

**Impact of Groundwater Abstractions on River Flows:  
Phase 2 – “A Numerical Modelling Approach to the  
Estimation of Impact” (IGARF II)**

**R&D User Manual W6-046/M**

# **IMPACT OF GROUNDWATER ABSTRACTIONS ON RIVER FLOWS: PHASE 2 – “A NUMERICAL MODELLING APPROACH TO THE ESTIMATION OF IMPACT” (IGARF II)**

User Manual W6-046/M

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This report summarises the findings of research into the impact of groundwater abstraction on river flows. A methodology for assessing such impacts is presented and demonstrated. The information within this document is for use by Environment Agency staff and others involved in managing water resources.

## **Keywords**

Groundwater, abstraction licensing, modeling, neural networks, hydrogeological classification, river-aquifer interaction, river flow depletion

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<b>CONTENTS</b>	page:
<b>LIST OF TABLES</b>	<b>ii</b>
<b>LIST OF FIGURES</b>	<b>ii</b>
<b>1 INTRODUCTION</b>	<b>1</b>
<b>2 THE IGARF II MODELLING APPROACH</b>	<b>2</b>
2.1 Overview	2
2.2 Limitations of the Approach	6
<b>3 IGARF II GRAPHICAL USER INTERFACE</b>	<b>8</b>
3.1 Overview	8
3.2 Input Data	10
3.3 Output Graphs	12
<b>4 RECOMMENDED PROCEDURE</b>	<b>14</b>
4.1 Introduction	14
4.2 Outline of Procedure	15
<b>5 WORKED EXAMPLES</b>	<b>19</b>
5.1 Case Study 1	19
5.2 Case Study 2	25
5.3 Case Study 3	27
<b>ACKNOWLEDGEMENTS</b>	<b>29</b>
<b>REFERENCES</b>	<b>30</b>

## LIST OF TABLES

page:

Table 2.1:	Model input data	5
Table 2.2:	Model input variables	6

## LIST OF FIGURES

Figure 2.1:	Example of response curves for 2 variables	2
Figure 2.2:	Approach used in this project	3
Figure 2.3:	Hydrogeological settings	4
Figure 2.4:	Comparisons of IGARF II phreatic surface levels for different settings	7
Figure 5.1:	Initial IGARF II screen	19
Figure 5.2:	Hydrological settings	20
Figure 5.3:	Physical property input data	21
Figure 5.4:	Abstraction/Recharge Data	21
Figure 5.5:	Impact of Pumping Test	22
Figure 5.6:	Zoomed in part of impact of pumping test	23
Figure 5.7:	Long Term Depletion	23
Figure 5.8:	Long Term Impacts	24
Figure 5.9:	Depletion Profile	24
Figure 5.10:	Aquifer Drawdown	25
Figure 5.11:	Abstraction/Recharge data (case study 2)	26
Figure 5.12:	Zoomed in part of impact of pumping test (case study 2)	26
Figure 5.13:	Physical Input Data (case study 3)	27
Figure 5.14:	Long Term Depletion (case study 3)	28

# 1 INTRODUCTION

The Environment Agency (the Agency) has initiated a programme of research and development to define consistent approaches to the evaluation of the impact of groundwater abstraction on river flows (the IGARF programme). In Phase I of this programme, a thorough review was carried out by Environmental Simulations Ltd. of current best practice in the Agency and of available analytical methods (Environment Agency, 1999a). A modelling tool was developed using an Excel spreadsheet to implement the analytical methods which were chosen to be most appropriate, and a set of procedures for use of the tool were documented in a User Manual (Environment Agency, 1999b).

It is recognised, however, that analytical methods are limited in their applicability, due to the simplifying assumptions that are necessary in order to make solutions to the governing equations possible. The Agency therefore initiated a second phase of the IGARF programme in which a method was sought that could address a wider range of hydrogeological conditions than was possible in IGARF I, while still remaining relatively simple to use in comparison with full numerical models. This second phase (IGARF II) was carried out by the Water Resource Systems Research Laboratory (WRSRL) in the Department of Civil Engineering, University of Newcastle upon Tyne.

This User Manual for the IGARF II modelling tool provides a user with a description of how to use the Graphical User Interface (GUI), and sufficient background information about the project to enable him/her to understand the use of the tool. A recommended procedure is given for the use of the IGARF II and IGARF I tools in the context of the evaluation of groundwater abstraction licensing applications, and limitations of the approach are explicitly defined. The procedure is illustrated using worked examples. A full description of the development of the modelling approach is given in the accompanying Project Report (Environment Agency, 2001). A summary of the development work is given in Parkin et al. (2001).

## 2 THE IGARF II MODELLING APPROACH

### 2.1 Overview

The approach taken in this study is to ‘mimic’ the results from a large set of generic numerical model simulations by training an artificial neural network using a subset of the input-output data from the model simulations. An artificial neural network (ANN) is a set of highly interconnected mathematical processing elements which are capable of representing non-linear multivariate mapping functions between input and output data sets. The forms of the mapping functions are determined through ‘training’ the ANN using sets of input and output data. The input and output data in this project were provided by running a large number of numerical model simulations using the SHETRAN modelling system (Ewen et al., 2000) for a set of generic aquifers representing the range of hydrogeological conditions seen in river-aquifer settings across England and Wales. Once trained, the ANN is embedded into a Graphical User Interface (GUI) which, in effect, gives the user access to a multi-dimensional “look-up table” (or, a set of multi-dimensional “type curves”), which represents numerical river-aquifer modelling results covering a wide range of practical problems. An example of a small part of this “response surface” is given in Figure 2.1, which shows the peak value of river depletion as a function of distance of a borehole from the river and of length of the abstraction period (all other parameter values being held constant).

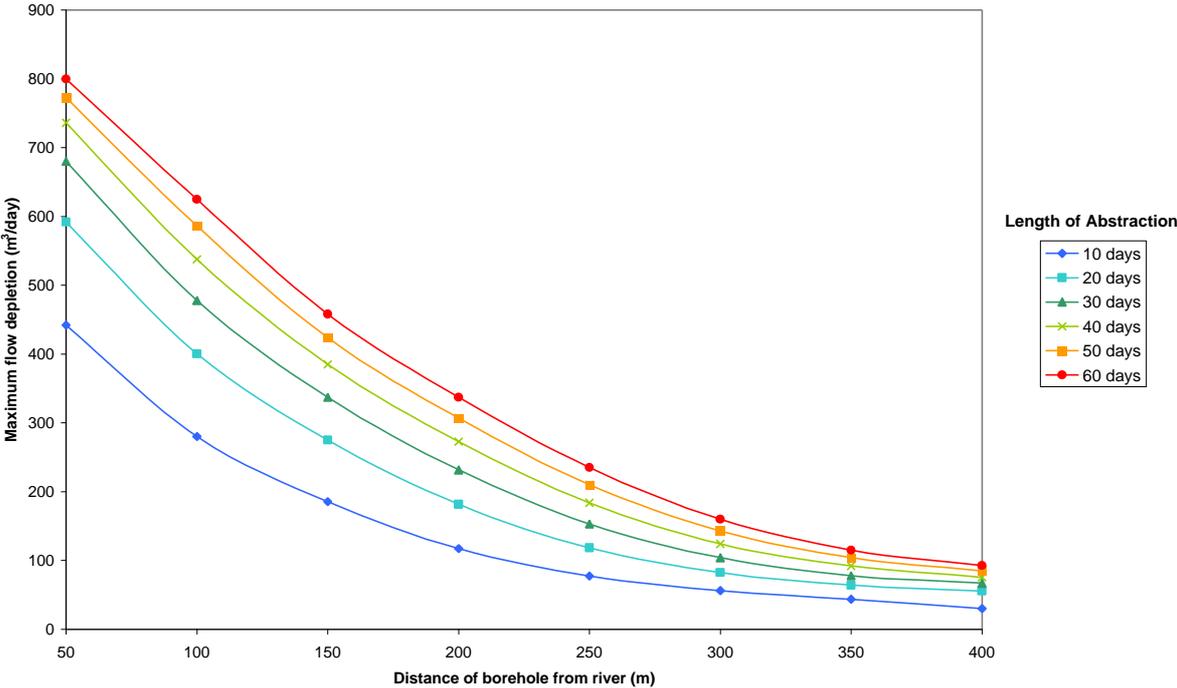
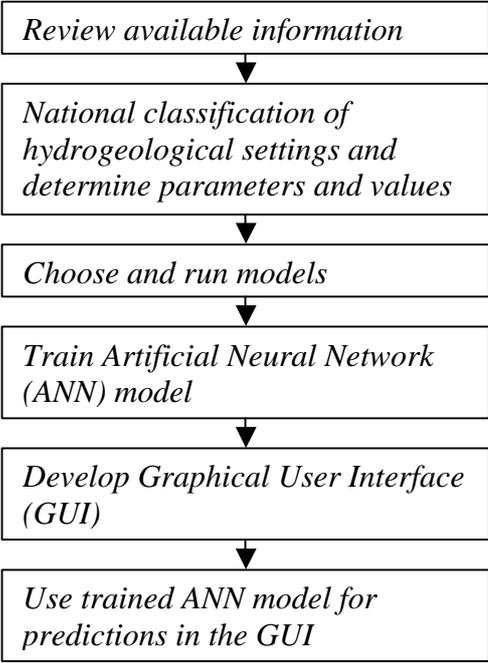


Figure 2.1 Example of response curves for 2 variables

The approach taken during this study can be summarised as follows (see Figure 2.2).

- *Review available information relevant to the project*; information on river-aquifer interactions and groundwater abstractions, and numerical modelling of these processes.
- *National classification of hydrogeological settings and determine parameters and values*: the scope of the study is defined to ensure that as many river-aquifer and abstraction scenarios as possible relevant to abstraction licensing officers are considered. Defining the input-output parameters and their ranges of values.
- *Choose and run models*: in general, any model could be used which is capable of representing the processes which are considered to be important; in this study, the SHETRAN model was used (Ewen et al., 2000), because of its capability of representing integrated surface and subsurface flows.
- *Train ANN model*: the ANN is trained ('calibrated') using the input-output data, and tested ('validated') against an independent set of numerical model results, to demonstrate that it is capable of reproducing the behaviour of the simulations.
- *Develop Graphical User Interface (GUI)*: the GUI allows easy input of the model parameters, and visualisation of the simulation results.
- *Use trained ANN model for predictions in the GUI*: once trained, the ANN can be used for predictions, within the range of its training data.

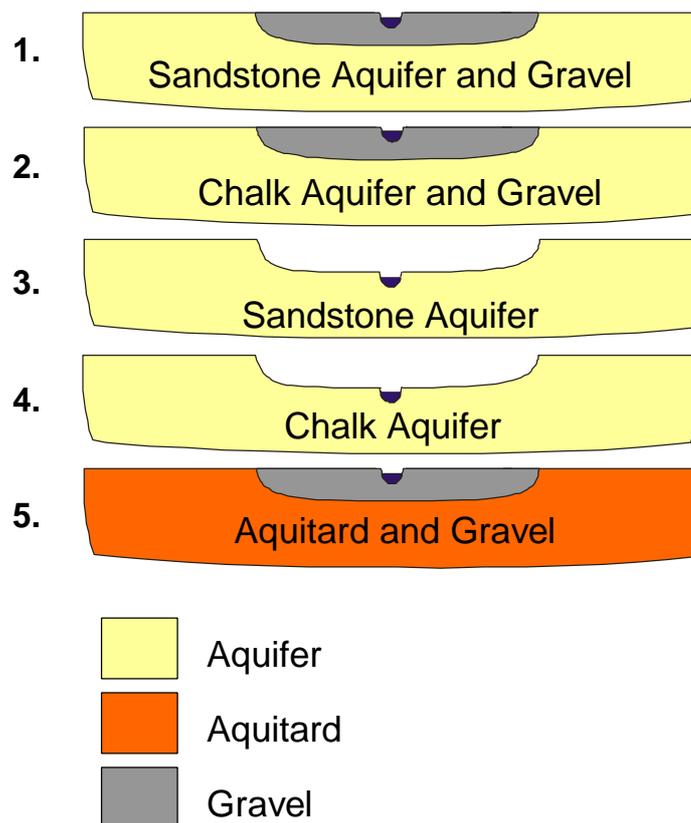


**Figure 2.2 Approach used in this project**

A key stage of the development of the model was in the definition of the hydrogeological settings used as the basis for the generic numerical model simulations. The settings were chosen by definition of:

- the full range of types of river-aquifer interaction configurations (‘hydrogeological settings’) found in England and Wales,
- physical property information to characterise those settings, and
- appropriate ranges of values for the physical properties.

The final model includes 5 hydrogeological settings (Figure 2.3). The results from the numerical model simulations were reproduced by the Artificial Neural Network in 3 groups: Settings 1 & 2, Settings 3 & 4, and Setting 5. The input parameters that define all of the settings are given in Table 2.1, together with the ranges of parameter values.



**Figure 2.3 Hydrogeological Settings**

**Table 2.1 Model input data**

Graphical User Interface				GUI input data sent to ANN	
Symbol	Description	Units	Range	Symbol	Description
D	Distance of borehole from river	m	25 – 500/4,000	D	Distance of borehole from river
Q <sub>a</sub>	Abstraction rate(s)	m <sup>3</sup> /day	500 – 5,000/10,000	Q	Abstraction rate
Q <sub>r</sub>	Compensation returns	m <sup>3</sup> /day	0 – 5,000		
t <sub>s</sub>	Start date(s) for abstraction	<i>date</i>	<i>any valid date</i>	t <sub>ss</sub>	Time from t <sub>s</sub> to t <sub>r</sub> (days from 0 -365)
t <sub>e</sub>	End date(s) for abstraction <u>or</u>	<i>date</i>	<i>any valid date</i>		
t <sub>d</sub>	Duration(s) of abstraction	days	1 – 365	t <sub>d</sub>	Duration of abstraction
T <sub>a</sub>	Aquifer transmissivity <u>or</u>	m <sup>2</sup> /day	10 – 60,000	T <sub>a</sub>	Aquifer transmissivity
K <sub>a</sub>	Aquifer hydraulic conductivity	m/day	1 - 200		
b <sub>a</sub>	Aquifer thickness	m	10 – 300		
T <sub>v</sub>	Valley-fill transmissivity <u>or</u>	m <sup>2</sup> /day	0 – 6,000	T <sub>v</sub>	Valley-fill transmissivity
K <sub>v</sub>	Valley-fill hydr. conductivity	m/day	1– 100		
b <sub>v</sub>	Valley-fill thickness	m	10 - 60		
Y <sub>a</sub>	Aquifer specific yield	-	0.1 – 0.5	Y <sub>a</sub>	Aquifer specific yield
Y <sub>v</sub>	Valley-fill specific yield	-	0.1– 0.5	Y <sub>v</sub>	Valley-fill specific yield
w	River width	m	5 - 50	C	Bed conductance per unit len.
K <sub>b</sub>	River bed sediment hydr. cond.	m/day	0.001 - 40		
d <sub>b</sub>	River bed sediment thickness	m	0.2 - 5		
R	Mean annual recharge	mm/year	0 – 1000	R <sub>eff</sub>	Mean annual effective recharge
t <sub>r</sub>	Date of peak recharge	<i>date</i>	<i>any valid date</i>		
R <sub>s</sub>	Recharge seasonality	-	0 – 1	R <sub>s</sub>	Recharge seasonality

Note that the independent variables used by the model are those listed in the right-hand column. So, for example, the user can input aquifer depth and hydraulic conductivity in the GUI, but these are combined into a transmissivity value for use in the model.

Each of the generic model simulations using SHETRAN created 74 output values. These were processed to give a smaller set of outputs that provide a representation of the same results in a self-consistent way, but using fewer variables. The ANN model embedded in the GUI uses 22 output variables (Table 2.2), which are used to create the 5 graphs in the Graphical User Interface.

**Table 2.2 Model output variables**

Symbol	Description	Units	No of values	Variable Number
$a_1$	Curve shape a for flow depletion curve up to time of max depletion	-	1	1
$p_1$	Curve shape p for flow depletion curve from the time of max depletion	-	1	2
$q_{max}/Q$	Max flow depletion/abstraction rate	-	1	3
$t_{max}/t_d$	Time of Max flow depletion/abstraction duration	-	1	4
$a_2$	Curve shape a for flow depletion curve up to time of max depletion	-	1	5
$p_2$	Curve shape p for flow depletion curve from the time of max depletion	-	1	6
$q_{9125}/Q$	Depletion at after 25 years/ abstraction rate	-	1	7
$a_{r1}$	Curve shape a for depletion profile in river at end of abstraction	-	1	8
$p_{r1}$	Curve shape p for depletion profile in river at end of abstraction	-	1	9
$a_{r2}$	Curve shape a for depletion profile in river at time of max depletion	-	1	10
$p_{r2}$	Curve shape p for depletion profile in river at time of max depletion	-	1	11
d	Aquifer drawdown	m	10	12-21
$d_w$	Drawdown in the well	m	1	22

The flow depletions and aquifer drawdowns were calculated using the SHETRAN numerical model by running a steady-state simulation with no groundwater abstraction, and a transient simulation with groundwater abstraction. The final results were obtained as the difference between the two sets of results.

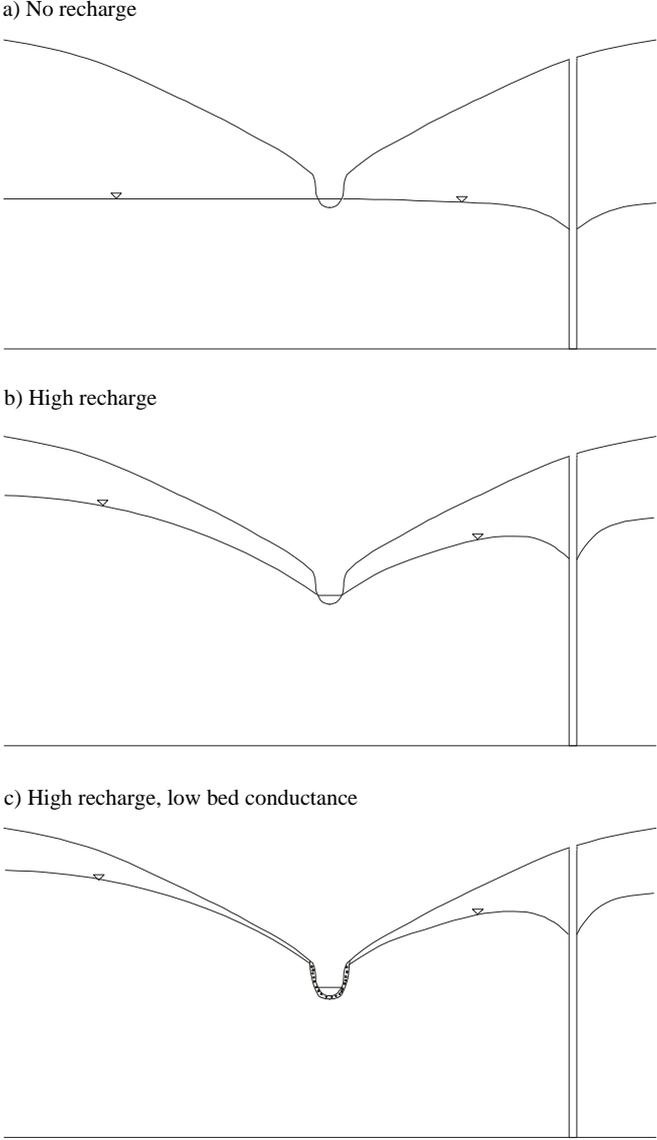
## 2.2 Limitations of the approach

The scope of this project specifically excludes consideration of the impacts of groundwater abstraction on wetlands and springs, and the use of water quality as an indicator of river impacts.

Various simplifying assumptions are made in the SHETRAN simulations about the river-aquifer system and the borehole abstraction:

- Each separate aquifer is homogeneous and isotropic;
- The base of the aquifer is uniform;
- There are no well losses;
- The well is fully penetrating;
- There are no interactions between groundwater and the land-surface (e.g. ponds, wetlands, springs (this was outside the remit of this project).
- There are no regional flow losses to other sinks than the river.

The numerical model simulations were based on fixed aquifer widths. The implication of this was that under steady-state conditions with recharge, there was a fixed amount of gain per unit length of the river. This is dependent upon the hydraulic gradient towards the river, which is a function of the recharge rate and the aquifer and river bed sediments physical properties (see Figure 2.4). In some cases this may not reflect the rates of river gain observed.



**Figure 2.4 Comparisons of IGARF II phreatic surface levels for different settings**

## **3 IGARF II GRAPHICAL USER INTERFACE**

### **3.1 Overview**

#### **3.1.1 Screen layout**

The Graphical User Interface (GUI) is based upon a standard Windows layout, with dropdown menus, icons, numerical input fields etc., and is designed to be similar in appearance to an Excel spreadsheet, as used for IGARF I. The GUI uses a series of ‘sheets’, which can be accessed using tabs along the bottom of the screen. These are divided into 3 sets: the first two are the title screen and the copyright statement; the next 3 are for data input, and the last 5 are for presentation of results. The results tabs are only available when a valid simulation has been run using the current input data.

The normal sequence of setting up a simulation is to work through the 3 input data sheets in sequence (Settings, Physical Data, Abstractions/Recharge), and then run the simulation to produce the output graphs. Once a simulation has been run and output graphs have been produced, then any change to the input data will remove the output graph sheets from the GUI until another simulation has been run. This ensures that the input data and output graphs are always consistent.

#### **3.1.2 Project files**

Each separate application of the IGARF II software can be saved as a ‘project’ in a file with default extension ‘.igarf’. The ‘File’ dropdown menu and the first 3 icons on the toolbar provide capabilities to open a new project, open an existing project, or to save the current project. Only the input data are stored in the project files. When an existing project is opened, the simulation must be run to recreate the output graphs.

#### **3.1.3 Agency regions**

The user can select the appropriate Agency region using the ‘Regions’ dropdown menu or the selection list within the Settings sheet. This only affects the local examples given on the Settings sheet (which may be added by the Agency at a later date), and does not in any way affect the results from the model simulations.

#### **3.1.4 Error checking of input data**

Each data input field has basic error checks for the data format, and to ensure that the value entered is within the valid range (see Table 2.1). Further error checks are carried out when a simulation is run.

#### **3.1.5 Running a simulation**

A simulation can be run from the ‘Project’ dropdown menu, or more usually by using the blue triangle ‘Run Simulation’ icon. When a simulation is run, the following steps are carried out.

- The input data are checked to ensure overall consistency (e.g. that at least one abstraction has been entered).
- A check is made that the steady-state hydraulic gradient across the aquifer is realistic for the given values of recharge and hydraulic properties (the limiting hydraulic gradient is 1:100).
- A check is made that the steady-state hydraulic gradient across the river bed sediments is realistic for the given values of recharge and hydraulic properties (the limiting value is a head difference across the sediments of 10 m).
- A check is made that the well does not dry out. This is achieved by running a first Artificial Neural Network (ANN1).
- If these checks are passed, the main Artificial Neural Network (ANN2) is run, and the output results are produced.

### **3.1.6 Printing output**

The user can use the 'Project' dropdown menu or the toolbar icons to print to the default printer either:

- the input data;
- the input graphs (abstraction/compensation/recharge);
- the output graphs; or
- a full report comprising of the input data, and the input and output graphs.

Any of the graphs can be printed individually by clicking the right-hand mouse button over the graph, and selecting 'Print' from the menu.

### **3.1.7 Exporting data and graphs**

All of the data and graphs can be copied to the clipboard and/or saved to file for inclusion in other software such as word processors. The input data can be copied to the clipboard in the same format as the print report using the toolbar icon. Any of the graphs can be individually copied or saved in bitmap format by clicking the right-hand mouse button over the graph, and selecting 'Copy' or 'Save as' from the menu.

### **3.1.8 Changing the appearance of graphs**

The appearance of any of the graphs can be changed by clicking the right-hand mouse button over the graph, and selecting 'Graph options' from the menu. This allows every aspect of the graphs to be changed, including graph types, line types and colours, titles, axis ranges etc. However, it is expected that the standard format would be used in most cases.

The visible part of any graph can be changed by zooming in or panning. Click and drag using the left hand mouse button over any part of the graph to zoom in. Click and drag using the

right hand mouse button over any part of the graph to pan. The axis limits on any graph can be reset by clicking the right-hand mouse button over the graph, and selecting 'Rescale' from the menu.

## 3.2 Input Data

### 3.2.1 Hydrogeological Settings

Before running a simulation, the user must select which hydrogeological setting is most appropriate. The choice of a setting here will establish which neural network model will subsequently be used, and will define the ranges of relevant parameters. A brief generic description of the setting is given on the right-hand side of the sheet, together with some typical examples. The settings are:

1. Gravel valley train deposits overlying regional sandstone aquifer
2. Gravel valley train overlying regional chalk aquifer
3. Regional sandstone aquifer
4. Regional chalk aquifer
5. Gravel valley train overlying regional aquitard

Settings 1 and 2 require physical property data for two aquifers to be supplied. Settings 3 and 4 (regional aquifer only) and Setting 5 (shallow aquifer only) require data for just one aquifer.

**Important note** Although it is possible to select any of the 5 settings, in this release of the software identical results will be obtained for Settings 1 and 2, and for Settings 3 and 4. This is because each of these pairs of settings were combined together to train the neural networks, using a continuum of parameter values to represent both the sandstone and chalk aquifers. The distinction between sandstones and chinks is, however, retained in the GUI for future eventualities.

### 3.2.2 Physical Property Input Data

The data required for input on this sheet are as follows.

<i>Site</i>	Alphanumeric text used in print outputs
<i>Run number identifier</i>	Numeric counter for simulation number in this project, used in print output. Can be set by the user; otherwise it is automatically incremented for each simulation.
<i>Distance of borehole from river (m)</i>	Perpendicular distance from the abstraction or test pumping borehole to an assumed straight line river
<i>Aquifer hydraulic conductivity (m/d)</i>	Saturated hydraulic conductivity of the regional aquifer. Used to calculate transmissivity. Not required for Setting 5.

<i>Aquifer thickness (m)</i>	Thickness of the regional aquifer. Used to calculate transmissivity. Not required for Setting 5.
<i>Aquifer specific yield (-)</i>	Specific yield of the regional aquifer. Not required for Setting 5.
<i>Valley hydraulic conductivity (m/d)</i>	Saturated hydraulic conductivity of the valley train gravel aquifer. Used to calculate transmissivity. Not required for Settings 3 and 4.
<i>Valley thickness (m)</i>	Thickness of the valley train gravel aquifer. Used to calculate transmissivity. Not required for Settings 3 and 4.
<i>Valley specific yield (-)</i>	Specific yield of the valley train gravel aquifer. Not required for Settings 3 and 4.
<i>River width (m)</i>	Effective width of the river. A value should be used representing the full wetted perimeter of the river channel. Used to calculate river bed conductance $C = w k_b / d_b$ , where $w$ is the river width, $k_b$ is the river bed sediment hydraulic conductivity, and $d_b$ is the river bed sediment thickness.
<i>River bed sediment conductivity (m/d)</i>	Saturated hydraulic conductivity of the river bed sediments. Used to calculate river bed conductance.
<i>River bed sediment thickness (m)</i>	Effective thickness of the river bed sediments. Used to calculate river bed conductance.

### **3.2.3 Abstraction / Compensation / Recharge Data**

This sheet contains fields for input of the time-varying input data for the model.

<i>Abstraction / Compensation data</i>	There are two tabs that can be used to select input of either abstraction or compensation rates. The method of input of data for each type is similar.
<i>Number of data points</i>	Any number of periods of abstraction and compensation data can be input. At least one period of abstraction data must be entered for a valid simulation.
<i>Duration</i>	Check this box to allow the duration of the abstractions to be input. The end date is then calculated automatically. Otherwise, the end date is input, and the duration is calculated automatically.
<i>Redraw</i>	Press this button to draw the 3 graphs showing the input time-series data.

<i>Rate (m<sup>3</sup>/d)</i>	Abstraction / compensation rate, assumed constant for the duration of the period.
<i>Start date</i>	Start date (day/month) for the abstraction / compensation.
<i>End date</i>	End date (day/month) for the abstraction / compensation. Not required if the 'Duration' box is checked.
<i>Duration (d)</i>	Duration of the abstraction / compensation. Only required if the 'Duration' box is checked.
<i>Mean annual recharge (mm/yr)</i>	Mean annual recharge rate.
<i>Date of peak recharge</i>	Date of peak recharge (day/month), assuming that the recharge follows a sinusoidal variation over the year.
<i>Recharge seasonality</i>	Index in the range 0 – 1, describing the range over which the recharge varies through the year. A value of zero indicates that recharge is constant. A value of one indicates that the sinusoidal variation of recharge has a minimum value of zero, and a maximum value of twice the mean annual rate.

**\*\* IMPORTANT NOTE:** The first period of the abstraction data is used in two different ways. The output graphs of 'Pumping test', 'Depletion profile', and 'Aquifer drawdown' relate ONLY to the first period of abstraction data, and are drawn for only a single year of abstraction. This can be used, therefore, in the design of a pumping test. The output graphs of 'Long-term depletion' and 'Long-term impacts' relate to all of the periods of abstraction data INCLUDING the first period, and are drawn for repeated periods of annual abstraction. These can be used for evaluating the long-term impacts of periodic abstractions.

### 3.3 Output Graphs

#### 3.3.1 Impact of Pumping Tests

This graph shows the abstraction rate and the river flow depletion for the first period of abstraction only, for up to 500 days after the start of the abstraction. The time of maximum depletion and the maximum depletion rate are shown at the top of the graph.

#### 3.3.2 Long-Term Depletion

This graph shows the cumulative effect of a pattern of repeated annual abstractions on river depletion, using all periods of abstraction, including the first period. Monthly values of river depletion are given as a cumulative stacked bar chart, showing the impact on the river after 1, 2, 5, 10 and 25 years. Note that the impact after 25 years may not be the final long-term steady-state impact, and some configurations of abstractions and stream-aquifer properties may have even longer impacts.

### 3.3.3 Long-Term Impacts

This graph shows the long-term effects of a pattern of repeated annual abstractions on river depletion, using all periods of abstraction, including the first period. The graph is identical to the 25-year total effect shown on the 'Long-term depletion' graph, except that the compensation flows are subtracted from the depletion rates. The impacts are shown in relation to the input rates of abstractions and compensation flows.

### 3.3.4 Depletion Profile

This graph shows the spatial extent of the impact of abstractions on river flow depletion, as a cumulative rate of depletion plotted against distance along the river for the first period of abstraction only. Two lines are shown on the graph – the river depletion at the end of the abstraction period, and at the time of maximum total depletion in the river. The profiles are drawn for a distance of 3 D up and down the river, where D is the perpendicular distance of the abstraction borehole from the river. The zero position on the X-axis corresponds to the position where the river is nearest to the borehole. The following additional information is displayed at the top of the graph.

<i>Time at End of Abs (d)</i>	Time of the end of the abstraction period
<i>Abs End Dep Rate (m<sup>3</sup>/d)</i>	Total depletion in the river at the end of the abstraction period
<i>Time of Max Dep (d)</i>	Time of maximum total depletion in the river
<i>Max Dep Rate (m<sup>3</sup>/d)</i>	Total depletion in the river at the time of maximum depletion

Note that in some cases the total depletion in the river may be greater than that shown on the graphical display (i.e. the spatial extent of the interaction between the cone of depression and the river is greater than 3 D).

### 3.3.5 Aquifer Drawdown

This graph shows the drawdown in the aquifer for the first period of abstraction only, at 5 key positions. These positions are illustrated in a schematic figure on the graph, and are: at a distance of D/2 from the abstraction borehole away from the river, parallel to the river, and towards the river; at the nearest point of the river to the borehole; and at a distance of D/2 from the river on the opposite side of the river to the borehole. The drawdowns are given at two times – at the end of the abstraction period, and at the time of maximum total depletion in the river. These two times are given at the top of the graph.

Due to the way in which the numerical model discretisation was set up, it can be taken that disconnection of the groundwater from the river occurs only when the drawdown beneath the river is greater than about 0.5 m.

## 4 RECOMMENDED PROCEDURE

### 4.1 Introduction

This procedure is given as a guideline only – users must rely on their own hydrogeological judgement to determine the best way to use the system. The overall procedure is essentially the same as that given in the IGARF I User Manual (Environment Agency, 1999b), and has been designed deliberately to be consistent with these earlier guidelines. Following this approach, the modelling tool can be used in two ways: firstly to help in the design of pumping tests, and secondly to calculate the short- and long-term impacts on rivers.

Note that this procedure gives estimates of the hydrological impact of a single groundwater abstraction on a river. This, in itself, is not sufficient for making judgements on whether or not a licence should be given, or the terms of a licence changed. The procedure described here should, therefore, be viewed within a wider context. Four aspects of the context are particularly worthy of note and should be carefully considered for any abstraction licence application.

#### *The significance of the predicted impact*

In addition to determining the extent (both in time and space) of the impact of groundwater abstraction from a borehole, it is necessary to determine whether the predicted impacts may be significant in terms of their effects on a river's value for ecological, water resources or amenity purposes. For example, in a study of the flow requirements for spawning sites for Atlantic Salmon, Webb et al. (2001) found that relatively high flow rates were required to maintain spawning activity in a tributary of the River Dee. Discharges were found to be at least the  $Q_{50}$  flow rate during active spawning seasons. This illustrates the need to know both the minimum permissible flow rate, and the period over which that flow rate is required to be maintained. The importance of setting target levels or flows as the first step in a systematic approach was also highlighted by Acreman and Adams (1998).

#### *Impacts on other surface water bodies (ponds, wetlands etc)*

As part of the development of a conceptual model for the planned abstraction area (see methodology outline below), all potential groundwater discharges should be identified. These can include surface water features other than rivers, including springs, ponds, wetlands or the sea. The assessment of the impacts on these other water bodies is outside the scope of this project, but methods should be used to evaluate, even in a relatively crude way, the possible impacts.

#### *Impacts of multiple abstraction*

This project has been concerned with evaluating the impacts of only a single abstraction borehole. However, it is often the case that there will be many licensed, unlicensed or potentially licensed boreholes which could each have an impact. The possible impacts could be on the other boreholes, or on rivers or other surface water features, where individual impacts may seem negligible, but the cumulative effects of many impacts could be significant. The IGARF II tool and procedure should then be used as part of an overall water balance strategy at the catchment or regional aquifer scale, for example within the procedures recommended for Catchment Abstraction Management Strategies (CAMS).

### *Impacts on adjacent catchments*

In contrast to the situation where multiple boreholes can have a cumulative impact within a single catchment, it is possible (and likely) that in many cases a single abstraction borehole can have an impact on more than one catchment. This is again something that should be considered within the CAMS framework.

## **4.2 Outline of procedure**

The following procedure is intended to provide the main steps that should be taken in assessing the impact of a proposed groundwater abstraction, as a basis for determining whether to issue a licence, or under what terms the licence should be granted. As with the procedures for IGARF I, this is not necessarily a linear process, and the user should be prepared to re-evaluate their views and repeat calculations using any new information at any stage in the process. The main review and re-evaluation stage that is recommended, however, takes place after completion of a pumping test, and this is built into these procedures.

### *1 Define the abstraction*

The proposed abstraction rates and durations will normally be given on the licence application. The effective abstraction rate should take into account any local returns to the groundwater system (i.e. these should be deducted from the total before being input to any model). Returns to the river can be input to both the IGARF I and IGARF II tools as compensation returns, and are simply deducted from the river flow depletions.

### *2 Collect available data*

Collate and assess all available data to characterise the area which may be affected by the proposed abstraction, using the Abstraction Licensing Manual as a guide. This will include:

- identification of the rivers, streams and other surface water features which may be affected by the abstraction, and any other groundwater abstractions or discharges in the area;
- basic hydrogeological parameters for the aquifer or aquifers affected, including aquifer type, transmissivity, storage co-efficients or specific yields, degree of heterogeneity or anisotropy etc;
- river bed hydraulic characteristics, if available (these will often be difficult to obtain, and secondary or indirect sources of information are often used);
- information on recharge to the aquifer, based on baseflow analysis, precipitation and evaporation data, soil and land-use cover, presence or otherwise and thickness of drift cover, etc.

### *3 Define the conceptual model*

As with any approach to modelling, the definition of a conceptual model of the system is of critical importance. The conceptual model should include at minimum a qualitative description of the physical dimensions of the system, the important sources and sinks, boundary conditions, and flow processes. Quantitative information should be used if

available. The use of simple diagrammatic maps and cross-sections is typically the best way to convey the appropriate information, and helps to clarify thinking about the system. The conceptual model should be maintained and updated as the assessment procedure is carried out.

#### *4 Select the modelling approach(es)*

Currently, there are basically 3 modelling approaches recommended by the Agency that are available to the user: the IGARF I modelling tool, the IGARF II modelling tool, numerical modelling (using the MODFLOW groundwater model implemented within the Groundwater Vistas graphical user interface), or some combination of these. The user should, however, be prepared to keep an open mind, and use any method which is appropriate to the issues relevant to the particular case at hand. It is important to ensure that (of the models available) a model is chosen that fits the conceptual model of the system, rather than changing the conceptual model to allow the use of a particular analytical or numerical model. In most cases, though, the 3 existing modelling approaches should provide appropriate tools.

The IGARF I modelling tool includes 3 different analytical solutions that can be used to assess aquifers with fully penetrating channels (Theis and Hantush) or partly penetrating channels (Stang), and with river bed lining material (Hantush and Stang) or without bed material (Theis). The methods were developed primarily for confined aquifers, but have been used for unconfined aquifers, provided the thickness of the aquifers is sufficiently large to allow the principle of superposition to be used. The user is referred to the IGARF I User Manual (Environment Agency, 1999b) for further information on how best to select one of the available solutions.

The IGARF II modelling tool includes 5 different ‘hydrogeological settings’ which have been chosen to represent most of the types of river-aquifer configurations known to exist in England and Wales. The user can select one of these settings, and carry out a set of calculations for this setting by using appropriate parameter values. The choice of a setting is based firstly on whether the conceptual model of the system contains either a ‘valley-train’ gravel aquifer overlying a regional aquifer (Settings 1 & 2), a regional aquifer only (Settings 3 & 4), or a valley-train gravel aquifer only (Setting 5). The IGARF II models are based primarily on unconfined aquifers.

The principle to follow when choosing an appropriate model is firstly to determine which of the available models best fits the conceptual model, then secondly carry out sensitivity studies and consider which of the results provides an over-estimation of the impacts.

#### *5 Determine parameter values for the model(s)*

For the IGARF I modelling tool, the required data are given in the User Guide (Environment Agency, 1999b), Table 6.1. For numerical modelling studies, the amount and type of data required depends upon the type and the complexity of the model being set up – consideration of these data is beyond the scope of this project.

For the IGARF II modelling tool, the data requirements are specified in Table 2.1 and described in Sections 3.2.2 and 3.2.3.

## 6 *Estimate likely impacts*

The likely impact on the river can now be estimated using the available parameter values. Multiple periods of different rates of abstraction can be used, and the results assessed in terms of the long-term depletion and long-term impact graphs, in addition to the other graphical outputs for the first period of abstraction.

If it is possible that there may be more than one river affected, then calculations can be carried out for each river. These calculations can initially assume that the full impact is felt in each river separately – the most pessimistic assumption. A more accurate estimation of impact can be achieved by partitioning the impacts, for example by using a simple reduction factor for each river.

The significance of the calculated impacts can be considered by looking at the river flows during critical periods – typically during low flow periods, although the timing of the ecological sensitive periods should be carefully considered. If the level of calculated flow depletion is less than about 5% of the river flow during critical periods, it is unlikely that it would be possible to detect the reduction in flows (however, note that the cumulative impact of multiple abstractions should also be considered, as discussed above).

Once a preliminary estimation has been made, a sensitivity study should be carried out to explore the effects of uncertainty in each of the model parameters on the impacts. Estimates of typical uncertainties in some of the model parameters are given in the IGARF I User Manual (Environment Agency, 1999b), Chapter 6.

## 7 *Design pumping test(s)*

The IGARF II modelling tool can be used to help in the design of a pumping test, by entering the proposed pumping test rate and duration on the first line of the ‘Abstraction/Recharge’ data sheet. Results are presented in the form of graphs of river depletion against time, river depletion against distance along the river, and aquifer drawdown. These results indicate over what period of time monitoring should be maintained, and how far upstream and downstream of the borehole monitoring of river flows should be made.

## 8 *Implement and interpret the pumping test(s)*

The pumping test should be carried out according to the guidelines in the Abstraction Licensing Manual, based on the above results. Ensure that all potentially affected surface water features are monitored over a sufficiently long period of time, measuring water levels and/or flows as appropriate. The interpretation of the pumping test results should include:

- evaluation of the degree of impact on surface water features – note that the conditions under which the pumping test was carried out may not reflect those which would characterise the sensitive flow periods
- calculation of aquifer physical properties, using standard analysis methods – take care to ensure that the effects of all water sources, including the river, are considered when carrying out the analysis (i.e. make sure that the type curves used for matching the well response are based as far as possible on the conceptual model)

## 9 *Review the conceptual model and modelling approach(es)*

Steps 3 to 5 above (conceptual model, selection of modelling approach, determination of parameter values) should now be reviewed and re-interpreted in the light of the new information from the pumping test. In particular, it should be considered whether the modelling tools used are adequate for carrying out the licence review, or if a numerical modelling approach is necessary.

## 10 *Carry out final calculations of impacts*

The final impact calculations can be carried out in a similar way to the preliminary impacts described in Step 6. A best estimate impact calculation should be presented, together with an uncertainty analysis giving the range of possible impacts. The uncertainty analysis can consider differences in the conceptual model if necessary, as well as uncertainties in the physical property values. The key points that can be recorded about the impacts are:

- what the maximum rate of river depletion is;
- when the impact on the river is felt;
- what length of river is affected;
- what the effects on aquifer drawdown are.

These results can be used for the response to the licence application, to help in determining whether the licence should be granted as is, if a reduced rate or duration of abstraction is recommended, what monitoring if any is required, and an appropriate time to review time-limited licences.

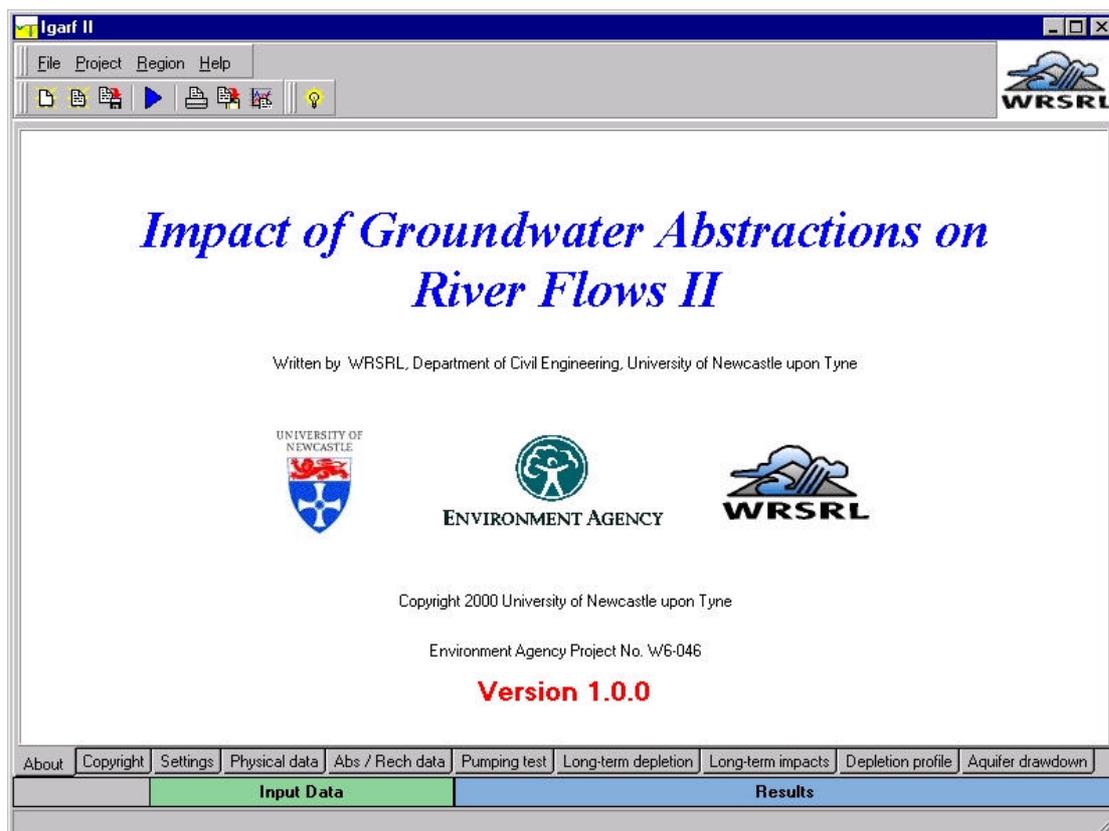
## 5 WORKED EXAMPLES

### 5.1 Case Study 1

#### 5.1.1 Input data

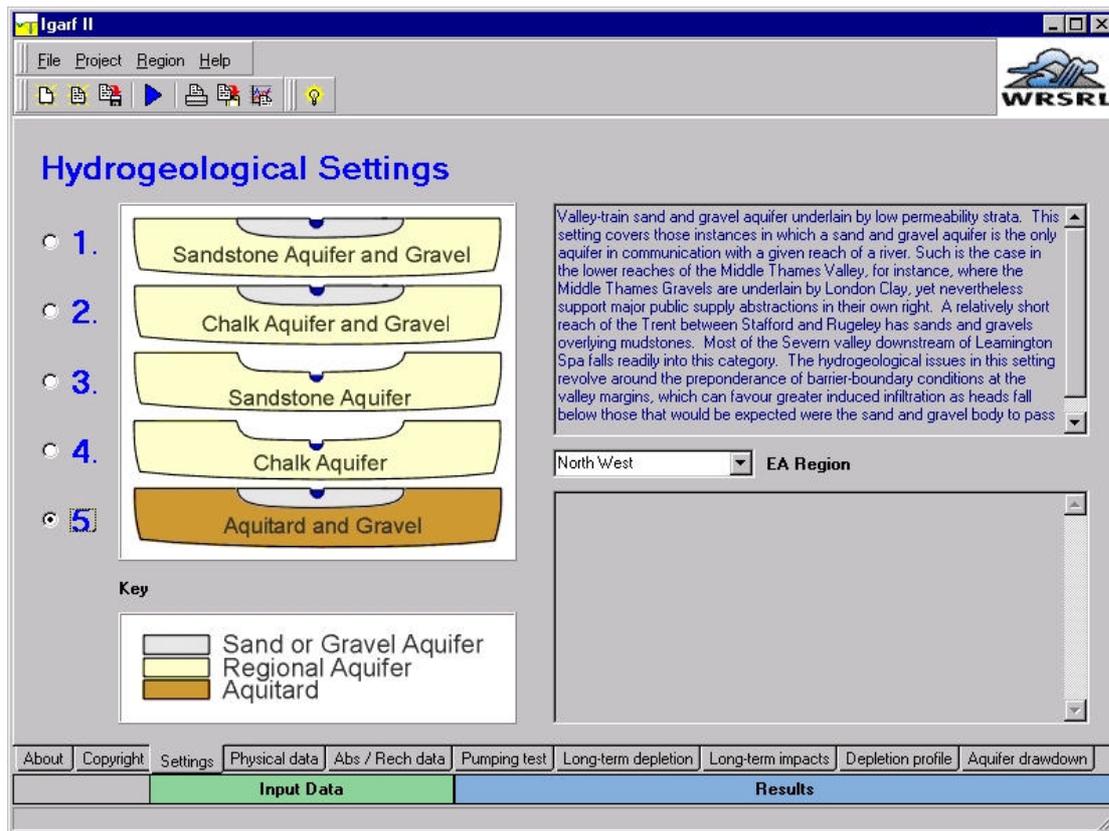
This section shows the steps taken to run the IGARF II modelling tool within the context of a licence application study, with the screen captured at each point in the process. The 3 Case studies are provided as project files with the IGARF II software.

The first step is to start IGARF II; this produces Figure 5.1.



**Figure 5.1 Initial IGARF II screen**

The next stage is to select one of the five hydrogeological settings. This is achieved by selecting the **Settings** tab towards the bottom of the screen in Figure 5.1; the display then changes to Figure 5.2. In Figure 5.2 select the appropriate hydrogeological setting: in this case it is **Aquitard and Gravel**, which is Setting 5. The text explaining about this setting will appear towards the top right of the screen.



**Figure 5.2 Hydrogeological settings**

The next stage is to input the data for this setting. This is achieved by selecting the **Physical data** tab towards the bottom of the screen. The display changes to Figure 5.3. Default data for Setting 3 will already be displayed on the screen and this data should be changed to the values in Figure 5.3. If a value is input outside the acceptable range that is given in Table 2.1, this will be modified to the acceptable limit for this variable. Note that data on the left side of the physical property data cannot be modified, as they relate to the regional aquifer which is not used for Setting 5. The remaining data can be input by selecting the **Abs / Rech data** tab towards the bottom of the screen. The display changes to Figure 5.4. The first stage is to set the **number of data points** to 1. For the abstraction data the default method of inputting data is to select the start date and the end date, and the duration is automatically calculated. By clicking on the **Duration** tick box, the start date and duration can be input and the end date is automatically calculated. The rest of the data should be input as in Figure 5.4.

Igarf II

File Project Region Help

Physical Property Input Data Default Physical Parameters

Site / run data Values

Site  Run number identifier

**Borehole data**

D Distance of borehole from river  m

**Physical property data**

Aquifer hydraulic conductivity  m/day Valley hydraulic conductivity  m/day

Aquifer thickness  m Valley thickness  m

$T_a$  Aquifer transmissivity   $m^2/day$   $T_v$  Valley transmissivity   $m^2/day$

$S_a$  Aquifer specific yield   $S_v$  Valley specific yield

**River data**

w River Width  m  $d_b$  River bed sediment thickness  m

$K_b$  River bed sediment hydraulic conductivity  m/day C Bed conductance  m/day

About Copyright Settings Physical data Abs / Rech data

**Input Data** **Results**

Figure 5.3 Physical Property Input Data

Igarf II

File Project Region Help WRSRL

Abstraction / Recharge Data

Abstraction  Compensation

	Rate $m^3/d$	Start Date	End Date	Duration
1	500	1/1	1/3	60

1  Number of data points  Duration

**Recharge**

Mean annual recharge (mm/yr)

Date of peak recharge  /

Recharge seasonality (Range 0 - 1)

**Abstractions**

**Compensation**

**Recharge**

About Copyright Settings Physical data Abs / Rech data

**Input Data** **Results**

Figure 5.4 Abstraction / Recharge Data

## 5.1.2 Results

The simulation is run by clicking on the blue forward arrow on the top of the screen. This produces five tabs above the **Results** label towards the bottom of the screen. Clicking on the **Pumping test** tab produces Figure 5.5. This shows the flow depletion in the river for the input data specified for this simulation. The display (as with all the results displays) can be modified by the user. Selecting a rectangle from top left to bottom right using the left mouse button zooms in on that area (selecting a rectangle in a different direction returns to the default). Clicking the right mouse button when the pointer is on the figure produces a complete range of graph options. Clicking on **graph** then **options** allows the limits on the axes to be specified and a zoomed in display of the pumping test data, such as Figure 5.6, can be produced. Clicking on the **long-term depletion** tab towards the bottom of the screen produces Figure 5.7. This shows the effect of the annual abstraction after up to 25 years using the input data specified. The red shows the depletion in Year 1, the red and green together the depletion after Year 2, the red, green and yellow the depletion after Year 5, and so on. Clicking on the **long-term impacts** tab towards the bottom of the screen produces Figure 5.8. This shows the effect of the annual abstraction after 25 years and compares it to the abstraction. Clicking on the **Depletion profile** tab towards the bottom of the screen produces Figure 5.9. This shows the depletion along the river for the pumping test abstraction. The distance along the river of 0 metres is where the river is closest to the abstraction well, negative values are upstream from this point and positive values are downstream. Clicking on the **Aquifer drawdown** tab towards the bottom of the screen produces Figure 5.10. This shows a cone of depression formed by the well at the end of the abstraction which has extended as far as the river, but has yet to reach the far side of the river.

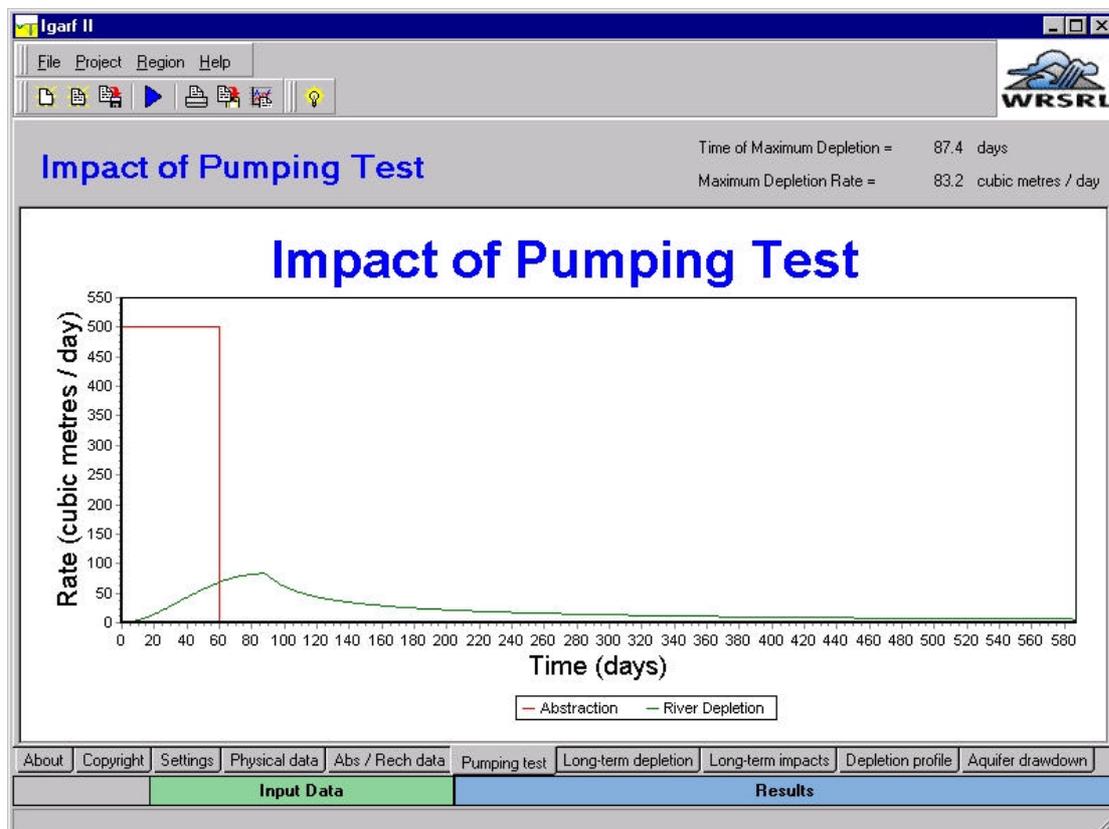


Figure 5.5 Impact of Pumping Test

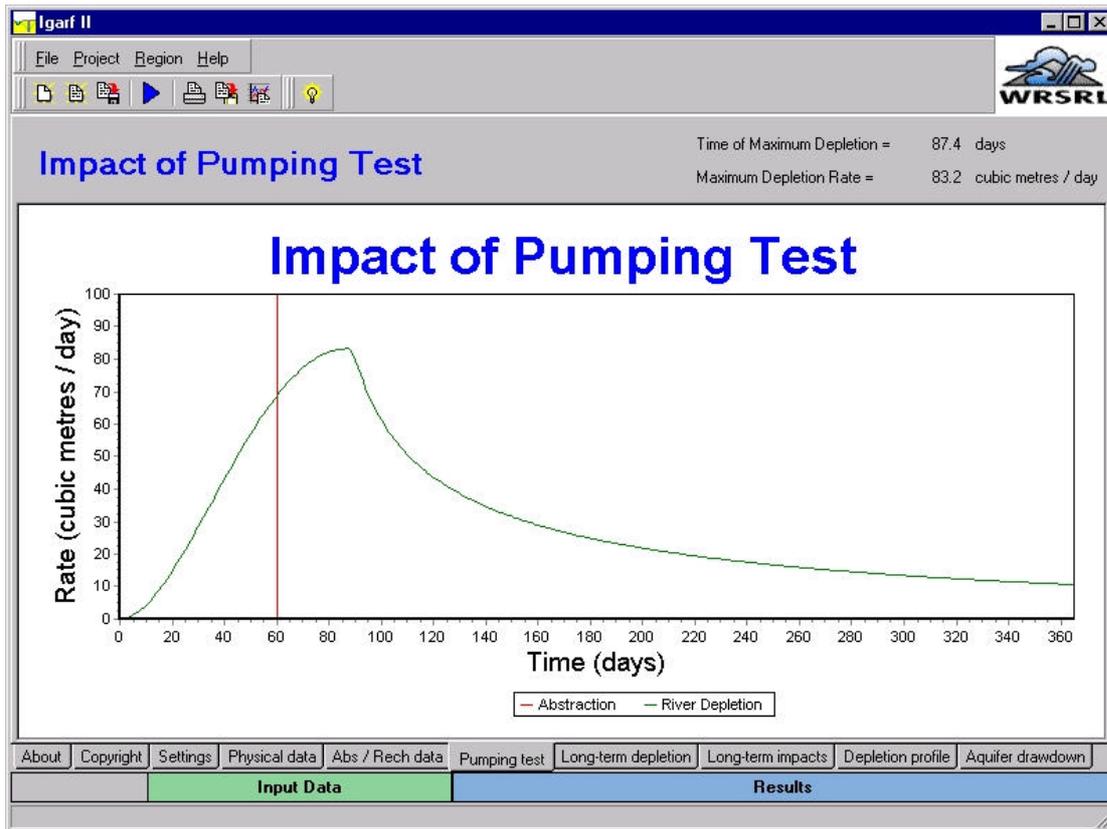


Figure 5.6 Zoomed in part of Impact of Pumping Test

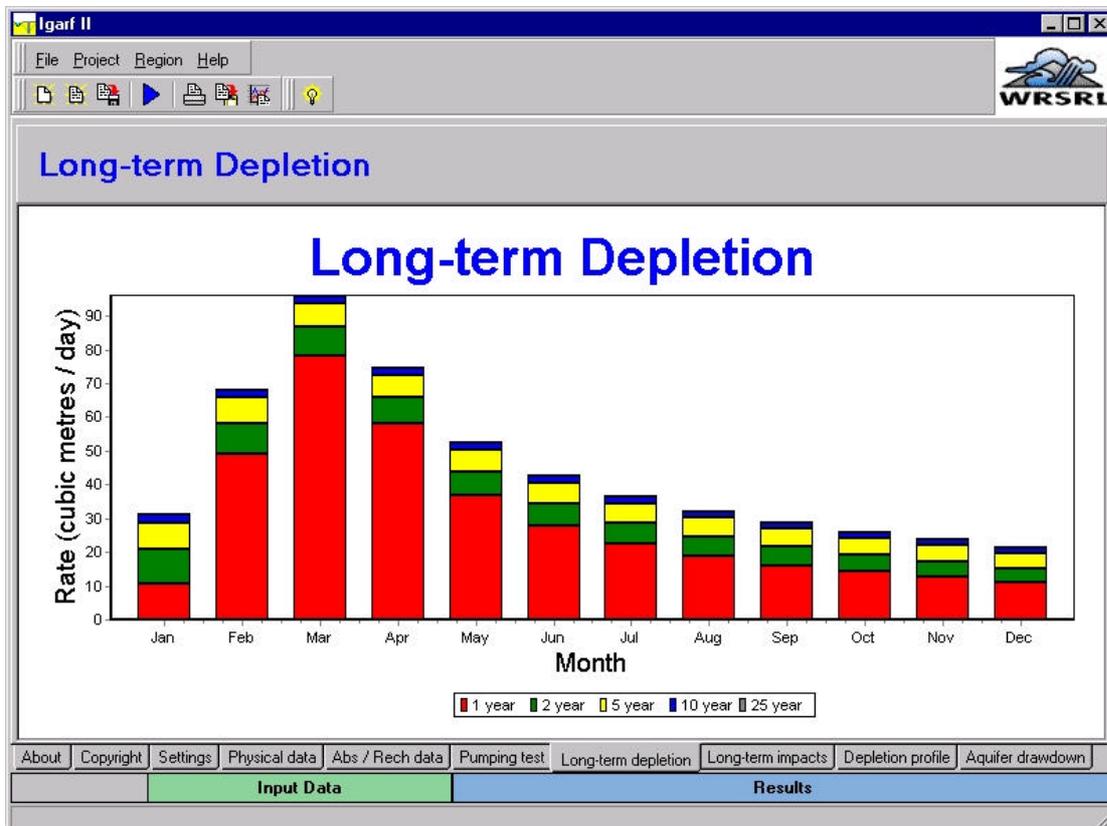


Figure 5.7 Long Term Depletion

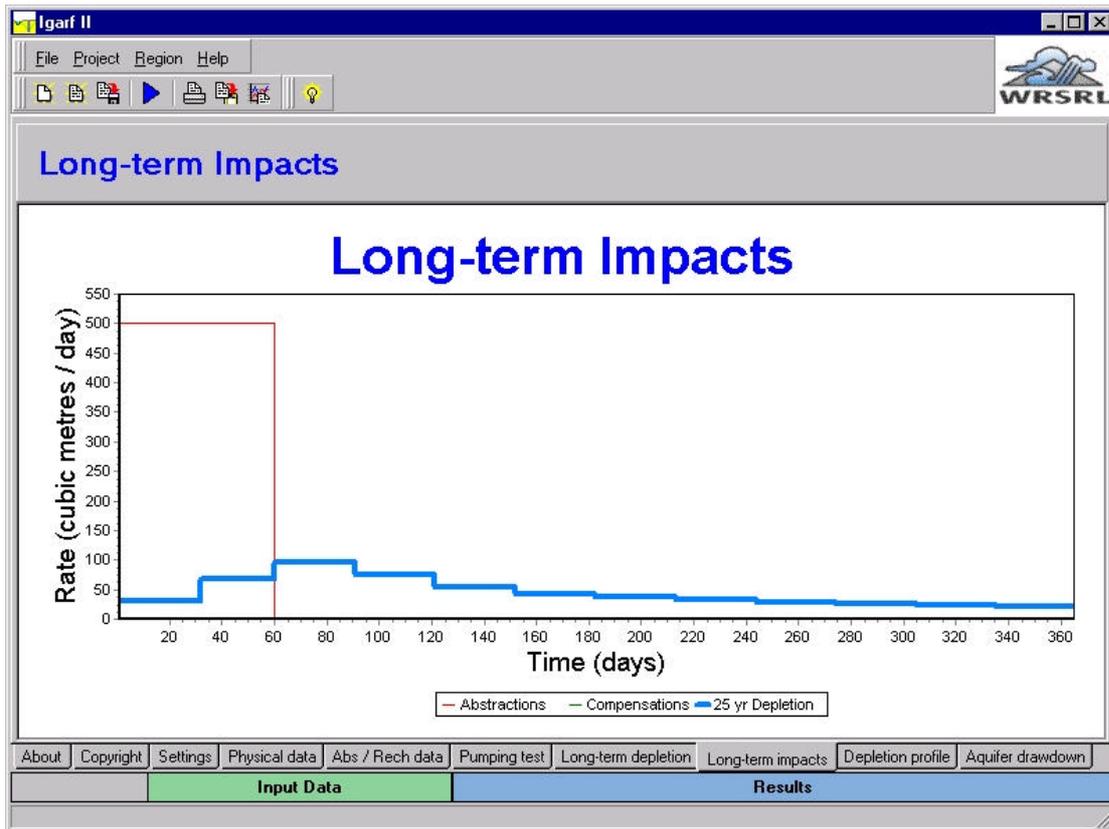


Figure 5.8 Long Term Impacts

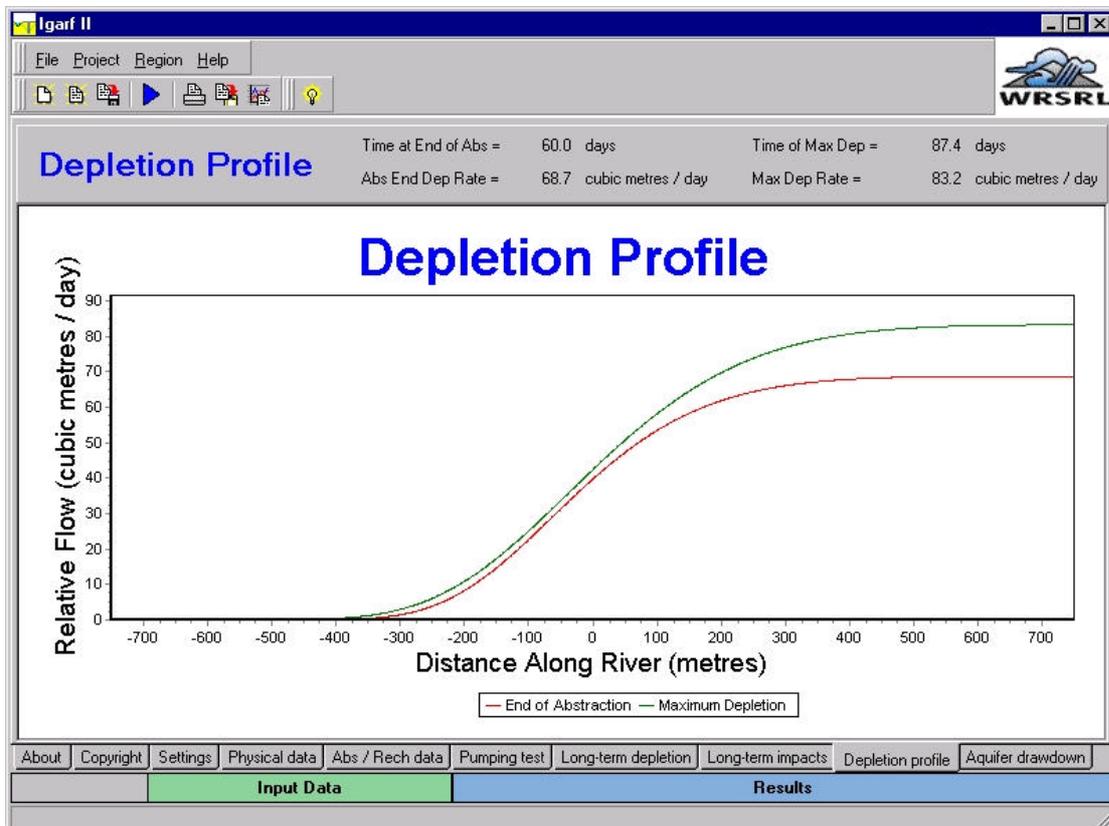


Figure 5.9 Depletion Profile

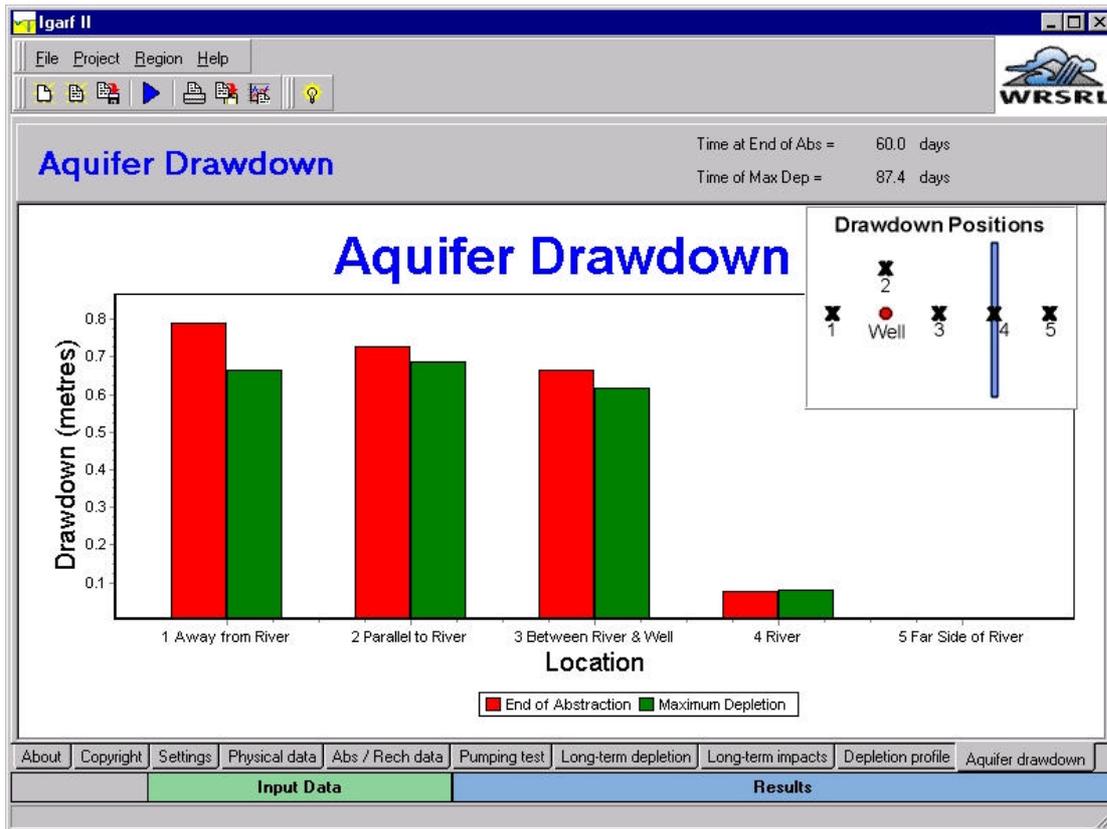


Figure 5.10 Aquifer Drawdown

## 5.2 Case Study 2

This is the same as Case Study 1 except that a different recharge duration is used. Selecting the **Abs / Rech** tab will produce the abstraction and recharge data used in Case Study 1. Case Study 2 uses a 20 day duration, so select the 60 day duration and change it to 20. Figure 5.11 is then produced, with a graph of the new abstraction. Running the simulation using the forward arrow produces the five output screens, as with Case Study 1. Selecting the **pumping test** tab shows that the maximum flow depletion is much smaller in this case than for Case Study 1, the value dropping from 83.2 to 45.9. By zooming in on the x axis between 0 and 365 and the y axis between 0 and 100, Figure 5.12 is produced and this can be compared directly to Figure 5.6. This shows again a large reduction in the maximum flow depletion but as expected the shape of both curves are similar.

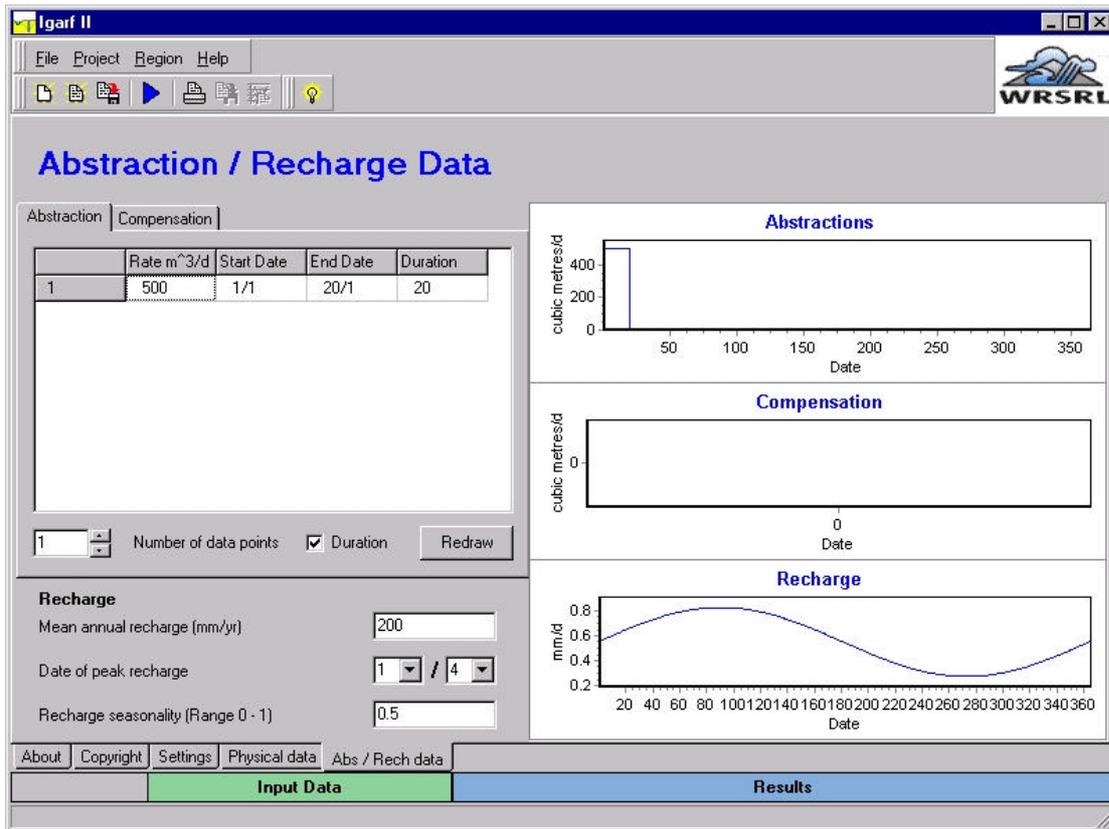


Figure 5.11 Abstraction / Recharge data (Case Study 2)

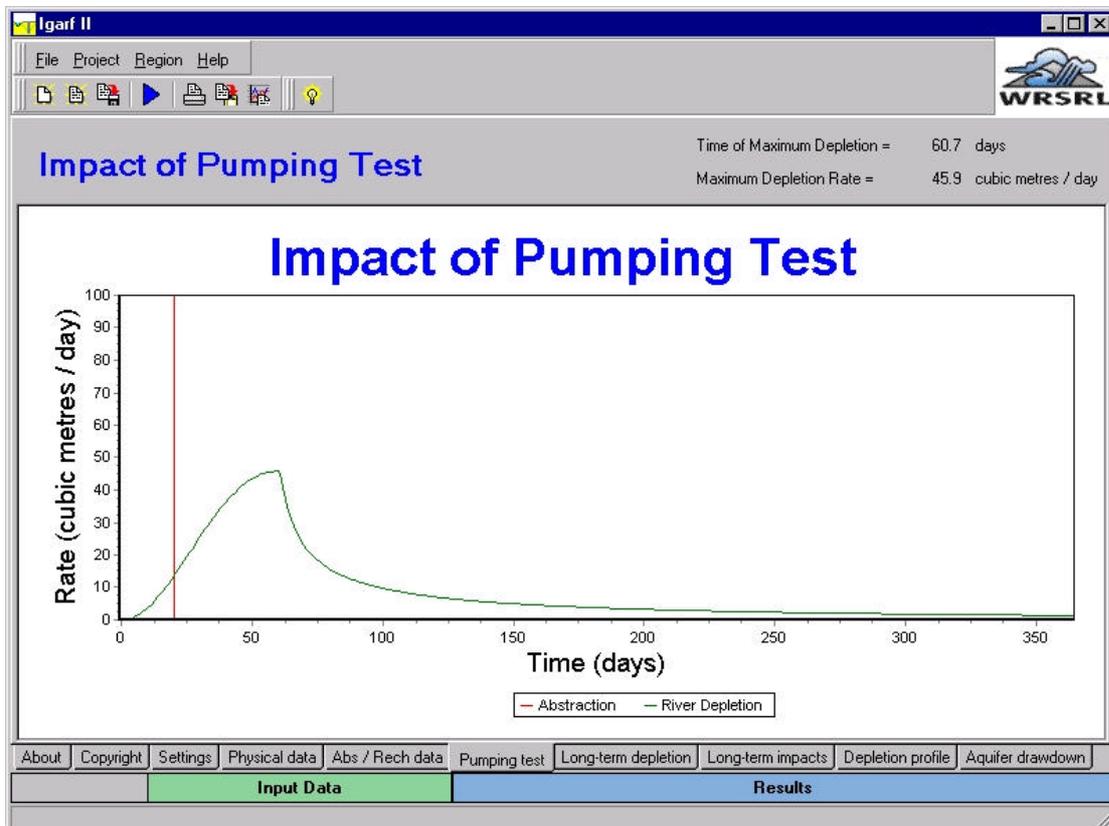


Figure 5.12 Zoomed in part of Impact of Pumping Test (Case Study 2)

### 5.3 Case Study 3

This is similar to Case Study 1 except hydrological Setting 3 is used. Select the **Settings** tab towards the bottom of the screen and select **Sandstone Aquifer**, which is Setting 3. Selecting the **Physical Data** tab produces a physical property input data screen which can be seen in Figure 5.13; this is very similar to Figure 5.3. The difference is that the sandstone regional aquifer data can now be input whilst the gravel aquifer data cannot be input. The numbers for the sandstone aquifer should be changed so they are the same as Figure 5.13. The remaining numbers for this screen and those in the abstraction / recharge screen are the same as in Case Study 1 (i.e. change the abstraction duration back to 60 days).

Running the simulation produces the five result graphs as in Case Study 1. The long-term depletion graphs can be seen in Figure 5.14. Compared to the results from Case Study 1, which can be seen in Figure 5.7, this graph shows a lower flow depletion in the river in response to the abstraction. The maximum flow depletion in the first year in this case study occurs in March and is about  $48 \text{ m}^3/\text{day}$ , whereas in Case Study 1 it was also in March but was  $72 \text{ m}^3/\text{day}$ .

**Figure 5.13 Physical Input Data (Case Study 3)**

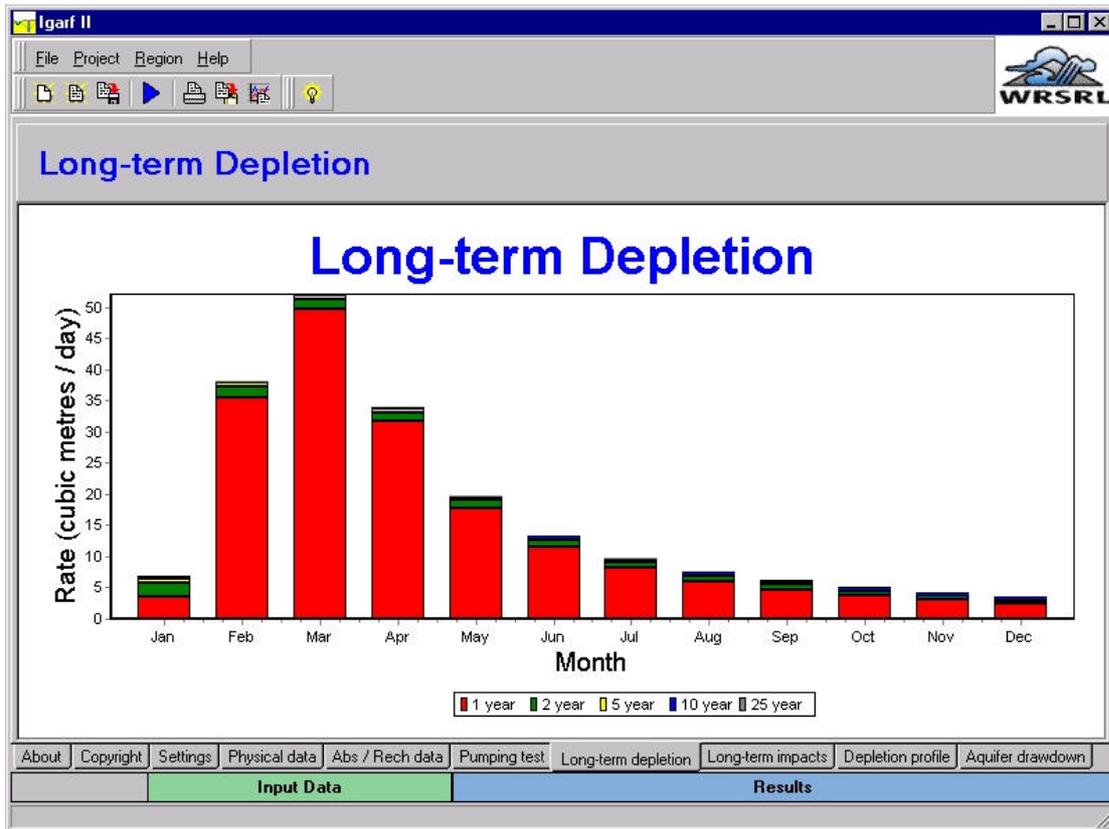


Figure 5.14 Long Term Depletion (Case Study 3)

## **ACKNOWLEDGEMENTS**

The authors would like to thank all of the Agency staff who have made contributions to this project. We thank in particular the members of the project board who have participated in many interesting and fruitful discussions that have helped clarify our ideas and to take forward all of our thinking on methods of evaluating the impacts of groundwater abstractions. We thank all of the Agency staff from regional and local offices who have responded to the questionnaire and to further requests for data, and who participated with enthusiasm in the first project workshop. We would also like to thank Prof. Enda O'Connell who put forward the original suggestion to use the method of combining neural networks with numerical modelling results for this project.

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