Impact of Human Activity on Groundwater Dynamics (Proceedings of a symposium held during the Sixth IAHS Scientific Assembly at Maastricht, The Netherlands, July 2001). IAHS Publ. no. 269, 2001.

A new approach to modelling river–aquifer interactions using a 3-D numerical model and neural networks

G. PARKIN, P. L. YOUNGER, S. J. BIRKINSHAW, M. MURRAY, Z. RAO
Water Resource Systems Research Laboratory, Department of Civil Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, UK
e-mail: geoff.parkin@ncl.ac.uk

S. KIRK
Environment Agency, National Groundwater and Contaminated Land Centre, Olton Court, 10 Warwick Road, Olton, Solihull B92 7HX, UK

Abstract The forthcoming European Union Water Framework Directive has increased awareness of the need to evaluate the impacts of groundwater abstraction on the environment. The Environment Agency of England and Wales is responsible for water resource management, which it achieves primarily by operating a formal abstraction licensing system. Judgements made on applications for groundwater abstraction licenses need to be both systematic and defensible. A novel approach has been developed in a project for the Environment Agency which uses a combination of numerical model simulations of generic river–aquifer systems and neural networks to quantify the impacts on river flows. This approach provides a model which is very fast to run, while retaining the advantage of numerical methods of being able to represent complex conditions. The outcome of the project is a user-friendly Graphical User Interface (GUI) and embedded neural network software, which is designed for use by abstraction licensing officers. The approach is illustrated using a case study.

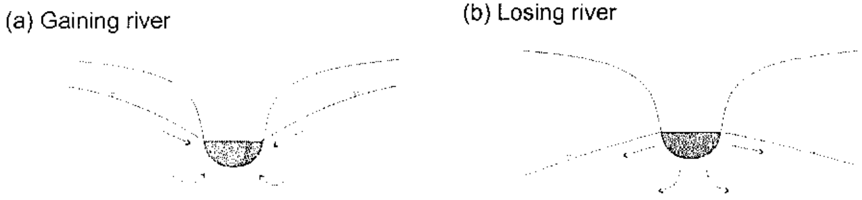
Key words groundwater abstraction; modelling; neural networks; river–aquifer interaction

INTRODUCTION

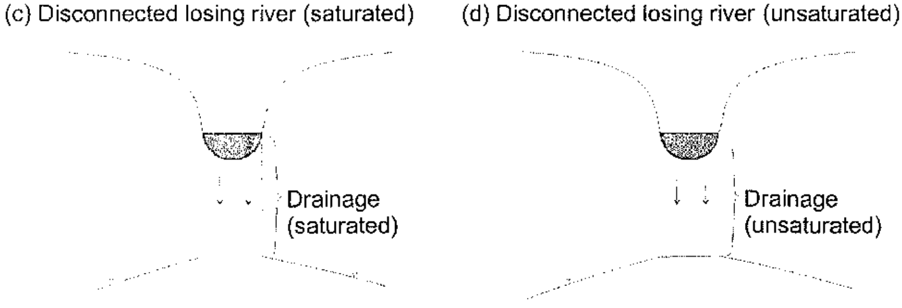
The Environment Agency (Agency) is responsible for water resource management in England and Wales. The principle means of management is a formal abstraction licensing system which was first introduced in 1963. Central to the Agency's philosophy and practice of abstraction licensing is the recognition that decisions about groundwater licence applications frequently have implications for surface water flows. The Agency is actively developing best practice procedures and tools to aid its estimation of the impacts on river flows, and thus make informed judgements on license applications. Most of this work is being carried out under the Agency's Impact of Groundwater Abstraction on River Flows (IGARF) programme, which is now in its second phase.

In the first phase (IGARF I) the Agency thoroughly reviewed currently available analytical models applicable in river–aquifer systems, and produced a spreadsheet tool and guidelines for their practical application to licensing decisions (Environment Agency, 1999). The assessment procedure developed for IGARF is now established best practice throughout England and Wales. The assessment procedure involves: firstly establishing a conceptual model; initial prediction from the model; design of a pumping test; carrying out and analysing the results of the pumping test; review of the conceptual model; and revised prediction for long-term impacts using the model as a guide only.

As with all analytical solutions, the models used in the spreadsheet tool are limited in their accuracy or applicability due to the models' assumptions of homogeneous, isotropic aquifer systems of infinite extent, which are in this case subjected to idealized river boundary conditions. Many analytical models can represent gaining or losing rivers which are in hydraulic connection with aquifers (Fig. 1(a, b)), but it is difficult to obtain solutions for such nonlinear problems as disconnected rivers (Fig. 1(c, d), or for other situations such as floodplain wetlands. The usual approach to increasing the realism in models is to opt for full-blown distributed numerical modelling. However, in many licence adjudication cases there will be neither the data nor the time to support distributed numerical modelling. Hence, an "intermediate" technique is desirable. The approach developed in this study (IGARF II) is to use artificial neural networks to mimic numerical model simulations of generic river–aquifer systems, providing a hybrid system which retains the complexity of numerical models and the speed of analytical models.


(a) Gaining river

(b) Losing river


(c) Disconnected losing river (saturated)

(d) Disconnected losing river (unsaturated)

Fig. 1 Schematic description of river–aquifer interactions.

OBJECTIVES

The objectives of the project are:

(a) To produce an easy to use, numerical modelling approach and "tool" to assist in the estimation of the impacts of groundwater abstraction on river flows.

(b) To produce recommendations and to assist in the establishment of best practice and a consistent approach to the estimation of the impacts of groundwater abstraction on river flows within the Agency.

METHOD

The approach taken in this study is to "mimic" the results from a large set of generic numerical model simulations by training an artificial neural network using a subset of the input-output data from the model simulations. An artificial neural network (ANN) is a set of highly interconnected mathematical processing elements (Fig. 2) which are capable of representing nonlinear 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. ANNs are a relatively recent innovation in water resources technology, and have previously been used to mimic process-based models for groundwater remediation and river water quality (Rao & Jamieson, 1997; Rao & O'Connell, 1999). Once trained, the ANN is embedded into a Graphical User Interface (GUI) which, in effect, gives the user access to a multi-dimensional "look-up table" (or, a set of multi-dimensional "type curves"), which represents numerical river–aquifer modelling results covering a wide range of practical problems.

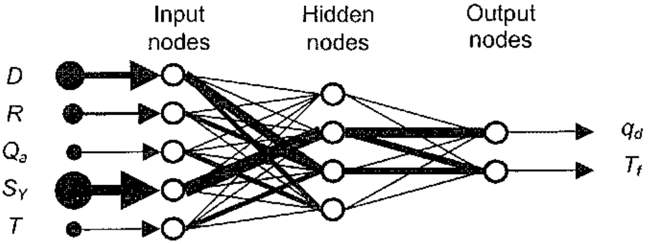


Fig. 2 Schematic representation of a simplified artificial neural network. For an explanation of the symbols, see Tables 1 and 2.

The approach taken during this study can be summarized as follows (some further details are given in the next section).

- *National classification of hydrogeological settings*: the scope of the study is defined to ensure that as many river–aquifer and abstraction scenarios as possible relevant to abstraction licensing officers are considered.
- *Determine parameters and values*: the "hydrogeological settings" are used as the basis for defining the input–output parameters which are passed from the numerical model to the ANN, and their ranges of values.
- *Define simulations*: the numerical model simulations are designed based on generic river–aquifer settings, using a subset of the parameter values.
- *Choose and run models*: in general, any model could be used which is capable of representing the processes which are considered to be important; in this study, the SHETRAN model was used (Ewen *et al.*, 2000), because of its capability of representing integrated surface and subsurface flows.
- *Train ANN model*: the ANN is trained (calibrated) using the input–output data, and tested (validated) against an independent set of numerical model results, to demonstrate that it is capable of reproducing the behaviour of the simulations.
- *Use trained ANN model for predictions*: once trained, the ANN can be used for predictions, within the range of its training data.

HYDROGEOLOGICAL SETTINGS AND PARAMETER SPECIFICATION

A key stage in the development of the modelling tool in this project is the identification of the range of hydrogeological conditions which must be addressed. This defines the applicability of the tool by defining the set of parameters which represent the processes modelled, and the ranges of parameter values over which the ANN is trained. For this study, a questionnaire was sent to representatives from each of the Agency regions in England and Wales, requesting information on the hydrogeological settings relevant to their region. This was followed up with a one-day workshop, at which the range of settings was agreed.

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. In Chalk aquifers, 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. 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.

The interactions between an aquifer and an overlying river depend upon the river geomorphology in relation to the aquifer. In particular, 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 some rivers this can cause the aquifer material between the river bed and the water table to become unsaturated, and the river to become disconnected from the aquifer.

As a result of this review questionnaire and workshop, a set of generic models was established to represent most of the conditions expected to be encountered by licensing officers. The three main models (or hydrogeological settings) were (Fig. 3):

(a) regional aquifer overlain by a valley sand and gravel aquifer,
(b) regional aquifer in direct contact with the river, and
(c) valley sand and gravel aquifer underlain by low permeability strata.

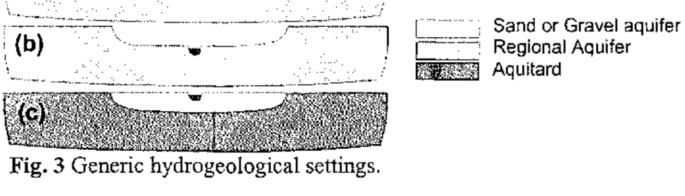


Fig. 3 Generic hydrogeological settings.

For each of these hydrogeological settings, sets of parameters were defined, including aquifer and river parameters, and data associated with recharge (an annual cycle of recharge was allowed for) and the abstraction scenario (rate and duration of abstraction, distance of borehole from the river). A wide range of plausible values was associated with each of these (Table 1), and a discrete set of parameter values (typically five values) were selected from these ranges. To run a full set of numerical model simulations with all combinations of each of these parameter values would have resulted in an unrealistically large number of simulations (many millions). A subset of these possible simulations was defined using an orthogonal array approach (Hedayat *et al.*, 1999), a structured combinatorial method which ensures that as much of the "input parameter space" as possible was covered with the simulations. This approach reduced the total number of simulations required to less than 2000.

Table 1 Input data and parameter ranges.

Symbol	Description	Units	Range
D	Distance of borehole from river	m	25–560/4000
Q_a	Abstraction rate(s)	m^3 day^{-1}	500–5000/10000 0–5000
Q_r	Compensation returns	m^3 day^{-1}	any valid date
t_s	Start date(s) for abstraction	date	any valid date
t_e	end date(s) for abstraction or	date	1–365
n_d	duration(s) of abstraction	days	10–60000
T_a	Aquifer transmissivity or	m^2 day^{-1}	1–200
K_a	aquifer hydraulic conductivity	m day^{-1}	10–300
b_a	Aquifer thickness	m	0–6000
T_v	Valley-fill transmissivity or	m^2 day^{-1}	0.0001–100
K_v	valley-fill hydraulic conductivity	m day^{-1}	0–60
b_v	Valley-fill thickness	m	0.0001–0.1
S	Specific storage	–	–0.5
S_{Ya}	Aquifer specific yield	–	0.1–0.5
S_{Yv}	Valley-fill specific yield	–	5–50
w	River width	m	0.001–40
K_b	River bed sediment hydraulic conductivity	m day^{-1}	0.2–5
d_b	River bed sediment thickness	m	0–1000
R	Mean annual recharge	mm year^{-1}	any valid date 0–1
t_r	Date of peak recharge	date	
R_s	Recharge seasonality	–	

CASE STUDY: SHALLOW VALLEY AQUIFER

Hydrogeological setting and parameter specification

The shallow valley aquifer setting is used here as a case study to demonstrate the system. This setting represents 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. The significant hydrogeological factors for this setting are the relative shallowness of the aquifer in comparison with more regional aquifers, and the existence of barrier-boundary conditions at the valley margins, which can favour greater induced infiltration from the river.

SHETRAN modelling

A SHETRAN model was set up for a generic region covering 1 km along a reach of a river running through the centre of a 1 km wide valley. An inflow boundary condition was used for the river inflow. No-flow boundary conditions were used for all aquifer boundaries. Approximately 400 simulations were set up to run over a 25-year period, for a systematically-determined subset of all possible parameter values. The output variables consisted of total river flow depletion (over short and long time scales), the spatial pattern of river flow depletion, and the spatial pattern of aquifer drawdown (Table 2). These were calculated by comparison between simulations run with zero groundwater abstraction and simulations with non-zero abstraction.

Table 2 Output data.

Symbol	Description	Units	No. of values	Variable number
q_d	Monthly/annual flow depletion	$m^3 day^{-1}$	31	1–31
q_p	Flow depletion time series	$m^3 day^{-1}$	18	32–49
q_r	depletion profile in river	$m^3 day^{-1}$	10	50–59
d	Aquifer drawdown	m	10	60–69
T_f	Time of maximum flow depletion	days	1	70
M_f	Maximum flow depletion	$m^3 day^{-1}$	1	71
d_w	Drawdown in the well	m	1	72

Training of artificial neural networks

All of the data (input and output) used by the ANN are normalized onto a range of 0.05–0.95. Since some of the data span several orders of magnitude, they were firstly put onto a logarithmic scale to provide a better representation of the variation in parameters over the full range. Two three-layer feed-forward ANNs were set up: the first is used to check the validity of the input data, the second to produce the actual results. Both used nine input nodes, the first had five hidden nodes and one output node, and the second had 45 hidden nodes and 72 output nodes. Some typical results from the validation simulations are given in Fig. 4. This shows the normalized output data from two of the simulations, in which the main difference is that the abstraction well is further from the river in the second simulation. It can be seen in these unprocessed ANN results, for example, that the river depletion profile (variables 50–59) is less for the second simulation with a more distant well than for the first.

Graphical user interface for licensing officers

The GUI is designed to allow an easy interface to the ANN, and therefore to the numerical simulation results upon which the ANN is based. The functions of the GUI are to: check the validity of the input data by comparison against the valid ranges (Table 1) and by running the first ANN; run the second ANN if the data are valid; process the output by converting back from the normalized data ranges used by the ANN. The GUI is set up to allow multiple abstractions from one borehole during each

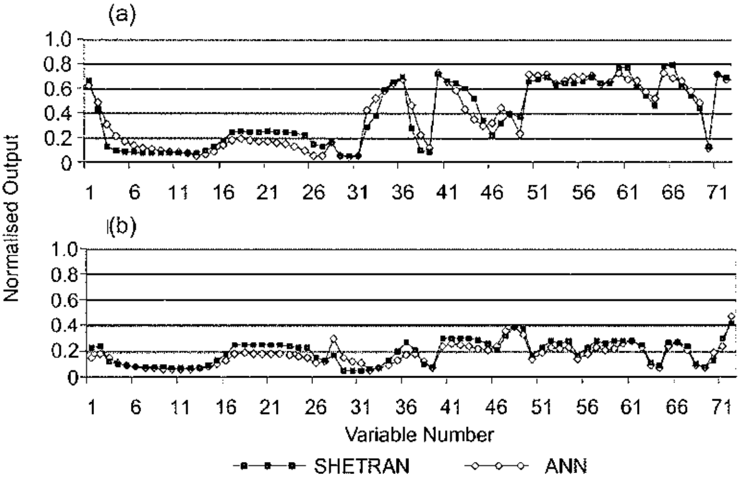
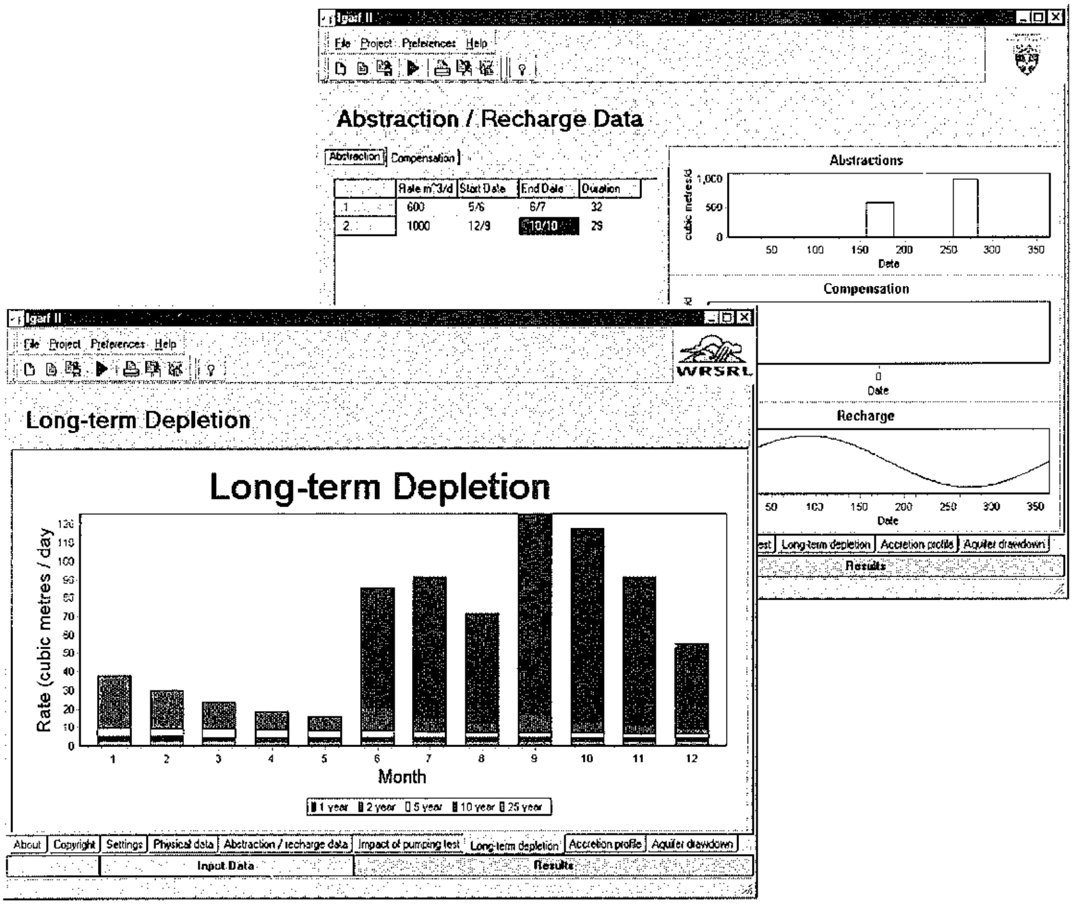


Fig. 4 Results from training of artificial neural network (see Table 2 for an explanation of the variable numbers). (a) Validation simulation with well 212 m from the river. (b) Validation simulation with well 362 m from the river.



	Rate m^3/d	Start Date	End Date	Duration
1	600	5/6	6/7	32
2.	1000	12/9	10/10	29

Fig. 5 Examples of GUI pages, showing the long-term impact of a repeated cycle of annual abstraction on river flow depletion.

year. In addition to the short-term impacts from a single pumping scenario, the long-term impacts of a repeated pattern of cyclical annual abstractions are calculated based on the principle of superposition. This is illustrated in Fig. 5 for a sequence of two periods of abstractions, in which the input data sheet shows the two abstraction periods and the annual recharge cycle, and the output sheet shows how the river depletion gradually increases over a period of 25 years.

CONCLUSION

This project confirms that the hybrid approach of using an artificial neural network to mimic numerical model simulations is a feasible method of providing rapid access to the results of detailed process-based simulations. Subject to further testing of the approach, the project is expected to deliver a fully functional modelling tool for use by the Agency within 2001. A significant advantage of the method is that it can, in principle, be extended to other complex scenarios (such as floodplain–aquifer interactions), provided that the input–output characteristics of the scenarios can be clearly defined.

Acknowledgements The authors thank Prof. P. E. O'Connell for the initial suggestion of using ANNs in this context, and S. Fletcher, J. Aldrick, D. Headworth, D. Burgess, P. Hulme, and other Agency staff who have contributed to the study. The work is funded by the Environment Agency as R&D project number W6-046.

REFERENCES

Downing, R. A. (1993) Groundwater resources, their development and management in the UK: a historical perspective. *Quart. J. Engng Geol.* **26**, 335–358.

Environment Agency (1999) Impact of groundwater abstractions on river flows. National groundwater and contaminated land centre project. *Report NC/06/28*, Solihull, UK.

Ewen, J., Parkin, G. & O'Connell, P. E. (2000) SHETRAN: a coupled surface/subsurface modelling system for 3D water flow and sediment and solute transport in river basins. *J. Hydrol. Engng ASCE* **5**, 250–258.

Hedayat, A. S., Sloane, N. J. A. & Stufken, J. (1999) *Orthogonal Arrays: Theory and Applications*. Springer-Verlag, New York, USA.

Rao, Z. & Jamieson, D. G. (1997) The use of neural networks and genetic algorithms for design of groundwater remediation schemes. *Hydrol. Earth System Sci.* **1**, 345–356.

Rao, Z. & O'Connell, P. E. (1999) Integrating ANNs and process-based models for water quality modelling. In: *Proc. Second Inter-Regional Conference on Environment-Water: Emerging Technologies for Sustainable Land Use and Water Management* (Lausanne, Switzerland, September 1999) (ed. by A. Musy, L. S. Pereira, & M. Fritsch). PPUR, EPFL, Lausanne, Switzerland.

Younger, P. L., Mackay, R. & Connorton, B. J. (1993) Streambed sediment as a barrier to groundwater pollution: insights from fieldwork and modelling in the River Thames basin. *J. Instn Wat. Environ. Manage.* **7**, 577–585.