British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Multi-scale groundwater modelling for the assessment of sustainable borehole yields under drought

Upton, K A[1], Butler, A P[2], Jackson, C R[1], Jones, M[3]

[1] British Geological Survey [2] Imperial College, London [3] Thames Water Utilities Ltd

Modelling sustainable borehole yields

Managing an aquifer as a water resource requires a socially and environmentally acceptable balance to be maintained between supply and demand. This relies on being able to quantify the total amount of water that can be extracted from an aquifer without causing any dramatic shortages or risk to the long-term supply. For management purposes, an aquifer may be divided into a series of water resource zones, within which all resources can be shared and are thus subject to the same risk of supply failure. The total amount of water available from a water resource zone can be determined from the sustainable yield of each individual supply borehole within that zone.

The sustainable yield of a borehole will be dependent on the antecedent groundwater levels in the aquifer. Water resources managers must be able to demonstrate a supply-demand balance for both high and low level conditions. However, this becomes more critical during droughts when groundwater levels are at their lowest and demand is likely to be high. Groundwater models can be useful tools in helping to determine the sustainable yield of a borehole, particularly where there is a lack of observed data under severe drought conditions.

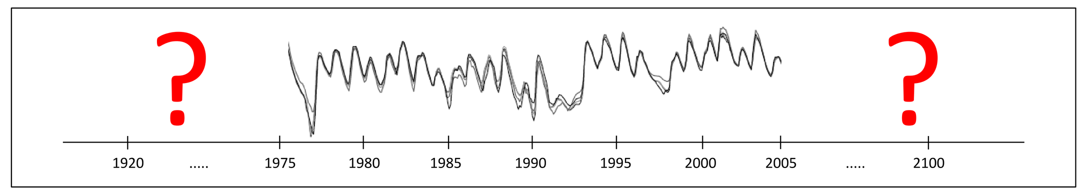
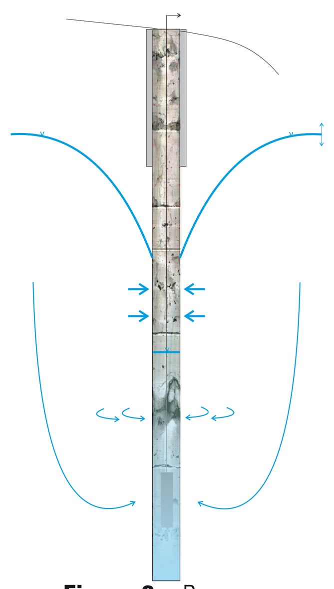


Figure 1 Groundwater level time-series showing time periods for historic reconstruction and climate change projections

Models can be used to:
1. Reconstruct groundwater level time-series at a supply borehole to investigate the behaviour of the borehole under historic drought conditions;
2. Apply climate change scenarios to investigate the potential impact of changing recharge patterns on sustainable yields;
3. Test abstraction management practices to determine optimum management strategies for an individual borehole or group of boreholes.

The issue of scale

The sustainable yield of a borehole is influenced by a number of processes operating over multiple scales. These should be represented in a groundwater model to provide a reliable estimate of the borehole yield.



Factors influencing sustainable yield at the local scale:
- Depth of borehole, pump and screening
- Vertical heterogeneity around the borehole
- Development of turbulent (non-linear) flow, particularly in fractured aquifers
- Development of a seepage face

Factors influencing sustainable yield at the regional scale:
- Spatial and temporal variations in recharge
- Vertical and lateral heterogeneity
- Discharge to/from rivers or springs
- Interference from other abstraction boreholes

Figure 2 Processes around an abstraction borehole.

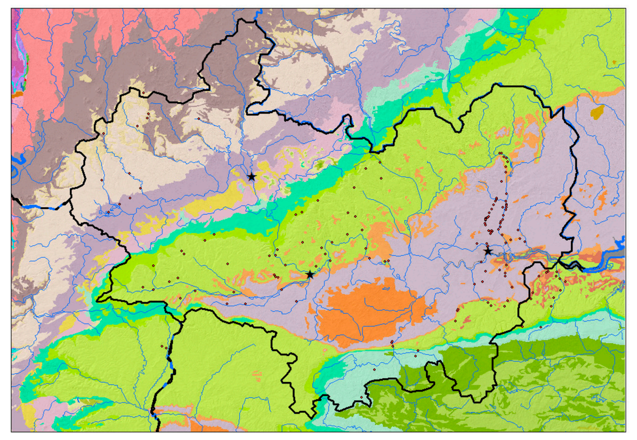


Figure 2 River Thames catchment.

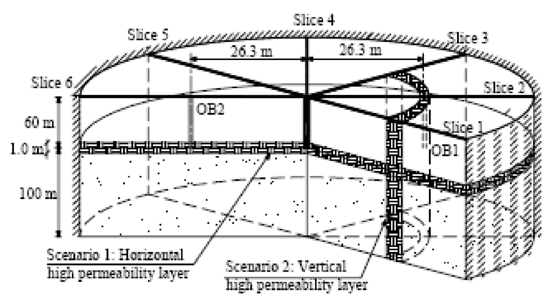
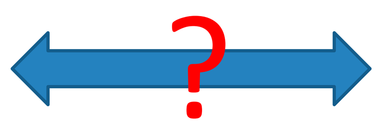


Figure 4 Radial grid for simulating flow converging on a borehole.



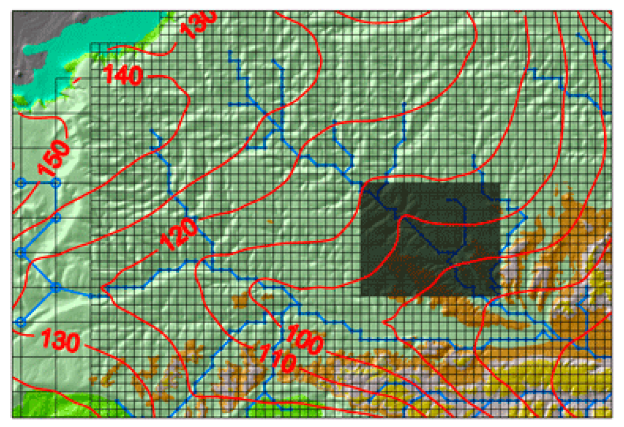


Figure 5 Typical refined Cartesian grid for regional groundwater modelling.

Radial flow models are often used to model the flow to an individual borehole. The radial grid may be refined down to the scale of the abstraction borehole (<1 metre) and the model is therefore able to resolve the curvature of the solution in the immediate vicinity of the borehole. The high grid resolution and radial gird structure mean these models are not well suited for simulating regional scale systems.

Groundwater systems are commonly modelled at the regional or catchment scale. Regional models may extend over areas of hundreds of square kilometres. The grid resolution of a regional model may therefore be on the order of 10^1–10^4 metres. Boreholes are assigned to individual nodes and the abstraction rate is averaged over a large area. The model is therefore unable to accurately represent the groundwater level in the borehole.

Multi-scale groundwater modelling

A multi-scale methodology has been developed which allows a small-scale radial model of an abstraction borehole, SPIDERR, to be coupled with the ZOOMQ3D groundwater modelling code (Jackson and Spink, 2004).

In SPIDERR, one or more radial grids are embedded within a single Cartesian grid (Figure 6). The hybrid finite difference method (Pedrosa Jr and Aziz, 1986) maintains mass balance across the boundary between the two grids. The outer Cartesian grid allows the SPIDERR model to be easily linked with the Cartesian grid of ZOOMQ3D.

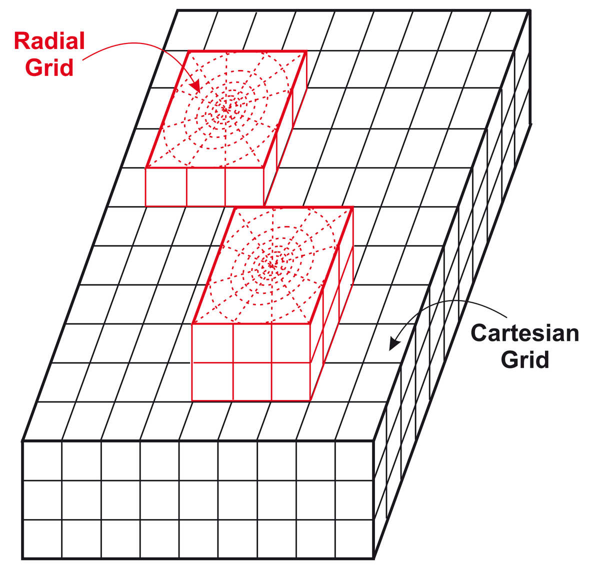


Figure 6 Hybrid radial-Cartesian grid of the SPIDERR Flow Model.

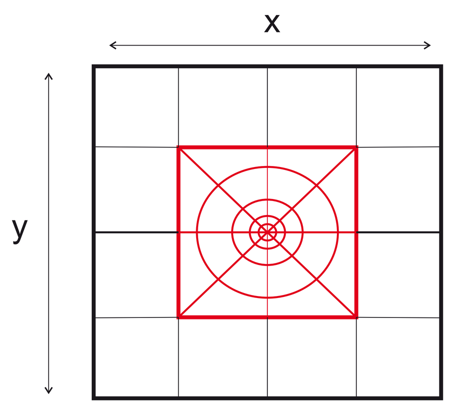


Figure 7 Representation of SPIDERR grid.

SPIDERR Flow Model

- Based on a finite difference approximation to the 2D governing flow equation in radial coordinates
- Vertical structure represented as a series of layers that are confined, unconfined or inactive
- Specific discharge is based on the Darcy-Forchheimer equation allowing linear and non-linear flow to be simulated
- Logarithmic refinement in radial dimension
- Represents borehole storage and seepage face development
- Fully or partially penetrating borehole with or without casing
- Incorporates abstraction management rules

ZOOMQ3D

- Based on a finite difference approximation to the 2D governing flow equation in Cartesian coordinates
- Vertical structure represented as a series of layers that are confined, unconfined or inactive
- Incorporates horizontal grid refinement
- Represents lateral heterogeneity, river-aquifer interaction, spatially and temporally varying recharge

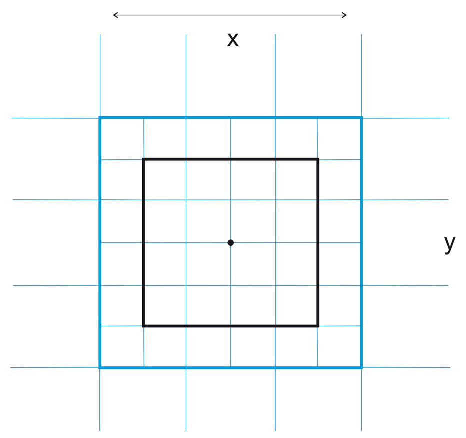


Figure 8 Representation of ZOOMQ3D grid.

Coupled SPIDERR-ZOOMQ3D Groundwater Model

The two models are coupled through the OpenMI interface (Moore et al., 2010). OpenMI is a standard for exchanging data between models at run-time. The two models, which are coded in different programming languages, have been made OpenMI compliant. They can therefore run simultaneously within the OpenMI framework, exchanging data at each time-step. The data exchange process is summarised in Figure 9. The Cartesian grids of the two models are equivalent in the horizontal but may be vertically refined in SPIDERR. This allows a more detailed representation of vertical heterogeneity around the abstraction borehole.

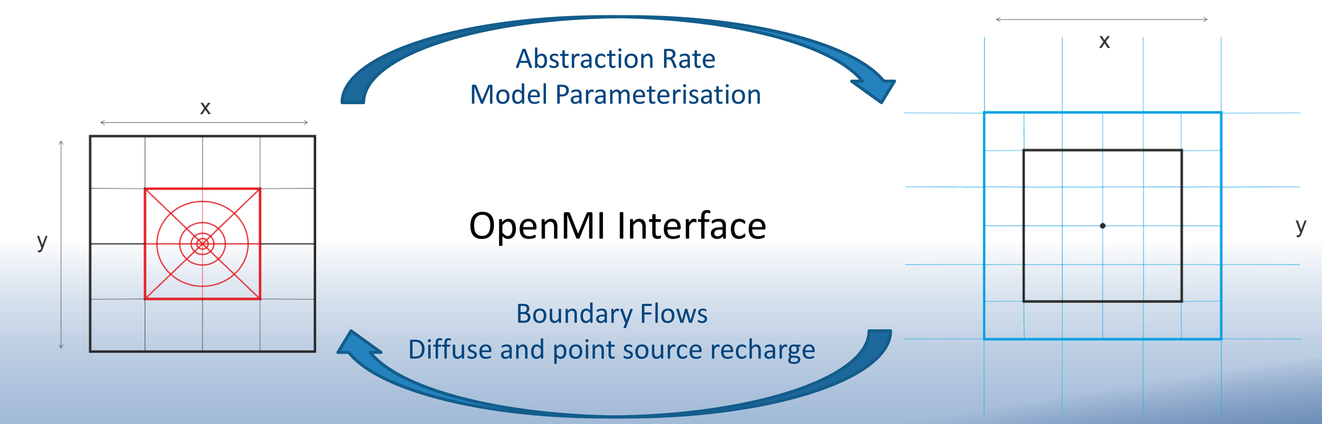


Figure 9 Overview of the coupled SPIDERR-ZOOMQ3D model.

Model application

The coupled SPIDERR-ZOOMQ3D model is applied to a supply borehole which is operated by Thames Water Utilities Limited. The abstraction borehole is situated in the Chalk aquifer of the Thames Basin in southern England. The Chalk is the principal aquifer in the UK, providing around 40% of the total public water supply in the Thames region.

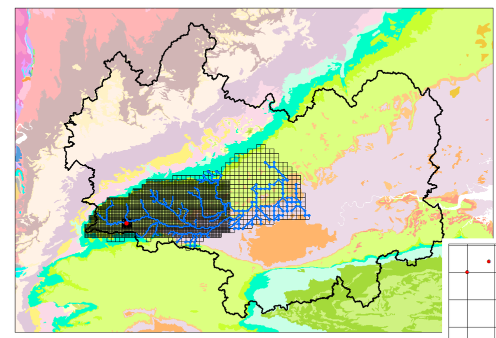


Figure 10 ZOOMQ3D model grid for the Marlborough and Berkshire Downs, Thames Basin.

The borehole sits within the boundaries of an existing ZOOMQ3D model of the Marlborough and Berkshire Downs (Figure 10). This model has 3 levels of refinement: a 2km and 500m grid over the eastern and western areas of the model, respectively, and a 250m grid within the area of interest around the supply borehole (Figure 11).

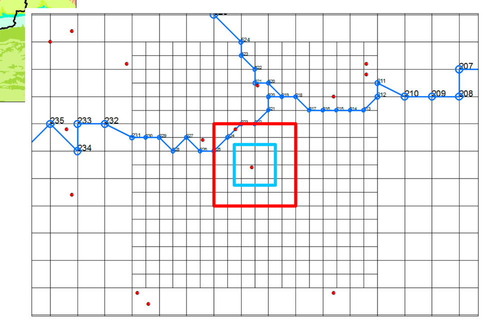


Figure 11 SPIDERR model grid of the supply borehole. Red boundary marks the extent of the Cartesian SPIDERR grid; blue boundary marks the extent of the radial SPIDERR grid. The supply borehole is located close to the River Kennet, a major tributary of the River Thames.

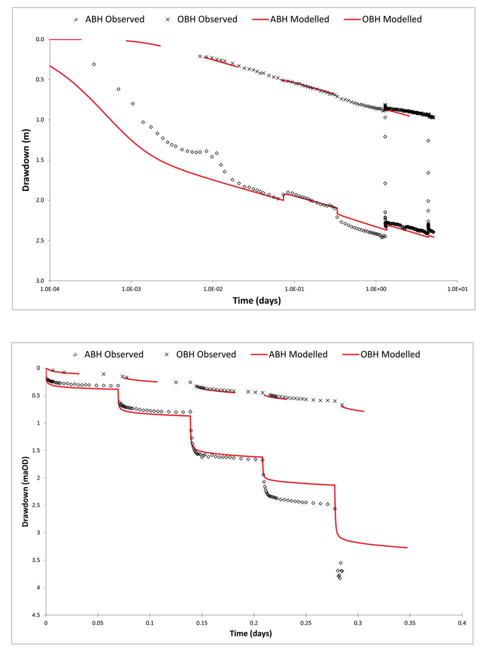


Figure 12 Calibration of the SPIDERR model against constant rate and step drawdown test data.

The SPIDERR model consists of a 250m resolution Cartesian grid with a 12 slice radial grid at its centre (Figure 11). The SPIDERR model replaces 7x7 nodes of the ZOOMQ3D model grid and is initially calibrated against pumping test data from the supply borehole (Figure 12).

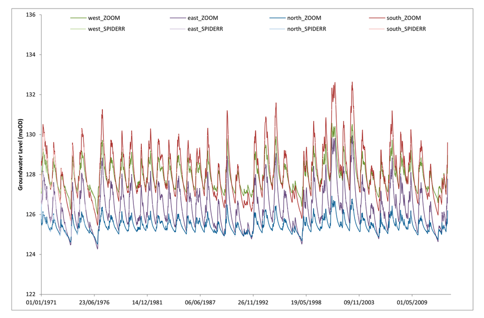


Figure 13 SPIDERR and ZOOMQ3D are consistent at equivalent points on the Cartesian grid when coupled through OpenMI.

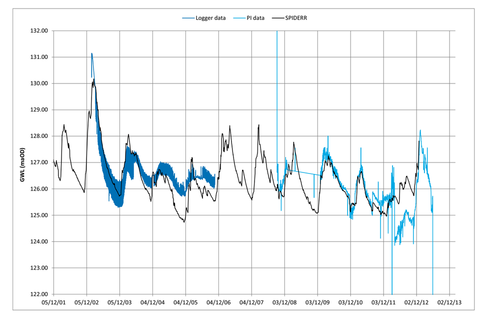


Figure 14 SPIDERR model reproduces operational data at the supply borehole.

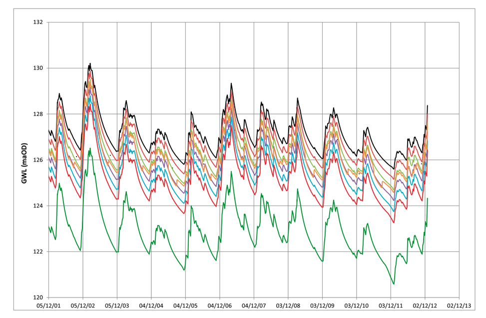


Figure 15 Simulated groundwater levels in the supply borehole under different abstraction scenarios.

The coupled model is then run over the historic simulation period 1971–2012 (Figure 13). The data exchange process through OpenMI ensures that the mass balance of the two models is the same and the simulated time-series are consistent at equivalent points on the Cartesian grids (Figure 13).

The SPIDERR model reproduces operational groundwater levels at the supply borehole over the period 2008–2012 (Figure 14). The reconstructed time-series prior to 2008 provides an improved understanding of the behaviour of the source under historical drought conditions. Abstraction scenarios are applied to the coupled model to investigate the behaviour of the source under increasing rates of abstraction (Figure 15). This provides more robust data on which to base an estimate of the sustainable yield of the source, particularly under low level or drought conditions.

Conclusions

- A methodology is presented for simulating abstraction boreholes in regional groundwater models
- The SPIDERR model represents local-scale features and processes around a borehole
- The SPIDERR model is linked with the ZOOMQ3D groundwater modelling code through OpenMI
- The coupling methodology allows a small-scale borehole model to be linked quickly and easily to an existing regional groundwater model
- The coupled SPIDERR-ZOOMQ3D model allows operational time-series to be reconstructed to investigate source behaviour during historic droughts
- The methodology is applied to a supply borehole in the Chalk aquifer of the UK; this application demonstrates the potential use of the model for assessing the sustainable yield of supply boreholes, which is essential for effective groundwater management
- Climate scenarios can also be applied to the coupled model to investigate the potential impact of climate change on the sustainable yield of supply boreholes

References

Jackson, C R. and Spink, A E F. (2004). User's manual for the groundwater flow model zoomq3d. British Geological Survey Internal Report. IR/04/140.

Moore, R, Gijsbers, P, Fortune, D, Gregersen, J, Blind, M, Grooss, J and Vanecek, S. (2010). Openmi document series: Scope for the openmi (version 2.0). The OpenMI Document Series. R Moore. Wallingford, UK, Centre for Ecology and Hydrology.

Pedrosa Jr, O A and Aziz, K. (1986). Use of a hybrid grid in reservoir simulation. SPE Reservoir Engineering.

Contact information

Kirsty Upton email: kirlto@bgs.ac.uk