

Conceptual modelling: monitoring, modelling and policy

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Groundwater Resource Assessment and Modelling: A Toolkit to Support Agency Business

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This paper presents progress with the Environment Agency's nationally-coordinated programme of groundwater resource assessment and modelling and looks at how this has recently been updated in view of new duties and the move to more integrated multifunctional working. The Agency's new Head Office Hydrogeology Policy and Process team has taken over responsibility for the recently-established national programme (Hulme *et al.*, 2002; Environment Agency, 2001). The Head Office team will work together with the Agency's Science function on the modelling programme, for example:

Policy and process establishing a method for post-project appraisal of the benefits of modelling;

Science picking up issues that operational modelling raises, e.g. not getting low flows in chalk streams right, uncertainty in recharge estimates (undercatch of rainfall, MOSES PE etc.);

Science and Area technical specialists being part of a peer review network.

Implementation of the programme by the Agency's Area Groundwater and Contaminated Land teams has progressed to the point where seven out of the eight Agency regions have a published ten-year strategy for groundwater resource assessment and modelling. These strategies reflect the recommendations made in the national framework (Hulme *et al.*, 2002), with an emphasis on investment in well-documented and adequately tested conceptual models. Where appropriate, regional numerical modelling projects are planned, however, these are being prioritised according to business needs, and the timetable harmonised with the published timetables for Catchment Abstraction Management Strategies and the Water Framework Directive (WFD).

To support the national programme, a toolkit of guidance is being prepared, based on existing guidance notes (Environment Agency 2002), through the Agency's Management System (AMS). The toolkit is intended to ensure that common technical standards and datasets are applied across England and Wales so that the work is repeatable and defensible. Considerable effort is being made to "de-mystify" the groundwater resource assessment and modelling process, to improve communication and delivery of results to end-users to meet business needs. This is essential considering the wide scope of applications for groundwater resource assessment and modelling work, ranging from detailed local eco-hydrological impact assessments at protected wetland sites (e.g. for the Habitats Directive Review of Consents) to sustainable management of groundwater resources (both quantity and quality) at the river basin scale (e.g. for the WFD Programme of Measures). In response, the new guidance must allow for sufficient flexibility such that it can be easily applied to simple, small-scale, small-budget studies which may require rapid assessment methods (currently under development by the Science function) or conceptual models, as well as much larger and more complex regional modelling studies with substantial resource management implications.

The toolkit is considered as a resource for use by the hydrogeological community both within the Agency and externally. A national quality review team comprising the Agency's groundwater modelling technical specialists has been established to ensure wide peer review and adoption of new guidance to be added to the AMS as new technical standards are developed and experience increases.

Variable hydraulic conductivity and storage with depth in MODFLOW

Paul Hulme (Environment Agency, ALWSG), Adam Taylor and Phil Hayes (WMC)

Observations of groundwater behaviour in fractured systems, such as chalk and limestone formations, reveal significant reductions in hydraulic properties with depth, due to reduced fracture frequency. These variations in properties with depth give rise to distinctive behaviour, such as large flow fluctuations in groundwater-fed streams (including ephemeral streams), and abrupt changes in water table elevations during drought.

The solution to these problems is to allow hydraulic properties to vary with depth within a single model layer. This gives a non-linear relationship between transmissivity and groundwater level, improving the representation of field conditions. This kind of relationship was first included in groundwater models of the chalk constructed at the University of Birmingham, including models of East Kent, the Berkshire Downs, Candover, and Lincolnshire.

Using the MODFLOW-96 code as a starting point, modifications have been made to allow hydraulic conductivity and specific yield to reduce with depth. The enhancements to MODFLOW includes the following:

- Variations in hydraulic conductivity with depth (VKD) allowed in any layer.
- Variations in specific yield with depth (VSD) allowed in any layer.
- Allow a maximum hydraulic conductivity and/or specific yield to be specified for each model cell.
- Make changes to the stream routing package to allow discharges, abstractions or tributary inflows to be specified at any stream node.
- Include an output of model progress to the screen when using the PCG solver package.
- Allow binary output files to be in the same format as those required by Groundwater Vistas (GV – Environmental Simulations Inc, 2001), the Agency's preferred MODFLOW user interface.
- Include an option to allow the input of X- and Y-direction transmissivities or hydraulic conductivities independently (without using the anisotropy ratio method).
- Allow a debugging option for the PCG solver so that the evolution of head values at each iteration could be examined – to identify problem areas in models that do not converge.

The code has been rigorously benchmarked, tested and peer reviewed and has been used in several regional modelling studies on the Chalk in southern England. These studies have shown that as expected the inclusion of VKD produces stream flows that are more variable, and groundwater levels that are less variable compared to a representation using constant hydraulic conductivity. However, although VKD has improved the representation of the behaviour of the Chalk, the improvement has not been as dramatic as expected.

Where does all the water come from?

Rob Soley (Entec UK)

Simulation of sustained low flows from a low saturated storage Chalk aquifer can be difficult, reflecting uncertainty and/or inadequacy in the related conceptual understanding of the Chalk aquifer. The paper will compare & contrast the Mimram and Itchen models, exploring the possible influences of; bypass recharge mechanisms, unsaturated zone storage/recharge delays & lags, saturated zone flow processes in karstic systems (VKD, large catchments/small outflow areas etc). Answers to the question 'How can you credibly keep the flows going?' will be explored.

The London Basin Groundwater Model: Development as a Groundwater Resource Management Tool**Mike Jones (Thames Water Utilities Ltd.) & Jan van Wonderen (Mott MacDonald)**

The London Basin Groundwater (LBG) model was developed as a key component of the GARDIT strategy to manage rising groundwater levels in London. The model's primary function was to assist assessing the control provided by the additional groundwater abstraction that formed the basis of the GARDIT strategy. Since its development for Thames Water Utilities Ltd. (TWUL) and the Environment Agency in 1990-2000, Mott MacDonald and TWUL have enhanced the conceptual and mathematical model to support TWUL's wider resource development programme.

The LBG model covers the confined Chalk of London and the unconfined Chalk of the North Downs to the south, an area of almost 2,400 km². Within this model area, TWUL has an extensive on-going resource development programme, including:

- The CLRG (Central London Rising Groundwater) programme
- North London Artificial Recharge Scheme (NLARS)
- South London Artificial Recharge Scheme (SLARS)
- East London Resource Development (ELRED).

Although geographically distributed and having different water resource management concepts, all of these resource developments are influenced by the distinct hydrogeological behaviour of the Chalk. From observations and inferences of geology, groundwater hydraulics and hydrochemistry, the Chalk appears to comprise a series of aquifers blocks, bounded by "barriers" of variable permeability. The result is that these aquifer blocks have variable inter-connection, and are a critical control on the impact of abstraction on groundwater resources and interactions with the River Thames. Using the Mott MacDonald ICMM code, aquifer block barriers have been defined using face permeabilities assigned to node boundaries without the need for low permeabilities to be assigned to whole nodes.

Through this enhancement of conceptual and mathematical modelling, the LBG model is now developing into a tool that can be used to assist regional groundwater resource management.

Model Refinement – An Iterative Approach**Dr Janet Riley, Mike Streetly (ESI) and Nigel Hoad (Environment Agency, Thames Region)**

As part of a project to assess perceived low flow problems in the catchment of the upper River Gade, the Environment Agency commissioned a catchment scale groundwater model of the Chalk aquifer in the Upper Colne catchment. The process of constructing the model illustrated the importance of a structured approach to model refinement. Key points that arose were: the role of lumped catchment water balances in constraining recharge prior to model construction, the use of spreadsheet based scoping calculations and investigative models to test the significance of different conceptual models of the behaviour of the Chalk (saturated and unsaturated zone), the different measures of model calibration, the resultant presentation options and their position in a structured approach to refinement. This paper presents an overview of this process, draws out the key lessons learned and identifies where the conceptualisation of the Chalk aquifer system needs further development.

Using a toolkit approach to estimating groundwater recharge.

David Johnson, Paul Hulme, Steve Fletcher (Environment Agency, ALWSG)

The Environment Agency (Agency) and its partners in Scotland and Northern Ireland have developed a nationally consistent tiered approach for estimating groundwater recharge. This has been used on a number of catchments to investigate and simulate the key processes that determine the amount, timing and spatial distribution of recharge. It is these processes, and their relative importance within each catchment, that need to be understood if we are to manage the groundwater resources efficiently.

The tiered approach ensures that the level of confidence in the recharge estimate reflects the risk that the groundwater body will fail to meet the required status under the European Water Framework or European Habitats Directives; the higher the risk the greater the confidence required. Because the approach includes the key processes that determine groundwater recharge it is suitable for investigating possible future scenarios and therefore helping the Agency to develop policies that will address both global change and new environmental legislation. This paper covers the development path that the approach has followed, including some of the blind avenues that we have been down and the tools that have been developed. Case studies have been used to highlight the issues that have been raised.

Assessing the Effect of Complex Glacial Drift on Recharge and river flows

Martin Shepley (Environment Agency, Midlands Region), Mike Streetly, Heather Streetly, C Young (ESI)

The Midlands Region of the Environment Agency and ESI are constructing a regional groundwater model of the East Shropshire Sherwood Sandstone aquifer system over the period September 2001 to June 2004. The aquifer is an important water resource both for Public Water Supply and for augmentation of the River Severn (Shropshire Groundwater Scheme).

In parts of the investigation area the Permo-Triassic Sandstone is covered by a complex mosaic of glacial drift. In these areas, the drift strongly influences both recharge to the sandstone aquifer and groundwater-surface water interaction. In order to assess the significance of the drift and to identify any issues prior to modelling, detailed water balances were calculated for the investigation area and various catchments within it. These used a recharge programme developed in conjunction with the National Groundwater and Contaminated Land Centre to calculate potential recharge over a distributed grid. Potential recharge was routed through a 'drift store' in order to distribute it between surface flows and recharge to the underlying aquifer.

There was a relatively small residual in the overall long term average water balance for the main part of the investigation area. In addition the recharge model generated time-series flows which corresponded well with observed river flows. This provided a measure of confidence that the main components of the conceptual model had been identified and quantified prior to the start of model construction. However, the calculations also indicated that some of the outflows from the shallow drift aquifers occurred on a similar timescale to outflows from the Permo-Triassic Sandstone. This places some limitations on the verification of recharge calculations by use of conventional baseflow separation techniques. The drift therefore has to be considered as an explicit part of a sandstone aquifer system, an approach that is now being adopted for the construction of the model.

Development of a new Kennet Groundwater Model: representation of recharge and aquifer-stream interactions

Lesley McWilliam, Birgitte Von Christierson, Emma Hewitson and Andrew Longley (Atkins) and Nigel Hoad (Environment Agency, Thames Region)

A new groundwater model of the Kennet Valley has been developed by Atkins for the Environment Agency Thames Region. The model covers the area of Chalk outcrop west of the River Thames on the edge of the London Basin, incorporating the Berkshire and Marlborough Downs, and includes the catchments of the River Kennet, its tributaries and the River Pang.

The Kennet catchment is extensively monitored, with data available on groundwater levels, stream flows and pumping tests; there have been many previous studies of the area including an earlier groundwater flow model. A thorough review of monitoring data and existing work on the catchment was carried out, before drawing together a conceptual hydrogeological model of the area. A numerical model was subsequently developed using the new version of MODFLOW developed by the Environment Agency to incorporate the variation of hydraulic conductivity with depth (VKD).

The conceptual model development and model refinement highlighted two key areas of interest (and uncertainty): unsaturated zone influence on recharge and stream–aquifer interactions.

A recharge model was developed based on the effective rainfall output from the Thames Catchment model, accounting for the influence of geology, urban coverage and local variations in effective rainfall. An element of delay and smoothing had to be applied to the recharge profile to account for the unsaturated zone processes. To assess the amount of delay needed in the model, the timing of the main winter groundwater peaks and the relationship between groundwater peaks and baseflow peaks was examined. Strong spatial variations in the timing of peaks were found, which did not appear to be related to the thickness of the unsaturated zone or the presence of drift deposits (clay-with-flints). In addition, zones of different groundwater behaviour were identified within the Pang catchment.

Field surveys and a review of borehole logs have indicated the presence of putty Chalk in some valley locations and revealed that the distribution and thickness of gravels in the model area is variable. It is thought that zones of very high conductivity valley-fill gravel deposits beneath stream channels may be significant in determining stream-aquifer interactions. The presence of putty chalk may provide a resistance to flow between the groundwater and surface water system. Stream bed conductance values in the model have been assigned in zones, taking these factors into account and examining the response of monitoring boreholes close to the streams. High conductance values were applied to upstream reaches, with lower values downstream.

Ongoing field investigations on the Kennet and Lambourn Floodplain cSAC should provide useful new information on the presence, nature and thickness of valley fill gravels and putty chalk and help further our understanding of aquifer-stream interactions.

Sensitivity Analysis: Practical experience with UCODE

Phil Hayes and Adam Taylor (WMC) and Paul Hulme (Environment Agency, ALWSG).

UCODE is a program developed by the USGS for detailed sensitivity analysis and parameter estimation on mathematical models of physical systems, such as groundwater models. In conjunction with MODFLOW, UCODE enables the calculation of the sensitivity of individual model predictions, such as heads and flows, to changes in multiple model parameters. The application of UCODE to the Wirral aquifer is used to show the overall sensitivity of the model to hydraulic conductivity and recharge and how the sensitivity varies at different observation borehole locations. The Bourne and Nine Mile River model is used to illustrate that time variant changes in model sensitivity can strengthen understanding of how the model operates. This presentation explores how sensitivity analysis techniques can also be used to aid validation of model predictions and considers alternative software for sensitivity analysis and parameter estimation.

One presentation will be given incorporating material from the following two abstracts on Object-Oriented Modelling.

Reality bites: An introduction to Object-Oriented groundwater modelling

Andrew Spink (University of Birmingham) and Andy Hughes (British Geological Survey)

Object-oriented methods have their origins in computer program development. They are extensively used in commercial software development and their proponents claim numerous advantages for the methodology in this environment. As groundwater models are essentially pieces of software, it is unsurprising that these methods have found their way into this field too. There is a more important aspect to the exploitation of object-oriented methods, which is that they lead to a new and better way of structuring and using groundwater models. A groundwater system can be more accurately represented using object-oriented techniques. The flexibility of object-oriented techniques mean that improvements to the model can be made during a project.

The ideas underpinning the object-oriented approach are explored and contrasted with traditional procedural programming. This leads to a fundamental re-appraisal of the structure of groundwater models. The practical implications of this are discussed and the consequences for understanding and incorporating a wide range of processes are highlighted. A review of the development of a family of models based on this technology illustrates many of its advantages. The extension of the work into an even more flexible system is previewed.

Object-Oriented Groundwater Modelling: Application to Multi-Scale Hydrogeological Investigations

Jamie Riches (Thames Water Utilities Ltd.) and Chris Jackson (BGS)

Object-Oriented (OO) modelling code offers hydrogeologists a more flexible approach to groundwater assessment particularly when the model has to fulfil a number of different objectives. Thames Water Utilities Limited (TWUL) is currently targeting a Chalk interfluvium in North Kent for resource development to replace existing abstractions as part of Phase 2 of the Darent low flow alleviation scheme.

Intensive field investigations comprising exploratory drilling, hydrogeochemistry, geophysics and fracture mapping, conducted by the British Geological Survey (BGS) and commissioned by TWUL, aided the construction of a conceptual model. The conceptual model provided the framework for the numerical groundwater model, which was constructed using the object-oriented code, ZOOMQ3D.

This study illustrates the advantages of the OO modelling code, with which more complex processes can be represented compared with conventional approaches. The initial regional model was constructed to assist water balance assessment within the Chalk block. Rapid refinement of the model enabled a more detailed assessment of the relationship between the low flow river, the proposed abstraction wellfield and a nearby Chalk quarry. The OO model was refined further and verified against a multiple well pumping test to provide greater confidence in the approach. The model was then used to predict the outcome of a variety of scenarios.

As a confidence gaining exercise a regional model was constructed in parallel using MODFLOW. The comparison showed good agreement between the two model codes however the OO model allowed rapid refinement where detailed assessment was required.

Groundwater Model Wars (3 Agency Regions, Some Consultants and 1 Chalk Aquifer ...)
Rob Soley (Entec UK)

An overview paper on some of the projects within the Agency's regional flow modelling programme, giving a chance to share, compare and contrast the results of the Itchen, Bourne & Kennet models. The similarities and contrasts in approach when tackling recharge calculation, Chalk structural/stratigraphic/parameter variation, and layering and output formats will be explored.

The issues of parameterisation of models and management of user expectations will also be explored, including:

- keeping model parameterisation simple or aiming for models which 'fit';
- distributed parameters from GIS v. simple zonation;
- progressive refinement
- use of optimisation codes

how can you use models which don't fit?