The Role of Groundwater Resources Models in Integrated Catchment Management

Farrell, R1 & Whiteman, M1

1Environment Agency for England and Wales. rolf.farrell@environment-agency.gov.uk, mark.whiteman@environment-agency.gov.uk

Abstract: Innovative work has been undertaken by the Environment Agency for England and Wales, and will continue to be required to successfully meet the challenges presented by recent domestic legislation (Water Act 2003) and the EU Water Framework Directive. This has required a more integrated approach to catchment management of groundwater and surface water quantity and quality to protect ecological receptors. We have made a significant investment in tools, methods and approaches to ensure proper integrated management of groundwater. This paper describes the water resources aspects, however, there are also equivalent methods for contaminant hydrogeology.

The Environment Agency for England and Wales has made a significant investment in catchment-scale groundwater modelling for the purpose of assessing the condition and available resources of the countries’ aquifer systems. It is important that the benefits of this substantial investment are maximised. Principal drivers for groundwater resource modelling include assessment of available groundwater resources for abstraction, assessment of baseflow to protect surface waters, determination of water balances for wetlands and the modelling of river augmentation schemes. Hydrogeologists are directly concerned with the impacts of new abstractions on existing sources; Water resources managers need to know how the groundwater regime impacts on surface waters; hydrologists need baseflow inputs to surface water models; and hydroecologists need knowledge of how the ecology might respond to stresses from the groundwater system during critical periods (e.g. droughts).

Keywords: groundwater; regulation; tools; guidance; benefits

1. INTRODUCTION

The Environment Agency for England and Wales has a statutory duty to manage the sustainable development of groundwater resources. Our role is to identify the sustainable yield of groundwater units, and to regulate abstraction to ensure that the impacts of abstraction on springs, rivers and wetlands are limited to a point which is acceptable [Burgess, 2002]. The Environment Agency also has a duty to protect groundwater quality. It is in line with Environment Agency policy that the management and regulation of groundwater should be based on a good scientific understanding of groundwater systems, and on good technical practice. Integrated catchment management, involving consideration of all aspects of the system rather than artificial focus on specific aspects of it such as surface water hydrology and water quality, is an important part of this. This paper describes the tools, methods and approaches used to deal with the groundwater resources component of integrated catchment management – equivalent methods are available for contaminant hydrogeology, although the latter is outside the scope of this paper. Integrated management of land and water requires that we consider the integration of data, understanding and decision making so that adopted remedial measures in one sector (such as risk) do not have negative effects in other sectors (such as fisheries). The UK Government is moving towards an ecosystems approach [Defra 2007] to conserving, managing and enhancing the natural environment in England. This is about adopting a new way of thinking and working, by:

• Shifting the focus of our policy-making and delivery away from looking at natural environment policies in separate ‘silos’ – e.g. air, water, soil, biodiversity – and towards a more holistic or integrated approach based on whole ecosystems; and
• Seeking to ensure that the value of ecosystem services is fully reflected in policy- and decision-making across Government at all levels.

The modelling of the major aquifers of England and Wales represents a significant investment for the Environment Agency. Catchment scale models, as they attempt to model a large part of the water cycle in some detail, tend to have potential benefits for a much broader cross section of the organisation’s work than might at first be considered.

This paper summarises how the Environment Agency is attempting to ensure that these benefits are realised by means of both practical tools (such as the National Groundwater Modelling System (NGMS)) and Guidance documentation (such as guidance on Catchment Abstraction Management Strategies) and how we are using them to support integrated catchment management.

2. TOOLS

The Environment Agency has a number of different tools that can be used for assessing groundwater resources and contaminant hydrogeology. This paper will focus on the groundwater resources tools. These range from simple risk screening methods and GIS-based tools, through simple analytical models to more complex numerical models (Table 1).

<table>
<thead>
<tr>
<th>Complexity/cost</th>
<th>Water Resources</th>
<th>Groundwater Contamination</th>
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<tbody>
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<td></td>
<td>Simple risk screening tools e.g. Water Resources GIS risk engine</td>
<td>Groundwater vulnerability maps</td>
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<td></td>
<td>Simple/analytical (deterministic) models e.g. IGARF (Environment Agency, 2001a)</td>
<td>Analytical (deterministic) models e.g. Remedial Targets Method</td>
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<td>Analytical (probabilistic) code (rarely used)</td>
<td>Analytical (probabilistic) code e.g. ConSim</td>
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<td></td>
<td>Numerical models e.g. MODFLOW</td>
<td>Numerical models (rarely used) e.g. MODFLOW+MT3D</td>
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*Table 1: Parallel structures/guidance for groundwater resources and contaminant modelling components of integrated catchment management*

2.1 GIS-based risk engine

To support implementation of the Water Framework Directive, the Environment Agency has developed a GIS-based risk engine for screening the level of risk from new water abstraction licences (Figure 1). The equivalent for groundwater contamination is the groundwater vulnerability map.

The GIS contains data sets of the different environmental classifications for rivers, lakes, groundwater etc along with supporting information (e.g. geology maps) that may help in assessing a site. The different layers allow a particular location to be assessed in terms of impact of, for example, a new abstraction on those features. It will be possible to export output from numerical groundwater models directly into the GIS allowing, for example, sample transient zones of influence to be viewed. Similarly, output from simple analytical models can also be viewed through the GIS. Also, it is intended that spatial plots from the numerical groundwater reports indicating zones of calibration accuracy of the models will be included to allow decisions to be made as to the best means to assess a catchments’ water resources.
Operationally, the Water Resources GIS will be mostly used by water resource regulatory managers though support and datasets will also come from specialist hydrogeologists and hydrologists.

Figure 1   Water Resources GIS tool.

2.2 Simple Groundwater Modelling Tools

There is no automatic presumption that a numerical assessment of a catchment will require a full distributed groundwater model; various analytical tools have been used as alternatives. The decision as to whether a distributed model is required depends on assessment of what it is needed to know and why; this decision must be made carefully if benefits are to be maximised. The degree of risk to the environment and/or existing abstractors from the decision, as well as cost, available timescales and conceptual understanding (e.g. is the aquifer in an area of complex geology where development of a numerical model will be inappropriate?) all need to be taken into account. Generally, the analytical tools are used to answer specific, relatively localised issues.

The existing analytical tools, which include IGARF (Impacts of Groundwater Abstraction on River Flows)[Environment Agency, 2001a], a simple spreadsheet-based tool, and also traditional groundwater investigation formulae, are thought only to be adequate for more straightforward abstraction licence assessments.

Another commonly used approach is to use Catchmod, a simple rainfall-runoff model (with groundwater module). This was successfully used by the Environment Agency to provide timely information in response to the 2005-06 drought in England by assessing baseflow in rivers at critical surface water locations, and groundwater levels at key locations. The numerical groundwater models were also used to model the impact of the drought on the resource balance as a whole, something that Catchmod cannot do.

2.3 Numerical Distributed Groundwater Models

The key focus for groundwater resource assessment are the catchment scale groundwater models usually based on the Modflow code. Other, steady state models have been created using Flowpath for determining capture zones for groundwater protection. To maximise the achievable benefits from regional scale models, consideration of groundwater quality modelling is also necessary. A similar hierarchy of tools is available to staff focussing on Groundwater Quality issues (Table 1).
Recent IT developments have provided an exciting opportunity for the Environment Agency to develop new, user-friendly, graphical and GIS-based methods for presenting and using the catchment-scale groundwater models. The National Groundwater Modelling System (NGMS) [Farrell et al., 2007] is a software front end (Figure 1), a development of the Delft Flood Early Warning System (FEWS) software (by Deltares, formerly Delft Hydraulics), already successfully proven by the Environment Agency’s National Flood Forecasting System. NGMS allows configured models to be run either according to pre-defined, standard scenarios; historic (i.e. modelled observed), naturalised, fully licensed and recent actual as well as user defined what-if scenarios involving changes or additions to abstractions as well as predictive scenarios for climate change or drought prediction. From an end user perspective, the purpose of NGMS is to provide a means of running and examining model output (and input) enabling water management decisions to be made. Tools that support this include:

- Hydrographs for all time variant data types.
- Pre determined river accretion profiles for main rivers and watercourses
- Flow duration curves and supporting statistics
- Spatial displays for model input and output data plus aquifer parameters

The system is designed to enable easy comparison of data sets - either between different types of data or between different scenarios (for example, comparison of a historic model run and a naturalised run for a spatial plot effectively produces a drawdown plot). Whilst NGMS itself has varied functionality for post processing and display of data, export to other applications such as the MS Office suite and GIS programmes is straightforward.

As well as the ability to run the models, the NGMS allows archiving of model versions, model runs and supporting data.

Figure 1  NGMS Groundwater Head Spatial Display

2.4 Use of Groundwater Models

The development of groundwater conceptual and numerical models is an important part of helping to meet the Environment Agency’s regulatory responsibilities, including strategic planning and operational management of groundwater resources in England and Wales. Strategic planning comprises successful implementation of European Directives including the Habitats Directive (92/43 EEC) and Water Framework Directive (2000/60/EC), restoring sustainable abstraction by addressing hydrogeological impacts upon rivers and wetlands of conservation value, and preparation of Catchment Abstraction Management Strategies (CAMS). Operational management includes water resource abstraction licensing and water availability forecasts. Groundwater resource assessment also provides a
framework for groundwater quality investigations, including Source Protection Zones (SPZ), and for contaminated land work.

An example of operational use is assessment of impacts upon groundwater-dependent wetlands. Understanding the links between the ecological functioning of wetlands and changes in groundwater quantitative and chemical status remains a significant challenge to successful catchment management [Lerner et al, 2007]. Groundwater models provide a decision support tool to help answer questions faced by regulators and wetland managers, such as:

- Whether reduced groundwater discharge to a wetland as a result of abstraction has an adverse impact on the ecology (e.g. EU Habitats Directive).
- If there is an adverse impact, what options are effective to mitigate or remove the impact to ensure that favourable condition can be met (e.g. can reduced groundwater flow be compensated for by increased surface water supply, without significant damage to the ecosystem?).

The Environment Agency’s eco-hydrological guidelines are used to determine the hydrological, chemical and management needs of the ecology [Wheeler et al, 2004]. The groundwater model is used to check if site-specific criteria are maintained including upflow to the topmost model layer, groundwater levels at the water table, spring flows and soil moisture characteristics [Whiteman et al, 2007]. A series of options for removing adverse impacts are then tested using the groundwater models, resulting in a Site Action Plan to restore the site to favourable condition.

At Foulden Common, in Norfolk (Eastern England), several wetland water supply mechanisms (WETMECS) [Wheeler and Shaw, in press] were identified [Whiteman et al 2007] and an eco-hydrological conceptual model for the site was developed to include these water supply mechanisms [Entec, 2007]. This helped guide the specification of local improvements within a regional scale groundwater model including, albeit relatively crudely, representation of ‘top-layer’ effects.

The Schoenus nigricans–Juncus subnodulosus mire (M13) vegetation community (National Vegetation Classification, Rodwell 1991 – 1995) represents the ecological feature of the site which is most sensitive to changes in the hydrology (e.g. to near surface groundwater levels and “flushing”). The criteria above were developed for this feature to help determine acceptable levels of abstraction on the basis that, if M13 were adequately protected, less sensitive communities would not be adversely affected.

Whiteman et al [2007] discuss the limitations of applying numerical groundwater models, which can only represent appropriate conceptual detail for the scale at which they are constructed. They conclude that existing relatively coarse scale models may be used, particularly to assess potential changes in hydrogeological behaviour, but that their application needs considerable care. Results from such models must not be used ‘blind’, and in particular should be interpreted with due regard to small scale variability.

3. GUIDANCE AND DOCUMENTATION

To ensure that the above tools are used by the right people at the right time, clear guidance and documentation is as necessary as the models and tools themselves. Examples of important Environment Agency guidance which are used to underpin management of groundwater resources include:

- Guidance for Catchment Abstraction Management Strategies (CAMS) - the principal aim of CAMS is to provide a framework for resource availability assessment and produce a licensing strategy which aids the sustainable management of water resources on a catchment scale, and each strategy is reviewed on a six-yearly cycle. CAMS is the first consistent methodology that has given us resource availability for the whole of England and Wales.
Groundwater modelling was used in the first cycle of CAMS in groundwater dominant areas, to assess the available groundwater resources. The second cycle of CAMS will see each catchment revisited and updated with the aim of improving further our confidence in the resource assessments.

The new, second cycle CAMS guidance and the Groundwater Modelling Guidance Notes will cross reference each other to ensure that the most appropriate groundwater modelling tools are used for assessing groundwater resources at any point of interest within a modelled catchment. This is in relation to both riverine and wetland ecological needs. In the future there will be the presumption to always use a groundwater model if there is one available and appropriate to the task.

- Groundwater Modelling Guidance Notes [Environment Agency 2002] have been developed to ensure that project managers are able to produce the right product at the right time. These notes are currently being updated to describe the use of models to address catchment management issues, based on recent experience. Supporting technical notes provide background aided by examples of good practice.

- Regional Groundwater Modelling Strategies provide basic descriptions of the Region’s major aquifers, how they will be modelled and what the drivers for those models are [Hulme et al, 2002]. They describe the principle water resource management issues that affect the main aquifer units. They then describe the current and proposed groundwater models and how they are expected to be used to address these issues. Supporting documents are updated annually to report back on progress against the strategy.

- Hosting of hyperlinked model documentation within the National Groundwater Modelling System allows people using the system to have immediate access to conceptual and technical information whilst reviewing the output of the models. Documents hosted on the system include conceptual reports, project reports, technical and non technical summaries and supporting plots and diagrams that may help in interpreting model output. Hyperlinks from NGMS into the model reports and within the documentation mean that the meaning of a model output can assessed quickly. For example, a scenario flow at a gauging station can be related back to documentation that describes the calibration accuracy and purpose of that gauging station.

4. FUTURE DEVELOPMENTS

4.1 Forecasting

Work is ongoing to ensure that groundwater models are kept sufficiently up to date for operational use (for example in drought scenario modelling):

- Planned data update programmes ensure that the models should never need more than 2 years worth of environmental data to be updated at any one time. This ensures that the task of updating shouldn’t be too onerous. For models configured to NGMS, the update process will be largely standardised and the process supported by guidance documentation.

- Forecast scenarios have been developed. In 2006, scenarios based on specific months’ rainfall patterns that represented 60, 80, 90, 120 and 140% of LTA were used to give a feel for the sensitivity of the system to certain quantities of rainfall. These scenarios were used with simple Catchmod model as well as the catchment-scale numerical groundwater models (figure 3).

- A rapid method of providing more immediate forecasts is needed; ideally such that a feel for how a drought might develop can be given within a day. One approach would be to make use of rainfall radar data that is gathered by the Agency National Flood Forecasting System (also based on Deltares FEWS). This can be configured to provide geostatistically corrected daily rainfall datasets which could be used to update the rainfall sequence, possibly calibrated against the telemetered rainfall observed data also used by NFFS. Combined with a simple utility to update abstraction records (perhaps by using the same rates as were abstracted in a previous year) it should be possible to provide a preliminary set of predictive scenarios within a few hours.

- Use of continuous monitoring (i.e data loggers) rather than periodic manual dipping, in observation boreholes ensures that we have real-time data that highlights the need for a
model or corrective action to be taken, and provides sufficient data resolution for short term event modelling as well as more longer-term resource assessments.

As well as providing the physical tools to enable forecasting to be carried out quickly, the appropriate guidance is being developed to support it as part of the guidance notes update. Examples of best practice, from the drought, as well as lessons learned will be incorporated so that we should be ready to provide timely answers when the climate next demands it.

Figure 3 Forecast groundwater levels in EA Thames Region, 2006

4.2 ‘Intermediate’ models

Jackson et al [2007] caution that the current analytical models do not produce results with sufficient confidence where, for example, a groundwater abstraction has a significant impact on more than two rivers, or a more accurate spatial or seasonal distribution of the impacts on both flow and groundwater level is important. For example, when the effects of several abstractions must be considered, and the regional context is important for estimating the local impact, which is often true for wetland sites.

Traditional catchment-scale Modflow models are inappropriate for the rapid assessment of these impacts since they often take two to three years to produce at a cost of £200k to £300k each. To address this need for “intermediate” models, the Environment Agency recently completed a proof of concept project for an intermediate tool which removes some of the limiting assumptions associated with the current low cost modelling tools (e.g. aquifer homogeneity or geometric simplicity) but which can be set up in a few hours [Jackson et al, 2007]. In future, this object-oriented tool should allow operational hydrogeologists to test many alternative scenarios quickly to get a better understanding of system behaviour, and to test the uncertainty associated with the key hydrogeological conditions which prevail for a particular site.

5. CONCLUSIONS

The Environment Agency for England and Wales has responded proactively to the challenges presented by recent legislation by taking a much more integrated approach to management of groundwater, where the primary driver for a new groundwater model is as likely to be to determine baseflow targets to meet in-river ecological needs as specifically groundwater resource related. It could also equally likely require velocity fields, not just bulk water flow, to address groundwater quality/contaminant hydrogeology issues.
This integrated approach also requires practices to be agreed between different disciplines which might have either input into models or have a requirement for their output. Considerable progress has been made towards effective, integrated catchment management, by making both numerical tools and guidance easily available. The guidance must take into account the different needs and benefits that the models may provide answers for. Further work is still required to meet the challenges of integrated catchment management, with a need for not only integrated models but inclusion of interdisciplinary processes (e.g. the hyporheic zone).

REFERENCES


