

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
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Keyworth, Nottingham, NG12 5GG, UK.
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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.

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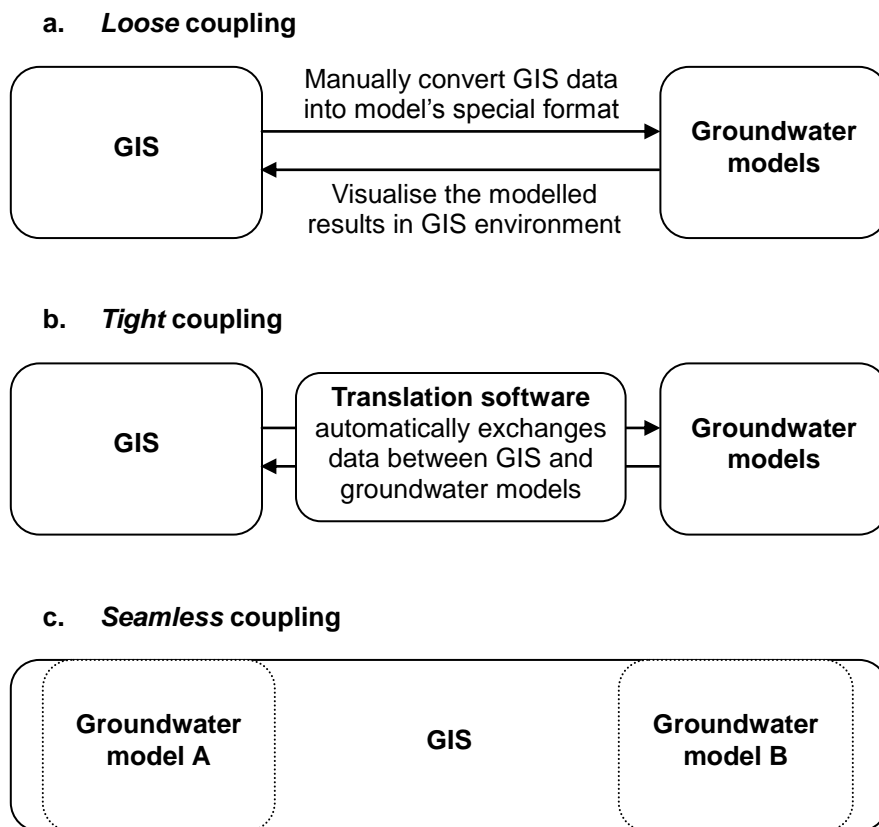
30 **1 Introduction**

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

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

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

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



77

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

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

83 2 Model development

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

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

89 2.1 Numerical groundwater flow model

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

92

$$93 \quad \frac{\partial}{\partial x} \left(T_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T_y \frac{\partial h}{\partial y} \right) = Q^A + Q^R - R \quad [1]$$

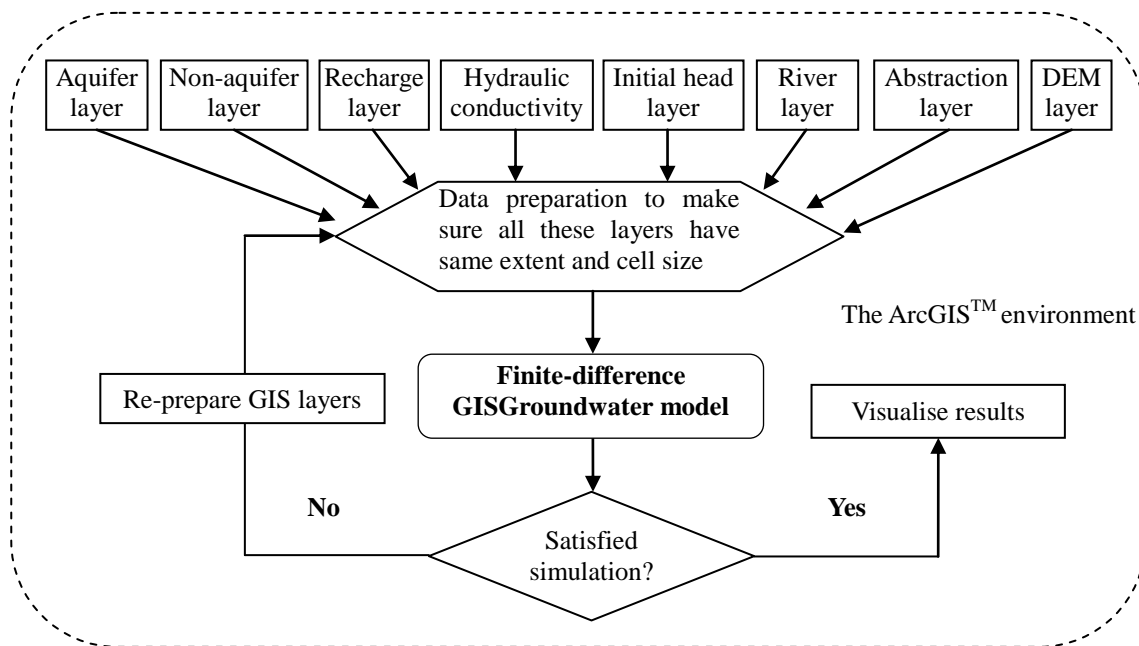
94 where h is the groundwater head [L]; T_x and T_y are the aquifer transmissivity in the x and
 95 y direction respectively [$L^2 T^{-1}$]; Q^A is groundwater abstraction rate [$L^3 T^{-1}$]; Q^R is leakage
 96 to or from rivers [$L^3 T^{-1}$]; and R is the amount of groundwater recharge [$L^3 T^{-1}$].

97

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

$$102 \quad T = \begin{cases} K \cdot b & \text{for confined aquifers} \\ K \cdot (h - z_{base}) & \text{for unconfined aquifers} \end{cases} \quad [2]$$

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



104

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

106

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

$$110 \quad Q^R = C \cdot L \cdot (h - z) \quad [3]$$

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

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

$$118 \quad \frac{\left(\frac{T_x^{i,i+1}(h_{i+1,j} - h_{i,j})}{\Delta x_{i+1/2}} - \frac{T_x^{i-1,i}(h_{i,j} - h_{i-1,j})}{\Delta x_{i-1/2}} \right)}{(\Delta x_{i-1/2} + \Delta x_{i+1/2})/2} + \frac{\left(\frac{T_y^{j,j+1}(h_{i,j+1} - h_{i,j})}{\Delta y_{j+1/2}} - \frac{T_y^{j-1,j}(h_{i,j} - h_{i,j-1})}{\Delta y_{j-1/2}} \right)}{(\Delta y_{j-1/2} + \Delta y_{j+1/2})/2}$$

119

$$120 \quad = Q^A + C \cdot L \cdot (h_{i,j} - z) - q \Delta x \Delta y$$

121

$$122 \quad [4]$$

122 where i and j are the column and row index of the cell; $\Delta x_{i-1/2} = x_i - x_{i-1}$,
123 $\Delta y_{j-1/2} = y_j - y_{j-1}$, and $T_x^{i-1,i}$ and $T_y^{j-1,j}$ are the harmonic mean of the transmissivity in
124 the x and y directions, between cells $i-1$ and i , and cells $j-1$ and j , respectively; and q
125 represents groundwater recharge or infiltration from the surface [$L T^{-1}$].

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

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

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

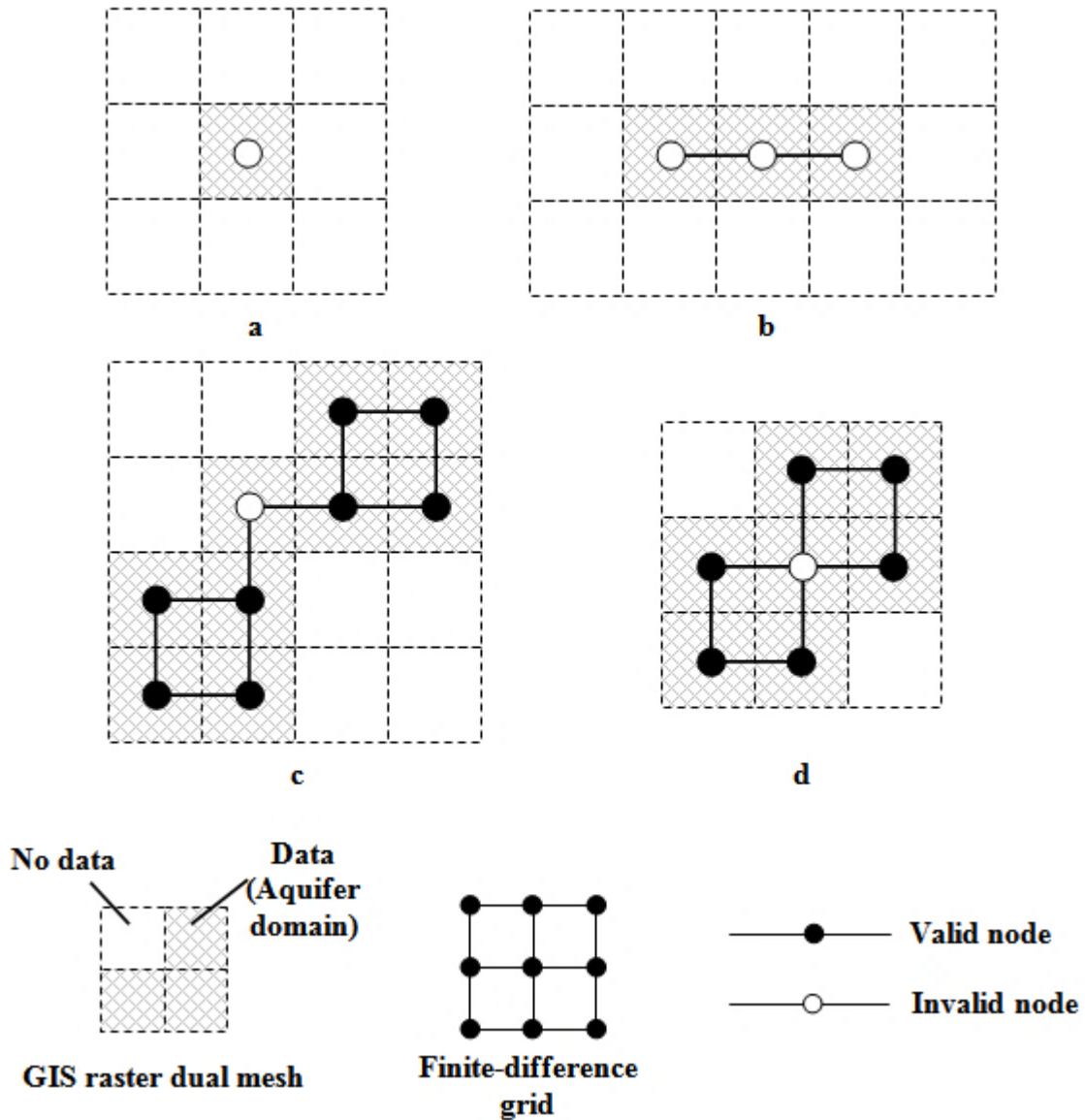
142 no flow (Neumann type) and fixed head (Dirichlet type) aquifer boundaries. This is
143 different from block-centred finite-difference models in which, a block, or cell, edge
144 coincides with Neumann boundaries, and the solution node is half a block width inside the
145 boundary. The model requires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

157

158 **2.2 User Interface**

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

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



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

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176

177 **3 Model application**

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

186

$$T=10\sqrt{x+1000}$$

[5]

187

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:

190

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

191

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.

193

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:

199

$$a = \frac{K}{2}, \quad b = -Kz_b, \quad c = \frac{qx}{2}(x-2L) - \frac{KH_0}{2}(H_0 - 2z_b) \quad [7]$$

200

for selected values of x .

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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 $10^{-5} \text{ m}^3 \text{ day}^{-1}$. 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.

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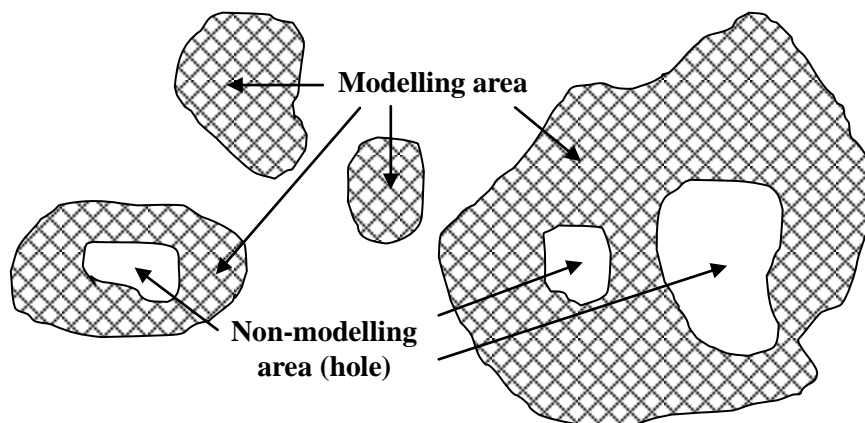
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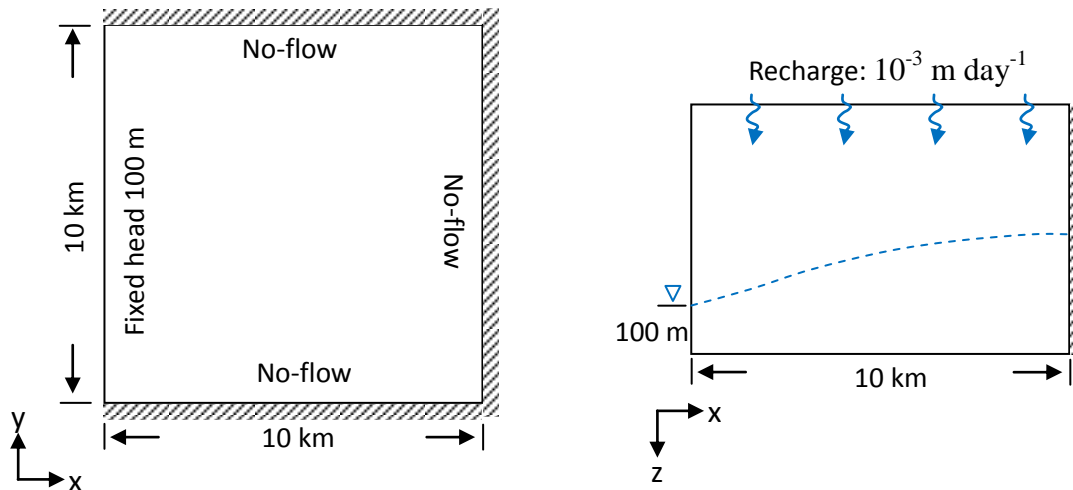


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Fig. 4 An example of complicated shapes for the modelling extent that BGS GISGroundwater supports.

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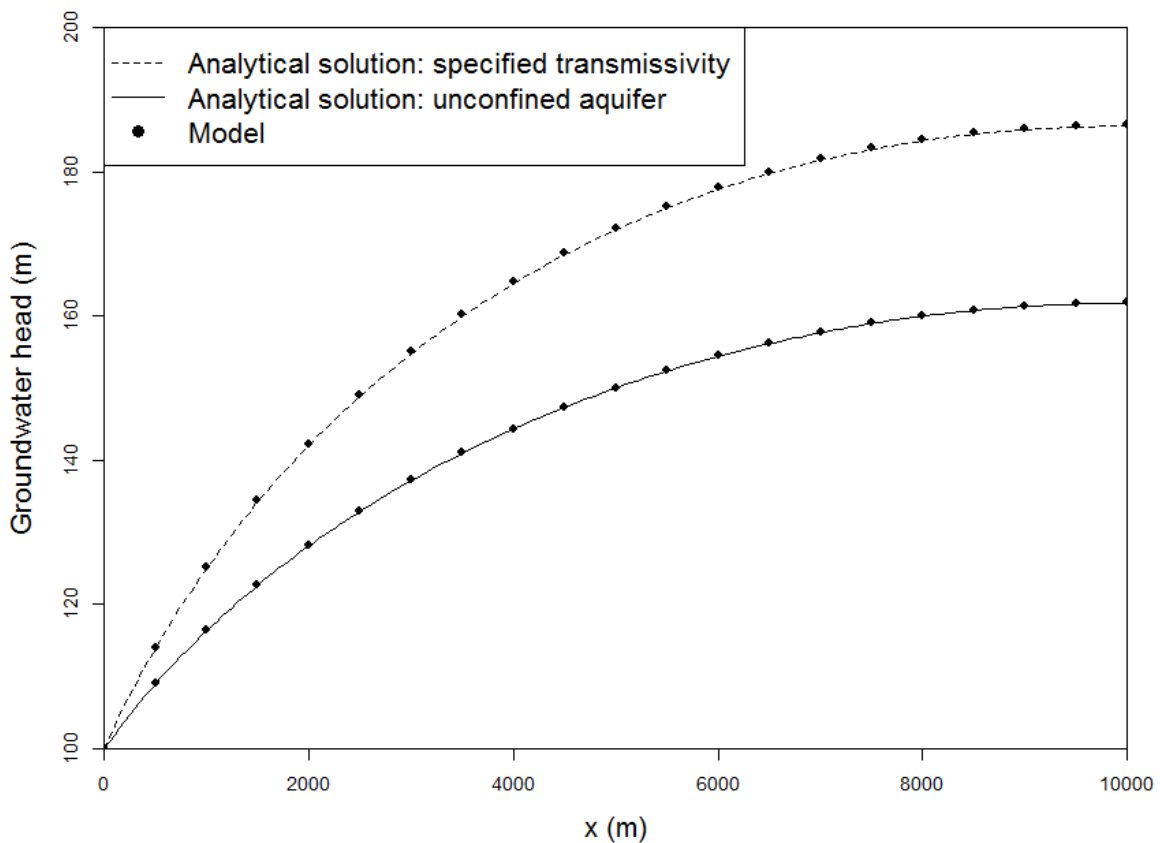
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223 Fig. 5 The sketch map of the aquifer for validating BGS GISGroundwater using an analytic
 224 solution.

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226



227

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

230

231 **4 Conclusions**

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

242

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