates the full river catchment. Branch 1 is the section along the central main channel. Branch 2 is the left-hand tributary and Branch 3 is the right-hand tributary. The pumped well is located at co-ordinate (4500, 5500) i.e. 500 m to the left of Branch 1 as shown in Figure 8.

The seven boundary condition scenarios are listed in Table 9. In the first four scenarios, the condition at the nodes on the boundary are all of the same type: either no-flow, specified flow or fixed head. In the final three scenarios the boundary conditions are mixed. By comparison of depletion rates calculated in each of these cases with that of the large model, conclusions can be made regarding the validity of the construction of sub-catchment models for the assessment of the impact of abstraction on river baseflow.

The following parameters are the same in all the simulations in this series:

- no recharge
- elevation of base of aquifer: 0 m
- flat river with elevation: 100 m
- constant transmissivity of aquifer: 500 $m^2 day^{-1}$
- homogeneous aquifer with storage coefficient of 10%.

Table 9 Summary of Series 6 impact modelling runs

Run number	Model used	Abstraction rate (m^3day^{-1})	Recharge rate ($mmday^{-1}$)	Description of boundary conditions	Pictorial representation of boundary conditions (see Figure 37)
S6_1a	C2	0	0	No-flow everywhere.	A in Figure 37
S6_1b	C2	5,000	0	No-flow everywhere.	A in Figure 37
S6_2a	C2	0	0	Specified flow using the flows simulated by the model C1 model with abstraction.	B in Figure 37
S6_2b	C2	5,000	0	Specified flow using the flows simulated by the model C1 model with abstraction.	B in Figure 37
S6_3a	C2	0	0	Specified flow using the flows simulated by the model C1 model with no abstraction.	B in Figure 37
S6_3b	C2	5,000	0	Specified flow using the flows simulated by the model C1 model with no abstraction.	B in Figure 37
S6_4a	C2	0	0	Fixed heads based on the model C1 steady-state head profile.	C in Figure 37
S6_4b	C2	5,000	0	Fixed heads based on the model C1 steady-state head profile.	C in Figure 37
S6_5a	C2	0	0	*Left and right hand boundaries*: no flow. *Top and bottom boundaries*: fixed heads based on the model C1 steady-state head profile.	D in Figure 37
S6_5b	C2	5,000	0	*Left and right hand boundaries*: no flow. *Top and bottom boundaries*: fixed heads based on the model C1 steady-state head profile.	D in Figure 37
S6_6a	C2	0	0	*Left and right hand boundaries*: no flow. *Top and bottom boundaries*: specified flow using the flows simulated by the model C1 model with abstraction.	E in Figure 37
S6_6b	C2	5,000	0	*Left and right hand boundaries*: no flow. *Top and bottom boundaries*: specified flow using the flows simulated by the model C1 model with abstraction.	E in Figure 37
S6_7a	C2	0	0	*Left and right hand boundaries*: no flow. *Top boundary*: fixed heads based on the model C1 steady-state head profile. *Bottom boundary*: specified flow using the flows simulated by the model C1 model with abstraction.	F in Figure 37
S6_7b	C2	5,000	0	*Left and right hand boundaries*: no flow. *Top boundary*: fixed heads based on the model C1 steady-state head profile. *Bottom boundary*: specified flow using the flows simulated by the model C1 model with abstraction.	F in Figure 37

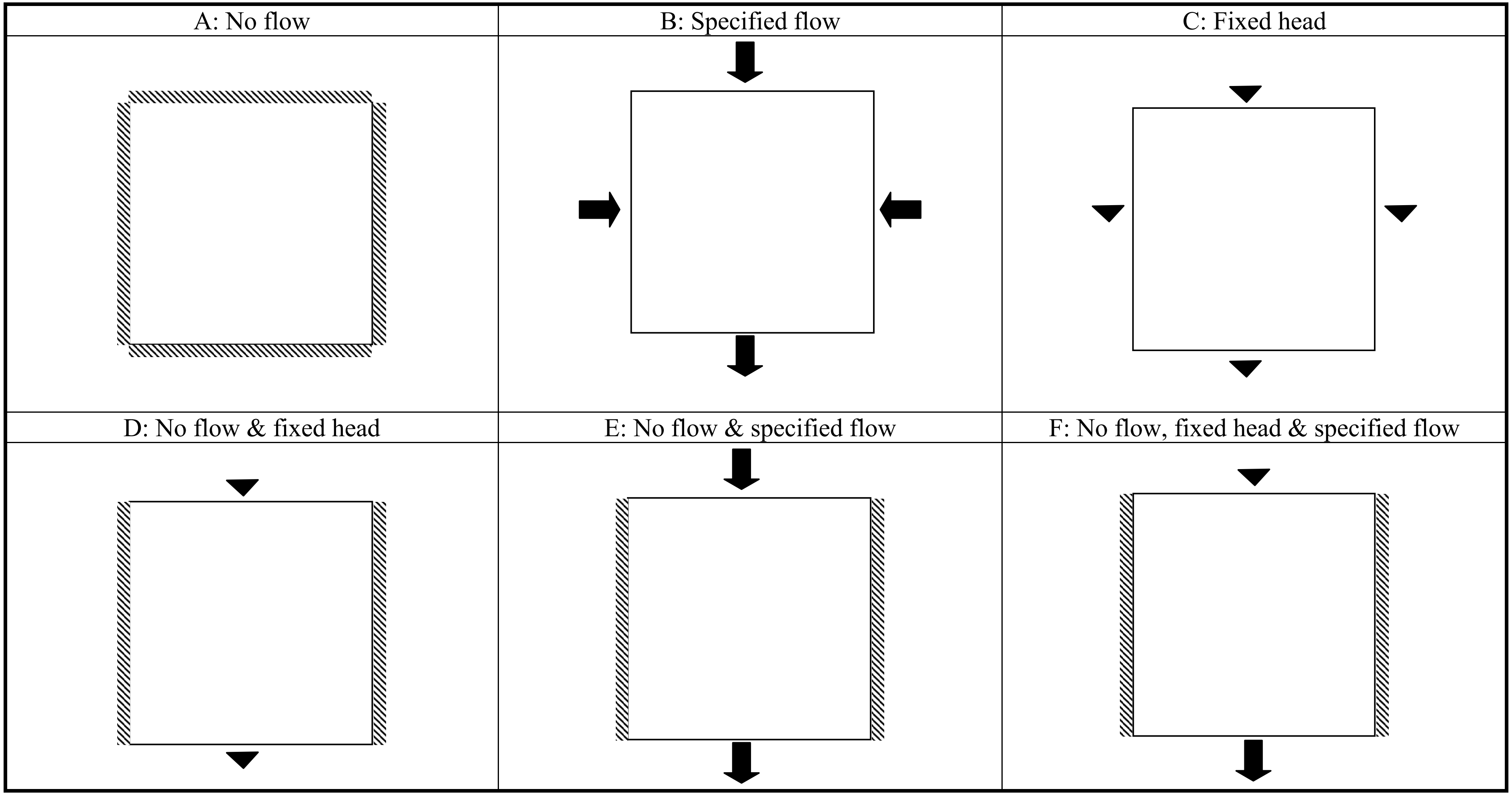


Figure 37 Types of boundary condition specified around Series 6 sub-model (refer to Table 9)

Results from this series of simulations

Comparison 6.1

	No flow boundary conditions specified around the sub-model C2 boundary and comparison with model C1.

In this comparison no-flow conditions are defined around all of the boundary of the sub-model. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction, i.e. the depletion rate, in the large scale model C1 and the sub-model C2 with these boundary conditions is shown in Figure 38. The differences in the depletion rates are shown in Figure 39 for each of the river channels. Towards the end of the simulations, when steady conditions have been reached the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	$m^3 day^{-1}$	% of abstraction
Branch 1 (central)	469	9.4
Branch 2 (left)	447	8.9
Branch 3 (right)	197	3.9

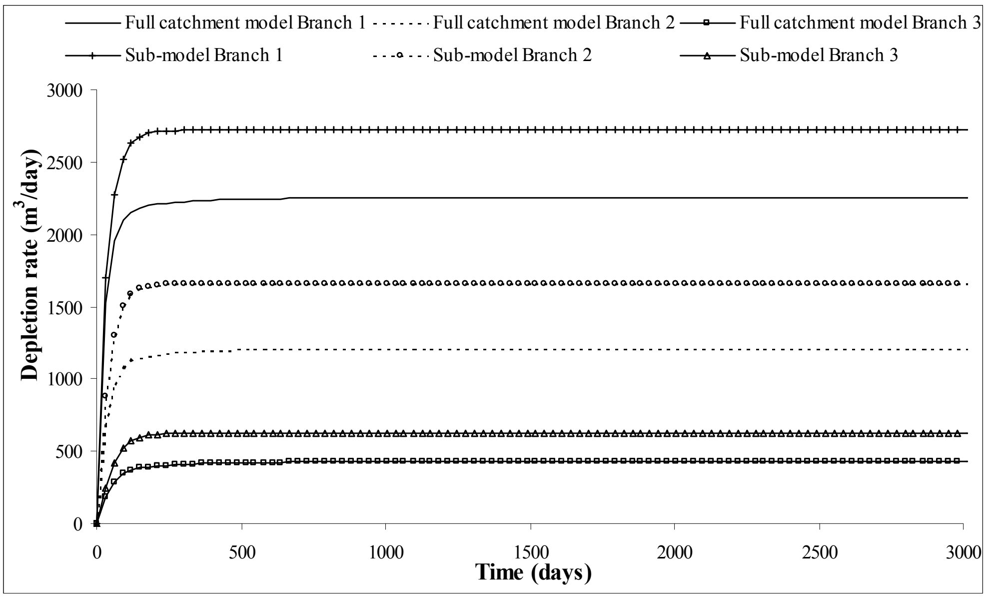


Figure 38 Total leakage induced by abstraction (Comparison 6.1)

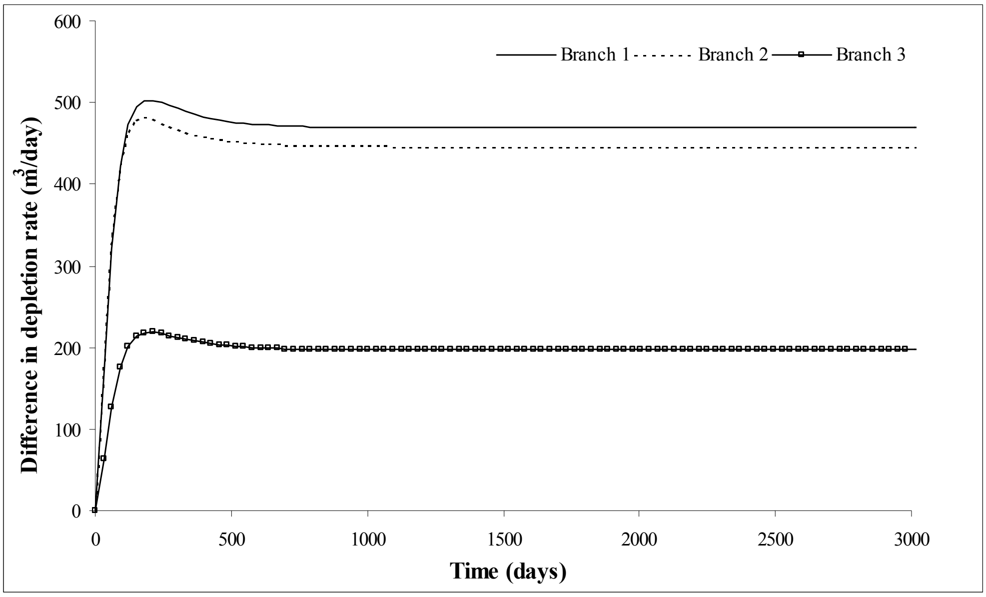


Figure 39 Difference in the depletion rate between model C1 and C2 (Comparison 6.1)

The shape of the curves showing the difference in the depletion rates simulated by the large and small model for each of the river branches (Figure 39) is of interest. Figure 39 shows that the difference in the depletion rate increases to a maximum before falling slightly to a constant rate. Whilst the models are simple, these results are difficult to interpret.

To illustrate the behaviour of the changes in state of the aquifer in the two models, the global model flow components are plotted against time in Figure 40 and Figure 41. In the large model the pumping well can access water from three sources: aquifer storage, river leakage and regional groundwater flow to the southern fixed head boundary. In the small model, the pumped borehole can only access water from the aquifer storage and the river because a no-flow condition is defined around its boundary in this first model comparison.

Figure 40 shows the variation of the total release of aquifer storage, leakage from the river and groundwater outflow to the fixed head boundary for the large model, C1, caused by the introduction of the pumping well. At the start of the pumping period water is sourced from aquifer storage and the river at approximately equal rates (~2500 $m^3 day^{-1}$). As the borehole continues to pump, less water is released from storage and more taken from the river until the system reaches a steady condition. When steady conditions have been reached, the pumping results in a reduction of flow to the fixed head boundary of approximately 170 $m^3 day^{-1}$.

Figure 41 shows that the shape of the curves are similar for the small model, C2, but the pump does not reduce the flow of water to the fixed head boundary because a no-flow condition is assigned around the model's edge. Again as more water is sourced from the river, less is released from aquifer storage. By comparing each of the two curves in this figure with those for the larger model, the difference in the behaviour of the two models can be illustrated. Such a plot is shown in Figure 42. As there is no fixed head boundary in the small model the difference between the two models for this outflow component is equivalent to the outflow to this boundary in the large model. This increases with time after the start of pumping.

The curves showing the difference in the release of groundwater from storage and river leakage have a similar shape to the difference in the depletion rates calculated by the two models shown in Figure 39; they rise to a maximum before falling to constant value. The difference in the river leakage curve is not the same as the river depletion rate curve as the full length of the river is considered in the large model. As expected, the curve showing the difference in storage release falls to zero when steady conditions are reached. The shape of the difference in total river leakage is governed by the shape of the storage release curve. Its shape is not affected by the variation in flow to the fixed head boundary; this conclusion has been corroborated by running an additional simulation in which there is no fixed head boundary in the large model.

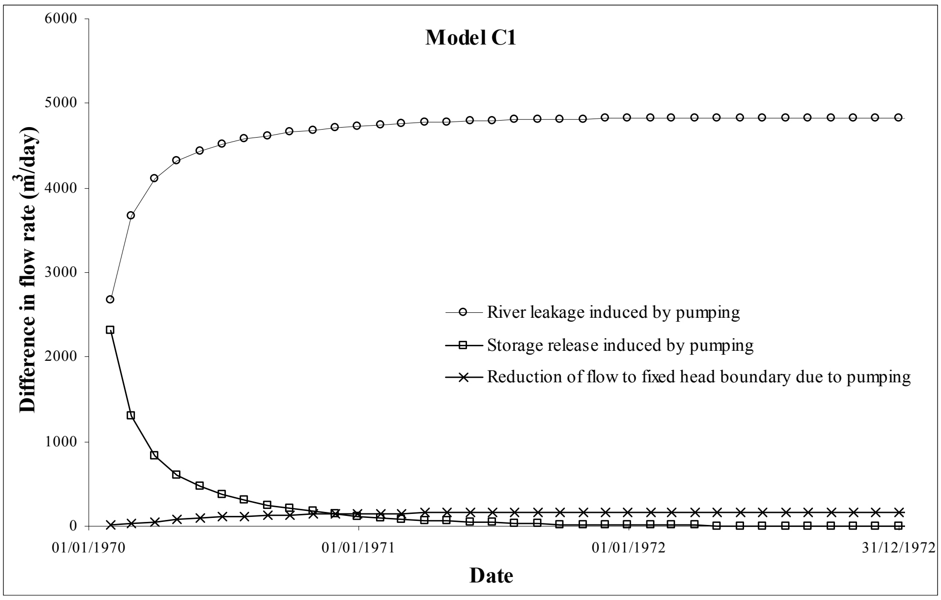


Figure 40 Difference in flow components between model C1 (Comparison 6.1) simulations with and without abstraction

The humped shape of the depletion rate and storage release curves is a result of the cone of depression around the abstraction borehole spreading and hitting different parts of the sub-model boundary at different times. This results in a complex time-variant release of storage from the aquifer when compared with the large model.

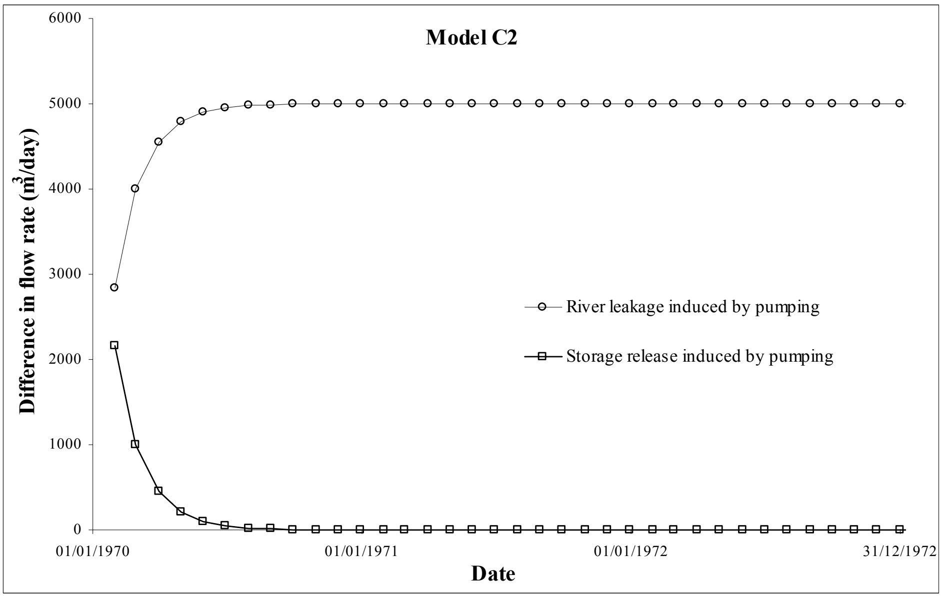


Figure 41 Difference in flow components between model C2 (Comparison 6.1) simulations with and without abstraction

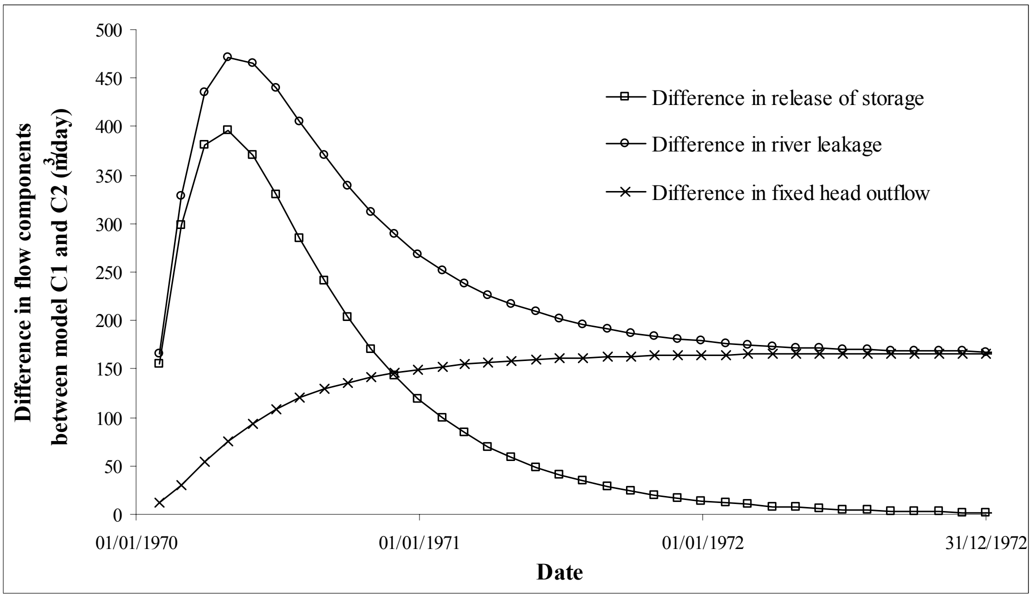
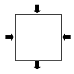


Figure 42 Difference between model C1 and model C2 impacts for Comparison 6.1

Comparison 6.2



Specified flow boundary conditions specified around sub-model C2 boundary based on model C1 simulation in which the abstraction borehole pumps water from the aquifer.

In this comparison specified flow conditions are defined around all of the boundary of the sub-model. These flows are derived from the simulation of the larger model in which the borehole pumps water from the aquifer. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction in the large scale model C1 and the sub-model C2 with these boundary conditions is shown in Figure 43. The differences in the depletion rates are shown in Figure 44 for each of the river channels. Towards the end of the simulations, when steady conditions have been reached the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	$m^3 day^{-1}$	% of abstraction
Branch 1 (central)	7.2	0.14
Branch 2 (left)	2.7	0.02
Branch 3 (right)	3.1	0.06

These differences are small but not zero as might be expected. This is due to slight difference in the positions of the cell walls across which the flows are calculated in the larger model and the position of the boundary in the sub-model. Because of the structure of the node centred mesh, the boundary flows relate to cell walls, which are actually half a mesh interval outside the boundary of the smaller model. If the positions of the cell walls in the large model and the sub-model boundary were identical the differences in depletion rate calculated by the two models would be negligible and of the order of the accuracy of the computed solutions.

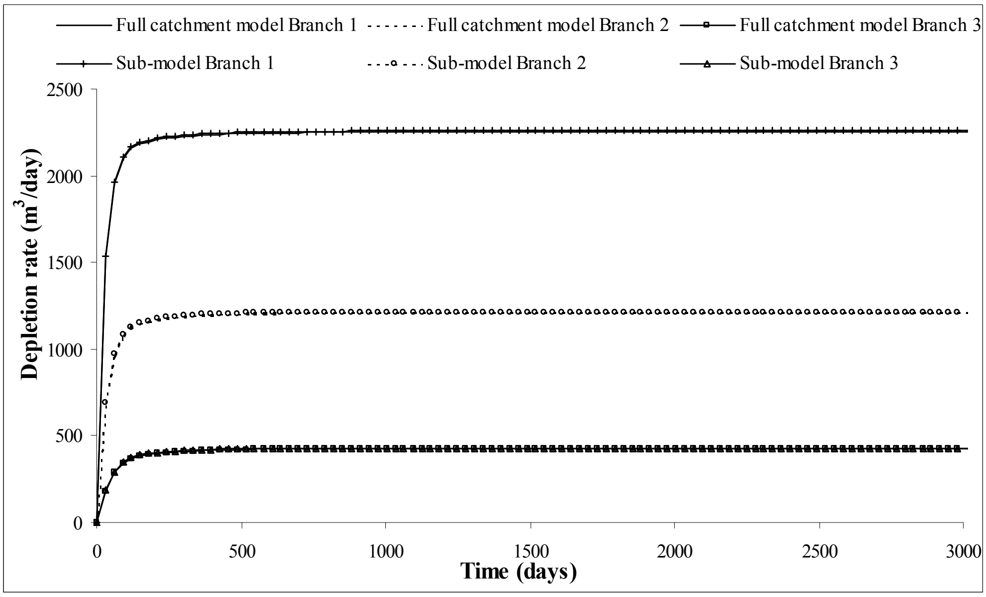


Figure 43 Total leakage induced by abstraction (Comparison 6.2)

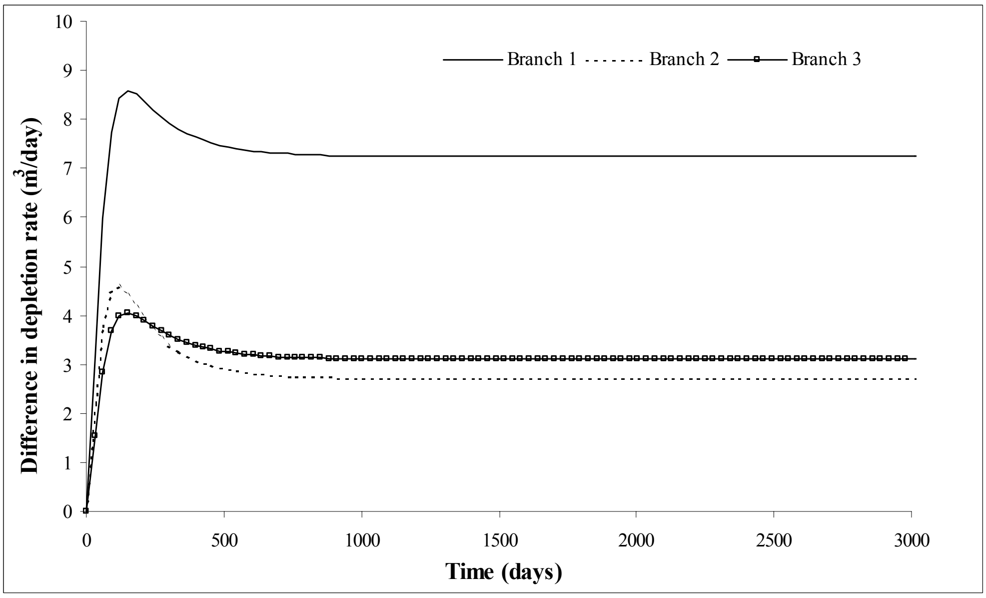
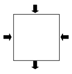


Figure 44 Difference in the depletion rate between model C1 and C2 (Comparison 6.2)

Comparison 6.3



Specified flow boundary conditions specified around sub-model C2 boundary based on model C1 simulation in which the abstraction borehole does not pump water from the aquifer.

In this comparison specified flow conditions are defined around all of the boundary of the sub-model. These flows are derived from the simulation of the larger model in which the borehole does not pump water from the aquifer. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction in the large-scale model C1 and the sub-model C2 with these boundary conditions are shown in Figure 45. The differences in the depletion rates induced by the abstraction in the two models, for each of the river channels, are shown in Figure 46. Towards the end of the simulations, when steady conditions have been reached the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	$m^3 day^{-1}$	% of abstraction
Branch 1 (central)	469	9.4
Branch 2 (left)	447	8.9
Branch 3 (right)	197	3.9

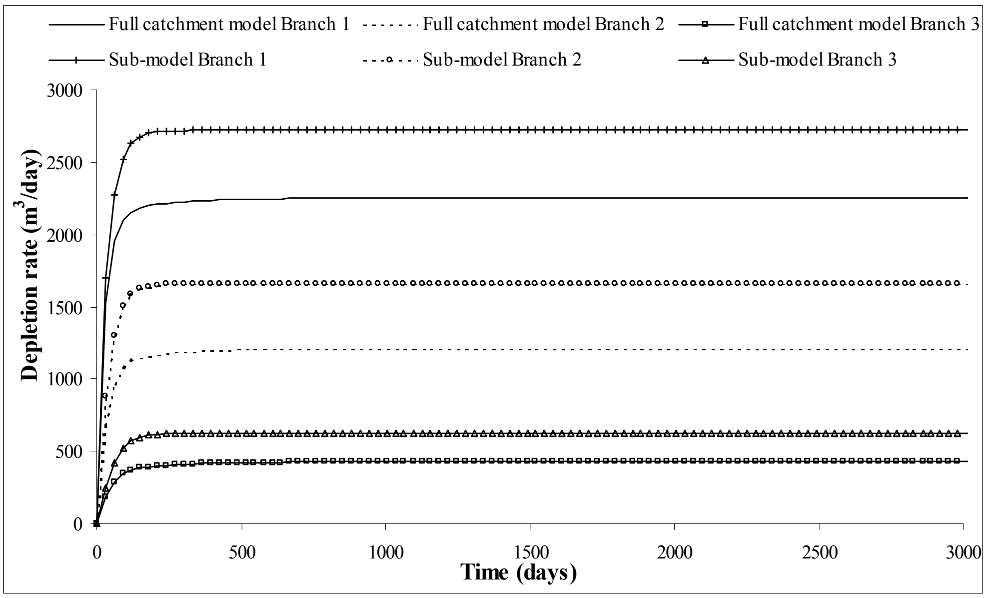


Figure 45 Total leakage induced by abstraction (Comparison 6.3)

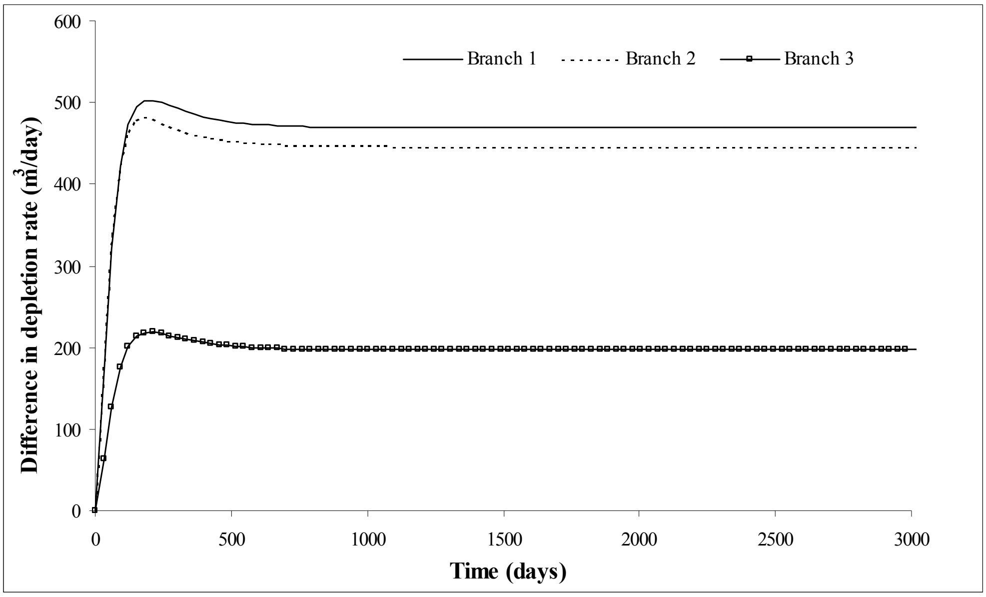
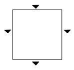


Figure 46 Difference in the depletion rate between model C1 and C2 (Comparison 6.3)

Comparison 6.4

	Fixed head boundary conditions specified around all of the sub-model C2 boundary based on the heads simulated in the model C1 steady-state simulation.

In this comparison a fixed head conditions is defined around all of the boundary of the sub-model. These fixed heads are the values simulated by the larger model at the end of the steady-state run in which recharge is applied but there is no abstraction. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction in the large scale model C1 and the sub-model C2 with these boundary conditions are shown in Figure 47. The differences in the depletion rates induced by the abstraction in the two models, for each of the river channels, are shown in Figure 48. Towards the end of the simulations, when steady conditions have been reached the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	m^3day^{-1}	% of abstraction
Branch 1 (central)	-468	-9.4
Branch 2 (left)	-520	-10.4
Branch 3 (right)	-202	-4.0

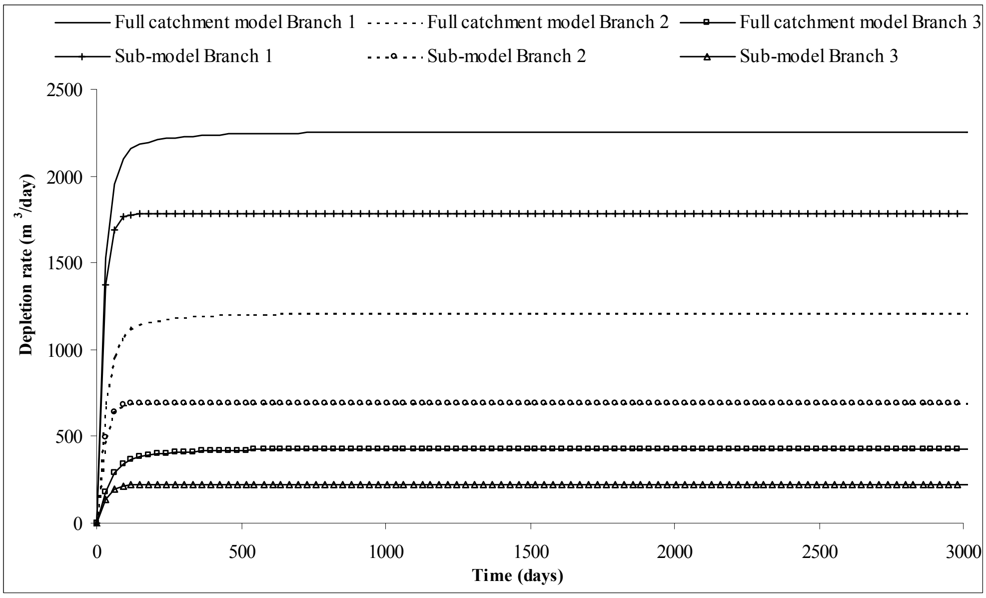


Figure 47 Total leakage induced by abstraction (Comparison 6.4)

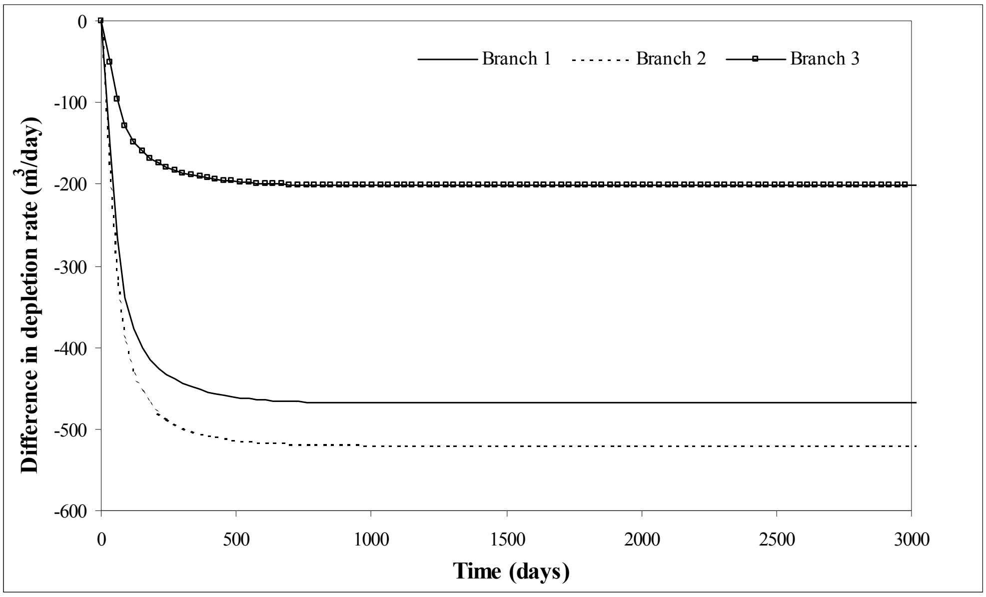
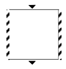


Figure 48 Difference in the depletion rate between model C1 and C2 (Comparison 6.4)

In contrast to the previous runs in this series the depletion rates calculated using the smaller model are lower than those calculated using the large model. This is because the fixed heads around the boundary of the sub-model provide an infinite source of water to the abstraction borehole. Consequently, less water is taken from the river in the sub-model.

Comparison 6.5



Fixed head boundary conditions specified along the top and bottom model boundaries. No-flow conditions along the left hand and right-hand boundaries. The boundary heads are based on those simulated in the model C1 steady-state simulation.

In this comparison no-flow conditions are defined along the left-hand and right hand boundary. Fixed head conditions are defined along the top and bottom boundaries based on the model C1 steady-state simulation. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction in the large scale model C1 and the sub-model C2 with these boundary conditions are shown in Figure 49. The differences in the depletion rates induced by the abstraction in the two models, for each of the river channels, are shown in Figure 50. Towards the end of the simulations, when steady conditions have been reached the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	m^3day^{-1}	% of abstraction
Branch 1 (central)	-372	-7.4
Branch 2 (left)	-61	-1.2
Branch 3 (right)	-92	-1.8

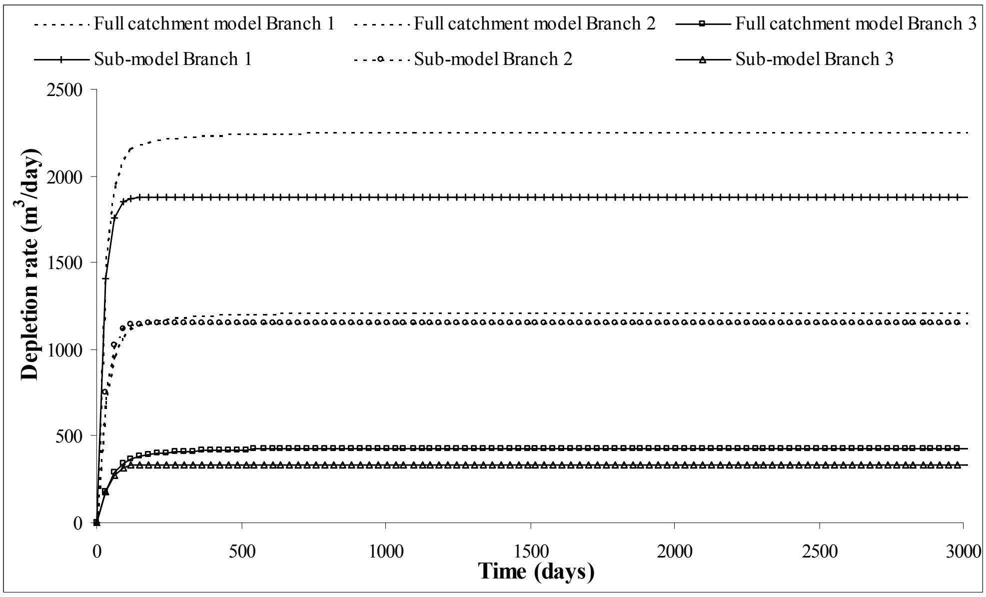


Figure 49 Total leakage induced by abstraction (Comparison 6.5)

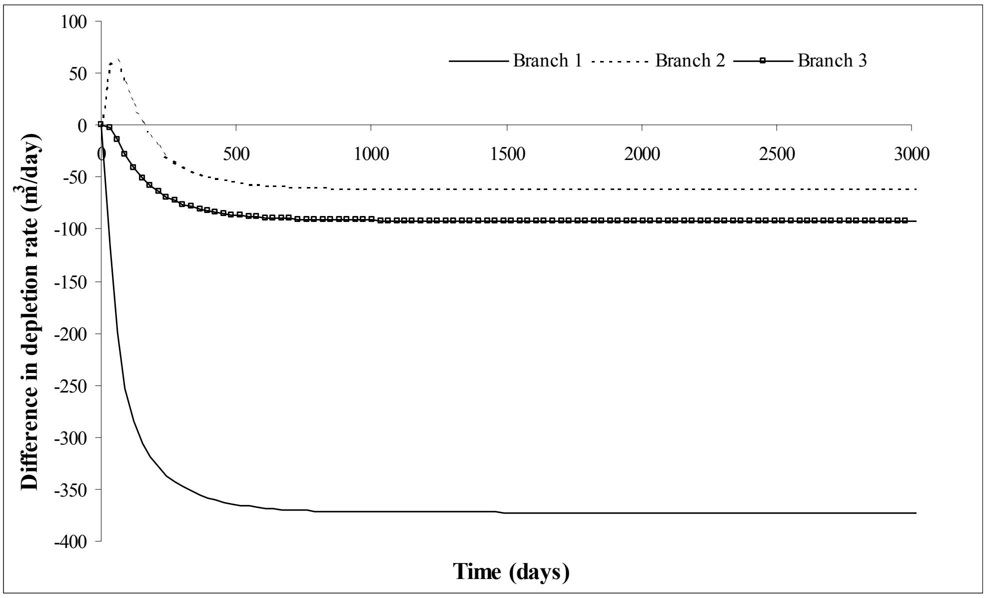
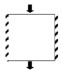


Figure 50 Difference in the depletion rate between model C1 and C2 (Comparison 6.5)

The mixture of the use of fixed head and specified flow boundary conditions tends to produce errors that cancel each other out to a certain degree. The inclusion of fixed heads along two of the sub-model boundaries reduces the amount of water that the abstraction borehole sources from the river. In contrast, the use of no flow conditions along the left and right boundary of the sub-model increases the amount of water that the pumped borehole sources from aquifer storage and river flow.

Comparison 6.6



Specified flow boundary conditions specified along the top and bottom model boundaries. No-flow conditions along the left hand and right-hand boundaries. The boundary heads are based on those simulated in the model C1 steady-state simulation.

In this comparison no-flow conditions are defined along the left-hand and right hand boundaries. Specified flows are defined along the top and bottom boundaries. These flows are based on the time-variant model C1 simulation with no abstraction or recharge, in which groundwater drains from the aquifer to the rivers. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction in the large scale model C1 and the sub-model C2 with these boundary conditions are shown in Figure 51. The differences in the depletion rates induced by the abstraction in the two models, for each of the river channels, are shown in Figure 52. Towards the end of the simulations, when steady conditions have been reached the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	m^3day^{-1}	% of abstraction
Branch 1 (central)	469	9.4
Branch 2 (left)	447	8.9
Branch 3 (right)	197	3.9

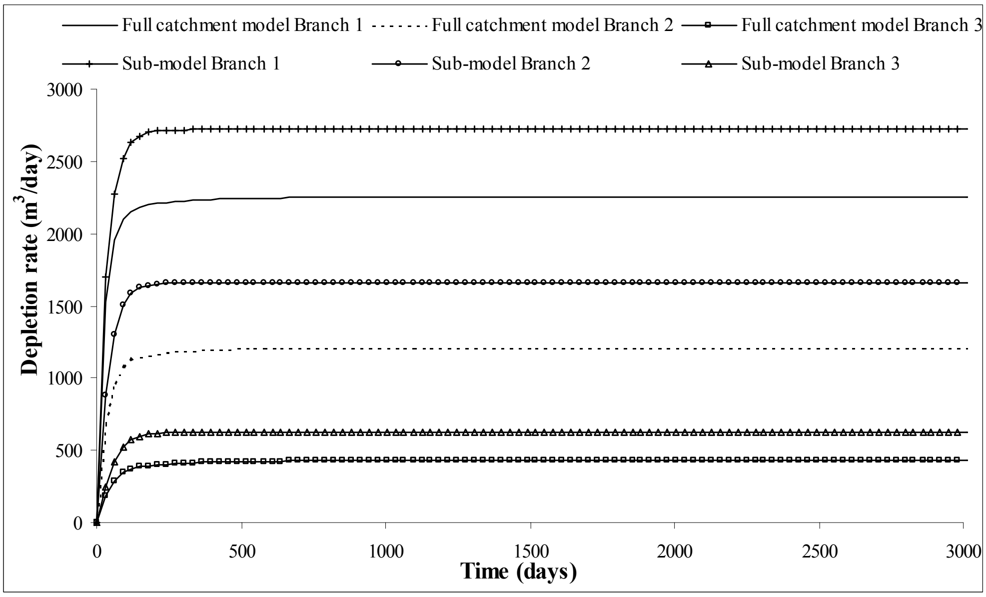


Figure 51 Total leakage induced by abstraction (Comparison 6.6)

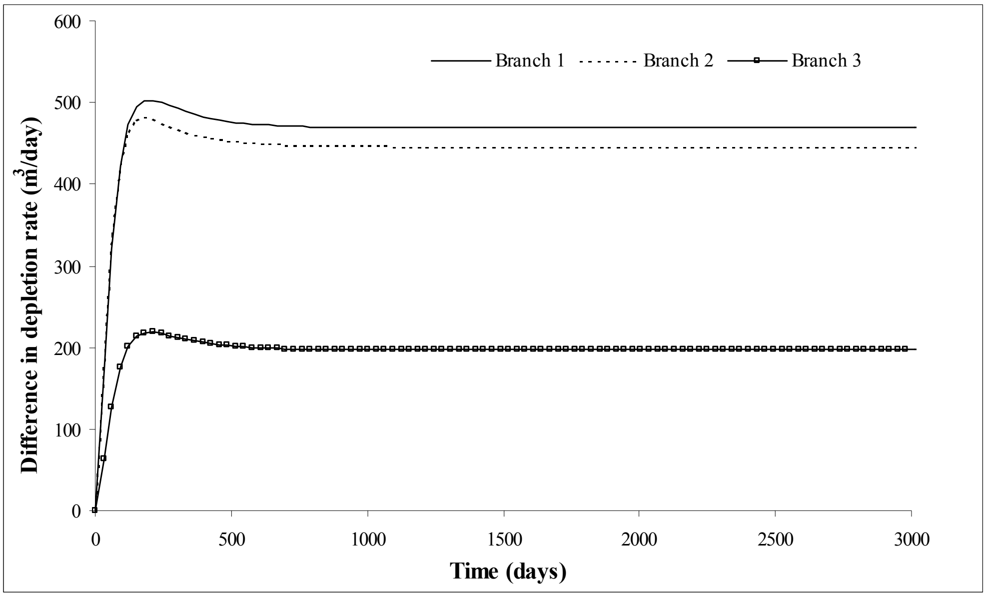
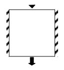


Figure 52 Difference in the depletion rate between model C1 and C2 (Comparison 6.6)

The errors associated with this sub-model are the same as for those in which no flow, or a mixture of no flow and constant (i.e. time-invariant) specified flow conditions are defined around the sub-model boundary. These cases are those presented in Comparison 6.1 and 6.4, in addition to this example. These runs illustrate that the use of a constant flow condition along a model boundary, for example derived from an estimate of the regional flow pattern, produces no better results than a model with impermeable boundaries. To obtain accurate results it is necessary to know the time-variant changes in groundwater flow across the sub-model boundary, as in Comparison 6.2, but these are impossible to know for a real system.

Comparison 6.7



No flow boundary conditions specified along the left hand and right-hand boundaries. Fixed heads specified along top boundary. Specified flows are defined along the bottom boundary

In this comparison no-flow conditions are defined along the left-hand and right hand boundaries. Fixed-heads are defined along the top boundary based on the model C1 steady-state head profile. Specified flows are defined along the bottom boundary. These flows are based on the time-variant model C1 simulation with no abstraction or recharge, in which groundwater drains from the aquifer to the rivers. Total depletion rates are calculated for the section of each of the three channels of the river catchment that exists within the area of the sub-model.

The total leakage induced by abstraction in the large scale model C1 and the sub-model C2 with these boundary conditions are shown in Figure 53. The differences in the depletion rates induced by the abstraction in the two models, for each of the river channels, are shown in Figure 54. Towards the end of the simulations, when steady conditions have been reached, the difference in the depletion rates for the three river branches are:

	Difference in depletion rate	
	m^3day^{-1}	% of abstraction
Branch 1 (central)	-302	-6.0
Branch 2 (left)	74	-1.5
Branch 3 (right)	-18	-0.4

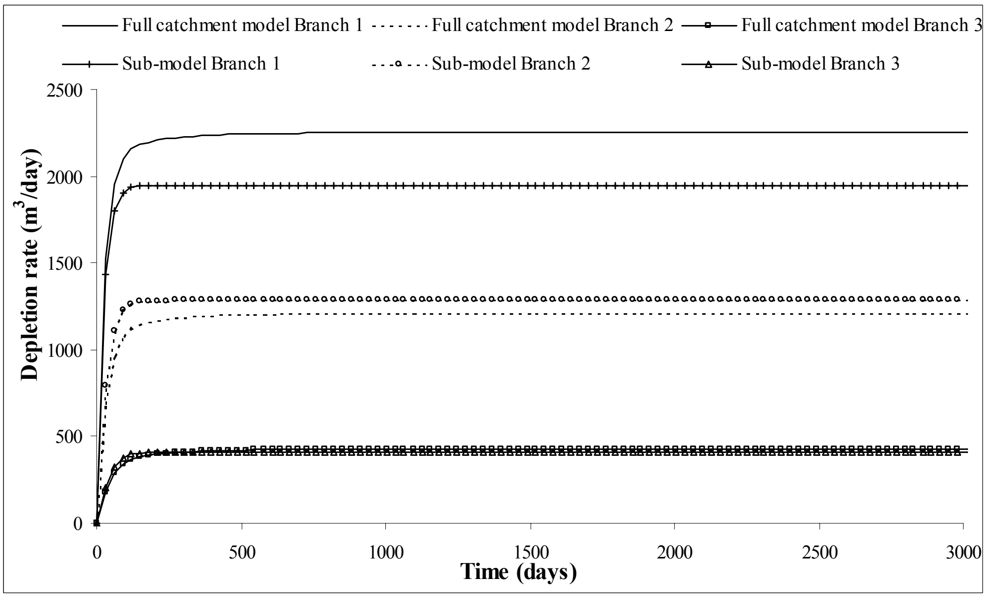


Figure 53 Total leakage induced by abstraction (Comparison 6.7)

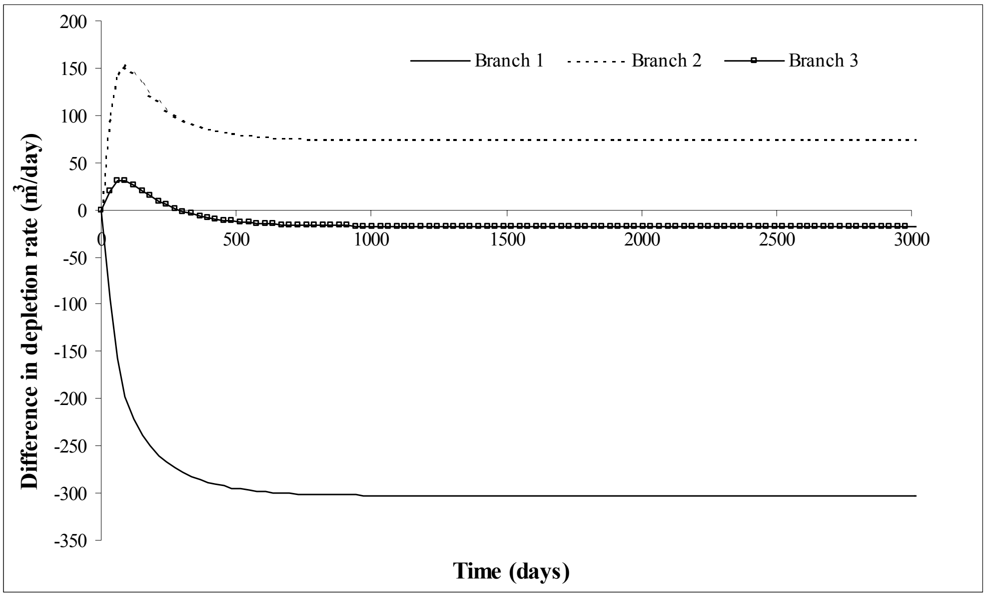


Figure 54 Difference in the depletion rate between model C1 and C2 (Comparison 6.7)

The combination of fixed head, no flow and constant specified flow boundary conditions using in this simulation produces the most accurate sub-model results when compared with the larger model, C1. Whilst the mixture of boundary conditions in this case proves to be the best it is difficult to make generalisations about other aquifer configurations from this result.

Conclusions from Series 6 runs

This series of runs comparing a full catchment model (C1) with a sub-catchment model (C2) for which different boundary conditions are assigned enables the following conclusions to be made:

1. A sub-catchment model is as accurate as a full catchment model if accurate time-variant boundary conditions can be defined for the full period of the model simulation. These flow rates would have to take into account the influence of the pumped well if its cone of depression reaches the edge of the sub-model within the simulation period. This will not be possible to do for a real system.

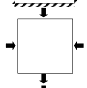
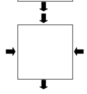
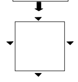
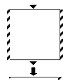
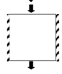
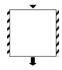
2. Depletion rates calculated using a sub-catchment model for which constant specified flow boundary condition have been estimated are as inaccurate as those calculated when no flow boundary conditions are defined around the boundary.

3. Depletion rates calculated using sub-catchment models in which fixed head conditions are assigned around the boundary will be underestimates of those calculated in the full catchment model.

4. Depletion rates calculated using sub-catchment models in which no flow or constant specified flow conditions are assigned around the boundary, will be overestimates of those calculated in the full catchment model.

5. By taking the average of the depletion rates calculated using the sub-catchment model with (i) no-flow boundaries (model S6_1) and with (ii) fixed head boundaries (model S6_4) more accurate results are obtained. The differences between the average of the simulations S6_1 and S6_4 depletion rates and the depletion rate calculated using the full catchment model C1 are shown in Figure 55 and Figure 56. Figure 55 shows the difference as values in cubic metres per day. Figure 56 shows the difference as a percentage of the abstraction rate. This comparison is also shown at the end of each of the sub-catchment model simulations in Table 10.

Table 10 Summary of the differences in depletion rate for the Series 6 simulations

		Difference in depletion rate as a % of abstraction at the end of the simulation period compared to full catchment model C1		
	Boundary conditions	Branch 1	Branch 2	Branch 3
Comparison 6.1		9.4	8.9	3.9
Comparison 6.2		0.14	0.02	0.06
Comparison 6.3		9.4	8.9	3.9
Comparison 6.4		-9.4	-10.4	-4.0
Comparison 6.5		-7.4	-1.2	-1.8
Comparison 6.6		9.4	8.9	3.9
Comparison 6.7		-6.0	-1.5	-0.4
Average of depletion rates calculated in Comparison 6.1 and 6.4		0.004	-0.73	-0.05

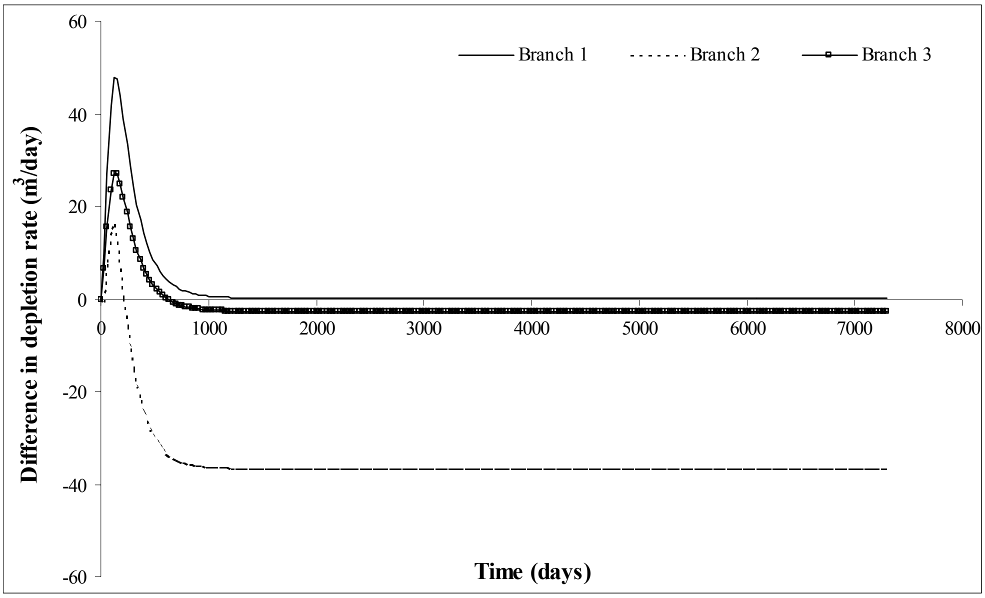


Figure 55 Average of Comparison 6.1 and 6.4 depletion rates

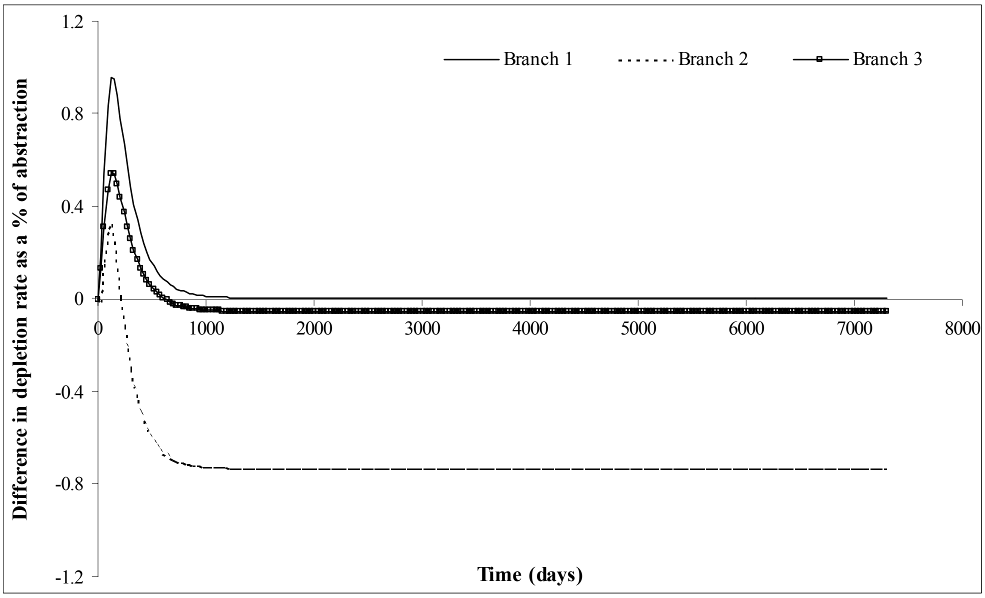


Figure 56 Average of Comparison 6.1 and 6.4 depletion rates as a percentage of abstraction

3.4.8 Impact modelling: Series 7. Effect of inclusion of VKD

In this series of runs the model A1 is used to investigate what effect the use of VKD has on the assessment of the impact of abstraction on river baseflows. All the runs have the same initial transmissivity (400 m^2day^{-1}). Model A1 contains a single flat straight-line river running from north to south through its centre. Model A1 is described in Section 3.2.

Purpose of the series runs

In this series of simulations model A1 is used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. Four pairs of simulations are performed. In the first simulation of each pair the abstraction well is not included in the model. In the second simulation of each pair the abstraction well pumps at a constant rate of 5,000 m^3day^{-1}. The depletion rate along the river is derived by calculating the difference in the total leakage rates along the channel over time between the 'no abstraction' and 'abstraction' runs. The aquifer properties differ between each pair of simulations. In the first pair the horizontal hydraulic conductivity is uniform in the vertical direction. However, in the final three pairs of simulations the horizontal hydraulic conductivity increases linearly with elevation over a 25 m interval both above and below the river. The VKD profiles are illustrated in Figure 57.

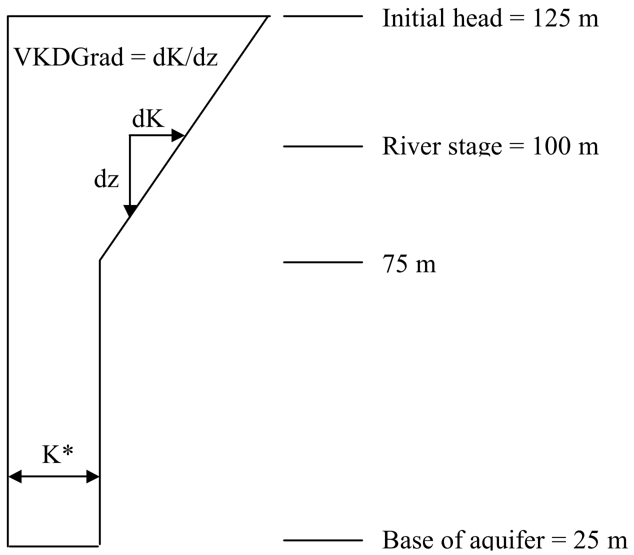


Figure 57 VKD profile applied in Series 7 simulations

The following parameters are the same in each of the simulations in Series 7:

- no recharge;
- elevation of base of aquifer: 25 m;

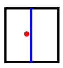
- flat river with elevation: 100 m;
- initial transmissivity of aquifer: 400 m^2day^{-1};
- homogeneous aquifer with storage coefficient of 10%;
- initial groundwater head: 125 m throughout model domain;
- initial flow along the river and inflow at top of the river: 50,000 m^3day^{-1};
- depletion rates are calculated over the full length of river.

The impact of abstraction on river baseflow is calculated by comparing the simulation with abstraction with that without abstraction for models with the same VKD parameters. The simulation runs performed in this series are summarised in Table 11.

Summary of model runs

The model parameters in this series are listed in Table 11. The initial transmissivity is the same in each of the simulations. The hydraulic conductivity at the base of the profile is lower, and the rate of increase of hydraulic conductivity above the profile inflection point is higher, in each subsequent pair of simulations.

Table 11 Summary of Series 7 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	K* (m^2day^{-1})	VKDGrad (m day^{-1} per m)	Initial transmissivity (m^2day^{-1})
S7_1	A1		0	4	0	400
S7_2	A1		5,000	4	0	400
S7_3	A1		0	2.75	0.1	400
S7_4	A1		5,000	2.75	0.1	400
S7_5	A1		0	1.5	0.2	400
S7_6	A1		5,000	1.5	0.2	400
S7_7	A1		0	0.25	0.3	400
S7_8	A1		5,000	0.25	0.3	400

Results from this series of simulations

Figure 58 shows the depletion rates calculated using these four pairs of simulations. The absolute differences in depletion rate between the final three pairs of simulations and the first pair (in which the hydraulic conductivity is uniform) are plotted in Figure 59. The differences are plotted as a percentage of the abstraction rate in Figure 60.

The depletion rates for model runs S7_6 and S7_4 are similar to S7_2 in which hydraulic conductivity does not vary with depth. For S7_4 the maximum difference in depletion rate is approximately 70 m^3day^{-1} or 1.4% of the abstraction rate compared to S7_2. For S7_6 the maximum difference in depletion rate is approximately 165 m^3day^{-1} or 3.3% of the abstraction, again compared to S7_2. The depletion rates are the same towards the end of the simulation when steady conditions have nearly been reached and the river is the only source of water for the abstraction borehole.

In models S7_7 and S7_8 the hydraulic conductivity at the base of the profile is 0.25 m day^{-1} and the rate of increase of hydraulic conductivity above the profile inflection point is 0.3 m day^{-1} per metre. This more marked increase in hydraulic conductivity results in the finite difference node at the abstraction well de-watering which switches off the pump. Consequently, the curve of the depletion falls to zero after approximately 260 days. This behaviour is illustrated in Figure 61 and Figure 62 which show the groundwater head variation at the finite difference nodes on the river nearest to the abstraction well and, at the well. When the head at the well falls below 25 m it ceases to pump.

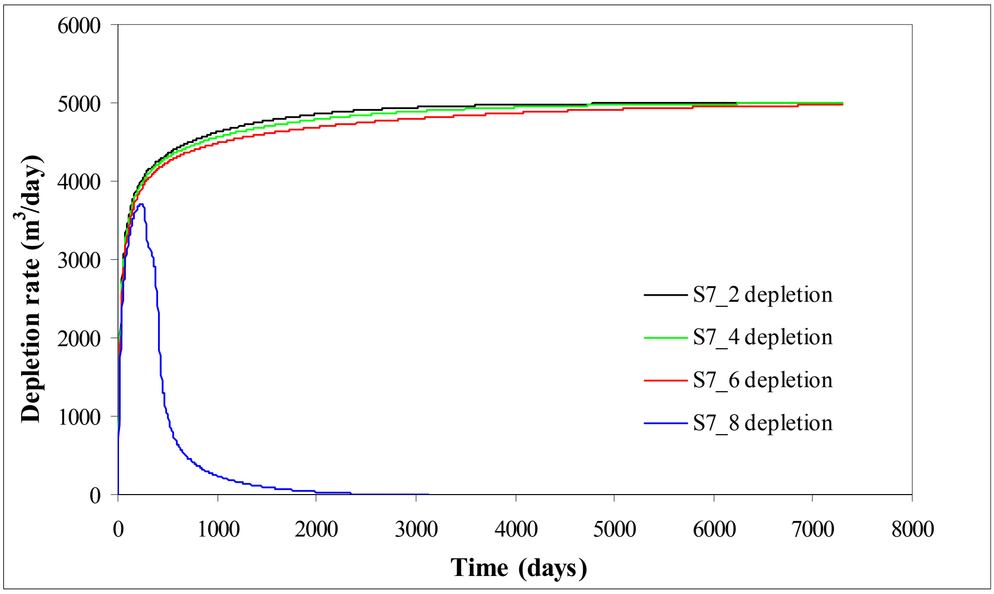


Figure 58 Series 7 simulated depletion rates

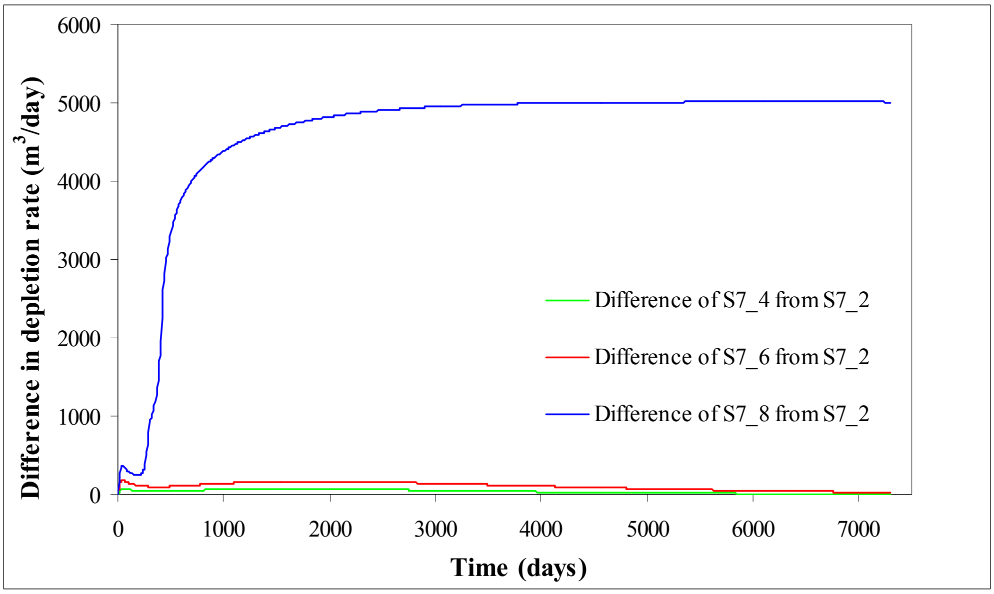


Figure 59 Difference between Series 7 simulated depletion rates

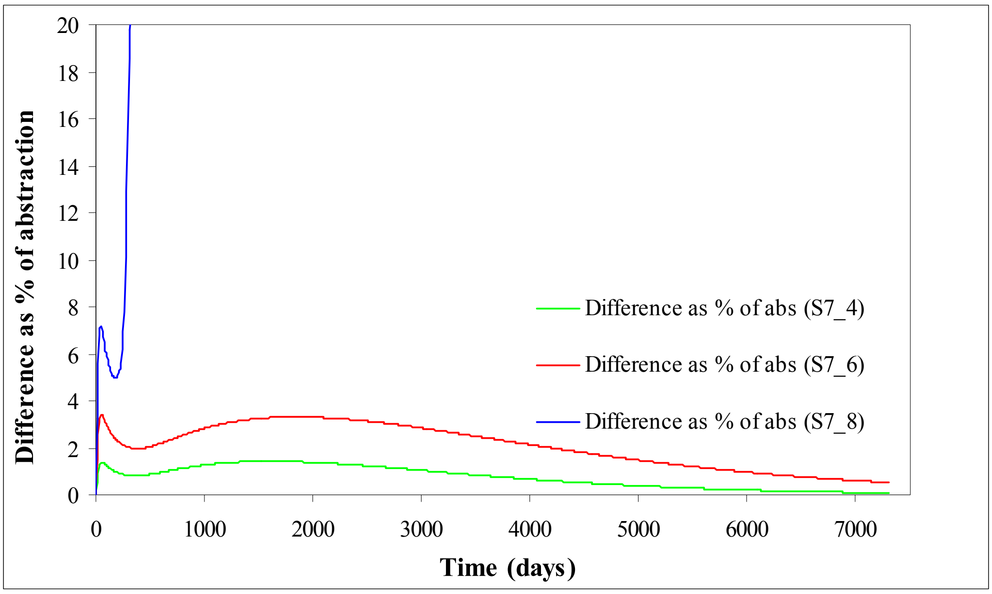


Figure 60 Difference between Series 7 simulated depletion rates as a percentage of abstraction

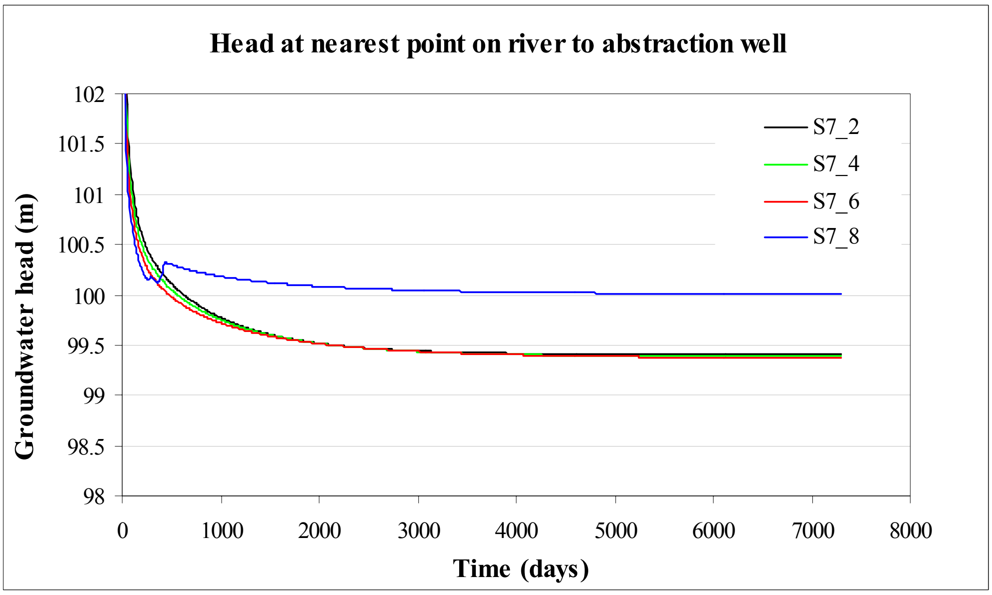


Figure 61 Groundwater head variation at nearest point on river to abstraction well (Series 7)

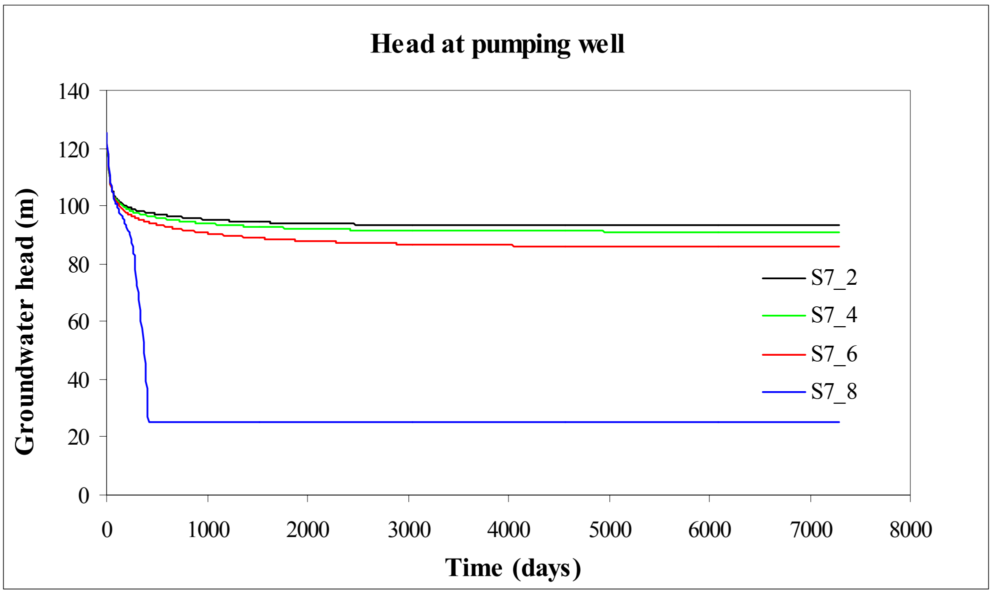


Figure 62 Groundwater head variation at abstraction well (Series 7)

Conclusions from Series 7 runs

As discussed in Series 5, the introduction of the dependence of transmissivity on groundwater level in a numerical model results in the non-linear behaviour of the aquifer system. This results in the depletion rates calculated using a numerical model also being dependent on the groundwater level. The introduction of the vertical variation of horizontal hydraulic conductivity in a numerical model increases this degree of non-linear behaviour in the system.

On examination of Figure 58, the differences between the calculated depletion rates in the models with different VKD profiles do not seem large. The maximum difference in the calculated depletion rates is approximately 7% of the pumping rate (ignoring the simulation in which the pumping well becomes dry).

3.4.9 Impact modelling: Series 8. Effect of inclusion of VKD

In this series of runs the model A1 is again used to investigate what effect the use of VKD has on the assessment of the impact of abstraction on river baseflows. The base hydraulic conductivity (K*) is the same in each run but the initial transmissivity is different for each pair. Model A1 contains a single flat straight-line river running from north to south through its centre. Model A1 is described in Section 3.2.

Purpose of the series runs

In this series of simulations model A1 is used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. Five pairs of simulations are performed. In the first simulation of each pair the abstraction well is not included in the model. In the second simulation of each pair the abstraction well pumps at a constant rate of 5,000 m^3day^{-1}. The depletion rate along the river is derived by calculating the difference in the total leakage rates along the channel over time between the 'no abstraction' and 'abstraction' runs. The aquifer properties differ between each pair of simulations. In the first pair the horizontal hydraulic conductivity is uniform in the vertical direction. However, in the final four pairs of simulations the horizontal hydraulic conductivity increases linearly with elevation over a 25 m interval both above and below the river. The VKD profiles are illustrated in Figure 63.

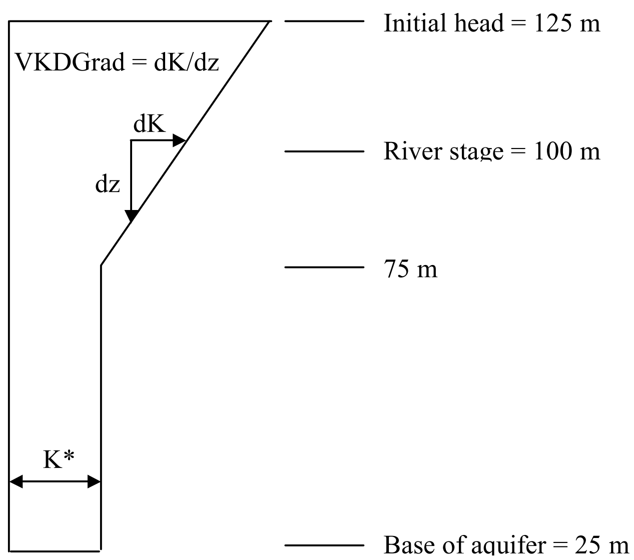


Figure 63 VKD profile used in Series 8 simulations

The following parameters are the same in each of the Series 8 simulations:

- no recharge;
- elevation of base of aquifer: 25 m;

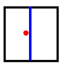
- flat river with elevation: 100 m;
- homogeneous aquifer with storage coefficient of 10%;
- initial groundwater head: 125 m throughout model domain;
- initial flow along the river and inflow at top of the river: 50,000 m^3day^{-1};
- depletion rates are calculated over the full length of river.

The impact of abstraction on river baseflow is calculated by comparing the simulation with abstraction with that without abstraction for models with the same VKD parameters. The simulation runs performed in this series are summarised in Table 12.

Summary of model runs

The model parameters in this series are listed in Table 12. In this series the hydraulic conductivity at the base of the profile is constant but the rate of increase of hydraulic conductivity above the profile inflection point is higher, in each subsequent pair of simulations.

Table 12 Summary of Series 8 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	K* (m^2day^{-1})	VKDGrad (m day^{-1} per m)	Initial transmissivity (m^2day^{-1})
S8_1	A1		0	2.75	0	275
S8_2	A1		5,000	2.75	0	275
S8_3	A1		0	2.75	0.05	337.5
S8_4	A1		5,000	2.75	0.05	337.5
S8_5	A1		0	2.75	0.1	400
S8_6	A1		5,000	2.75	0.1	400
S8_7	A1		0	2.75	0.2	525
S8_8	A1		5,000	2.75	0.2	525
S8_9	A1		0	2.75	0.5	900
S8_10	A1		5,000	2.75	0.5	900

Results from this series of simulations

The depletion rates for each of the five pairs of simulations are plotted in Figure 64. The differences in the depletion rate from that using the first pair of simulations are shown in Figure 65 and Figure 66 for the final four pairs of simulations. Towards the end of the simulation period when steady conditions have almost been reached, the depletion rates are nearly the same in each of the models. This is because the abstraction borehole derives all of its water from the river at these later times.

The differences between the calculated abstraction rates are greatest at the start of the simulation period immediately after the onset of groundwater abstraction. The comparison between the first and last pair of simulation runs, which have a greater than three fold difference in initial transmissivity, shows that the maximum difference in depletion rate is approximately 350 m^3day^{-1} or 7% of the abstraction.

The variation in the gradient of the VKD profile and hence initial transmissivity are relatively large and probably exceed the range of parameters that would be selected by a modeller for a single site. Whilst the models in this series use parameter values which vary significantly, the differences between the model results are less than 10% of the abstraction which may not be considered significant.

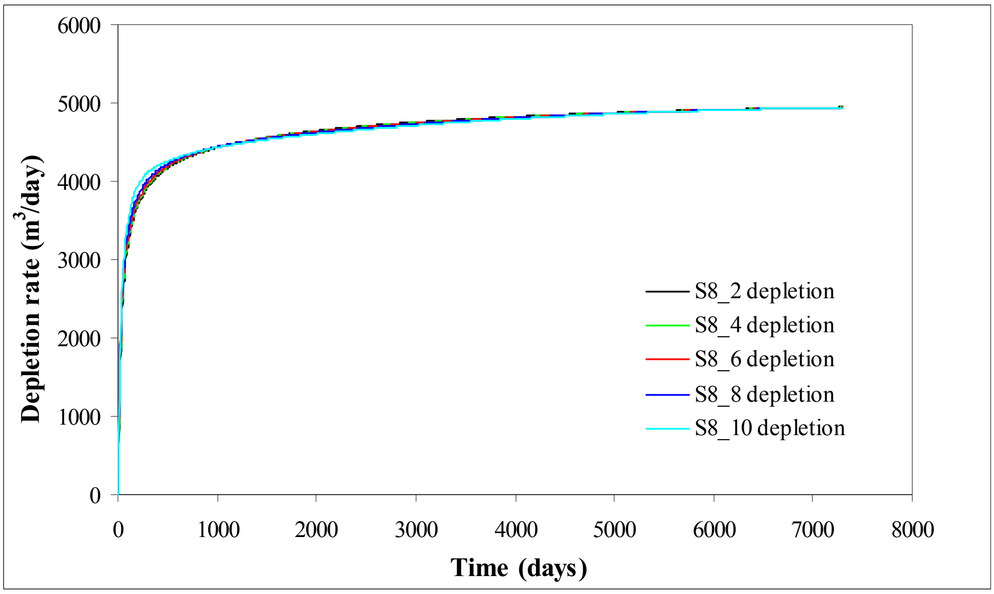


Figure 64 Series 8 simulated depletion rates

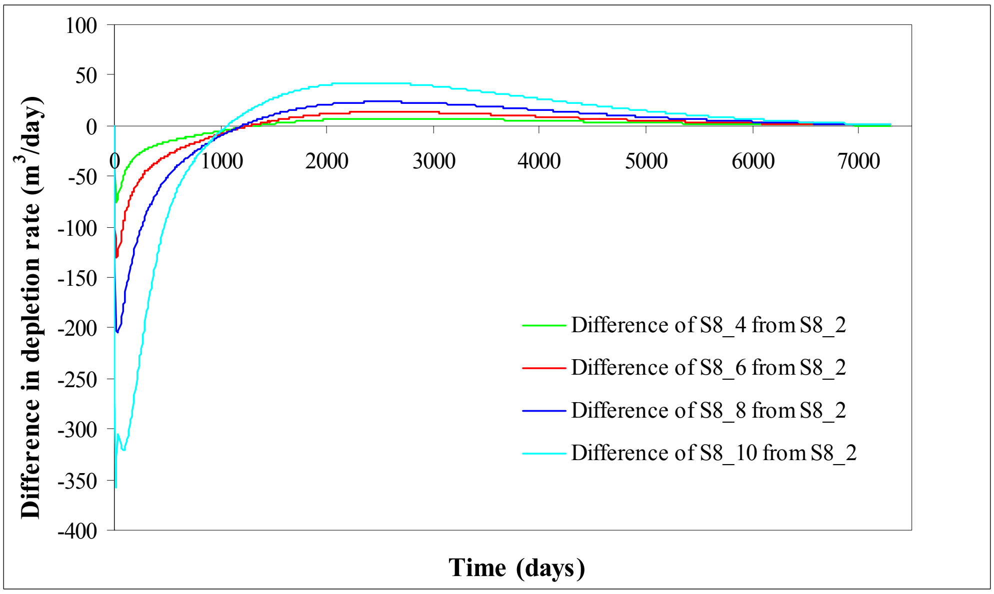


Figure 65 Difference between Series 8 simulated depletion rates

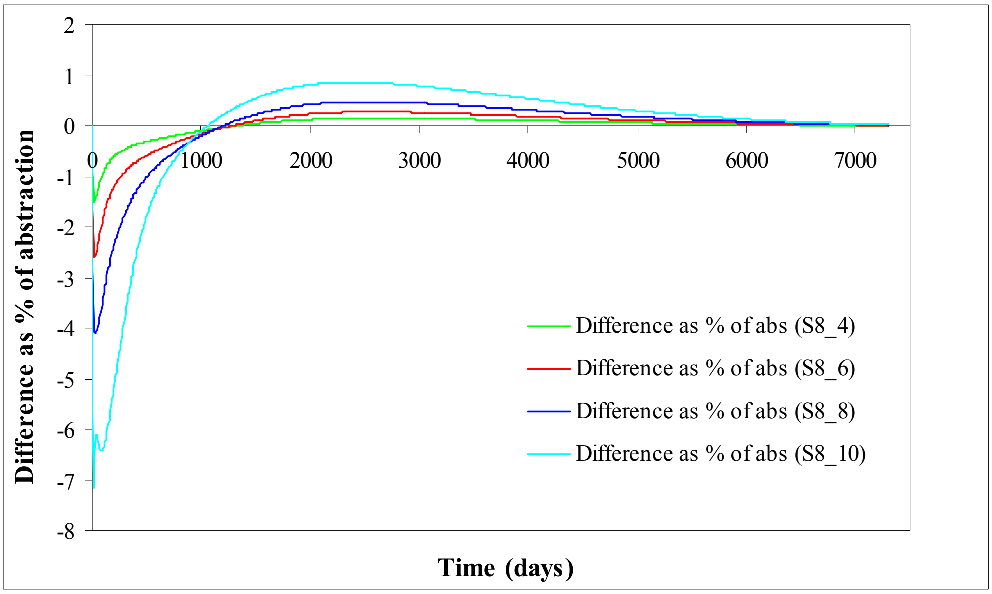


Figure 66 Difference between Series 8 simulated depletion rates as a percentage of abstraction

Conclusions from Series 8 runs

Whilst the VKD profiles and initial transmissivity vary significantly between these model simulations, the differences between the calculated depletion rates are not as marked. Expressed as a percentage of the pumping rate, the maximum difference between the calculated rates is approximately 7%. Whilst this may not be considered significant, it should be noted that the model used in this series contains a single river only. In a more complex aquifer system, with additional river catchments, the difference between the calculated depletion rates may be more significant. Further simulations are required to investigate this.

3.4.10 Impact modelling: Series 9. Spatial variation of recharge

Models used in this series

Model A1 is used in this series of runs to investigate the effect of spatially varying recharge rates on the impact of abstraction on river baseflows. Model A1 contains a single flat straight-line river running from north to south through its centre and is described in Section 3.2. In each of these simulations the transmissivity does not vary with saturated aquifer thickness and is set to 500 m^2day^{-1}.

Purpose of the series runs

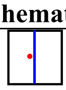
In this series of simulations, the model is used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. The effect of applying either a uniform spatial distribution of recharge or a non-uniform distribution of recharge is investigated. This is performed to illustrate the magnitude of the errors that may be produced, if any, by a numerical model that does not include the correct spatial distribution of recharge.

Summary of model runs

Three runs are performed using model A1 in which recharge is applied at a rate of 1 mm day^{-1} in a rectangular area along the river but not along the left and right-hand edges of the model (Figure 67). Depletion rates are calculated for the full length of the river, when the abstraction borehole pumps at a rate of 5,000 m^3day^{-1} and 10,000 m^3day^{-1}. These depletion rates are compared to those calculated when recharge is not applied in the model, as simulated in Series 1. The simulation runs performed in this series are summarised in Table 13. The following parameters are the same in each of the models:

- elevation of base of aquifer: 0 m;
- flat river with elevation: 100 m;
- constant transmissivity of aquifer: 500 m^2day^{-1};
- homogeneous aquifer with storage coefficient of 10%;
- initial groundwater head: 110 m throughout model domain;
- initial flow along the river and inflow at top of the river: 50,000 m^3day^{-1};
- depletion rates are calculated over the full length of river.

Table 13 Summary of Series 9 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	Recharge rate (mm day^{-1})
S1_1	A1		0	0
S1_2	A1		5,000	0
S1_3	A1		10,000	0
S9_1	A1		0	1.0 (central area)

S9_2	A1		5,000	1.0 (central area)
S9_3	A1		10,000	1.0 (central area)

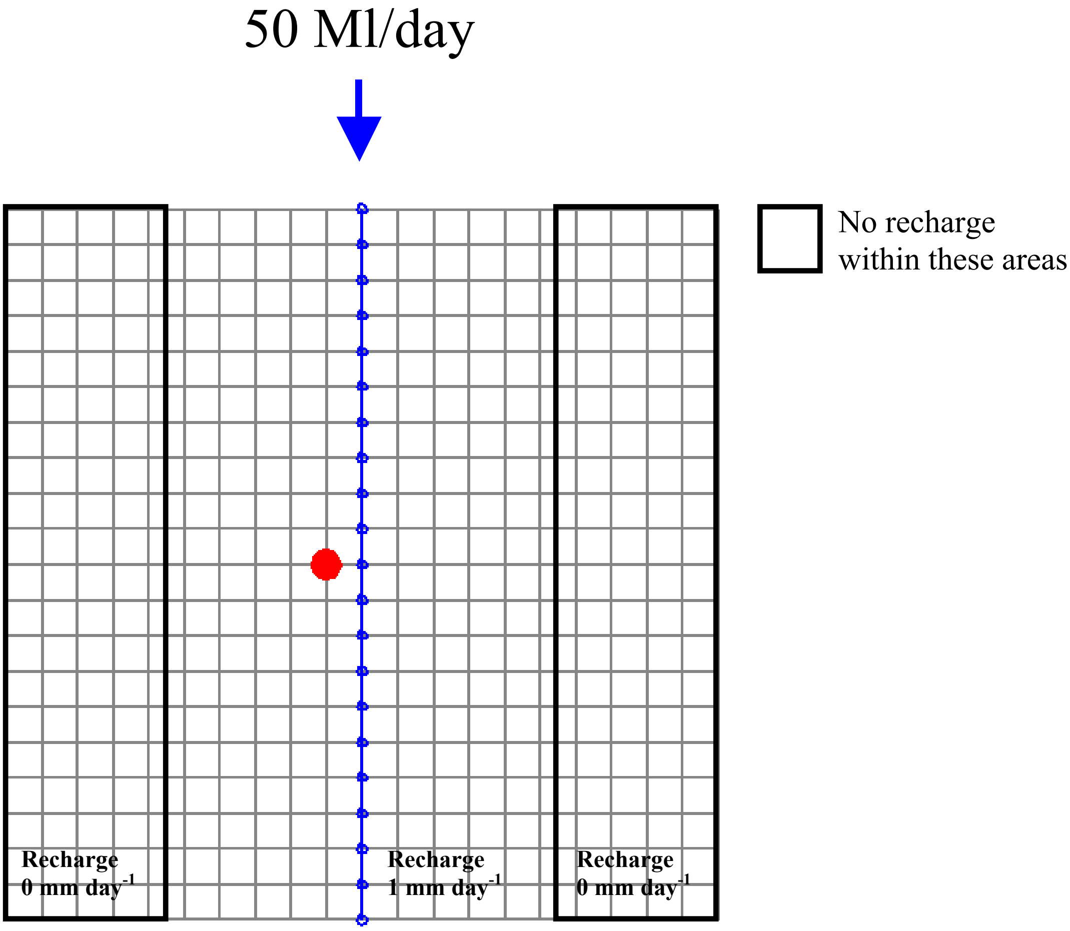
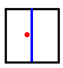
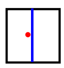


Figure 67 Structure of model used in Series 9 simulations

Results from this series of simulations

Comparison 9.1

In this comparison the total depletion rates are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 m^{3}day^{-1}. In the first model from Series 1 recharge is not applied to the aquifer. In the second model recharge is applied at a rate of 1 mm day^{-1} to the central section of the aquifer as shown in Figure 67.

		
Run	S1_2	S9_2
Abstraction rate	5,000 m^{3}day^{-1}	5,000 m^{3}day^{-1}
Upstream river inflow	50,000 m^{3}day^{-1}	50,000 m^{3}day^{-1} per river
Recharge	0 mm day^{-1}	1.0 mm day^{-1} over central section

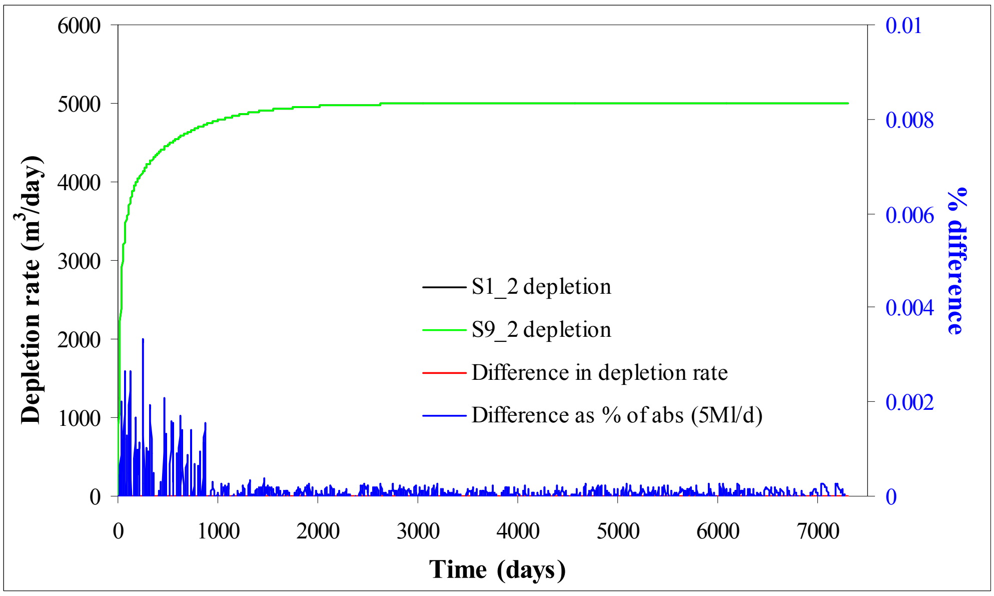
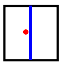
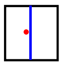


Figure 68 Depletion rates for Comparison 9.1 simulations

Comparison 9.2

In this comparison the total depletion rates are calculated for the two simulations in which the abstraction borehole pumps at a rate of 10,000 $m^3 day^{-1}$.

		
Run	S1_3	S9_3
Abstraction rate	10,000 $m^3 day^{-1}$	10,000 $m^3 day^{-1}$
Upstream river inflow	50,000 $m^3 day^{-1}$	50,000 $m^3 day^{-1}$ per river
Recharge	0 mm day^{-1}	1.0 mm day^{-1} over central section

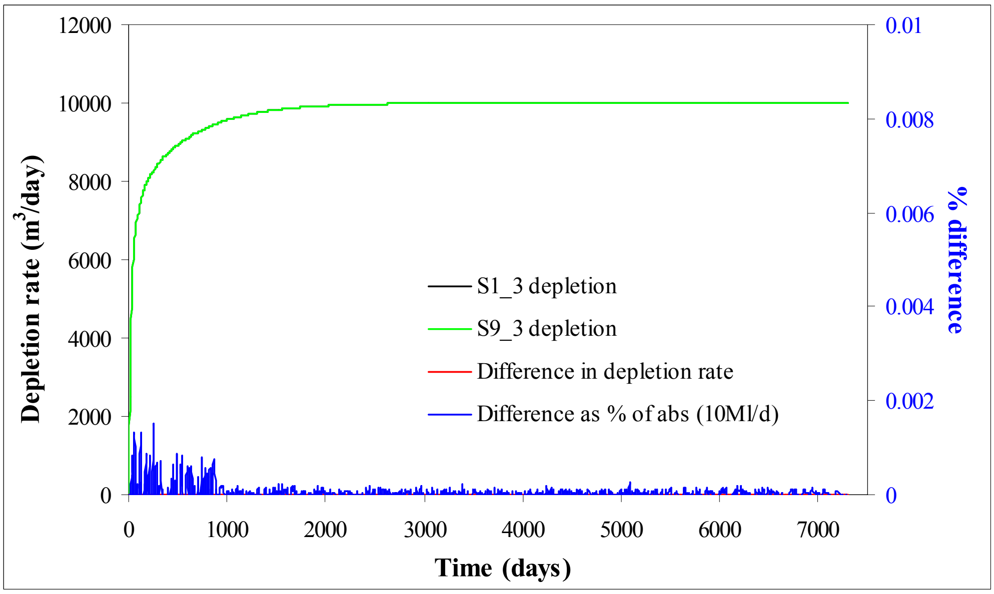


Figure 69 Depletion rates for Comparison 9.2 simulations

Figure 68 and Figure 69 show the depletion rates calculated using the two abstraction rates. The difference between the depletion rates calculated by the Series 9 and Series 1 models is also shown in cubic metres per day and as a percentage of the abstraction rate. The figures show that the models in which recharge is applied over only part of the aquifer produce identical results, to within the accuracy of the computed solution, to those in which no recharge is applied.

Conclusions from Series 9 runs

The introduction of a non-uniform spatial distribution of recharge does not break down the linearity of the system being modelled.

Consequently, the depletion rates from the models in which recharge is applied over only part of the aquifer are the same as those in which no recharge is applied. This conclusion is only valid, however, if the river does not become perched during the simulation period in either of the models, the occurrence and timing of which can be affected by the application of recharge.

3.4.11 Impact modelling: Series 10. Temporal variation of recharge

Models used in this series

Model A1 is used in this series of runs to investigate the effect of temporally varying recharge rates on the impact of abstraction on river baseflows. Model A1 contains a single flat straight-line river running from north to south through its centre and is described in Section 3.2.

Purpose of the series runs

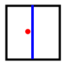
In this series of simulations, the model is used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. The effect of applying a time-variant recharge rate on the calculation of depletion rates is investigated. This is performed to assess the magnitude of the errors that may be produced, if any, by a numerical model that does not include the correct time-variant recharge distribution.

Summary of model runs

Three runs are performed using model A1 in which the recharge rate varies over time. In these runs no recharge is applied during the first six months of each year of the simulation. During the second six months of each year, recharge is applied at a rate of 1.0 mm day^{-1} uniformly across the aquifer. Depletion rates are calculated for the full length of the river, when the abstraction borehole pumps at a rate of 5,000 m^{3}day^{-1}. These depletion rates are compared to those calculated when recharge is not applied in the model as simulated in Series 1. The simulation runs performed in this series are summarised in Table 14. The following parameters are the same in each of the models:

- elevation of base of aquifer: 0 m;
- flat river with elevation: 100 m;
- constant transmissivity of aquifer: 500 m^{2}day^{-1};
- homogeneous aquifer with storage coefficient of 10%;
- initial groundwater head: 110 m throughout model domain;
- initial flow along the river and inflow at top of the river: 50,000 m^{3}day^{-1};
- depletion rates are calculated over the full length of river.

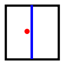
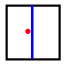
Table 14 Summary of Series 10 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^{3}day^{-1})	Recharge rate (mm day^{-1})
S1_1	A1		0	0
S1_2	A1		5,000	0
S10_1	A1		0	1.0 (for second 6 months of year)
S10_2	A1		5,000	1.0 (for second 6 months of year)

Results from this series of simulations

Comparison 10.1

In this comparison the total depletion rates, along the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 m^3day^{-1}.

		
Run	S1_2	S10_2
Abstraction rate	5,000 m^3day^{-1}	5,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river
Recharge	0 mm day^{-1}	1.0 mm day^{-1} (July to December)

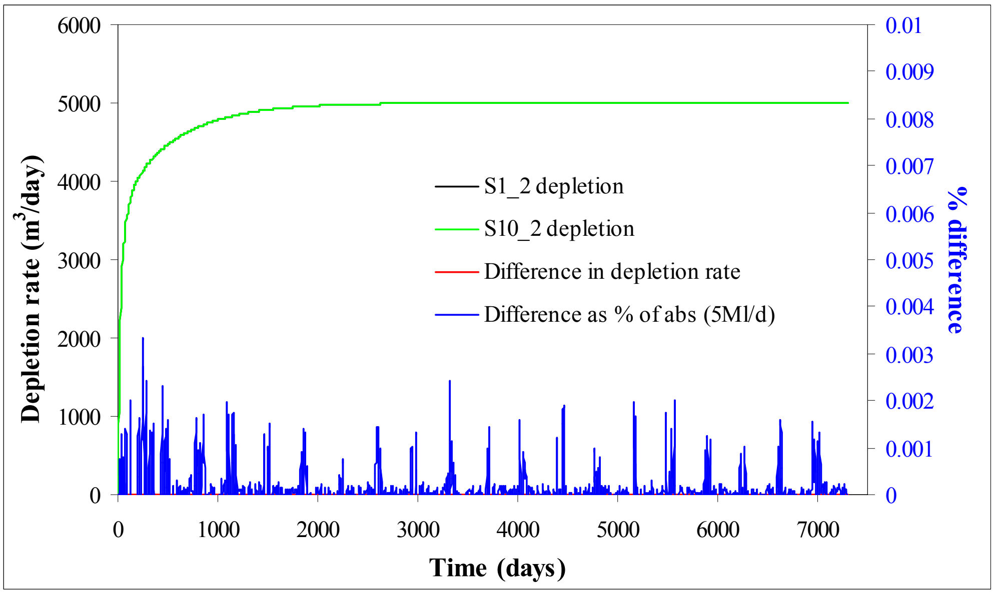


Figure 70 Depletion rates for Comparison 10.1 simulations

Figure 70 shows that the depletion rates calculated using the S1_1/2 and S10_1/2 models. The differences between the two curves are also shown in cubic metres per day and as a percentage of the abstraction rate. As with a non-uniform spatial distribution of recharge, the introduction of a time-variant recharge pattern does not alter the calculation of the depletion rate when compared to the model in which no recharge is applied. Again, in this comparison, the difference between the depletion rates is of the order of the accuracy of the computed solution, which is very small.

Conclusions from Series 10 runs

The introduction of a time-variant recharge does not break down the linearity of the system being modelled. Consequently, as with the non-uniform spatial distribution of recharge (Series 9), the depletion rates are no different to those in which recharge is not applied. Again this conclusion is only valid if the river does not become perched during the simulation period in either of the models, the occurrence and timing of which can be affected by the time-variant recharge.

Nor is the conclusion valid if the transmissivity is allowed to vary with groundwater head. In this model, A1, the transmissivity is constant (500 m^2/d), see summary of model runs above. However, the error introduced by ignoring recharge will depend upon the change in transmissivity. More work is required to confirm how this error varies with transmissivity and whether it is frequently small in practice.

3.4.12 Impact modelling: Series 11. Effect of catchment size

Models used in this series

The two models used in this series of runs are A3 and A4, which are described in Section 3.2. Model A3 contains a single flat straight-line river running from north to south through its centre. Model A4 includes two additional and identical river catchments to the west and east of this central river catchment. Models A3 and A4 are four times larger than modes A1 and A2, respectively.

Purpose of the series runs

In this series of simulations, the two models, A3 and A4, are used to calculate baseflow depletion rates along the river due to pumping from an adjacent abstraction well. The effect of representing either single or multiple river catchments is investigated similarly to the runs in Series 1. This is performed to assess the magnitude of the errors that may be produced by a numerical model that considers that all the water pumped from a borehole derives from the nearest river. This will be the case if the numerical model only includes a single river catchment as in model A3. In reality, abstraction from a pumped well can reduce the flow of groundwater to rivers in other surface water catchments, which may also be located within other groundwater catchments. As explained in the description of the Series 1 runs (Section 3.4.2), this is possible because abstraction from the pumping well will cause a cone of depression to continue to spread until it has stopped an equal amount of water from leaving the aquifer and a groundwater divide is no barrier to this spreading. This series of runs is similar to those performed in Series 1 except that larger models are used. Comparisons are made between the depletion rates calculated in this series with those calculated in Series 1.

Summary of model runs

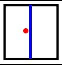
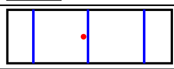
The only difference between the two models in this series of simulations is that model A4 incorporates two additional river catchments. The following parameters are the same in the models A3 and A4:

- no recharge;
- elevation of base of aquifer: 0 m;
- flat river with elevation: 100 m;
- constant transmissivity of aquifer: 500 m^2day^{-1};

- homogeneous aquifer with storage coefficient of 10%;
- initial groundwater head: 110 m throughout model domain;
- initial flow along each river and inflow at top of each river: 50,000 m^3day^{-1};
- depletion rates are calculated over the full length of river closest to the abstraction borehole i.e. central river in model A4.

Two simulations are performed using model A3 and two using model A4. In the first of each pair the abstraction borehole does not pump. In the second simulation using each model the well pumps at a rate of 10,000 m^3day^{-1}. The impact of abstraction on river baseflow is calculated by comparing the simulation with abstraction with that without abstraction. The simulation runs performed in this series are summarised in Table 15.

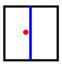
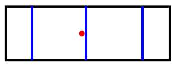
Table 15 Summary of Series 11 impact modelling runs

Run number	Model used	Model schematic	Abstraction rate (m^3day^{-1})	Recharge rate ($mmday^{-1}$)
S11_1	A3		0	0
S11_2	A3		10,000	0
S11_3	A4		0	0
S11_4	A4		10,000	0

Results from this series of simulations

Comparison 11.1

In this comparison the total depletion rates, along the full length of the river closest to the abstraction borehole, are calculated for the two simulations in which the abstraction borehole pumps at a rate of 5,000 m^3day^{-1}.

		
Run	S11_2	S11_4
Abstraction rate	10,000 m^3day^{-1}	10,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

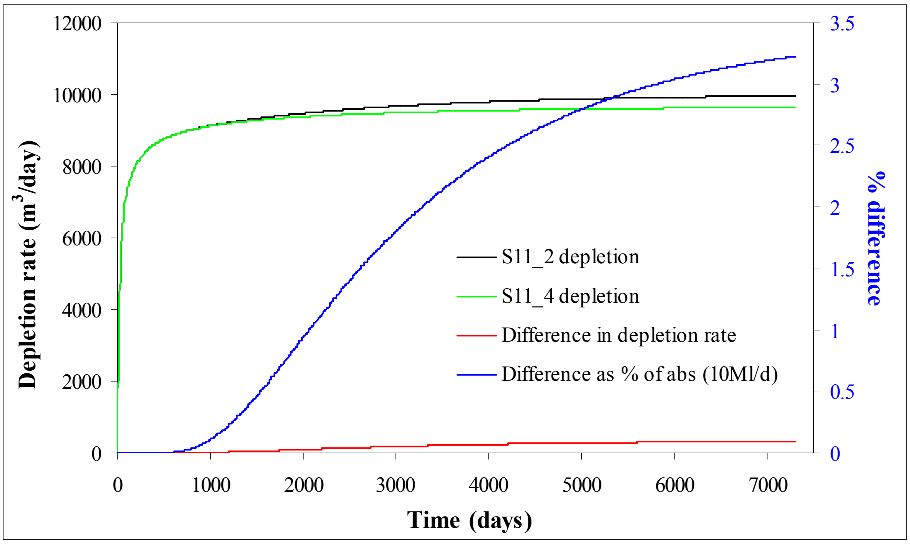
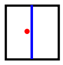
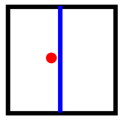


Figure 71 Depletion rates for Comparison 11.1 simulations

Comparison 11.2

In this comparison depletion rates are calculated and compared using two models that are identical except for their size. The first model is 5 km square and the second model is 10 km square. The abstraction borehole pumps at a rate of 5,000 m^3day^{-1} in both models.

	 (5 km by 5 km)	 (10 km by 10 km)
Run	S1_3	S11_2
Abstraction rate	10,000 m^3day^{-1}	10,000 m^3day^{-1}
Upstream river inflow	50,000 m^3day^{-1}	50,000 m^3day^{-1} per river

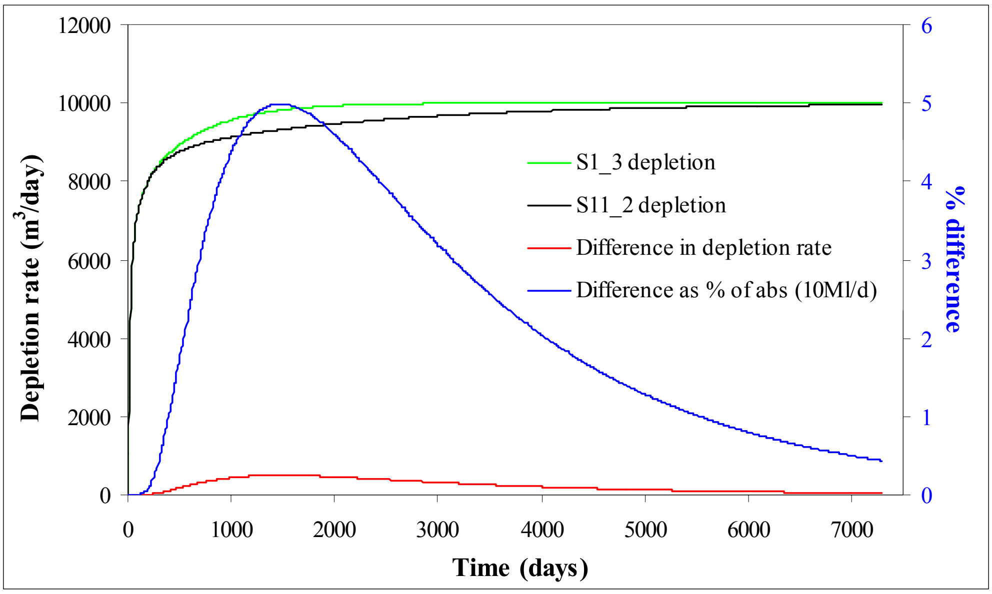


Figure 72 Depletion rates for Comparison 11.2 simulations

The first comparison illustrates the differences in depletion rate that can be produced between a model containing only one catchment and multiple river catchments. The comparison is identical to that of Comparison 1.2 except that a larger model is used.

The depletion rates calculated using simulations S11_1/2 are the same as those calculated using simulations S11_3/4 for approximately 700 days. After this time the abstraction borehole sources water from outside of the area of the middle river catchment and consequently, the depletion rate is greater after this time in the single catchment model (Figure 71).

The similar graph of depletion rates calculated using the smaller models A1 and A2 discussed in Comparison 1.2 is presented again in Figure 72. The comparison of Figure 71 and Figure 72 allows a simple, and perhaps obvious, conclusion to be made about how the size of the river catchment affects the need to model more than one catchment when quantifying the impact of an abstraction borehole.

Conclusions from Series 11 runs

The comparison between the results of simulations S1_3 and S1_8 in Figure 12 shows that the difference in depletion is approximately 7% of the pumping rate towards the end of the simulation period. The comparison between the models S11_2 and S11_4 shows a difference of approximately 3.3%. These results indicate that when a smaller catchment is modelled there is a greater need to ensure that the model also contains its adjacent catchments if a more accurate depletion rate is to be calculated. In models of smaller catchments the effects of an abstraction will reach the boundary after a shorter period of time than in a model of a larger catchment.

3.5 Conclusions from the impact modelling

A number of simulations have been performed and compared as part of this *impact modelling* task in order to assess by how much an estimate of the impact of abstraction on river baseflow can vary when different models are used. This assessment has been based on the calculation of a 'depletion rate', which is defined as the difference in the leakage rate along a section of a river, calculated using a model in which the abstraction borehole pumps and one in which it does not. The following paragraphs summarise the findings of this impact modelling work and it is recommended that those hydrogeologists involved in the application of models for the assessment of the impacts of abstraction of rivers should be familiar with these conclusions. Whilst it is likely that only relatively simple models would be constructed by, for example, Environment Agency staff during the consideration of a borehole licence application, it is of crucial importance to understand not only which hydrogeological features are important when applying such models but also how a numerical model represents these features.

3.5.1 How areally extensive should a model be?

When assessing the impact of abstraction it is important to include all of the rivers that could be affected by pumping. In such cases it is good practice to define the boundaries of the model using the physical extent of the aquifer if possible. It is not acceptable to select a stable groundwater divide between two catchments as a numerical model boundary when assessing the impact of abstraction on river flows because the impacts frequently spread beyond any such divide. This is possible because abstraction from the pumping well will cause a cone of depression to continue spreading, regardless of any groundwater divides, until it has stopped an equal amount of water from leaving the aquifer. This will usually be in the form of reduced discharges (reduced spring flow, reduced baseflow, or reduced seepage) - see Section 2.4 of the Environment Agency's guidance on how to assess the hydrogeological impact of groundwater abstractions (Environment Agency, 2007 a).

In this work simulations were performed to investigate the differences in depletion rate that can be calculated by a model of a single catchment, and by one with two identical catchments on either side. Differences in depletion rate of the order of 10% of the abstraction rate were produced for the river nearest to the abstraction borehole. These calculated errors are only indicative and will depend on the particular features of aquifer system and river catchments being modelled. It is obviously more important to include more river catchments in a model if the catchment of interest is small.

3.5.2 How fast might the cone of depression spread from the borehole?

As a guide to how rapidly (but not how far) a cone of depression will spread radially outwards from an abstraction borehole, the following equations can be used:

$$t_{point} = \frac{r^2 S}{4T}, \qquad r_{circle} = \sqrt{\frac{2\,T\,t}{S}}$$

where:

t_{point} is the time (days) when the *rate* of drawdown at a *point* at radius, r, (m) from the well is a maximum,

r_{circle} is the radius (m) of the *circle* around which the rate of drawdown is integrated and found to be a maximum at time t (days),

T is the transmissivity of the aquifer (m^2day^{-1}) and,

S is the aquifer storage coefficient (dimensionless).

These equations can be used to provide a very rough estimate of how quickly an abstraction borehole might affect the baseflow in a river. However, these expressions are derived from the Theis (1935) equation and are thus subject to the assumptions on which this solution is based; it supposes that the aquifer is confined, homogeneous, isotropic and of infinite extent and, that groundwater is pumped at constant rate from a well with an infinitely small radius. In reality the hydrogeology is likely to be complex and this must always be borne in mind.

The Environment Agency's IGARF spreadsheet (Environment Agency, 2004) may also be used to estimate the time it takes for a pumping well to influence a river.

The Theis solution cannot be used to estimate how far the impacts will spread and hence which rivers to include because it assumes that the aquifer is infinite and that there are no sources of water other than aquifer storage. The drawdown predicted by the Theis equation will not cease spreading until pumping stops whereas in reality the drawdown stops spreading when it has prevented an equal amount of water from leaving the aquifer.

3.5.3 Neglecting peripheral catchments

If for some reason a model has to be developed that contains only part of the river of interest, or only a sub-reach of such a river, then the following points should be considered. These relate to the effect that the specification of different boundary conditions has on the resulting modelled estimate of depletion rate:

- The depletion rates calculated using a model for a sub-area of a catchment are in error by the same amount regardless of whether no flow, specified flow or fixed head boundary conditions are used. However the sign of these errors is different.
- Depletion rates calculated using sub-catchment models in which only fixed head conditions are assigned around the boundary will be **underestimates** compared with those calculated using a model of the full catchment. This is because when the drawdown reaches the fixed head boundaries, they respond by supplying more water than is really available from the aquifer beyond them. The error in the depletion rate was about -10% of the pumping rate for these runs.
- Depletion rates calculated using sub-catchment models in which only no flow or constant specified flow conditions are assigned around the boundary, will be **overestimates** of those calculated in the full catchment model. This is

because when the drawdown reaches the no flow or specified flow boundaries, no more flow can be induced as a result. But in reality additional flow from the aquifer beyond would be induced. The error in the depletion rate was about +10% of the pumping rate for these runs.

- If boundary conditions are difficult to define for a sub-area of a catchment, then it is likely that a better estimate of the depletion rate will be derived if the average is taken of the rates calculated using two models: (i) the sub-catchment model in which the boundaries are defined as no-flow and (ii) the sub-catchment model in which the boundaries are defined as fixed heads. By taking this average, the effect of the poorly defined boundary conditions can be reduced.

3.5.4 Application of recharge

The application of recharge to a model which is used to calculate differences in river flow, that is depletion rates, only affects the results when:

1. transmissivity depends on groundwater head;

2. the introduction of recharge affects the timing when parts of the river become perched or sections of the channel become dry;

3. the introduction of recharge causes another flow mechanism to exhibit non-linear behaviour.

The application of recharge does not *directly* affect the depletion rates that are calculated using a model because its introduction does not cause the governing flow equation to become non-linear. In a linear aquifer model, e.g. in which transmissivity does not depend on groundwater head and in which the operation of the river-aquifer interaction mechanism does not change in time, spatial and temporal variations in recharge have no effect on the calculated river flow depletion rate.

3.5.5 Ephemeral rivers

If the length of the river being modelled changes during a simulation due to sections running dry, then the impact that an abstraction borehole has on its discharge will change. A change in the length of the river results in a breakdown in the linear behaviour of the aquifer. In such a case, care must be taken to represent the changing length of the river if depletion rates are to be calculated accurately.

3.5.6 River elevation

The elevation of a river does not *directly* affect the impact that an abstraction borehole has on its flow. The calculated depletion rate will be the same for rivers at different elevations, if all other model features are identical, unless:

1. their different elevations cause sections of the river to become perched at different times;

2. their different elevations cause sections of the river to dry out at different times;
3. the saturated aquifer thickness and thus transmissivity is different beneath the rivers due to their different elevations.

3.5.7 Unconfined aquifers

The governing equation describing the flow in an unconfined aquifer is a non-linear equation because transmissivity depends on groundwater head. Consequently, the modelled depletion rate for an unconfined aquifer depends on the elevation of the water table.

When this change in water table elevation and the resulting change in transmissivity are small, we can ignore recharge, river elevations and rates of abstraction from other boreholes. But when they are not, the system must be represented more accurately. That is, the initial groundwater levels, river elevations and rates of abstraction from other boreholes must all be included. In short, the numerical model must be a more realistic representation of the aquifer system.

The error introduced by not including recharge varies with transmissivity. Running IGARF with two transmissivities, one calculated using a typical saturated thickness and another with that expected after pumping has depressed groundwater levels, will provide an indication of how large the error might be. A number of different simulations were run in which the profile of the vertical variation of horizontal hydraulic conductivity varied significantly. The comparison of these simulations showed that, when expressed as a percentage, the maximum difference between the calculated depletion rates was approximately 7% of the pumping rate. Whilst this is significant, the simulations showed that the accurate representation of the VKD profile is not as important as, for example, the correct definition of model boundary conditions or the inclusion of all of the impacted river reaches in the model.

4 SOFTWARE DEVELOPMENT

As discussed in Section 1, the tools currently available to the Environment Agency to assess the impacts of groundwater abstraction on rivers flows fall into two categories. First, spreadsheet models, which use analytical solutions to assess impacts can be used. However, whilst these are simple and quick to use they are subject to a significant number of assumptions and provide only a general indication of the likely spatial and temporal distribution of the impacts of abstraction. In contrast to these 'simple' approaches the Environment Agency have developed regional numerical groundwater flow models of many UK aquifers and these can also be used to investigate the impacts of groundwater abstraction on river flows. However, regional groundwater models cannot be developed. within the time available for assessing a normal abstraction license. The cost of developing a regional groundwater model, where one does not currently exist, is approximately £200k to £300k. Consequently, a tool is required to assess the impact of groundwater abstraction on river flow, which is relatively easy and quick to use but which incorporates some of the complex features that can be simulated by regional groundwater models.

One of the objectives of this project was to address this problem and produce a modelling tool which enables users to include some of the features that are in regional groundwater models but which can be run and provide results within the operational time-scales of license applications. These additional features, which cannot be represented in the Environment Agency's IGARF analytical spreadsheet models include:

- non straight-line rivers i.e. dendritic river catchments;
- more than two rivers;
- sloping rivers;
- aquifer boundaries other than parallel straight-line impermeable boundaries e.g. irregular fixed head, no flow or specified flow boundaries;
- transmissivity variation with saturated aquifer thickness;
- multiple abstraction boreholes;
- recharge;
- head dependent leakages;
- multiple groundwater level observation boreholes;
- multiple river reaches along which depletion rates are monitored.

To fulfil this objective a simple spreadsheet interface has been developed using Microsoft Excel, that can be used to run the regional groundwater model ZOOMQ3D (Jackson and Spink, 2004) and analyse its results. The Excel spreadsheet, ZOOM_IGARF, is used as pre and post-processor for the groundwater flow model ZOOMQ3D with which a user can construct models including, for example, multiple dendritic river catchments. It is then possible to run the model and process the output to analyse the impact of an abstraction borehole on one or more reaches of a river within a catchment. The benefit of the use of Excel is that its application requires little prior knowledge of the structure of the input and output of the flow model, ZOOMQ3D. A full description of the ZOOM_IAGRF spreadsheet is given in the user's manual (Mansour and Jackson, in press), which has been produced as part of this project. Consequently, only a brief introduction to the tool is presented here.

The Excel workbook "ZOOM_IGARF.xls" has been developed to enable the rapid assessment of the impact of an abstraction borehole on river baseflow using the numerical groundwater flow model, ZOOMQ3D. The spreadsheet provides clear and simple methods to (i) construct the input files required by the flow model (ii) run the flow model and (iii) analyse its output. Whilst the flow model can provide information on the variation of groundwater head and river baseflow over-time, the spreadsheet modelling process has been designed to quantify and plot the amount of water that an abstraction borehole draws from a river reach or multiple reaches. An example of the output of the spreadsheet modelling process is shown in Figure 73 in which the depletion rate is calculated for two river reaches for a single abstraction borehole.

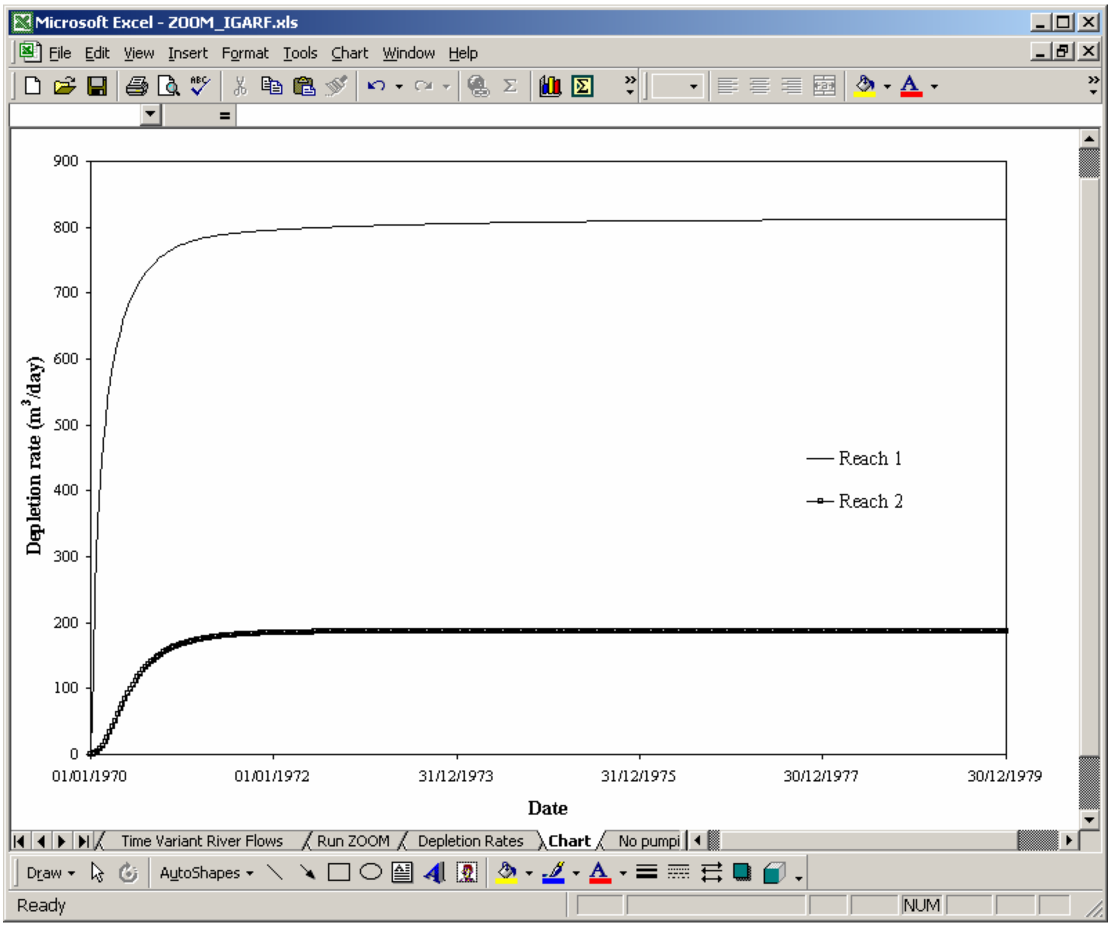


Figure 73 Example depletion rate curves plotted using the Excel spreadsheet

The aim of the Excel workbook is to prepare the input files of the numerical groundwater model ZOOMQ3D and analyse the impact of abstraction on river baseflow by running the flow model. The number of input files required to define the structure of the numerical model varies with its complexity. This depends on the conceptual model used to represent the aquifer system. This spreadsheet tool produces the basic files required by ZOOMQ3D to simulate the impact of abstraction on a groundwater system. For example, ZOOMQ3D is capable of simulating groundwater flow in three dimensions in heterogeneous aquifers, but the Excel workbook only allows the consideration of homogeneous aquifers using one layer of finite-difference nodes. This level of complexity has been deemed adequate for the assessment of the impact of the abstraction using this tool given the time available for a license assessment. Additional complexity can be introduced into the model by manually editing the model text input files produced by the spreadsheet tool. However, this requires a more detailed knowledge of the ZOOMQ3D input files structure.

Each worksheet of the Excel workbook deals with one specific type of model data. The input data varies from that which is spatially varying such as the physical structure of the model to temporally varying information such as pumping rate. The worksheets of the Excel workbook are organised so that if they are followed from left to right, the process of constructing and running the model is undertaken.

Figure 74 shows the “Rivers” worksheet which is one of the worksheets contained in the spreadsheet interface. This is used to define the rivers in the model. The worksheet can be used to add multiple straight-line rivers to a model, which can be orientated in any horizontal direction. The parameters values defining these rivers are entered at the bottom of the sheet in the yellow cells. The final operation to be performed within this sheet is to press the “Run ZETUP” button. This runs the console application program ZETUP, which is associated with ZOOMQ3D. ZETUP writes the ASCII text input files for ZOOMQ3D by processing the data in the spreadsheet which describes the structure of the model.

If more complicated rivers, for example dendritic river catchments, are to be simulated, the Windows application CREATE_RIVER_SPLINES must be used prior to running ZETUP. This is run when the “Run river interface” button, shown in Figure 74, is pressed. This application is described briefly in Section 4.1 and has been developed as part of this project. It is described in detail in the user’s manual for the ZOOM_IGARF spreadsheet (Mansour and Jackson, in press).

After the ZETUP program has been run to create the ASCII text input files required by the numerical groundwater flow model ZOOMQ3D, the data in the remaining worksheets in the ZOOM_IGARF Excel tool can be modified to complete the definition of the model, for example by adding abstraction boreholes or changing the transmissivity of the aquifer. The flow model can then be run and the results analysed.

Figure 75 shows the worksheet that is used to run the model and process the results relating to river depletion rates. By performing the operations shown in the left hand flow chart, the user can run the model and calculate depletion rates along specific sections of rivers. The procedure for running the model and plotting the graph of depletion rates shown in Figure 75 is as follows:

- After having constructed the model of the aquifer system using the previous worksheets either add or remove the pumping wells for which the impacts on river flow are to be calculated.

- Press the “Run ZOOM” button and wait for the simulation to be run.

- Press either the “Import results with no abstraction” or “Import results with abstraction button” depending on whether the pumping boreholes have been included in the model or not.

- Add the pumping wells for which the impacts on river flow are to be calculated if they were not included in the first simulation or vice-versa.

- Press either the “Import results with no abstraction” or “Import results with abstraction button” depending on whether the pumping boreholes have been included in the model or not.

- Press the “Calculate depletion rates” button. This will calculate the difference in flows between the two runs and calculate the variation in river flow depletion due to the pumping boreholes. These data are copied into the “Depletion rates” worksheet.

After this procedure has been completed the time-depletion rate data contained in the “Depletion rates” worksheet can be plotted as an x-y scatter plot. This will produce a graph similar to that shown in Figure 73.

In addition to the flow chart for running the model, the button “Modify model river parameters” is contained in the worksheet “Run ZOOM”. When this is pressed the Windows application MODIFY_MODEL_RIVERS is run. This application is described briefly in Section 4.2 and has been developed as part of this project. It is described in detail in the user’s manual for the ZOOM_IGARF spreadsheet (Mansour and Jackson, in press).

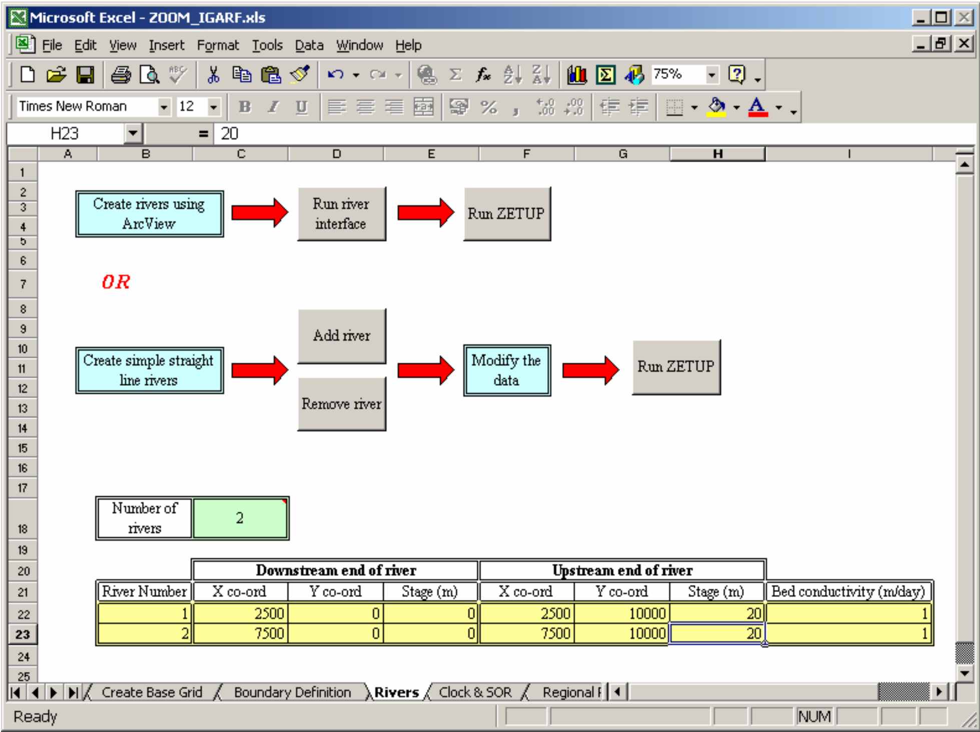


Figure 74 The "Rivers" worksheet

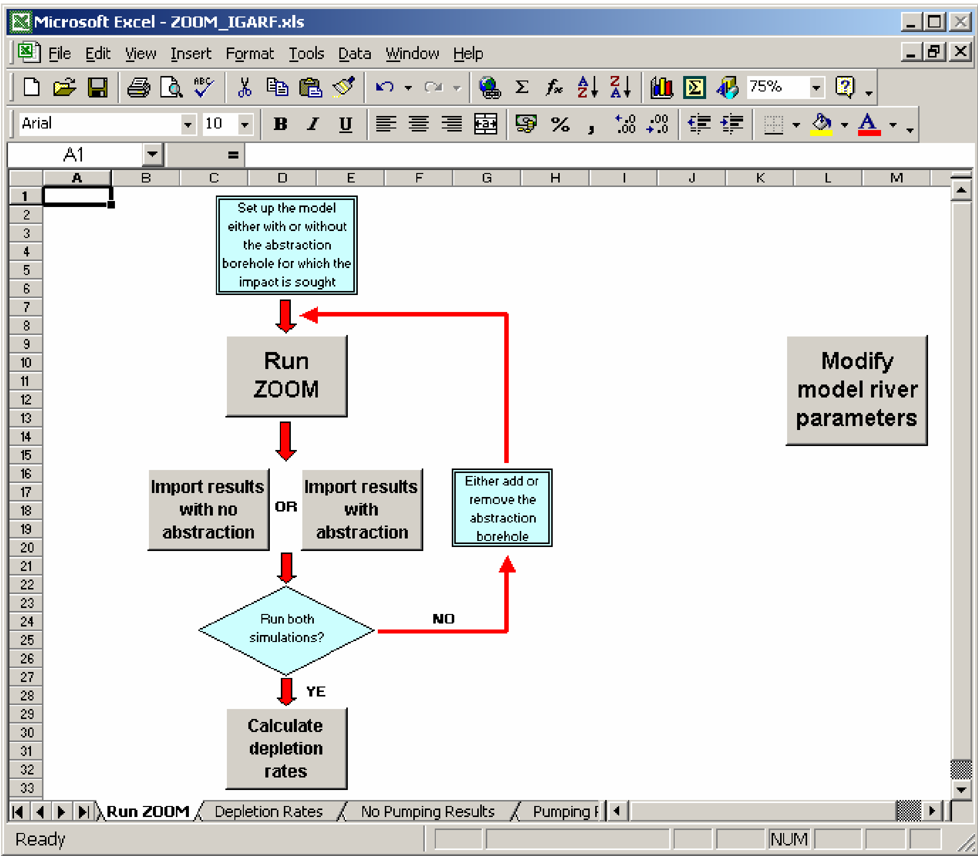


Figure 75 The "Run ZOOM" worksheet

4.1 The CREATE_RIVER_SPLINES Windows application

A technique is implemented in ZETUP and ZOOMQ3D that differentiates between *model* rivers and data structures that describe their real geometry and hydraulic characteristics. Information is defined in ZETUP to represent the real structure of rivers. This data is read into the program using text files, which the user must create for non-straight line rivers. These input files for ZETUP are termed *spline files* and can be produced using the Windows application CREATE_RIVER_SPLINES.

The application CREATE_RIVER_SPLINES (Figure 76) has been developed as part of this project and is used to create the text spline files required by ZETUP. In summary this application allows the user to join a series of points by lines to define a dendritic river catchment. The user then numbers each river and each of its branches represented by the set of connected points. After this has been performed the information describing the structures of the rivers, i.e. the connectivity of the points, is written to an ASCII text file. This output file is read by ZETUP when it is run, which then generates the ZOOMQ3D model rivers as a series of nodes on the finite difference mesh, for example as shown in Figure 77. A full description of this Windows application is given in the user's manual (Mansour and Jackson, in press).

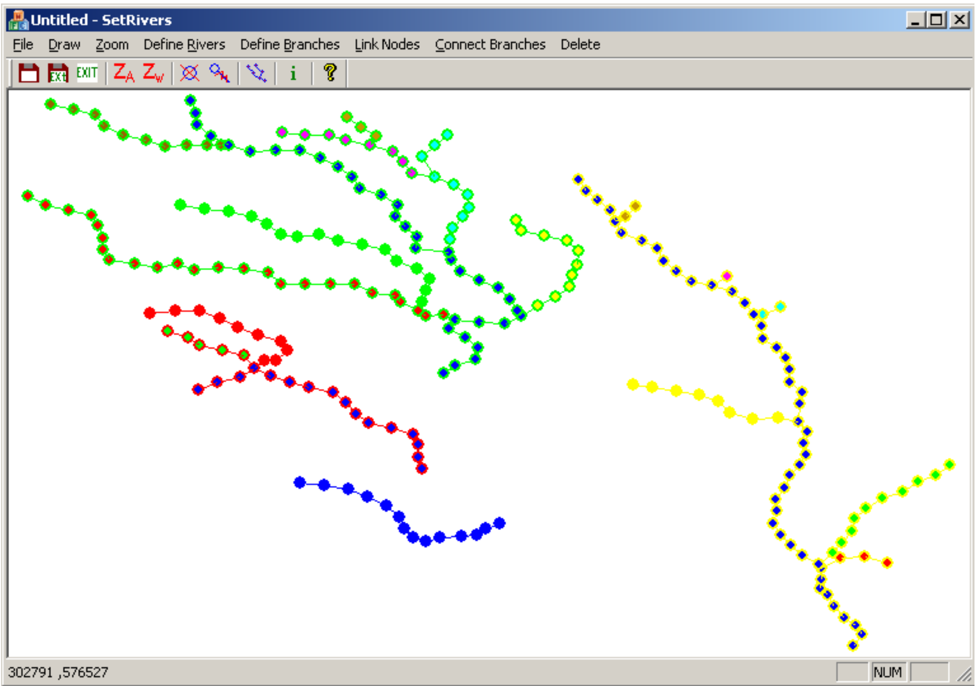


Figure 76 Example CREATE_RIVER_SPLINES application

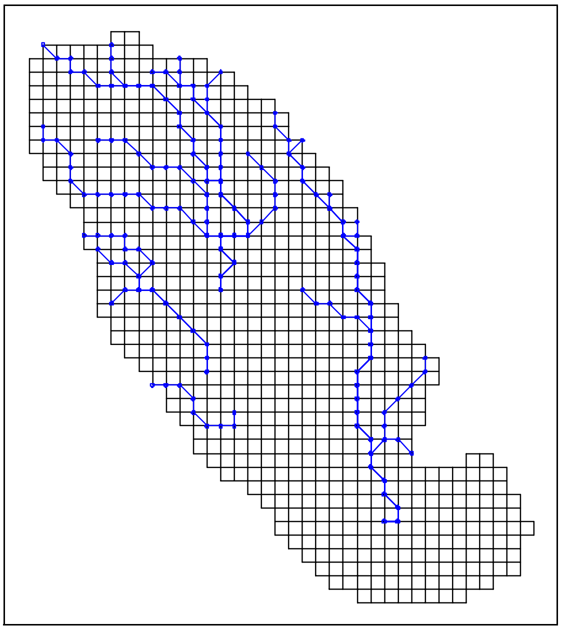


Figure 77 Model rivers after having been mapped onto the model mesh by ZETUP

4.2 The MODIFY_MODEL_RIVERS Windows application

ZETUP produces the file text file “rivers.dat”, which contains all the information describing the structure of the rivers on the finite difference mesh and their hydraulic parameters. For simplicity only the river bed hydraulic conductivity and river stage can be modified without manually editing the ZOOMQ3D input text file. However, the river bed permeability and river stage at each river node can be modified using the Windows application MODIFY_MODEL_RIVERS. This is run from the worksheet “Run ZOOM” in the Excel tool “ZOOM_IGARF.xls” (Figure 75). This program modifies the ZOOMQ3D input file “rivers.dat”.

This application has a display window and a menu bar with one function only. This is to save the work and to exit. When the application is launched, the data file “rivers.dat” produced by ZETUP is read and the river networks are drawn in the display window (Figure 78). The values of the parameters at the nodes can then be modified. The parameter values at one node or at a series of nodes can be modified by selecting the appropriate points. A dialog box is launched showing values of the river stage and the bed conductivity (Figure 78), which can then be adjusted.

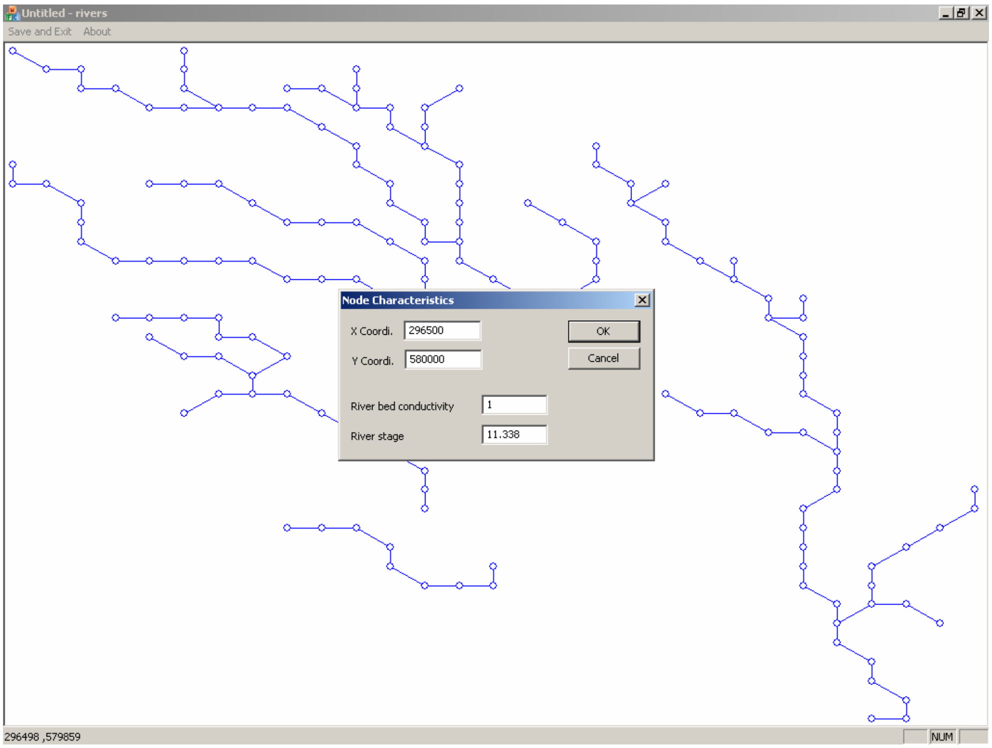


Figure 78 Example use of MODIFY_MODEL_RIVERS Windows application

5 INVESTIGATIVE MODELLING

5.1 Purpose of investigative modelling

The purpose of the *investigative modelling*, as this task is referred to in this report, is to examine the application of a numerical model to the assessment of groundwater abstraction impacts in a real catchment. The approach adopted attempts to recreate the process by which an Environment Agency hydrogeologist would assess the impact of a groundwater abstraction on river flows. As presented in Section 1.2 the objective of this task is as follows:

> *Based on a real catchment study of the impacts on groundwater abstraction on river flow, for which river flow depletion rates have been calculated, undertake an assessment using numerical models.*
>
> *The numerical modelling should start by applying the most simplistic approach to assessing abstraction impacts. The numerical model should then be made to represent the aquifer more closely by incorporating additional hydrogeological features in a step-wise manner. An assessment should be made of the changes in the predicted results as the model is developed and how much work is involved in making these changes. It is possible that the final model may resemble a regional groundwater model.*

By developing the model iteratively, an assessment is made of the effect that each modification has on the simulated results. This is achieved by comparing the output of each model with the river flow depletion data estimated from the observed data. However, as will be discussed, there is some uncertainty associated with the calculation of the depletion rates using the observed data. This observed data is taken from a river flow augmentation scheme developed for the River Itchen in Hampshire. This involved the abstraction of groundwater within the River Candover catchment, which was then discharged to this tributary of the Itchen. During the seven-month trial of the scheme, river flows were monitored. It is from this information that the impact of the abstraction on river flows can be estimated. The main features of the scheme are described next.

5.2 The River Candover flow augmentation scheme

The River Candover flow augmentation scheme provides information on the impact of groundwater abstraction on river flow and has been selected as the basis for the investigative modelling work which is described in Section 5, this section. This engineering scheme was developed in the early 1970s and first operated during the drought of 1976. The development of the scheme was proposed by the Hampshire River Authority in 1970 to regulate the flow in the River Itchen through augmentation from groundwater abstraction in the upper catchment. The following description of the scheme and the resulting data are taken from the report entitled "Itchen groundwater regulation scheme. Final report on the Candover Scheme" by the Southern Water Authority (1979). The report provides information on the impact of three newly constructed abstraction boreholes on the flows in the Candover and other neighbouring streams. It is this data that is used for the comparison with the results of the models developed in this investigation.

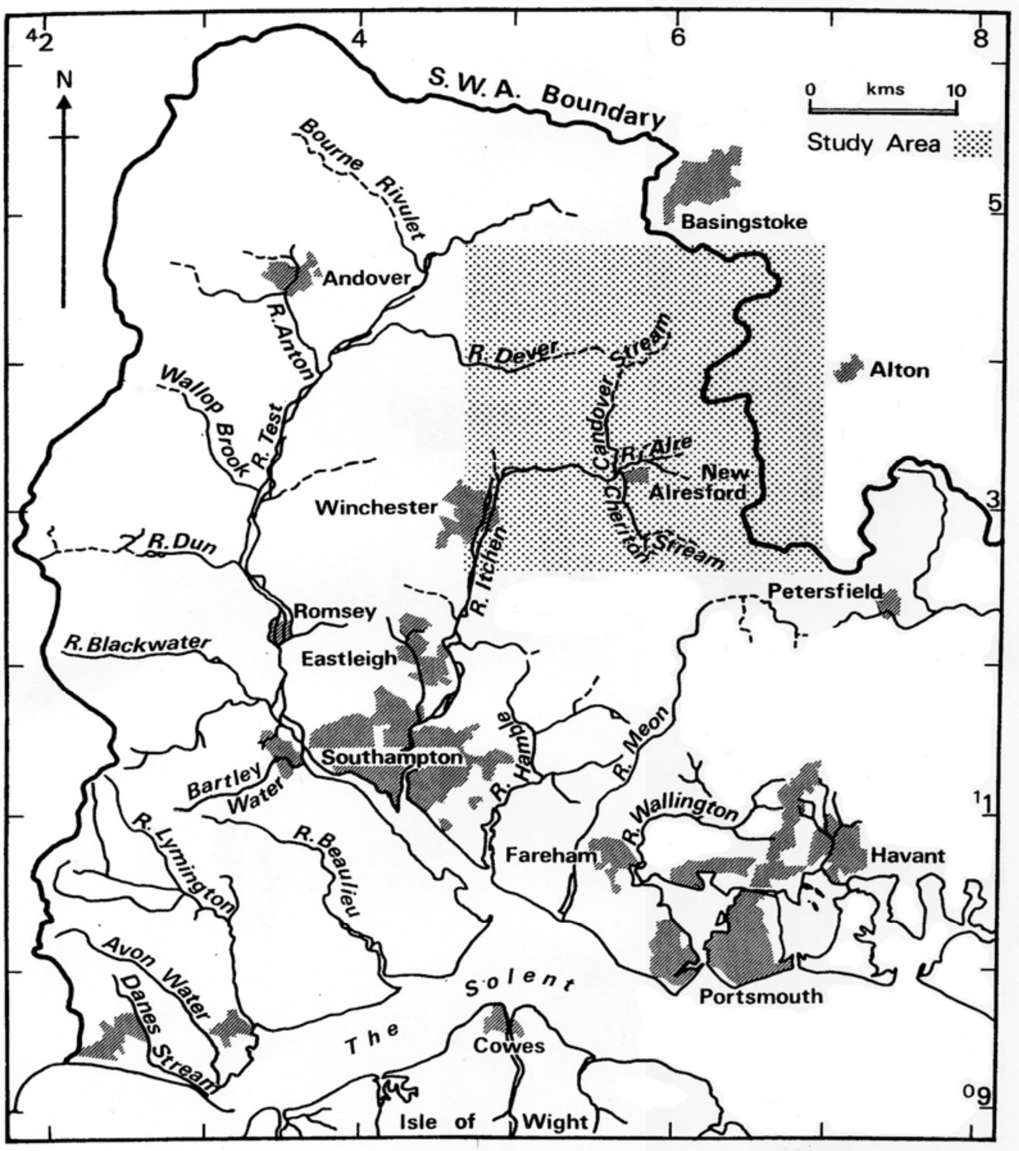


Figure 79 Location of the Itchen and Candover catchments after Southern Water Authority (1979)

5.2.1 Description and objectives of the scheme

The locations of the River Itchen and its tributaries, the River Alre and the Candover and Cheriton Streams are shown in Figure 79. The Candover Scheme involved the augmentation of the flow in the Candover Stream and the River Itchen with groundwater by developing six boreholes north of the perennial head of the Candover Stream. The development of the scheme involved the assessment of the effects of groundwater abstraction during a drought period on groundwater levels, streams flows and river ecology both during and after the low flow period.

The features of the scheme are shown in more detail in Figure 80. During 1974 and 1975 six river flow augmentation boreholes were drilled and tested at three sites around Preston Candover, approximately 5 km to the north east of the perennial head of the Candover Stream, which is near Brown Candover. Two boreholes were drilled at each of the Axford (boreholes 1A and 1B), Bradley (boreholes 2A and 2B) and Wield (boreholes 3A and 3B) sites, which were made to discharge to the Candover Stream through the construction of a pipeline. Discharges to the stream were made at two sites near Northington, 250 m and 550 m below the perennial head of the Candover Stream.

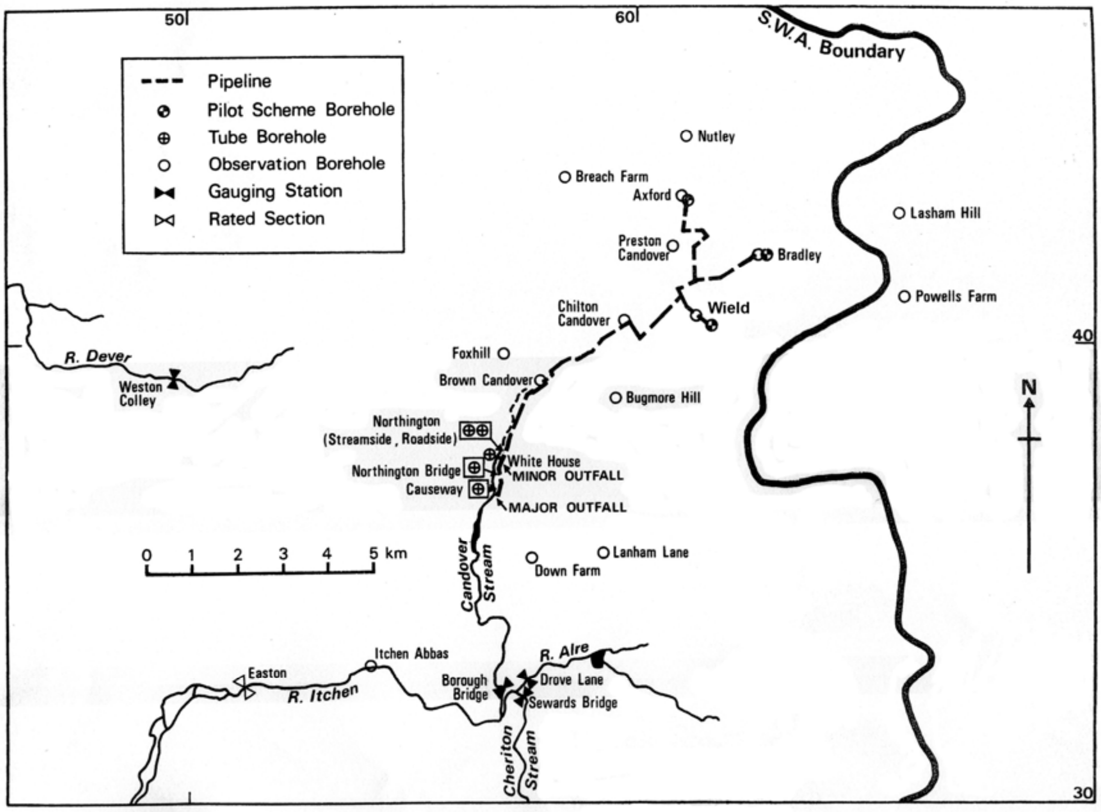


Figure 80 Location of main features of the Candover Scheme after Southern Water Authority (1979)

The scheme first came into operation during the summer drought of 1976. Between 3 May and 30 November 1976 the six abstraction boreholes pumped at an average rate of 23.9 Ml day^{-1}. During this period, groundwater levels and river flows were measured at the observation boreholes and gauging stations shown in Figure 80. These data were used to assess the impact of the abstraction on the flow in the Itchen catchment and on the River Dever in the Test catchment. The calculation of the impact is described in the final report of the scheme (Southern Water Authority, 1979) and it is this assessment which is used for comparison with the numerical models developed in this work.

A complete description of the Itchen catchment and the Candover Scheme is not presented here as this is provided in the final report by the Southern Water Authority (1979). However, a brief summary of the hydrological and hydrogeological features of the area is presented next, which is relevant to the subsequent modelling and to the understanding of the calculation of the impacts of the scheme.

5.2.2 Hydrology

As described above the Candover Stream is a tributary of the River Itchen, which drains part of the Hampshire Downs. Mean annual precipitation is 875 mm and mean recharge is approximately 400 mm (Southern Water Authority, 1979). The relatively high recharge is related to the permeable Chalk geology not promoting surface run-off. Estimates of winter recharge are provided in the Final Report of the Candover Scheme (Southern Water Authority, 1979) for five years and these are reproduced in Table 16. Mean flows are also presented for the permanent flow gauging stations and these are reproduced in Table 17 to provide an indication of the size of the rivers.

Table 16 Estimated winter recharge (mm) for the Candover and Itchen catchment after Southern Water Authority (1979)

	Candover catchment	Itchen catchment to Easton
1972/1973	202	220
1973/1974	323	350
1974/1975	560	626
1975/1976	160	164
1976/1977	640	679
Long-term average	383	380

Table 17 Mean river flows after Southern Water Authority (1979)

River	Site	Mean flow up to end of 1977 (Ml day^{-1})
Cheriton Stream	Sewards Bridge	54.4
River Alre	Drove Lane	138
Candover Stream	Borough Bridge	53.8
River Itchen	Easton	396

5.2.3 Hydrogeology

The Rivers Itchen and Test drain the Chalk of the South Downs, which is between 80 m and 120 m thick in this part of Hampshire. Figure 81 shows part of the geological map covering the two catchments. In the northern parts of the area, surface water drains towards the River Kennet over the Palaeogene. The Chalk is also covered by Palaeogene deposits in the south-west. Clay-with-Flints deposits cover approximately 20% of the outcrop Chalk in the interfluves between the many dry valleys, though these thin superficial deposits are not shown in Figure 81.

In the Alresford area the base of the Upper Chalk (Lewes Nodular Chalk) is at a depth of approximately 90 m and boreholes derive most of their water from the Seaford Chalk. Boreholes farther north on the Chalk outcrop draw their water predominantly from the Newhaven Chalk (Southern Water Authority, 1979).

Groundwater flow in the Candover catchment is generally towards the south-west (Figure 82), though in the centre of the catchment the slope of the water table is stated to be very shallow (Southern Water Authority, 1979). This shallow gradient is related to the high transmissivity that is associated with the Chalk in this area. Evidence for the high transmissivity of the aquifer is also provided by the groundwater level data, with observed annual fluctuations being as between only 1 m and 5 m. In most other Chalk catchments in Hampshire, annual groundwater level fluctuations are stated to be in the range of 10 m to 20 m.

Analysis of pumping tests performed at each of the six newly drilled boreholes in the Candover catchment provided estimates of the transmissivity and storage of the Chalk aquifer. The data for the pumping tests carried out between May and October 1975 is reproduced in Table 18. This shows transmissivity estimates in the range 1400 to 8500 m^2day^{-1}. The average of the estimates is 4300 m^2day^{-1}. Estimates of storativity are in the range 0.4 to 2.6%. The average is 1.3%.

Table 18 Estimates of transmissivity from pumping test analysis after Water Resources Authority (1979)

Pumped borehole	Transmissivity (m^2 day^{-1})	Storativity %
Axford 1A	1400-3300	1.2-2.6
Axford 1B	2600	2.4
Bradley 2A	2400-5100	1.1-2.5
Bradley 2B	2600	1.1
Wield 3A	5100-6800	0.6-1.1
Wield 3B	5300-8500	0.4-1.1

The significant groundwater abstractions in the Itchen catchment at the time of the development of the augmentation scheme were those used for public water supply. Abstraction boreholes at Totford, near the perennial head of the Candover Stream, and at Easton are within the Itchen catchment (Figure 80). The Mid-Southern Water borehole at Lasham is in the Wey catchment but on the edge of the Itchen groundwater divide. Its is stated in the Southern Water Authority's final report (1979) that approximately 80% of the resources of this borehole are drawn from the Itchen catchment.

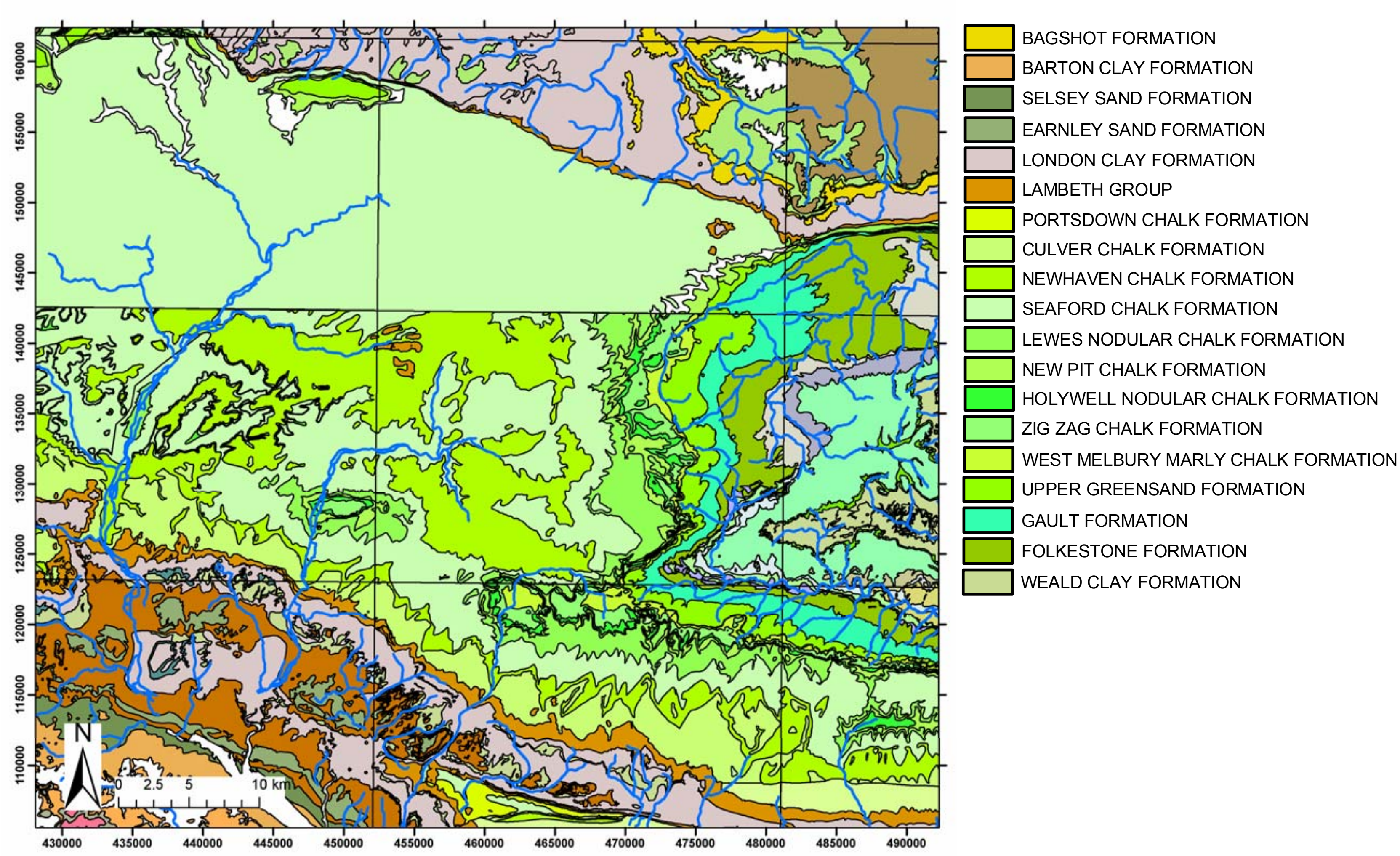


Figure 81 Bedrock geology of the Itchen catchment

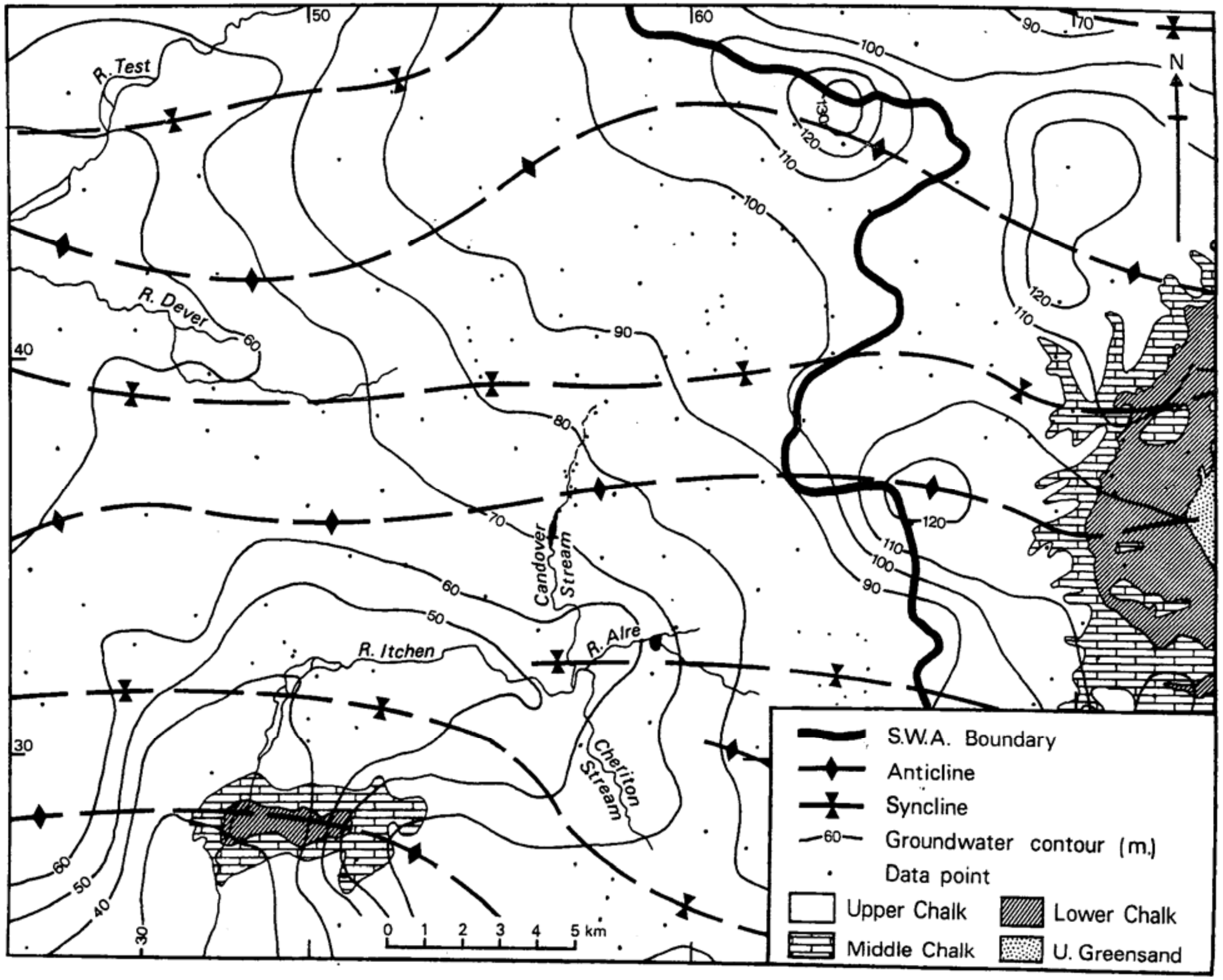


Figure 82 Groundwater level contours for March 1975 after Water Resources Authority (1979)

5.2.4 Operation of the scheme during 1976

The scheme was finally tested for a significant period of time between May and November 1976. During this period all six abstraction boreholes pumped groundwater from the aquifer, which was discharged to the Candover Stream at Northington. As described by the Southern Water Authority (1979) pumping started on 3 May and continued until the end of November. Over this period a quantity of 5.06×10^6 m^3 of groundwater was pumped from the aquifer at a mean rate of 23.9 Ml day^{-1}. The total output of the augmentation boreholes decreased during the testing period from 31 Ml day^{-1} to 27 Ml day^{-1} but there were also minor interruptions during the operation of the scheme (Figure 83).

The augmentation boreholes were switched off between 27 October and 30 November 1976. At the start of the shut down period 4.73×10^6 m^3 had been pumped from the aquifer at an average rate of 26.7 Ml day^{-1}. The augmentation boreholes were switched off in the order shown in Table 19, which is illustrated in Figure 84. This figure shows the yield of each of the six augmentation boreholes during operation of the scheme. The yields of most of the boreholes were adequately maintained during the six month period, except for borehole 1A, whose output fell from over 5 Ml day^{-1} at the start of the test to less than 2 Ml day^{-1} at its end.

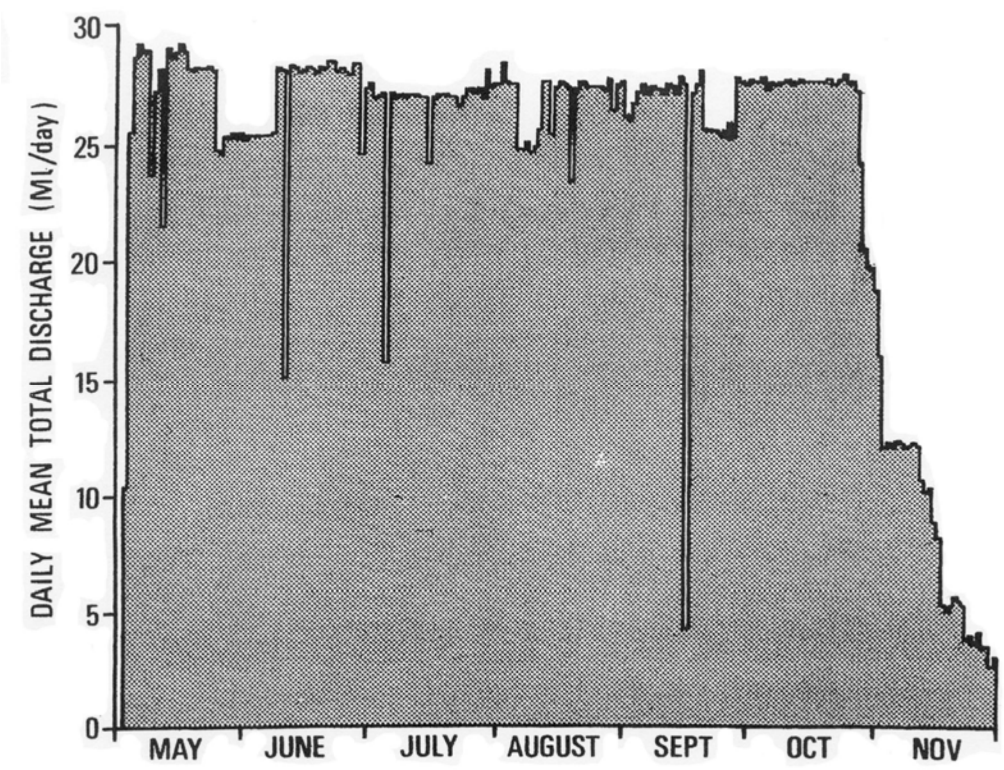


Figure 83 Total yield of augmentation boreholes after Southern Water Authority (1979)

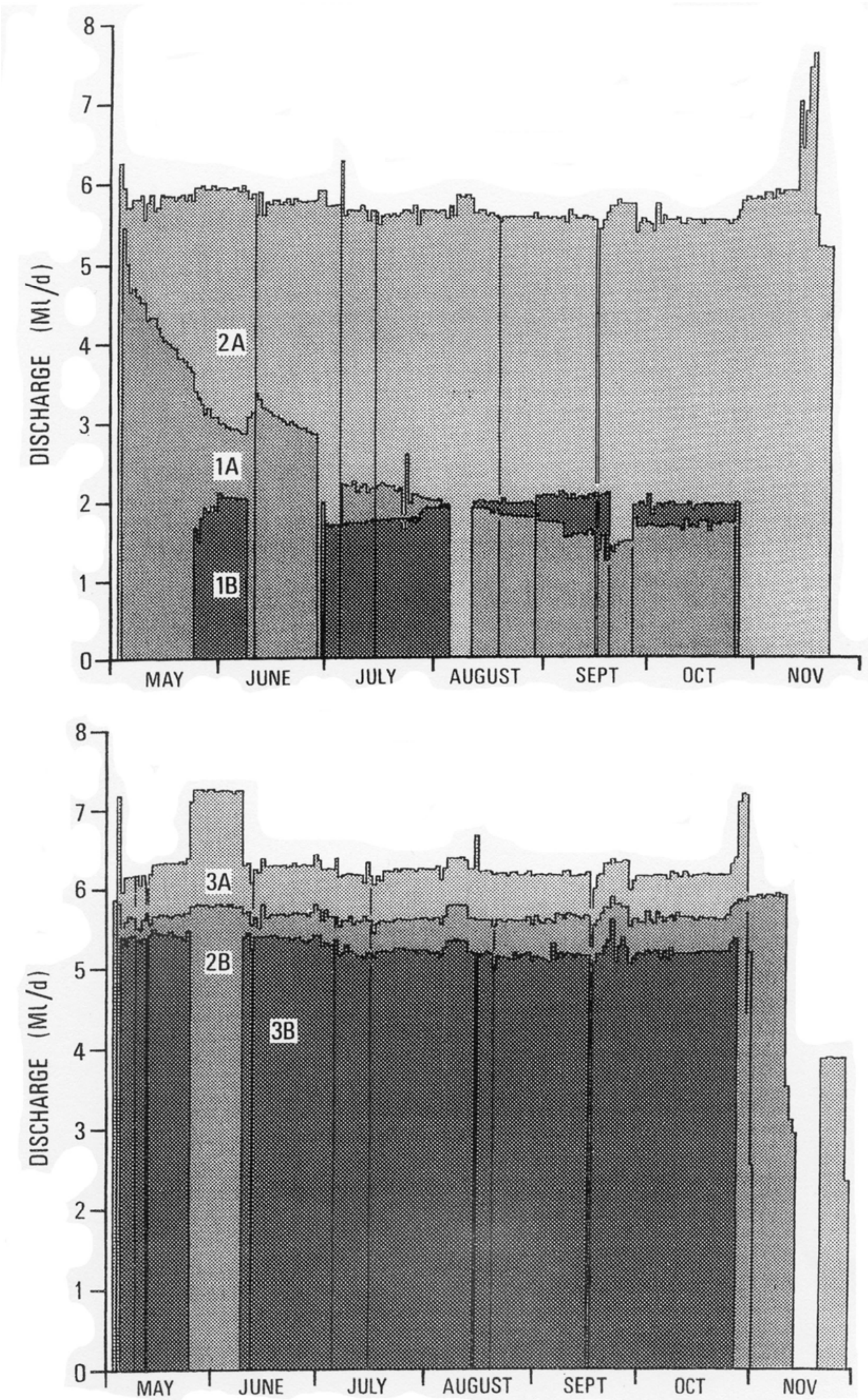


Figure 84 Pumping rates for individual augmentation borehole after Southern Water Authority (1979)

Table 19   Programme of augmentation borehole shut down

		Total remaining pumping rate (Ml day^{-1})
Prior to shutdown		27.0
27th October	Axford 1B shutdown	25.2
28th October	Axford 1A shutdown	23.4
29th October	Wield 3B shutdown	18.8
1-3rd November	Wield 3A shutdown	11.8
12-15th November	Bradley 2B shutdown	7.6
17th November	Bradley 2A reduced to 5.2 Ml day^{-1}	5.2
22nd November	Pumping switched to Wield 3A	4.0
30th November	Wield 3A shutdown	0

Estimating the impact on streams flows

As the Southern Water Authority (1979) describe, the initial aim of the Candover Scheme was to determine the net gain or loss in stream flows due to additional groundwater abstraction. This required a method of estimating what the natural stream flows would have been if the augmentation boreholes had not been pumped. This was achieved by using regression analysis to define relationships between the flows in the Cheriton Stream with those in the Candover Stream and the Rivers Alre and Dever. The Cheriton Stream was chosen as the control as it was considered to be sufficiently far from the augmentation boreholes to not be affected by the pumping.

The Southern Water Authority (1979) use the term *stream depletion* to describe the reduction in stream flows due to groundwater abstraction. However, they use a number of different units when quantifying this impact which represents:

- an impact on just the Candover Stream or on all streams;
- a volume of water or a percentage of the pumping rate;
- an instantaneous or a cumulative quantity.

These different quantities need to be borne in mind when examining the figures presented in this section which are reproduced from the Southern Water Authority's final report (1979). In addition to stream depletion, the term *net gain* is used to denote the increase in flow in a river due to augmentation when compared to the estimated natural flow.

As described above, the natural flows in the streams that would have occurred if the scheme did not operate had to be calculated. This was performed by defining relationships between the natural flow in the Cheriton Stream at Sewards Bridge with those at gauging stations on the Candover Stream and River Alre using regression analysis. After estimating what the natural flows would have been, the stream depletion and, net gain or net loss in river flow, could be estimated by comparing the natural flows with those observed during the six month pumping period.

Figure 85 shows the observed flow in the Candover Stream at Borough Bridge and the calculated natural flows after the onset of the abstraction from the augmentation boreholes. The method used to calculate what the flow in the Candover would have been if the scheme had not been operating (referred to as the ‘natural’ flow) is described at the end of this section. The figure shows the net gain in flow during the six month period of augmentation and the net loss after the cessation of abstraction caused by the reduction in groundwater levels.

The figure shows that the magnitude of the net gain fell sharply at the end of September 1976 even though pumping was continuing at the full rate. This was due to the recovery of the flows in the Cheriton Stream due to the onset of winter recharge. The Southern Water Authority (1979) state that the use of regression analysis led to similar predicted natural flows for the Candover Stream but observed flows were suppressed because of the pumping. The calculated sharp fall in computed net gain, therefore, reflects the delay in the recovery of the flows in the Candover Stream compared to the Cheriton Stream and not a change in the hydrogeological conditions in the Candover catchment.

The shaded areas in Figure 85 represent the quantities of water gained by the Candover Stream during pumping and lost during recovery. The quantity gained by the river is 3.3×10^6 m^3 (dark grey area) and the quantity lost is 2.1×10^6 m^3 (dashed area). The difference between the two values, 1.2×10^6 m^3, represents the amount of water that was drawn from outside the Candover catchment. At the end of the period of abstraction the total quantity pumped was 5.06×10^6 m^3 and consequently, the quantity of water drawn from the Candover catchment is 3.86×10^6 m^3 (5.06×10^6 m^3 minus 1.2×10^6 m^3). Similar calculations of the components of the scheme water balance enable the Southern Water Authority (1979) to present the components of the volume pumped at the end of the pump shutdown. These are reproduced in Table 20.

Table 20 Components of volume pumped at the end of pump shutdown after Southern Water Authority (1979)

	10^6 m^3
Volumetric stream depletion of Candover Stream	1.76
Volumetric stream depletion of peripheral catchments	0.55
Draught on groundwater storage in the Candover catchment	2.10
Draught on groundwater storage in peripheral catchments	0.65
Total volume pumped	5.06

The volumetric stream depletion of peripheral catchments listed in Table 20 could not be apportioned between the different peripheral river catchments by regression analysis. However, an estimate of the impact of abstraction on flow in the Rivers Dever and Alre and, in the Itchen below its confluence with the Candover, was made by considering the proportion of the volume of the cone of depression in each of the catchments. Of the 5.5×10^5 m^3 of total stream depletion in the peripheral catchments, 54% of this was assigned to the Itchen and 23% to each of the Alre and Dever.

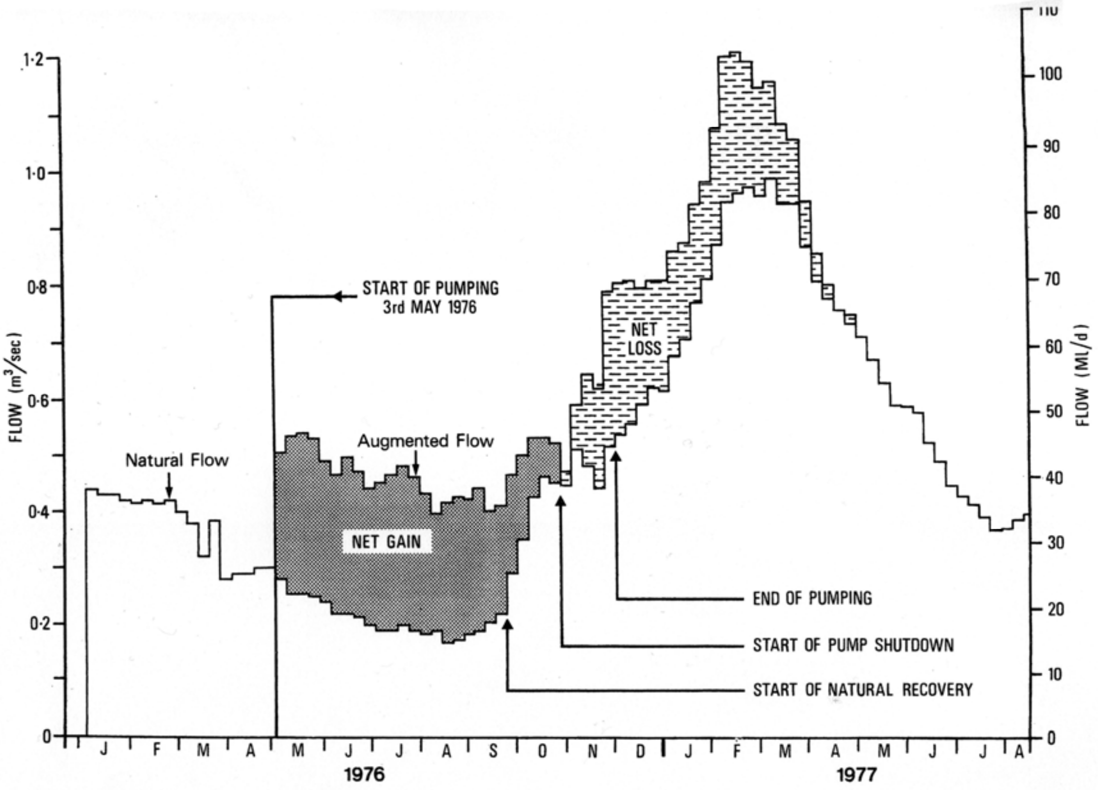


Figure 85 Augmented and estimated natural flows of the Candover Stream at Borough Bridge after Southern Water Authority (1979)

Using similar methods of calculation to those described above, the component losses from the rivers and groundwater storage could be estimated both during and after the period of operation of the augmentation boreholes. These values are plotted in Figure 86 which is reproduced from the Southern Water Authority's final report (1979). The components are plotted as *cumulative volumes*. As shown in the figure, each area of the graph represents one of the four sources from which the pumped boreholes derive water.

To convert this figure to one in which *mean monthly rates* of stream depletion and groundwater storage release are plotted, the differences between the curves need to be calculated. First, the differences between the curves need to be determined for each month. Then because the curves represent cumulative values, the amount by which each component increases from month to month needs to be calculated. These volumetric monthly components can then be divided by the number of days in each month to obtain the mean monthly rates for the four components. These mean monthly rates are plotted in Figure 87. They have been derived by digitising Figure 86 of the Final Report of the Candover Scheme (Southern Water Authority, 1979).

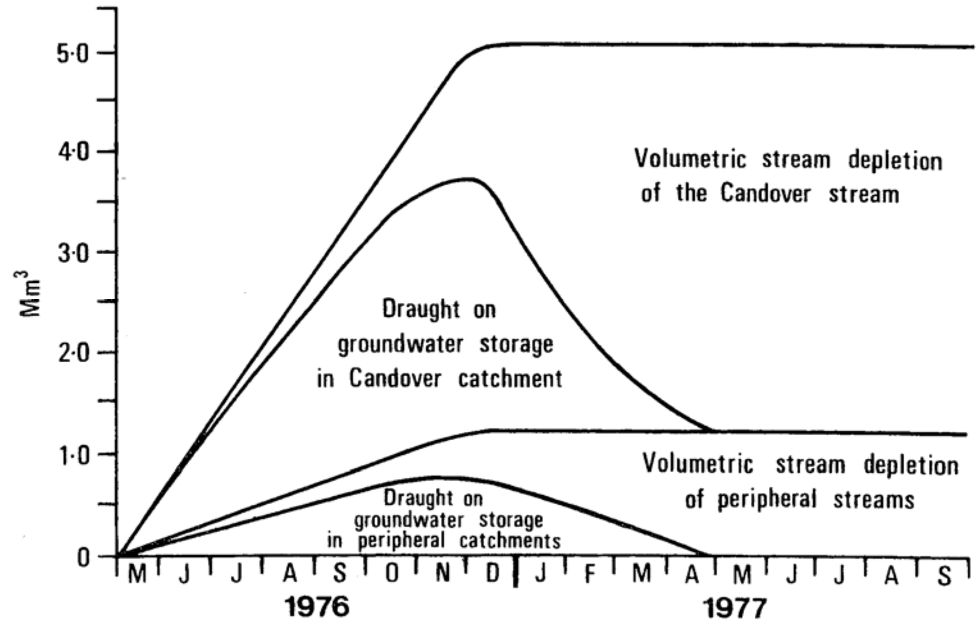


Figure 86 Separation of volume pumped into component losses after Southern Water Authority (1979)

The curves plotted in Figure 87 as mean monthly rates are slightly easier to interpret than those based on the cumulative volumes plotted in Figure 86. Figure 87 shows that during the first months of the scheme the pumped boreholes access most of their water from groundwater storage, predominantly in the Candover catchment, and little from stream flow. From October 1976 the amount by which the augmentation boreholes deplete the Candover Stream becomes more significant and this peaks in January 1977. The rate of depletion of the peripheral streams increases gently during the operation of the scheme. However, some error is introduced when estimating this rate because the data has been taken from Figure 86 and no raw data has been obtained. This is particularly the case towards the start of the period plotted.

The curves showing the changes in storage in Figure 87 show both positive and negative values. During the period of abstraction, between May and November 1976, groundwater is released from storage and the plotted rates are positive. However, after the cessation of pumping groundwater levels recover and water is taken into storage which is supplied by the rivers. After May 1977 the rate of storage release incurred by the scheme returns to zero.

The data plotted in Figure 87 are also presented in Table 21. It is these data that are compared with the results of the numerical modelling described in Section 5.4. The values in the last column of the table are the sum of the four components listed in the previous columns. A check on the accuracy of the interpretation of the data presented in Figure 87 is that for the months during which the augmentation boreholes pumped, the summed values equal the pumping rate. This comparison proves sufficiently accurate. The average of the first seven monthly values in the last column of Table 21 is 23.3 Ml day^{-1}. The actual mean monthly pumping rate during this period was 23.9 Ml day^{-1}.

The components of steam depletion shown in Table 21 indicate that 75% of the water pumped by the augmentation boreholes is drawn from the River Candover and only 25% from the peripheral catchments, which include the Itchen, Alre and Dever. It is possible that the pumping could have affected flows in other peripheral rivers which are farther away, such as the Wey, Meon and Whitewater, but this not considered in the analysis by the Southern Water Authority (1979).

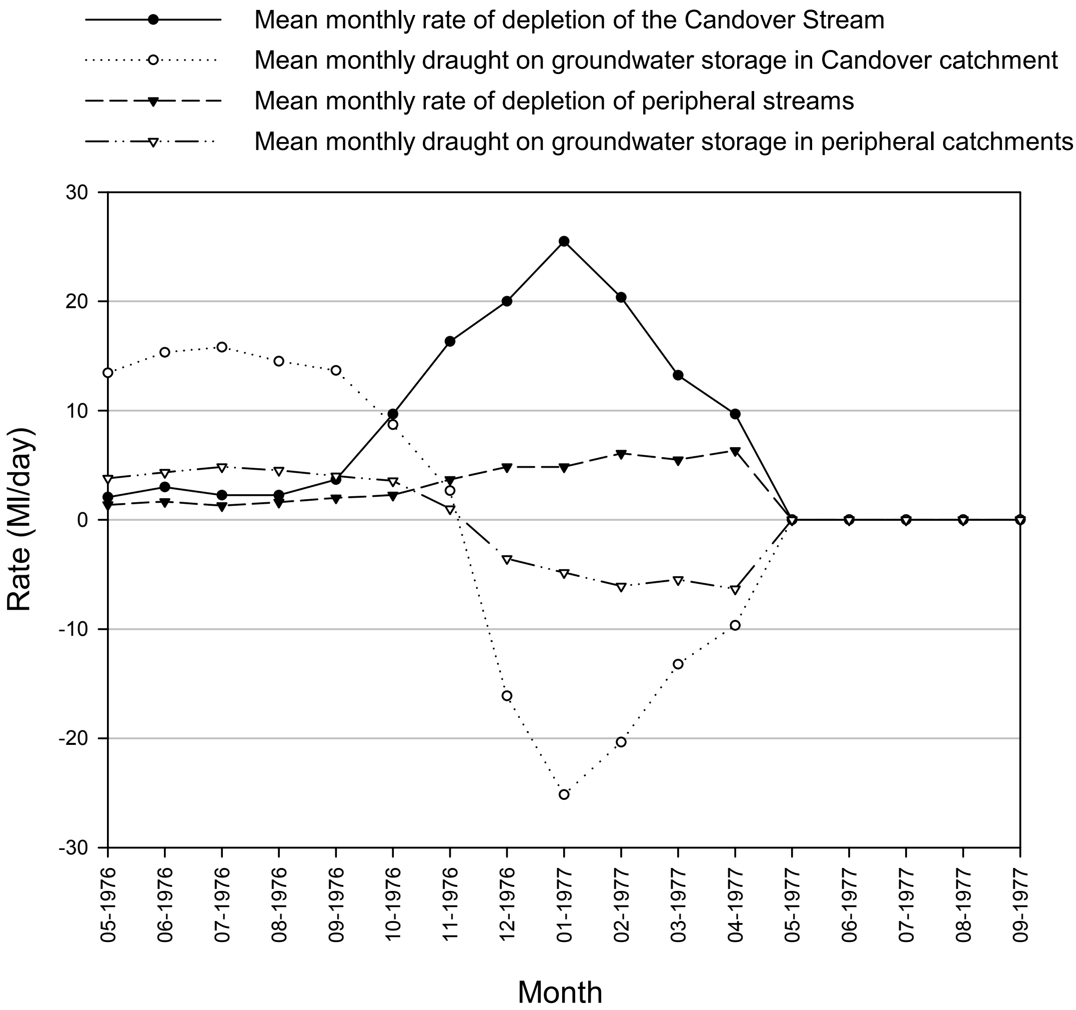


Figure 87 Mean monthly components of stream depletion and releases from groundwater storage (Ml day^{-1}) as calculated from Figure 86.

Southern Water Authority (1979) discusses the behaviour of the catchment, as described by Figure 86, in relation to the Chalk hydrogeology. Perhaps the most notable feature of Figure 86 and Figure 87 is the delay of approximately five months between the onset of abstraction and impact on flow in the Candover. Southern Water Authority (1979) relates this to the low transmissivity associated with the low groundwater levels during the summer of 1976. It is proposed that this results in the abstraction boreholes "mining" the aquifer for the first few months but when groundwater levels rise in September of 1976, an upper, thin, highly permeable zone, which feeds the river, is re-activated and this caused the delayed impact on the Candover.

Table 21 Mean monthly components of stream depletion and releases from groundwater storage (Ml day^{-1}) as calculated from Figure 86

Month	Mean monthly rate of depletion of the Candover Stream	Mean monthly draught on groundwater storage in Candover catchment	Mean monthly rate of depletion of peripheral streams	Mean monthly draught on groundwater storage in peripheral catchments	Sum of previous four columns. Equivalent to pumping rate of augmentation boreholes
May 76	2.07	13.45	1.38	3.79	20.69
Jun 76	3.00	15.33	1.67	4.33	24.33
Jul 76	2.26	15.81	1.29	4.84	24.19
Aug 76	2.26	14.52	1.61	4.52	22.90
Sep 76	3.67	13.67	2.00	4.00	23.33
Oct 76	9.68	8.71	2.26	3.55	24.19
Nov 76	16.33	2.67	3.67	1.00	23.67
Dec 76	20.00	-16.13	4.84	-3.55	5.16
Jan 77	25.48	-25.16	4.84	-4.84	0.32
Feb 77	20.36	-20.36	6.07	-6.07	0
Mar 77	13.23	-13.23	5.48	-5.48	0
Apr 77	9.67	-9.67	6.33	-6.33	0
May 77	0	0	0	0	0
Jun 77	0	0	0	0	0
Jul 77	0	0	0	0	0
Aug 77	0	0	0	0	0
Sep 77	0	0	0	0	0

Whilst the methodology used by the Southern Water Authority (1979) to calculate the component losses shown in Figure 86 is as good as possible given the available data, the approach does incorporate a number of assumptions and therefore, there is some uncertainty associated with the results. Of course, one of the assumptions is that the flow in the Cheriton is not affected by pumping during the test and this is probably reasonable because the modelled long-term depletion from the Cheriton is about 2% of the abstraction when all the adjacent rivers are included (Table 31). However, a second assumption is that the build up of in-stream depletion borne by the peripheral catchments was similar to that observed in the Candover Stream. This may be the case, however, the behaviour and flow of the Candover and River Alre are significantly different. This is indicated by the difference in mean flow of the Alre and Candover, which are 134 and 45 Ml day^{-1}, respectively. Therefore, the Alre has a much larger groundwater catchment than that of the Candover.

Further evidence of the difference between the two rivers is provided by a comparison of their flows with that of the Cheriton. Southern Water Authority (1979) developed relationships between the flow in the Cheriton, denoted Q_{CH} here, and the flows in the Candover and Alre using regression techniques. Both linear and logarithmic regressions were applied to produce the following relationships:

For flow in the Candover, Q_{CA}:

$$Q_{CA} = 0.76\,Q_{CH} + 0.054 \qquad \text{(linear regression)}$$

$$Q_{CA} = 0.18\,Q_{CH}^{0.89} \qquad \text{(log regression)}$$

For flow in the Alre, Q_{AL} :

$$Q_{AL} = 1.35\,Q_{CH} + 0.666 \qquad \text{(linear regression)}$$

$$Q_{AL} = 2.0\,Q_{CH}^{0.57} \qquad \text{(log regression)}$$

In Figure 88, the observed river flows are plotted for the River Alre and Candover Stream between 1974 and 1977. The estimated flows for both streams are also plotted, which have been calculated using the above regressions equations derived by Southern Water Authority (1979). Examining the plots for the Candover Stream shows that, before May 1976 and after May 1977 (i.e. when the river is not affected by the pumping test), the observed and estimated river flows are very similar. This shows that the Cheriton and Candover behave in a similar manner. However, the comparison between the observed and estimated flows for the Alre is somewhat different indicating that the two catchments are not behaving in the same way.

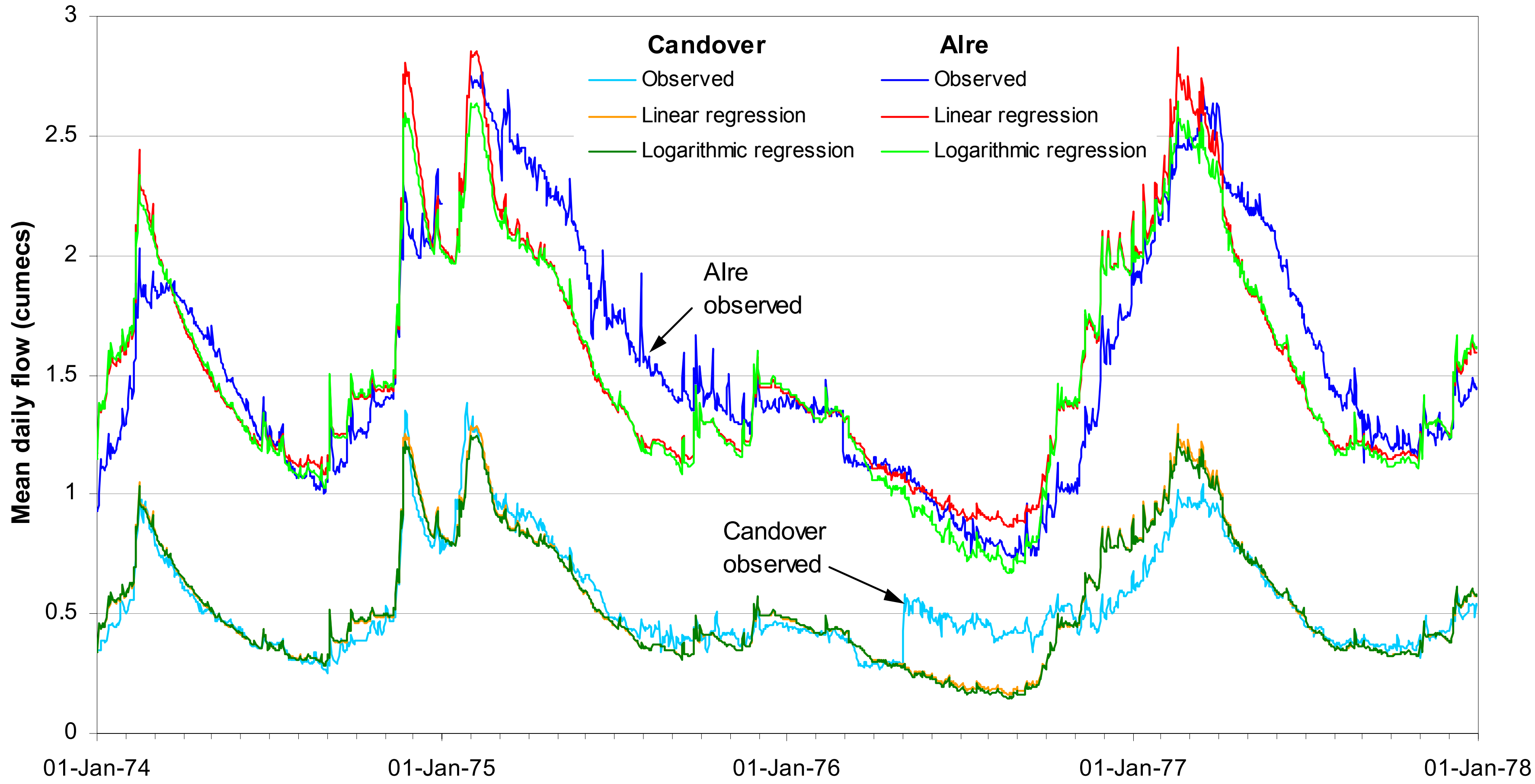


Figure 88 Observed and estimated river flows (based on regression against Cheriton) for the River Alre and Candover

Estimating the impact on groundwater levels

To assess the impact of the augmentation boreholes on groundwater levels, an estimate had to be made of what the groundwater levels would have been if the six augmentation boreholes did not pump i.e. under natural conditions. To estimate the natural groundwater levels and thus be able to calculate the drawdowns, three methods were implemented: (i) the examination of groundwater level recession characteristics, (ii) correlation with wells unaffected by pumping and (iii) multiple linear repression. A description of these methods is not of importance to this investigation and consequently, is not presented here. However, by using these methods Southern Water Authority (1979) could estimate natural groundwater levels at each of the observation wells in the study area and then calculate drawdowns.

Figure 89 shows contours of the observed and natural, or calculated, groundwater levels on the 10th September 1976, which represents the time of the maximum effect of the pumping boreholes on heads. By calculating the difference between the two sets of groundwater levels plotted in this figure, the cone of depression can be defined. Contours plots of the drawdowns around the augmentation boreholes are calculated in this way by the Southern Water Authority (1979) at four different times during the pumping period and these are reproduced in Figure 90. Drawdown contours are plotted at 30, 60, 90 and 130 days after the start of abstraction, which correspond to the 1st June, 1st July, 31st July and 9th August 1976.

The contours of drawdown reproduced in Figure 90 are used for comparison with the numerical models developed in Section 5.4. They represent a second data set which can be used to assess the accuracy of the different numerical models in addition to the stream flow depletion data.

Estimates of transmissivity

Using the time-drawdown data calculated for each of the observation borehole, estimates of transmissivity could then be made. Estimates of transmissivity were made by assuming that the drawdown at each observation borehole could be calculated using the Theis (1935) equation and that the observed drawdown was equal to the sum of the drawdowns produced by each of the abstraction boreholes. The best estimate of the transmissivity distribution was then made by minimising the sum of the squares of the differences between the observed and computed drawdowns. The distribution of transmissivity defined using this approach is presented in Figure 91, which is reproduced from the Final Report of the Candover Scheme (Southern Water Authority, 1979). This distribution of transmissivity provides a basis for specification of the transmissivity in the models developed in this investigation, which are described in Section 5.4. However, additional transmissivity information has been obtained from the final report of the regional groundwater modelling investigation commissioned by the Environment Agency (Entec, 2002). This is discussed briefly in the next section.

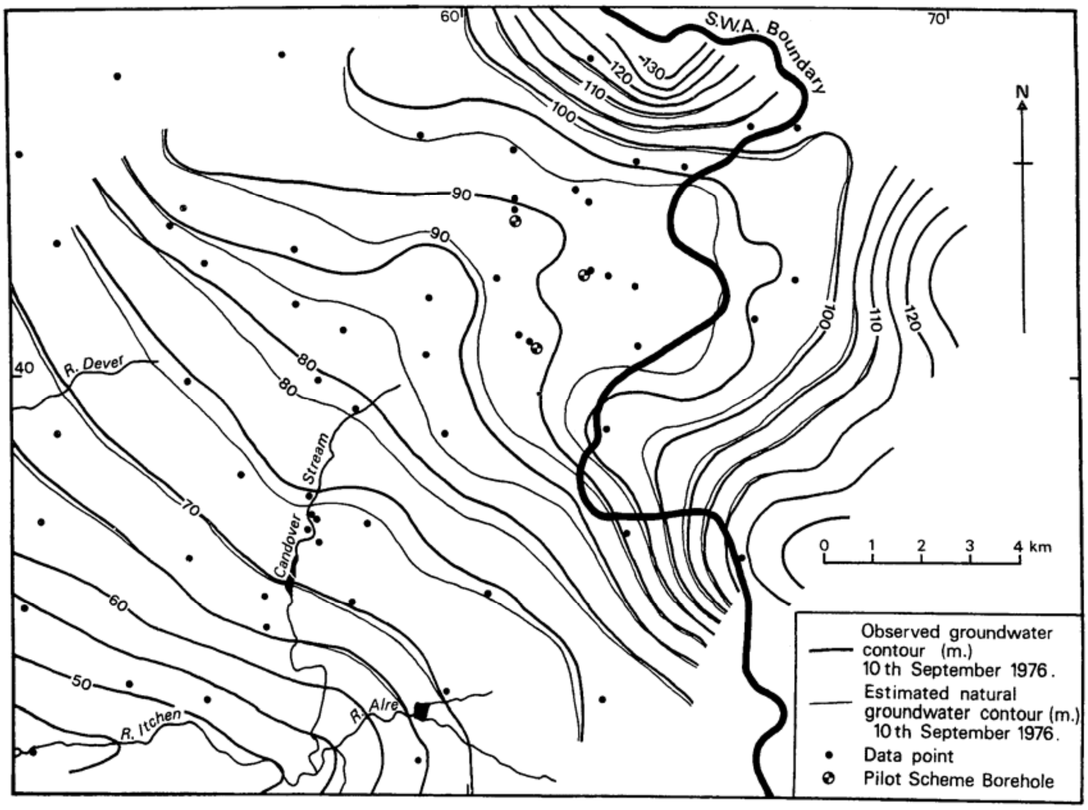


Figure 89 Observed groundwater levels (10/09/1976) at the time of the maximum effect of pumping and the estimated natural groundwater level contours for the same time after Southern Water Authority (1979)

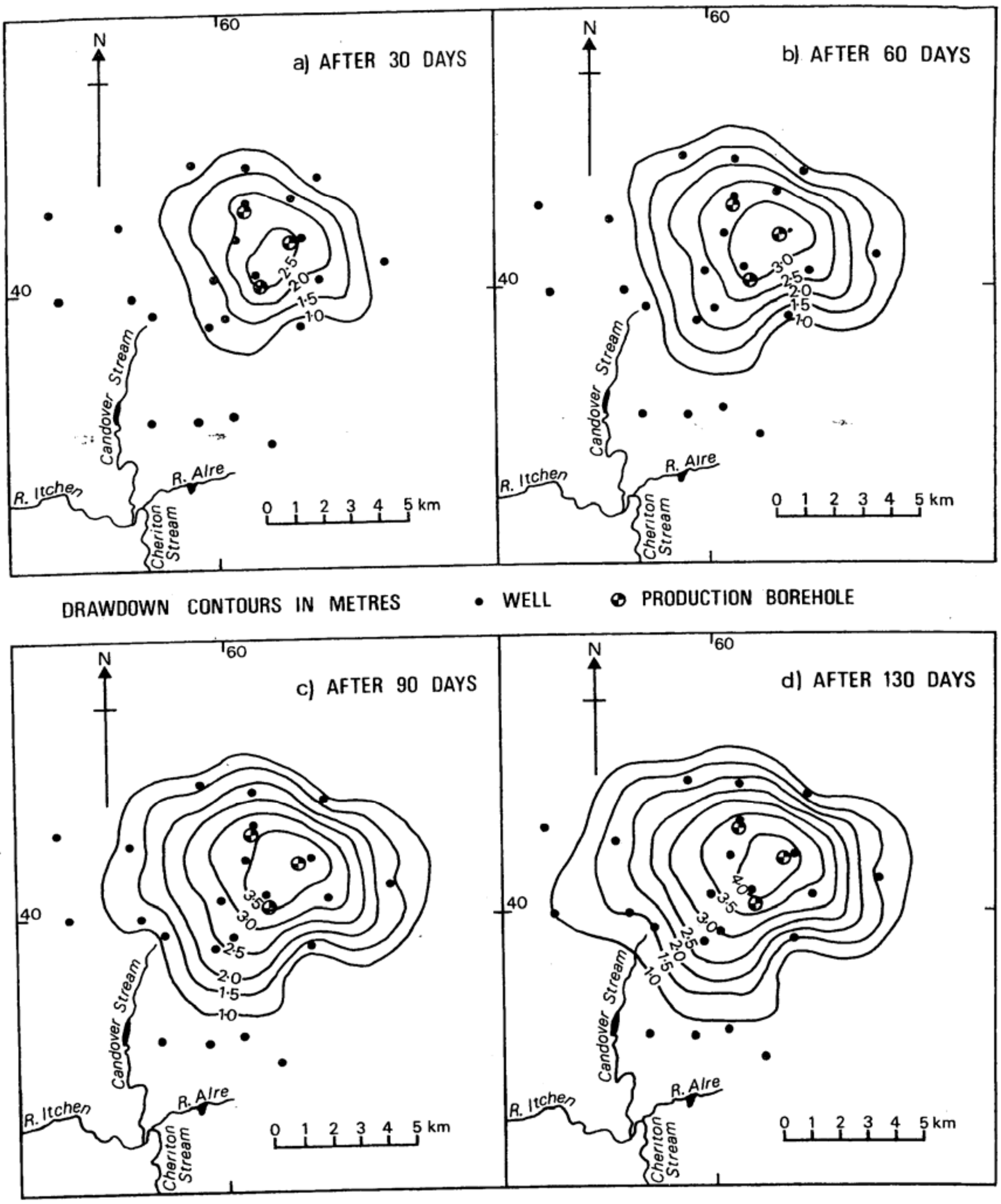


Figure 90 Contours of drawdown showing the expansion of the cone of depression between May and September 1976 after Southern Water Authority (1979)

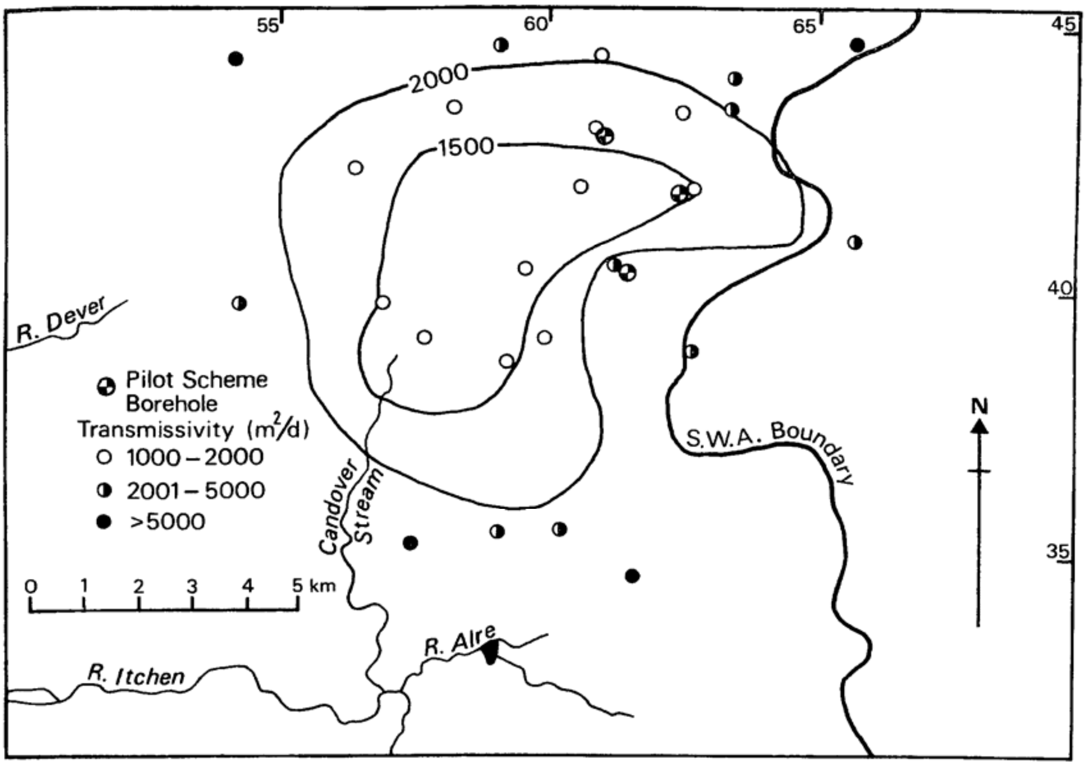


Figure 91 Areal distribution of transmissivity from least-squares analysis of observed drawdowns after Southern Water Authority (1979).

5.3 Regional groundwater model of the Itchen catchment

5.3.1 Background

The Itchen model (Entec, 2002) is a regional groundwater flow model developed to understand the low flow issues on the River Itchen. The model was built to answer the following four questions:

- What impact do the public water supply (PWS) groundwater abstractions operated by Southern Water at Easton, Totford, Twyford and Otterbourne have on river flow?

- What is the impact on river flow of using all the PWS at their full licensed abstraction rates under a low flow scenario?

- How do other groundwater abstractions, including those for watercress beds, agriculture and river support, impact on river flows?

- What are the impacts of effluent discharges to the ground on river flows and the groundwater water in low recharge and high recharge years?

The model was developed in a number of phases: (1) data collation and conceptualisation, (2) development of the groundwater model, (3) management runs (4) final report and, (5) handover to client.

This summary of the Itchen model is based on the Phase 2 final report (Entec, 2002) and using the parameterisation of the model to develop the model of the Candover scheme used for this project (see below).

5.3.2 Summary of the Itchen model

The model is a MODFLOW model (McDonald and Harbaugh, 1988) and covers the Itchen river system. It is a two-layer model with both layers representing the Chalk and a regular 250 m grid. The boundaries of the model are the River Test in the west and the groundwater divide in the east. In the north and south the boundary is specified where the Chalk dips beneath the overlying Palaeogene deposits (Figure 92). There are nine transmissivity zones and the variable hydraulic conductivity with depth mechanism (VKD, Environment Agency, 1999) is used. The transmissivity zones are summarised in Figure 93 and the VKD parameters used in the model are summarised in Table 22. A storage coefficient of 2.5 % is applied on the unconfined Chalk and 10 % is used in the alluvium filled river valleys. A confined storage coefficient of 10^{-4} is applied to the Chalk where it is confined by the Palaeogene deposits.

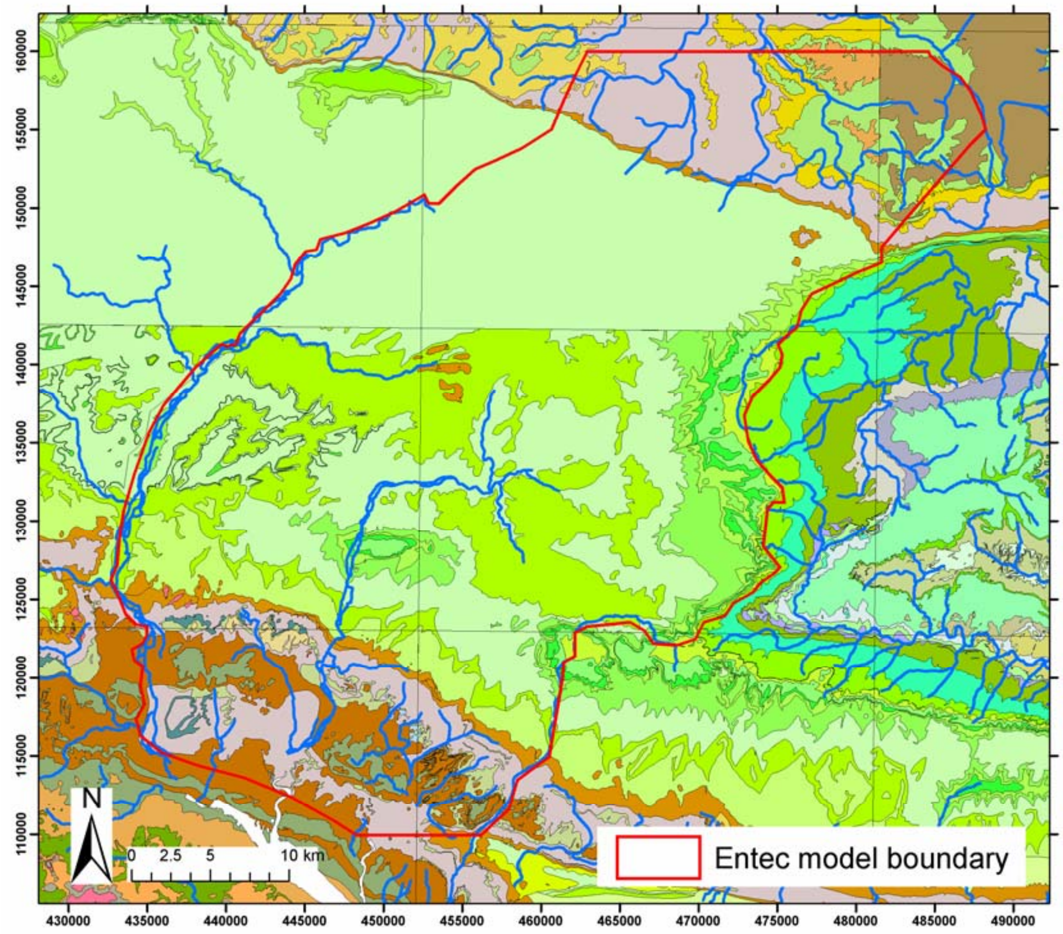


Figure 92 Boundaries of Entec (2000) Itchen model (See Figure 81 for key to geology)

Table 22 VKD parameters for each transmissivity zone

Zone	Description	Depth from min water level to inflection point (m)	Kbase (m/d)	Facx	Kmax (m/d)
1	Dead confined Chalk Lowest T	3	0.33	0.01	1.5
2	Valley Margin Chalk	30	1	1.5	100
3	Lower T anticline/interfluve Chalk	7.5	0.66	1	30.3
4	Alre catchment	45	2	1.25	50
5	Perennial river highest T Chalk	60	2	1	50
6	Dry Valley/Higher T Chalk	45	1.2	1	83.3
7	Undeveloped Chalk, v. low T	7.5	0.33	0.01	1.5
8	Middle/Lower Chalk, Low T	7.5	0.66	1	30.3
9	Candover Catchment	34	1.2	1	83.3

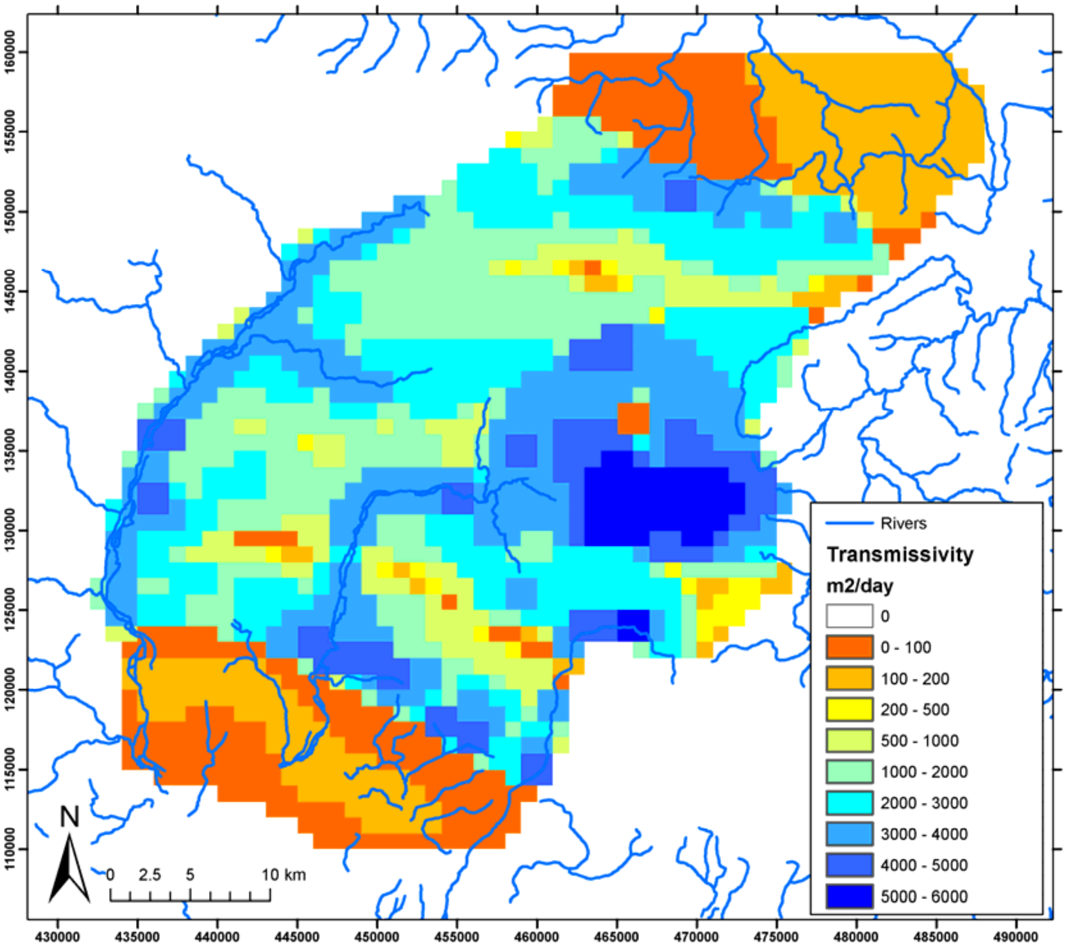


Figure 93 Itchen model transmissivity zones

The main components of the water balance for the system are recharge as input, river flows and abstraction as outputs. Recharge to the model is provided by Entec's 4Rs model (Heathcote et al., 2004) and is a combination of rainfall recharge, as calculated by the Food and Agriculture Organization of the United Nations method (FAO, 1998), and urban recharge processes. Runoff is not applied to the rivers in the groundwater flow model, but is used to supply input to a separate river model, developed using ISIS by Halcrow. The main rivers in the system include the Itchen and its three main tributaries; Candover, Alre and the Cheriton. The river Test is used as the western boundary. Various other smaller rivers are included such as the Dever, which is a tributary of the River Test, the Meon, the Wey and the Caker stream. Groundwater abstractions included in the model are public water supply, industrial abstractors and irrigation boreholes. In addition, the input to the cress beds along the Itchen and its tributaries are supplied by artesian boreholes, and these are represented in the model as head dependent outflows using the stream mechanism.

The model is run from January 1965 to December 2000 using the groundwater heads from November 1985 as the initial conditions. A dynamic balance is run for the first five years to ensure that the time variant mechanisms within the model are operating correctly. A repeated cycle of monthly recharge and abstractions are used to provide the input to enable the model to move towards a dynamic balance.

The size of the data files for the recharge and the groundwater flow model and the associated runtimes are summarised in the Phase 2 report (Entec, 2002). The run times are given for a P4 Pentium processor running at 1.7 GHz with 256 Mb of memory. The recharge model (4Rs) data files are 1 Gigabyte in size and the model takes 4 hours to run a simulation. The groundwater model data files are over 1.7 Gigabytes in size and the model takes 2 hours to run.

The approach used in developing the model is to encapsulate the conceptual model developed during the Phase 1 work in its entirety into a numerical model and refine the model by making small changes. The modelling logs for the development of the model are included in Appendix A in the Phase 2 final report. Examining these modelling logs show that most of the changes were related to the recharge (rainfall and proportion of by-pass recharge) and transmissivity distribution (adding in new zones that encompass the Alre). In all 48 runs were undertaken for the Phase 2 work.

The Candover and the Alre augmentation scheme was included in the model (Entec, 2002; Figure 2.20) and was operated at the appropriate time.

5.3.3 Water balance

A water balance for the period 1991 to 1995 is presented for an area consisting of the Itchen, Upper Dever, Caker Stream and Wey (Entec, 2002; Section 4). The total area for this region is 547.56 km^2 and is presented in Figure 3.10 in the Phase 2 report. The main components of the water balance are recharge as inflow and groundwater abstraction and river baseflow as outflow (Table 23). The water balance is in balance, but it would be useful to compare the change in storage predicted by the water balance with that observed from groundwater heads.

Table 23 Summary of the Itchen model water balance

	Component	Groundwater	Surface water	Total
Inflow	Total Recharge	604		648
	Run off		32	
	STW discharge		12	
Outflow	Groundwater abstraction	-101		-628
	Surface water abstraction		-24	
	River flow		-29	
	Baseflow	-474		
Imbalance		29	-9	20

5.3.4 Model performance

River flows

Four sets of output are used to examine the match between modelled flows and observed. These are:

- scatter plots comparing modelled and observed baseflow along channels;
- time series of modelled and observed baseflow;
- dot plots of river-aquifer interaction;
- accretion profiles.

The scatter plots show a reasonable match between the modelled and observed flows, but highlight issues with the Rivers Dever and Wey.

A summary of the comparison between modelled and observed time series of baseflow is presented in Table 24. As indicated by the scatter plots, the model does reproduce the baseflow reasonably well. Particular issues are the Dever and the high and low flows for the Itchen.

Table 24 Summary of modelled baseflows

Location	Figure No. in Phase 2 report	Comments	Long-term average baseflow (1970-1998)	
			Observed	Modelled
River Alre (Drove Lane)	4.3	Looks ok, note very high baseflow compared to other tributaries of the Itchen	127.3	120.8
River Candover (Borough Bridge)	4.4	Looks ok, high flows maybe not well represented	44.4	50.1
River Cheriton (Stewards Bridge)	4.5	Ok, but overestimates low flows	53.1	57.8
River Itchen (Eastern)	4.6	Ok, but peaks and low flows not very well represented	344.4	330.7
River Itchen (Highbridge/ Allbrook)	4.7	Ok, but peaks and low flows not very well represented	447.8	453.3
River Dever (Weston Colliery)	4.8	Range too great	9	14.5

Accretion profiles are produced for the Itchen (including the Alre), the Candover, Cheriton and the Dever. Comparisons between modelled and observed are reasonable with both the magnitude of flows and the pattern of accretion reproduced by the model. The spot gauging data, however, are too limited to draw firm conclusions.

The "dot" plots showing the interaction between groundwater and surface water are produced for high (end of March 1995), average (end of May 1982) and low (end of November 1989) groundwater levels. Examining the plots shows that for the high groundwater levels the river network mainly receives flow from the aquifer apart from parts of the River Test, associated with groundwater abstraction, and the Wey and Caker stream. The situation under average conditions is similar to those at high groundwater levels, but with more losing sections on the River Test. However, for low groundwater levels, then the majority of the river system has less flow length and there are more losing sections on the River Itchen.

Groundwater heads

The groundwater hydrographs for the model are presented in three figures in the Phase 2 report (Figs 4.30 to 4.32). The comparisons between modelled and observed at each observation borehole location are summarised in Table 25.

Table 25 Summary of modelled groundwater level hydrographs

Name	Project ID	Comments
Twyford Moors	242	Reasonable, but limited data record.
Lanham Lane	163	Good match.
Graces Farm	223	Scale too small; close to river, so head could be controlled.
Itchen House Farm	220	As above.
British Pipeline Agency	229	Model fluctuations too high.
Bramdean	141	Good, but limited data record.
Kilmeston Roadside	143	As above.
Brashfield (Bailey's Down Farm)	84	Timing reasonable, but fluctuations too low.
Longwood	255	As above.
Crabwood	247	Satisfactory, limited data record ~30 m difference.
Upper Cranbourne Farm	34	Good.
Preston Candover	210	Good.
Rotherfield	126	Fluctuations too low ~20m difference in head (limited field data).
Powells Farm	211	Magnitude of fluctuations too high.
Walnut Cottage	20	Satisfactory.

Various sections showing the comparison between modelled and observed groundwater head are produced (Figures 4.33 to 4.39; Phase 2 report). The majority of these sections are along river valleys and show reasonable agreement between modelled and observed.

Two sets of contours plots are provided in the Phase 2 report; modelled groundwater contours with observed value posted for low (November 1989), average (May 1992) and high (March 1995), groundwater levels (Figs 4.24 to 4.26), and differences between modelled and observed for the same time period (Figs 4.27 to 4.29). Self evidently, as the groundwater water levels increase, then the area where heads are too high also increases.

The consistent problem with all three plots is that the modelled groundwater levels are too high east of the Alre.

5.3.5 Water balance

Two time series of water balances are presented: monthly from January 1991 to December 1995 (Fig 4.40; Phase 2 report) and annual average for the duration of the model simulation (January 1970 to December 2000). Both these plots show that the main water balance components in the model are recharge as the inflow and a combination of baseflow and groundwater abstraction as the outflow. Recharge and baseflow are seasonal with abstraction being more or less constant over the period of model simulation.

5.3.6 Concluding statement

A short review of the Itchen model produced by Entec for the Environment Agency has been undertaken. This model was constructed in MODFLOW and is a two layer model to include the layering observed within the Chalk. The model has grid spacing of 250 m and is run from January 1970 to December 2000 with a five year lead in using a dynamic balance. The main inflows are recharge and the main outflows are river baseflow and abstraction. The VKD mechanism has been applied to Chalk where it is unconfined.

The comparison between the modelled and observed data shows a reasonable match, although there are problems in getting the flow right in the Alre. The two main issues identified are the high proportion of by-pass recharge (30 % of total recharge) and the transmissivity distribution in the Alre catchment.

Table 26 Summary of Candover model runs

Run number	Description	Comments
R1	IGARF solution.	• Straight-line river. • Single abstraction borehole. • Average abstraction rate.
R2	ZOOMQ3D model 60 x 60 km homogeneous aquifer with a straight line river flowing from the upper to the lower edges of the grid	• Comparison with IGARF solution. • Average abstraction rate.
R3	Same as Run 2 but the river is only 6 km long.	• To study the effect of shortening the river. • Average abstraction rate.
R4	Same as Run 3 but abstraction is applied at three abstraction boreholes instead of one representative borehole.	• 6 km long straight-line river. • Three abstraction boreholes. • Monthly abstraction rate.
R5	Introduction of grid refinement to represent the River Candover accurately.	• Three abstraction boreholes. • Monthly abstraction rate. • Refinement to improve the River Candover representation.
R6	As Run 5 with the addition of the Rivers Itchen, Alre and Cheriton.	• Rivers Itchen, Alre and Cheriton added.
R7	As Run 6 but all the rivers interacting with the Chalk in the model area are added.	• Three abstraction boreholes. • Monthly abstraction rate. • Refinement to improve the River Candover representation. • All rivers in model area added.
R8	As Run 7 but with river conductances based on Entec (2002) model of Itchen catchment.	• All rivers. • Homogeneous aquifer. • River conductances are changed.
R9	As Run 8 with the inclusion of the distribution of transmissivity based on Entec (2002) Itchen model.	• Distribution of transmissivity. • River conductances based on Entec (2002) Itchen model.

Table 26 cont.

R10	As Run 9b higher storage coefficient specified in the valleys.	• All rivers. • Distribution of transmissivity. • River conductances based on Entec (2002) Itchen model. • Modification of the storage coefficient in the river valleys.
R11	Inclusion of the dependence of transmissivity on saturated thickness.	• All rivers. • Distribution of transmissivity. • River conductances based on Entec (2002) Itchen model. • Modification of the storage coefficient in the river valleys. • Unconfined conditions. • Flat rivers.
R12	Inclusions of correct river elevations.	• All features included in Model 11 plus river-bed elevations based on DTM.
R13	Inclusions of very high transmissivity linear zone between the augmentation boreholes and the Candover stream.	• 1 km wide zone with a transmissivity 100 times that of the surrounding aquifer.

5.4 Investigative modelling of the River Candover flow augmentation scheme using ZOOM_IGARF

In this section a number of models are developed of the River Candover augmentation scheme, incorporating different levels of in complexity. The process of model development recreates the process that an Environment Agency hydrogeologist is likely to undertake when assessing the impact of a new abstraction on river flows. The models are applied to calculate how much of the water abstracted by the three augmentation boreholes at Axford, Bradley and Wield, is derived from the Candover Stream and the other rivers in the region. The results of each model are compared with the depletion rates that have been estimated from the observed data, before adding another feature to the numerical model. The results of each pair of models are also compared to assess which features of the aquifer system are important to represent when modelling the river-aquifer interaction.

The first model that is used to estimate the impact of the abstraction on river flow is the Theis (1941) solution as incorporated in the IGARF1v4 spreadsheet. The second model is developed using ZOOMQ3D and is a numerical equivalent of the first analytical model. A further ten ZOOMQ3D models are then developed in a step-wise manner. Each of these contains one additional feature compared with its predecessor. The final model contains a degree of complexity that is similar to a regional groundwater model, for example developed by the Environment Agency. However, all the numerical models contain only one layer. As in the impact modelling, the depletion rates are calculated by performing two simulations: one in which the augmentation boreholes pump and one in which they do not. The depletion rate for a river reach is the difference between the total river leakage from each simulation. A summary of all of the simulations undertaken as part of this *investigative modelling* is presented in Table 26. Each model simulation is described subsequently.

5.4.1 Investigative model 1: IGARF1 version 4 analytical model

In this first simulation the Environment Agency spreadsheet tool IGARF1v4 (Environment Agency, 2001) is used to calculate the impact of groundwater abstraction from the three abstraction boreholes (Axford, Bradley and Wield) on the Candover Stream. This spreadsheet uses analytical solutions to calculate the impact of abstraction on the river flow. These analytical solutions can be used to calculate the impact on two parallel straight-line rivers after the start of pumping. The spreadsheet incorporates:

- the Theis (1941) solution for fully penetrating rivers;
- the Hantush (1965) solution for fully penetrating rivers with river bed conductivity that differs from that of the aquifer;
- the Hunt (1999) solution for a partially penetrating river.

The Theis (1941) solution is selected here to calculate the impact of groundwater abstraction on the river. This solution assumes that the river fully penetrates the aquifer, that there are no zones of altered aquifer properties next to the river and that the river is in hydraulic continuity with groundwater along its infinite length.

Model structure

The IGARF spreadsheet allows the inclusion of a maximum of one abstraction borehole and two rivers. It considers a homogeneous aquifer which is of infinite extent. The rivers are represented as straight lines that are also infinitely long, however, the spreadsheet enables the calculation of depletion rate along specific reaches of the river. The Candover Stream is represented by the straight-line shown in Figure 94. Though the analytical solution assumes that the river is infinitely long, the spreadsheet is used to calculate the depletion rate along the 6 km section representing the Candover. Since only one abstraction borehole is allowed in the model, the abstraction rates at the three boreholes are added and applied at a representative abstraction borehole located 3,500 m away from the upstream end of the Candover Stream as illustrated in Figure 94. The transmissivity of the aquifer is 2000 m^2day^{-1} and the storage coefficient is 1.5 %. These values are based on those identified by Southern Water Authority (1979).

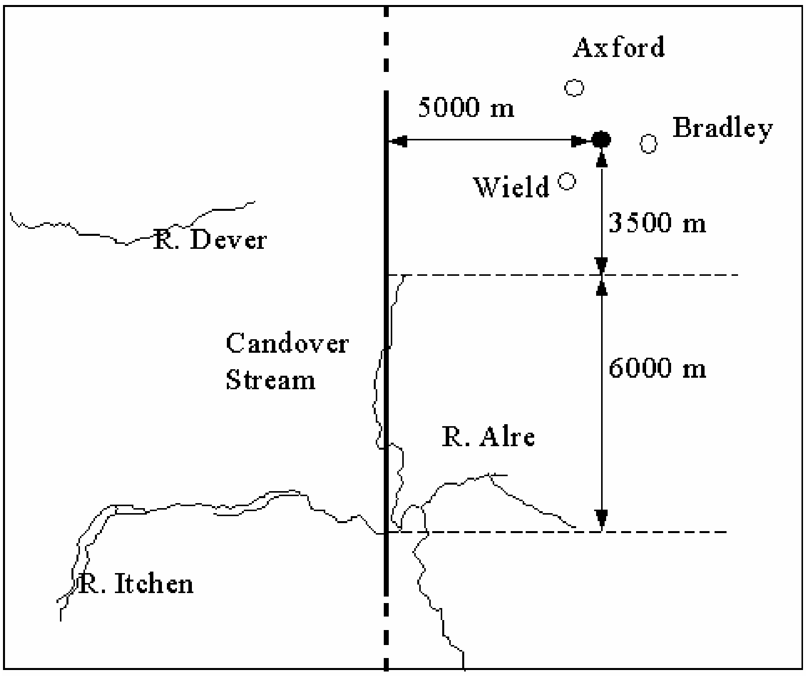


Figure 94 Representation of the Candover Stream by a straight-line river in the IGARF spreadsheet model

Results

An average abstraction rate of 24,620 m^3day^{-1}, determined from the abstraction rates of the individual augmentation boreholes shown in Figure 84, is applied at the representative abstraction borehole. This borehole pumps for a period of seven months from May 1976. The total depletion rate from the 6 km long reach is calculated for a period of two years. Figure 95 shows a plot of the simulated depletion rates and the depletion rates calculated from the observed data. This figure shows that the calculated depletions rates are significantly different from the field results. The maximum simulated depletion rate is 2197 m^{3}day^{-1} while the maximum field depletion rate is approximately 25,000 m^{3}day^{-1}. The field data also seems to show a 105-day delay between the start of pumping and the impact on the river and a complete cessation of river depletion after approximately 375 days. The simulated results, however, show a rapid response to abstraction with a lag of only 22 days between the start of abstraction and the impact on the river.

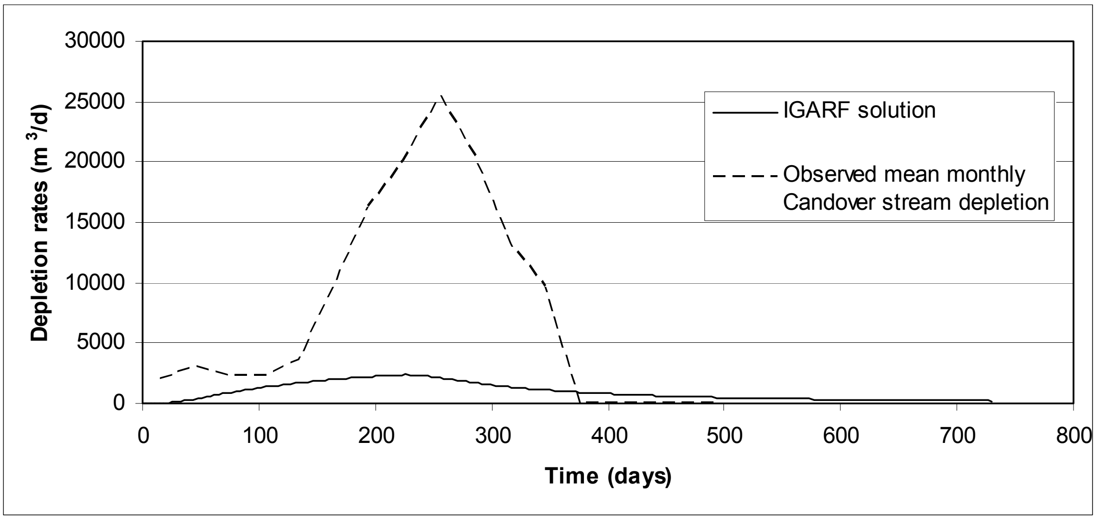


Figure 95 Comparison between the observed and simulated depletion rates using the IGARF spreadsheet model

5.4.2 Investigative model 2: ZOOM_IGARF model of a straight river and one abstraction borehole

The aim of this second simulation is to calculate the depletion rates from the Candover Stream using the ZOOMQ3D numerical model. A comparison is made between the results produced by the numerical model to those produced by the analytical solution of the previous section. As in the analytical solution the aquifer is homogeneous, the river is fully connected to the aquifer and pumping occurs from a single abstraction borehole.

Model Structure

The analytical solution considered in the IGARF spreadsheet assumes that the aquifer is homogeneous and infinite in extent. The numerical model, however, has finite dimensions and specified boundary conditions. To minimise the effects of the boundaries on the numerical results, so that they can be compared with the analytical solution, a relatively large model is constructed, which is 60 km square. Impermeable boundary conditions are specified on the four sides of the model and the river runs through its centre from its northern to its southern boundary, as illustrated in Figure 96.

The model is composed of a mesh of 1000 m square cells whose co-ordinate origin is specified as the lower left corner. The location of the representative abstraction borehole is specified at the grid node with co-ordinates (35000, 30000). The depletion rate is calculated for the 6 km section of the river between (30000, 20500) and (30000, 26500). This reach is approximately equivalent in length to that of the Candover Stream. The river is the only source of water in the numerical model, other than aquifer storage.

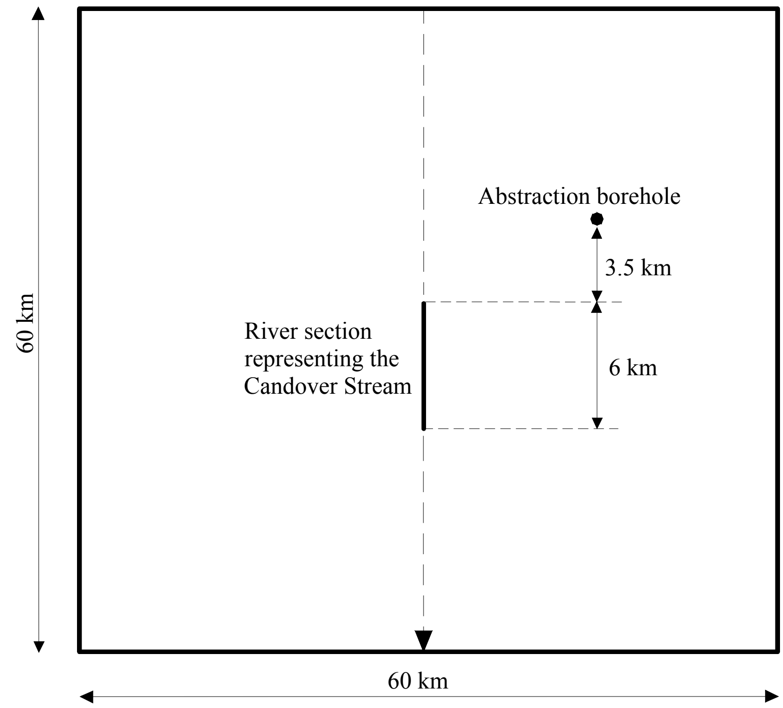


Figure 96 Representation of the Candover Stream by a straight-line river in the ZOOMQ3D numerical model

Results

An average abstraction rate of 24,620 $m^3 day^{-1}$ is applied at the representative abstraction borehole for seven months from May 1976. However, the depletion rate along the specified 6 km section of river is monitored for a period of 3 years. The same aquifer characteristics considered in the IGARF model (Section 5.4.1) are used in this model, i.e. the transmissivity is set to 2000 $m^2 day^{-1}$ and the storage coefficient is set to a value of 1.5 %. As expected the depletion rates calculated using the numerical model are almost identical to those produced by the IGARF model and the effect of the numerical model boundaries is minimal. The numerical results show that the maximum depletion rate is 2,096 $m^3 day^{-1}$ which occurs after 222 days. These results also show that the time lag between the start of pumping and the initial impact of abstraction on the rivers is approximately 20 days (Figure 97). The ZOOMQ3D results agree with the analytical IGARF solution, which both show a rapid impact of abstraction on the river and a prolonged impact of abstraction on river flow.

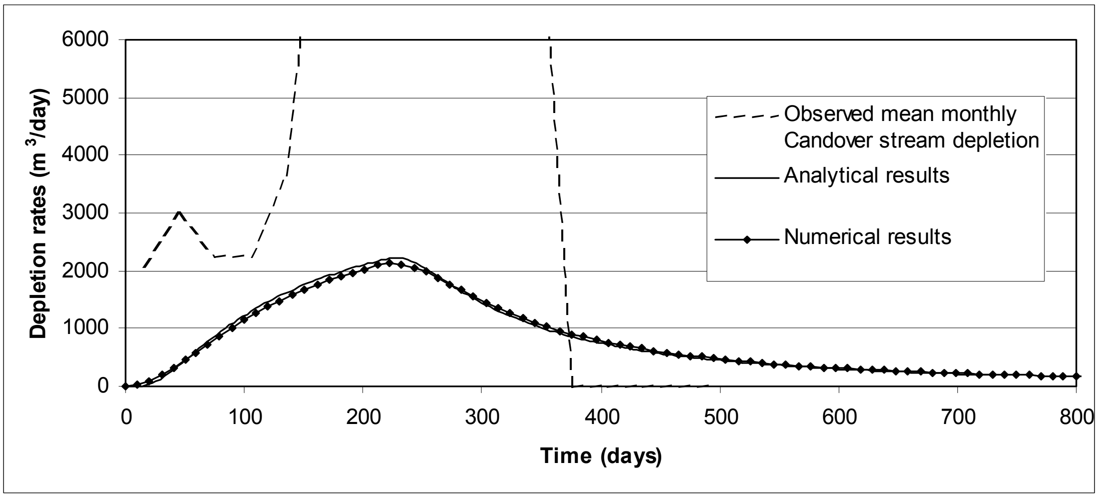


Figure 97 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D (Model 2)

5.4.3 Investigative model 3: ZOOM_IGARF model of a shortened straight river and one abstraction borehole

The numerical model ZOOMQ3D can represent rivers of different geometry and length. In this simulation the model river is shortened to the same length as that of the Candover Stream (6 km). The model, therefore, represents a better approximation to the system. The effect of shortening the straight-line river is examined.

Model Structure

The same numerical model considered in the previous section (Model 2) is used in this simulation except for the shorter river. The shortened reach runs between (30000, 20500) and (30000, 26500). All other model parameters are the same as those used in the previous model.

Results

The single representative abstraction borehole is defined at the node with co-ordinates (35000, 30000). An abstraction rate of 24,620 m^{3}day^{-1} is applied for seven months at this node and the depletion rates of the river is monitored for 3 years. The reduction of the river length increases the maximum depletion rate from 2096 m^{3}day^{-1} in Model 2 to 4398 m^{3}day^{-1} (Figure 98). It should be noted that the impact of pumping on the river lasts for a longer period of time in this model. After 800 days, the depletion rate calculated in Model 3 is 836 m^{3}day^{-1}, which is more than twice the depletion rates calculated in Model 2 (166 m^{3}day^{-1}). This is expected because, unlike Models 1 and 2, the section of the river for which the depletion rate is calculated is the only available source of water that replenishes the aquifer after the cessation of abstraction.

Model 3 considers a straight river whose length is equivalent to that of the Candover Stream. This is the only improvement on Model 2. This has increased the maximum depletion rate from 2096 m^{3}day^{-1} to 4398 m^{3}day^{-1}. However, the maximum depletion rate and the time lag between the start of pumping and the initial impact on the river remain significantly lower than those calculated from the observed data.

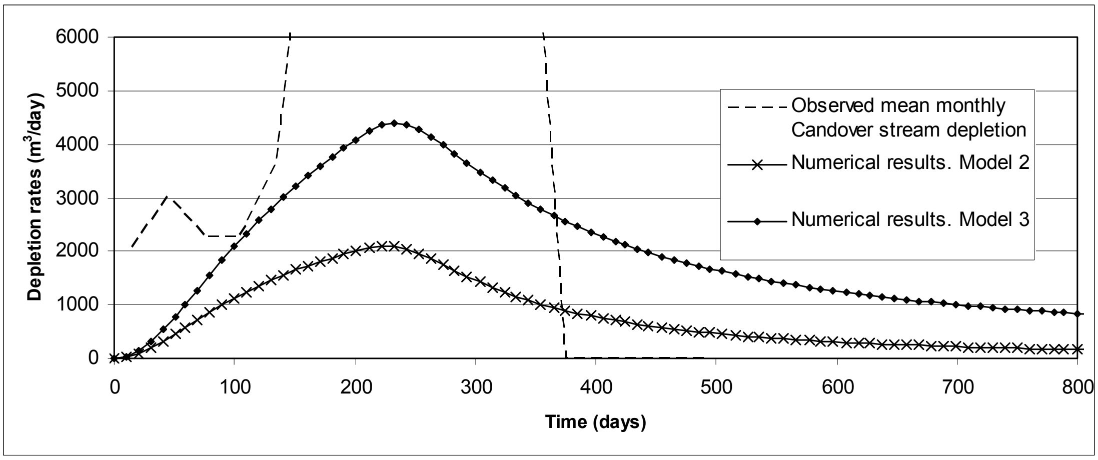


Figure 98 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D (Model 3)

5.4.4 Investigative model 4: ZOOM_IGARF model of a straight river and three abstraction boreholes

In this simulation, abstraction is applied at three abstraction boreholes rather than at one representative abstraction borehole. The effects of this change from Model 3 on the river depletion are examined. The monthly average abstraction rates shown in Table 27 are applied at the three augmentation boreholes.

Model Structure

As before the model consists of a 60 km square aquifer with a transmissivity of 2000 m^2day^{-1} and a storage coefficient of 1.5 %. Impermeable boundaries are specified at the four sides of the aquifer and the river is represented by a straight line 6 km long. The river flows between (30000, 20500) and (30000, 26500). Axford, Bradley and Wield abstraction boreholes are represented in the model by the nodes located at (35000, 31000), (36000, 30000) and (35000, 29000).

Results

The depletion rates calculated using this model are similar to those calculated using Model 3 (Figure 99). However, on closer investigation differences between the results of the two models can be distinguished. The first is that the time lag between the start of pumping and the initial impact of abstraction on the river is shorter in this model (10 days) than in Model 3 (20 days). The second is that the maximum depletion rate recorded in this model (4360 m^3day^{-1}) is slightly smaller than the maximum depletion rate calculated in Model 3 (4398 m^3day^{-1}) and that it is recorded at an earlier time in this model (212 days) compared with Model 3 (232 days). The locations of the Wield and the Axford abstraction boreholes cause this difference. The Wield abstraction borehole is closer to the river than the representative abstraction borehole considered in Model 3. This causes the impact of groundwater abstraction on the river to occur earlier. The Axford abstraction borehole is, however, farther from the river than the Model 3 representative abstraction borehole which delays the impact of the abstraction on the river.

In this simulation abstraction is applied at the three augmentation boreholes. This has slightly reduced the maximum depletion rate and caused the initial impact of abstraction on the stream to occur earlier. The results, however, are again significantly different from the field data.

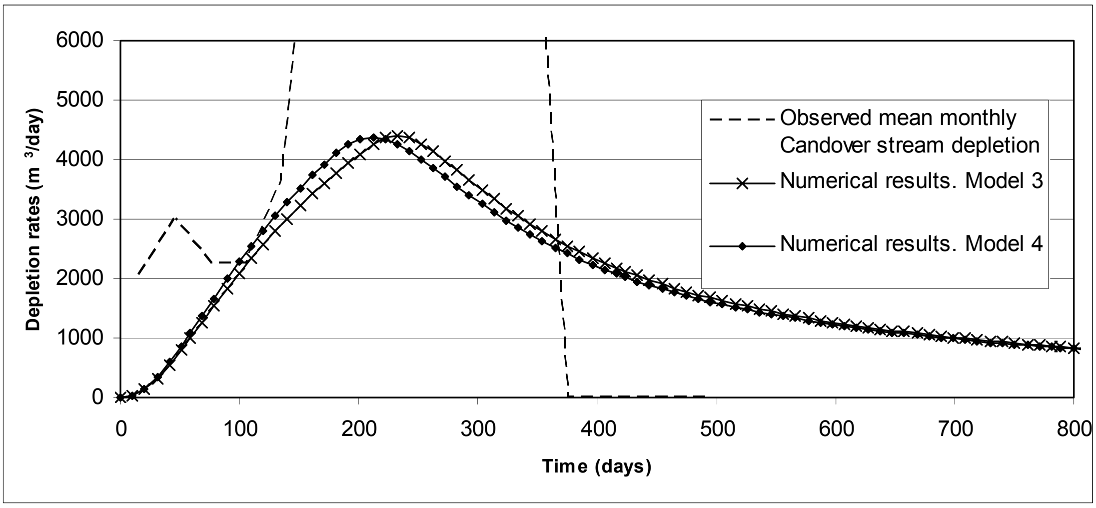


Figure 99 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D (Model 4)

Table 27 Augmentation borehole abstraction rates during summer 1976 test

	May	June	July	August	September	October	November
Axford	4582	3888	38887	2841	3110	3369	0
Bradley	11870	11870	11714	11714	11714	11714	8293
Wield	10730	10678	11818	11818	11766	11237	1213

5.4.5 Investigative model 5: ZOOM_IGARF model. Improved representation of the Candover Stream using grid refinement

In this simulation the Candover Stream is represented more accurately by refining the mesh in the region shown in Figure 100. Grid refinement serves two objectives: first it increases the number of grid nodes in the model enhancing the representation of the river and second it allows the abstraction boreholes to be positioned more accurately. In this model the real site coordinates of the boreholes and all other features are used. The coordinates of the lower left grid corner of the grid in this case are (428000, 109000).

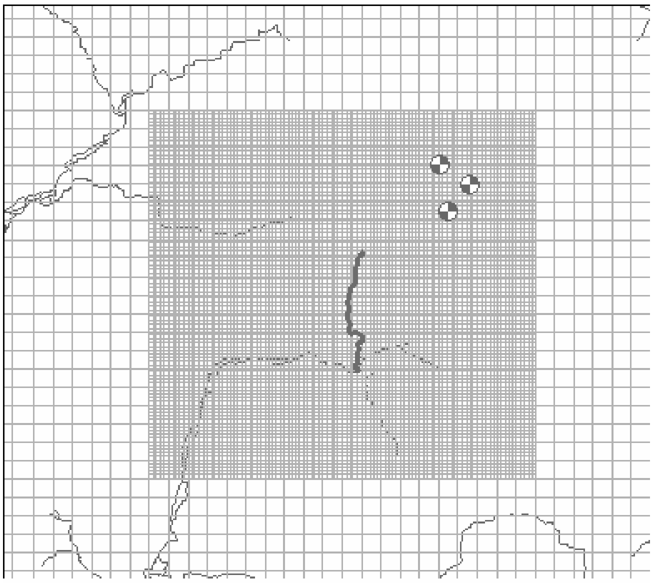


Figure 100 Region of the grid refinement around the Candover Stream

Model Structure

As in Model 4, Model 5 consists of a 60 km square aquifer with a transmissivity of 2000 m^2day^{-1} and a storage coefficient of 1.5 %. All the model boundaries are impermeable. The geometry of the Candover Stream is extracted from an ArcView theme and processed using the “CREATE_RIVER_SPLINE.EXE” application to prepare the spline files required by ZETUP (see Section 4.1). The cells in the 20 km square refined area are 200 m square. The south-west and north-east corners of the refined area are at (446000, 126000) and (466000, 146000) respectively.

Results

The monthly abstraction rates applied at the three boreholes are listed in Table 27. The peak depletion rates calculated using this model are slightly higher (4972 m^3day^{-1}) than those calculated in Model 3 (4398 m^3day^{-1}) and Model 4 (4359 m^3day^{-1}). Although the shape of the river is now irregular, and consequently increased in length, it is believed that the repositioning of the abstraction boreholes using their real coordinates accompanied with the introduction of refinement are the cause of this increase in depletion rates. The use of refinement enables better positioning of the abstraction boreholes. Using a coarse grid with 1000 m square cells it is possible that abstraction is allocated at a node that is 500 m away from the real location of the abstraction borehole. When refinement is introduced and the cell size of the mesh is reduced to 200 m, the accuracy of positioning the borehole is increased by five times. This improvement changes the calculated depletion rates as shown above. The results of this model run are shown in Figure 101.

In this simulation the representation of the Candover Stream and the three augmentation boreholes is improved by refining the grid. This has an impact on the calculated river depletion rates. In this case, the maximum depletion rate increases by 14% from that calculated using Model 4. However, this maximum depletion rate remains significantly less than the one calculated from the field data.

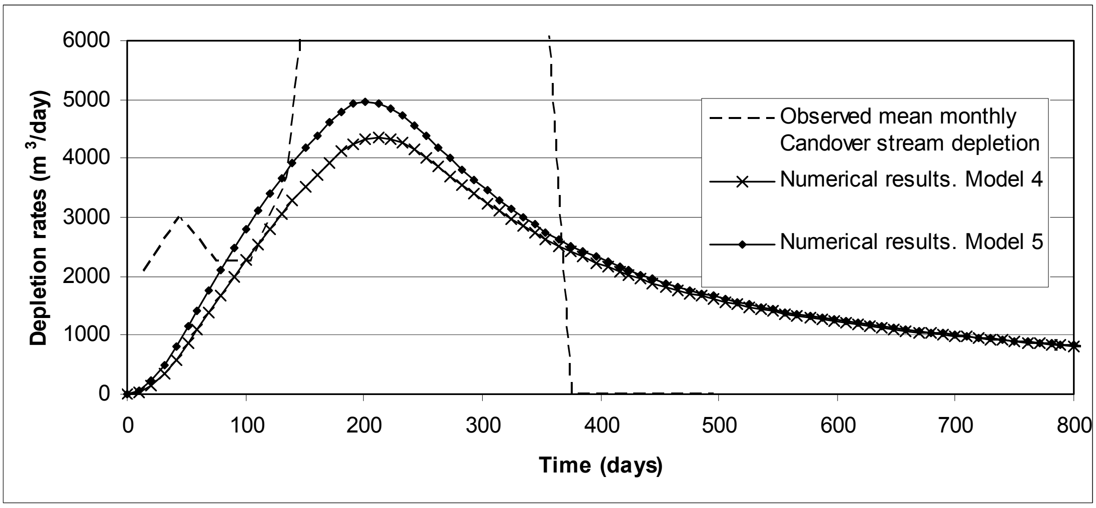


Figure 101 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D (Model 5)

5.4.6 Investigative model 6: ZOOM_IGARF model of the Itchen catchment. The inclusion of Rivers Alre, Cheriton and Itchen

The aim of this simulation is to add the Rivers Itchen, Alre and Cheriton (Figure 102) to the model and to investigate how the introduction of these rivers affects the simulated depletion rate for the Candover. The model is otherwise then same as Model 5.

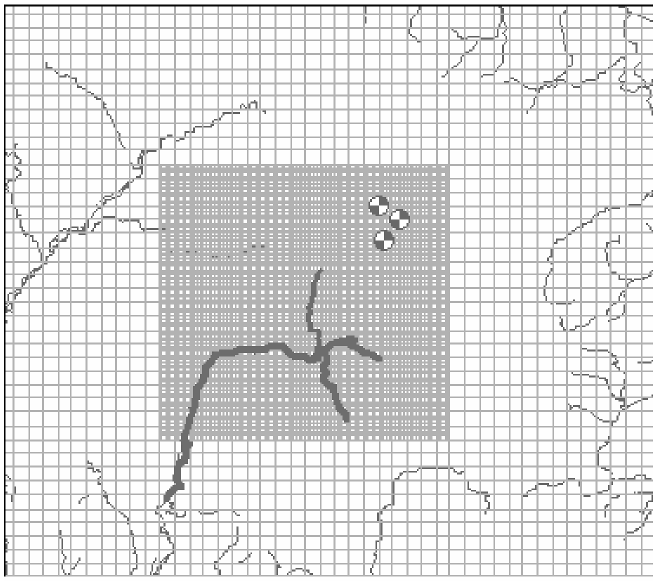


Figure 102 Addition of the Rivers Alre, Cheriton and Itchen to the model

Model Structure

Model 6 consists of a 60 km square aquifer with a transmissivity of 2000 $m^2 day^{-1}$ and a storage coefficient of 1.5 %. Impermeable boundaries are specified at the four sides of the grid. The shapes of the Rivers Candover, Itchen, Alre and Cheriton are extracted from ArcView themes and processed using the "CREATE_RIVER_SPLINE.EXE" application to prepare the spline files required by ZETUP. The numerical mesh is refined in a 20 km square area and the mesh cells are reduced in size from 1000 m to 200 m. The south-west and north-east corners of the refined area are at (446000, 126000) and (466000, 146000) respectively.

Results

The monthly abstraction rates applied at the three boreholes are listed in Table 27. As expected, the inclusion of the other rivers reduces the depletion rate calculated for the Candover Stream. This is caused by the additional source of water provided by the presence of the other rivers in the area. The maximum depletion rate from the Candover Stream is reduced from 4398 $m^3 day^{-1}$ calculated in Model 5 to 4202 $m^3 day^{-1}$ in this model. After the Candover, the Alre experiences the greatest impact of abstraction; the maximum depletion rate for the Alre is 1453 m^3day^{-1}. The maximum depletion rates for the River Itchen and the River Cheriton are 261 m^3day^{-1} and 172 m^3day^{-1}, respectively (Figure 103). The plot of groundwater contours (Figure 104) shows that the Candover Stream is the first river to be affected by the groundwater abstraction followed by the River Alre. The effect of including the three rivers compared to only the Candover Stream is apparent in the increase of the slope of the line representing the recession of depletion rates at this river. The tendency of the depletion rates to reduce to zero is much higher in this model and can be examined by the depletion rates reducing to 439 m^3day^{-1} after 800 days at the Candover Stream compared to 830 m^3day^{-1} in Model 5 at the same time.

In this simulation the complete Itchen catchment is included in the model. The additional rivers provide extra sources of water thus reducing the depletion of the Candover Stream.

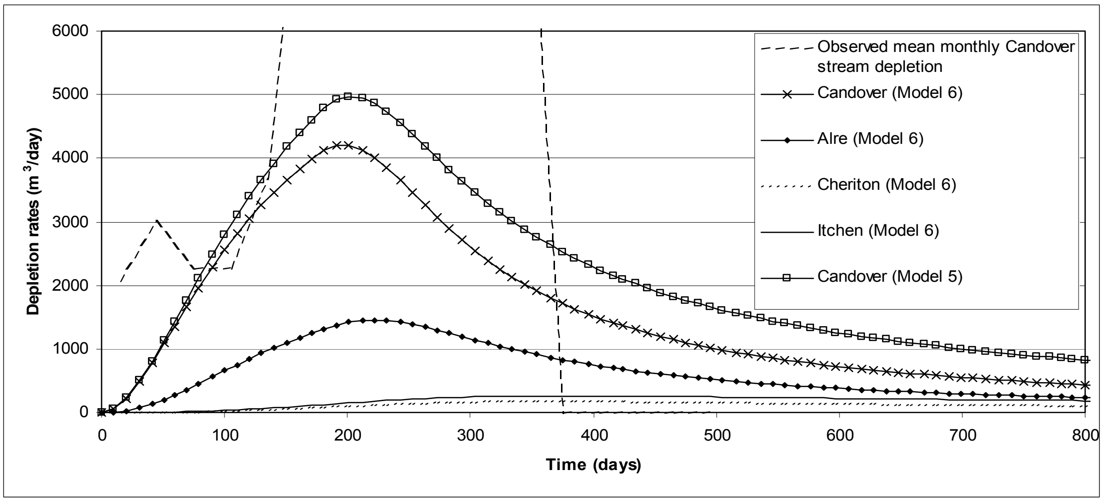


Figure 103 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D model of the Itchen catchment (Model 6)

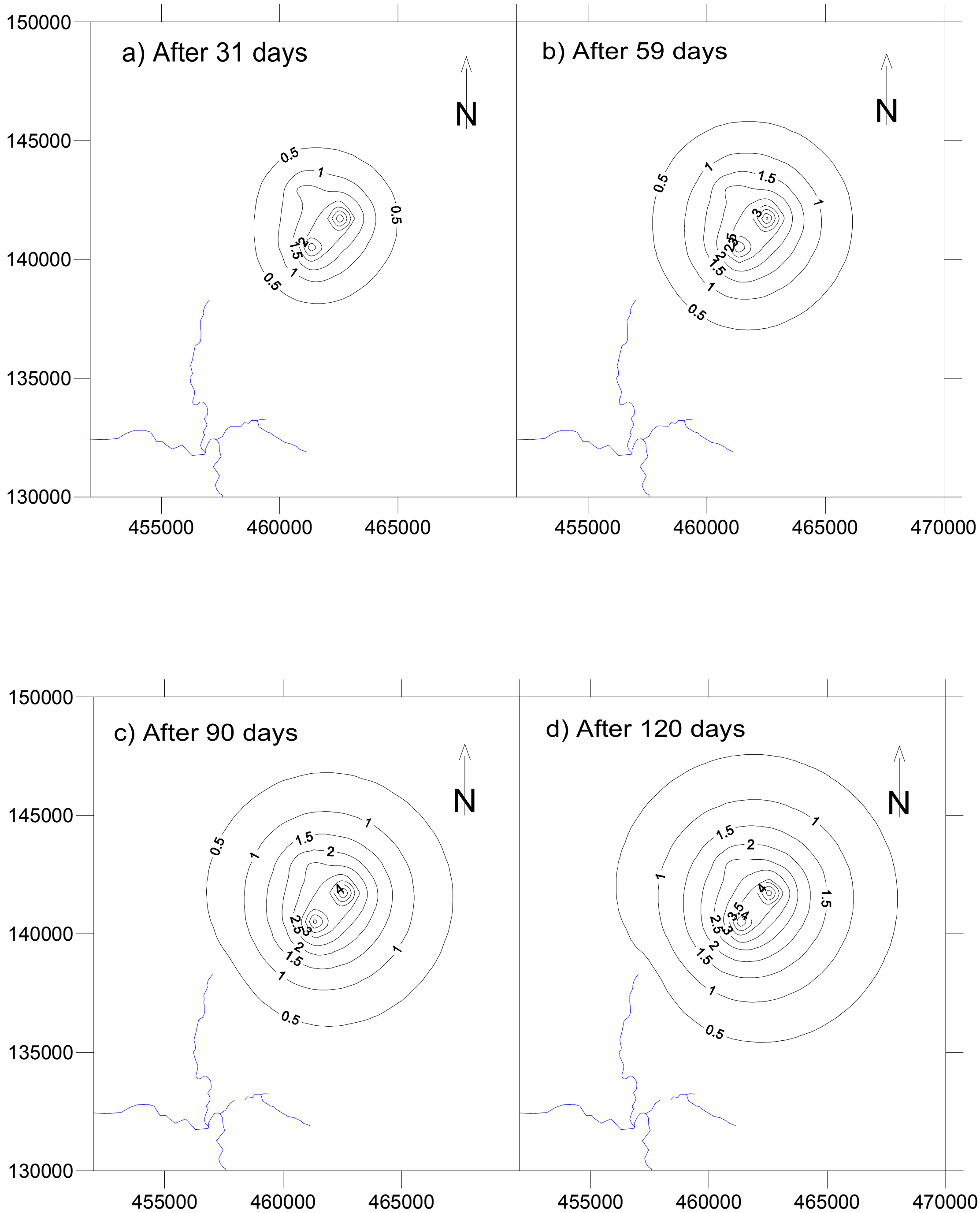


Figure 104 Contours of drawdown 31, 59, 90 and 120 days after the start of abstraction (Model 6)

5.4.7 Investigative model 7: ZOOM_IGARF model of the Itchen catchment. The inclusion of all rivers

The aim of this simulation is to examine the modelled depletion rates when representing all of the rivers that could possibly be affected by the abstraction. These are the Rivers Anton, Bourne Rivulet, Dever and Test in the west, parts of the Rivers Loddon and Whitewater in the north, and of the Rivers Oakhanger, Wey and Rother in the east and the River Meon in the south. These rivers are shown in Figure 105. The model grid is the same as that used in Model 6.

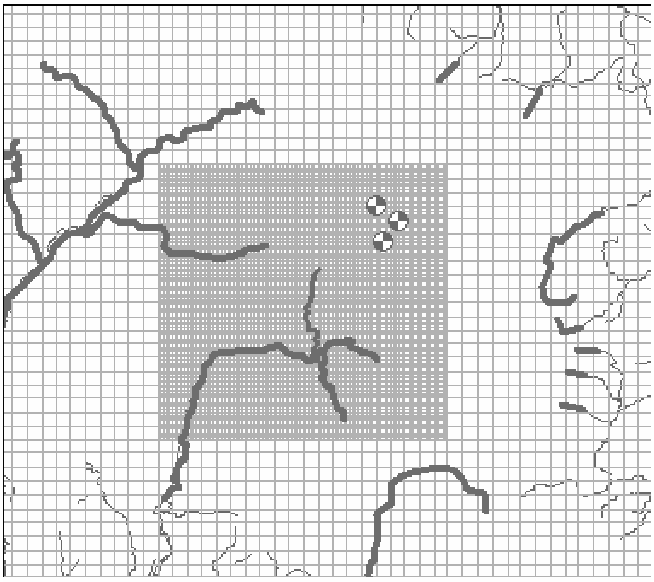


Figure 105 Rivers interacting with the Chalk in the Model 7

Model Structure

As with previous models, Model 7 consists of a 60 km square aquifer with a transmissivity of 2000 $m^2 day^{-1}$ and a storage coefficient of 1.5 %. All model boundaries are impermeable and the rivers are the only source of abstracted groundwater. All the river shapes are extracted from ArcView themes and processed using the “CREATE_RIVER_SPLINE.EXE” application to prepare the spline files required by ZETUP and ZOOMQ3D. However, an accurate numerical representation of the rivers is obtained in the refined area only. This is not considered a major issue since the previous runs show that the improvement in the representation of the rivers has small effect on the simulated depletion rates. The south-west and north-east corners of the refined area are at (446000, 126000) and (466000, 146000), respectively (Figure 105).

Results

The monthly abstraction rates listed in Table 27 are applied again in Model 7. The only difference between this model and Model 6 is the inclusion of the rivers mentioned above. This run confirms that the inclusion of more rivers, i.e. the existence of additional sources of water, reduces the values of depletion rates calculated for the River Candover. Some of the abstracted water is obtained from these rivers and this reduces the impact of abstraction on the River Candover. Figure 106 shows that the maximum depletion rate from the Candover Stream is 4041 m^3day^{-1} compared to 4202 m^3day^{-1} calculated in Model 6. The maximum depletion rate decreases from 1453 m^3day^{-1} in Model 6 to 1442 m^3day^{-1} for the River Alre, and from 261 m^3day^{-1} to 144 m^3day^{-1} for the River Itchen and from 172 m^3day^{-1} to 109 m^3day^{-1} for the River Cheriton. The depletion rates from the Rivers Dever, Wey, Loddon and Meon are shown in Figure 107.

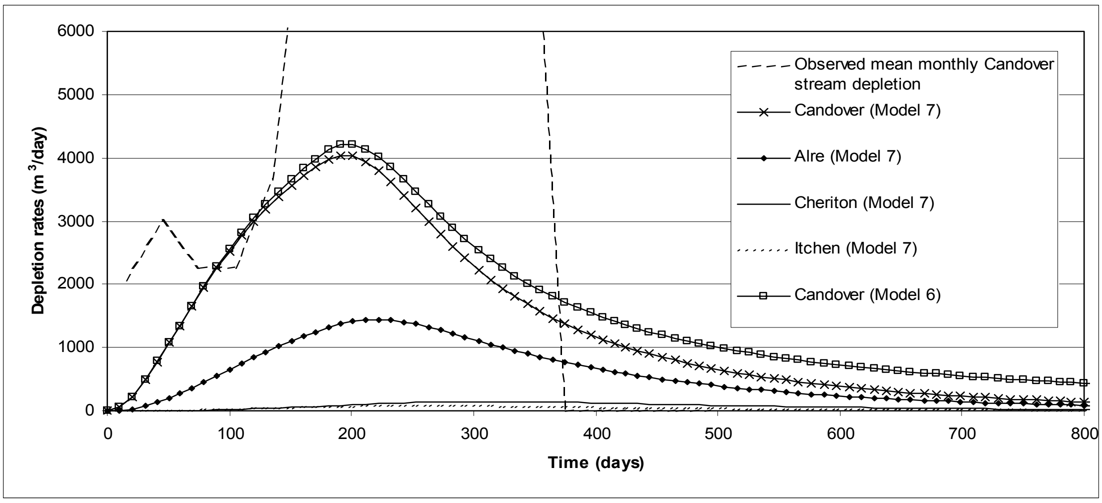


Figure 106 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover Stream and Rivers Alre, Cheriton and Itchen (Model 7)

Figure 108 shows a plot of the change in releases from aquifer storage that can be compared to the monthly draught on groundwater storage plot shown in Figure 87. The numerical results show that water is released almost completely from the aquifer storage at the start of the simulation. The water released from the aquifer then diminishes reflecting the start of the impact on the rivers. The simulation indicates that the aquifer switches from the state of releasing water to a state of recovery after approximately 180 days and that the maximum rate of water being taken into storage is 12,370 m^3day^{-1} which should be compared with a rate of approximately 25,000 m^3day^{-1} based on the field data. In addition, the field results show that water is released from the aquifer at a relatively constant rate for approximately four months and that the aquifer changes from the state of delivering water to a state of recovery after six months, which is not consistent with the numerical model. Although the impact of abstraction on the Candover Stream is different from the previous simulation, the plot of contour lines (Figure 109) do not show significant differences from those produced by Model 6.

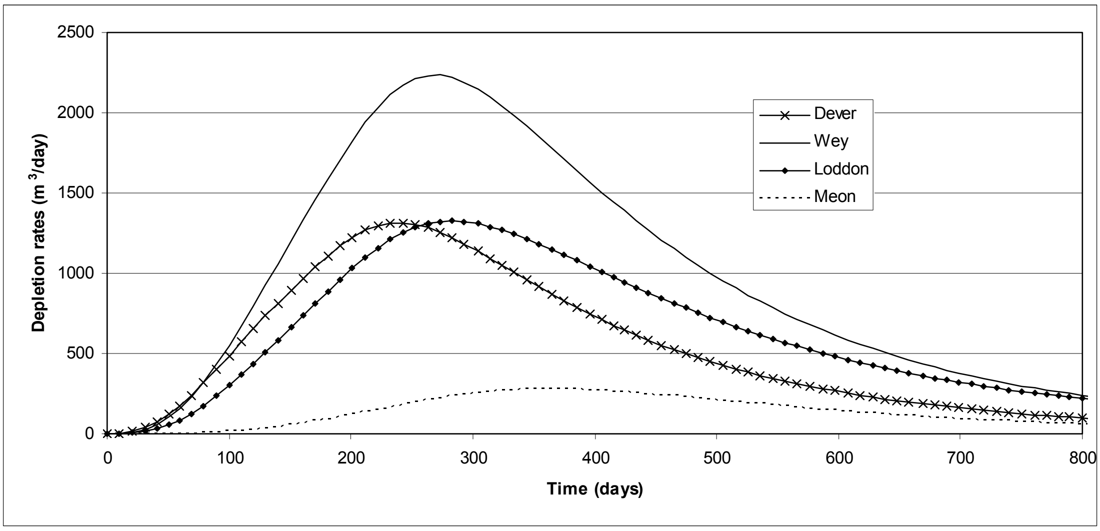


Figure 107 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Rivers Dever, Wey, Loddon and Meon (Model 7)

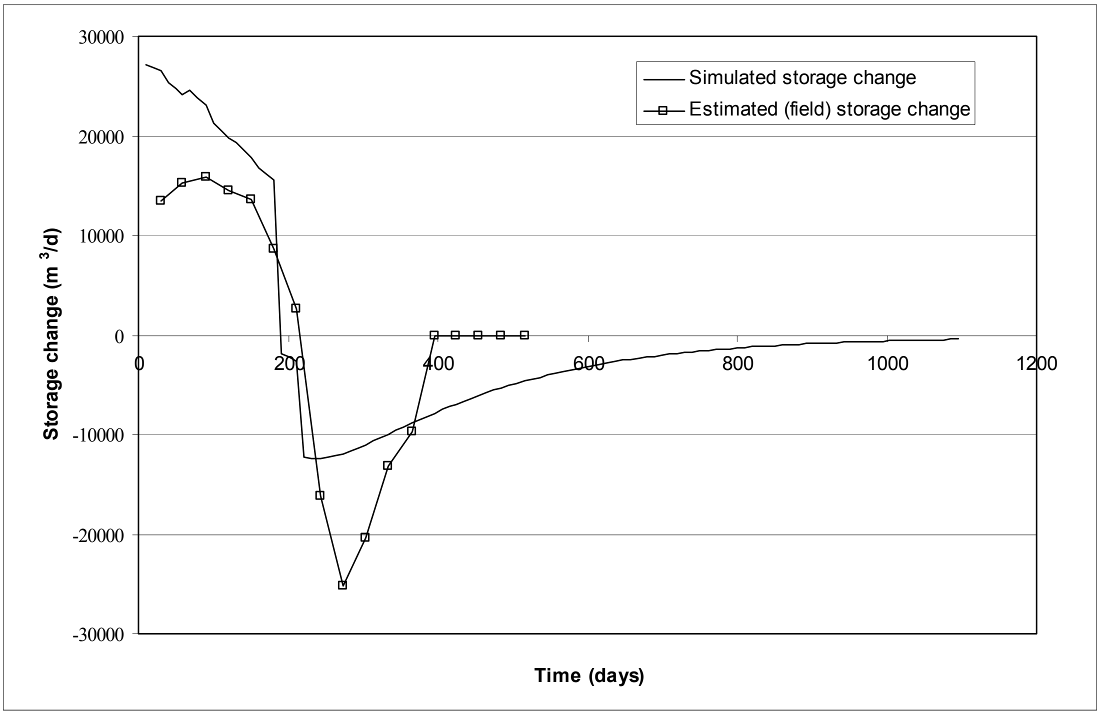


Figure 108 Aquifer storage change with time (Model 7)

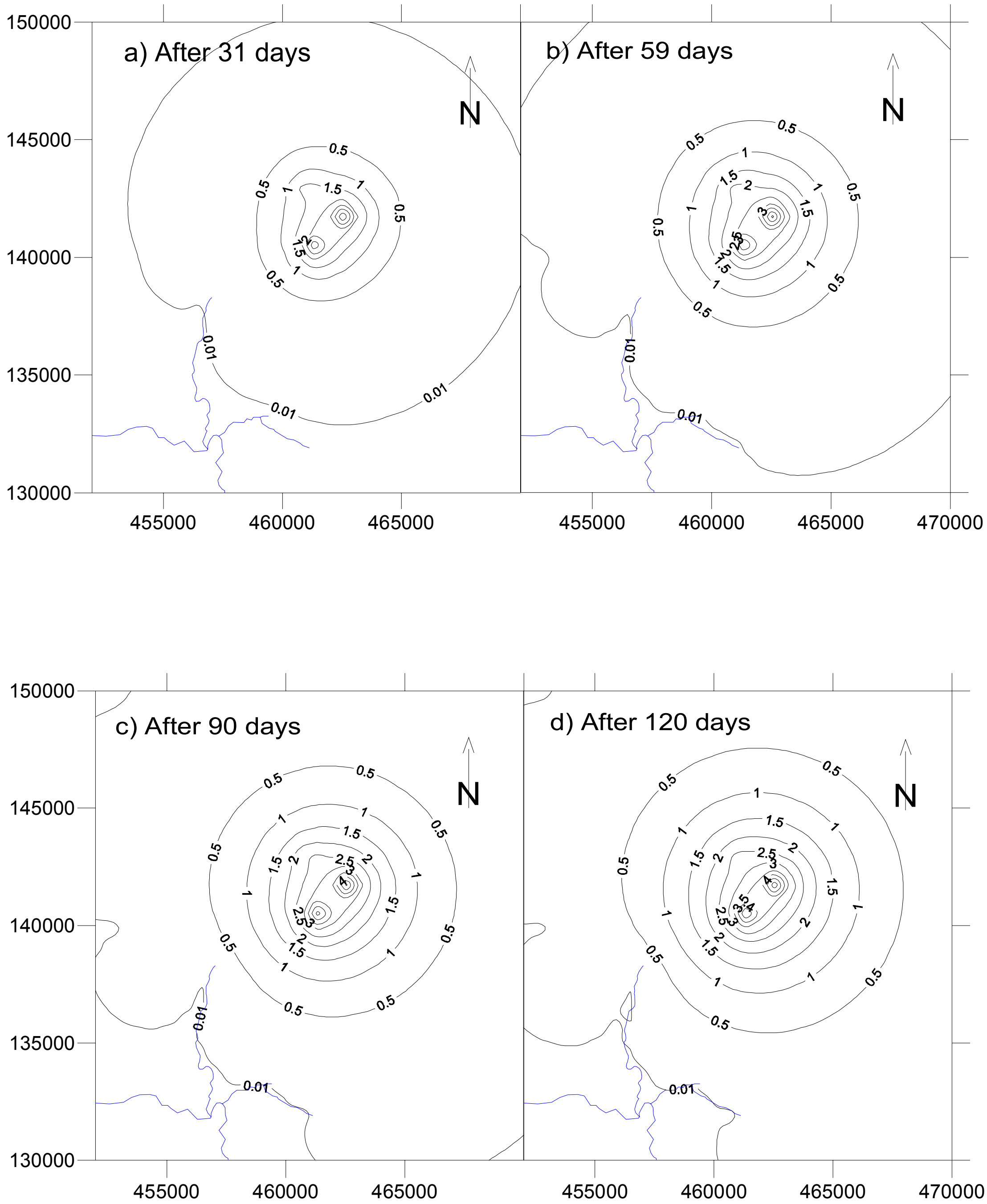


Figure 109 Contours of drawdown 31, 59, 90 and 120 days after the start of abstraction (Model 7)

5.4.8 Investigative model 8: ZOOM_IGARF model of the Itchen catchment. Changing the conductance values of the rivers

In this simulation, the conductance values of the rivers are based on those applied in the regional groundwater model of the River Itchen catchment developed by Entec (2002) for the Environment Agency. The aim of the model run is to examine the effect of changing river conductances on the River Candover depletion rates.

Model Structure

Model 8 is the same as Model 7 except for the specification of river-bed conductance. In Model 7 the conductance values are set to high values so that water can be drawn easily from the river. In this model, the conductance values of the majority of the River Candover and River Cheriton nodes and the nodes of the upstream section of the River Dever are set to 1000 $m^2 day^{-1}$ while the conductance values of the nodes of the other rivers are set to 5000 $m^2 day^{-1}$ (Figure 110). These values are taken from the Entec (2002) model.

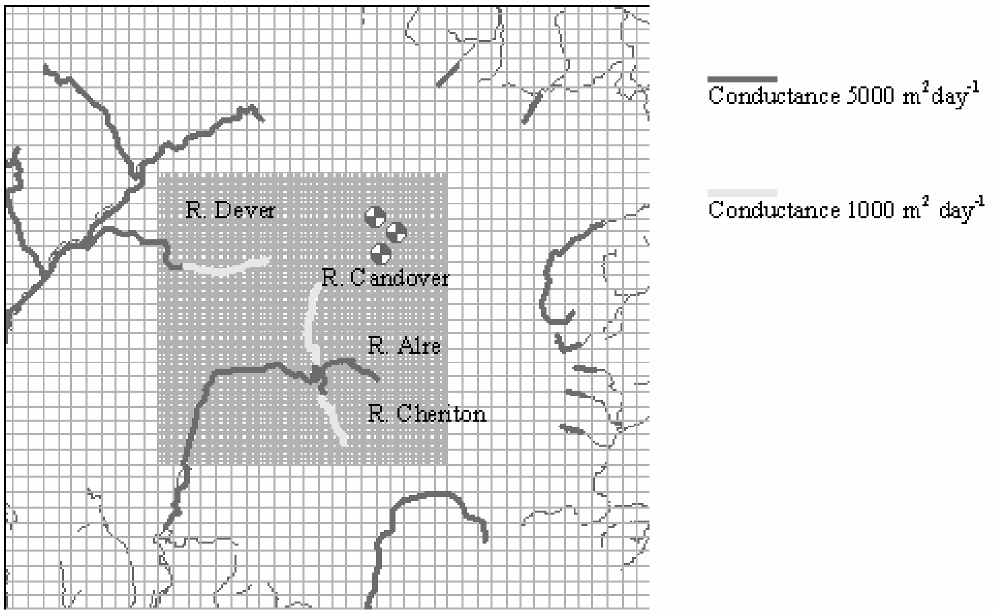


Figure 110 Distribution of river conductance in Model 8

Results

As expected, reducing the conductance values of the river nodes, resulted in lower depletion rates. This is reflected by the decrease of the maximum depletion rate of the Alre and Candover compared to those calculated in Model 7. The plot of depletion rates from the larger rivers included in the model is shown in Figure 111 and Figure 112. A comparison between the maximum depletion rates calculated in this model and those of Model 7 is given in Table 28. The table shows that the depletion rates from some of the rivers have increased when compared to Model 7 (Rivers Meon, Cheriton and Itchen for example). This can be explained as follows. The reduction of river conductance values prevents the rivers that are close to the abstraction boreholes from leaking the same amount of water as in Model 7. The aquifer is, therefore, put under more stress and more water is released from the storage and the drawdown at nodes farther from the abstraction boreholes increases and causes more water to be drawn from the more distant rivers. The differences between the plots of the changes in storage in Model 7 and Model 8 are difficult to identify (Figure 113). Though it cannot be distinguished from Figure 113, Model 8 switches from releasing water from storage to being replenished after approximately 195 days compared to 190 days in the previous model and this confirms that the stress on the aquifer has increased. The plot of the contours of drawdown (Figure 114) shows that the cone of depression has spread further (compared with Figure 109) and that the degree of river-aquifer interaction is less.

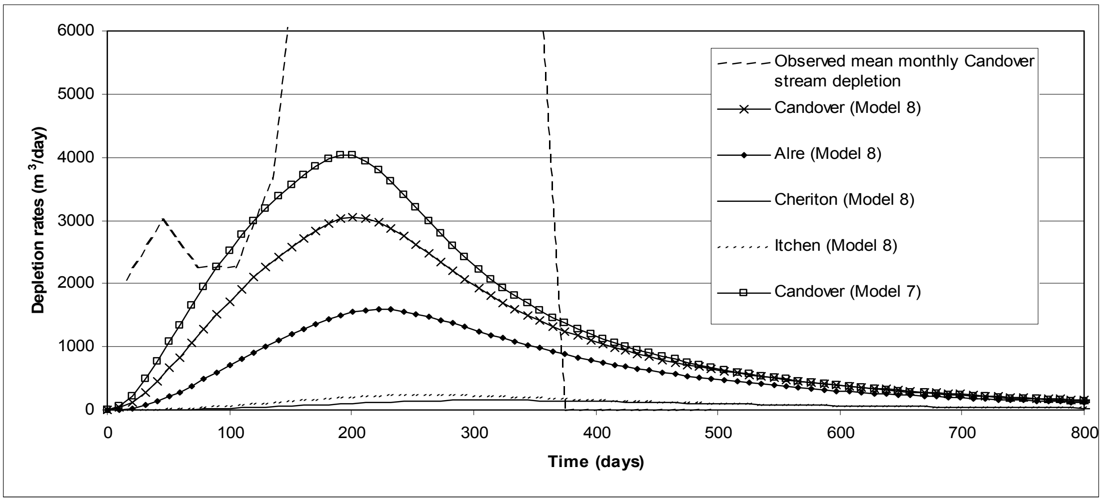


Figure 111 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover, Alre, Cheriton and Itchen (Model 8)

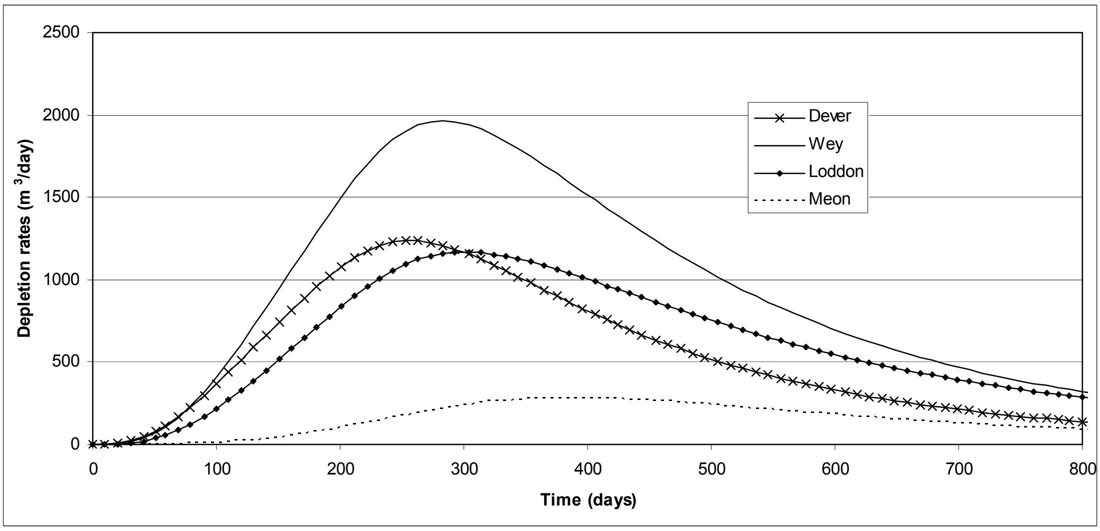


Figure 112 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Rivers Dever, Wey, Loddon and Meon (Model 8)

Table 28 Maximum depletion rates from the considered rivers (Model 8)

River	Maximum depletion rate (m^3day^{-1}). Model 7	Maximum depletion rate (m^3day^{-1}). Model 8
Candover	4040.6	3049.1
Alre	1441.8	1591.2
Itchen	79.3	238.2
Cheriton	143.9	152.4
Dever	1314.3	1236.7
Loddon	1326	1167.4
Meon	278.7	283.1
Wey	2235.1	1965.5

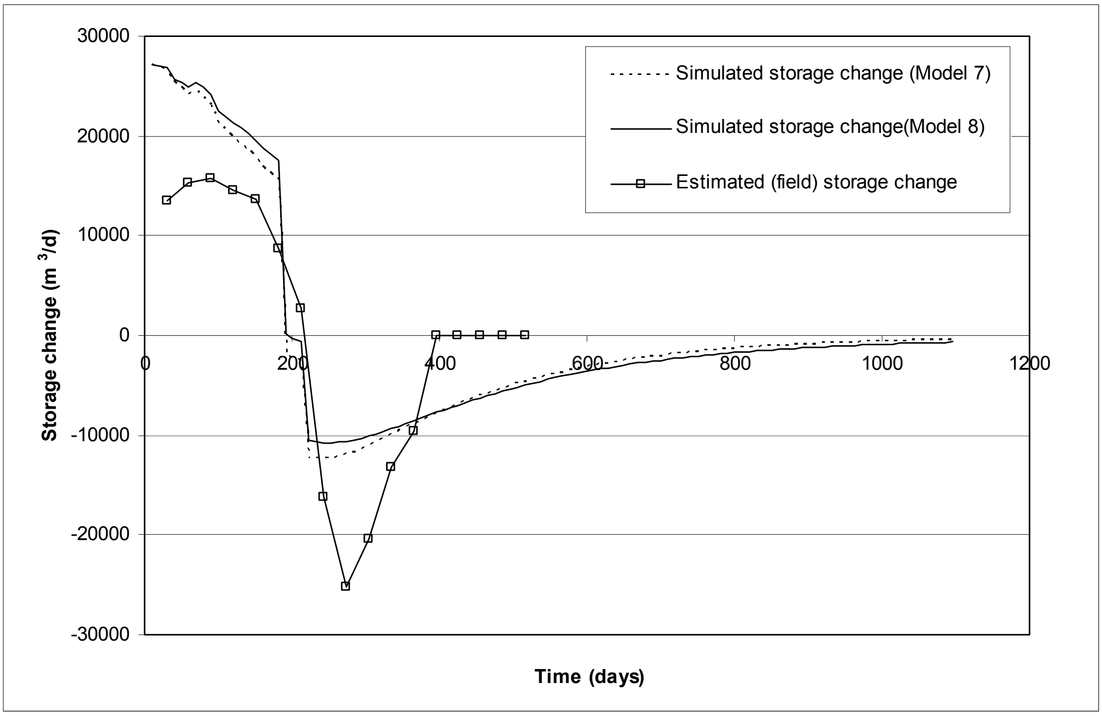


Figure 113 Aquifer storage change with time (Model 8)

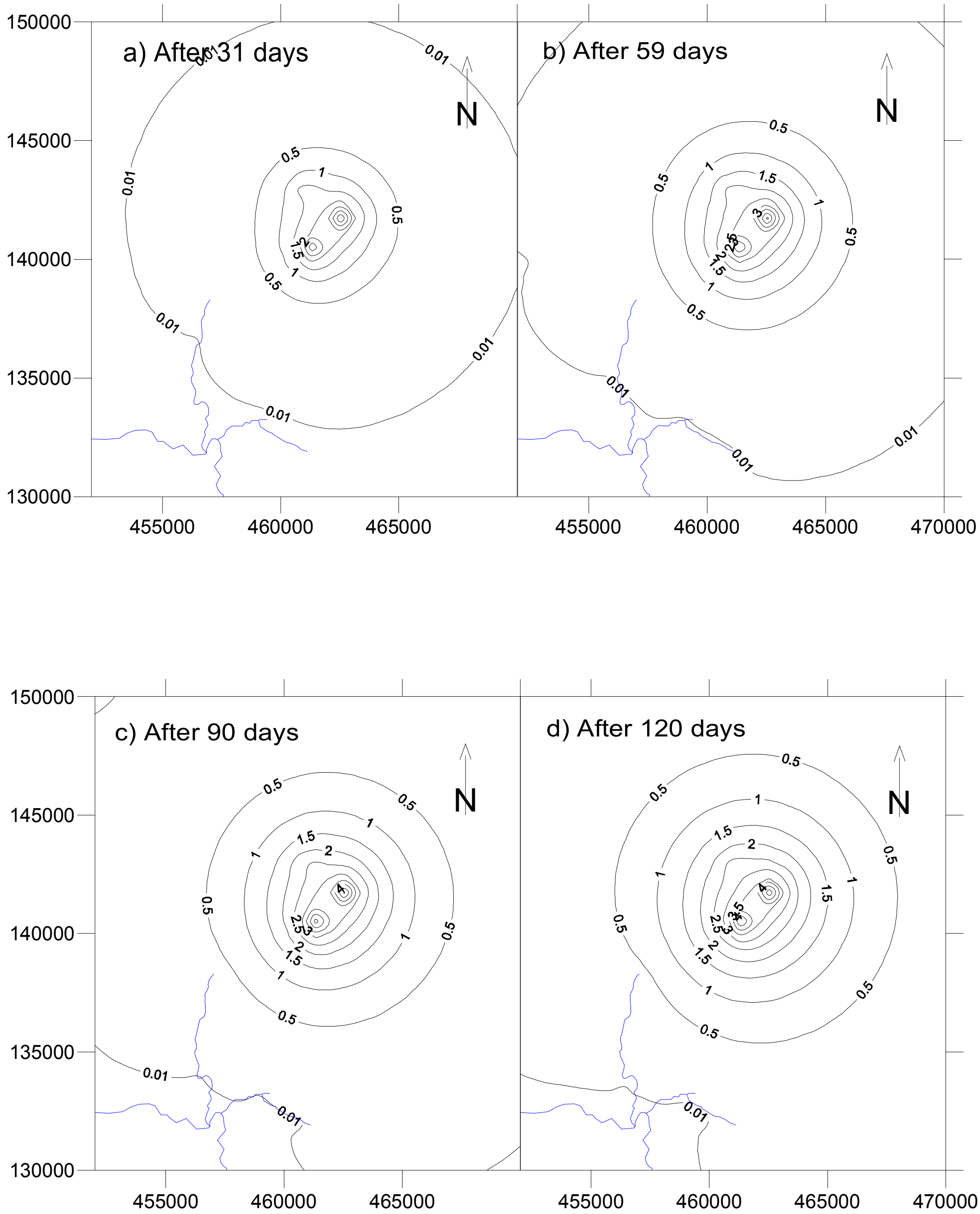


Figure 114 Contours of drawdown 31, 59, 90 and 120 days after the start of abstraction (Model 8)

5.4.9 Investigative model 9: ZOOM_IGARF model of the Itchen catchment. Considering the spatial variation of transmissivity values

In this model a spatial variation of transmissivity (Figure 115) is applied based on that incorporated in the model of the Itchen catchment developed by Entec (2002) for the Environment Agency. The aim of this simulation is to examine the effects of incorporating aquifer heterogeneity on simulated depletion rates.

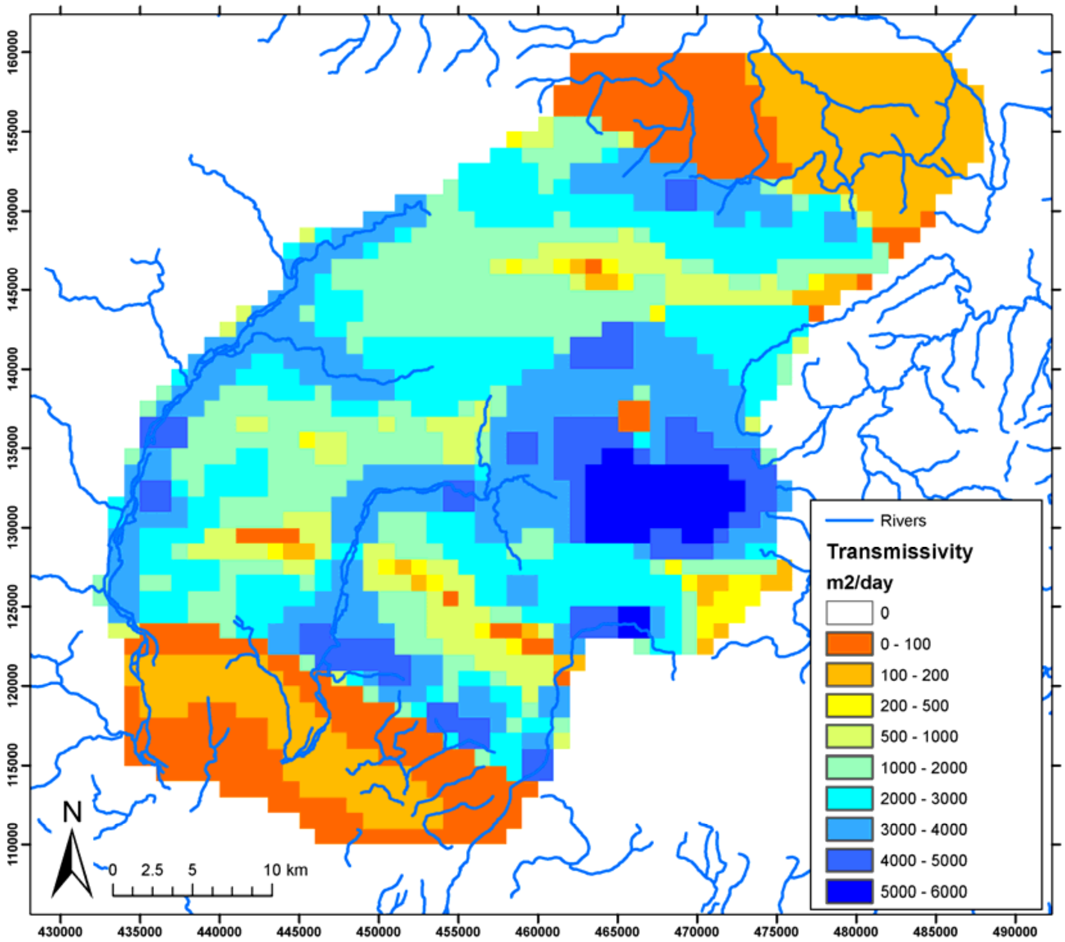


Figure 115 Spatial variation of the transmissivity values included in Model 9

Model Structure

This model is the same as Model 8 except that a heterogeneous distribution of transmissivity is included in Model 9. The transmissivity distribution is based on that used by Entec (2002) in the groundwater model of the River Itchen catchment (Figure 115).

Results

While a constant transmissivity value of 2000 m^2day^{-1} is used in Model 8, the transmissivity in this model varies between zero and 6000 m^2day^{-1}. The transmissivity is set to zero towards the edges of the model to reproduce the shape of the boundary of the Entec (2002) model. Because the resulting model is smaller and the transmissivity is higher in the valleys it might be expected that the abstraction boreholes would have a greater impact on the Candover. However, the numerical results show neither an increase in the depletion rates in the Candover Stream nor a time lag that is comparable with the field data. On the contrary, the depletion rates from the Candover Stream are lower in this model than in the homogeneous Model 8. The depletion rates from the River Alre, however, almost double. The transmissivity distribution has a significant role in determining where water is released in the aquifer and consequently, the amount of water depleted from the rivers. In this particular case, the region of high transmissivity between the River Alre and the abstraction boreholes increases the depletion from the River Alre. The depletion of the Candover reduces because of the lower transmissivity in this direction. The less smooth shape of the drawdown contour lines shown in Figure 119 reflects this. The change in storage during this simulation is similar to that of Model 8. However, significant differences are calculated for the distribution of the impacts on the rivers. For the Candover, Dever, Itchen and Loddon the depletion rates fall whilst for the Alre, Cheriton, Meon and Wey they increase.

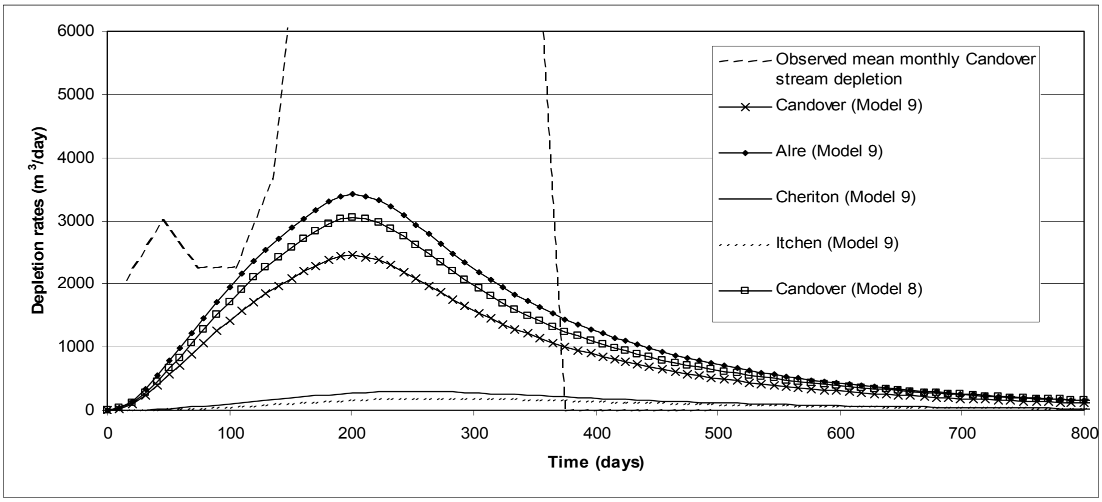


Figure 116 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover, Alre, Cheriton and Itchen (Model 9)

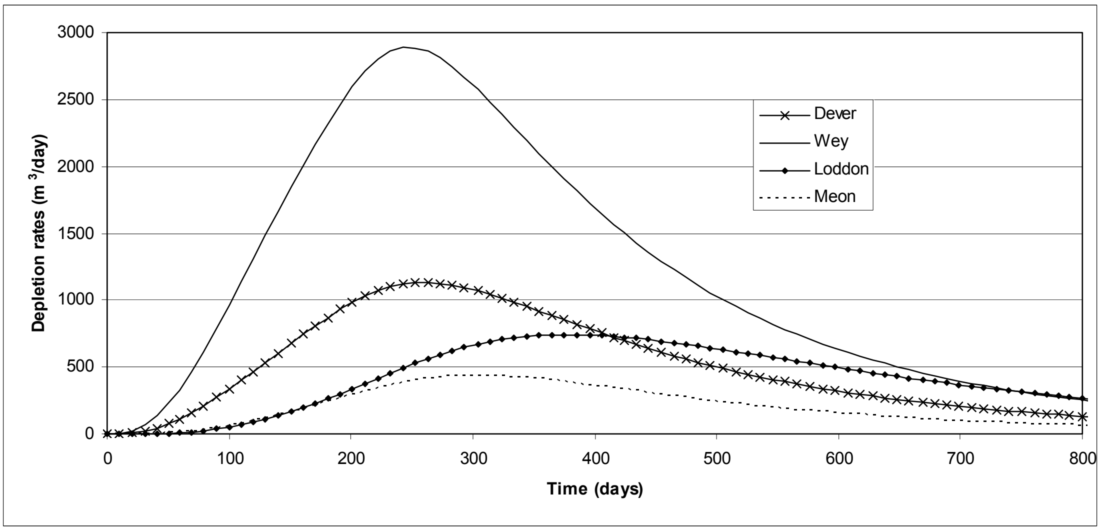


Figure 117 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Dever, Wey, Loddon and Meon (Model 9)

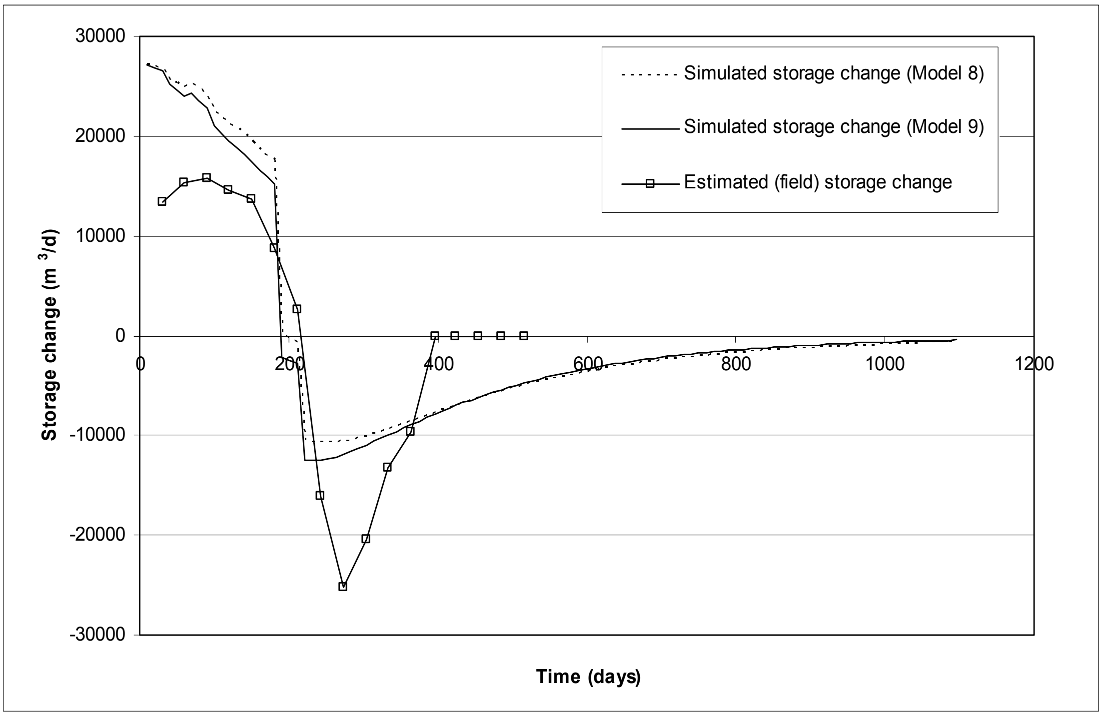


Figure 118 Aquifer storage change with time (Model 9)

Table 29 **Maximum depletion rates from the considered rivers (Model 9)**

River	**Maximum depletion rate ($m^3 day^{-1}$). Model 8**	**Maximum depletion rate ($m^3 day^{-1}$). Model 9**
Candover	3049.1	2452.4
Alre	1591.2	3415.6
Itchen	238.2	186.9
Cheriton	152.4	297.5
Dever	1236.7	1131.3
Loddon	1167.4	742
Meon	283.1	435.7
Wey	1965.5	2886.9

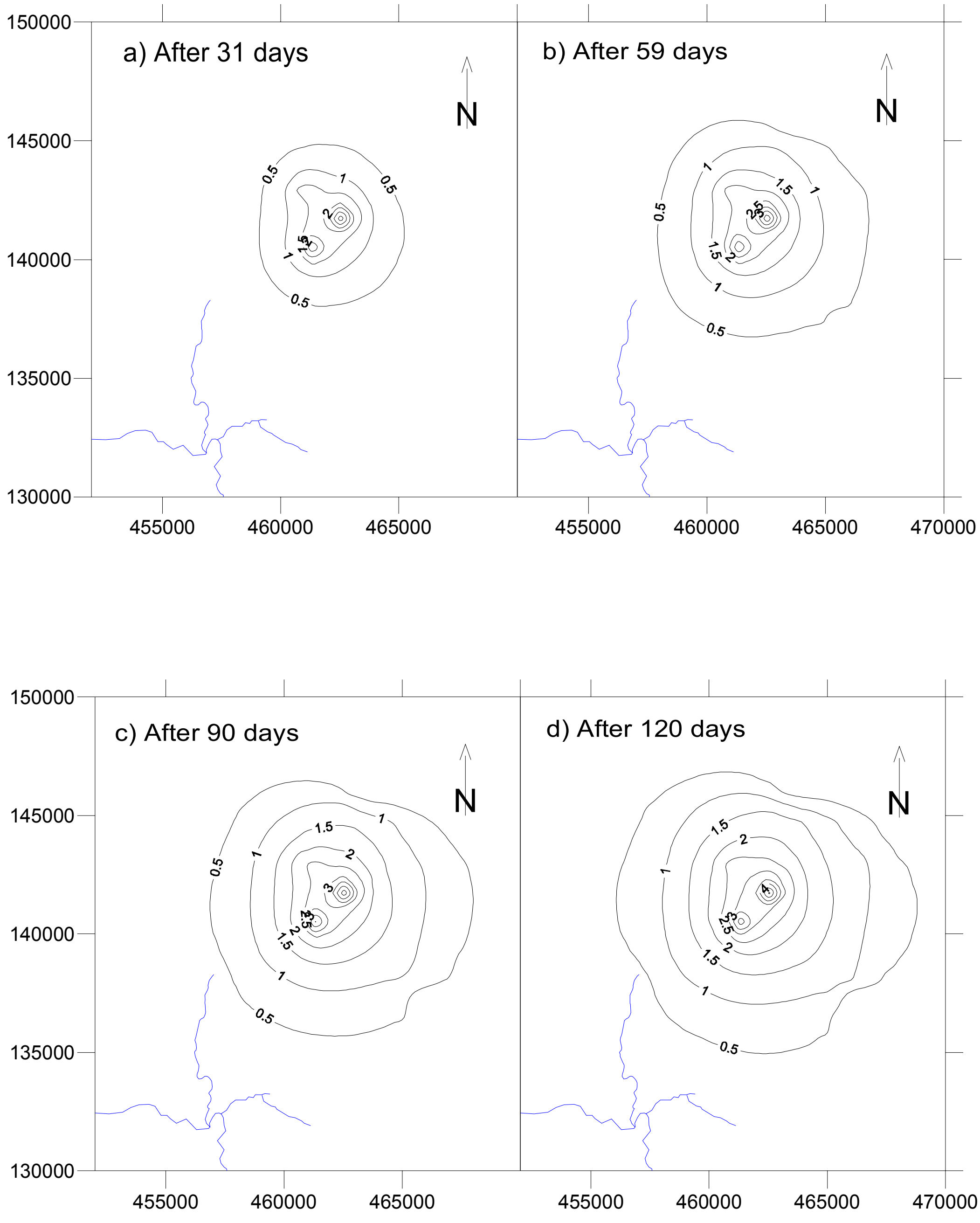


Figure 119 Contours of drawdown 31, 59, 90 and 120 days after the start of abstraction (Model 9)

5.4.10 Investigative model 10: ZOOM_IGARF model of the Itchen catchment incorporating the spatial variation of transmissivity and storage coefficient

In this simulation, the storage coefficient is different between the valleys and the interfluves. The conductance of the river nodes is based on that used in the regional groundwater of the Itchen catchment developed by Entec (2002).

Model Structure

Model 10 is the same as Model 9 except that the distribution of storage coefficient is adjusted. The storage coefficient is set to 10 % in the river valleys (Figure 120) and increased from 1.5 % to 2.5 % elsewhere. This distribution is again based on that included in the regional groundwater model of the Itchen catchment developed by Entec (2002).

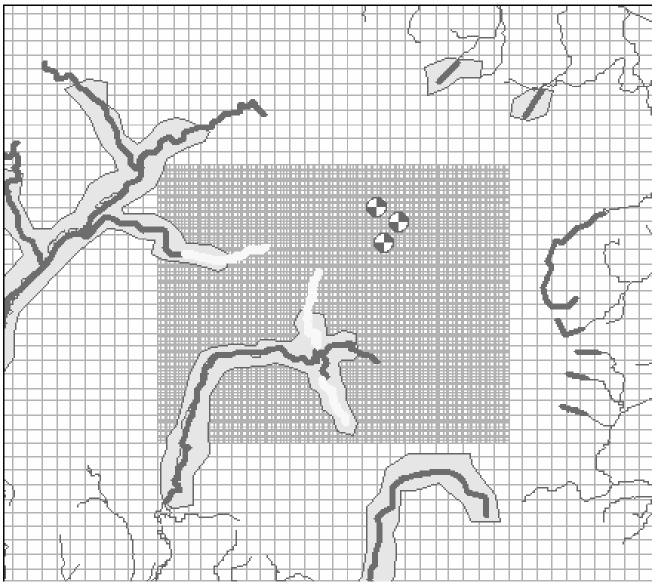


Figure 120 Regions along river valleys within which storage coefficient is increased to 10 %

Results

The overall increase of the storage coefficient and the introduction of zones of significantly higher storage in the valleys cause the depletion rates from all rivers to fall. The maximum depletion rate for the Candover Stream drops from 2452 m^3day^{-1} in Model 9 to 1752 m^3day^{-1} in this model. The depletion rates for the other rivers also fall significantly. The maximum depletion rates for the Rivers Alre, Wey and Dever, for example, fall from 3416, 2887 and 1131 m^3day^{-1} in the previous run to 2453, 1950 and 733 m^3day^{-1} in this run, respectively. The increased storage results in smaller drawdowns and therefore less of an impact on the rivers. The plots of the depletion rates for the larger rivers are shown in Figure 121 and Figure 122. The comparison between the release of water from storage (Figure 123) in Model 9 and 10 illustrates the effect of the increase in the storage coefficient. In this run 20,470 m^3day^{-1} is released from storage after 181 days compared to 15,240 m^3day^{-1} in Model 9. In addition the aquifer changed status from delivering water to receiving water from the rivers after 215 days in this model. This is a longer period of time than that simulated in Model 9 which is 190 days. The comparison between Figure 119 and Figure 124 shows that the cone of depressions does not spread as far in Model 10 because of the increase of storage.

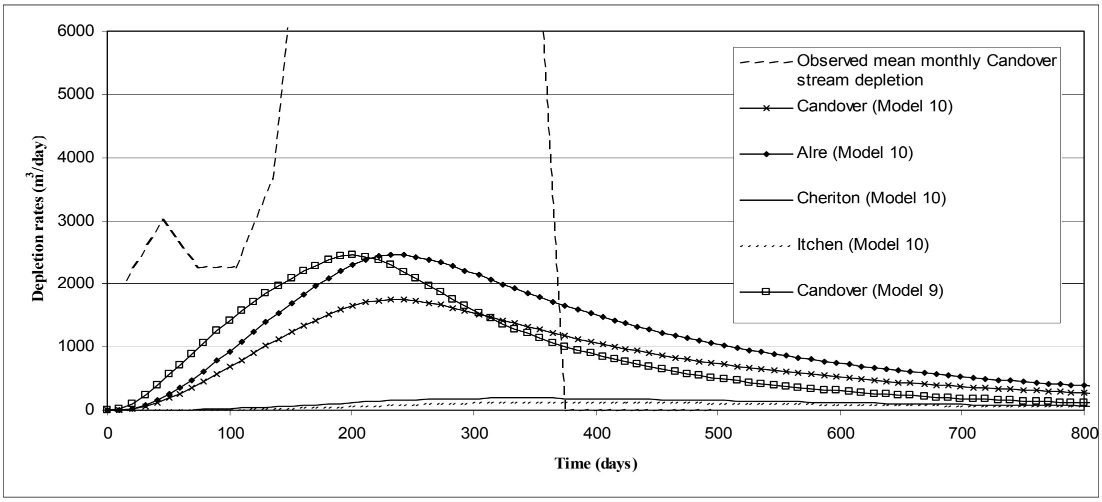


Figure 121 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover Alre, Cheriton and Itchen (Model 10)

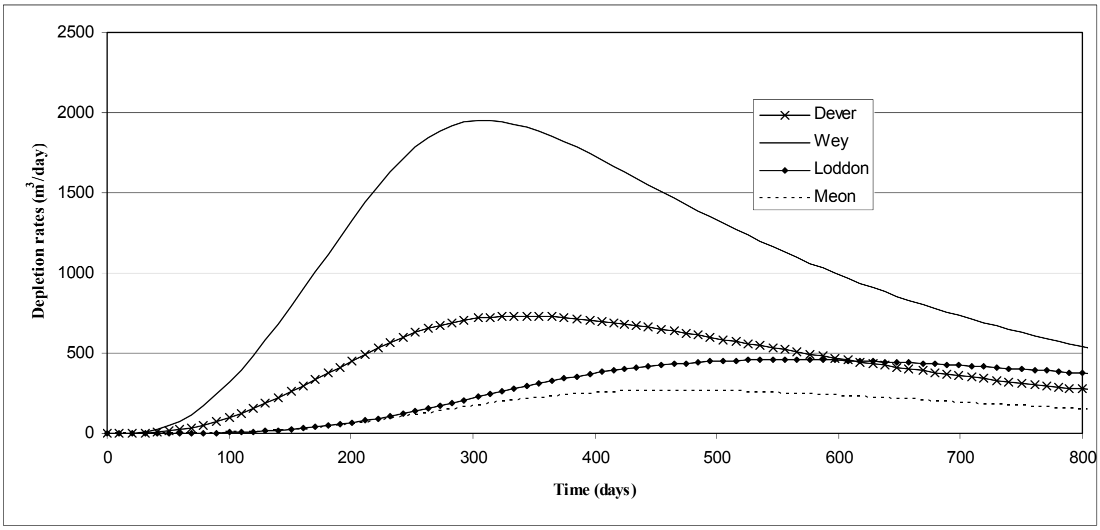


Figure 122 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Dever, Wey, Loddon and Meon (Model 10)

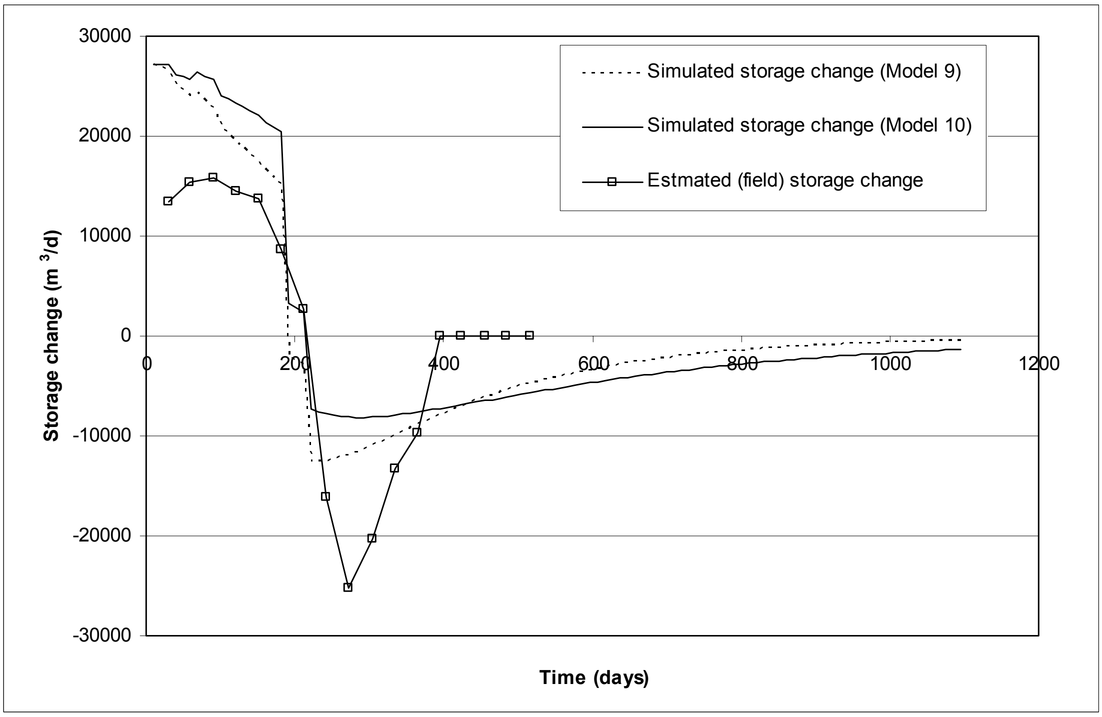


Figure 123 Aquifer storage change with time (Model 10)

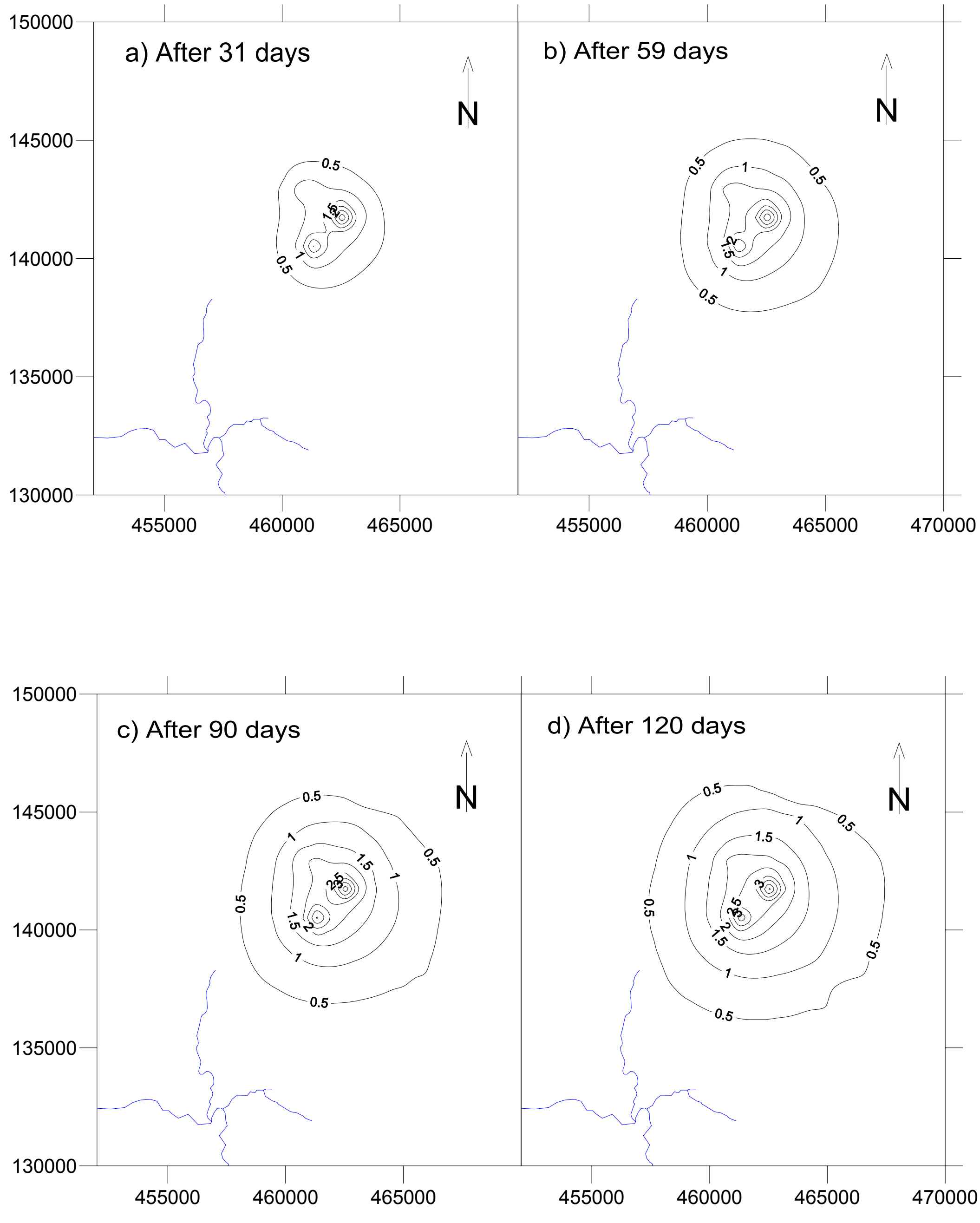


Figure 124 Contours of groundwater head after 31, 59, 90 and 120 days from the start of abstraction (Model 10)

5.4.11 Investigative model 11: ZOOM_IGARF model of the Itchen catchment incorporating unconfined conditions

This model is the same as Model 10 except the transmissivity now depends on saturated aquifer thickness. The aquifer is heterogeneous and both storage coefficient and transmissivity vary across the region. The values of transmissivity, storage and river conductance are the same as those specified in the regional groundwater model of the Itchen catchment developed by Entec (2002).

Model Structure

Model 11 is the same as Model 10 except the aquifer is considered to be unconfined. The specific yield of the aquifer nodes is set to 2.5 % except in the river valleys where it is 10 % (Figure 120). The hydraulic conductivity values change spatially according to the distribution of transmissivity specified in the Itchen model developed by Entec (2002) (Figure 115). The hydraulic conductivity values are set by dividing the transmissivity (Figure 115) by the initial saturated thickness of the aquifer which is assumed to be 100 m. The rivers are horizontal and the elevation of all the river nodes is set to zero metres above Ordnance Datum. The initial groundwater head profile is flat and also has an elevation of zero metres above Ordnance Datum.

Results

A period of time of 3 years is simulated and the abstraction rates listed in Table 27 are applied in the model. Although the transmissivity in this model is head dependent and, therefore, spatially varying, the results of this model are found to be almost identical to those produced in Model 10. In the unconfined aquifer model the transmissivity reduces over time because of the falling water table. However, the difference between confined and unconfined conditions is difficult to distinguish because of the high hydraulic conductivity, which result in only a small reduction in the saturated aquifer thickness. Consequently, the results are not described in any more detail.

5.4.12 Investigative model 12: ZOOM_IGARF model of the Itchen catchment incorporating unconfined conditions recharge and correct river elevations

In this simulation the base of the aquifer is based on contours constructed from observed groundwater level data for May 1982, which represent average conditions. The aquifer is assumed to have a constant thickness of 100 m and the base elevation of the model is calculated by subtracting 200 m from the May 1982 groundwater levels. The river-bed elevations are based on a digital terrain model (DTM) of the area. In addition to the three augmentation boreholes at Axford, Bradley and Wield, the other abstraction boreholes in the model area are included e.g. those for public water supply. As with Model 11, the aquifer is heterogeneous and unconfined.

Model Structure

Under unconfined conditions the hydraulic characteristics of the aquifer change with time with the change of the saturated thickness of the aquifer. Initially, the hydraulic characteristics of the aquifer are assumed to be identical to those specified in the regional groundwater model of the Itchen catchment developed by Entec (2002) (Figure 115). The hydraulic conductivity values are, therefore, determined by dividing the aquifer transmissivity values of the Entec model by the aquifer thickness, which is assumed to be constant and equal to 100 m. These transmissivity values change during the simulation because of the change of the saturated thickness of the aquifer.

Results

The initial groundwater heads are of great importance in this simulation because they affect the river-aquifer interaction. Specifying the initial groundwater heads was less important in the previous models because the rivers were assumed flat and always gaining. In this simulation, however, the groundwater heads determine the condition of the rivers, i.e. if they are perched, influent or effluent. The river status affects the amount of water that can be leaked from it. The initial groundwater head conditions for this model are determined by applying an average pumping rate at all the abstraction wells excluding the augmentation boreholes, applying recharge of 1 mm day^{-1} and performing a simulation with a period of time that is large enough to reach steady-state conditions. The incorporation of all the historically operational abstraction wells (which are included in the Entec (2002) model) in this ZOOMQ3D model results in low groundwater heads causing the Candover Stream to dry up at its upstream and downstream ends as illustrated in Figure 125. Included in the Entec model are a number of 'cress-bed boreholes'. These represent groundwater abstractions next to the rivers in the upper Itchen catchment, which supply water to a series of water cress-beds. Under non-drought conditions these boreholes are generally artesian (Entec, 2002) and consequently are not consumptive. Because of this a second simulation is performed in which the 'cress-bed boreholes' are removed from the model. In this simulation the Candover Stream is dry in its upper reaches only (Figure 126).

The groundwater head contours produced at end of the steady-state simulation (Figure 127) are in relatively good agreement with those calculated from the observed data. These model results are, therefore, considered acceptable for use as initial conditions for subsequent time variant simulations.

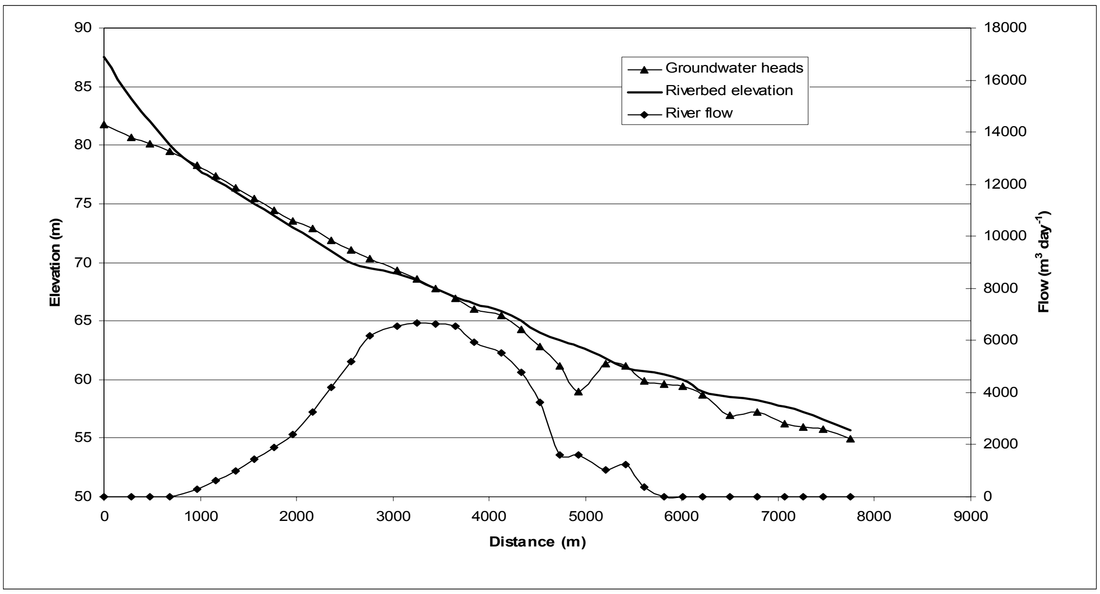


Figure 125 Groundwater and river heads with Cress-bed boreholes included

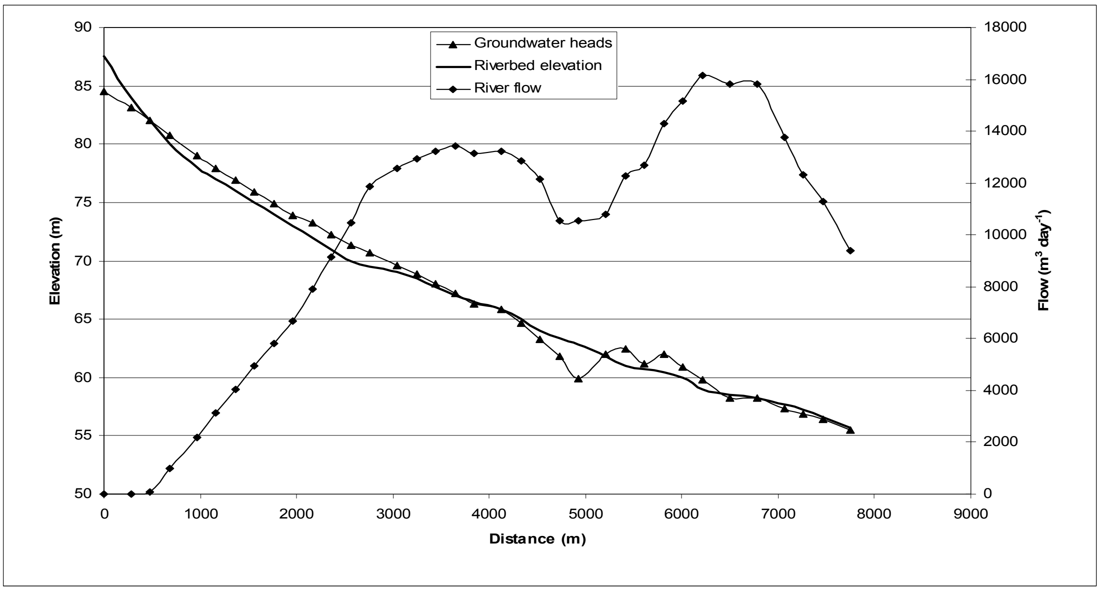


Figure 126 Groundwater and river heads without Cress-bed boreholes

Three different scenarios are considered in this section to study the depletion rates from the Candover Stream. All the scenarios are based on a simulation period of three years and involve two runs; one without (Run 1) and one with (Run 2) pumping from the Axford, Bradley and Wield augmentation boreholes. The differences between the three scenarios are as follows:

- scenario 1 is similar to the runs undertaken in the previous models;
- in Scenario 2 the water abstracted from the augmentation boreholes is discharged at the top of the Candover Stream in Run 2;
- in Scenario 3 the water abstracted from the augmentation boreholes is discharged at the top of the Candover Stream in both Run 1 and Run 2.

Figure 128 shows the difference between the six runs.

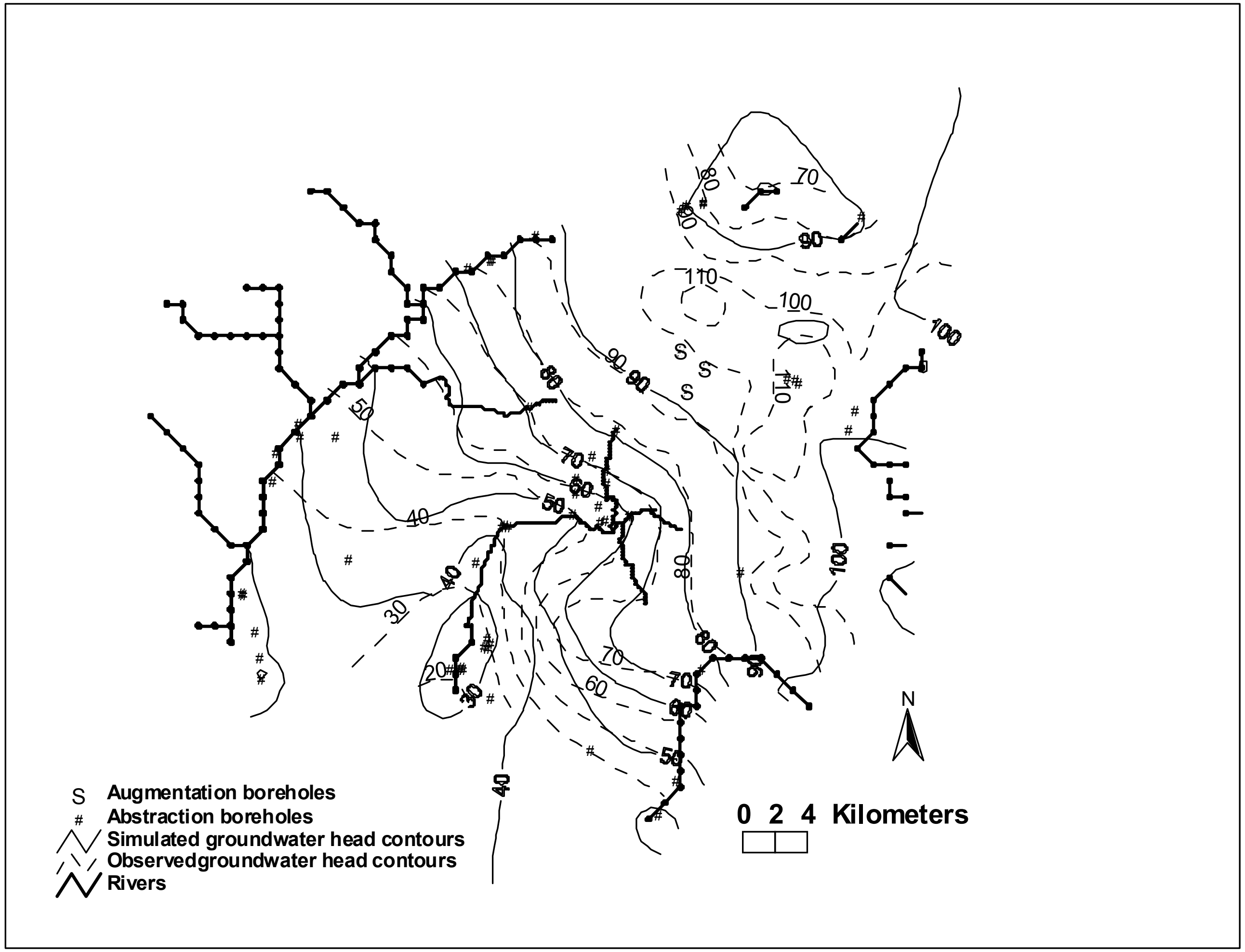


Figure 127 Observed and calculated groundwater head contours

The depletion rates calculated in Scenario 1 for the Rivers Candover, Alre, Cheriton and Itchen are shown in Figure 129. The depletion rates are lower for the Candover Stream in this scenario compared with those calculated in Model 11. The peak depletion rate for the Candover falls from 1752 m^3day^{-1} in Model 11 to 1524 m^3day^{-1} in this model. This is expected because as no water is added to the upstream end of the Candover, the simulated length of the river is shorter. This increases the effects of pumping on the other rivers, which, if they do not run dry, release more water. This is reflected by the increase of depletion rates for the Rivers Alre, Itchen and Cheriton. The depletion rates for these rivers increase from 2453, 199 and 123 m^3day^{-1} in Models 10 and 11 to 2886, 242 and 220 m^3day^{-1} in this run, respectively.

The depletion rates from the Candover Stream calculated in Scenario 2 vary abruptly as shown in Figure 130. Recall that in the second run of this scenario, in which the augmentation boreholes pump, the abstracted water is discharged into the Candover. This curve, showing the variation of depletion rate over time has three distinct parts defined by three peaks and two troughs highlighted by the letters (a) to (e) (Figure 130). The features of this curve are analysed next.

Figure 131a shows a 'snapshot' of the river-bed elevations, the groundwater head values and the leakage flows from the upper ten nodes of the Candover Stream at the time when the first peak (a) shown in Figure 130 occurs. This figure shows that a total quantity of 5939 m^3day^{-1} is lost through the first four nodes of this river. However, the augmented water causes the groundwater heads to recover and consequently the depletion rates to decrease.

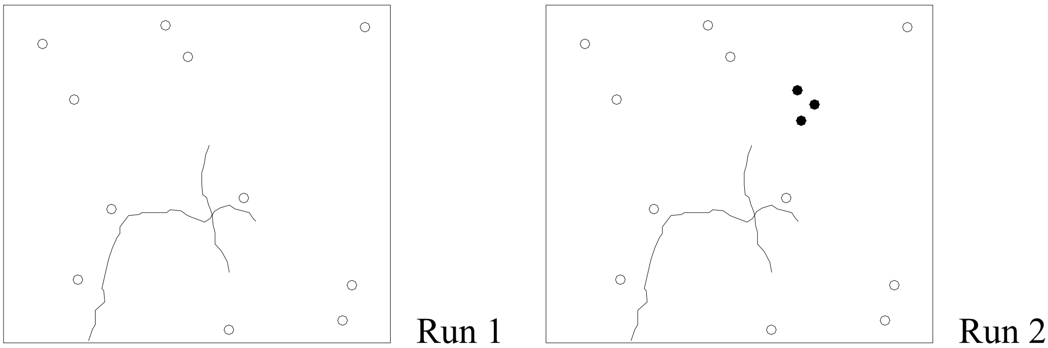
Another 'snapshot', taken at some time before the occurrence of the first trough (b) in Figure 130, is shown in Figure 131b. This figure shows that the groundwater head has recovered to an extent that the leakage out of the river is occurring through the first three nodes only and that the depletion rates from these nodes is equal to 3930 m^3day^{-1} in this case.

Depletion rates increase again when pumping effects cause the groundwater heads to significantly drop directly beneath the river. A third 'snapshot', taken at the time when the second peak (c) in Figure 130 occurs, is shown in Figure 131c. This 'snapshot' shows that the water table has dropped causing more river leakage at the first three nodes. The total depletion from these nodes in this case is equal to 4150 m^3day^{-1}.

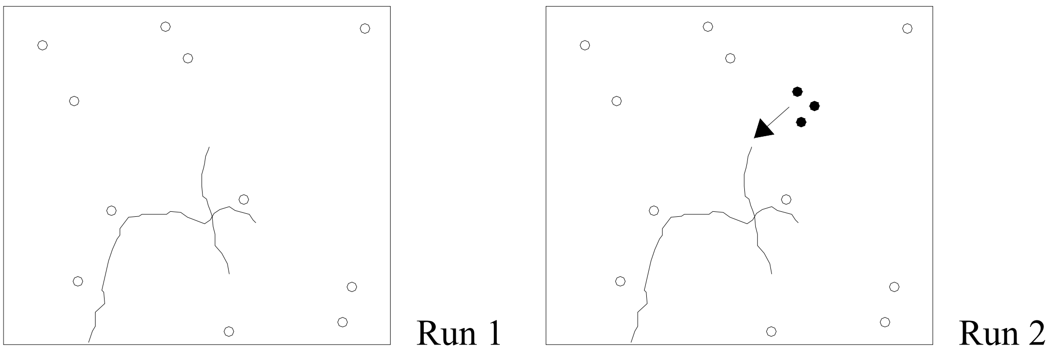
The sudden drop in the depletion rate curve, from the second peak (c) to the second trough (d), is caused by the cessation of pumping and consequently the end of water addition at the upstream end of the Candover. As a consequence of this, the upstream part of the Candover Stream dries up again and no water is leaked from the first four river nodes. This condition is illustrated in the fourth 'snapshot' shown in Figure 131d.

Finally, the depletion rates from the river increases again to compensate the water lost at the upstream end of the river. This depletion rate reaches a maximum, the third peak (e), which is equivalent to the single peaks observed in the depletion rates plots for the previous simulations. This peak occurs just before the groundwater heads beneath the river start to recover.

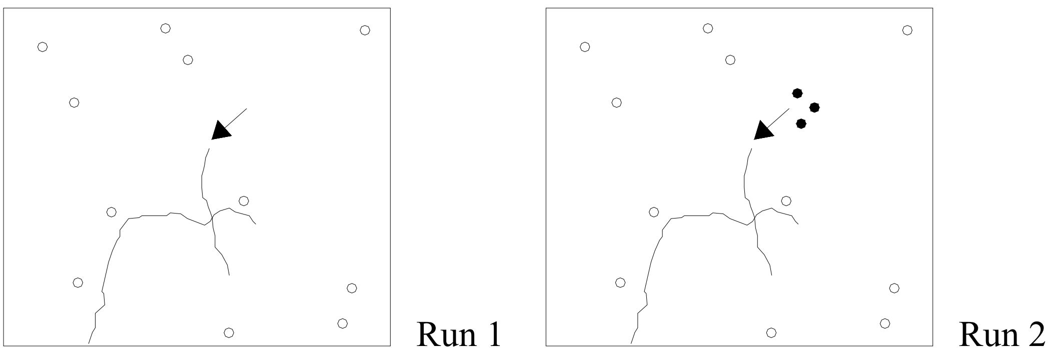
In the third scenario water is added at the top of the Candover Stream in both Runs 1 and 2. The depletion rate curve for the Candover Stream is shown in Figure 132. The distinct drop in the depletion rate between (a) and (b) corresponds to the augmentation boreholes being switched off. The first point of the curve, therefore, relates to when water is added at the top of the river and all the river nodes leak water. The second point (b) corresponds to when the discharge of augmentation water to the river ceases in both runs 1 and 2 and the upstream section of the river goes dry.



a) Scenario 1: No water added at the top of the Candover Stream



b) Scenario 2: Water added at the top of the Candover Stream in Run 2



c) Scenario 3: Water added at the top of the Candover Stream in Run 1 and Run 2

• Augmentation boreholes ○ Other groundwater abstractions

Figure 128 Three scenarios simulated using Model 12

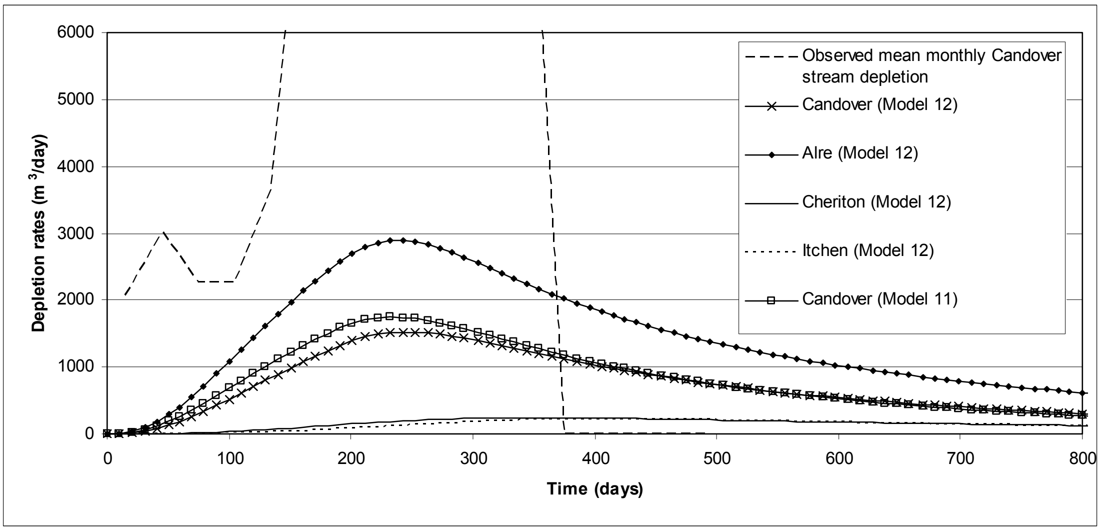


Figure 129 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover, Alre, Cheriton and Itchen (Model 12, Scenario 1)

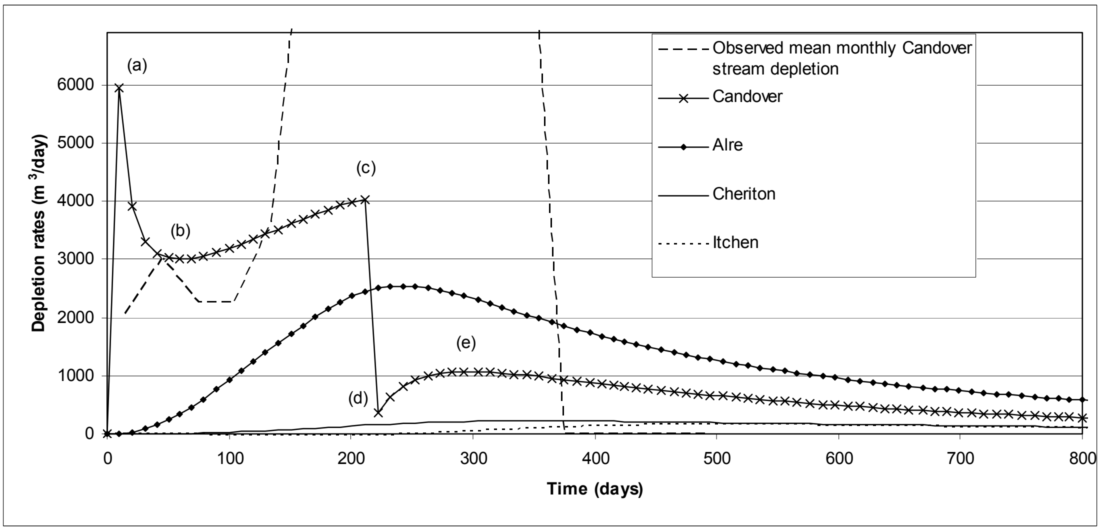


Figure 130 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover, Alre, Cheriton and Itchen (Model 12, Scenario 2)

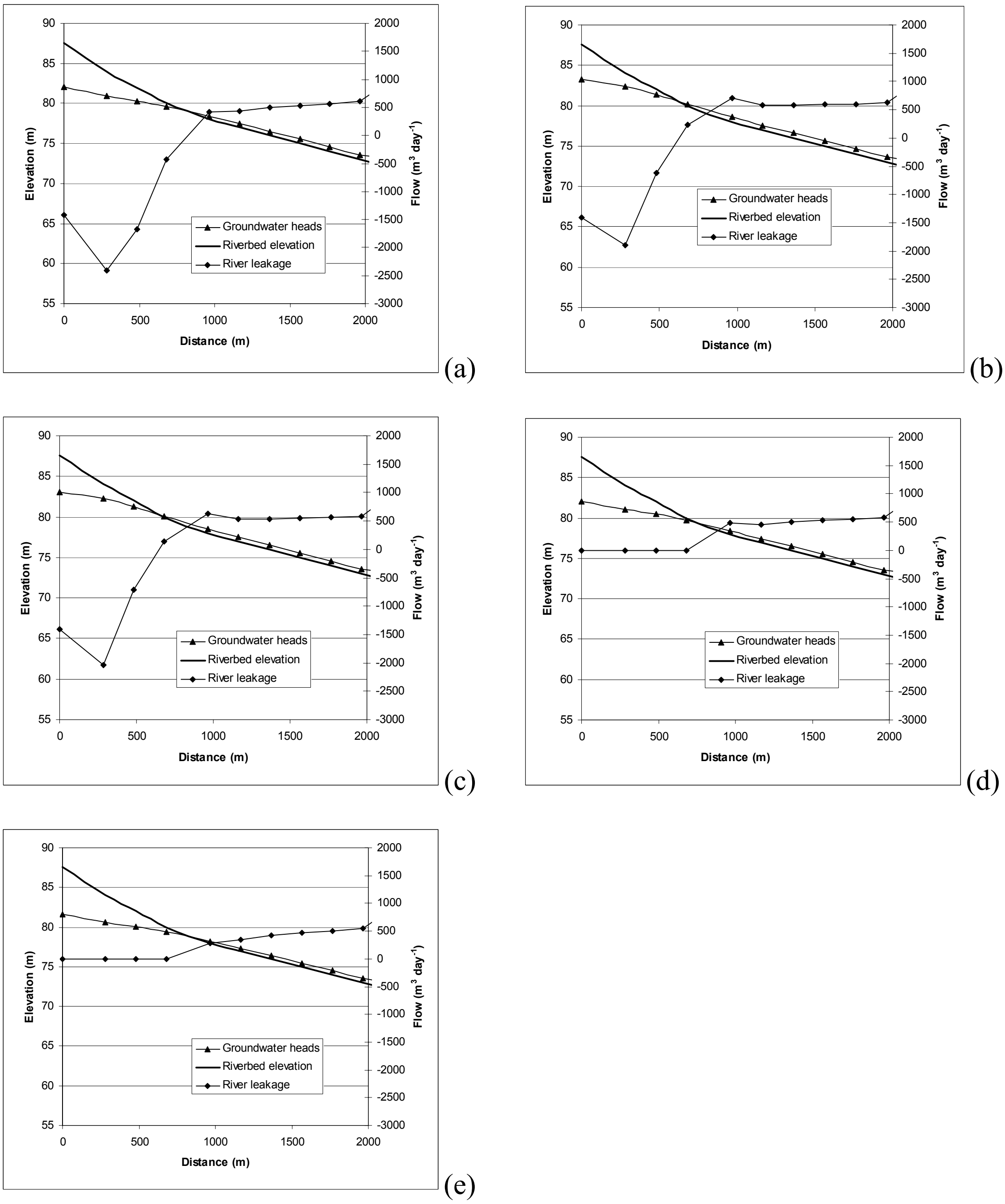


Figure 131 Conditions at the upstream section of the Candover Stream at specified times. (a) When the first peak in Figure 130 occurs. (b) When the first trough in Figure 130 occurs. (c) When the second peak in Figure 130 occurs. (d) When the second trough in Figure 130 occurs. (e) When the third peak in Figure 130 occurs.

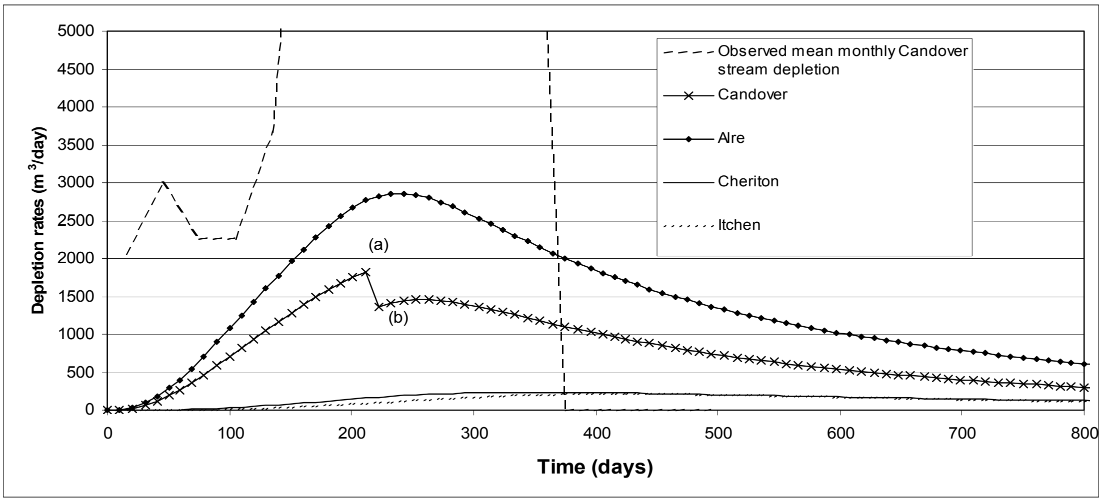


Figure 132 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover, Alre, Cheriton and Itchen (Model 12, Scenario 3)

The three scenarios simulated using this model, Model 12, produce different simulated depletion rates. Scenario 2 most closely approximates the operation of the augmentation scheme and produces the most complex temporal distribution of river impacts. This is because the discharge of the augmentation water into the Candover changes the length of the river. Whilst Scenario 2 is probably the best representation of the field situation, it may not be the best simulation to use when undertaking an impact assessment. This is because it is difficult to deconvolute the various processes operating and consequently, it is likely to be the most difficult to present to non-hydrogeologists. Because, there is little observed data for such schemes, such a complicated approach may not be defensible. Rather, a simulation in which depletion rates are determined by fixing the length of the river to its ‘average’ length may be more justifiable.

5.4.13 Investigative model 13: ZOOM_IGARF model of the Itchen catchment incorporating a representation of fractures

This model is the same as Model 12 except a high transmissivity zone is incorporated between the augmentation boreholes and central section of the River Candover as shown in Figure 133. The transmissivity in this zone, which is 1 km wide, is one hundred times greater that that of the highest transmissivity in Model 12 and is approximately 500,000 $m^2 day^{-1}$. This high transmissivity zone is incorporated in the model to represent the occurrence of fractures which may provide a very good connection between the augmentation boreholes and the River Candover. However, it must be stated this high transmissivity zone is only incorporated in the model as an 'experiment' to examine the possible impact on the Candover.

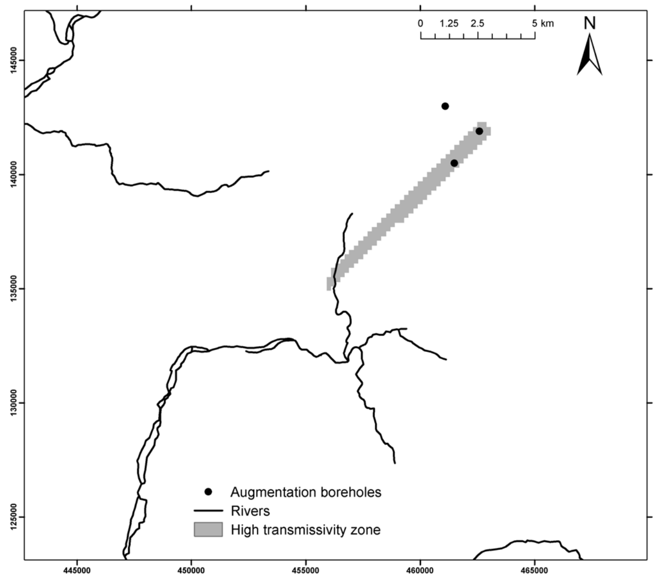


Figure 133 High transmissivity zone connecting augmentation boreholes and River Candover

Model Structure

Model 13 is the same as Model 12 except for the inclusion of the high transmissivity zone. As in Model 12 the aquifer is considered to be unconfined. The specific yield of the aquifer nodes is set to 2.5 % except in the river valleys where it is 10 %. Again, the hydraulic conductivity values change spatially according to the distribution of transmissivity specified in the Itchen model developed by Entec (2002).

Results

The depletion rates calculated using Model 13 for the Rivers Candover, Alre, Cheriton and Itchen are shown in Figure 134. These are comparable with the Scenario 1 run of Model 12, in which the water abstracted by the augmentation boreholes is not discharged to the River Candover. In Model 13 the depletion rates are significantly higher for the Candover Stream compared to those calculated in Model 12. The peak depletion rate for the Candover increases from 1524 $m^3 day^{-1}$ in

Model 12 to 11560 m^3day^{-1} in this model. This is obviously caused by the incorporation of the high transmissivity zone in the model, resulting in the augmentation boreholes sourcing a significantly higher proportion of their water from the River Candover. The effect on the Rivers Alre, Itchen and Cheriton is more variable, with the peak depletion rates for these rivers changing from 2886, 242 and 220 m^3day^{-1} in Model 12 to 2780, 160 and 715 m^3day^{-1} in Model 13, respectively. This shows that more water is sourced from the upper catchments of the Alre and Cheriton than from the lower Itchen catchment.

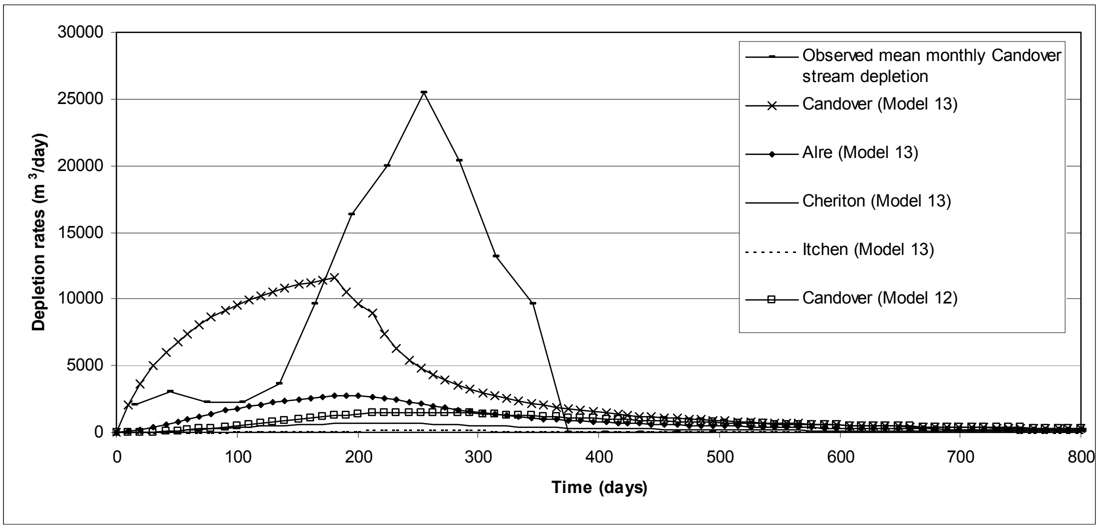


Figure 134 Comparison between the observed and simulated depletion rates calculated using ZOOMQ3D for the Candover, Alre, Cheriton and Itchen (Model 13)

The incorporation of the high transmissivity connection between the augmentation boreholes and the River Candover has provided a means by which a model can be developed to simulate higher peak depletion rates. This model, Model 13, simulates a peak depletion rate (of 11.5 Ml day^{-1}) for the River Candover, which compares more favourably to that calculated using the observed river flow data (25.5 Ml day^{-1}). However, the model does not reproduce the delay in the onset of the impact on the river after the start of abstraction at the augmentation boreholes. Whilst this model indicates that there may be a good hydraulic connection between the augmentation boreholes and the River Candover, the representation of the aquifer within the numerical model is inadequate.

5.4.14 Steady-state: ZOOM_IGARF model of the Itchen catchment

In this example Model 10 is used to calculate the depletion rates from the rivers when the augmentation boreholes have been pumped a period of time that is long enough to reach steady-state conditions. Model 10 incorporates the parameters applied in the Entec (2002) model of the Itchen catchment but represents the aquifer as a single horizontal layer with horizontal rivers. Because of the continuous abstraction the depletion rates calculated at the end of the simulation period represent the maximum amount of water that can be released from the rivers. Consequently, the depletion rates are greater than those calculated in the previous simulations because the boreholes pump continuously rather than for only six months. Table 30 shows the abstraction rates applied at the three abstraction boreholes.

Table 31 shows the depletion rates for the rivers at the end of the steady-state simulation. The depletion rates are significantly larger than those calculated in Model 10. The maximum depletion rate for the Candover Stream in this simulation, for example, is equal to 4083 m^3day^{-1}, which is approximately 15 % of the quantity of water abstracted from the augmentation boreholes, and is more than double the maximum value calculated in Model 10 (1752 m^3day^{-1}). This increase in depletion rates, compared with Model 10, is similar for all the rivers.

Table 30 Abstraction rates applied at the augmentation boreholes in the steady-state simulation

Abstraction well	Pumping rate (m^3day^{-1})
Axford	3880
Bradley	11700
Wield	11700

Table 31 River depletion rates at the end of the steady-state simulation

River	Depletion rate (m^3day^{-1})	% of abs	River	Depletion rate (m^3day^{-1})	% of abs
Candover	4083	15.0	Lower Test	13	~0.0
Itchen	414	1.5	Meon	961	3.5
Alre	5685	21.0	White Water	831	3.0
Cheriton	605	2.2	Loddon	2262	8.3
Upper Test	1763	6.5	Oakshott Stream	481	1.8
Dever	2447	8.9	River Rother	475	1.7
Bourne Rivulet	14	~0.0	Rother tributary	189	0.7
Wey	5621	20.6	Oakhanger Stream	728	2.7
			Other minor streams	709	2.6

5.5 Summary and discussion of the Candover modelling

5.5.1 Summary of results

The aim of the investigative modelling of the Candover catchment has been to examine how much depletion rates vary when calculated using numerical groundwater flow models containing differing degrees of hydrogeological complexity. This has been achieved by using ZOOMQ3D to examine the impact of the three abstraction boreholes on the flow in the River Candover. The first model was relatively simple and based on the IGARF1v4 analytical model spreadsheet tool that the Environment Agency currently uses. A ZOOMQ3D numerical model was then constructed and made more complex in a series of steps until a more sophisticated numerical model was developed. Thirteen models were constructed in total and all but Model 1 were built using ZOOMQ3D.

Models 1 and 2

The first model was based on the simplest conceptual model. The aquifer is assumed to be homogeneous with a constant transmissivity, the three abstraction boreholes are represented by one pumping well and the river by an infinite straight line.. This conceptual model was built first using IGARF (Model 1, Section 5.4.1) where the depletion was calculated for a 6 km section of the infinite river. In Model 2 (Section 5.4.2) the river is represented by a long (but not infinite) river stretching from the northern to the southern boundary (60 km). Again the depletion was calculated for a 6 km section of this long river. Model 2 reproduces the results of Model 1. The volume depleted from the Candover Stream over the three year simulation period was 684 Ml, which is 13.3% (column one, Table 32) of the total volume abstracted (5143 Ml).

Model 3

In Model 3 the Candover was shortened to 6 km to approximate the real length of the stream. The effect of reducing the stream length leads to an increase in the depletion (to almost 36% of the abstraction). This is because in Models 1 and 2 the abstraction can access water from the sections of river beyond the 6 km reach that is representing the Candover. In Model 3 these sections no longer exist.

Model 4

In Model 4 the three augmentation boreholes are represented in the numerical model as three separate boreholes, which produces hardly any change in the volume of water deleted from the Candover during the three-year simulation period.

Model 5

Model 5 incorporates a realistic representation of the geometry and length of the Candover Stream. The grid is refined to improve the representation of the Candover and the locations of the augmentation boreholes. These changes do not result in significantly different results (depletion volume = 38.7%) compared with those in Models 3 and 4.

Models 6 and 7

In Model 6 the Rivers Alre, Cheriton and Itchen are added to the model. In Model 7 all the other rivers which are outside of the Itchen catchment but within the model area and in hydraulic continuity with the Chalk are represented. As expected the incorporation of these additional rivers provides additional sources of water for the abstraction boreholes and leads to a decrease in the modelled depletion from the Candover Stream. The volume depleted from the Candover falls from 38.7 % of the abstraction in Model 5 to 28.0 % in Model 6 and 22.5 % in Model 7.

The second column in Table 32 shows the volume depleted from all the rivers, not just from the Candover. In Models 2, to 5 the Candover is the only river included so these depletion volumes are identical to those in the first column. However, with the addition of the other rivers, the volume of water depleted rises to 45.4 % of the abstraction in Model 6 and 92.9 % in Model 7. This increase is because the abstraction boreholes obtain water preferentially from the additional rivers rather than from aquifer storage.

Model 8

In Model 8 and those developed subsequently, some parameters values are based on those specified in the regional groundwater model of the Itchen catchment developed by Entec (2002). In Model 8 the conductance of the bed of the rivers is set to the values specified in the Entec model. The reduction of the river conductance values in this model decreases the volume depleted from the Candover to 18.3% and the volume depleted from all the rivers to 89.7% of the total abstraction. Models 9 and 10

The spatial distribution of the transmissivity and storage coefficient proposed by Entec (2002) are incorporated in Model 9 and Model 10, respectively. The transmissivity distribution is generally typical for that of an unconfined Chalk aquifer in which higher values are specified in the valleys and lower values in the interfluves. However, a large high transmissivity zone is defined to the south west of the augmentation (abstraction) boreholes in the Entec model to obtain adequate simulated flows in the River Alre. This high transmissivity zone caused the modelled abstraction boreholes to preferentially source water from the Alre instead of from the Candover. Consequently, the total volume of water depleted from the Candover fell to 14.7 % of the total abstraction and the total volume depleted from all rivers increased to 94.8 %. The inclusion of zones of high storage coefficient around some of the rivers in Model 10 decreased the depletions slightly.

Model 11 is the same as Model 10 except the transmissivity varies with saturated thickness (unconfined). The results from Model 11 differed very little from those of Model 10 because the saturated thickness of the aquifer does not change significantly during the simulation.

Model 12

In Model 12 the top and the base elevations of the aquifer are based on the observed water table elevation and the river elevations are determined from a DTM. Furthermore, the other groundwater abstractions in the region are included in the model e.g. those used for public water supply. It is unlikely that a hydrogeologist would build a more complex model than Model 12 within the time-constraints of a licence application. Consequently, such a model would be considered the ‘best’ tool available to determine the impact of abstraction on river flows unless a full regional model was available. The estimate of depletion from the Candover for Model 12 is 13.3 % of the total volume abstracted.

Model 13

In Model 13 a 1 km-wide high transmissivity zone was added to Model 12 along a line between the augmentation boreholes and the central section of the River Candover. The transmissivity of this zone was 100 times that of the highest transmissivity in Model 12. It represents a possible conceptual model where fractures are providing a very good hydraulic connection between the wells and the river. There is no geological evidence for specific fractures linking the wells and the river and so Model 13 is an ‘experiment’ (see Section 5.4.13). This good hydraulic connection between the boreholes and the river in Model 13 results in significantly more water being drawn from the Candover (34.5% of the volume abstracted) but this is still much less than the estimates of observed depletion (75%, Table 21). The peak depletion rate also increases dramatically to 11500 m^3day^{-1} (red bar in Figure 135) but this is also much less than the observed peak of over 25000 m^3day^{-1} (Figure 134). Furthermore Model 13 does not produce the observed delay in the onset of the impact on the Candover Stream (Figure 134).

5.5.2 Discussion of results

In Figure 135 the red bars show the simulated maximum depletion rate for the Candover Stream and the blue bars plot the data from column one in Table 32 (the simulated volume of water drawn from the Candover as a percentage of the abstraction). This plot provides a means of rapidly comparing the results of the thirteen models that were developed for the Candover catchment. Model 1 is the IGARF model and models 2 to 13 are the ZOOM numerical models.

The graph shows that the penultimate ‘complex’ model (Model 12) produces results that are similar to those produced by the IGARF spreadsheet (Model 1). However, this is a coincidence and should not be considered to be typical.

The differences between the simulated depletion rates indicate which features of this river/aquifer system are important to represent accurately. The two largest changes to the modelled depletion of flows on the Candover were caused by more realistically representing the rivers which act as sources of water for the abstraction boreholes. Using the correct length of the Candover Stream produced the largest change in the modelled river flow depletion, an increase from 13.3% in Model 2 to 35.9% in Model 3. The inclusion of other river catchments produced the next largest change, a decrease from 38.7% in Model 5 to 28% in Model 6.

One of the simplifying assumptions of the IGARF spreadsheet is that a single infinitely long river is the ultimate source of water for the abstractions whereas it is in fact a network of finite rivers. Ignoring these two factors, the correct river length and the presence of more than one river, produces errors in different directions. So to some extent they cancel each other out and IGARF may be a good first approximation of the possible range of flow depletion in a river.

However, these results show that when we want to add more complexity to provide more accurate estimates of depletion, we will need to represent the correct length and geometry of all the main rivers which are hydraulically connected to the aquifer. And the use of a numerical model which represents these features, even one as simple as Model 7, is a significant advantage.

Table 32 Total depletion as percentage of abstraction over three years

Model	Description	% (Depletion volume from the Candover Stream / Abstraction volume) over three-year simulation period	% (Depletion volume from all rivers / Abstraction volume) over three-year simulation period	Total volume abstracted over first seven months of three-year simulation period (Ml)
2	ZOOM (Theis)	13.3	13.3	5132.64
3	6 km river	35.9	35.9	5132.64
4	3 boreholes	35.6	35.6	5132.64
5	Better defined river	38.7	38.7	5132.64
6	All Itchen catchment	28.0	45.4	5132.64
7	All river catchments	22.5	92.9	5132.64
8	River conductances	18.3	89.7	5132.64
9	T distribution	14.7	94.8	5132.64
10	S distribution	14.1	86.6	5132.64
11	Unconfined	14.1	86.6	5132.64
12	Correct river elevations	13.3	99.5	5132.64
13	High T line	34.5	92.6	5132.64

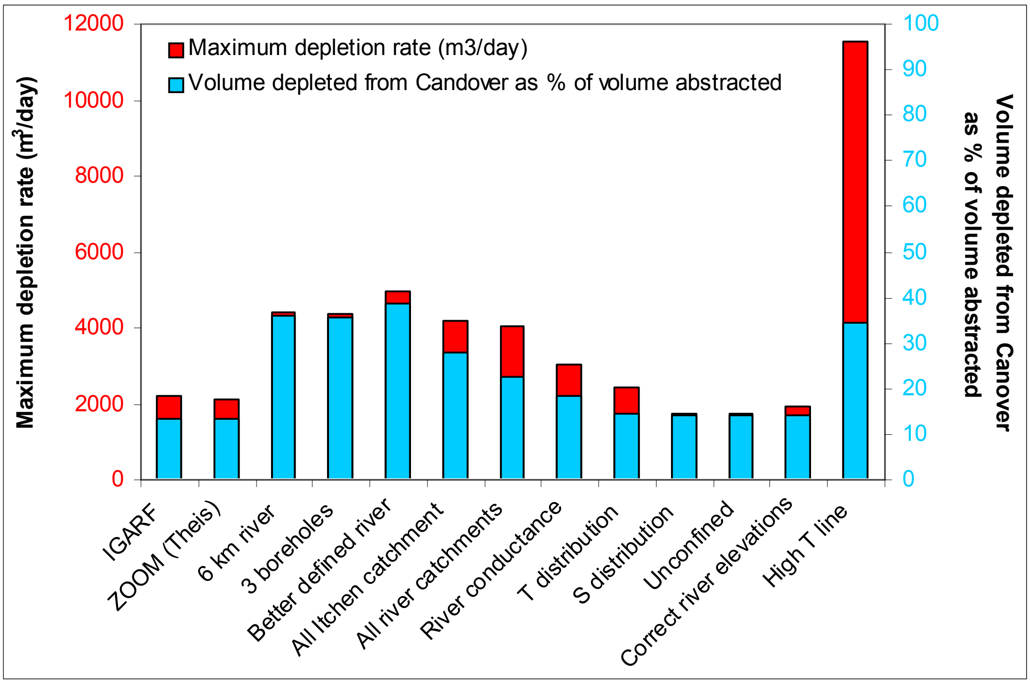


Figure 135 Comparison between simulated depletion rates calculated for the River Candover using the IGARF spreadsheet and numerical models 2 to 13 for the three-year period after the start of abstraction

In this example the accurate positioning of the three augmentation boreholes resulted in only a small change to the simulated results (Model 4). This was because the three augmentation boreholes are relatively close to each other. In other situations the accurate positioning of the abstraction boreholes may be more important. The Candover scheme involved the development of three new boreholes but many licence applications are for individual supplies, which can be adequately represented in the IGARF tool.

In this example changes to the model hydraulic parameters had less of an effect on the simulated depletion rates. For example the inclusion of the distribution of transmissivity based on the Entec (2002) model caused a smaller change to the simulated results (18.3% in Model 8 to 14.7% in Model 9). Changing to simulate unconfined conditions had a minimal impact on the results (Model 11).

These results show that the largest changes to the predictions of river flow depletion by groundwater abstraction were caused by changing the structure of the numerical model (river geometry), and not merely by changing model parameter values such as river conductance, transmissivity or storage. However, this lesser sensitivity to changes in hydraulic parameters may not be generally applicable. This Chalk aquifer has a high transmissivity and in other lower transmissivity aquifers, it may be more important to represent the spatial variation of hydraulic properties.

5.5.3 Comparison of observed and simulated flow depletion in the Candover Stream

In Section 5.2.4, the field data from the Candover augmentation scheme was used to estimate the depletion of flow in the Candover Stream as a result of abstracting groundwater in 1976. Table 21 shows that there was 128 Ml less water in the river, which is 75% of the groundwater pumped. The remaining 25% is assumed to come from peripheral streams. As described in Section 5.2.4, this ‘observed’ depletion is not measured directly but is derived from field data using several assumptions which produce a large degree of uncertainty in the estimate. Hence, during this discussion, we will refer to this figure of 75% (of groundwater abstracted) as the ‘observed’ depletion from the Candover.

We might expect the modelled river flow depletion to get closer to the ‘observed’ depletion as the model becomes more complex. However, some of the early models (Models 3, 4 and 5) predict higher depletions (around 35% of abstraction) than most of the later models (Table 32 and Figure 135). The most complex numerical model of the Itchen catchment developed here is Model 13, which predicts a depletion of about 35% of the abstraction. But Model 13 was considered an ‘experiment’ to test the effect of possible, but unsubstantiated, good connection between the boreholes and the stream. The most complex *plausible* model is Model 12, which predicts a depletion from the Candover of only about 13% of the abstraction. The rest of this section considers what we can learn from this.

We propose the following three hypotheses to explain this disparity between the simulated depletion rates and those derived from the observed data:

1. The numerical model does not include some crucial mechanism(s) that are governing the flow behaviour of the system. In other words the conceptual model is inadequate for the predictive purpose of the modelling (river flow depletion).

2. The analysis of the observed data is flawed so that the estimate of 'observed' depletion from the Candover (75% of abstraction) is wrong.

3. The parameter values used in the models are seriously in error. For example, the river conductances in the Candover could be higher and those in the peripheral rivers lower than in the Entec (2002) model.

The authors have not been able to identify other studies comparing the results of numerical models with depletion rates estimated using observed data. Consequently, the problems experienced in this investigation in trying to produce a model that can reproduce the 'observed' depletion rates cannot be assumed to be typical. A discussion of the issues raised by the above three hypotheses follows.

Hypothesis 1

Several mechanisms can be envisaged which have not been included in the current modelling.

- The field response may have been significantly affected by the fractured nature of the Chalk aquifer. The incorporation of a high transmissivity zone to simulate a good hydraulic connection between the augmentation boreholes and the Candover has been represented using Model 13. This has shown that a model can be produced which better approximates the high depletion rates calculated using the observed data, however, the model still does not produce a good match to the observed depletion rates.

- The Candover test took place during the extreme drought year of 1976. The unusually dry low water table may have dewatered the more highly permeable layers in the zone of normal water-table fluctuation.

- The unusually low groundwater levels may mean that the aquifer became disconnected from the river and only reconnected later in the year when the groundwater levels rose with the onset of winter recharge. However, if the augmentation boreholes took water from aquifer storage and not from the river while they were disconnected, lower depletion rates would expected.

Incorporating such mechanisms in a model is difficult and time-consuming. It is beyond the scope of our aim here, which is to build a *simple* model for estimating river flow depletion. More work would be required to find out whether including such mechanisms would improve the predicted depletion for the conditions in 1976. In addition, it is possible that under more usual climatic conditions these mechanisms may not be necessary and the Chalk could be adequately represented by the simple models we have developed here.

Hypothesis 2

There are some assumptions in the analysis of the observed data that could change the estimate of 'observed' depletion but it is difficult to imagine these changes being large. One limitation of this analysis is that not all of the peripheral catchments are considered. However, including additional sources of water (the rivers in peripheral catchments) would only reduce the 'observed' depletion from the Candover. In addition, the observed data suggest that there could be a very good hydraulic connection between the augmentation boreholes and the Candover Stream, in which case this omission would not be important.

Hypothesis 3

It is most unlikely that the modelled depletion rates could reproduce those calculated using the observed river flow data by merely adjusting the hydraulic parameters, without setting them to unrealistic values. However, further systematic sensitivity analyses, perhaps with a parameter optimisation package such as PEST (Doherty, 2005), could be carried out to confirm this.

Whilst the work undertaken to simulate the Itchen catchment has shown that some complex features may need to be incorporated in the numerical model if accurate predictions are to be made during the conditions of 1976, this finding does not mean that numerical modelling is superfluous. Rather it illustrates the need to compare more frequently the results of numerical models with observations. Using data and modelling together like this is a powerful means of investigating and testing hypotheses about how the real system is operating.

5.6 Lessons learnt in using ZOOM_IGARF to estimate the depletion in the Candover due to groundwater abstraction

This task involved the use of the analytical solutions of the IGARF spreadsheet and the numerical model ZOOMQ3D to calculate the depletion rates from the Candover Stream. It is believed that a similar amount of time and effort is required to learn to apply the Excel sheet that complements ZOOMQ3D (ZOOM_IGARF spreadsheet) as the IGARF spreadsheet.

While the use of the IGARF spreadsheet is limited to very simple conceptual models, the ZOOM_IGARF spreadsheet allows the construction of numerical models that can represent more complicated hydrogeological features, for example multiple rivers with the correct geometry. However, the application of the ZOOM_IGARF spreadsheet is also limited to a certain degree of conceptual model complexity. The models numbered 5-12 developed as part of the Candover modelling required the use of other applications in addition to the Excel spreadsheet. In such cases, the construction of the model can be relatively time consuming especially when working with rivers in the ArcView environment. The most complex model constructed as part of this work took approximately two days to build and run, though much of this time was spent extracting and processing data from the Entec (2002) model.

When the heterogeneity of the aquifer is included some of the model files (e.g. the .cod and .map files) must be edited outside the ZOOM_IGARF spreadsheet prior to running the model from within the spreadsheet.

Sometimes it is easier to modify input files without using the ZOOM_IGARF spreadsheet. Model 12, for example, includes sixty-two abstraction boreholes and involves three scenarios. The abstraction rates must be defined three times, one time for each scenario. It is more convenient in this case to edit the file "pumping.dat" outside the Excel sheet.

The amount of information the ZOOM_IGARF spreadsheet can hold is limited. This is because the Excel spreadsheets are limited to a certain number of columns and rows. This problem is encountered in Model 7 onward when all rivers in the model area are added. This problem can be solved by creating more than one spreadsheet for each model, however, this is not ideal.

6 CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The conclusions reached during the project are divided into three sections. In the first, the technical conclusions that have arisen out of the impact and River Candover modelling are summarised. The points that are raised in this section are aimed at helping hydrogeologists involved in assessing abstraction licenses undertake an impact assessment using a *numerical model*. The technical conclusions relate to the applicability of models in different aquifer systems with different degrees of complexity. It is important to understand the assumptions made in any modelling approach and the nature of groundwater flow in the aquifer when considering the results of an impact assessment undertaken using a groundwater model.

In the second sub-section more general considerations about the worth of modelling and the role of models when being used for impact assessment are discussed. Models are considered to be powerful tools for developing the understanding on which to base licensing decisions. However, they must always be 'fit for purpose', in other words good predictors. The question of whether regional groundwater models, which have been developed at significant cost, are fit for purpose is discussed. This involves a consideration of the original purpose of the regional model and of the accuracy with which it can be expected to reproduce local groundwater flow behaviour.

Finally conclusions are drawn about how the ZOOM_IGARF model could be used on an operational basis if it is adopted as a tool for groundwater abstraction impact assessment. These conclusions may need to be the subject of review, given the likely changing pressures on aquifers, for example in response to climate change.

6.1.1 Technical conclusions

Conclusions from the impact modelling

A number of simulations were performed and compared as part of the *impact modelling* exercise to assess how much the modelled impact of abstraction on river baseflow varies when different models are used. This assessment has been based on the quantification of the 'depletion rate'. The depletion rate is defined as the difference in the leakage rate along a section of a river, calculated between a model in which the abstraction borehole operates and one in which it does not. The following paragraphs summarise the findings of this impact modelling work. It is recommended that hydrogeologists involved in the application of models for the assessment of the impacts of abstraction of rivers should be familiar with these conclusions. If there is no regional model already available, it is likely that an Environment Agency hydrogeologist would construct only relatively simple models during the consideration of a borehole licence application. Nevertheless, it is of crucial importance to understand not only which hydrogeological features are important when applying models, but also how a numerical model represents these features.

How areally extensive should the model be?

When assessing the impact of abstraction it is important to include all of the rivers that could be affected by pumping. It is good practice to define the boundaries of the model using the physical extent of the aquifer if possible. It is not acceptable to select a stable groundwater divide between two catchments as a model boundary when assessing the impact of abstraction on river flows. This is because abstraction from the pumping well will cause a cone of depression to continue spreading, regardless of any groundwater divides, until it has stopped an equal amount of water leaving the aquifer. This will usually be in the form of reduced discharges (reduced spring flow, reduced baseflow, or reduced seepage) and is described in more detail in Section 2.4 of the Environment Agency's guidance on how to assess the hydrogeological impact of groundwater abstractions (Environment Agency, 2007 a).

Simulations were performed to investigate the differences in depletion rate that can be calculated by a model of a single catchment, and by one with two additional, identical catchments on either side. Differences in depletion rate of about 10% of the abstraction rate were produced for the river nearest to the abstraction borehole. These calculated errors are only indicative and will depend on the particular features of aquifer system and river catchments being modelled. It is obviously more important to include more rivers catchments in the model if the region of interest is small.

As a guide to how rapidly (but not how far) a cone of depression will spread radially outwards from an abstraction borehole, two equations are presented based on the Theis (1935) solution. These equations can be used to provide a very rough estimate of how quickly an abstraction borehole might affect the baseflow in a river. The Environment Agency's IGARF spreadsheet may also be used (Environment Agency, 2004).

The Theis solution cannot be used to estimate how far the impacts will spread and hence which rivers to include because it assumes that the aquifer is infinite and that there are no sources of water other than aquifer storage. The drawdown predicted by the Theis equation does not cease spreading until pumping stops. However, in the real river/aquifer system, the effect of groundwater abstraction (the drawdown) continues to spread until it prevents an amount of water equal to the abstraction rate leaving the aquifer (see Section 3.4.2).

Neglecting peripheral catchments

If for some reason a model has to be developed that contains only part of the river of interest, or only a sub-reach of such a river, then the following points should be considered. These relate to the effect that the specification of different boundary conditions has on the resulting modelled estimate of depletion rate:

- The depletion rates calculated using a model for a sub-area of a catchment are in error by the same amount regardless of whether no flow, specified flow or fixed head boundary conditions are used. However the sign of these errors is different.
- Depletion rates calculated using sub-catchment models in which only fixed head conditions are assigned around the boundary will be **underestimates** compared with those calculated using a model of the full catchment. This is

because the fixed heads around the boundary of the sub-model provide an infinite source of water to the abstraction borehole and so less water is taken from the river. The error in the depletion rate was about -10% of the pumping rate using the models in this work.

- Depletion rates calculated using sub-catchment models in which only no flow or constant specified flow conditions are assigned around the boundary, will be **overestimates** of those calculated in the full catchment model. The error in the depletion rate was about +10% of the pumping rate using the models in this work.
- If boundary conditions are difficult to define for a sub-area of a catchment, then it is likely that a better estimate of the depletion rate will be derived from the average of the rates calculated using two models: (i) the sub-catchment model in which the boundaries are defined as no-flow and (ii) the sub-catchment model in which the boundaries are defined as fixed heads. This average can reduce the effect of the poorly defined boundary conditions. The approach caused the errors in the depletion rate to be reduced to less than 1% of the abstraction when compared to the multiple catchment (i.e. full aquifer) model.

Application of recharge

The application of recharge to a model which is used to calculate *differences* in river flow, that is *depletion rates*, only affects the results when:

- transmissivity depends on groundwater head i.e. unconfined aquifers. But the effect on depletion may be small (see below *Unconfined aquifers*);
- the introduction of recharge affects the timing when parts of the river become perched or sections of the channel become dry;
- the introduction of recharge causes another flow mechanism to exhibit non-linear behaviour.

In a linear aquifer model (see Appendix D Properties of linear equations), i.e. an aquifer in which transmissivity does not depend on groundwater head and in which the operation of the river-aquifer interaction mechanism does not change in time, spatial and temporal variations in recharge have no effect on the calculated river flow depletion rate. Obviously, if recharge to the groundwater system increases, there will be more baseflow in the river, but the *change* in river flow (the depletion) as a result of groundwater abstraction is not affected by this extra recharge.

Ephemeral rivers

If the length of the river being modelled changes during a simulation due to sections running dry, then the impact that an abstraction borehole has on its discharge will change. A change in the length of the river results in a breakdown of the linear behaviour of the aquifer. We must represent the changing length of the river if depletion rates are to be estimated accurately. Consequently, care must be taken, for example, when assessing the impact of abstraction on a Chalk winterbourne. As a *very* rough guide the simulations in this work indicated that the impact an abstraction borehole has on a river will halve if the length of the river halves.

River elevation

The elevation of a river does not *directly* affect the impact that an abstraction borehole has on its flow. The calculated depletion rate will be the same for rivers at different elevations, if all other model features are identical, unless:

- the different elevations cause sections of the river to become perched at different times;
- the different elevations cause sections of the river to dry out at different times;
- the saturated aquifer thickness and thus transmissivity is different beneath the rivers due to their different elevations.

Unconfined aquifers

The governing equation describing the flow in an unconfined aquifer is a non-linear equation because transmissivity depends on groundwater head. Consequently, the depletion rate calculated using a numerical model of an unconfined aquifer depends on the elevation of the water table. In the models used in this study when the saturated aquifer thickness was increased by 50% simulated depletion rates changed by less than 2%, however, this will depend on the hydraulic conductivity of the aquifer and therefore, cannot be regarded as a general rule. These figures were determined using models with relatively high transmissivities e.g. >400 $m^2 day^{-1}$.

The hydrogeologist should investigate the change in depletion for the anticipated change in groundwater level for their system. Running the IGARF spreadsheet or the ZOOM_IGARF numerical model with two transmissivities, one calculated using a typical saturated thickness and another with that expected after pumping has depressed groundwater levels, will provide an indication of how large the error might be.

When the change in water table elevation and the resulting change in transmissivity produce only a small change in river flow depletion, we can ignore recharge, river elevations and rates of abstraction from other boreholes. But if the changes are large, the system must be represented more accurately. That is, the initial groundwater levels, river elevations and rates of abstraction from other boreholes must all be included. In short, the numerical model must be a more realistic representation of the aquifer system. A number of different simulations were run in which the profile of the vertical variation of horizontal hydraulic conductivity varied significantly. The comparisons between these simulations showed that, when expressed as a percentage, the maximum difference between the calculated depletion rates was approximately 7% of the pumping rate. Whilst this is significant, the simulations showed that the accurate representation of the VKD profile is not as important as, for example, the correct definition of model boundary conditions or the inclusion of all of the impacted river reaches in the model.

Conclusions from the modelling of the Candover augmentation scheme

The numerical modelling of the Candover river flow augmentation scheme has highlighted the difficulties associated with modelling the impacts of groundwater abstraction. Whilst these difficulties need to be made clear to those who will use such tools to assess abstraction licences, their occurrence does *not* negate the usefulness of models. Developing even simple models of aquifers nearly always improves our understanding of the system. And once a model has been developed it can be used to test ideas about how the aquifer behaves.

In total thirteen models of the Candover aquifer system were developed using the ZOOM_IGARF tool, which incorporated different levels of complexity. All of these models produced results for the impact of abstraction on river flow that differed significantly from those calculated using the observed river flow data for the Candover Stream. Even the most complex of these models (Model 12), incorporating parameter values derived from a regional model of the Itchen catchment developed by Entec (2002) produced results that were significant different from the field data.

A probable reason for the inadequacy of the numerical models is that they did not incorporate a sufficiently detailed representation of the flow in the Chalk aquifer, for example the fractured nature of the aquifer was not adequately described. An attempt was made to represent fracturing in the Chalk and the possibly very good hydraulic connection between the augmentation boreholes and the Candover in Model 13. Whilst this improved the magnitude of the Candover depletion rates, these remained too low when compared to those calculated using the observed data. Furthermore, none of the models simulated the delay in the onset of the impact on the Candover after the start of abstraction at the augmentation boreholes.

There is also considerable uncertainty associated with the estimation of the ‘observed’ depletion because it is not measured but derived indirectly from the field data.

The flow in the Candover Stream is estimated to be depleted by 75% of the total abstraction rate from the pumping wells. The most complex plausible numerical model (Model 12) predicts that the flow in the Candover Stream is depleted by about 15% of the abstraction rate (Table 32). At this stage we consider that the reasons for this large discrepancy are that:

- the model did not include some crucial mechanism that is governing the flow behaviour of the system, perhaps fractures providing a good hydraulic connection between the pumping wells and the River Candover or processes related to the unusually low water levels during the drought of 1976;
- the estimate of 75% of the pumping being supplied by depletion from the Candover Stream is an incorrect analysis of the observed data;
- the parameter values used in the models are seriously in error.

The first of these reasons is the most likely. The second two reasons are likely to introduce uncertainty into the calculation of the observed and modelled depletion rates but not produce such significant differences between the two.

This is the first study of which the authors are aware which compares simulated and observed river flow depletion rates. Because this investigation has been based on data collected during an extreme drought period, more comparison studies are required to assess the general applicability of models to more usual aquifer conditions.

Given the possible limitations of a numerical model developed as part of a process of assessing an abstraction licence, a critical assessment of the validity of the results should always be undertaken. This requires an assessment of the adequacy of a numerical model. The development of an accurate numerical model of the Candover augmentation scheme is a difficult task because of the complexity of the Chalk aquifer and the conditions in which the pumping test took place, i.e. during the drought of 1976. However, it may be that for other abstraction licence applications the aquifer system is less complex. For example, in a more homogeneous aquifer in which the abstraction borehole is at a considerable distance from any river, the use of a model that represents the aquifer as a continuous porous medium may provide reasonably accurate results.

Even though the numerical models of the Itchen catchment have produced different depletion rates from those derived using the observed data, the development of a suite of numerical models of a system can provide a better estimate of the range of possible impacts. The ZOOM_IGARF tool can be used to develop and simulate a number of different models in a relatively short period time (i.e. one day) and therefore to test ideas about how an aquifer may behave.

If a hydrogeologist wants to assess the impact of a proposed groundwater abstraction on river flows, the ZOOM_IGARF could be used as follows:

- Build an initial model. This should contain all the rivers that could be affected by the pumping but can otherwise be simple, i.e. homogenous, constant transmissivity, no recharge. Groundwater divides should not be used to define model boundaries. Use this initial model to calculate the impact on the river.

- Make a number of modifications to this model to incorporate a more realistic representation of the aquifer. For example using hydrogeological judgement adjust the transmissivity and storage of the aquifer and the river-bed conductance. The following features could be modified but this would require that the current version of ZOOM_IGARF is not used to run the model but that the model is run from the command line:

    - Represent the dependence of transmissivity on hydraulic head. This will require the inclusion of a realistic initial groundwater head profile, recharge and possibly other abstraction wells.

    - The saturated aquifer thickness.

    - The inclusion of the vertical variation of hydraulic conductivity with depth.

- Compare the predicted depletion rates with the Q95 flow of the rivers impacted and examine if this is significant. The Q95 for the Candover at

Borough Bridge is 23.3 Ml day^{-1}, which is approximately 97% of the pumping rate from the augmentation boreholes of 23.9 Ml day^{-1}.

- Qualitatively assess the uncertainty in the model by considering if it ignores any possible important features of the conceptual model.

- If the simulated depletion rates are significant compared to the Q95 flows then assess if any further hydrogeological investigations are required e.g. examine pumping test and river flow data for the catchment, conduct new long-term pumping tests or additional simulations using an Environment Agency regional groundwater model.

6.1.2 Role of models

The simulation of the River Candover augmentation test has enabled the ZOOM_IGARF spreadsheet, developed as part of this work, to be tested. Whilst this was a valuable exercise, the primary purpose of the work focusing on the River Candover was to assess the applicability of models of different complexity. Considering the results of the simulation of Candover scheme, it could be asked whether models can provide any useful information on the impact of abstraction on river flows? If it is decided that a model should be developed during a river flow impact assessment study, the type of model to be constructed will also have to be determined.

The Candover test has shown that the impact of abstraction on a river may be complex and depends on the heterogeneity of the aquifer, particularly in a fractured medium such as Chalk. A current problem is that it is not known whether the response seen during the operation of the Candover scheme is typical (ignoring the uncertainties associated with the estimation of the real response of the system) because the observed data are limited; the state of the aquifer during the testing of the Candover scheme was certainly not typical because it took place during the drought of 1976. It is, therefore, also difficult to determine if the models that are constructed are likely to be accurate or not.

Such uncertainty, coupled with the lack of observed data, may discourage people from developing numerical models. However, the lack of data should be viewed as a strong reason *to* promote the development of models. Models are built precisely because not everything is known about a groundwater system and they allow us to test the plausibility of our hypotheses. Models should therefore be viewed as tools to develop understanding and to focus data collection requirements. The important question is "Is the model *fit for purpose?*"

The examination of behaviour observed during the Candover scheme has shown that if the purpose of the modelling exercise is the *accurate* prediction of the impact of an abstraction on river baseflows in a highly complex setting, then a significant amount of time may have to be spent in developing a detailed conceptual model of the aquifer. This is obviously not feasible for licence applications for small groundwater supplies.

However, the ZOOM_IGARF tool is appropriate for giving a rough estimate of the magnitudes of the impacts, their distribution between different rivers and importantly their sensitivity to our data uncertainties. This is both valid and useful.

Whilst the use of the ZOOM_IGARF tool developed as part of this study, cannot provide a high confidence estimate of the impact of abstraction on river flow, it does represent an improvement over the methods that are currently used by Environment Agency hydrogeologists, for example the IGARF analytical spreadsheet tool. This is because it can incorporate an accurate representation of the geometry of the network of rivers and the location of an abstraction borehole and it allows more comprehensive sensitivity analysis. The ZOOM_IGARF model should, however, still be viewed as a tool to improve the understanding of an aquifer and *assist* in the assessment of a licence.

6.2 Recommendations

6.2.1 Guidelines for Environment Agency hydrogeologists

The following paragraphs are provided as the starting point for the formulation of a set of guidelines to help hydrogeologists use numerical groundwater models to assess the impacts of groundwater abstraction on river flows. They distil the findings from this project and consequently, do not include all the possible issues surrounding the use of models for estimating the impact of groundwater abstraction.

The ZOOM_IGARF tool should not be used as the sole basis for assessing an application for a new abstraction borehole. The tool can be used to develop an initial understanding of a river aquifer system but this should be carried out in conjunction with other hydrogeological assessment methods. For example, the use of the ZOOM_IGARF tool should be complemented by the development of a water balance for the catchment, an examination of the observed data, e.g. river flows during periods of low flow and, assessment of the uncertainties contained in the system.

The role of models

Within the time available for assessing a new licence application, it will be difficult to develop a numerical model that incorporates all of the important features of an aquifer system. However, valuable insights can be gained within a few hours or a day or so. Indeed it should be possible to create numerical models that incorporate multiple river catchments and their correct geometry within an hour if the certain information is readily available e.g. shape files of river catchments. These features cannot be represented in the currently available analytical tool (IGARF spreadsheet). A particular benefit of the use of a numerical model is the ability to perform sensitivity analyses. By modifying the structure and parameter values of a model, a range of possible outcomes can be obtained and hypotheses can be tested. The lack of data is not a reason to neglect the application of numerical models. Rather it is a strong driver for their use because models are constructed, precisely because not all of the data is available and hypotheses need to be tested. Once a model has been developed it can then be improved over time.

Build a model that is larger than the catchment under investigation

When assessing the impact of abstraction it is important to include all of the rivers that could be affected by pumping. In such cases it is good practice to define the boundaries of the model using the physical extent of the aquifer if possible. It is *not* acceptable to select a stable groundwater divide between two catchments as a numerical model boundary when assessing the impact of abstraction on river flows. (See *How areally extensive should a model be?* in Section 6.1.1)

Comparisons of models of a single catchment with one incorporating two additional and identical catchments either side show that the differences in the simulated depletion rate can be of the order of 10% of the abstraction rate. These errors are only indicative and will depend on the particular features of aquifer system and river catchments being modelled. It is obviously more important to include more river catchments in the model if the catchment of interest is small.

How fast might the cone of depression spread from the borehole?

As a guide to how rapidly (but not how far) a cone of depression will spread radially outwards from an abstraction borehole, an expression based on the Theis solution can be used (Appendix C). Also the Environment Agency's IGARF spreadsheet (Environment Agency, 2004) may be used to estimate the time it takes for a pumping well to influence a river

If it is only possible to build a model of a single catchment

If for some reason a model has to be developed that contains only part of the river of interest, or only a sub-reach of such a river, then the errors in depletion rates from having the wrong boundary conditions can be reduced by constructing two models. For example a groundwater divide could be represented (badly) as either a no flow boundary or a fixed head boundary. In this study the errors in the depletion rates caused by doing this are about 10%. But if two models are built, one with a no flow boundary and the other with a fixed head boundary and the average of the depletion rates is calculated, the errors are reduced. See *Neglecting peripheral catchments* in Sections 3.5.3 and 6.1.1

Is it necessary to add recharge?

The application of recharge to a model which is used to calculate differences in river flow, that is depletion rates, only effects the results when:

1. Transmissivity depends on groundwater head. However the effects of ignoring recharge may be small (see *Unconfined aquifers* in Section 6.1.1).

2. The introduction of recharge affects the timing when parts of the river become perched or sections of the channel become dry.

3. The introduction of recharge causes another flow mechanism to exhibit non-linear behaviour.

The application of recharge does not *directly* affect the depletion rates that are calculated using a model because its introduction does not cause the governing flow equation to become non-linear. In a linear aquifer model, e.g. in which transmissivity does not depend on groundwater head and in which the operation of the river-aquifer interaction mechanism does not change in time, spatial and temporal variations in recharge have no effect on the calculated river flow depletion rate.

Which features of an aquifer must be incorporated in the model?

If the length of the river being modelled changes during a simulation due to sections running dry then the impact that an abstraction borehole has on its discharge will change. A change in the length of the river results in a breakdown in the linear behaviour of the aquifer. In such a case, care must be taken to represent the changing length of the river if depletion rates are to be calculated accurately.

The elevation of a river does not *directly* affect the impact that an abstraction borehole has on its flow. The calculated depletion rate will be the same for rivers at different elevations, if all other model features are identical, unless:

1. their different elevations cause sections of the river to become perched at different times;
2. their different elevations cause sections of the river to dry out at different times;
3. the saturated aquifer thickness and thus transmissivity is different beneath the rivers due to their different elevations.

The governing equation describing the flow in an unconfined aquifer is a non-linear equation because transmissivity depends on groundwater head. Consequently, the depletion rate calculated using a numerical model of an unconfined aquifer depends on the elevation of the water table.

The hydrogeologist should investigate the change in depletion for the anticipated change in groundwater level for their system. Running the IGARF spreadsheet or the ZOOM_IGARF numerical model with two transmissivities, one calculated using a typical saturated thickness and another with that expected after pumping has depressed groundwater levels, will provide an indication of how large the error might be.

When the change in water table elevation and the resulting change in transmissivity produce only a small change in river flow depletion, we can ignore recharge, river elevations and rates of abstraction from other boreholes. But if the changes are large, the system must be represented more accurately. That is, the initial groundwater levels, river elevations and rates of abstraction from other boreholes must all be included. In short, the numerical model must be a more realistic representation of the aquifer system.

The following list provides a **very rough** guide as to which features of a system are the most important to represent in a numerical model. **The first two points are true for any system, however, the importance of representing the remaining features will depend on the aquifer being modelled and therefore require investigation by the hydrogeologist.**

- The full extent of the aquifer out to the physical boundaries and associated major streams which are in hydraulic contact with the aquifer being pumped must be included in the model.

- The correct geometry of the network of the rivers.

- Ephemeral sections of streams.

- Any perching or drying of streams, which may mean we have to include recharge unless we can represent seasonal variation in river length empirically.

- Heterogeneity of aquifer properties

- Unconfined behaviour thus requiring the inclusion of a reasonable initial groundwater head profile, recharge and other groundwater abstractions.

- The vertical variation of hydraulic conductivity with depth.

6.2.2 Further Work

During this project it has only been possible to obtain data from one field investigation with which estimates of the impact of abstraction on river flows could be calculated. The analysis of the data for the Candover study is complicated by the fact that it was collected during the drought of the summer of 1976, when the Chalk aquifer was under significant stress. The observed estimates of river baseflow depletion appear to incorporate features that relate to the dewatering of the upper permeable part of the aquifer.

It is for these reasons that more data need to be collected from the field studies to produce additional estimates of the impact of abstraction on river flow. Once this information has been collected and analysed it will be possible to judge whether the complex behaviour observed in the Candover is typical. It is important that data are collected for different types of aquifer and not just the Chalk.

The most complex model of the Itchen catchment incorporated transmissivity, storage and river-bed conductance data from the Entec (2002) regional groundwater model but did not simulate river depletion rates that were similar to those calculated using the observed data. To try to determine which additional features need to be incorporated in the ZOOMQ3D model, the Entec model of the Itchen catchment should be applied to the Candover scheme. Two simulations should be performed using the Entec model: one in which the Candover augmentation boreholes pump and one in which they do not. The discharge from the Candover boreholes should be fed into the Candover Stream when the scheme is modelled. Hopefully, the Entec model will be able to reproduce the estimates of depletion based on the observed river flow data, however, it is possible that this may not be the case due to the complex flow processes operating in the Chalk during the summer of 1976.

It is likely that hydrogeologists who are assessing new groundwater abstraction licences will have different levels of experience of the application of numerical groundwater flow models. If this is the case, then some may be less aware of how models can be used to aid the assessment of a licence. Hence some will need training in the use of the software and some may need more general training in groundwater modelling. This more general training should focus on how models can be used to develop understanding rather than focussing on providing ‘the answer’. When assessing a license application hydrogeologists will rarely have enough time to develop complex models. Consequently, the ZOOM_IGARF tool can only be used to develop understanding. Sometimes the view that models are either detailed and good or, simple and bad can be prevalent but most models if used with an attitude of investigation can help challenge and hence develop understanding.

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APPENDIX A SUMMARY OF SELECTED OO MODELLING PAPERS IN THE LITERATURE

The use of OO techniques within surface water and groundwater research and GIS applications is extensive. Whilst the wider computing community have been using OO techniques commonly since the 1980s, the potential for water resources applications was only recognised in the mid-1990s (e.g. Larsen and Gavarnovic, 1994 and Wurbs, 1994). The use of OO techniques has been widely adopted for the development of user interfaces, relational databases and GIS systems (Murray, 2003). However, the use of OO techniques in the solution of the partial differential equations (PDEs), i.e. within numerical model algorithms has been more limited.

The following tables summarise some of the applications of object-oriented methods in environmental modelling that have been reported in the literature. This review is not exhaustive but is provided to highlight the breadth of use of OO techniques in the field of water resources research.

Alfredsen, K. and Saether, B. (2000)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
The focus is on building a program for flood calculations in river systems with several reservoirs and water transfer structures. An object-oriented framework for representing river systems has been developed.	During the development phase, the base framework has been used as a foundation for the redesign of the Norwegian physical habitat modelling system. The first application of the flood model is now underway, building a model for the Gudbrandsdalslagen river system in southern Norway.	A common tool for obtaining the desired modularity and re-use in software development is the application of object-oriented analysis and design methods.	By building on defined interfaces and using inheritance, the user can integrate new modules into the existing hierarchy. Separation of calculation methods from the components that describe the structure of the system The ability to reuse components during development. Gives a significant reduction in development time and also in the time spent on correcting errors. Both factors contribute to a reduction in an overall project costs.	This paper presents a flood routing, production and impact assessment model implemented as a set of modules (classes) that can be combined to closely represent the natural system. The encapsulation of information in a hydroinformatics system is handled by encapsulation mechanism in the object-oriented design. To take advantage of previously developed program systems, the model design allows for inclusion of these as both internal methods and as external data providers in the system. If an external program is to be used, an interface must be derived from the method hierarchy encapsulating the external program system. During the model design phase a system was specified with separation between the computational methods and the classes that describe the structural components in the system. The flexible method of connection is achieved by building a separate hierarchy of computational methods and connecting these to the structural hierarchy through their base classes.

Argent, R. M. and Houghton, B. (2001)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
Integrated management of natural resources require models of hydrology, ecology, economics and other aspects of the natural and social system to be modelled in an integrated fashion. This paper discusses some of the Software Engineering (SE) approaches and development that are being used in integrated modelling and also discusses the link between integrated modelling and the needs of managers and planners.	Integration of legacy land and water resources modelling code.	Some of the practices that are being used to address these problems include: Object-oriented design Modular development and remodelling The use of formalised modelling languages Development and integrated modelling frameworks Drag and drop style modelling environments.	The focus on model integration has included the redesign of existing models to increase their capacity for reuse, often by using object-oriented approaches to produce flexible and reusable program modules.	Re-design of existing models using OO languages.

Gartner, H., Bergmann, A. and Schmidt, J. (2001)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
An object-oriented approach is compared with classic concepts of data representation.	An example from an interdisciplinary research project on landslides and slope evolution. The investigation is a typical example of a multisource and multi-method approach, common in geosciences, using heterogeneous data and tools.	The aim of object technology as a tool in developing models is often described as enabling understanding of the domain, taking into account that the development of models explicitly requires detailed knowledge about the domain. Furthermore, this way of modelling may lead to a closer approximation of real world conditions because of the consideration of the semantics of the data objects	Not discussed.	Object-oriented modelling is used for a detailed representation of the data sets including all metadata that was necessary for all steps of data "handling" and representation. This means that each data set is represented within one special data object model. In addition, every standard used that is related to the data is separately represented in a standard object. Object based models are founded in the concept objects that own properties, behaviour, and relationships with other objects in space and time. For this reason it is necessary to revise the objects of the conceptual model in view of their semantics.

Hajjar, D., AbouRizk, S. and Xu, J. F. (1998)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
The paper presents the development and implementation of a construction dewatering analysis framework based on the idea of special purpose simulation (SPS).	A framework is presented for the analysis of construction site dewatering projects.	Not discussed.	Not discussed.	The modelling module encapsulates all data provided by the user and provides a graphical user interface for the definition, manipulation and viewing of these data in a variety of formats. This module was designed using an object-oriented approach under an event driven graphical user interface.

Harris, J. R. W. and Gorley, R. N. (2003) EcoS, a framework for modelling hierarchical spatial systems, *Science of the Total Environment,* 314, 625-635.				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
A general framework for modelling hierarchical spatial systems has been developed. The paper describes a framework for the development of numerical simulation model that was implemented and used during the UK Land-Ocean Interaction study The model is a hierarchy of a range of types of components. The core of an EcoS model is made up of three kinds of components, the *system*, *spaces* and *constituents*.	Transport of multiple constituents in estuaries by the solution of the advection-diffusion equation.	The model is effectively described in object-oriented terms, with all its components, and ultimately of the system components.	Ease the development of this kind of spatial model.	The modular structure of an EcoS model lends itself to a cut and paste approach to constructing models and individual constituents can be saved from one model and read into another. In addition, groups can be formed from arbitrary sets of components within a model, saved and read into other models within similar structures. The modular structure enables sets of template model components to be constructed that can be assembled into models.

Hatakeyama, M., Watanabe, M. and Suzuki, T. (1998)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
Proposed a new object-oriented modelling and programming paradigm to the CFD problems, especially the Navier-Stokes flow problems. The modelling procedures are integrated and reconstructed according to the object-based (OB) modelling and programming paradigm, which is one of the object-oriented paradigms	Simulation of fluid flows by solving Navier-Stokes equation.	The flexibility to change the configuration s of the fluid flow simulation system is the most remarkable feature of the OB simulation system.	The generalised formal modelling methodology and the programming procedures have explicitly and systematically been established The various OO programming languages, the programming technique documents for developing the OO system are widely obtainable. The execution efficiency is rather low. According to our experience, about at least 20 % more CPU load is needed. The concept and the consideration of the Object-oriented or the Object-based paradigms are not necessarily and sufficiently known and used.	The OB design/implementation model of the fluid object. It contains some sets of (data+method). The discretised Navier-Stokes schemes are implemented as one of these methods. The mutual relationship mechanism is composed of the object interface. The object interface generates / interprets / transmits the “message” to communicate with other object modules by making use of the “message passing” in the OO paradigm. Any function like the visualization and the mechanism must be equipped and operated outside the simulation world. Therefore, some kinds of OB integrated support environments are essentially needed for the OO simulation system to generate the full play of the features of the OB simulation.

Jansson, P. E. and Moon, D. S. (2001)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
Encapsulation of Fortram legacy code into an OO framework including a graphical interface.	Modelling thermal and hydrologic processes and the correspondent biological processes that regulate carbon and nitrogen transfer in a soil-plant-atmosphere environment.		The retention of legacy Fortran code with the addition of fully object-oriented modules accessing shared memory is the primary accomplishment of the CoupModel development.	C program for handling the user interface, a FORTRAN 77 program for the calculations, and a mixed-language program for input and output of time series data. Although the legacy code has been kept in use, the approach to further model development has become more object-oriented especially concerning the GUI.

Jones, T. A. (2001)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
This paper describes flowpaths, shows how to use them to generate vector fields, and then outlines an algorithm to use a vector field to create appropriate channels.	Simulations of flow paths in deep reservoirs.		Flowpaths and vector fields may be used to introduce paleogeographic and paleostructural features into geologic, object-based models. These provide very powerful tools to model quantitatively the geologist's interpretation. Use of such capabilities should enhance the value of such models for applications.	Object based (also called Boolean models) are special types of geologic block models in which idealised facies elements (objects) with well-defined geometries are distributed in three dimensions. Objects of given shapes are assigned dimensions and other characteristics based on sampling from geologic probability distributions. The objects and their properties may vary as a function of stratigraphic or spatial position.
Ludwig, R. et al (2003)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
The paper discusses the work of the GLOWA-Danube	An integrated decision support system, DANUBIA, covers	The object can be implemented in any desired language and	The standardised communication infrastructure,	The methodology used to develop DANUBIA applies integrative

project, its approach of model coupling and network-based communication, and object-oriented techniques to simulate physical processes and interaction at the land surface. A GIS-based integration methodology of socio-economic and environmental modelling techniques is designed to support water management for various decisions in representative European catchments.	simple scenarios about the future developments and their influence upon water quantity and quality in the Upper Danube catchment.	can easily be replaced by any improved process description upon availability.	which is needed for the distribution of the objects in the network, has been implemented in order to integrate the different model elements of various groups, which were developed in different places and with different programming languages The possibility to reuse the developed code, the easy serviceability of the standardised interfaces and the inherent explicit documentation through the use of the meta-modelling language in this approach, creates new integrative structures between the participating scientists.	numerical, network based models, integrative analysis of complex scenarios and integrative monitoring. In the GLOWA-Danube project, UML (Unified Modelling language) has been used for the design of the model framework of the DANUBIA system. With the common commitment to design interfaces, a clear and unambiguous basis for the exchange of parameters and variables between the core models could be established. A variety of already existing models have been rewritten and implemented in DANUBIA-compatible Java code.

McKim, H. L., Cassell, E. A. and Lapotin, P. J. (1993)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
This paper examines the use of object-oriented programming techniques to create dynamic hydrological models, and explores their potential to receive real and near real-time data from remote sensors as input to improve hydrological forecasting.	Simulation of hydrological systems in near real time using remote sensing.	Object-oriented programming is a relatively new development design to make computer code easier to write, understand and maintain (Baase, 1988). Software writing using OOP tends to be more flexible and often demonstrates superior information exchange capabilities.		In object-oriented simulation modelling, the model is created by placing objects that represent the important elements of the system on the computer screen and then connecting the objects to allow messages (and control instructions) to be routed among the objects.

McKinney, D. C. and Cai, X. M. (2002)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
Through the object-oriented approach, data, model and users interfaces are integrated in the GIS environment, creating great flexibility for modelling and analysis. The concept and methodology described in this paper is also applicable to connecting GIS with models in other fields.	The river basin used as a case study in this paper is the Kashkadarya River basin, which is a sub-basin of the Amudarya River basin in the Aral sea region of Central Asia.	Object-oriented methods are promising for tight coupling of GIS and environmental models.	Data, models and user's interactions are integrated in the GIS environment, which creates great flexibility for modelling analysis.	In this object-oriented method, a model is defined as a set of enquiring schemes acting on an abstracted representation of the river basin and based on physical laws and management policies. To implement the object-oriented method, some extended GIS functions were developed using an object-oriented programming language.

Meysman, F. J. R. et al (2003)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
MEDIA (Modelling Early DIAgenesis) software package for simulating 1D reactive transport in surface sediments. The paper focuses on the assumptions underlying model construction, numerical methods, verification and the application of MEDIA.	As an illustration of the capabilities of MEDIA, a comprehensive dataset from the Santa Barbara Basin is modelled.	MEDIA is built on two fundamental strongholds: (1) Problem-Solving Environment (PSE) and (2) Object-Oriented Technology (OOT). Both techniques enhance the software quality of reactive transport codes, and as consequence they lower the threshold for using diagenetic model codes as a routine instrument for geochemical data analysis.	The development of a flexible and extensible software system that provides problem-solving assistance for simulating the biogeochemistry of various types of surface sediments. The modular structure of MEDIA code, enforced by its object-oriented design, allows the model user an easy and flexible incorporation of new processes and functions.	Rather than focusing on a single model, different diagenetic models can be constructed within MEDIA without specialised knowledge of the programming language underlying the computer code. The application user assembles his own diagenetic model from a toolbox of available model components. New components (e.g. new elements, species, parameters, reactions) can be created and added via object-oriented database.

Newell, C. J., Haasbeek, J. F. and Bedient, P. B. (1990)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
OASIS is a modelling software where groundwater models, data, and knowledge are integrated together using a graphical interface and easily modified software architecture.	Decision support system for groundwater contaminant modelling.	Object-oriented programming permitted scientists with little programming experience to develop the system by manipulating pre-existing software objects instead of writing code, greatly increasing the productivity of the project team. Graphical interfaces are improved way to transfer information between the computer and the user.	Graphical interfaces simplify routine microcomputer tasks such as file management and eliminates the need to type special commands needed to use the computer. Object-oriented programming produces a remarkable change in point of view that increases the expensive power of the programmer. Some programmers suggest that the appeal of object-oriented programming is not a particular technical advantage, but a more intangible quality that crosses a threshold of perception. One tangible benefit of object-oriented programming is higher productivity for programmers. One potential drawback to a system such as OASIS is that the modelling technology may be misused by people who do not have the necessary background to use the models correctly.	OASIS was built using HyperCard, a software package supplied with the Apple Macintosh. HyperCard contains an object-oriented programming language which allows developers to define more complex behaviours for an object.

Spanou, M. and Chen, D. Y. (2000)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
An object-oriented approach is developed for the analysis of point-source pollution control in river basins. The physical entities of the river basin and the conceptual entities of its water-quality simulation and control are represented through objects.	The South Nation river system in the province of Ontario in Canada. The Upper Mersey river system in the North West of England.		The analysis and design have delivered re-usability of the code, and enhanced the user friendliness of the software.	The developed framework integrates the analytical tools for water-quality management study with a graphical user interface, as well as with components for the data management, the generation of results reports and the interaction with external software applications. The architecture is based on reusable and easily modifiable objects, and facilitates its extension to deal with other aspects of water quality and catchment management.

Tucker, G. E. et al (2001)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
Describe a new set of data structures and algorithms for dynamic terrain modelling using a triangulated irregular network (TIN) TINs is well suited for simulating the dynamics of surface change; however, the use of TINs has not been widespread because of the increased complexity of data structures and algorithm development in a TIN	The data structures and algorithms are applied in simulation models of long-term landscape evolution and of catchment rainfall-runoff. Another use is in a hydrologic application of the same concepts. In this case water depth is simulated in a small catchment in Kansas in response to spatially uniform recharge. The hydrologic model and the	TIN data structures and algorithm take advantage of the unique capabilities of the object-oriented programming language to provide a general framework for (1) storing and rapidly accessing information about mesh connectivity, (2) constructing and updating mesh geometry, (3) computing mass fluxes and maintaining continuity of mass within mesh elements using a finite difference or finite volume	A useful advantage of an object-oriented approach is that the functionality related to processes can be added in a hierarchical fashion without modifying the basic underlying mesh data structures. This type of hierarchical design has the advantage of allowing one to create flexible and extensible applications. The object-oriented implementation allowed the	

framework.	landscape evolution model share the same code for mesh handling and drainage network delineation, which highlights the advantages of a modular, object-oriented approach in terms of code reusability.	approach and (4) establishing drainage pathways across the terrain surface.	isolation of mesh implementation from the calculations that are performed on the mesh. This type of strategy enhances modularity and portability, and has the potential to reduce software development time.	

Wu, Q. and Xu, H. (2003)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
Modelling geological faults in 3D. An object-oriented framework, is used to carry out computer modelling and visualisation of complex faults in 3D.	3D models generated in Anhui, China.		The object-oriented framework modelling have the major advantage of achieving 3D modelling and visualisation of structure restoration, which establishes a stable foundation for further development and applications.	Based on a spatial object class hierarchy and the layered characteristics of rock strata, a subframe work model is designed, which includes an upper hypersurface, a lower hyper surface and a closed surface. The proposed methods are programmed in Visual C++ 6.0 and the OpenGL graphics library on a PC platform.

Yang, L. et al (2002)				
Focus of the paper	Type of application	Reason for use of OO	Advantages/Disadvantages	How OO was used
The paper details the development of the integrated modelling g system, FASTER, which is capable of predicting water elevations, velocities and solute and sediment concentration distributions in well-mixed rivers or narrow estuaries.	The hydroinformatics software tool FASTER 1.0.1 has been used to predict the flow features and to evaluate the water quality characteristics in the Ribble estuarine and river basin in the north-west coast of England, UK.		Object-oriented methodology provides the foundation for building integrated modelling software tools.	The model is modified to include user interface based on an object-oriented methodology implemented in Visual Basic.

APPENDIX B BRIEF REVIEW OF OTHER MODELLING CODES THAT CAN SIMULATE RIVER-AQUIFER INTERACTION

The following sub-sections provide brief descriptions of some of the other commercially available groundwater model codes that can simulate river-aquifer interaction and therefore, could be used to assess the impacts of groundwater abstraction on river flows. These descriptions are not meant to be exhaustive but rather provide some background information to the codes and sources of additional information.

MODFLOW

The Environment Agency uses the general version of MODFLOW through the Groundwater Vistas (GV) graphical interface; currently version 3.5. Other versions of MODFLOW which include significant enhancements are not available through GV (e.g. VKD, TMR, SURFACT).

GV3.5 allows simple groundwater models with drains, rivers or streams to be set up quickly by designing the model grid on-screen. Model cell parameters are assigned on a zone or reach basis which is simple to use but restrictive for heterogeneous modelling problems. Mistakes in setting up a model in GV are not easy to rectify because there is no ‘undo’ button.

The following options are listed under ‘MODFLOW version’ in GV: Original 88/96, MODFLOW2000, SURFACT, MODFLOWT and SEAWAT. However, only MODFLOW88/96 and MODFLOW2000 are documented and SEAWAT is for variable density models. DLLs are included for MODFLOW88/96 and MODFLOW2000 only.

MODFLOW includes three channel packages – DRN (drains), RIV (rivers) and STR (streams). The most sophisticated of these is the stream package. The STR files can be set up easily in GV but only for simple problems. Branching stream networks require complex STR files which are difficult to set up. STR can account for groundwater heads being above stream water level (leakage into the stream), below water level but above bed level (leakage out of the stream) or below bed level (constant rate of leakage out of the stream). However, there is no representation of the change from saturated to partially saturated conditions below the stream bed as the aquifer head continues to fall. A limitation of the general version of the MODFLOW STR package is that it only caters for single inputs to stream reaches; multiple inputs (say from discharges) cannot be handled (MODFLOW-VKD does allow for this but cannot be accessed through GV). STR is not a true surface water flow model but can provide estimate of stream stage based on Manning’s equation for rectangular channel geometry.

Refinement of a MODFLOW finite difference mesh may be necessary to deal with problems where there are rapid changes in hydraulic gradient (e.g. near pumping wells), where there is heterogeneity at a smaller scale or for contaminant transport modelling (or the simple advective flow tracking used for source protection zone delineation). It is usually too computationally demanding to refine the whole mesh so some form of localised mesh refinement is needed. GV3.5 only allows for use of general MODFLOW or possibly a MODFLOW-TMR code (currently not included in the GV package).

Mesh refinement with general MODFLOW produces a variably spaced grid which is not fully satisfactory when judged against the alternatives. It leads to refinement where its not necessary (grid lines must cross the entire width or height of the mesh) and is prone to undesirable numerical errors (because of large aspect ratios). Repairing the mesh (resetting boundary parameters) after refinement is tedious, requiring much manual correction. Telescopic mesh refinement (TMR) would offer some advantages if it was made available through GV (more economical refinement, in the area of interest only) but the method is subject to errors in the child mesh solution because there is no feedback from child to parent mesh. These errors are tedious to resolve and may be overlooked.

More sophisticated iterative mesh refinement methods are possible with the MODFLOW code (Mehl and Hill, 2002) but they are not yet available through GV. These methods use iteration-based feedback with shared nodes to link the parent and child grids. They offer better accuracy than TMR and remove the need for error assessment. They are faster but can be less accurate than variably spaced grids. The main disadvantages with variably spaced grids (currently available through GV) are the need to consider numerical errors and difficulties in setting up then repairing the mesh.

Additional information on MODFLOW can be found on the United States Geological Survey's web site (http://water.usgs.gov/nrp/gwsoftware/modflow.html).

AQUA3D

AQUA3D is a finite element, fully three dimensional groundwater flow and contaminant transport modelling package. It has been developed by Vatnaskil Consulting Engineers from Iceland and costs US$900. The model code is not public domain or open source. Most of the information below is taken from the Scientific Software Groups website - http://www.scisoftware.com.

AQUA3D is described as menu driven and user friendly with automatic mesh generation. There is graphical output of all results, contours, flow arrows and time series and direct transfer of results to Surfer, Grapher or Excel.

One of the main features described is that once a model has been set up it can be changed at any time including adding layers and nodes and expanding or contracting boundaries. Sub-models can also be created from the main model. All this could help in grid refinement.

Rivers can be simulated in three different ways. An average head condition can be specified with leakage into or out of the aquifer depending on the surrounding aquifer head. An intermittent leakage condition can be defined so that when groundwater level falls below the bed of the river, leakage can cease or become constant. A variable head condition can be defined for each river node where the hydraulic head varies according to a known analytical function or according to real river water level hydrograph data. The time-varying hydrograph data can be entered at whatever time interval is desired.

The last feature of interest is that any layer can be wetted and de-watered anywhere within the model area any number of times. The saturation level at which a layer is to be considered dry can be set manually by the user which is useful for increasing the speed of the initial calibration runs where there are a small number of thin aquifers in a multiple-aquifer system.

MODHMS

The following information about MOD-HMS is based on the Users Guide (HydroGeoLogic, Inc., 2001. MOD-HMS: A Comprehensive MODFLOW-based Hydrologic Modeling System. Version 1.1. Document and Users Guide, HydroGeoLogic Inc., Herndon, Virginia). More information can be found on the web site www.modhms.com.

MODHMS is an integrated surface/groundwater flow code developed by HydroGeoLogic, Inc. The groundwater flow module is based on the U.S. Geological Survey modular three-dimensional (3-D) groundwater flow model, MODFLOW. MODHMS represents the interactions between overland flow, channel flow, and groundwater for example to simulate water supply management scenarios, flood control and river flow analyses, and wetland restoration analyses. Additional modules have been incorporated into the MODFLOW code to provide a spatially-distributed surface/subsurface modelling framework, that includes 3-D variably saturated subsurface flow, 2-D overland flow and, flow through a network of 1-D channels or pipes.

IHM

The Integrated Hydrologic Model (IHM) couples the codes Hydrologic Simulated Program-Fortran (HSPF) and MODFLOW to simulate the full hydrologic cycle. HSPF is used to simulate the surface water budget while MODFLOW is used to simulate saturated groundwater flow.

IHM is designed to model surface water-groundwater interactions in shallow water-table environments. Input requirements include precipitation time series, potential ET time series, surface topological features (i.e. land use, soils, topography, derived slopes), irrigation fluxes, hydrography characteristics, rating conditions, hydrogeologic parameters of the groundwater system, and well pumping and surface diversions. The code implements a GIS pre-processor to assist model development

IHM outputs water balance information for all major hydrologic processes such as surface water and groundwater flows to wetlands, streams and lakes, ET losses from all storages, reach stage and soil moisture, recharge to the groundwater system, storage, heads, and fluxes in the groundwater system. Further information about IHM is available on the Intera web site (http://www.intera.com/techology_ihm.php).

FEFLOW

FEFLOW is a finite element program developed and marketed by the Institute for Water Resources Planning and Systems Research, Berlin-Bohnsdorf, Germany operating as WASY GmbH. The program is available in various forms and at various prices, depending on the level of facilities included. A demonstration copy of version 5.1 has been mounted on a PC and a tutorial and two case study examples have been run. The current version is 5.2.

The program has 2-D and 3-D versions but the 3-D version is similar to a layered model as the elements are prismatic. Triangular and quadrilateral elements are supported though there are some restrictions on the use of quadrilateral elements. All elements have nodal points at their vertices and extended versions are available which also have nodes at the mid-points of their sides. The program allows the definition of so-called super-elements within which triangular elements are automatically generated. This is a convenient way of defining boundaries, both external and internal. If quadrilateral elements are used, the super-elements are limited to quadrilaterals. Mesh refinement can be applied anywhere and local refinement is automatically applied at locations representing pumped wells. There are routines for checking the geometry of elements to avoid problems associated with triangles which contain obtuse angles.

Rivers are represented by a leakage mechanism which allows different values of vertical hydraulic conductivity to be specified for influent and effluent conditions. River elements remain connected to the aquifer whatever the difference in level between the river and the local groundwater head but a maximum leakage rate can be set. There does not appear to be any routing of the flow in the river so the rivers can never run dry. The latest version has the capability to connect to the river flow model MIKE-11.

The user interface is comprehensive but it clearly has its origins in an XWindows Motif environment. An X-server program is bundled with the software and is installed automatically. There is a vast amount of information presented to the user and much of the material is hard to read, even on a high performance 21" monitor.

The documentation provided with the program is extensive, including a user manual and a reference manual. The user manual covers the extensive set of menus and includes an extended tutorial example. The reference manual is important as a source of explanations about the meaning of the various choices that can be made. Whilst this is comprehensive, it relies on mathematical statements to describe the operation of the model, rather than plain language descriptions. It is hard to believe that a user other than an experienced modeller would obtain much benefit from the contents.

Overall, FEFLOW looks a typical example of a finite element modelling system aimed at the assessment of regional scale problems supported by large quantities of data and an experienced modeller. It is difficult to imagine it being a useful tool in the hands of a user lacking in modelling experience and unfamiliar with the mathematical background to the finite element formulation.

APPENDIX C RATE OF SPREAD OF A CONE OF DEPRESSION BASED ON THE THEIS SOLUTION

The Theis (1935) solution allows the calculation of drawdown, induced by pumping from an abstraction borehole in a confined aquifer, at a radius, r, and time, t, after the start of pumping. It is expressed as:

$$s = \frac{Q}{4\pi T} W(u) \qquad \text{(Equation A1)}$$

where

$$u = \frac{r^2 S}{4Tt}$$

The term W(u) is the referred to as the Theis well function and is given by:

$$W(u) = \int_u^\infty \frac{e^{-u}}{y} dy = \int_0^t \frac{e^{-u}}{t} dt$$

The remaining terms in the above expressions are:

s is the drawdown (m) at radius r (m) and time t (days),

Q is the pumping rate ($m^3 day^{-1}$),

T is the aquifer transmissivity ($m^2 day^{-1}$) and,

S is the storage coefficient.

By taking the partial derivative of Equation A1 with respect to time, t, the expression for the *rate* of drawdown is derived. This is:

$$\frac{\partial s}{\partial t} = \frac{Q}{4\pi T} \frac{\exp\left(-r^2 S/4Tt\right)}{t} \quad (\text{m day}^{-1}) \qquad \text{(Equation A2)}$$

$\frac{\partial s}{\partial t}$ is plotted against t at a distance of 100 m from the well in Figure 136; the other aquifer parameters are listed in the figure. This shows that the rate of drawdown reaches a maximum some time after the start of pumping. The time at which this peak occurs can be calculated by taking the derivative of $\frac{\partial s}{\partial t}$ with respect to time and setting the resulting expression to zero.

$$\frac{\partial}{\partial t}\left[\frac{\partial s}{\partial t}\right] = \frac{Q}{4\pi T} \frac{\partial}{\partial t}\left[\frac{\exp\left(-r^2 S/4Tt\right)}{t}\right] = 0 \qquad \text{(Equation A3)}$$

$$= \frac{Q}{4\pi T t^2} \; e^{-u}\left(u-1\right) = 0$$

Therefore, the peak shown in Figure 136 occurs at the time, t_{point}, defined by:

$$u = 1 \quad \text{or} \quad t_{point} = \frac{r^2 S}{4T} \qquad \text{(Equation A4)}$$

t_{point} is the time when the *rate* of drawdown at a *point* at radius r from the well is a maximum (m).

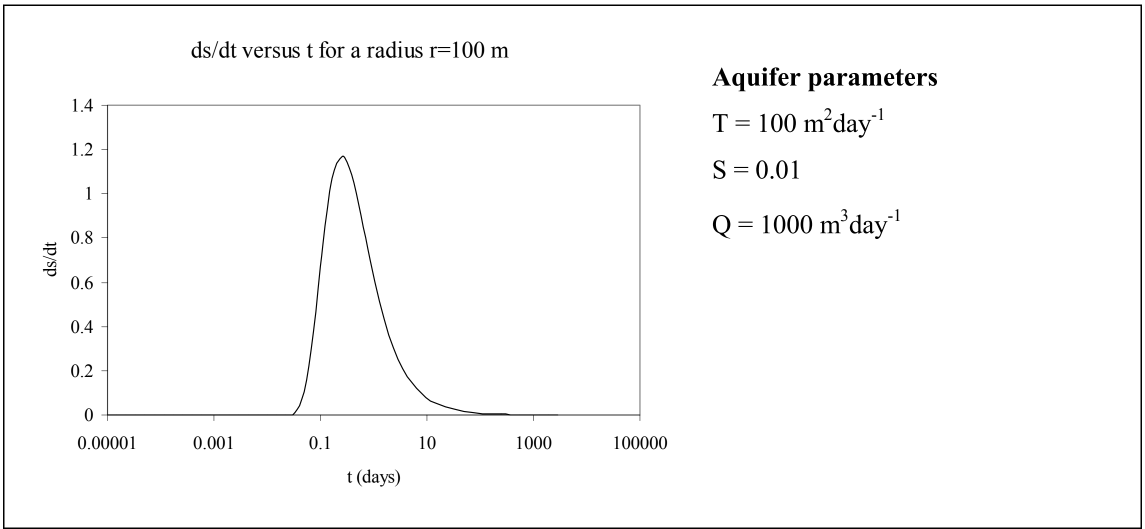

Figure 136 Rate of drawdown at a point at radial distance, r, over time

Alternatively, if $\frac{\partial s}{\partial t}$ is multiplied by $2\pi r S$ then the equation for the rate of release of water from a circle around the well is derived. This is:

$$2\pi r S \frac{\partial s}{\partial t} = \frac{Q r S}{2T} \frac{\exp\left(-r^2 S / 4 T t\right)}{t} \quad (m^2 day^{-1}) \qquad \text{(Equation A5)}$$

The curve defined by Equation A5 is plotted against radius, r, for two times in Figure 137. The aquifer parameters used for this example are given next to the graph.

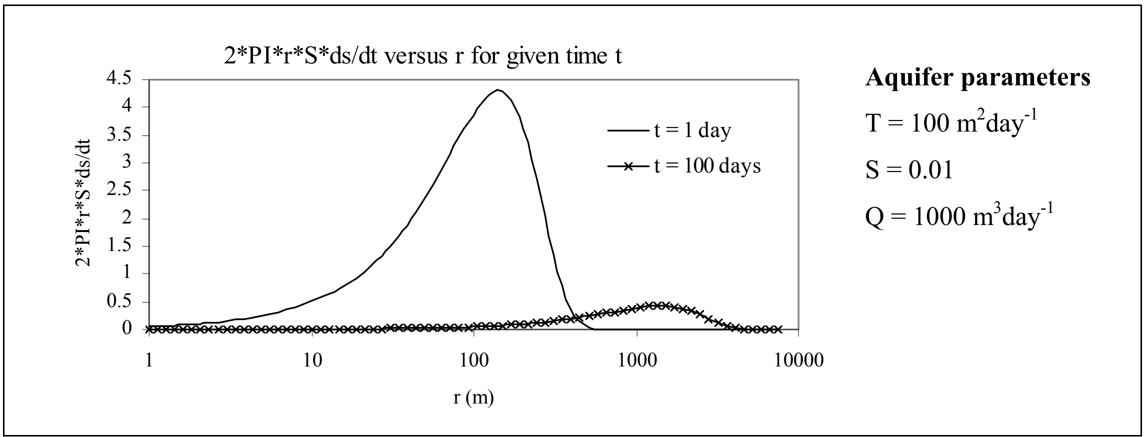

Figure 137 Time instant rate of release of water from a circle around an abstraction borehole

The radius, r_{max}, at which the maximum value of Equation A5 occurs is derived by calculating its derivative with respect to the radial distance from the well, r, and then setting the resulting expression to zero. This is given by:

$$\frac{\partial}{\partial r}\left[2\pi r S\frac{\partial s}{\partial t}\right] = \frac{\partial}{\partial r}\left[\frac{QSr}{2T}\frac{\exp\left(-r^2S/4Tt\right)}{t}\right] = 0$$

$$= \frac{QS}{2Tt}e^{-u}\left[1-\frac{r^2S}{2Tt}\right] = 0$$

This is true when $\frac{r^2S}{2Tt} = 1$ which specifies the positions of the peak of the curves shown in Figure 137. The radius of the peak, r_{max}, is given by:

$$r_{max} = \sqrt{\frac{2Tt}{S}} \qquad \text{(Equation A6)}$$

r_{max} is the radius of the *circle* around which the rate of drawdown is integrated and found to be a maximum. Equation A6 can also be used to indicate how far the cone of depression around a pumped borehole spreads with time in addition to Equation A4. However, it must be remembered that these two equations do not represent the same feature of the system. Reiterating, Equation A6 does not represent the “edge” of the cone of depression but rather the position of a specific *circle* around which the *rate* of drawdown has been integrated and found to be a maximum. Whereas, Equation A4 represents the time at which the rate of drawdown at a *point* at radius, r, is a maximum.

APPENDIX D PROPERTIES OF LINEAR EQUATIONS

A number of references are made throughout this report to the behaviour of the aquifer being modelled as *linear*. This refers to the type of equation that governs the groundwater flow within the numerical model. As shown in Section 3, when depletion rates are calculated as differences between two model runs using a linear model, some model parameters, such as recharge, do not affect the calculated result. Consequently, under certain circumstances, it is not necessary to include recharge when assessing the impact of abstraction on river flow. To provide some background to the properties of linear equations the following information is provided:

- The first derivative of a function y' is called a first order derivative. The second derivative of a function y'' is called a second order derivative.

- The order of a differential equation is the order of the highest derivative in the equation. For example $y'' + y' - 2y = c$ is a second order differential equation.

- The degree of a term of a differential equation is equal to the power of the dependent variable. For example the degree of $\frac{\partial h}{\partial x}$ is one and the degree of $\frac{\partial h^2}{\partial x}$ or $\left(\frac{\partial h}{\partial x}\right)^2$ is two.

- A differential equation is linear if it is of the first degree in the dependent variable and its partial derivatives i.e. a linear differential equation is one of the form:

$$a_0 y + a_1 y' + a_2 y'' + a_3 y''' + \cdots = b$$

  where y is a function of x and a_i and b are either constants or functions of x.

The groundwater flow governing equation in two dimensions for a confined aquifer takes the following form:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} - C\left(h_{river} - h\right) - q_{recharge} - Q_{abstraction}$$

Since the governing flow equation is of first degree in the dependent variable *h* and its derivatives, it is a linear equation. This is not the case, however, for the following governing flow equation in an unconfined aquifer, taking the form:

$$\frac{\partial}{\partial x}\left(k_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y h \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} - C\left(h_{river} - h\right) - q_{recharge} - Q_{abstraction}$$