A seamlessly coupled GIS and distributed groundwater flow model

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Highlights

- A seamless GIS-groundwater flow model is presented
- It directly uses GIS data for groundwater flow modelling within the GIS environment
- This easy-to-use and flexible model can be used by non-modellers
- It is downloadable and can be used for any purpose free of charge
- The model developed herein can be integrated into other raster GIS packages.

Abstract

There are three approaches for coupling groundwater models with GISs, i.e. *loose*, *tight*, and *seamless*. In seamless coupling a model code is written into, and run from within, a GIS. We implemented BGS GISGroundwater in a GIS in this way for the first time. It facilitates the construction and simulation of the model, and the visualisation of the results all within the GIS environment. The model consists of a 2D finite-difference groundwater flow model and a simple user-interface. It can represent heterogeneous aquifers, variably confined and unconfined conditions, and distributed groundwater recharge and abstraction. It offers benefits in terms of ease of use and in streamlining the model construction and application process. BGS GISGroundwater has been validated against analytical solutions to groundwater-head profiles for a range of aquifer configurations. This model lowers barriers to entry to groundwater flow modelling for a wider group of environmental scientists.

Keywords: GIS; Groundwater flow model; Finite-difference method; GISGroundwater

Software availability

Name of software:	BGS GISGroundwater
Developer:	Dr. Lei Wang
Contact address:	British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, UK. Email: lei.wang@bgs.ac.uk
Year first available:	2014
Software required:	ESRI ® ArcMap™ 10.0 and above

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Program Language:	C++
Availability and cost:	BGS GISGroundwater can be freely downloaded (with manual and tutorial materials) from http://www.bgs.ac.uk/GISGroundwater, and used for any purpose under the Open Government License.

1 Introduction

Geographic Information Systems (GISs) are routinely used to process data for input into complex stand-alone numerical groundwater flow models, such as MODFLOW (Harbaugh *et al.*, 2000) and FEFLOW (Diersch, 2005). This is because these models require numerous spatial and temporal datasets that are easily accessed and processed using GIS. Whilst GISs save users significant time in processing data, in most instances their outputs cannot be transferred directly into groundwater flow models due to the use of model-specific file formats. For example the MODFLOW, which is written in the Fortran programming language, reads text input files using bespoke formats and specific file structures.

It has become common practice to couple different numerical models with GISs, and many efforts have been made to link a GIS and groundwater model using *loose* and *tight* coupling methods (Bhatt *et al.*, 2014; Vairavamoorthy *et al.*, 2007). In *loose* coupling (Fig. 1a) a GIS is used to manually prepare spatial and temporal datasets for numerical groundwater models, and to visualise the results generated by them (e.g. Wang *et al.*, 2012, 2013, 2016). In *tight* coupling (Fig. 1b) computer code is written to automate the exchange of data between a GIS and a groundwater model, and to translate output from one into the correct format for the other (e.g. Carrera-Hernández and Gaskin, 2006). The commercial MODFLOW Analyst code developed in Arc Hydro Groundwater (Strassberg *et al.*, 2011), which uses the *tight* coupling method, enables users to view, manage and map MODFLOW models in ArcGIS.

In addition to *loose* and *tight* coupling methods, numerical models can be integrated fully within a GIS using a method referred to as *seamless* coupling (Fig. 1c). Approaches to *seamless* coupling can be split into two groups. In the first group, groundwater related models are developed by adopting the existing GIS spatial analysis functions, such as interpolation, extraction, and raster-layer math (i.e. addition, subtraction, multiplication and division). Modelling examples listed below belong to this approach: identifying groundwater recharge zones (Yeh et al., 2009), assessing groundwater pollution vulnerability (Wang and Yang, 2008; Yang and Wang, 2010) and evaluating groundwater availability (Ganapuram et al., 2009). In the second group, new models, which use GIS data format, are developed for GIS from scratch using a computer language (such as C++). The second group approach makes it possible to develop models representing sophisticated processes, but complex and time-consuming programming work might be a drawback of this method. Examples of the second group approach include Arc Hydro (Maidment, 2002) and the groundwater analysis module in ArcGIS™ (ESRI, 2012). The latter was developed based on the porous medium-advection dispersion model of Tauxe (1994). This ArcGIS™ groundwater module generates a groundwater flow velocity field using groundwater heads. It is, therefore, actually a post-processing tool for groundwater heads rather than a

groundwater flow model that generates groundwater heads. To date there have not been any examples of numerical groundwater flow models seamlessly integrated into a GIS for producing groundwater heads. Comparing with other coupling methods, the *seamless* coupling method makes the groundwater models more efficient and easy-to-use, for the processes of data preparation, numerical modelling, post-processing and the visualisation of the modelling results are all implemented within a GIS environment. In addition, using the standard GIS data formats in *seamless* coupling method means that there is no extra work for data exchanging or no extra costs for purchasing coupling interface programs in *tight* coupling method (Huang and Jiang, 2002). In this study, we developed a seamless GIS groundwater flow model using the second group approach in *Seamless* coupling method.

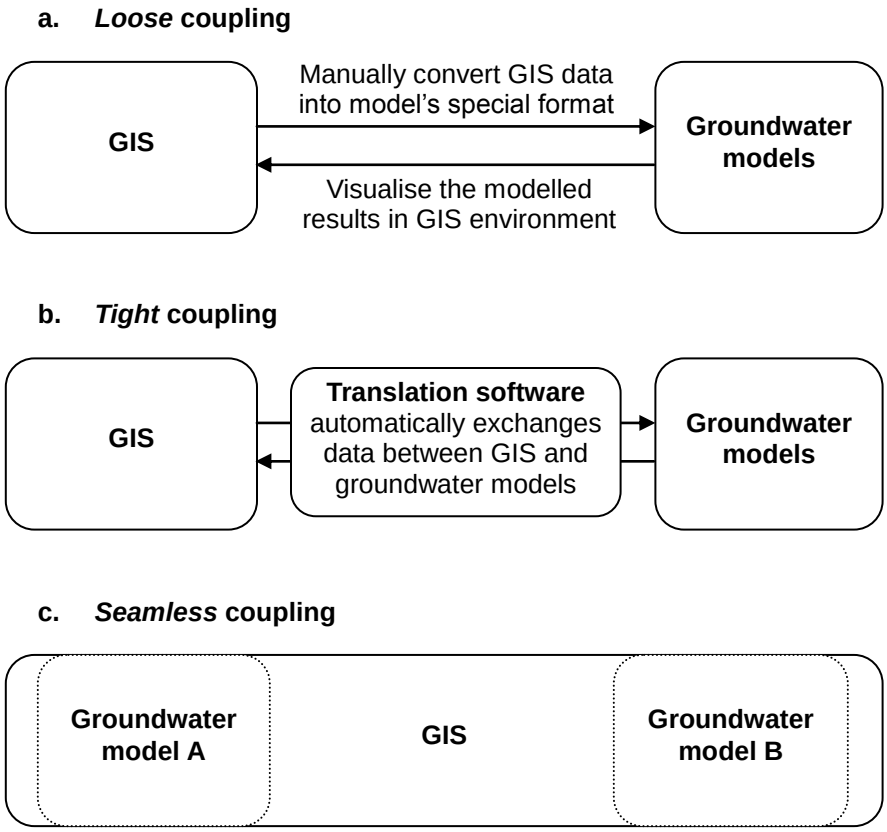


Fig. 1 Different methods for coupling groundwater models with GIS.

We present a *seamless* GIS-groundwater flow model: BGS GISGroundwater. This model uses standard GIS file formats as input and can be regarded as a spatial-analysis tool in ArcGIS™. It facilitates the preparation of model input data, simulation of groundwater flow, and the visualisation of the modelled results all within a GIS environment.

2 Model development

BGS GISGroundwater is composed of a finite-difference groundwater flow model and a User-Interface (UI), which are packaged up as an add-in for ArcGIS™ (Fig. 2). This add-in was developed using ArcObjects, a development environment for the ArcGIS™ suite of

applications. It generates spatially-distributed groundwater heads by simulating groundwater flow in porous media.

2.1 Numerical groundwater flow model

The numerical groundwater flow model solves the governing 2D steady-state groundwater flow continuity equation of the form:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)=Q^A+Q^R-R \qquad [1]$$

where h is the groundwater head [L]; T_x and T_y are the aquifer transmissivity in the x and y direction respectively [L^2T^{-1}]; Q^A is groundwater abstraction rate [$L^3\ T^{-1}$]; Q^R is leakage to or from rivers [$L^3\ T^{-1}$]; and R is the amount of groundwater recharge [$L^3\ T^{-1}$].

Whilst equation 1 is the governing equation for aquifers in which transmissivity does not vary with saturated thickness, the model can simulate both confined and unconfined conditions. To do this the model calculates transmissivity using the hydraulic conductivity, K [$L\ T^{-1}$], as follows:

$$T=\begin{cases} K\cdot b & \text{for confined aquifers} \\ K\cdot(h-z_{base}) & \text{for unconfined aquifers} \end{cases} \qquad [2]$$

where b is the aquifer thickness [L]; and z_{base} is the elevation of the aquifer base [L].

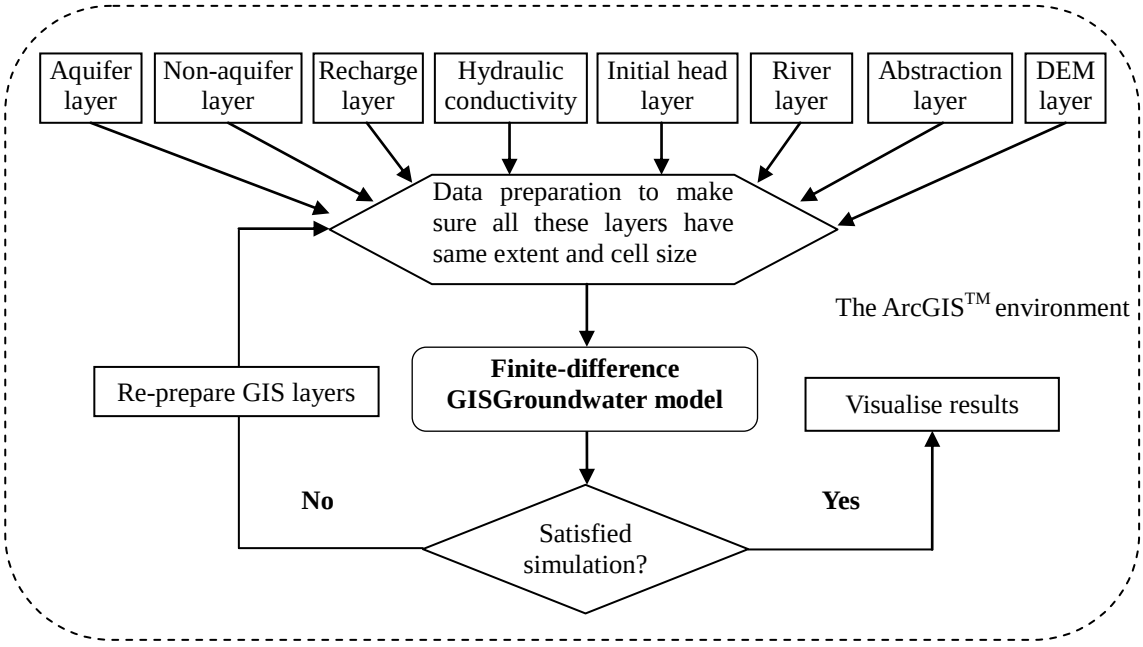


Fig. 2 Structure of BGS GISGroundwater add-in for ArcGIS™.

Rivers and other surface-water features are represented in the model using a Darcian head-dependent leakage mechanism, in which inflows and outflows, Q^R, between the aquifer and the river, are calculated according to:

$$Q^R = C \cdot L \cdot (h - z) \qquad [3]$$

where L [L]is the length of the river reach associated with a model cell; z is the elevation of surface-water feature [L]; and C is a leakage coefficient [LT^{-1}]. The leakage coefficient C can be considered to be equivalent to $K_z w / B$, where w is the width of the river, and K_z and B are the hydraulic conductivity and thickness of the river bed, respectively.

The groundwater model solves Equation 1 for groundwater head using the finite-difference method (Wang and Anderson, 1982). The aquifer domain is converted into a uniform grid of cells, at each of which a finite-difference equation is constructed of the form:

$$\frac{\left(\frac{T_x^{i,i+1}\left(h_{i+1,j} - h_{i,j}\right)}{\Delta x_{i+1/2}} - \frac{T_x^{i-1,i}\left(h_{i,j} - h_{i-1,j}\right)}{\Delta x_{i-1/2}}\right)}{\left(\Delta x_{i-1/2} + \Delta x_{i+1/2}\right)/2} + \frac{\left(\frac{T_y^{j,j+1}\left(h_{i,j+1} - h_{i,j}\right)}{\Delta y_{j+1/2}} - \frac{T_y^{j-1,j}\left(h_{i,j} - h_{i,j-1}\right)}{\Delta y_{j-1/2}}\right)}{\left(\Delta y_{j-1/2} + \Delta y_{j+1/2}\right)/2}$$

$$= Q^A + C \cdot L \cdot (h_{i,j} - z) - q\Delta x\Delta y \qquad [4]$$

where i and j are the column and row index of the cell; $\Delta x_{i-1/2} = x_i - x_{i-1}$, $\Delta y_{j-1/2} = y_j - y_{j-1}$, and $T_x^{i-1,i}$ and $T_y^{j-1,j}$ are the harmonic mean of the transmissivity in the x and y directions, between cells i-1 and i, and cells j-1 and j, respectively; and q represents groundwater recharge or infiltration from the surface [$L\,T^{-1}$].

The resulting matrix of finite-difference equations for the governing flow equation is solved using the Point Successive Over-Relaxation (PSOR) method (Wang and Anderson, 1982). The user defines the maximum number of iterations, a convergence criterion as a maximum nodal flow imbalance ($m^3\,day^{-1}$), and the algorithm's over-relaxation parameter, ω (Wang and Anderson, 1982). For unconfined aquifers, the user also defines the number of transmissivity recalculation cycles to perform.

Distributed information on groundwater recharge, abstraction, aquifer hydraulic conductivity, initial heads and boundary conditions are required for a groundwater flow solution to be calculated (Fig. 2). Model boundaries are assumed to be no-flow unless specified as constant head, though flux boundaries can be specified through assignment of pumping wells.

The extent of the model domain, and therefore finite-difference grid, are defined using a GIS raster layer that maps the area of the aquifer to be modelled. The centre of each raster cell defines the location of the finite-difference node, and therefore the raster cell edges can be regarded as forming the *dual mesh* of the finite-difference grid (Fig. 3). We implement a commonly-used mesh-centred finite-difference grid in which solution nodes are located on

no flow (Neumann type) and fixed head (Dirichlet type) aquifer boundaries. This is different from block-centred finite-difference models in which, a block, or cell, edge coincides with Neumann boundaries, and the solution node is half a block width inside the boundary. The model requires at least two lines (i.e. rows and columns) of finite-difference nodes to be constructed in each Cartesian direction i.e. a single line of finite-difference nodes is not acceptable. Other problems could arise when converting the aquifer GIS raster layer into the finite-difference grid in a few specific cases (e.g. Fig. 3). For example, the invalid node in Fig. 3c is actually located in a non-modelling area in the finite-difference domain after conversion. In Fig. 3d, the invalid node, which is surrounded by four boundary nodes, stops groundwater flow in each Cartesian direction within the central dual mesh. However, these are recognised and automatically removed by the model. The removal of invalid nodes could create new invalid ones, so this process is iterated until all nodes in a model are valid. Consequently, the construction of the finite-difference grid for aquifers with complicated shapes (e.g. Fig. 4) is a straightforward process when using BGS GISGroundwater.

2.2 User Interface

The BGS GISGroundwater UI for ArcGIS™ incorporates functions to process model input data, run a simulation, and visualise the model results. Data preparation functions are included to enter and check the extent and cell size of GIS data, and to modify data when necessary to meet the requirements of BGS GISGroundwater. For example, when GIS raster layers are larger than the extent of aquifer layer, they will automatically be clipped to the required extent by the interface. If a river shapefile is selected, it will automatically prepare the river input data by extracting river level values from a Digital Terrain Model (DTM) layer. The full input data formats for the model are described in Wang *et al.* (2014).

Before starting a simulation, the model will check the inputs and highlight any errors. If the model run is successful the simulated groundwater head layer is displayed in ArcMap™, along with the modelled area. A message is sent to the user if there are any problems during the simulation. However, the interface remains open and retains the input data whether there are errors or not, and subsequently adjusting and re-running a model is straight forward (Fig. 2).

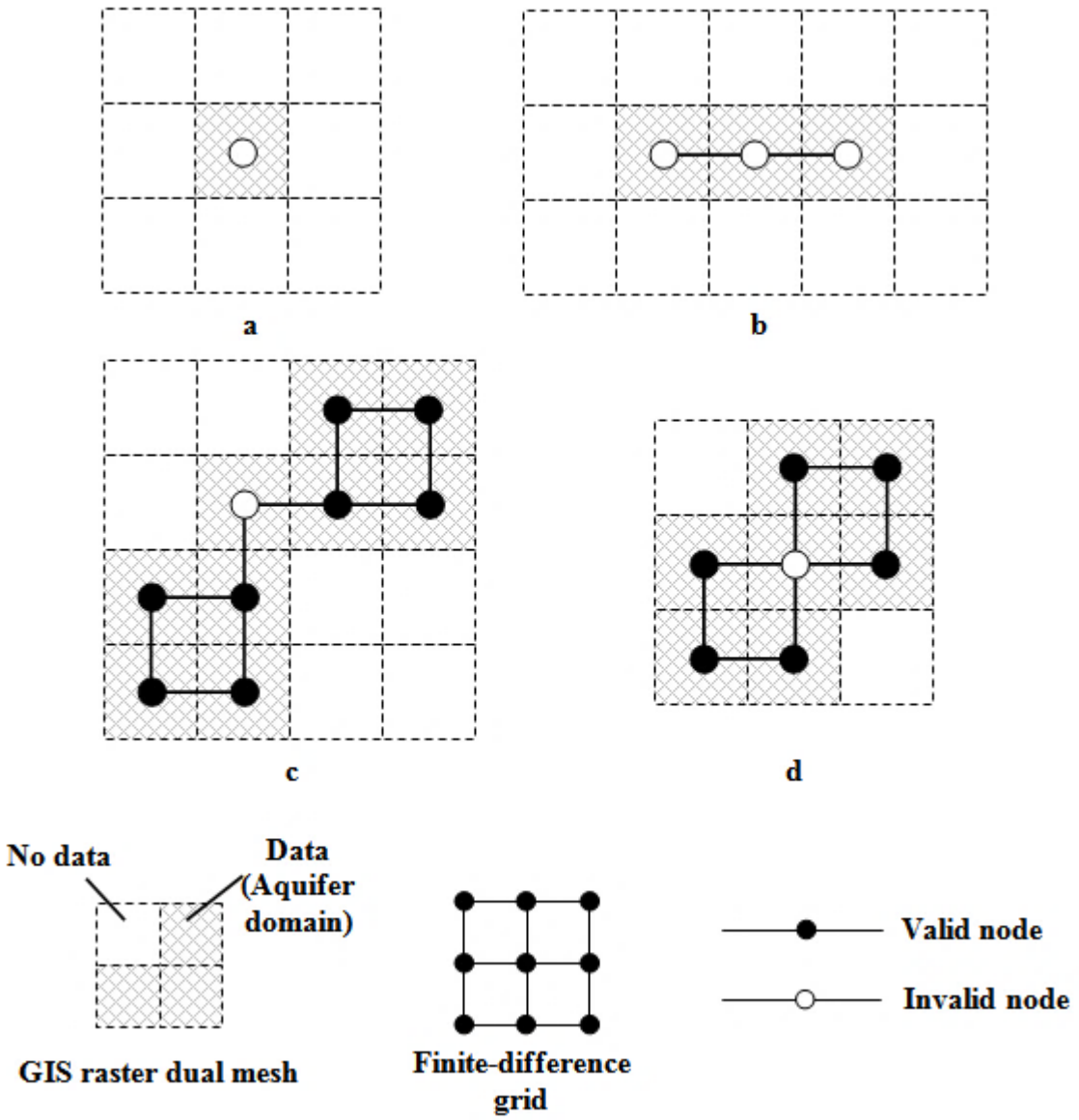


Fig. 3 Some examples of GIS grids that create invalid nodes for BGS GISGroundwater.

3 Model application

BGS GISGroundwater has been validated against analytical solutions to groundwater-head profiles, for a range of aquifer configurations. For example, the groundwater-head profile in two variants of the aquifer shown in Fig. 5. This 10 km square is represented using a uniform, node-centred finite-difference mesh of 500 m-square cells. Recharge is applied uniformly across the aquifer at a rate of 10^{-3} m day^{-1}. All of the boundaries of the domain are specified as impermeable except in the left-hand column of nodes (x = 0) where the groundwater head is fixed at 100 m. In the first model simulation, transmissivity, *T*, is not a function of groundwater head and is defined according to the equation:

$$T = 10\sqrt{x + 1000} \qquad [5]$$

where x is the distance in the x direction from the centre of the left-hand column of fixed-head nodes. The analytical solution of the 1D steady-state groundwater-head profile for this aquifer configuration is:

$$h(x) = \frac{q}{5}\sqrt{x+1000}\,(L - x) + \frac{2q}{15}(x+1000)^{1.5} - \frac{2q}{15}(1000)^{1.5} - \frac{\sqrt{1000}\,qL}{5} + H_0 \qquad [6]$$

where L is the length of the aquifer in the x direction (10000 m); and H_0 is the fixed-head value on the left-hand boundary.

In the second simulation the model is specified to be unconfined, in which case the transmissivity is calculated as the saturated thickness of the aquifer multiplied by the hydraulic conductivity. The aquifer is homogenous with a hydraulic conductivity, K, of 10 m day^{-1} and base elevation, z_b, of 50 m. For this aquifer configuration, the analytical solution to the steady-state groundwater-head profile is calculated by solving the quadratic equation $ah^2 + bh + c = 0$ where:

$$a = \frac{K}{2}, \qquad b = -K z_b, \qquad c = \frac{q x}{2}(x - 2L) - \frac{K H_0}{2}(H_0 - 2 z_b) \qquad [7]$$

for selected values of x.

Fig. 6 shows that the results of both models and the analytical solutions are in close agreement. In both simulations the model converges when the maximum nodal flow imbalance at each model cell is less than the specified value of 10^{-5} m^3 day^{-1}. In the unconfined simulation, 50 transmissivity-recalculation cycles are performed. The maximum differences in groundwater head between the simulated results and analytical solution occur on the right-hand boundary, and are 0.23 m and 0.07 m in the specified-transmissivity and unconfined models, respectively.

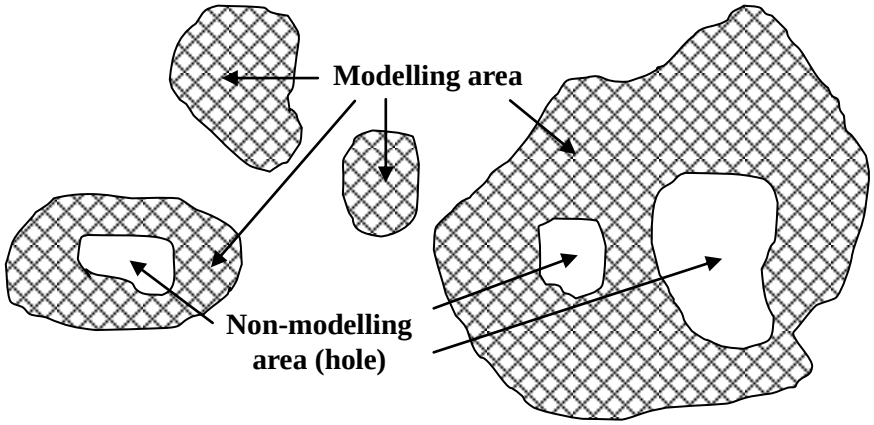
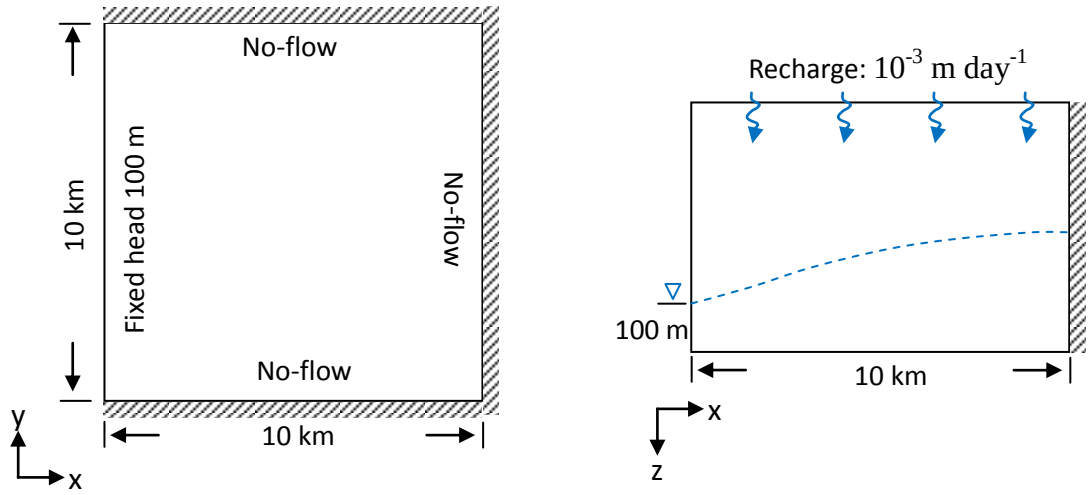


Fig. 4 An example of complicated shapes for the modelling extent that BGS GISGroundwater supports.



223 Fig. 5 The sketch map of the aquifer for validating BGS GISGroundwater using an analytic
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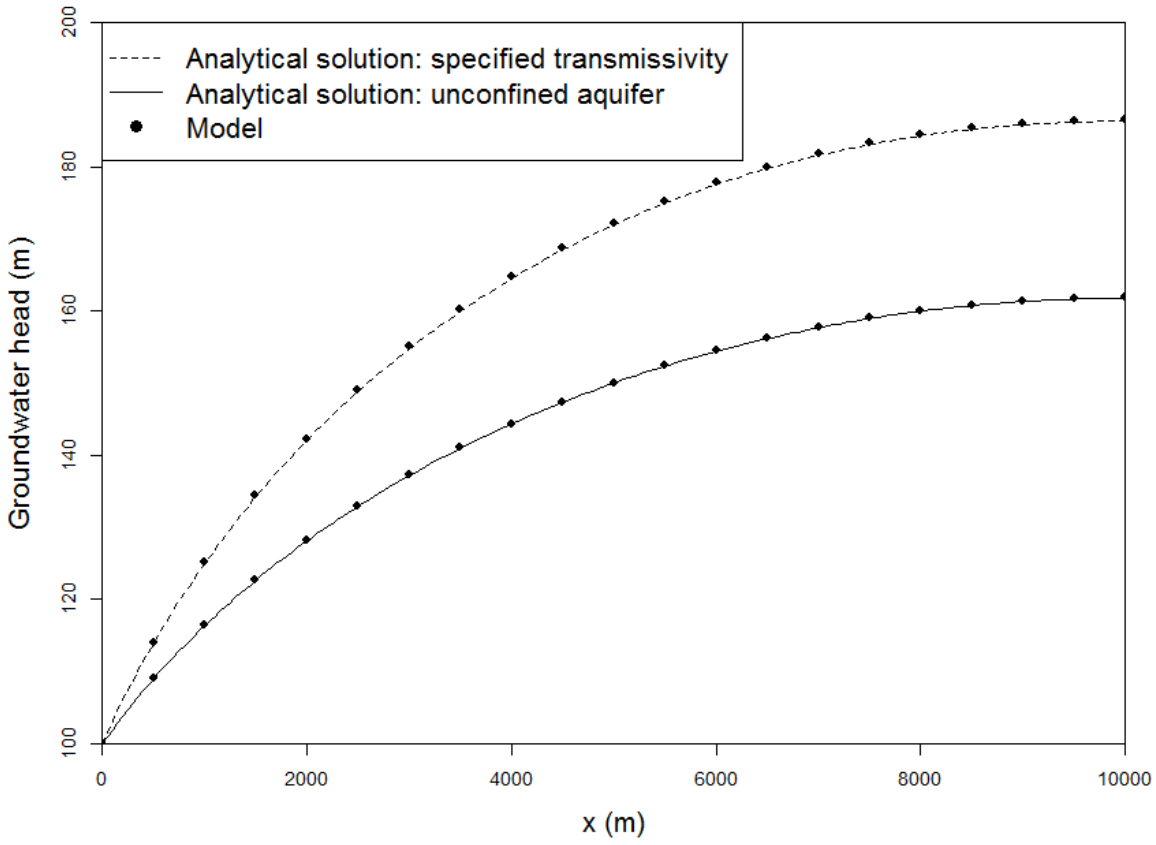

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228 Fig. 6 The comparison of analytical solutions with the modelled results using BGS
229 GISGroundwater.

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4 Conclusions

BGS GISGroundwater, which is a seamlessly coupled GIS and distributed groundwater flow model, has been successfully developed, verified and tested in this study. It facilitates the construction and simulation of the model, and the visualisation of the modelled results all within the GIS environment. BGS GISGroundwater is relatively simple but can represent heterogeneous aquifers, variably confined and unconfined conditions, and distributed groundwater recharge and abstraction. It is an easy-to-use and flexible tool that lowers barriers to entry to groundwater flow modelling, and enables those with an interest in understanding aquifers, but with little or no experience in modelling, to develop groundwater flow models. In addition, the numerical model developed in this study can be integrated into other GIS packages that support GIS raster data.

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