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Short communication

# A seamlessly coupled GIS and distributed groundwater flow model

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A R T I C L E I N F O

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A B S T R A C T

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.



## 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
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

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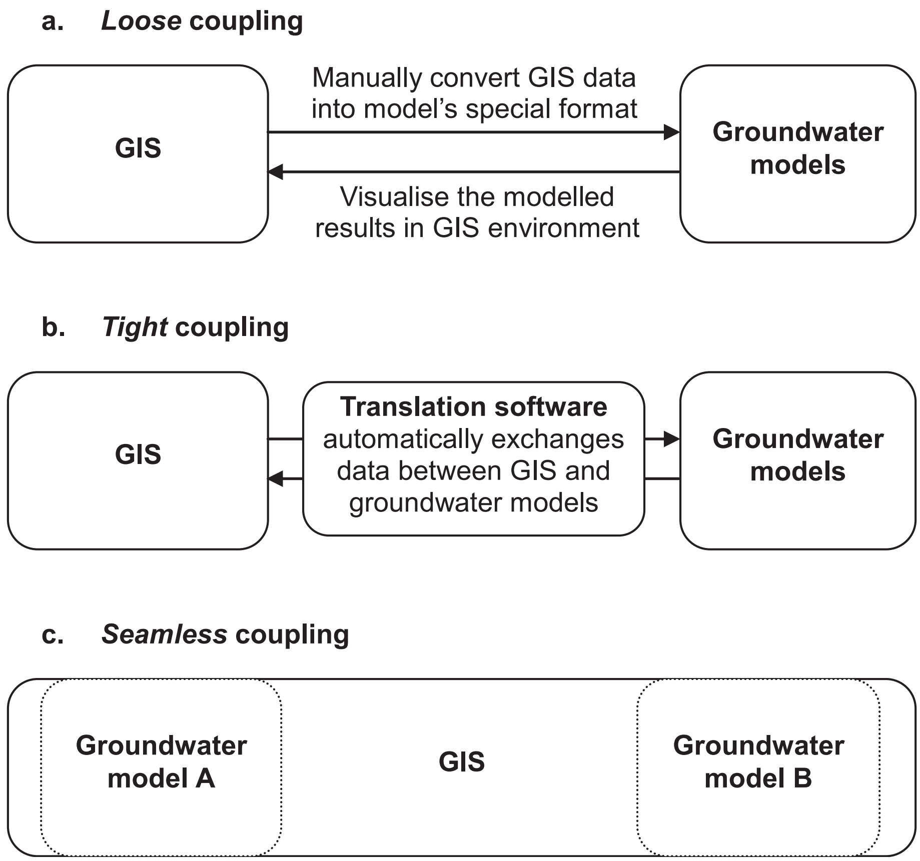


**Fig. 1.** Different methods for coupling groundwater models with GIS.

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.

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:

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

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 [$L^3T^{-1}$]; $Q^R$ is leakage to or from rivers [$L^3T^{-1}$]; and $R$ is the amount of groundwater recharge [$L^3T^{-1}$].

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