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

R&D Project Record W6-046/PR

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

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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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PHASE 2 – "A NUMERICAL MODELLING APPROACH TO THE ESTIMATION OF IMPACT" (IGARF II)

Inception Report

January 2000

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FOREWORD

This inception report is the first outcome of the Environment Agency project "Impact of groundwater abstractions on river flows: phase 2 – a numerical modelling approach to the estimation of impact (IGARF II)", EA project no. W6-046. The project started in December 1999, and is managed by a Project Steering Committee under the Chairmanship of Stuart Kirk, EA National Groundwater and Contaminated Land Centre.

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1 INTRODUCTION

The Environment Agency have implemented a programme of research and development, with the aim of developing numerical software tools and procedures to help Agency staff estimate the impact of groundwater abstractions on river flows. The programme is entitled "Impact of Groundwater Abstractions on River Flows" (IGARF). The first phase of this programme has been completed, and a software tool has been developed by Environmental Simulations Limited which uses simple analytical solutions to the equations describing river-aquifer interactions, implemented in a user-friendly Excel spreadsheet. The second phase of the programme seeks to produce an approach and tool that has better capabilities to represent realistic river-aquifer interactions than is possible with the IGARF I tool. The contract to develop this tool has been awarded to the Water Resource Systems Laboratory (WRSRL), Department of Civil Engineering, University of Newcastle upon Tyne, and work started in December 1999.

The approach proposed by WRSRL uses a combination of numerical model simulations of generic river-aquifer systems, and neural networks to mimic the input-output characteristics of the numerical simulations. The outcome of the project will be a software tool comprising of a user-friendly Graphical User Interface (GUI), and neural network software embedded within the GUI. Although the final software tool will not use numerical model simulations, the results from a large number of model simulations will be implicit within the tool. It is expected that the tool will be comparable with the IGARF I tool in its ease of use.

Results from the first two tasks of the IGARF II project are given in this report. These tasks are:
1) to review available information relevant to the project; and
2) to identify a small set of hydrogeological 'settings' which encompass the wide variety of river-aquifer configurations that exist in England and Wales.

The task of identification of settings is of crucial importance to the project, as it will form the basis upon which the numerical model simulations will be designed and executed. The definition of these settings will draw upon the combined experience of the authors of this report, and of a range of experts and practitioners both within the Environment Agency and within the wider hydrological community. *This first draft of the report does not include information received from Environment Agency staff or other organisations which are being consulted as part of the information search.*

2 INFORMATION SEARCH

2.1 Objectives

The objectives of the information searches were:

a) to identify the range and type of hydrogeological conditions (river-aquifer interactions) that need to be considered for this project;
b) to consider the options for the development of a suitable approach;
c) to assess in particular the effects on river flow depletion of (i) seasonal recharge patterns and (ii) the distances of boreholes from rivers.

To achieve these objectives, searches were undertaken for:

1. conceptual literature relating to river-aquifer interactions and the impacts of groundwater abstractions on river flows (Section 2.3);
2. existing numerical modelling tools relevant to this study (Section 2.4);
3. information and data from case studies that may be relevant to this study (Section 2.5).

Information and data from case studies will also be used within this project for validation of the generic numerical models. Site-specific model validation does not, however, fall within the remit of this project.

2.2 Information Sources Consulted

The sources of information consulted included:

- the reports on the Agency's IGARF I project (Environment Agency, 1999a,b);
- published (e.g. Younger, 1995) and unpublished (Younger, 1987; Younger, 1990) literature reviews on stream-aquifer interactions available in house at WRSRL;
- existing professional contacts of the WRSRL;
- a range of library services, including relevant indexing and abstracting databases;
- World Wide Web sources, including US EPA and USGS;
- Environment Agency staff.

A summary list of the key contacts, sources, World Wide Web addresses etc. which were consulted is given in Appendix 1. A draft letter to be sent to hydrological organisations in the UK and neighbouring countries is given in Appendix 2.

2.3 River-Aquifer Interactions and Impacts of Ground Abstractions

2.3.1 Processes

Details of the main processes involved in river aquifer interactions were considered in the IGARF I study (Environment Agency, 1999); this information is summarized here.

Rivers can either gain water from or lose water to aquifers, the direction and rate of flow depending on the difference between the river stage elevation and the groundwater heads and the hydraulic connection between the two:

- a gaining river occurs when the aquifer head is above the river stage, and there is a flow from the aquifer to the river;
- a losing river occurs when the aquifer head is below the river stage, and there is a flow from the river to the aquifer;
- a disconnected river occurs when the aquifer head falls below the base of the river, and there is a column of water from the base of the river bed to the water table.

Other important factors affecting this relationship between the river and aquifer are:
- geomorphology of the surrounding land. Upstream rivers have a different response to downstream river
- bank storage. Banks can have a significant effect in attenuating flood flows. The storage occurs during high flows and is released as the river level drops.
- sediments in the river bed. Fine sediments are deposited in the river-beds and banks in many rivers and these sediments can cause significant resistance to the flow of water between the river and aquifer (Younger et al., 1993). In disconnected rivers this can cause the aquifer material between the river-bed and the water table to become unsaturated.

2.3.2 Types of aquifer

The principle aquifers in England and Wales are in the post-Carboniferous younger rocks and include the Chalk, the Middle Jurassic Limestones, the Lower Cretaceous Sandstones and the Permo-Triassic Sandstones (Downing, 1993). These can be either confined or unconfined. Many of the major rivers in the UK also run along sand and gravel alluvium valleys and these can be locally significant aquifers. Downing *et al*. (1974) and Downing (1993) reviewed river aquifer interactions for UK aquifers.

For all the main aquifers there are examples of gaining rivers, losing rivers and disconnected rivers. This depends on the local conditions such as recharge from the unsaturated zone and nearby abstractions. However, there are distinct hydrogeological settings that depend on the aquifer types around the rivers. Examples of information published for a variety of aquifer types are given below.

Chalk is the most important and widespread aquifer in the UK, with approximately half the groundwater sources coming from the chalk (Headworth *et al*. 1982). Storage and permeability are almost totally restricted to fissures, which generally make up about 1-2% of the total volume and comprise an intersecting network of bedding planes, joints and fractures. Therefore Chalk aquifers generally have a high transmissivity and a low storativity. Headworth *et al*. (1982) reviewed some of the data on the effect of groundwater abstractions from unconfined Chalk aquifers in the UK and found that in general the top 20-50m below the water table provides most of the aquifer yield. Headworth *et al*. (1982) also consider the effect of abstractions from a Chalk aquifer on the Candover stream, a tributary of the river Itchen, in Hampshire. Keating (1982) considers the same river but from a modelling perspective. Other recent studies include Morel (1980) and Rushton *et al*. (1989) who consider the effect of abstractions from Chalk aquifers in the upper Thames basin from a modelling perspective. Owen (1991) consider the effects of abstractions from Chalk aquifers on the River Colne and its tributaries in the Chilterns. Cross *et al*. (1995) consider the interaction between aquifer and rivers in the east Kent chalk aquifer during the 1988-92 drought. Robins *et al*.

(1999) considers the long-term management of river aquifer interactions in the Chalk South Down aquifers.

Younger *et al.*, (1993) considers integrated fieldwork and modelling in the chalk aquifers in the middle Thames from Oxford to Slough. However, the river aquifer interactions are different from many of those considered above because the river channel flows on gravel river sediments with the Chalk aquifer below and surrounding the gravel. The River Thames is also lined with silts of low hydraulic conductivity, which the modelling work showed to be a much more sensitive parameter than the aquifer parameters.

Sandstone aquifers have very different properties from those of Chalk. Generally, interstitial porosity means there is a much higher storativity than in chalk but fewer joints and fractures results in a lower transmissivity than the Chalk. Seymour *et al.* (1998) consider the Flyde aquifer in Lancashire. This is a Permo-Triassic Sandstone, which in some areas is confined by boulder clay and in other cases is unconfined. Considerable abstraction takes place from a variety of boreholes. Younger (1998) considers the effect of groundwater abstractions on the carboniferous sandstone of North Numerberland. Rushton and Tomlinson (1995) consider the effect on surface water of pumping from the Permo-Triassic Sherwood Sandstone aquifer in Nottinghamshire.

The interactions of surface water and groundwater is particularly complicated in Limestone aquifers because of the complex hydraulic interconnections of fractures in the rocks. The storativity and transmissivity vary considerably between different Limestone types. Carey and Chanda (1998) analysed the relationship between the River Derwent and the Corallian Limestone aquifer in North Yorkshire. Groundwater abstractions of water 1.5 km from a river are thought to be mainly supplied by water lost from swallow holes in the stream bed. Gray (1995) considers the effect of groundwater abstractions from Oolitic Limestone on flow in the Malmesbury Avon catchment in the southern Cotswolds. There was found to be hydraulic connection between the two main aquifers and the river system in the lower part of the catchment. Rushton and Tomlinson (1999) modelled the Lincolnshire Limstone aquifer in South Lincolnshire. They found that a combined surface-groundwater model provided a significant improvement over their previous models.

There are fewer examples of the effect of groundwater abstractions on river discharges in river gravels surrounded by an aquitard. Younger *et al.* (1993) considers abstractions from the river gravels at Dorney in the Thames basin, which are underlain by silt and clay aquitards. Chen *et al*. (1997) consider the abstraction from river gravels in the River Spey in North East Scotland.

2.4 Numerical Modelling Tools

Analytical models for river aquifer interactions are summarised in Environment Agency (1999a), where a spreadsheet was developed which predicts the river depletion from groundwater abstractions using one of three analytical models (Theis,1941; Hantush, 1959; and Stang 1980 / Hunt 1999). All of these models make various assumptions that are specified in detail in Environment Agency (1999a). A key problem which reduces the quality of the predictions is that the approximation that the transmissivity is independent of head is not valid in shallow aquifers. Any aquifer heterogeneity or combination of aquifers, such as a gravel alluvium aquifer in the river valley overlying a sandstone aquifer, is also not valid.

Improvements on these analytical models can be made by using numerical modelling techniques. Recent developments are reviewed in Dillon (1983), Winter (1984), Vasiliev (1987), Younger (1987, 1990), Winter (1995) and Winter (1998).

A numerical model of river aquifer interactions generally requires simulation of the surface water and groundwater by employing numerical solutions of equations for surface water routing and groundwater flow. Coupling between two models is also required, and most models use a simple Darcy calculation (Winter, 1995). In this the river is included within a normal grid cell and exchange between the river and the aquifer is vertical. The exchange flow is usually equal to the channel-bed conductance multiplied by the contact area between the channel and the aquifer and by the hydraulic gradiant.

The industry standard groundwater flow model that has been developed by the US geographical Survey is MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). This models two or three dimensional groundwater flow using a finite-difference representation of the equations governing flow in confined or unconfined multi-aquifer systems. Timesteps of days and months are acceptable and the spatial data is also very flexible. To simulate river-aquifer interactions add-on modules have been developed. The original module was RIVER, which considered a constant river head with respect to time and hence no river flows. The STREAM module (Prudick, 1989) considered instantaneous flow routing. The BRANCH module (Perkins and Koussis, 1996) considered the diffusive wave approximation of the Saint-Venant equations and was coupled to MODFLOW to create the MODBRANCH model (Swain, 1994). In all of these models the flow between the surface water and groundwater is vertical and depends on a channel bed conductance and the head difference between the aquifer and river. However, since groundwater flows are usually three dimensional in nature, and this is not represented in the model, the conductance term must normally be calculated and does not have a clear physical representation (McDonald and Harbaugh, 1988). Recent examples of using MODFLOW for applications involving river aquifer interactions include Modica *et al*. (1997), Chen *et al*. (1997), Carey and Chanda (1998) and Wroblicky *et al*. (1998).

In additions to the simplifications involving the river aquifer interactions considered above, MODFLOW does not calculate evapotranspiration, infiltration, unsaturated zone flow or recharge. Recharge is an input to the model, calculated separately, usually using river base flows or simple representations of the water balance in the unsaturated zone, assumed to be valid for the long timesteps used. Havard *et al*. (1995) made improvements to MODFLOW by developing the LINKFLOW module to simulate one-dimensional unsaturated flow.

Other models, in which recharge is an input to the model and which employ a similar coupling technique, include those of Wilson and Akande (1995) and Rushton and Tomlinson (1995). Mwaka *et al*. (1995) consider a similar model and coupling technique but sediment erosion and routing are also considered.

Approximately three-dimensional surface groundwater coupling is included in some models, e.g., SHETRAN (Ewen *et al*., in press) and ICMM (van Wonderen and Wyness 1995). This is achieved in SHETRAN (Parkin and Adams, 1998) by including the rivers and narrow bank elements along the boundary of grid elements. Each element is made up of many horizontal layers, called cells, and flow between any adjacent cells is allowed to occur, depending on Darcy's law and mass continuity. This produces an approximately three-dimensional flow field near the channels. SHETRAN also provides the facility to simulate unsaturated conditions under the stream channels and to include data for layered porous media beneath the channel.

Comparisons of analytical and numerical solutions on the effect of stream depletion by abstractions can be found in Spalding and Khaleel (1991), Sophocleous *et al*. (1995) and Conrad and Beljin (1996). These comparisons are useful as the effects of the simplifications in the analytical models can be evaluated. Spalding and Khaleel (1991) consider Theis and Hantush analytical solutions but not the more complex Stang / Hunt solution. The numerical model used was AQUIFEM, a two-dimensional saturated groundwater flow model. Their analysis shows that the most important errors in the analytical solutions are the effects of not including sediments, the simplification that the river fully penetrates the aquifer and that aquifer storage beyond the stream is not considered, although all of these are included in the Stang / Hunt solution. Sophocleous *et al*. (1995) compare an analytical solution similar to the Hantush solution and a MODFLOW numerical model which uses the RIVER module. They also report that simplifications in the analytical models concerning sediments and penetration of the river are the most important aspects. However, they also considered aquifer heterogenity, which is not included in analytical models and it was also found to have a significant effect. Similar effects were found by Conrad and Beljin (1996), who also used MODFLOW and a similar analytical model, but the analytical model also specifies the proportion of the well water that is derived from induced infiltration.

Artificial neural networks (ANNs) are a recent innovation in water resources technology which have potential for use in river-aquifer interaction studies. An 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. Their use in the UK within a water resources context has been largely pioneered by the Newcastle team (Rao and Jamieson, 1997; Rao and O’Connell, 1999). Within the field of river-aquifer interaction studies, ANN’s have the potential to represent the relationships between groundwater abstraction data and river flow depletion using data from numerical models and from field observations where available.

It is worth noting here that a recent review of priority research areas for hydrological and hydrogeological modelling in the context of low flows, groundwater and wetland interactions (Acreman and Adams, 1998) identified the need to improve models in this context as a high priority.

2.5 Relevant Case Studies

Case studies are required for the generic validation of the modelling approach developed in this project using each of the scenarios identified in Section 3. The aim of the testing within this project is to ensure that the models reproduce the typical behaviour expected for each scenario. However, it is anticipated that detailed information on river-aquifer interactions will be available from some of the case studies, which will also be of use in validation studies at specific locations in later projects.

A list of possible case studies which may be of use within this project and later projects is given below. The data available from these studies have not been evaluated at this stage of the project. *It is expected that more sites are likely to be identified from the consultations with Environment Agency staff and with other hydrological organisations.*

Site name:	**Otterton No 4 Borehole**
Location:	River Otter, South Devon
Aquifer Type:	Unconfined Sandstone near river, confined further away
River channel:	Some river alluvium
Organisation:	Environment Agency
Data collected:	Pumping Test data and licensed abstraction rate
Reference:	Environment Agency (1999b)
Description of study:	Effect of abstraction on river flows from a borehole 25m from the river Otter

Site name:	**Houghton St. Giles**
Location:	River Stiffkey catchment, North Norfolk
Aquifer Type:	Unconfined Chalk
River channel:	
Organisation:	Environment Agency
Data collected:	Pumping Test data and effect of pumping on river flows, licensed abstraction rates
Reference:	Environment Agency (1999b)
Description of study:	Effect of abstraction on river flows from two borehole 250m from the river Stiffkey

Site name:	**Helshaw Grange Abstraction Borehole**
Location:	River Tern catchment, near Shrewsbury
Aquifer Type:	Unconfined Sandstone aquifer
Organisation:	Environment Agency
River channel:	Some river alluvium
Data collected:	Pumping test data and licensed abstraction rate
Reference:	Environment Agency (1999b)
Description of study:	Effect of abstraction on river flows from a borehole 400m from the river Tern

Site name:	**Candover**
Location:	Tributary of the river Itchen, in Hampshire
Aquifer Type:	Unconfined Chalk
River channel:	

Organisation: Southern Water Authority
Data collected: Significant data from 1972-1975. Pumping test data and abstraction rates from three boreholes. Fortnightly measurements from 17 purpose built observation boreholes, fifty existing boreholes and five riverside tubes. Flows in the Candover stream from one permanent guaging station and five temporary weirs. Several nearby rainguages.
Reference: Southern Water Authority (1979)
Description of study: Effect of increasing abstraction in three boreholes on flow in the Candover stream

Site name: Colne
Location: Focus on part of the river Colne catchment in the Chilterns north of London, e.g. the river Ver or River Misbourne
Aquifer Type: Unconfined Chalk
River channel:
Organisation: Environment Agency (formerly NRA)
Data collected: A variety of raingauges, river flow gauging stations, river flow spot gauging stations, groundwater abstraction boreholes and observation boreholes
Reference: Owen (1991)
Description of study: Effect of abstraction on flows in the river Colne and its tributaries

Site name: Thames at Gatehampton
Location: Between Reading and Oxford
Aquifer Type: Unconfined Chalk
River channel: Gravel with streambed sediment
Organisation: Thames Water
Data collected:
Reference: Younger *et al*.(1993)
Description of study: Effect of streambed sediment as a barrier to groundwater pollution

Site name: Thames at Dorney
Location: Near Windsor
Aquifer Type: Gravel
River channel: Streambed sediment between the river and gravel
Organisation: Thames Water
Data collected:
Reference: Younger *et al*. (1993)
Description of study: Effect of streambed sediment as a barrier to groundwater pollution

Site name: Fylde Aquifer
Location: Focus on part of the large aquifer between Preston and Morecambe Bay
Aquifer Type: Unconfined and confined Sandstone
River channel: Significant river alluvium in places
Organisation: Environment Agency

Data collected:	27 Rainguages, 12 river flow gauging stations and 38 spot gauging stations beween 1994 and 1996. Monthly records from 50 groundwater observation boreholes and 21 abstraction sites.
Reference:	Seymour *et al*. (1998)
Description of study:	Develop an understanding of the mechanisms of groundwater recharge and flow and groundwater/surface water interaction

Site name:	**Sherwood Sandstone Aquifer**
Location:	Focus on part of the large aquifer typically 10 km wide between Nottingham and Doncaster
Aquifer Type:	Unconfined and confined Sandstone
River channel:	
Organisation:	Environment Agency, University of Birmingham
Data collected:	A variety of rainguges, river flow guaging stations, river flow spot gauging stations, groundwater abstraction boreholes and observation boreholes
Reference:	Rushton and Tomlinson (1995)
Description of study:	Develop an understanding of the mechanisms of groundwater recharge and flow and groundwater/surface water interaction

In addition to the above list, further useful information is likely to become available from the following sources in the near future:

- The Eden catchment, within which a large-scale river-aquifer interaction field experiment will be initiated during 2000, as part of the CHASM (Catchment Hydrology and Sustainable Management) initiative, with initial funding from the NICHE programme (National Infrastructure for Catchment Hydrology Experiments);
- The Frome, Pang/Lambourne, and Tern catchments, which are being studied within the NERC LOCAR (LOwland CAtchment Research) thematic programme, with initial funding from the NICHE programme;
- *** Ann Calver (IH) study into hydraulic properties of river bed sediments*

3 HYDROGEOLOGICAL SETTINGS

3.1 Objectives

The development of a generic tool for the assessment of the impacts of groundwater abstractions on river flows requires that some assumptions be made about the kinds of hydrogeological circumstances in which such assessments are most likely to be made. It would be simply impossible to develop a tool so generic that it covered every eventuality in England and Wales; however, it is our contention that a tool can be produced which reflects the majority of circumstances within which assessments of this sort are likely to be made by Agency licensing officers. To achieve this, it is necessary that we base the development of modelling tools on configurations (i.e. combinations of positions) of rivers, aquifers and aquitards in and near valleys which accord with common experience. Once having defined such configurations, virtually all other aspects of the hydrogeology (e.g. recharge regime; topography; structural relief on geological contacts; numbers, positions and rates of pumping wells; streambed properties etc) can be treated as simple *parameters* to be defined on a case-by-case basis, rather than basic, immutable elements of the system.

To facilitate the development of the IGARF-II modelling tool, we therefore propose to adopt six generic "hydrogeological settings", which we consider encompass the vast majority of river-aquifer-aquitard configurations likely to be encountered in practice. These settings are illustrated in Figure 1. It is important to realise that topographic relief is not illustrated in Figure 1. In hydrogeological terms, surface steepness may be viewed as just one of the several factors which govern the degree to which effective rainfall is partitioned between direct runoff and infiltration, and as such it can be taken into account in choosing appropriate recharge values.

The following section presents a brief commentary on Figure 1, covering the settings envisaged, their accordance with reality, and their proposed use as a platform for code development under IGARF-II.

Before proceeding to this commentary, it is perhaps worth briefly noting here that the definition of "standardised" hydrogeological settings is by no means unusual in applied groundwater hydrology. Perhaps the earliest examples of the *genre* are the standardised ground water regions of the United States, which were initially promoted by the US Geological Survey to facilitate comparative hydrogeological studies (Heath, 1984), and were subsequently used as the basis for extrapolating ground water vulnerability mapping (using the DRASTIC index) from data-rich to data-poor areas (Aller *et al*., 1987). A more recent example is provided by Robins (1999), who defined standardised hydrogeological settings for crystalline basement terrain, to allow definition of credible protection zones for small ground water sources without recourse to intensive field investigations at every site. The hydrogeological settings outlined below are thus no more than a further application of a well-tried concept to a different ground water management issue.

3.2 Preliminary Classification of Hydrogeological Settings

Figure 1 and the following commentary are offered solely as working draft suggestions of a preliminary nature. The authors confidently expect that these suggestions will be subjected to strong (though hopefully constructive) criticism. At the very least, however, it is hoped that these settings will serve as a useful "conversation piece" for forthcoming discussions with practitioners within the Agency.

The six settings outlined on Figure 1 are in part discriminated on the basis of aquifer diffusivity (D), which is the ratio T / S (transmissivity / storativity or specific yield). Values of D are typically low to moderate in the Triassic Sandstones (2×10^3 to 1×10^4 $m^2.d^{-1}$), but high in the Chalk (1×10^5 to 4×10^5 $m^2.d^{-1}$). In Figure 1, Settings 1 and 3 are for "moderate diffusivity" aquifers (e.g. the Sandstones), whilst Settings 2 and 4 correspond to "high diffusivity" settings (e.g. Chalk). The distinction may seem a little artificial at first inspection, as the reason for making it is not especially geological, but rather lies in the fundamental contrast in the dynamics of river-aquifer exchanges between aquifers of contrasting diffusivity. This has been most thoroughly documented in relation to the prediction of "net gain" for river augmentation boreholes in the UK (see, for instance, Downing *et al*, 1981). In essence, it has been found that the higher the diffusivity of the aquifer, the further must the river augmentation boreholes be from the river if net gain is to be maximised. This is because recirculation of water from a river to adjoining boreholes is likely to be most vigorous where diffusivity is high. In practical terms, this distinction:

- is likely to be fairly important (in terms of computer run times etc) for the kind of modelling proposed to under-pin the IGARF-II modelling tool, and
- has the advantage that it should allow the eventual end-user of the modelling tool to simply choose between "Chalk" and "Sandstones" where they either cannot or do not wish to specify aquifer characteristics with any greater precision.

The numbered sections which follow correspond to the numbers given on Figure 1.

1. **Regional aquifer of moderate diffusivity overlain by a valley-train sand and gravel aquifer.** These are major aquifers which exchange waters with rivers *via* Quaternary sand and gravel deposits which typically line the valley floor and flanks (hence "valley train"). On a solid geology map, the rivers in question would appear to cross the outcrop of the major aquifer. On a drift geology map, the rivers will actually be flanked (and by inference underlain) by orange (sand and gravel) and pale yellow (alluvium, typically fine-grained, but usually underlain by sand and gravel) ornament, denoting the valley-train deposits. Many examples of this genre can be imagined, of which only two are quoted on Figure 1: The River Eden (Cumbria) in its lowland reaches crosses the outcrop of the Penrith Sandstones, but the channel is flanked virtually everywhere by fluvio-glacial sand and gravel deposits. While the Penrith Sandstones definitely discharge ground water to the Eden, they do so through the medium of the sands and gravels. Downstream of Burton-on-Trent, the River Trent displays a similar relationship with the Sherwood Sandstone Aquifer, receiving base flow from the latter *via* the Trent Gravels.

2. **Regional aquifer of high diffusivity overlain by a valley-train sand and gravel aquifer.** This setting is essentially similar to setting number 1, but the temporal dynamics of the river-aquifer exchange can be expected to be sufficiently more vigorous than in the case of the moderate diffusivity aquifers that a separate setting is warranted from a modelling point of view. Probably the prime example of this setting in England (at least in economic terms) is the Middle Thames Valley, where first the Corallian, and then the Upper and Middle Chalk, underlie the main channel of the Thames as it flows from Oxford through the Goring Gap and onwards to the western fringes of the London conurbation. Throughout this reach to Slough, the major carbonate aquifers (all of high diffusivity) interact with the Thames exclusively via the Middle Thames Gravel Formation.

3. **Regional aquifer of moderate diffusivity in direct contact with the river.** This setting may be viewed as "Setting 1 minus the sands and gravels", though in reality it will also correspond to many upland reaches of rivers on permeable bedrock (and hence to many sites in Wales and the Pennines), where drift is either thin or has been thoroughly fluvially incised during the Flandrian (Holocene) to ensure direct contact between the river channel and the bedrock (notwithstanding streambed sediment, which is in fact a modifying parameter across all six settings). In lowland settings, one can conceive of areas of drift-free Sherwood Sandstone in direct communication with rivers (eg the small tributaries of the Dee, and the Cote Brook, between Frodsham and Delamere in Cheshire), or the locally-important deposits of Quaternary sands termed the "Crag" in East Anglia (for instance, the extensive deposit beneath and to the east of Ipswich, which feeds groundwater as base flow to the Mill River, as well as sustaining a number of borehole abstractions).

4. **Regional aquifer of high diffusivity in direct contact with the river.** Possibly the classic example of this genre is the Chalk in the steep-sided tributary valleys of the Middle Thames, such as the Kennet and the Lambourn, where the rivers are in virtually direct contact with Chalk bedrock. Much of the outcrop of the Carboniferous Limestone in Mendip, South Wales and the Pennines would also fall into this setting, notwithstanding the perils of predictive modelling where this is extensively karstified. Other limestone aquifers also fit readily into this setting, such as the Oolites in the catchment of the Malmesbury Avon, or the Magnesian Limestone in those areas where the River Skerne has incised through the till mantle to bedrock.

5. **Valley-train sand and gravel aquifer underlain by low permeability strata.** This setting covers those instances in which a sand and gravel aquifer is the *only* aquifer in communication with a given reach of a river. Such is the case in the lower reaches of the Middle Thames Valley, for instance, where the Middle Thames Gravels are underlain by London Clay, yet nevertheless support major public supply abstractions in their own right. A relatively short reach of the Trent between Stafford and Rugeley has sands and gravels overlying mudstones. Most of the Severn valley downstream of Leamington Spa falls readily into this category. The hydrogeological issues in this setting revolve around the preponderance of barrier-boundary conditions at the valley margins,

which can favour greater induced infiltration as heads fall below those that would be expected were the sand and gravel body to pass laterally and subjacently into a regional aquifer

6. **Aquitard in a river valley underlain by a regional aquifer.** In some ways the “negative” of Setting 5, we consider here cases where the river flows over impermeable deposits, and river-aquifer exchange must occur by some leakage process. In some cases, extensional fracturing of aquitards (due to stress release in response to fluvial removal of overburden) may favour leakage in the vicinity of river channels (the implication of the dashed vertical lines in the Figure). In other cases, this may not be the case at all, and the aquifer may be virtually hermetically sealed from the overlying river. This appears to be the case in the southern part of the Vale of York, for instance, where piezometry and hydrochemistry provide no striking evidence for flow (in either direction) between the River Aire and the Triassic Sandstones *via* the glaciolacustrine clays (deposited by Devensian Lake Humber) which separate the two. It should be noted that the lateral extent of the aquitard in Setting 6 may be much greater in proportion to channel width than we have shown. Where the aquitard is thin, one might expect springs to develop at the contact with the adjoining aquifer, yielding ground water to the river via small surface tributaries, the derogation of which might itself be an issue.

By way of conclusion of this brief commentary, it is perhaps worth noting that the presence or absence of features such as riparian wetlands and springs has deliberately not been addressed (being beyond the remit of this project), but these features may be found in any of the settings. Similarly, these generic settings do not consider the presence / absence or nature of streambed sediments (despite their potentially great importance in modifying river-aquifer exchanges; Younger *et al*., 1993). These factors are essentially independent variables, which will vary as much within any one setting as they may between river-aquifer systems belonging to any of the different settings.

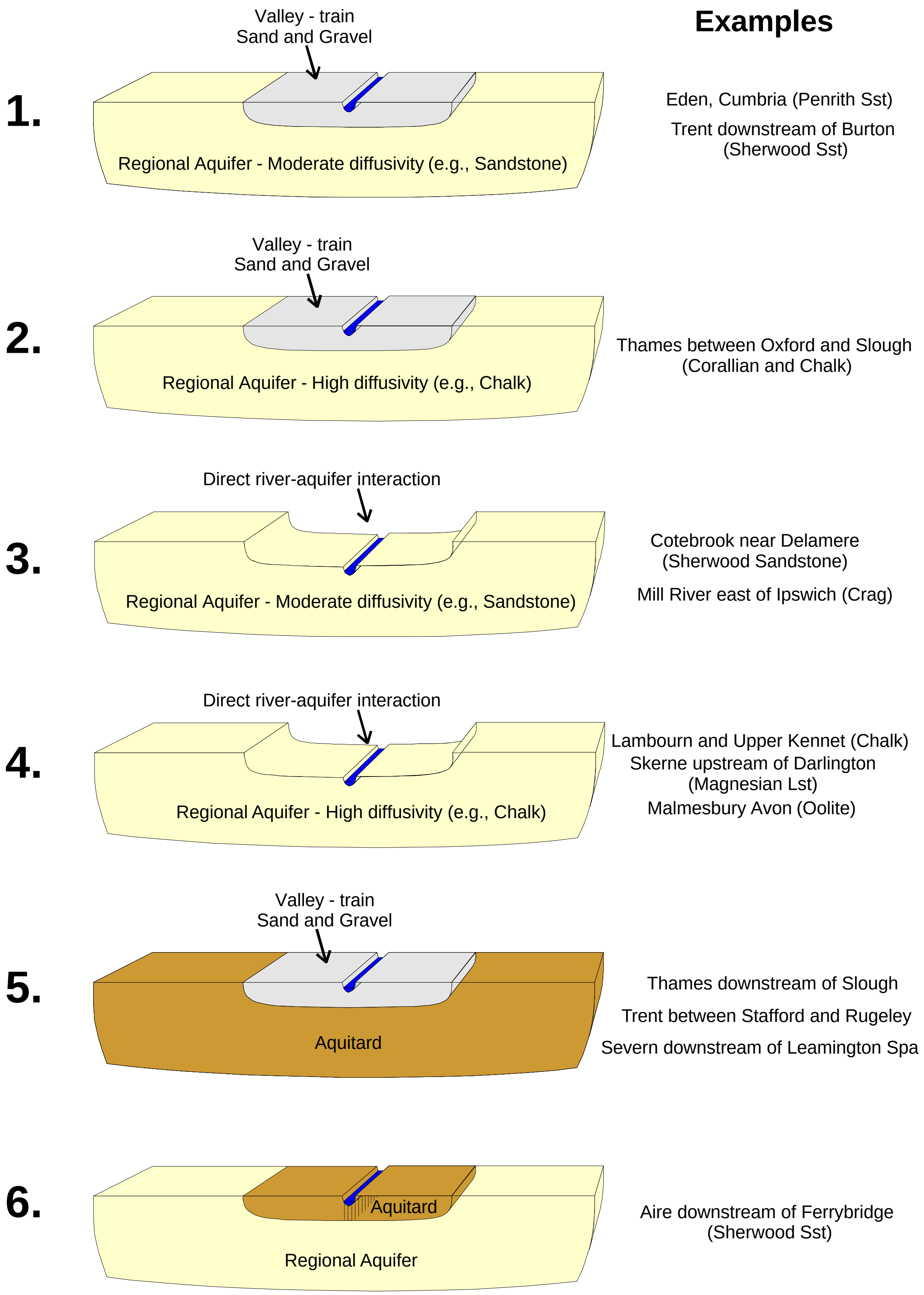

Figure 1 **Schematic illustration of 6 hydrogeological settings for river-aquifer interactions**

4 CONCLUSIONS AND RECOMMENDATIONS

The first tasks of the IGARF II project were to review information on river-aquifer interactions and the impact of groundwater abstractions on river flows, on numerical modelling tools, and on relevant case studies, and to identify hydrogeological 'settings' which will be used as a basis for developing the modelling tool.

The processes governing river-aquifer interactions and the impact of groundwater abstractions on river flows were identified and described as part of the IGARF I project (Environment Agency, 1999a). In this report, these processes are summarised, and the relevance of these processes to particular hydrogeological settings within England and Wales are described. The main classification is between chalk (and some other high diffusivity limestone) aquifers and sandstone aquifers. The importance of valley-train sands and gravels is recognised.

The main modelling approaches to river-aquifer interactions use either analytical or numerical solutions to the equations governing groundwater flow. All analytical models (the most appropriate of which have already been evaluated within the IGARF I project) have limitations on their use. The effects of these limitations have been evaluated by comparison between analytical models and either field observations or results from numerical models. Important limitations are due to partially-penetrating rivers, disconnected rivers, river bed sediments, aquifer heterogeneities, and shallow unconfined aquifers (although some of these can be addressed by the Stang / Hunt analytical model). These limitations can be overcome by the use of appropriate numerical models which can handle river-aquifer interactions. The SHETRAN modelling system (Ewen *et al.*, in press) has the capability to model all of the required processes.

A summary list of case studies is given which have been identified as being of potential relevance to the validation of the models used in this project. The validation will be carried out to ensure that the model results are typical of each of the hydrogeological settings. Direct comparison between model results and field measurements will not be made within the scope of this project. *It is likely that further case studies will be identified from the consultations with other hydrological organisations.* Evaluation of the data from the case studies will be carried out later in this project.

Six hydrogeological settings have been identified which are intended to encompass the main river-aquifer interactions within England and Wales. A distinction between high diffusivity aquifers (particularly Chalk) and moderate diffusivity aquifers (particularly Sandstones) is made. For each of these, examples are given both with and without the presence of valley-train sands and gravels, making four settings in total. In addition, the existence of valley sands and gravels as important aquifers in their own right, and rivers flowing over impermeable deposits with a more tenuous connection to a regional aquifer, provide a further two settings.

Recommendations from this initial phase of the project are:

1 to use SHETRAN as the basis for the numerical model simulations, together with an Artificial Neural Network to mimic the results from the simulations;

2 to evaluate data from the case studies to provide generic validation of numerical model simulations;

3 to consider the six proposed hydrogeological settings as a basis for model simulations and for the classification of river-aquifer systems in the IGARF II software tool.

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APPENDIX 1: Information Sources Consulted

Key Papers and Reports:

Environment Agency (1999 a)
IGARF I Project Report. Detailed references on analytical methods. Also references to comparisons of analytical and numerical solutions. References to reviews of stream aquifer interactions in the UK and references to more recent case studies in the UK.

Younger (1987) and Younger (1990)
Detailed review of everything to do with stream-aquifer interactions. Very useful information on numerical modelling in a chronological order.

Younger (1995)
BHS Occasional Paper. Modeling river-aquifer interactions 1985. Both case studies and modelling techniques

Parkin and Adams (1998)
Review of case studies and a comparison of MODFLOW and SHETRAN version 4.

Web Pages:

United States Geological Survey (www.usgs.gov)
United States Environmental Protection Agency (www.usepa.gov)
United States National Groundwater Association (www.ngwa.org)
United States Department of Agriculture (www.usda.gov)
Environment Agency of England and Wales (www.environment-agency.gov.uk)
British Geological Survey (www.bgs.ac.uk)
Institute of Hydrology (www.nwl.ac.uk/ih)
British Hydrological Society (www.salford.ac.uk/civils/BHS/homepage.html)

Web Searches using Search Engines, with Keywords:

Stream (or river) aquifer
River groundwater
Surface water groundwater

BIDS and other Electronic Databases Searches, with Keywords:

Stream (or river) aquifer
Surface water groundwater
Groundwater abstractions
Chalk aquifer
Sandstone aquifer
Limestone aquifer
River gravel

Industry Contacts:

A standard letter has been sent to contacts throughout the UK water industry, requesting information on models and case studies involving river aquifer interactions (see Appendix 2).

Libraries:

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Note: Further References identified but not yet obtained

Spinazola, J (1999) A spreadsheet Notebook Method to Calculate Rate and Volume of Stream Depletion by Wells. In Pacific Northwest Focus Ground Water Conference

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APPENDIX 2: Draft text of letter to be sent to hydrological organisations

Dear Sir / Madam,

Assessing the Impacts of Ground Water Abstractions on River Flows

We are currently undertaking a research project on behalf of the Environment Agency on the above theme. As part of our initial information search activities, we would be most grateful if you could offer us any insights into the approach(es) your organisation takes in evaluating the possible impacts of ground water abstractions on flows in adjoining rivers, and/or information on any relevant case studies of which you are aware. Any answer (including "none") will be helpful to us in establishing the current baseline of industrial practice in the UK and adjoining countries.

We will be sure to acknowledge all contributions made in response to our requests when reporting our findings to the Environment Agency.

We thank you in anticipation for any information you can send us.

Yours sincerely,

Dr Paul L Younger
Reader in Water Resources

Dr Geoff Parkin
Lecturer in Sustainable Hydrology

List of correspondents:

SEPA
BGS
Geological Survey of Ireland
Norwegian Geological Survey
ITGE Spain
?Others
All water companies in England/Wales
Institute of Hydrology

2. River Groundwater Interaction – IGARF II
R&D Project W6D(99)02

Minutes of Project Meeting No. 1

10 January 2000
Agency Offices, Olton Court, Solihull

Present:	Environment Agency	Newcastle University
	John Aldrick	Geoff Parkin
	Dave Burgess	Paul Younger
	Janet Evans	
	Dave Headworth	
	Paul Hulme	
	Mike Jones	
	Stuart Kirk (Chair)	
	Alastair Picken	
	Lamorna Zambellas	

ACTIONS

1. Contractual and financial matters

The Purchase Order for the contract has been posted to Newcastle University.

UNUT Newcastle are to invoice at the end of January for all work completed up to the end of January, and by the 10th March for work completed and anticipated to be completed by the end of March.

2. Presentation and discussion of Inception Report

The draft inception report produced by Newcastle was reviewed.

UNUT Newcastle are to find more information on the work being carried out in Kansas State, referenced in the NGWA conference.

EA EA are to send a copy of the Aquifer Properties Manual to Newcastle.

Under hydrogeological setting 6, it was noted that there may be a special case for East Anglia, where there is drift covered chalk, and drift filled buried channels.

UNUT A geomorphologist should be contacted to review the proposed model configurations. Possible candidates were: Malcolm Newson (Newcastle), John Lewin (Aberystwyth), Phil Gebhard (Cambridge).

EA Members of the project board should send review comments to Stuart Kirk who will forward them to Newcastle.

3. Proposed Agency questionnaire

Stuart Kirk described the draft outline questionnaire, which was agreed.

EA EA are to add text to the questionnaire to request information on groundwater schemes as well as pumping test data.

EA EA are to arrange a workshop for key EA staff to present and discuss their views on the proposed hydrogeological settings.

4. Review of programme of work and project milestones

EA Paul Hulme is to arrange to visit Newcastle to inspect the SHETRAN simulations later in the programme.

The issue was raised of why SHETRAN has been proposed as the main modelling tool for the project in preference to MODFLOW (as the Agency's currently recommended model). The following points were noted during discussion of this issue:

- SHETRAN has advantages over MODFLOW in its representation of processes, especially complex geology, river-aquifer interactions including disconnected rivers, and groundwater – surface water interactions on flood plains
- It is more efficient to run a large number of simulations and process their results in batch mode at Newcastle using SHETRAN on unix systems
- This R&D project provides an opportunity for the Agency to explore the use of a new model (SHETRAN)
- The project contract has been written to include clauses ensuring that the Agency is not tied in exclusively to the use of SHETRAN if there is any continuation of the project.

UNUT A preliminary SHETRAN model of hydrogeological setting 1 is to be run at Newcastle and reported by the next progress meeting. A comparable model of the same setting is to be run using MODFLOW (using the GWVistas GUI) for comparison against SHETRAN.

Some preliminary ideas on the features of the IGARF II modelling tool were noted (these will be discussed further at the next progress meeting and workshop):

- Design of a pumping test for a borehole near to a river
- The use of a single borehole only
- Evaluation of the impact of licensed borehole abstractions on river depletion, including seasonal impacts
- Outputs for up to 25 years
- Outputs of water levels for a small set of observation boreholes
- Outputs for the length of river affected

It was noted that the principle of superposition will not be strictly valid for some of the IGARF II simulations. The implications of this have yet to be fully considered.

Meteorological data sets for simulations are available at Newcastle for average, dry and wet scenarios for various locations in the UK from a previous Agency project.

East Anglia Region currently use 150 days with no significant recharge as a rule of thumb to represent worst case drought for assessments of the impact of abstractions. This should be considered as a possible basis for IGARF II scenarios.

In the first instance, priorities for scenarios will be taken from the limitations of analytical models described in the Sophocleus paper referenced in the draft inception report.

5. Opportunities to promote the project – presentations and papers

To be discussed at a future meeting.

6. AOB

Date of next meeting: Thursday 17th Feb. in London
Project workshop to be held on Fri. 18th Feb. in London

River Groundwater Interaction – IGARF II
R&D Project W6D(99)02

Minutes of Project Meeting No. 2

18 May 2000
Royal Station Hotel, York

Present:	Environment Agency	Newcastle University
	John Aldrick	Geoff Parkin
	Dave Burgess	
	Steve Fletcher	
	Stuart Kirk (Chair)	

Apologies:

Dave Headworth
Paul Hulme (a prior discussion was held between Paul Hulme and Geoff Parkin on 16th May 2000 at Newcastle)

ACTIONS

Background notes on SHETRAN and neural networks have been distributed.

If any dry wells occur during simulations, these will be flagged with a special code for processing by the neural network.

GP Minimum system requirements for the GUI are to be circulated.

GP A demo disk containing the IGARF II GUI is to be set up and sent to Stuart Kirk for wider circulation.

The following comments were noted on the GUI design:

- the EA logo should be added
- the EA titles should be given similar prominence to the University titles
- hydrogeological setting selection should be on a separate sheet
- input and output tabs should be clearly distinguished
- output tabs should be disabled until a simulation is run
- input data entry sheets should be clearly labelled as such
- the neural network should use both K and d (rather than transmissivity) for the valley aquifers and for the main aquifer
- explanation help boxes should be added to the input data sheet

SK Stuart Kirk is to send the official EA logo to Newcastle.

It was noted that superposition of the impact from multiple pumping periods would be carried out within the GUI (not within simulations).

It was noted that depletions are absolute values (units, l/s), and not actual flow rates.

All of the proposed user inputs were agreed, except for the upper limit of the abstraction rates, and the aquifer thickness.

GP GP is to check if we need to have river depths as an input parameter.

It was agreed that the revised end date for the project would be 31/12/2000.

GP GP is to produce a revised work plan and budget for the project.

River Groundwater Interaction – IGARF II
R&D Project W6D(99)02

Minutes of Project Meeting No. 3

1 August 2000
Agency Offices, Olton Court, Solihull

Present:	Environment Agency	Newcastle University
	John Aldrick	Geoff Parkin
	Steve Fletcher	Steve Birkinshaw
	Dave Headworth	
	Mike Jones	
	Stuart Kirk (Chair)	

Apologies:	Environment Agency	Newcastle University
	Dave Burgess	Paul Younger
	Paul Hulme	

ACTIONS

1. Comments on GUI design

4 comments on the demo GUI have been received to date. These were considered in detail, and the following comments were noted.

UNUT Newcastle are to assess the feasibility of adding an option of selecting a region within a 'preferences' menu, splitting the settings text into two halves – the first half to display a general description of the setting, and the second half to display regional examples. This would require 7 text files (one for each setting) for the general descriptions (to be prepared by Newcastle), and 56 text files (one for each combination of region and setting) for the examples, to be prepared by the Agency.

EA SK is to consider the recommended procedures for using the GUI, in the context of the current design in which the first abstraction period is used as the pumping test input.

There should be a facility to display the long-term depletion impacts in a tabular form as a text output.

A warning flag should be displayed if the total river flow depletion over 25 years is less than 50% of the total abstraction.

UNUT Alternative display formats for the long-term depletion graph were considered. GP is to send a selection of possible alternative display formats for consideration by the committee, including display of the abstraction and compensation inputs, and display of the depletions as a line graph rather than a bar chart.

The accretion profile should be changed to a depletion profile. If possible, the units will be displayed as m^3/s on the left-hand axis, and Ml/day on the right-hand axis.

It was noted that the accretion (depletion) profile and aquifer drawdown outputs are calculated only for the pumping test at certain specified times (at the end of the pumping test and at the time of maximum total river flow depletion). It was considered whether these outputs should be prepared also for the impacts from repeated annual abstractions. This matter was not resolved. As an interim measure, Newcastle will consider how to implement such long-term impacts and whether this would be feasible within the project. Newcastle will also run additional simulations to look at the change in the accretion (depletion) profile over time, with repeated annual abstractions modelled within the simulation (rather than by external superposition).

A small image showing the layout of the observation boreholes is to be added to the aquifer drawdown plot.

The time of maximum depletion is to be added to plots.

It is not necessary for Newcastle to acknowledge the receipt of any comments on the GUI.

2. Progress report on modelling and ANN

A first set of about 200 SHETRAN model simulations have been run for setting 5 (shallow valley-train aquifer). There has been a significant amount of work in preparing a system to allow large numbers of simulations to be run efficiently. The output data from these simulations will be used to train the neural network in the next few weeks.

Six changes have been made to the ranges of input data described in the ‘Briefing note on proposed modelling, 10 April 2000’, which were agreed as follows:

- river width, 5-50 m
- river bed sediment conductivity, 0.001-40 m/day
- river bed sediment thickness, 0.2-0.5 m (these changes were made to limit the range of river bed conductances, which were unrealistically large)
- distance of borehole from river, 25-4000 m (the lower limit of 5 m was too low to be represented realistically within the discretisation of a regional scale model)
- abstraction rates, 500-10,000 m^3/day (agreed at the previous meeting; note that an upper limit of 5,000 m^3/day has been used for the valley aquifer, case 5, to prevent excess dewatering of the aquifer)
- (regional) aquifer thickness, 10-300 m (agreed at the previous meeting)

When dry wells occur during a simulation, a flag is generated to indicate that no outputs are available for the ANN. This will be processed as an additional output parameter by the ANN, and will be recognised and flagged with a message in the GUI to indicate that a particular set of input parameter values are outside the physically realistic input parameter space.

It was noted that it will not be possible (within this project) to trap dry wells which occur due to superposition of multiple abstractions or repeated annual abstractions. (This is possible in principle, but would require much more output data than is currently being used.) However, a message will be output in the GUI to indicate if the drawdown at the abstraction well grid element falls close to the base of the aquifer. Note that this drawdown is at the model scale, and is not the actual drawdown at the well; it will not be output directly in the GUI, but will only be used as an indicator of a potentially dry well.

Additional outputs from the SHETRAN model which will be passed to the ANN are:

- time of maximum depletion
- water level in the abstraction borehole grid element

UNUT Some output results from SHETRAN simulations were presented. These will be sent to SK for distribution to the committee, together with a brief description of the simulations, prior to the next meeting.

3. Publications

An abstract submitted to the 6th Scientific Assembly of the IAHS, July 2001, Maastricht, the Netherlands, has been accepted for oral presentation. The deadline for production of a 10-page paper for the conference is 31 October 2000.

4. Forward programme and budget

UNUT GP presented a draft revised programme to the end of Dec 2000. GP is to send this revised programme together with a budget breakdown to SK.

It was noted that there is now no spare time or budget allocation available if any significant changes in the programme are requested.

5. Any other business

MJ briefly outlined some issues relating to the potential commercialisation of the software product arising from this project. It was agreed that the software would be trialled internally within the Agency (suggested period, 6-12 months), before any commercialisation is considered. The details of the internal trialling (both within and after the project period) are yet to be agreed. Any involvement of Newcastle staff in training sessions for the software would be financed outside this project.

6. Date of next meeting

Wed. 13th Sept, 2000, in Newcastle.

This will cover some of the modelling issues not discussed in detail at this meeting, and will give an opportunity to inspect some of the SHETRAN output in more detail. An updated (but not final) version of the GUI will be available for inspection, and it is likely that some results from the ANN modelling will also be available.

River Groundwater Interaction – IGARF II
R&D Project W6D(99)02

Minutes of Project Meeting No. 4

13 September 2000
WRSRL, Newcastle University

Present:	Environment Agency	Newcastle University
	John Aldrick	Geoff Parkin
	Steve Fletcher	Steve Birkinshaw
	Dave Headworth	Paul Younger
	Stuart Kirk (Chair)	Zhengfu Rao
		Michael Murray

Apologies:	Environment Agency
	Dave Burgess
	Paul Hulme

ACTIONS

1. GUI

EA — The text on the settings page has been split into two parts, with a 'preferences' box added to allow the user to select the EA region for which example locations will be displayed. SK is to co-ordinate setting up the text files for each region.

UNUT — The following changes to the GUI, requested by the project committee, were agreed and will be implemented:

- the sizes of the text boxes on the settings page are to be reduced, and headings added above each text box
- a facility will be added to display the long-term depletion impacts in a tabular form as a text output
- the depletion profile plot will be displayed in units of m^3/day on a single axis
- a small image showing the layout of the observation boreholes is to be added to the aquifer drawdown plot (on screen only; it will not be displayed on print outputs due to the difficulty of scaling bitmap images on different resolution printers)
- the time of maximum depletion is to be added to depletion profile and aquifer drawdown plots
- the labels on various plots are to be reconsidered to make the descriptions more precise – in particular, the labels on the river depletion and aquifer drawdown plots should refer to the end of the pumping test and the time of maximum river depletion, and the axis should refer to river depletion (not flows)
- the abstraction rate is to be added to the river depletion plot in a text box

UNUT The committee requested that the long-term impacts output sheet should also show the abstraction and compensation patterns. As it is not possible within the current capabilities of the graphics software to display combined side-by-side and stacked graphs on one sheet, it was proposed that the best option would be to create a further output sheet containing the abstraction, compensation, and 25-year depletions. Mock-up pages will be created and sent to SK, together with the additional costs of adding this capability.

It was agreed that it is not necessary to display a warning flag if the total river flow depletion over 25 years is less than 50% of the total abstraction (as agreed at the previous meeting).

SK stated that the recommended procedures for using the GUI (for pumping test design and evaluation of long-term impacts) should be based on those presented in the IGARF I documentation.

UNUT There is a requirement to know the position along the river where the total impact of abstractions is felt (for locating river gauging installations). It was agreed that an additional output from the SHETRAN simulation would be implemented, for depletion at a distance of 2D downstream of the borehole (where D is the distance of the borehole from the river). This is not required for scenario 5, as the maximum impact here is only 500m downstream of the borehole. The possibility of extrapolating the cubic splines used for interpolation between the points to define an approximate position of total depletion will also be considered.

UNUT The committee noted that there is a requirement for additional output of river depletion profiles in response to repeated annual cycles of abstraction. The Newcastle team commented that this would require far more output variables to carry out the superposition (31 variables would be needed for each spatial position), and this would not be feasible to model with the ANN. As an alternative, ways in which the existing data can be used (in sensitivity studies, for example) to give an indication of the long-term impacts will be considered.

2. SHETRAN modelling

UNUT Newcastle will also run an additional simulation to look at the change in the depletion profile over time, with repeated annual abstractions modelled within the simulation (rather than by external superposition).

An additional simulation will be run with repeated annual abstractions to examine the possible long-term impacts of changed river-aquifer processes during breakaway conditions, and the error that may be introduced by approximating these effects using superposition.

3. ANN

A first training exercise for the ANN for setting 5 has been completed, and some preliminary results were tabled. Work is continuing on analysis of these results.

4. Publications

The outline of the paper to be submitted for the IAHS conference next year was agreed. The full paper must be submitted by 31 Oct 2000.

5. Forward programme and budget

Due to the amount of work involved in processing data, and to the changes in the scope of the work, only settings 1-5 will be completed by the end of Dec 2000. Settings 1-5 include all of the most significant settings identified during the early part of the project. UNUT are to define the budget and timescale required for completion of settings 6 and 7, post Dec 2000.

6. Date of next meeting

To be arranged.

3. Meeting Notes

IGARF II - Design Seminar
R&D Project W6D(99)02

18 February 2000
The Comfort Inn, Kensington, London

1 Introductions

Welcome and introduction by Steve Fletcher and Stuart Kirk NGWCLC

2 Seminar objectives

These were presented by Stuart Kirk as:

-To identify up to six hydrogeological 'settings' to encompass a wide variety of river-aquifer configurations that exist in England & Wales

-To identify the features to be incorporated and reported in the IGARF assessment

3 Background to the IGARF programme

These were presented by Stuart Kirk as comprising a sequence of projects, namely:

- IGARF I - Consolidation of best practice using analytical solutions
- IGARF II - Seeks to accommodate a wider range of hydrogeological settings and hydraulic conditions
- IGARF III - Field investigations and further model development

4 The proposed approach for IGARFII

The approach was presented by the contractor, Geoff Parkin, of the University of Newcastle-Upon-Tyne. This entails numerical modelling of a range of 'hydrogeology type settings', the training of Neural Nets and construction of a user friendly interface. In response to requests from the participants, Geoff Parkin agreed to provide supporting information on the proposed approach and on Neural Nets in particular.

5 Results of preliminary modelling

Geoff Parkin described the work carried out to date on the modelling, presenting example outputs from the various models applied.

6 The users' requirements

6.1 Summary of questionnaire results on:

Stuart Kirk presented a brief summary of the findings of the preceding questionnaire exercise (skset-t0.doc attached). The findings highlighted the range of hydrogeological settings that are of concern across England and Wales and their relative importance in the different regions and areas.

6.1.1 The hydrogeological settings to be considered

Stuart Kirk referred to the project team's suggested settings as featured in the IGARF II questionnaire. To this selection was added a number of additional settings proposed by Agency staff via the questionnaire (Semaddsets.doc, attached). These were then discussed in the workshop.

6.1.2 What features are required?

6.2 Group discussion on:

John Aldrick (NE) chaired the group discussions on the following:

6.2.1 The hydrogeological settings to be considered

Geoff Parkin made comments on the settings proposed by the project team and those proposed via the questionnaire exercise. It became clear during the discussions that all but one of the proposed additional settings could be considered as a sub-set of those proposed by the project team. In order to adequately constrain the modelling exercise the attendees provided comments on the range of parameter values and the features they thought should be included in the models. The parameter values and features were recorded on a flip chart. In summary, these were:

Aqufier transmissivity ranging from $10m^2/d$ to $10{,}000m^2/d$
Valley fill permeability ranging from 10^{-4}m/d to 100m/d
Wetted perimeter: wetted bank 0 to5m; bed width up to 150m
Thickness of valley fill 0-60m, width: 10m to 1km.
Thickness of aquifer below valley fill: 10m to 50m.
Period of no significant recharge should extend to 150 or 200 days
Modelled abstraction b/h could be from 5m to 4km from the river
Abstraction periods to be reported = short term p.test (12hr,24hr), 1, 2 ,5, 10, & 25 years
River sinuosity will be considered in sensitivity analysis
Partial penetration of river to be explored, but wells will be assumed to be fully penetrating
In addition to the previously proposed settings a further seventh confined setting was adopted

It was further agreed that catchpit abstractions and spring discharges would be excluded from the current project. K variation with depth would be incorporated in the model to check for its significance. Consideration would also be given to modelling seasonal drying out of rivers.

6.2.2 What features are required?

Reference was made to the questionnaire results which confirmed that the features suggested by IGARF I were indeed a good representation of the users' requirements (Features.doc attached). A number of aspects were discussed further these were:
Requests for both flow depletion over time and flow accretion along the river to be produced;
Drawdowns at several points around the pumping borehole and river would be desirable, the optimum number could be derived from the modelling trials. It was suggested that flow conditions should include or focus on Q95 flow. However, although the numerical model simulations will provide river flows, the outputs used will be the difference between river flows with and without abstraction (i.e. flow depletion) – the model will not be used to provide the hydrological response at a full catchment scale in this project.

6.3 Summary of conclusions

Sufficient feed back was provided by the Agency, to allow the contractor to produce a detailed modelling specification for the project. However, it remains to be seen if all of the requirements can be accommodated, given technical and resource constraints. Geoff Parkin undertook to provide the specification in the form of a modelling plan to the project team. He further undertook to provide supporting information on both Neural Nets and SHETRAN. Stuart Kirk agreed to distribute this information along with notes of the meeting and some information on the modelling plan/specification of the modelling tool.

7 Sources of data for validation of the models

These were sufficiently covered by the questionnaire responses and were not discussed further.

8 Close of meeting

The meeting was closed with thanks to all those who had contributed to the consultation process.

4. ENVIRONMENT AGENCY R&D PROJECT NO. W6-046.

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

Briefing note on proposed modelling
10 April 2000

The purpose of this briefing note is to expedite agreement on the detailed workplan for the numerical model simulations, input-output parameters for the Artificial Neural Network (ANN), and Graphical User Interface (GUI). The parameters, data and methods proposed here are all provisional, and are dependent upon a more thorough assessment of the feasibility of completion of the work within the available time.

The input and output parameters for the GUI and the ANN are given in Tables 1 and 2. Example mock-ups of the proposed GUI layout are attached.

The GUI has been designed to have a similar 'look and feel' to the IGARF I Excel spreadsheet, although it is more sophisticated. This has been achieved through the use of 'tabs' to select 'sheets' of input and output data. Help facilities and automatic parameter value validation (e.g. out-of-range checking) will be built into the GUI.

Facilities are being designed to allow the user an appropriate level of flexibility in designing the appearance of graphical output. Dialogue boxes are illustrated on the attached pages to allow, for example, grid lines and titles to be added to or removed from charts.

The number of outputs from the ANN model is limited (the more output variables are defined, the more data are required to train the ANN). The suggested outputs are intended to pass just enough information to the GUI to allow a reasonable graphical display of the data for the user. The graphical display for the first two types of output (impact of pumping test, long-term depletion) will be similar to IGARF 1. The display for the other outputs (accretion profile, aquifer drawdown) has yet to be determined.

Table 1: Input variables

Graphical User Interface				Neural Network		
Symbol	Description	Units	Range	Symbol	Description	No. of values
D	Distance of borehole from river	m	5 – 4,000	D	Distance of borehole from river	1
Q_a	Abstraction rate(s)	m^3/day	500 – 5,000	Q	Abstraction rate	1
Q_r	Compensation returns	m^3/day	0 – 5,000			
t_s	Start date(s) for abstraction	*date*	*any valid date*	n_s	Time from to t_s to t_r	1
t_e	End date(s) for abstraction or	*date*	*any valid date*			
n_d	Duration(s) of abstraction	days	1 – 365	n_d	Duration of abstraction	1
T_a	Aquifer transmissivity or	m^2/day	10 – 10,000	T_a	Aquifer transmissivity	1
K_a	Aquifer hydraulic conductivity	m/day	1 - 200			
b_a	Aquifer thickness	m	10 – 50			
T_v	Valley-fill transmissivity or	m^2/day	0 – 6,000	T_v	Valley-fill transmissivity	1
K_v	Valley-fill hydr. conductivity	m/day	10^{-4} – 100			
b_v	Valley-fill thickness	m	0 - 60			
S	Specific storage	-	10^{-4} – 0.1	S	Specific storage	1
S_y	Specific yield	-	0.1 – 0.5	S_y	Specific yield	1
w	River width	m	1 – 150	C	Bed conductance per unit len.	1
K_b	River bed sediment hydr. cond.	m/day	10^{-4} – 100			
d_b	River bed sediment thickness	m	0.1 – 10			
R	Mean annual recharge	mm/day	0 – 1000	R	Mean annual recharge	1
t_r	Date of peak recharge	*date*	*any valid date*			
R_s	Recharge seasonality	mm/day	0 – 1000	R_s	Recharge seasonality	1
						Total: 11

Notes

1. The GUI will allow for multiple abstractions (rates, start dates, end dates or durations) to be input, based on the superposition principle. The modelling studies and the neural network will only use one abstraction. The validity of the superposition principle has yet to be discussed fully.
2. The recharge is assumed to follow a sinusoidal curve through the year. The recharge seasonality is the difference between the maximum and minimum rates of recharge (i.e. the amplitude of the sine function).
3. Parameters related to curvature of the river and/or variability of hydraulic conductivity with depth may be added, depending upon results from preliminary model sensitivity analysis simulations

Table 2: Output variables

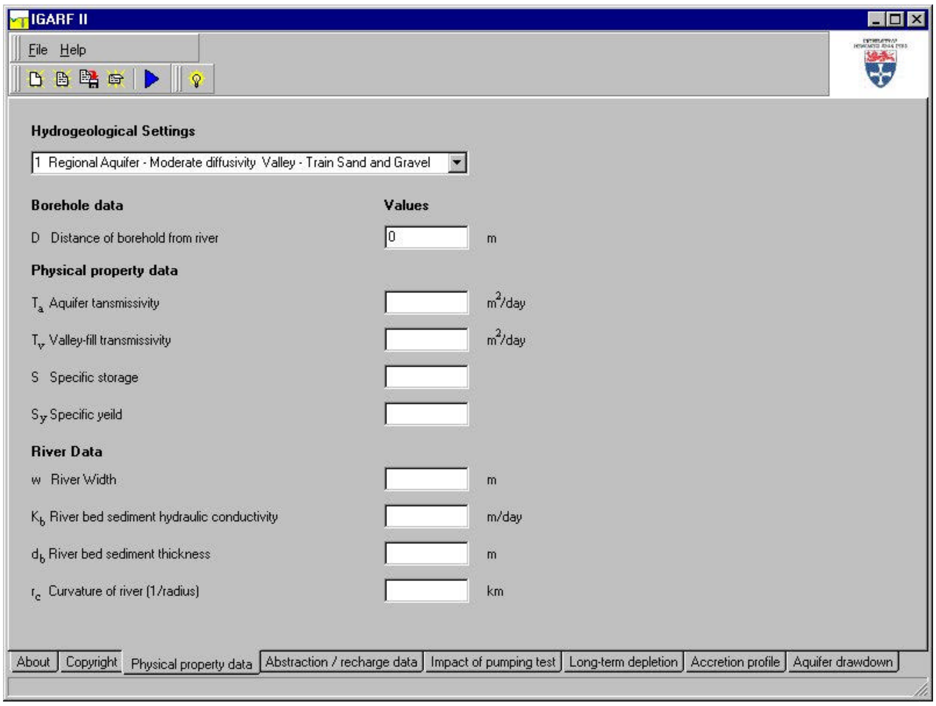
Graphical User Interface / Neural Network			
Symbol	Description	Units	No. of values
q_d	Monthly flow depletion after 1, 2, 5, 10, 25 years	m^3/s	60
q_p	Flow depletion time-series for pumping test	m^3/s	9
q_r	Accretion profile in river	m^3/s	5
d	Aquifer drawdown	m	5
			Total: 79

Notes

1. Values for flow depletion for pumping test are given after 1, 2, 5, 10, 20, 50, 100, 200, 500 days
2. Values for flow are given for the accretion profile at steady-state at distances of 0, ±D/2, and ±D along the river
3. Values for drawdown are defined at the river nearest to the well, and at a distance D/2 from the well towards, away from, and parallel to the river, and at a distance D/2 from the river on the opposite side to the well.

Front page and 'about' box

Physical data input page



Time-series data input page
(note: graph data is random, for illustration only)

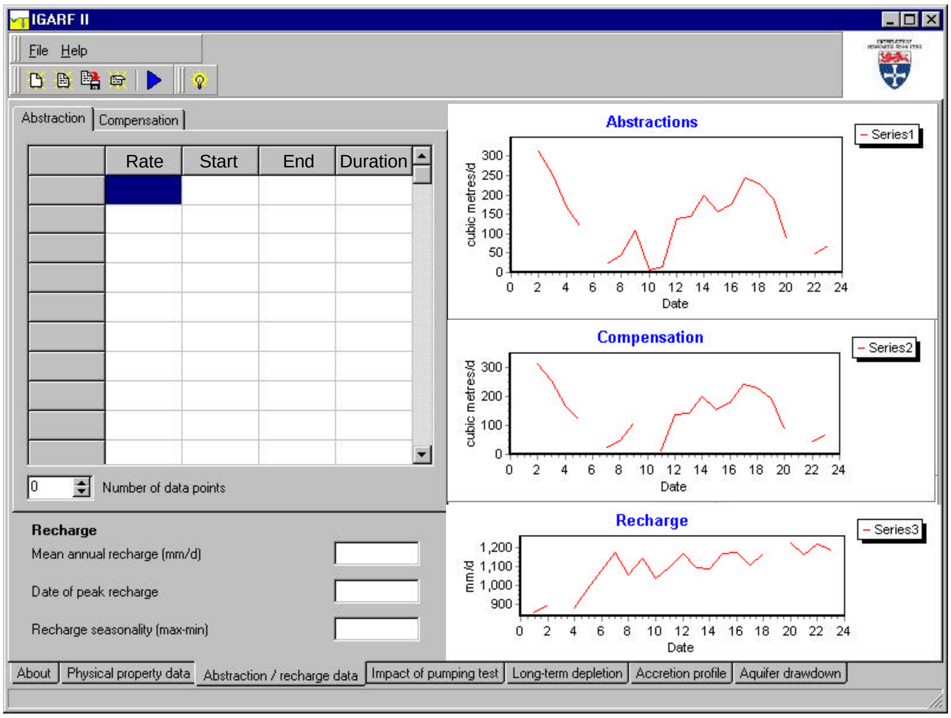
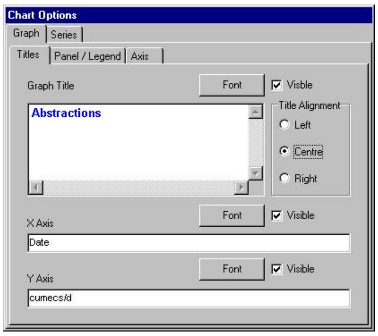
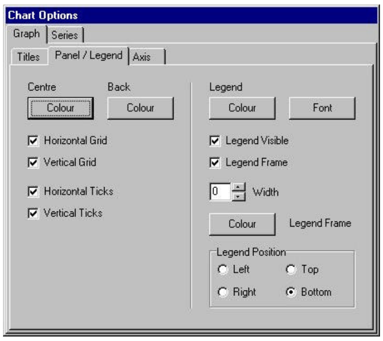
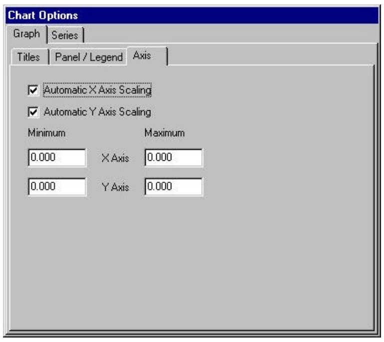
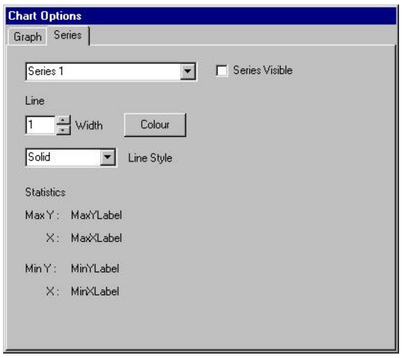


Chart style editor boxes









5. SHETRAN – A Brief Introduction for the Environment Agency IGARF II project

Water Resource Systems Research Laboratory
Department of Civil Engineering
University of Newcastle

11 April 2000

1 *Background and purpose*

SHETRAN is a physically-based distributed modelling system for water flow, sediment and contaminant transport in river basins. SHETRAN [1] has its origins in the SHE (Système Hydrologique Europeén), which was developed by a consortium of the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH, France [2,3]. Although earlier versions of SHETRAN were based closely on the SHE, the current version (V4) has been substantially redesigned. Additional components for sediment erosion and transport have been designed and integrated into the system (the name derives from SHE-TRANsport). SHETRAN has been developed within the Water Resource Systems Research Laboratory, Department of Civil Engineering, University of Newcastle upon Tyne.

Some of the potential uses identified in the early days of the SHE model included: "catchment changes"; "ungauged catchments"; "spatial variability in catchment inputs and outputs"; and "movement of pollutants and sediments" [2,3]. A key issue that could be addressed by SHE was identified as land-use change (the explosion of interest in climate change effects was not, at that time, foreseen). Since then, a considerable body of work has been undertaken in all of these areas using SHETRAN [1]. This work has involved model development for new process representation and new computational methods, improvements in methods of obtaining model parameters, and the development of new approaches to model validation.

2 *Processes*

SHETRAN contains components for water flow, and sediment and contaminant transport. The main processes modelled in SHETRAN are illustrated schematically in Figure 1 and listed in Table 2 at the end of this report.

The SHETRAN water flow component contains four process-based modules:

- **VSS:** 3D Variably-Saturated Subsurface flow
- **ET:** EvapoTranspiration
- **SM:** SnowMelt
- **OC:** Overland/Channel flow

The processes included in each module are listed in Table 1.

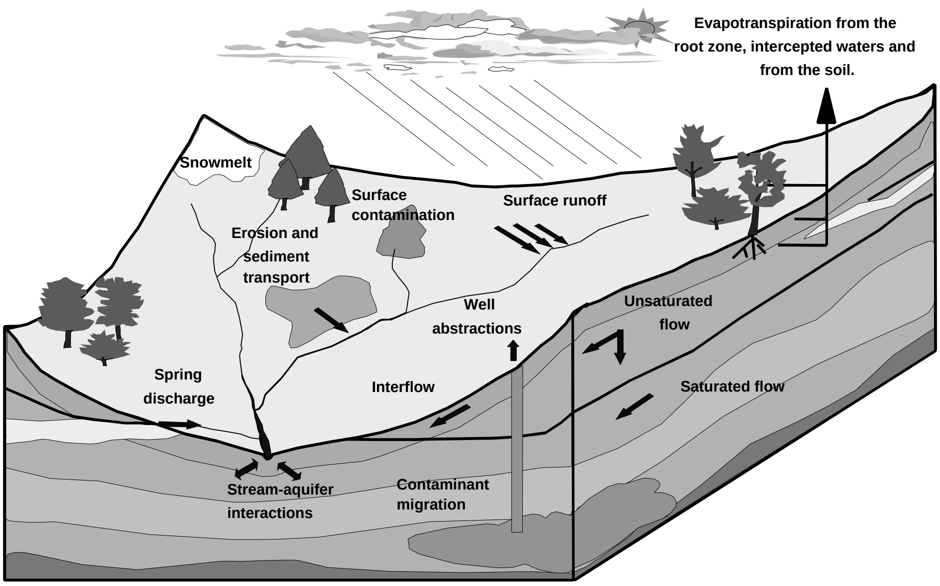


Figure 1 Processes represented in SHETRAN V4

Table 1: Processes represented in the SHETRAN water flow component

Module	**Processes Represented**
Evapotranspiration (ET) Module	Canopy interception (Rutter model) Options for calculating evapotranspiration: Penman Monteith model Actual evapotranspiration calculated from input potential evapotranspiration as function of matric potential in root zone
Snowmelt (SM) Module (optional)	Energy balance or degree-day melt model
Overland and Channel Flow (OC) Module	Diffusive wave approximation to St. Venant equations for both overland flow (2-D) and channel network (1-D)
Variably Saturated Subsurface Flow (VSS) Module	3-D variably saturated flow equation (based on Richards equation), enabling simulation of confined, unconfined and perched aquifers. Incorporates terms for: channel-aquifer exchange flows infiltration and exfiltration spring discharge, and well abstraction

3 Outputs

The following list of variables can be calculated by SHETRAN, and displayed using Graphical User Interfaces (GUIs). All variables are two-dimensional unless indicated otherwise. This list is being updated continually as new capabilities are added to the model.

```
-------------------
1   Net rainfall
2   Potential Evapotranspiration
3   Actual evapotranspiration
4   Evaporation from soil surface
5   Evaporation from intercepted storage
6   Drainage from intercepted storage
7   Canopy storage
8   Infiltration
9   Vertical subsurface flows (3D)
10  Snow pack depth
11  Temperature of snow pack
12  Phreatic depth below surface
13  Lateral subsurface flows (3D)
14  Overland flow
15  Surface water depth
16  Recharge
17  Stream-aquifer flow
18  Spring discharge
19  Pressure potential (3D)
20  Soil water content (3D)
21  Total depth of sediment
22  Depth of sediment in particle size fraction
23  Sediment infiltration rate into deep bed layer
24  Sediment infiltration rate into bed surface layer
25  Rate of ground surface erosion
26  Rate of lateral erosion of each stream bank
27  Sediment concentration
28  Flow carrying capacity for suspended sediments
29  Density of sediments in the active layer
30  Density of sediments in the parent bed layer
31  Total cross-sectional area of net sed. deposition
32  Rel. conc. in soil dynamic region (3D)
33  Rel. conc. in soil dead-space (3D)
34  Rel. conc. in surface waters
35  Rel. conc. in stream bed surface layer
36  Rel. conc. in stream bed deep layer
37  Rel. conc. at base of columns
38  Rel. conc. in well water
39  Rel. conc. in permanent plant material
40  Rel. conc. in non-permanent plant material
41  Total well abstraction rate
42  Well abstraction rate for well screen
50  Mass balance summary
```

4 Spatial and temporal scales

As SHETRAN has developed with particular attention being paid to river flows and near-surface processes, the timesteps used are usually one or two hours, reduced to as short as a few minutes for intense storms. Less typically, in the groundwater application described below, longer timesteps are used (12 hours).

Lateral spatial scales are typically similar to those used for MODFLOW studies (with the exception of those used near stream channels, described below). The grid sizes used for modelling in the vertical, however, tend to be much finer than those used for MODFLOW. This again reflects the needs of near-surface modelling, since a fine vertical resolution is necessary for capturing wetting fronts in the unsaturated zone.

5 Stream-aquifer interaction

In SHETRAN, stream-aquifer interactions are modelled based upon the difference in hydraulic head between the aquifer and the river stage, using the aquifer and river bed hydraulic conductivity as the main parameters controlling flow. Grid refinement can be used for the near-channel region of the aquifer, by using 'bank elements'. This provides the capability for an approximation to the three-dimensional flow field near channels, and also provides the facility to model unsaturated conditions under stream channels, and to include data for layered porous media beneath the channel.

6 Evapotranspiration, infiltration, unsaturated zone flow, and recharge

In SHETRAN, a fairly detailed evapotranspiration module simulates canopy interception of rainfall, evaporation from the canopy, from bare soil, and from open water, and transpiration. Infiltration is calculated as a head-dependent boundary condition to the subsurface variably-saturated flow equation. Flow in the unsaturated zone is modelled, including vertical and lateral flow, and flow associated with perched aquifers. Natural groundwater recharge is implicitly calculated as part of the model solution, and recharge rates are therefore functions of physical processes in the unsaturated zone.

7 Solution methods

Finite difference methods are used to solve the partial differential equations for flow and transport that are at the heart of SHETRAN. As such, the catchment area is discretised into rectangular computational elements, and the underlying soil zone and aquifer are represented by columns of cells which extend downwards from each of the surface grid squares. The river network is represented by a network of links which run around the edges of ground surface grid elements. This grid and column based structure allows the representation of spatial variability in topography, soils and geology, land-use and meteorological inputs, to be explicitly incorporated into catchment models.

8 *Recent developments*

In addition to the many applications of SHETRAN, the capabilities for modelling distributed flow and transport are being extended further to allow studies to be made of practical environmental and water resource issues. The following examples illustrate some of the recent developments. The contaminant component has been extended to represent nitrogen transformations in soils. A two-dimensional analytical solution to groundwater flow has been embedded within the three-dimensional VSS component to represent flows near abstraction wells (treated as singularities in the flow field), and is being used with a particle tracking code for the design of well fields and the mapping of groundwater protection zones. An existing pipe network model has been integrated with the VSS component, and is being used for studies of minewater pollution and the sustainable management of groundwater resources in karstic regions.

9 *References*

A comprehensive list of SHE/SHETRAN references are available. The following three references are the key papers on SHE and SHETRAN.

[1] Ewen, J., Parkin, G., and O'Connell, P.E. (in press). SHETRAN: Distributed River Basin Flow and Transport Modelling System. ASCE J Hydrologic Engineering.

[2] Abbott, M.B., Bathurst, J.C, Cunge, J.A., O'Connell, P.E. and Rasmussen, J. (1986a). An introduction to the European Hydrological System - Système Hydrologique Européen, "SHE", 1: History and philosophy of a physically-based, distributed modelling system. J. Hydrol., 87, 45-59.

[3] Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connell, P.E., and Rasmussen, J., An introduction to the European Hydrological System - Système Hydrologique Européen, "SHE", 2: Structure of a physically-based, distributed modelling system, J. Hydrol., 87, 61-77, 1986b.

The following papers also contain key material, and are referenced in Table 3.

Ewen, J., Contaminant transport component of the catchment modelling system SHETRAN, in Solute Modelling in Catchment Systems, edited by S.T. Trudgill, pp. 417-441, John Wiley and Sons, UK, 1995.

Parkin, G., A three-dimensional variably-saturated subsurface modelling system for river basins, PhD thesis, University of Newcastle upon Tyne, UK, 1996.

Purnama, A, and Bathurst, J.C., A review of three features of sediment transport in stream channels: dynamics of cohesive sediment, infiltration of transported sediment into the bed, and stream bank erosion, Report NSS/R233, 124 pp., UK Nirex Ltd, Harwell, UK, 1991.

Wicks, J.M., and Bathurst, J.C., SHESED: a physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system, J. Hydrol., 175, 213-238, 1996.

Table 2. Main Processes Represented in SHETRAN.

Component	Processes
Water flow: surface water flow on ground surface and in stream channels; soilwater and groundwater flow in unsaturated and saturated zones, including systems of confined, unconfined and perched aquifers	• canopy interception of rainfall • evaporation and transpiration • infiltration to the subsurface • surface runoff (overland, overbank, and in channels) • snowpack development and snowmelt • storage and 3D flow in variably-saturated subsurface • combinations of confined, unconfined and perched aquifers • transfers between subsurface water and river water • groundwater seepage discharge • well abstraction • river augmentation and abstraction • irrigation
Sediment Transport: soil erosion and multi-fraction transport on ground surface and in stream channels	• erosion by raindrop and leaf drip impact and overland flow • deposition and storage of sediments on the ground surface • total-load convection with overland flow • overbank transport • erosion of river beds and banks • deposition on the river bed • down channel advection • infiltration of fine sediments into the river bed
Solute Transport: multiple, reactive solute transport on ground surface and in stream channels and the subsurface	• 3D advection with water flow • advection with sediments • dispersion • adsorption to soils, rocks, and sediments • two-region mobile/immobile effects in soils and rocks • radioactive decay and decay chains • deposition from the atmosphere • point or distributed surface or subsurface sources • erosion of contaminated soils • deposition of contaminated sediments • plant uptake and recycling (simple representation only) • exchanges between river water and the river bed

Table 3. Flow and Transport Equations for SHETRAN. References: (A), Abbott et al. [1986b]; (E), Ewen [1995]; (P), Parkin [1996]; and (W), Wicks and Bathurst [1996] and Purnama and Bathurst [1991].

Process	Equation
Subsurface flow	Variably-saturated flow equation (3D) (P)
Overland flow	Saint-Venant equations, diffusion approximation (2D) (A)
Channel flow	Saint-Venant equations, diffusion approximation (flow in a network of 1D channels) (A)
Canopy interception and drip	Rutter equation (A)
Evaporation	Penman-Monteith equation (PME) (or as fraction of potential evaporation rate) (A)
Snowpack and melt	Accumulation equation and energy budget melt equation (or degree-day melt equation) (A)
Overland sediment transport	Advection-dispersion equation (2D) with terms for deposition and erosion by raindrop and leaf drip impact and overland flow (W)
Channel sediment transport	Advection-dispersion equation (transport in network of 1D channels) with terms for deposition and erosion, and infiltration into the bed (W)
Land surface and subsurface solute transport	Mobile/immobile advection-dispersion equation (3D) with terms for adsorption, dead-space, radioactive decay, erosion of contaminated soil, deposition of contaminated sediments, plant uptake, and deposition from above (E)
Channel solute transport	Advection-dispersion equation (transport in network of 1D channels) with terms for adsorption to sediments, radioactive decay, erosion and deposition of contaminated bed materials, overbank transport, and deposition from above (E)

Table 4. Main Data for Physical Properties and Initial and Boundary Conditions in SHETRAN

Component	Data
Water Flow	• precipitation and meteorological data for each station • station numbers for each column and river link • size and location of columns, river links and finite-difference cells • soil/rock types and depths for each column • land-use/vegetation for each column • man-controlled channel flow diversions and discharges • rates of borehole pumping, artificial recharge, flow diversions, etc. • initial hydraulic potentials for subsurface • initial overland and channel flow depths • initial snowpack thicknesses and temperatures • boundary hydraulic potentials (or flow rates) • boundary stream inflow rates • canopy drainage parameters and storage capacities • ground cover fractions • canopy resistances and aerodynamic resistances (for PME) • vegetation root density distribution over depth • porosity and specific storage of soils/rocks • matric potential functions for soils/rocks • unsaturated hydraulic conductivity functions for soils/rocks • saturated hydraulic conductivity of soils/rocks • snow density, zero-plane displacement and roughness height
Sediment Transport	• raindrop size distribution • drop sizes and fall distances for canopy drainage • proportion of canopy drainage falling as leaf drip • initial thickness of sediments and channel bed materials • sediment concentrations in waters entering via inflowing streams • sediment porosities and particle size distributions • erodibility coefficients
Solute Transport	• initial concentrations in surface and subsurface waters • concentrations in rainfall • dry deposition rates • concentrations in flows entering at boundaries • dispersion coefficients for soils/rocks • adsorption distribution coefficients (and exponents, if non-linear) • mobile fractions for soils/rocks • fractions of adsorption sites within mobile regions in soils/rocks • exchange coefficients for mobile and immobile regions in soils/rocks • decay constants (e.g. for radioactive decay) • plant-uptake constants

6. Artificial Neural Networks (ANNs) – A Brief Introduction for the Environment Agency IGARF II project

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1 Introduction

In this project, detailed numerical modelling exercises will be used to "train" an ANN to understand and reproduce the details of interactions between aquifers, rivers and abstractions. The "fully-trained" ANN can then be used in a very simple manner (using graphical user interfaces designed to mimic those of Groundwater Vistas^{TM} in style and terminology). The user will enter information on flow rates and site layout into a computer package, and the ANN will then rapidly compute streamflow depletion rates and timings etc for the defined problem. The computing tool behind the user interface might reasonably be viewed as a multi-dimensional "look-up table" (in effect, a set of multi-dimensional "type curves"), which has been constructed by using an ANN to transform numerical river-aquifer modelling results covering a wide range of practical problems. In this way the user will experience all the benefits of a full numerical analysis, and all the rapid computing power of an ANN, without having to understand or access either.

Artificial neural networks (ANN) are a relatively recent innovation in water resources technology, and their use for this purpose in the UK has been largely pioneered by the Newcastle team (Rao and Jamieson, 1997; Rao and O'Connell, 1999). An 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 principal advantages which ANN offer over conventional modelling approaches are:
- the ability to handle multi-parameter problems with speed and accuracy (a feature which is beyond the capabilities of most analytical models)
- rapid execution of large-domain problems (a few seconds for a problem which would take MODFLOW several hours)

The particular approach to ANN application developed at Newcastle is:
(i) to use the insights of standard hydrological models (analytical and numerical) to construct input-output data-sets for complex problems
(ii) to use these data-sets to train an ANN to provide rapid "intuitive" mathematical solutions to problems which can be interpolated within the field of experiences represented by the standard hydrological model simulations

2 Method

An ANN is a computing system made up of a number of simple, highly interconnected nodes or processing elements that process information by its dynamic-state response to external inputs. The attractiveness of the ANNs is their ability to learn from input-output data sets. Recent studies have shown that any continuous nonlinear function can be approximated by a feedforward network to any arbitrary degree of accuracy. Hence, theoretically an ANN can be used to model most water/environmental systems.

2.1 Architecture

The three-layer neural network ANN(*I*, *J*, *K*) is shown in Fig. 1 with *I* neurons in the input layer, *J* neurons in the hidden layer and *K* neurons in the output layer. The network is fully connected between adjacent layers. Each hidden node *j* receives input from every node *i* in the input layer. Associated with each input (x_i) is a weight (w_{ji}^h).

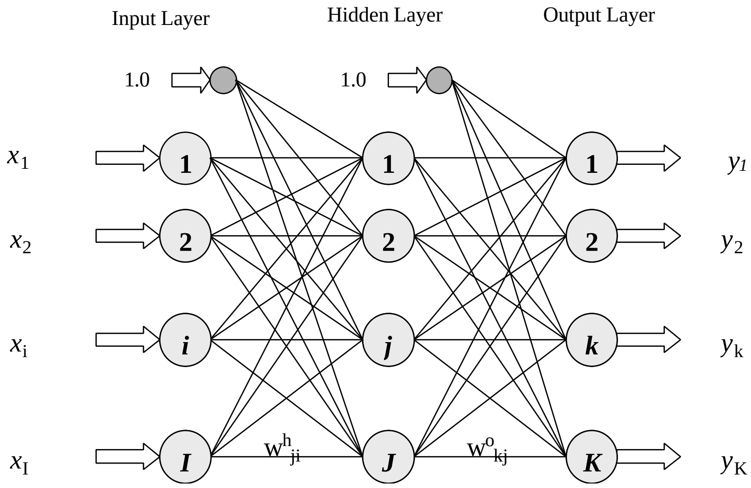

Fig. 1 Architecture of an ANN

The effective input (W_j) to node *j* is the weighted sum of all the inputs:

$$\Omega_j = \sum_{i=0}^{I} w_{ji}^h x_i \qquad (1)$$

where x_0 and w_{j0}^h are called the bias (x_0 = 1.0) and the bias weights, respectively. The effective input, W_j, is passed through a nonlinear activation function (sometimes called a transfer function or threshold function) to produce the output (h_j) of the node.

The most commonly used activation function is the sigmoid function. The characteristics of a sigmoid function are that it is bounded above and below, it is monotonically increasing and it is continuous and differentiable everywhere. The sigmoid function most often used for ANNs is the logistic function:

$$h_j = f(\Omega_j) = \frac{1}{1+e^{-S_j}} \quad j = 1,2,...,J \qquad (2)$$

in which W_j can vary on the range ±∝, but h_j is bounded between 0 and 1. The output neuron is defined as

$$y_k = f\{\sum_{j=0}^{J} w_{kj}^{o} f\{\sum_{i=0}^{I} w_{ji}^{h} x_i\}\}, \quad k = 1,2,...,K \qquad (3)$$

where w_{ji}^{h} is a weight between the *i*th input neuron and the *j*th hidden neuron, w_{kj}^{o} is a weight from the *j*th hidden neuron to the *k*th output neuron, and *f*( ) is a sigmoid function as defined by Eq. (2).

The identification of the structure of the ANN, i.e., the value of *J*, is usually done using a strategy of progressively adding nodes to the hidden layer until a structure appropriate to the complexity of the problem is achieved, and values for the network weights w_{ji}^{h} and w_{kj}^{o} are estimated by means of backpropagation algorithms so that the predicated error is minimised.

2.2 Training procedure

Developing a neural network includes two major steps. The first step is "training" (or "learning"); a set of known input-output data are repeatedly presented to the network and the weights associated with each node are adjusted until the specified input yields the desired output. Through these adjustments, the network "learns" the correct input-output response behaviour. This training process is usually accomplished by using some specific algorithms in which a cost function, specified as the sum of squared errors between the true output and the output produced by the network, is minimised. When the cost function approaches a minimum, the network is considered to have converged. The minimisation of the cost function can be achieved in different ways. The most popular technique is back-error propagation.

After training, the second step is to validate the neural network, referred to as "generalization." The trained neural network is subject to a wide range of the inputs used in the previous training as well as new data. Based on the performance of the neural network, further adjustments may be introduced to make the model more reliable and robust.

3 Demonstration of Proposed Methodology

3.1 Introduction

The case study used here is designed only as an illustration of the general method, and would not necessarily form part of the full study within IGARF II.

3.2 Proposed methodology

The proposed method involves using physically-based numerical models to derive consistent input-output data-sets for relevant hydrogeological settings. These data-sets can then be used to “teach” an Artificial Neural Network (ANN) how a river-aquifer system functions. As such the ANN mimics the behaviour of the full system as represented by the numerical model, and interpolates behaviour between known bounds.

3.3 Description of case study

The case study uses a data set representing a simple isotropic homogeneous unconfined aquifer, with no-flow boundary conditions around the edge of a square domain, with a small river crossing the aquifer, and an abstraction well at a distance (D) from the river (Figure 3.1). The river has a steady inflow into the upstream boundary, and a stage control at the lower boundary. There are no other inflows or outflows (in particular, there is no precipitation recharge in this simple example). The case study is modelled using SHETRAN V.4, which includes a recently developed well model.

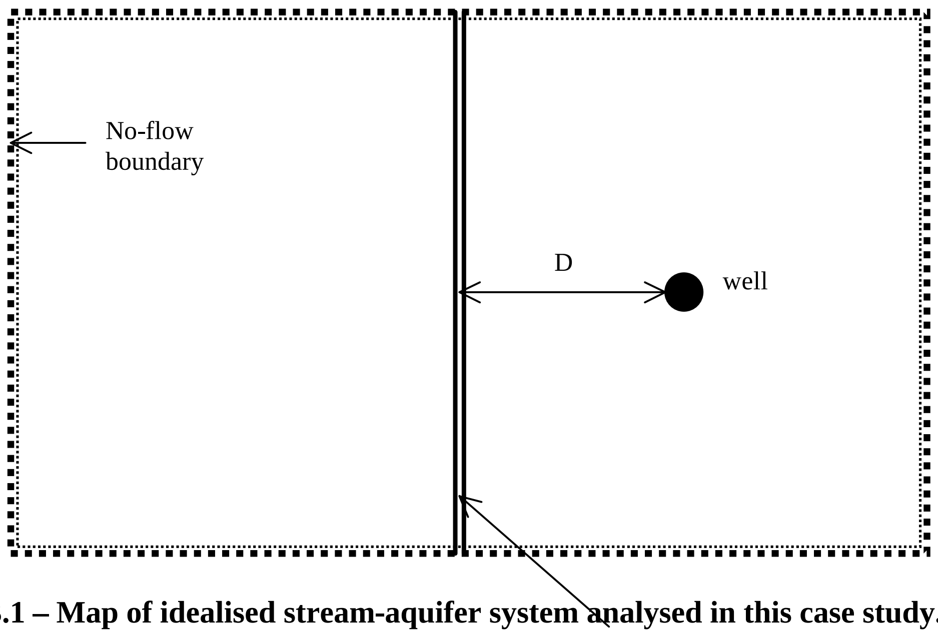

Figure 3.1 – Map of idealised stream-aquifer system analysed in this case study.

For this example, a small subset of the possible hydrological and hydrogeological configurations was chosen, representing only differences in river distance from the abstraction well to the river (D), and the steady pumping rate (Q_w). Five values for each of these variables were used, resulting in 25 simulations in total:

D (m) = 50, 125, 250, 500, 1000

Q_w (l/s) = 25, 37.5, 50, 75, 100 .

Each simulation was run for a period of 6 months, so that the river depletion could approach steady state for the majority of the runs.

Two output variables were defined for this example: the river depletion after a period of one month (Q_d), and the lag time (T_{50}). T_{50} is defined here (for this example only) as the time for the river depletion to reach 50% of its expected value (the long-term steady state value can be easily calculated in this case, since there are no other recharge sources or losses). The Artificial Neural Network (ANN) for this example consists therefore of two input variables and two output variables (Figure 3.2).

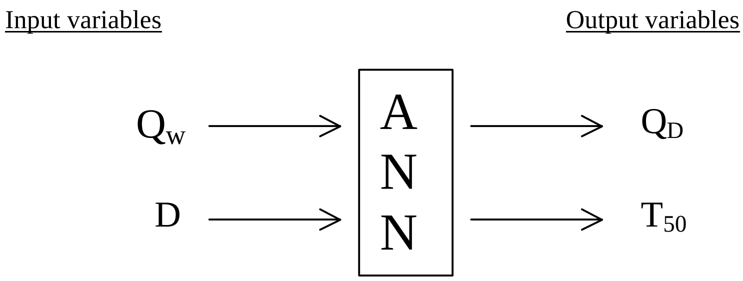

Figure 3.2 – Schematic sketch of the artificial neural network used in this case study

3.4 Results

The outcome of the SHETRAN modelling exercise is a set of 25 values of each of the output variables Q_d and T corresponding to each possible combination of the five values for each of the two input variables Q_w and D. A measure of the success of the training of the ANN is how well these output values are reproduced. The correspondence between the SHETRAN and ANN results following training of the ANN is illustrated in Figure 3.3.

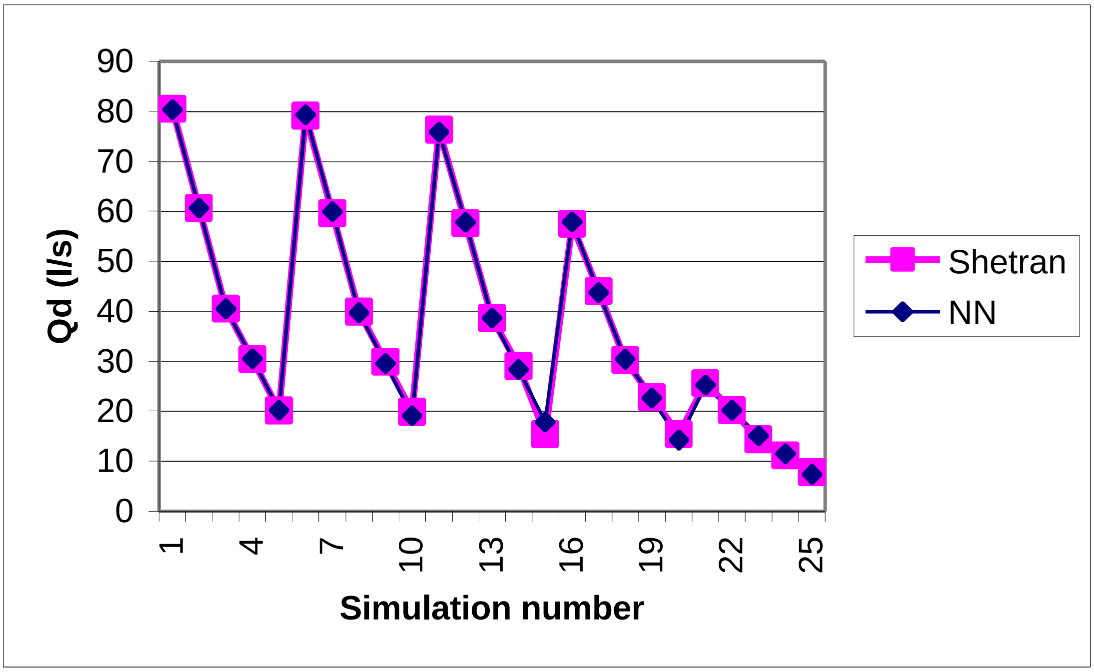

Figure 3.3 – Excellent correspondence between neural network (NN) and SHETRAN output following the training of the former (root mean-squared error = 1.7%)

Once trained, the ANN can be used to predict the outcome from any combination of values for the two input variables, within the limits of the training sets (i.e. it interpolates between the SHETRAN simulation results). This can be used to create "type curves" for combinations of values, as illustrated in Figure 3.4.

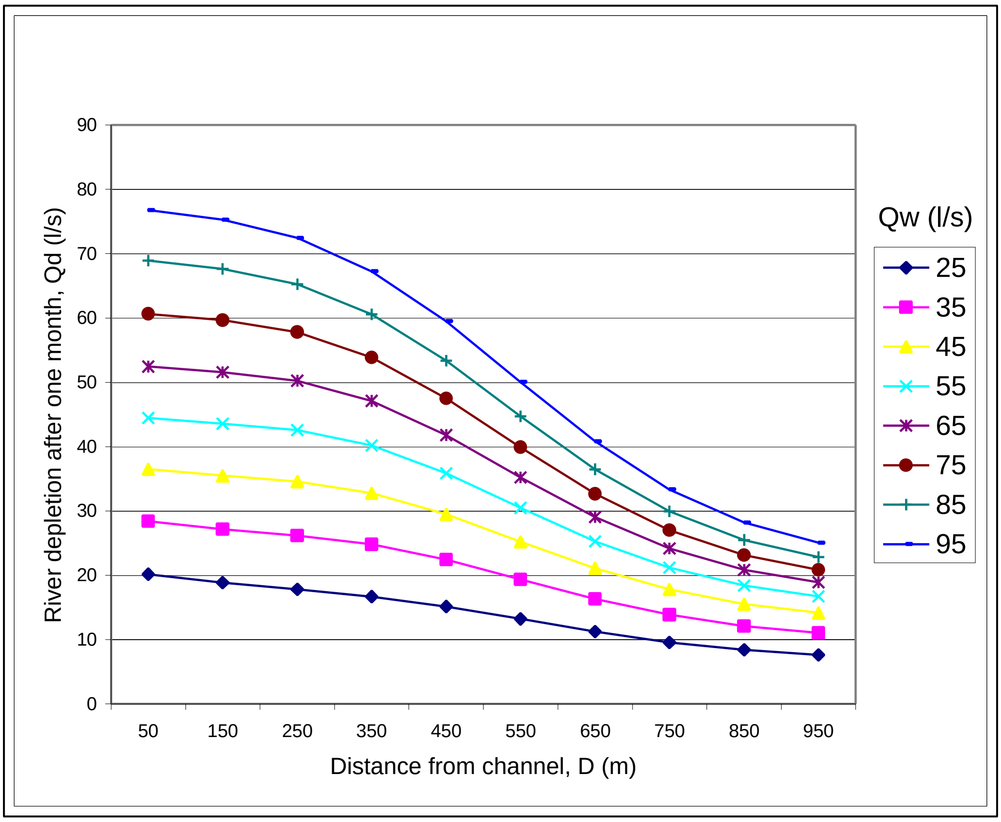

Figure 3.4 – Depletion of river flow due to pumping a well at a variety of abstraction rates and a variety of distances from the river

The capability of the ANN model to mimic the numerical model results was tested by running an extra set of simulations using both SHETRAN and the ANN model separately for a combination of input values which were not used for training the ANN model. Figure 3.5 illustrates the excellent predictive capabilities of the ANN in relation to Q_D. The results thus demonstrate the capability of the ANN to mimic the SHETRAN results, and to interpolate between them. It must be emphasised that the ANN runs took only seconds to execute, compared with tens of minutes for each SHETRAN simulation. The computational efficiency of the ANN is the principal reason for recommending its use for this application.

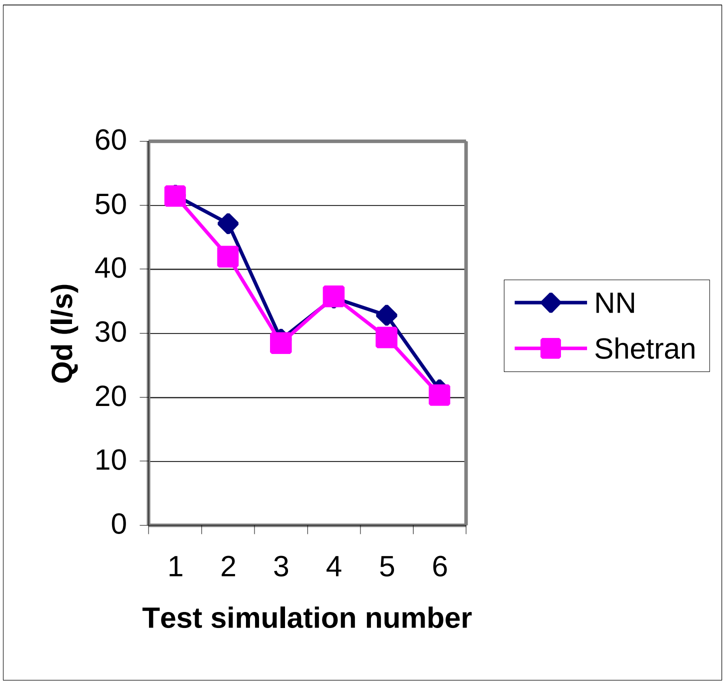

Figure 3.5 – Comparison of independently predicted values of Q_D using both SHETRAN and the trained ANN.

3.5 Conclusions

This simple case study has demonstrated the principles of the combined use of a numerical model and an artificial neural network for predicting the impact of groundwater abstraction on river depletion. The case study does not necessarily represent a realistic scenario that would be used in a full modelling study. The real benefits of using an artificial neural network become increasingly apparent when larger numbers of input and output variables are modelled over a larger range of combinations of parameters.

4 References

Rao, Z., and Jamieson, D.G., 1997, The use of neural networks and genetic algorithms for design of groundwater remediation schemes. Hydrology and Earth System Sciences, 1, pp 345 – 356.

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