The National Groundwater Modelling System: providing wider access to groundwater models

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Abstract: The National Groundwater Modelling System (NGMS) is a map-based, client–server system for holding groundwater models and supporting documentation. Models can be run, new 'what-if' scenarios created, and time series and spatial data rapidly viewed and exported. Use of the system will result in greater standardization of data formats, model codes and methods used by the Environment Agency without stifling technological progress. NGMS enables a wider audience of water resource staff to access groundwater models. The system is being used to improve representation of groundwater in Catchment Abstraction Management Strategies and to forecast the potential impacts of climate change upon water resources. However, the day-to-day, operational use of groundwater models by the Environment Agency remains a challenge that requires engagement with other specialists (e.g. hydrologists and IT systems specialists). Considerable effort is required to roll out the system, train people and adapt operational decision-making processes to bring NGMS into regular and safe use.

The Environment Agency for England and Wales has a statutory duty to manage the sustainable development of groundwater resources. It follows that one of the Environment Agency's roles is to quantify the available water resources in those principal aquifers under the greatest abstraction pressure, and to regulate abstraction to ensure that the impacts of abstraction on springs, rivers and wetlands are limited to an acceptable extent. The Environment Agency uses a risk-based approach, balancing the threat to the environment with the benefits from the proposed activity or development. Often the available data do not provide the full picture, yet a decision still has to be made, making a judgement of the risks involved (Environment Agency 2008*a*). Conceptual and numerical models are therefore an essential part of the risk-based approach. These are based on scientific principles and use available data and a professional assessment of the local circumstances. Conceptual and numerical regional groundwater models have been developed by all eight regions of the Environment Agency (see Whiteman *et al.* 2012, fig. 1).

Role of NGMS in the Environment Agency's regulatory decision-making process

The National Groundwater Modelling System (NGMS) provides a scenario tool that assists in the regulatory decision-making process. Interpretations of the model output and decisions are made by the user in discussion with non-technical managers and other external partners such as water companies. NGMS is not intended to provide a complete 'decision support system' as many other factors are involved in the decision-making process, such as legal, economic and ecological aspects.

The main categories of regulatory decisions that need to be made, and with which the models can help, are catchment abstraction management and licensing. Models have also assisted in monitoring network design, investigating groundwater quality and implementing groundwater source protection zones (Whiteman *et al.* 2012, tables 1 & 2). Bespoke training sessions guide NGMS users through the decision-making process for abstraction licensing using real local regulatory examples. Guidance has also been provided on how to use groundwater models to estimate catchment scale water availability and impacts of abstractions upon river flows (see Hampshire Avon example below).

Embedding the use of the NGMS model repository, processing and visualization tools, and what-if scenarios within the regulatory decision-making process is an ongoing area of work. In fulfilling the Environment Agency's statutory role in authorizing applications for groundwater abstraction

From: Shepley, M. G., Whiteman, M. I., Hulme, P. J. & Grout, M. W. (eds) 2012. *Groundwater Resources Modelling: A Case Study from the UK*. Geological Society, London, Special Publications, **364**, 49–63. http://dx.doi.org/10.1144/SP364.5

licences (permits), it is important to develop a sound conceptual understanding of the impact of a proposed abstraction on water resource availability and other water interests and users. NGMS ensures that the models already developed for the principal aquifers in England and Wales (Fig. 1) are readily accessible to technical officers whose job it is to scope and assess the groundwater investigations, and ultimately to provide technical recommendations on the acceptability of the proposed abstraction. The use of 'what-if' scenarios is particularly valuable for assessing larger-scale abstractions. It is recognized, however, that there are other factors in the decision-making process beyond resource availability, for example local impacts, that may not be well represented in numerical models, even where they exist.

Groundwater modelling in the Environment Agency

Conceptual models and the role of groundwater models in a regulatory decision-support framework are discussed by Whiteman *et al.* (2012). The process whereby hydrogeologists interpret the available information to produce a justifiable set of simplifying assumptions to describe a groundwater system is called 'conceptual model development' (Brassington & Younger 2010). For the purposes of this paper, a conceptual model is considered to be an integration and interpretation of the field data and an associated water balance. The conceptual model provides an explanation of the way in which water moves through the surface water–groundwater system. Groundwater resource investigations are undertaken to help gain this conceptual understanding of the groundwater system, in order to assess and manage groundwater resources and the impacts of natural and anthropogenic factors upon resource availability and resource behaviour. Brassington & Younger (2010) provide a framework for conceptual model development to assist with the planning of groundwater investigations and to act as an audit trail for independent scrutiny. The process of conceptual model development is also described in the Environment Agency's groundwater modelling guidance notes (Environment Agency 2002, 2008*b*) and groundwater protection policy (Environment Agency 2008*a*). Within the Environment Agency's modelling approach, the conceptual model is quantified and tested by means of simple water balances, which may include long-term average or seasonal balances.

Numerical modelling is being used increasingly to quantify the water resource availability of the complex, dynamic groundwater–surface water systems in England and Wales and to take account of the environmental impact of abstraction. However, to be credible, modelling tools must be a technically valid and agreed representations of the real system. Therefore, one of the key objectives of any resource study is the process of developing a shared understanding (the conceptual model) of the essential

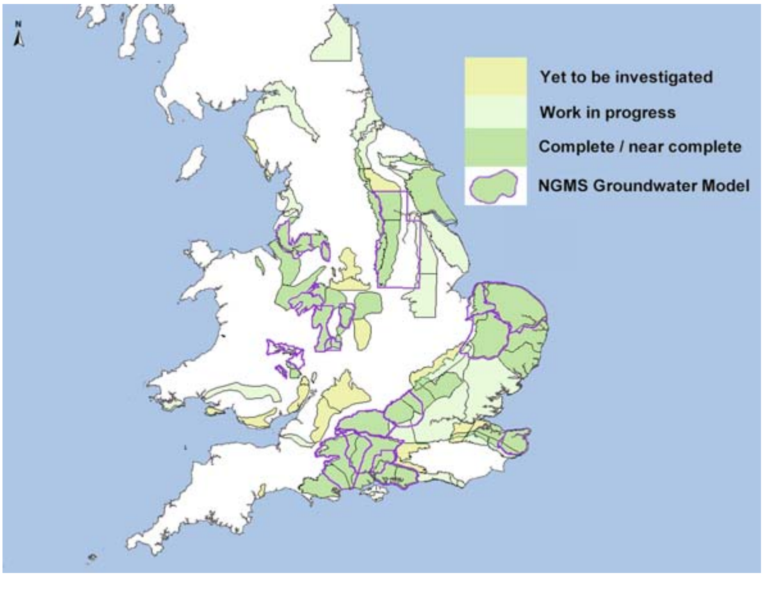

Fig. 1. Groundwater resource investigation areas (shaded) and groundwater models currently uploaded onto NGMS (outlined in purple).

flow mechanisms. Only then can the numerical model be used as a predictive tool to investigate different future conditions (such as new abstraction regimes and changes in climate). Distributed numerical models are not always required. It is not unusual that decisions on groundwater resources issues can be based on the quantified conceptual model and possibly with the use of analytical or lumped parameter modelling tools.

Regional groundwater models are developed in accordance with the Environment Agency National Modelling Framework (Brown & Hulme 2001; Hulme *et al.* 2002; Grout *et al.* 2004) to ensure that they are fit for purpose. However, due to their complexity, the models are usually installed individually on 'standalone' computers (Farrell *et al.* 2008). Local operational staff such as hydrogeologists and water resources staff want to use the model results, but lack access as the models can only be used by a small group of regionally based groundwater modelling specialists. Therefore there is a risk that water resource management decisions could be made without the benefit of the conceptual and numerical objectivity contained in the models.

To address these issues, the NGMS has been developed. Although most of the models currently in use by the Environment Agency are based on the USGS MODFLOW code, the system permits the use of other codes – this requires the development of a 'model adaptor' that enables the system to handle the data inputs and output from a specific model code (Gijsbers *et al.* 2006). For example, work is currently in progress to provide an adaptor for the 4R recharge code (Heathcote *et al.* 2004). Models on the NGMS platform are significantly easier to use than standalone MODFLOW models. NGMS enables a much wider audience to access the models, following appropriate training, ensuring greater benefits from their operational use to meet Environment Agency business needs.

In this paper we describe what NGMS is, what it does, and progress to date, giving examples of operational use, and conclude by discussing benefits, risks and challenges arising from the development.

The national groundwater modelling system

Operational structure

NGMS hosts calibrated groundwater models on a central server-based system using software developed by Deltares (formerly Delft Hydraulics) for the Environment Agency based on the existing National Flood Forecasting System (Gijsbers *et al.* 2006). Each NGMS model has a set of pre-run 'default scenarios', such as naturalized, historic and fully licensed model runs. The default scenario runs have been approved as 'fit for purpose' following model development and calibration. Model validation is achieved through updating the model and comparing the model output with observed surface water flows and groundwater heads at calibration targets throughout the model area. NGMS has the ability to allow the user to deal with the most common regulatory issues through running 'what-if' scenarios by adding new abstractions, changing existing abstraction rates or a combination of the two. This is clearly of use in managing groundwater resources, but also has potential application for assessing climate change impacts upon groundwater and surface water resources. The initial design kept the functionality of the system as simple as possible, since it was intended for the specific purpose of providing a central, secure on-line access to and repository for the regulatory groundwater models, and a scenario tool to estimate the potential impacts of abstraction scenarios. Increased flexibility could be offered by increasing the functionality; however, a key design criteria was making the system accessible to a wider group of water resources regulatory staff.

A sequence of data processing steps are executed by NGMS to pre-process groundwater model input, run MODFLOW using a 'Module Adaptor' and post-process the model outputs. Data are converted from MODFLOW format into NGMS (Published Interface) format (Gijsbers *et al.* 2006, fig. 2). Post-processing model outputs can be time-consuming using standalone MODFLOW models; this is done automatically by NGMS and model results can be displayed in various graphical and tabular formats.

Groundwater models on NGMS are located on a central server while Operator Client applications are distributed to individual staff in any of the Environment Agency offices (Gijsbers *et al.* 2006). Through the Client-application, staff can download groundwater model data from the central server for analysis using NGMS or export from NGMS to other applications such as Microsoft Excel or ArcGIS. The what-if scenarios are set up by individual users and run on the central server. Although NGMS does not permit the user to make changes to the model (other than adding groundwater abstractions), a procedure has been developed for updating the regulatory version of the model on NGMS with updates to the calibrated standalone MODFLOW model, for example following local model refinement. In this situation, the previous version(s) of the model can be stored on NGMS using the system's archiving functionality. NGMS has a configuration manager tool that ensures that all files contained within a model configuration have version control applied when updates are made to a model. This tool, along with accompanying guidance, ensures that changes and updates to models are managed to avoid the situation where approved models diverge when used by different users.

In addition to the groundwater model interface, NGMS also has a webserver where documentation is held, including summary reports for each groundwater model. The webserver ensures that information is readily available from the whole modelling process, from data collection and conceptualization through to numerical model development, calibration and validation (through updating). The webserver can also be used to hold analytical models that are commonly constructed in areas where fully distributed numerical groundwater models are not appropriate.

Groundwater models are uploaded to NGMS by putting the MODFLOW datasets into the standard NGMS file structure and configuring the necessary data processing steps. Datasets for all models on NGMS are held in the same xml format. Models are initially uploaded onto a test server and acceptance testing is undertaken to check that the NGMS version of the groundwater model gives the same results as the original MODFLOW model. Two types of checks are undertaken – firstly, checks on locations data such as abstractions and discharges and, secondly, rigorous numerical checks to compare the output of the NGMS and MODFLOW versions of the model, including transient water balances. Only when the acceptance testing criteria are passed is the NGMS model considered fit for operational use; the models are then moved from the test server onto a production server that is available to all users.

Standardization of the NGMS input datasets means that groundwater models can be updated easily with time series data to extend the model calibration period. However, NGMS is not intended to be a tool for model development or refinement. When the groundwater models require recalibration, for example due to review of the conceptual understanding in the light of new information (perhaps associated with investigations supporting an abstraction licence application), the starting point is to export the ‘approved model’ from NGMS. The recalibration is undertaken outside NGMS using the MODFLOW model in standalone form. The revised groundwater model is then imported back into NGMS and acceptance testing repeated. By using the configuration management tool, which contains a version history for each file in the model configuration, it is possible to go back to a previous version if required. Model runs undertaken with a previous version of the model can be archived for later re-use.

Roles, responsibilities and training

Standardization of the NGMS model interface brings the benefit that groundwater model results are available for use by a much wider range of users than previously; for example, those involved in developing Catchment Abstraction Management Strategies (CAMS) and making operational regulatory decisions about water abstraction licences. There are, however, risks associated with opening models up to a wider group of users, who may not have detailed understanding of the assumptions underlying the model, or have the strong conceptual hydrogeological understanding of the model area which goes with this. To minimize the risk of users misinterpreting the model results, the Environment Agency is:

(1) providing a programme of training to aid interpretation, using real examples developed from operational experience;
(2) standardizing procedures to check that the model has been run correctly;
(3) providing different levels of access to the system dependant on the skills and knowledge of the different users;
(4) providing model reports, including a model summary stating the main uses and assumptions underlying the model, on the NGMS webserver.

Access for Environment Agency staff to NGMS is controlled by the creation of different security groups: Administrators, Custodians, Users and Viewers. NGMS Administrators are responsible for managing and maintaining the NGMS software and hardware with support from Deltares. Custodians are responsible for individual groundwater models and are usually more experienced groundwater modellers. The role of the Custodian includes keeping the model up to date, testing acceptance and providing technical support to Users and Viewers on use of the models to support different Environment Agency business drivers. This includes provision of advice on model uncertainties and how to use the models in different situations. NGMS Users can access the NGMS default scenarios and create new what-if scenarios to investigate specific issues relating to groundwater abstractions. NGMS Viewers are only able to view the default scenarios and are not able to create new what-if scenarios. Managing security groups in this way will balance the benefits of giving a wide audience access to the models while limiting the risk of misinterpreting the model results.

Current status of NGMS and management into the future

During the past five years, the NGMS software has been developed by Deltares by adapting the existing National Flood Forecasting System, which is based on the Delft-FEWS software. Regular software development workshops have been held involving

Environment Agency groundwater modellers across different regions to determine their requirements, particularly in terms of the functionality and graphical displays.

Between 2008 and 2010, 19 groundwater models were uploaded to NGMS. Of these, 11 are models of chalk aquifers, seven are models of Permo-Triassic sandstone aquifers and one model is of a gravel aquifer. Table 1 lists the groundwater models currently on NGMS (also shown in Fig. 1). A process has also been developed to update models on NGMS, for example to extend the calibration period which, so far, has been applied to the East Kent (Southern Region), West Midlands–Worfe (Midlands Region), and the Yare and North Norfolk (Anglian Region) models.

To date, an investment of around £1.9 million has been made covering feasibility, system design, pilot and full implementation, hardware, software development and configuration of individual models into the system. At the time of writing, the on-line system of NGMS is under the final development and testing stage. Once this is complete, routine operational use can begin.

All the NGMS Custodians have undergone training in how to use NGMS and their role as Custodians. A programme of User training has begun, and will continue into the future. Ongoing IT and technical system support is provided both internally and by the system developer, Deltares, alongside support for the National Flood Forecasting System.

Table 1. *Groundwater models uploaded onto NGMS (status as of November 2010)*

Environment agency region	Groundwater models uploaded to NGMS
Anglian	Yare and North Norfolk
	North West Norfolk
	Ely Ouse
Midlands	West Midlands Worfe
	East Shropshire
	Bromsgrove
	Lichfield (standalone)
North East/ Midlands	East Midlands – Yorkshire
North West	Lower Mersey Basin
	East Cheshire
Southern	Test and Itchen
	East Kent
	North Kent (standalone)
	East Hampshire Chichester Chalk
South West	Hampshire Avon
	Wessex Basin (standalone)
Thames	Kennet
	South West Chilterns
Wales	Yazor Gravels

A small team provides central technical support for the system internally.

User and Viewer training is focused on how to use NGMS to support Environment Agency operational decisions (see section above on the role of NGMS in the Environment Agency's decision-making process). Training includes real examples such as working through the steps required to determine a water abstraction licence, or to estimate the groundwater resources available as part of a Catchment Abstraction Management Strategy, taking account of river–aquifer interactions (see below). Work instructions are also being prepared as part of the Environment Agency's document management system. Considerable effort is required to embed new tools, such as the groundwater models and NGMS, into Environment Agency business processes.

Groundwater models already on NGMS will be updated and new models will be uploaded when they are complete. The NGMS software is updated on an annual basis and functionality changes to improve system performance or to support particular uses will be implemented where appropriate. Users from organizations other than the Environment Agency, such as water companies, may be given access to groundwater models on NGMS in the future.

To date, NGMS has been used to investigate the impacts of moving a public water supply borehole location in the Hampshire Avon catchment, and to support Catchment Abstraction Management Strategies (see section below on using NGMS to manage water resources), and to forecast the potential impacts of climate change upon water resources (Environment Agency 2008*b*). NGMS has also been used to support an Environment Agency groundwater modelling post-graduate level training course to help students understand how to use and interpret results from regional groundwater resource models.

Functionality

NGMS provides a map-based standard front end interface, and also other menus that can display observed field data, model input and output in various ways, including time series, spatially and in tabular format. In the main NGMS user interface ('Explorer' window – Fig. 2), a map of the UK is displayed with standard map viewing functionality to enable the user to zoom in to view particular groundwater models. Shape files such as rivers, geology and Groundwater Investigation Areas can be viewed to aid interpretation of output.

Locations data, including observation boreholes, abstractions and gauging stations, are displayed graphically on the map and in a list; sites can be selected by either clicking or searching the list, or through the map view. Each data type has associated

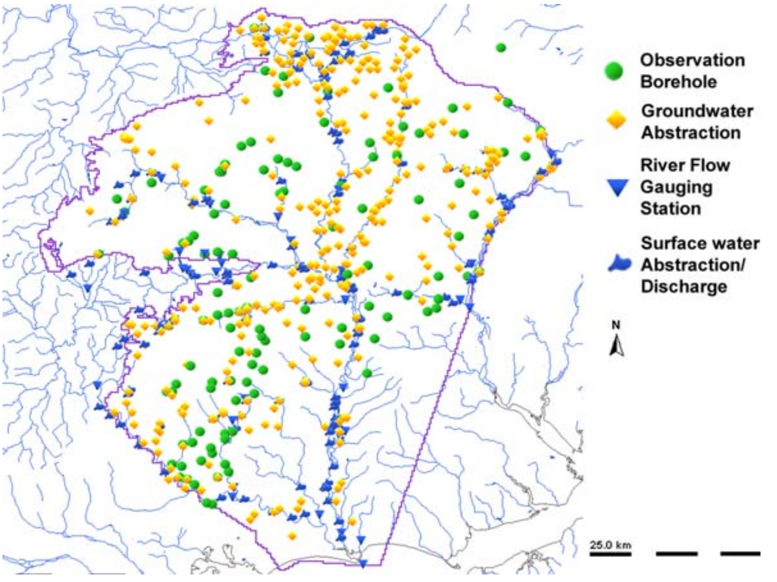

Fig. 2. NGMS Explorer Window showing the Hampshire Avon groundwater model.

parameters, such as groundwater level, abstraction rate and river flow, which can be viewed for each available model run type, for example historic, recent actual and fully licensed abstraction rates, depending on the default scenarios that have been uploaded. Figure 2 shows the map-based interface for the Hampshire Avon Chalk groundwater model situated in the South West Region of the Environment Agency.

Time series data. User-defined graphs of data such as abstractions or groundwater levels can be created by selecting different combinations of locations and parameters from the Explorer window. Alternatively, pre-configured graphs can be viewed. Data from different scenarios can be displayed on the same axis for comparison, and the difference between scenarios is calculated automatically. Figure 3 shows a user defined graph comparing groundwater levels and nearby surface water flows for the historic and naturalized scenarios at Brixton Deverill in the Hampshire Avon catchment.

Tables of data can be displayed and exported into other standard software packages such as MicroSoft Excel, Word and Wordpad. Data for particular gauging stations can be displayed, including flow duration curves. Pre-configured river accretion profiles are also available, and can be animated to aid understanding of interactions between surface water and groundwater in time and space.

Spatial data. Groundwater model input and output data can be displayed spatially and can be animated to show changes through time in one or two dimensions. Spatial plots include recharge, river flow, interaction between groundwater and surface water, groundwater contours, groundwater flow vectors and model build information. Cross-sections can be drawn through spatial data and time-series obtained for any location. Water budgets can be requested for pre-defined areas selected from the spatial plot. Difference plots can also be displayed – for example, the difference between historic and naturalized scenarios to show drawdown/anthropogenic influence. Figure 4 shows Chalk groundwater heads for the Hampshire Avon groundwater model as an example of typical output from NGMS.

Abstraction scenarios. New what-if scenarios for groundwater abstractions can be set up, for example, the impacts of a new abstraction licence or investigating the impacts of changes to existing abstractions on surface water bodies. Currently single deterministic predictions are made for several standard scenarios (for example naturalized, historic and fully licensed) and the differences between them are compared. However, the underlying Delft-FEWS software has the capability to handle ensembles to deal with uncertainty (used for flood forecasting), although this approach has not yet been used with the groundwater models. This means that in future probabilistic forecasts could be undertaken using NGMS, although it is possible that most of the scenarios would be undertaken using the recharge models rather than the groundwater models (see future development section below).

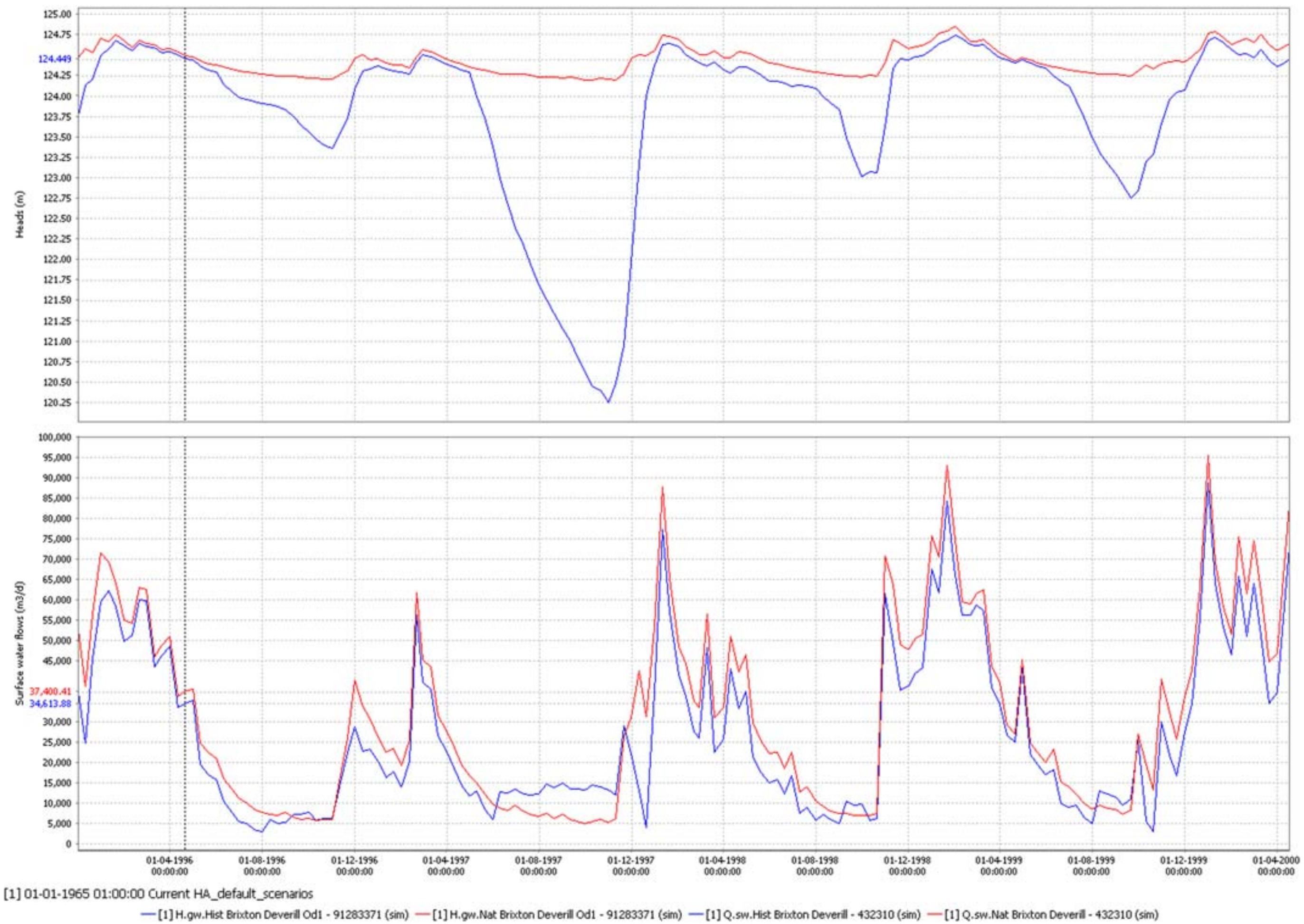

Fig. 3. User-defined NGMS graph showing groundwater heads and surface water flows for two model scenarios (historic and naturalized).

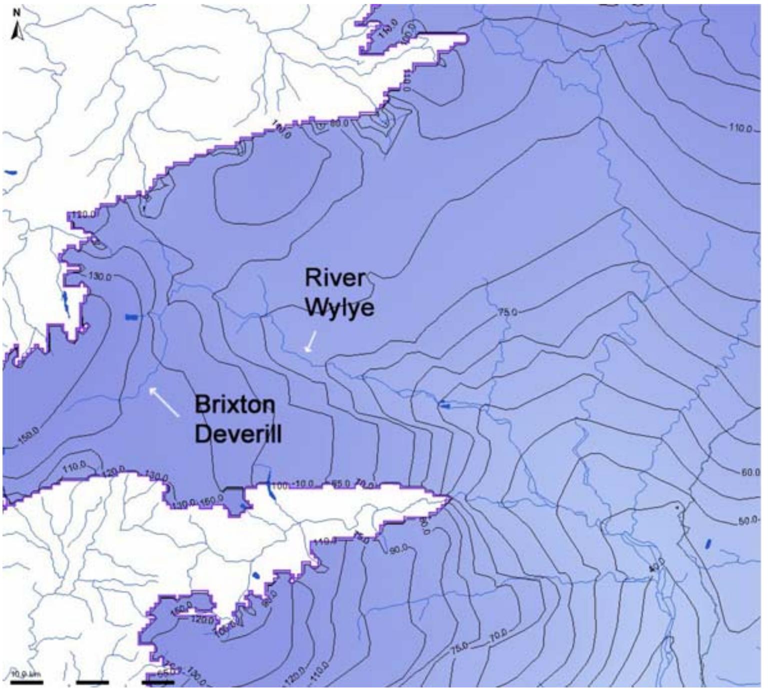

Fig. 4. Spatial plots window showing groundwater heads in part of the Hampshire Avon groundwater model.

The wide functionality of NGMS enables users to readily obtain in depth information about the behaviour of a catchment.

Examples of operational use

Use of NGMS to manage water resources

Catchment Abstraction Management Strategies provide a framework for resource availability assessment and produce a licensing strategy that aids the sustainable management of water resources at a catchment scale. Field information and numerical groundwater models can be used to check and improve this information. The conceptual model reports are stored on the NGMS webserver to help with this work. The numerical models are particularly well suited to investigate the impacts of groundwater abstractions on surface water bodies (also required to meet the requirements of the European Union Water Framework Directive) and on groundwater-dependent wetlands. Thus NGMS is a valuable tool to investigate the different types of impacts of groundwater abstraction upon rivers, discussed by Soley *et al.* (2012) and Shepley & Soley (2012). NGMS enables these impacts to be assessed far more easily than in the past. For example, the simple NGMS what-if scenario tool enables individual abstractions to be switched off in the model to identify their impacts on surface water bodies. NGMS also enables different data types such as interactions between surface water and groundwater, stream flows and groundwater heads to be rapidly interrogated and interpreted. Because NGMS automatically post-processes and displays model results, more time can be spent interpreting the results and assessing hydrogeological behaviour.

Management decisions are made easier by how NGMS allows the modelled groundwater system to be analysed and understood (see section above on the role of NGMS in regulatory decision-making). The use of NGMS groundwater model data has been trialled for the Hampshire Avon CAMS area, located in the Environment Agency South West Region. For example, the impacts of the Leckford Bridge public water supply abstraction (see the paper by Soley *et al.* in 2012 for a description of the behaviour of river–aquifer interactions at this location) on surface water bodies were identified by creating two new what-if scenarios. Both scenarios were based on the recent actual scenario (this scenario represents the current, or ‘contemporary’, level of anthropogenic influence within the model area, based on typical abstraction and discharge rates and patterns within the last six years), but the first with the Leckford Bridge abstraction switched off, and the second with Leckford Bridge increased to the fully licensed abstraction rate. The automatic post-processing of model results undertaken by NGMS saved considerable time compared with the equivalent tasks using the standalone MODFLOW model, and allowed focus on interpretation of the data to understand the impacts of groundwater abstraction at different flow percentiles (Soley *et al.* 2012).

The Wylye river augmentation scheme in the Hampshire Avon catchment provides another example to illustrate how NGMS can be used to understand river–aquifer interactions and the impacts of groundwater abstractions upon surface water bodies. The River Wylye has long been identified as being significantly impacted from groundwater abstractions, particularly since much of the water is exported to supply the communities of Bath, Trowbridge and Yeovil. There is a large public water supply abstraction at Brixton Deverill that is also linked to abstraction at Heytesbury. The impact of the abstraction is mitigated during periods of low river flows by stream support from boreholes at Brixton Deverill and Kingston Deverill. Under these conditions, NGMS can show how river flows are higher in the protected reach in the historic scenario than in the naturalized scenario (Fig. 5). In contrast, Figure 6 shows how, once high flow conditions apply (January 1990), the scheme is switched off and flows are once more lower than in the naturalized scenario.

The impact of the augmentation can be seen to reduce downstream as unsupported tributaries contribute to total flow. An effective way to see this is via accretion profiles – Figures 7 and 8 show the difference between historic and naturalized model runs on the same dates as the above spatial plots. Data are shown as impact on river flow and on surface water–groundwater interaction (highlighting the impact of abstraction on the river in general). The impact of the augmentation scheme in supporting flows at or above the natural flow (i.e. the zero line on the plots) is clear (Fig. 7), indicating a positive net gain, although the river–groundwater interactions remain largely unchanged.

Using spatial plots of groundwater level data, the impact of the abstractions can be related to the changes in surface water flow. A spatial plot of the differences in groundwater heads between historic and naturalized scenarios illustrates the cone of depression caused by the abstraction at Brixton Deverill augmenting stream flows (Fig. 9). NGMS what-if scenario functionality allows assessment of the environmental impacts and benefits of switching

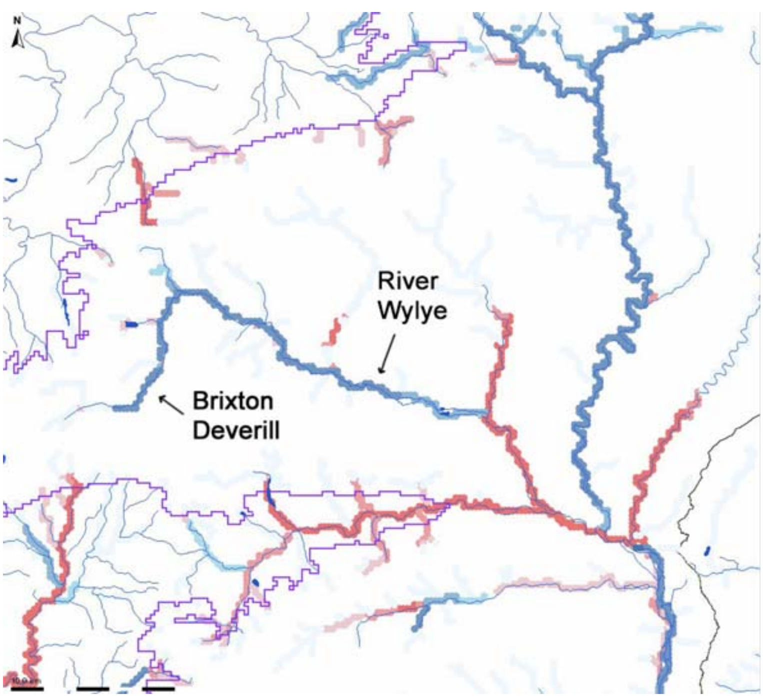

Fig. 5. Abstraction impact at low flows on in the River Wylye; blue shows model river cells where anthropogenic influence (i.e. the augmentation scheme on the Wylye) have increased flows above those of the naturalized model run.

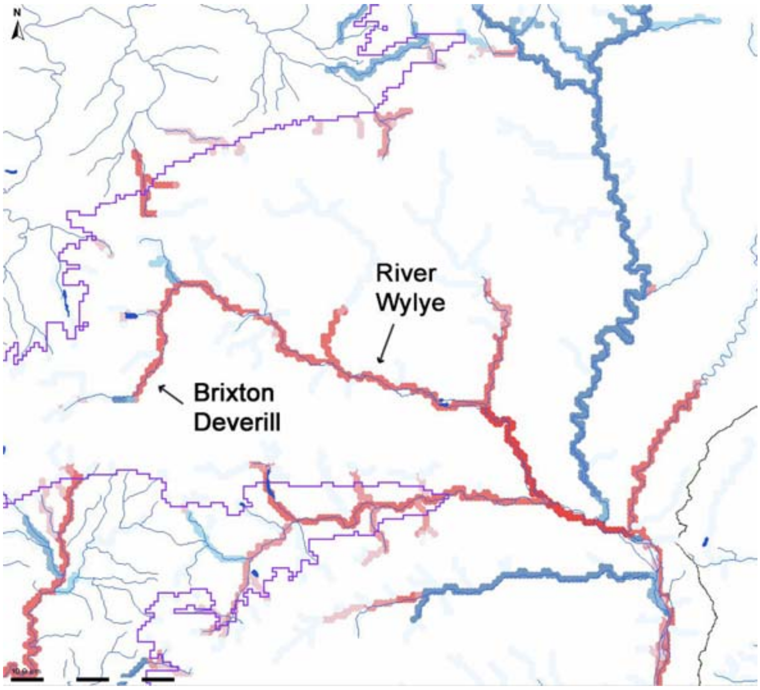

Fig. 6. Abstraction impact at high flows on the River Wylye; red cells show that, with the augmentation scheme off, the flow is now less than in the naturalized model run.

off and relocating abstraction boreholes. In cases like the Hampshire Avon, Environment Agency hydrogeologists use and interpret model outputs such as that contained in Figures 5–8 to inform sustainability decisions on enhancements to river augmentation schemes and changes to abstraction licences. In heavily stressed catchments in England and Wales, the Environment Agency has identified reductions in abstractions that it requires from water companies. These reductions are then implemented through the Restoring Sustainable Abstraction process (see Whiteman *et al.* 2012) and five-yearly water company asset management plans. As such, the NGMS-configured groundwater models can be invaluable where there is concern that there has been historic over-abstraction and an options appraisal is to be conducted to restore abstraction to a sustainable level. The baseline scenarios may also be used at an early stage in the groundwater investigation consenting process for new abstractions, to provide a preliminary assessment of local water resource availability and potential environmental impacts.

Use of NGMS for forecasting

Long-term deterministic climate change scenarios, using a recharge model outside of NGMS, have already been undertaken in support of the Environment Agency's national Water Resources strategy (Environment Agency 2008*b*). Currently a module adaptor is being written to allow recharge models to be run through NGMS. This will mean that input of predicted rainfall and abstraction will allow future climate scenario model runs to be undertaken on NGMS very rapidly. The new functionality will also enable shorter-term scenarios to be run to assess potential impacts of both groundwater drought and flood.

Discussion and conclusions

Benefits, risks and challenges

Considerable effort is required to roll out the system, train people and adapt operational decision-making processes and protocols to bring NGMS into regular and safe use. Everyday use of groundwater models by an environmental regulator such as the Environment Agency remains a challenge that requires engagement with other specialists (such as hydrologists and IT systems specialists). It is difficult to find the balance between standardization/stability and openness for local refinement/improvements, but hopefully the uptake and successful use of

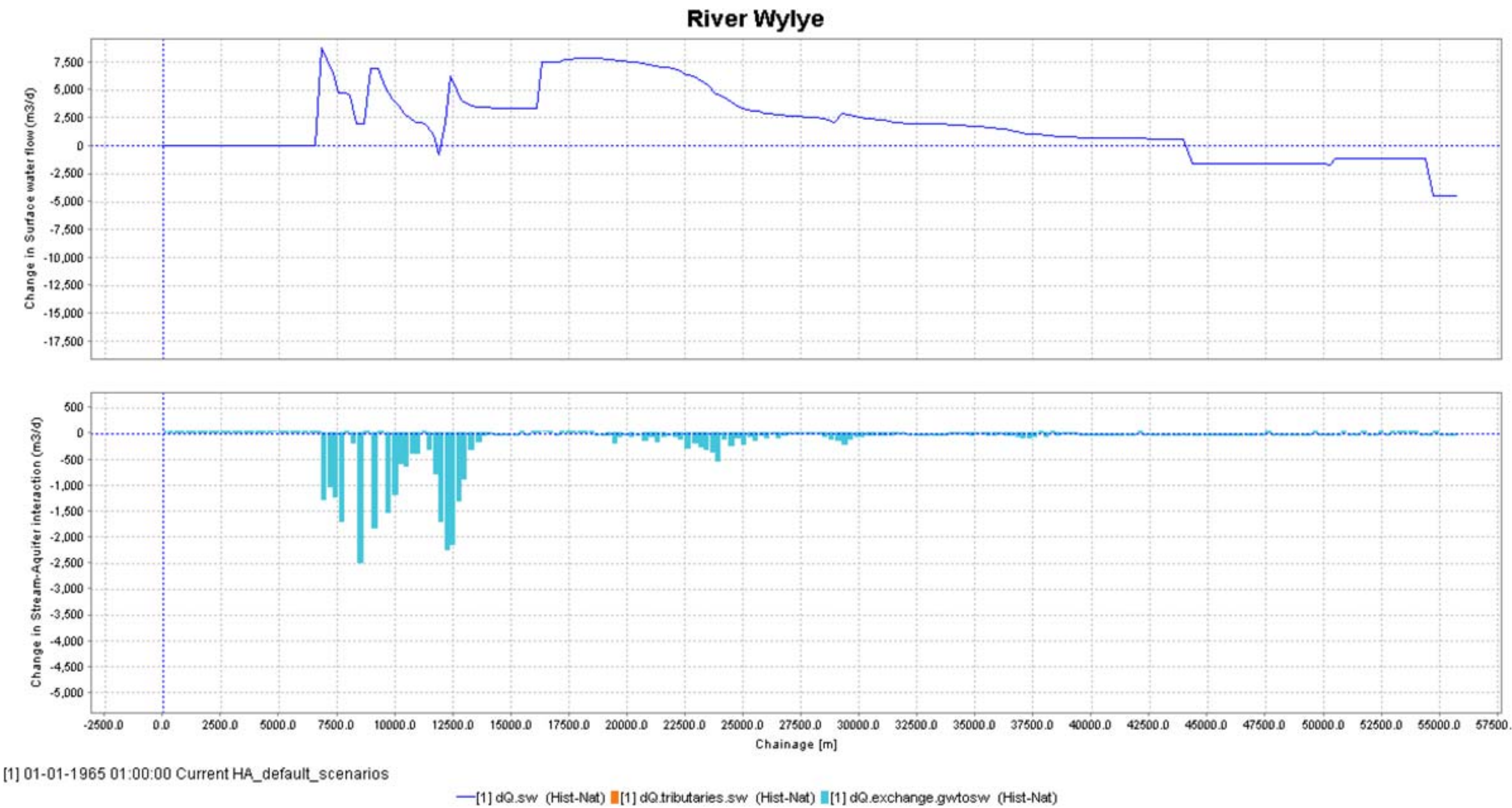

Fig. 7. Accretion profile at low flows of the River Wylye, flow accretion above, groundwater–surface water interaction below. Augmentation scheme on.

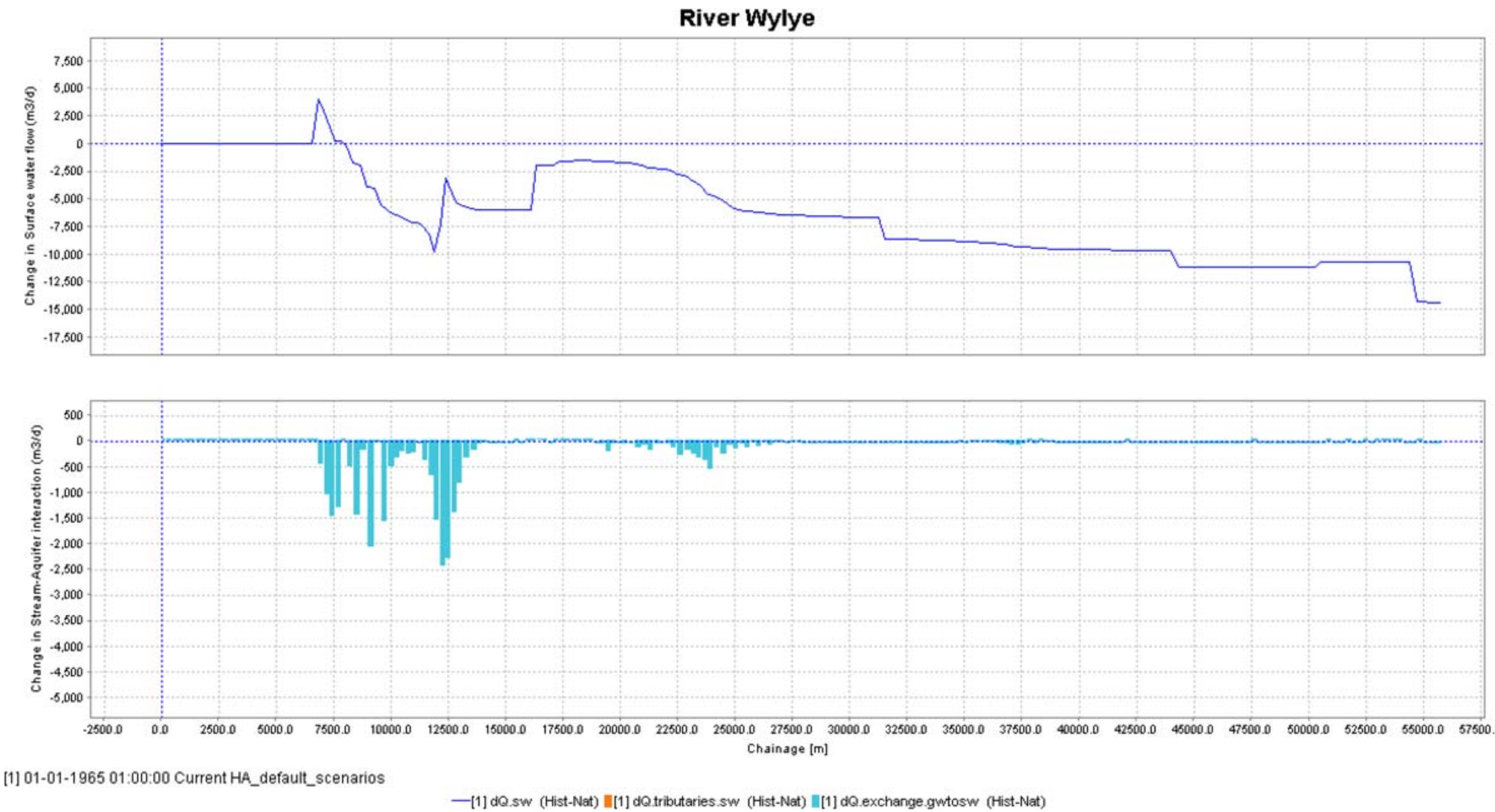

Fig. 8. Accretion profile at high flows of the River Wylye, flow accretion above, groundwater–surface water interaction below. Augmentation scheme off.

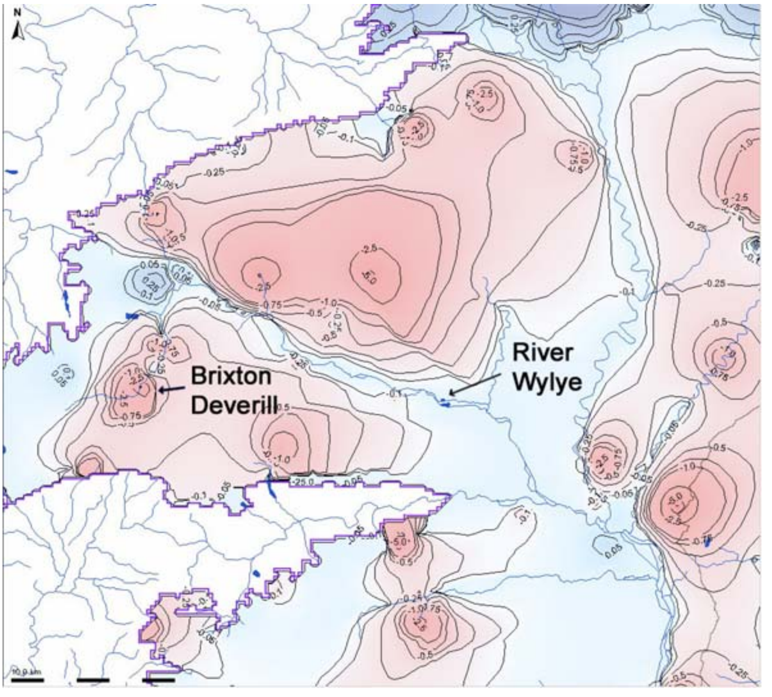

Fig. 9. Groundwater level difference plot (historic − naturalized) showing impact of groundwater abstractions and discharges in the Wylye catchment.

NGMS will indicate that this balance has been found. The following examples of lessons learned from development of NGMS illustrate some of these issues.

Lessons learned: testing

Several useful points have been learned during setting up and testing the NGMS IT platform which will help with future work:

(1) From a regulatory point of view, it is very important to correctly represent the spatial distribution and inter-relationships between abstraction licences in the model. Multiple abstractions from the same cell must be properly combined in the time series visualized and extracted from the correct model cell, while abstractions for the same borehole in different model layers must be properly accounted for when providing accumulated abstractions. NGMS handles these relations effectively by assigning a parent abstraction (the borehole), with multiple child abstractions (the abstraction at a specific model cell). The quality control associated with these complex relationships can be a time-consuming task, primarily dependent on model size, but it has also enabled identification and elimination of inconsistencies in various models that have been uploaded to the system. A certain amount of time, up to 25 days, is therefore required to put each individual regional model on the system and to test it, depending on the complexity of the model and the experience of the individuals uploading the model.

(2) Work is also required to ensure that all the spatial and time-series data are correctly displayed. In large models NGMS enables rapid visualization of the data and identification of errors that can be hard to spot in conventional MODFLOW model input and output. A generic MODFLOW adapter ensures that NGMS is able to read the MODFLOW input files, run the model and produce output that NGMS can display.

(3) When models are prepared in future, more testing should be undertaken earlier using the system to gain confidence that the model is producing the right results. This means that preparation of the NGMS configuration should be commenced from the start in new groundwater modelling projects. This would

mean that, as the numerical modelling progresses, genuine model data, geometry, locations data, and initial model run output can be seen via NGMS. This will ensure that errors are solved as the project progresses rather than being only found later on when the preliminary model is delivered.

(4) The work has highlighted the importance of streamlining the preparation of data into standard formats and templates for NGMS and checking of model runs.

Lessons learned: Custodians

Easy access to graphical model output can give new insights into model behaviour, and enables anomalous features or errors to be spotted readily. Custodians see benefits from using NGMS but also feel somewhat uncomfortable as they adapt and leave their old tools and standalone scripts behind. The standalone models will still be required for model recalibration; however, as confidence in NGMS increases, it is expected that reliance on the standalone systems to run and interpret output from model scenarios will reduce.

Increasing the number of users of groundwater models and embedding them within business processes will also require Custodians to take on a mentoring role in supporting other users, and cascading training to users.

Future development

The objective of the NGMS is to strengthen the typical standalone modelling approach by creating a model repository with 'approved' models and to add useful tools for processing and visualization. It is recognized that some workers have developed complex decision-support systems involving groundwater models (for example Fredericks *et al.* 1998), which bring in other factors such as cost–benefit analysis and ensemble modelling/uncertainty analysis. The Environment Agency has not taken this approach, rather the aim of NGMS is to make groundwater models more accessible, provide a secure repository and introduce some version control and audit trail functionality for model updates. The scope of NGMS has therefore been limited to the main regulatory uses of the models, which is quantifying the groundwater resources and estimating the impacts of abstractions upon rivers and other groundwater-dependent water bodies. Embedding the use of models into the regulatory processes undertaken by the Environment Agency (such as providing a framework of support for decisions supporting implementation of the European Union Water Framework Directive) is currently a more significant focus than enhancement of NGMS software functionality. This also requires the development and updating of guidance and business processes, including the use of the groundwater models.

However, some further development of the system may be required in future. For example, in addition to MODFLOW groundwater models, the NGMS software is currently being adapted to host and run recharge models. Combining MODFLOW with a recharge model gives a 'total catchment' model that can deal with the complex interactions between groundwater and surface water systems that are affected by natural and anthropogenic influences. Incorporation of recharge models into the system will enable climate change scenarios to be analysed, and seasonal or drought forecasts to be made.

The underlying Delft-FEWS software, upon which NGMS is based, is an open shell system, which means that in future other types of models can be added into the system, for example finite element codes (such as FEFLOW) for modelling the impacts of ground source heat pumps and saline intrusion.

Other potential developments for the future include:

(1) improving functionality, for example the ability to perform model cell scale water balances and user-defined water balances;
(2) using higher resolution datasets, such as rainfall to improve the simulation of intense storm recharge events (likely to become more frequent with climate change);
(3) speeding up the performance of the groundwater models, for example by using submodels or parallel models to make models run faster;
(4) interaction of surface and groundwater models using standards for model communication such as the OpenMI.

Conclusions

NGMS is a map-based, client–server system for holding groundwater models and supporting documentation. Models can be run, new 'what-if' scenarios created and time series or spatial data rapidly viewed or exported. NGMS enables a wider audience of water resource staff to access groundwater models for operational decision-making. Use of the system will result in greater standardization of data formats, model codes and methods used by the Environment Agency without stifling technological progress. However, considerable effort is required to roll out the system, train people and adapt operational decision-making processes to bring NGMS into regular and safe use.

The authors would like to thank those members of the UK groundwater community both within the Environment

Agency and externally who have contributed to the design and implementation of NGMS, including P. Shaw, S. Gebbett, M. Shepley, N. Hoad, T. Kelly, A. Rahman, M. Walford, K. Croker, P. Hayes, A. Taylor, J. Riley and N. Thomas.

Disclaimer

The views expressed in this paper are those of the authors, and do not necessarily represent those of the Environment Agency for England and Wales.

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