The Groundwater Modeling Tool for GRASS (GMTG): Open Source Groundwater Flow Modeling [*]

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Abstract

Geographic Information Systems (GIS) are used to store, manipulate and visualize both spatial and non-spatial data. Because of their data manipulating capabilities, GIS have been linked to different simulation models in different research areas and are commonly used for both surface and ground water modeling. Unfortunately this has been done mainly with proprietary GIS which are expensive and which do not provide access to their source code thus making them hard to customize. In order to overcome these problems, a module was created in the Open Source Geographic Resources Analysis Support System (GRASS) GIS to integrate it with the finite difference groundwater flow model MODFLOW, to take full advantage of the GIS capabilities. The results obtained with this module, when compared to those obtained with an existing MODFLOW pre and post-processor show that it can be used to develop groundwater flow models using uniform grid spacing on the horizontal plane. This module provides a tool for groundwater flow modeling to those users who can not afford the commercially available processors and/or to those who wish to develop their models within a GIS.

Key words: MODFLOW, GRASS, Geographic Information Systems, Groundwater

modeling.

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1 Introduction

Modeling spatial variables is a data intensive task for which Geographic Information Systems (GIS) have become powerful tools. Because of their capacity to handle both spatial and non-spatial data, GIS are widely used in local or regional studies as different types of data (e.g. surface geology, land-use, spatial variability of rainfall) can be superimposed for different analyses. The popularity of GIS is also indicated by the fact that data are prepared as ready-to-use GIS maps. The capabilities of GIS have led them to be used in a wide range of research areas and geographical locations such as wild life management in Europe (Herborg et al., 2003; Rushton et al., 1997), transportation (Waters, 1999), or civil protection in Hong Kong (Chau et al., 2004). GIS have evolved from a simple tool used to manipulate data into a tool in which complex modeling can be achieved through the use of both internal and external programs.

GIS are common tools whenever spatial modeling is attempted due to its capabilities to both manipulate and display data and hydrological modeling has been an area in which GIS have played an increasing role. The importance that GIS have acquired in this area is indicated by the number of publications that deal with both of these two topics such as the compilations by Lyon (2003) and Gurnell and Mont-

★ The source code and the data used on this paper are available at the GMTG web page: http://grass.gdf-hannover.de/twiki/bin/view/GRASS/JaimeCarrera

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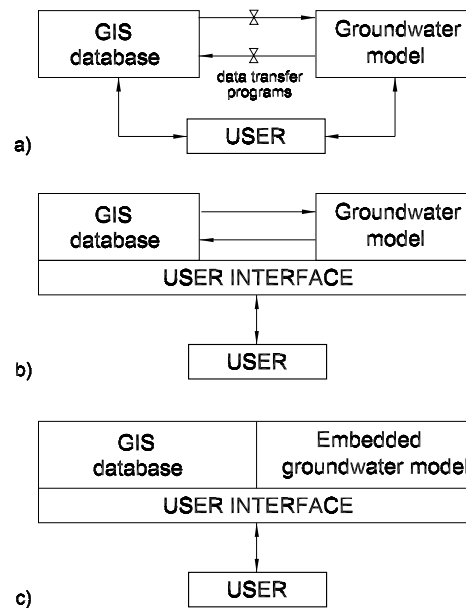susan.gaskin@mcgill.ca (S. J. Gaskin).

Fig. 1. Interaction of GIS with modeling software, adapted from Watkins et al (1996)

gomery (2000) as well as by conferences dealing with GIS and water management.

GIS have been increasingly used in conjunction with simulation models. A simulation model is either linked, integrated or embedded with a GIS (Watkins et al., 1996) as illustrated in Figure 1. A model is said to be linked with a GIS when both of them are used independently and the user has to transfer input/output files between them; a model is integrated with a GIS when the user interacts solely with the GIS or the simulation model (i.e. the GIS provides the user interface for the simulation model); in addition, both programs share a common database; finally, a model is embedded when it makes use of the GIS capabilities and/or libraries.

In the field of water resources, most of the work presented to date deals with the use of GIS in surface water, although GIS have been used to undertake groundwater flow modeling: Biesheuvel and Hemker (1993) linked the finite element groundwater flow model MICRO-FEM with the Integrated Land and Water Information System (ILWIS) GIS through the exchange of files which were in drawing exchange format (DXF) and by Lieste et al. (1993) who coupled the finite element ground-

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water model AQ-FEM with ARC/INFO to develop a groundwater model for The Netherlands. The groundwater models developed so far within a GIS framework have used propietary software; which is why the module `r.gmtg` was developed using the GRASS GIS and MODFLOW which are both open source software. This module falls between a linkage and an integration as the user runs it from the GRASS command line without interacting with MODFLOW as the module takes care of this; however, the module writes the ASCII files required by MODFLOW and then imports its output into GRASS as raster maps.

2 Groundwater Flow Modeling with MODFLOW

Different programs are currently available for groundwater flow simulations; however, the decision was made to link GRASS with the finite difference groundwater flow program MODFLOW (Harbaugh and McDonald, 1996; McDonald and Harbaugh, 1988). Because the idea behind GMTG development was to develop a free tool for users whom can not afford the commercial MODFLOW processors or even commercial compilers, it currently supports MODFLOW-96 as this is the latest version which can be compiled with the g77 compiler. The g77 compiler is available for free from the Internet (http://gcc.gnu.org/) and is provided on Linux distributions.

MODFLOW was the chosen groundwater flow model for the following reasons: its source code is available on the internet, allowing it to be customized; it has extensive modeling capabilities which allow simulation of transient, multi-aquifer systems, and it is widely used and accepted. This last argument is supported by the number of publications available that have used MODFLOW to analyze groundwater flow such as the special number of the GROUND WATER journal (Vol 41,

No 2). In addition MODFLOW has been used not only in the US but also in many other countries.

The advantage of MODFLOW is that it provides different modules to undertake 3-D groundwater flow simulations in confined and unconfined aquifers as well as in aquifers with variable confinment with both constant and variable transsmisivity values. The modules provided by MODFLOW can be used to simulate the effect on an aquifer system caused by different stresses such as the presence of extraction and/or injection wells, of aereal distribution of recharge and/or evapotranspiration or of different hydrological features such as rivers, drains (e.g. springs) and lakes. Due to its open source nature, new modules can be created in FORTRAN if needed; its portability has also played a crucial part in its popularity, as its source code can be compiled in different operating systems.

Although MODFLOW is a powerful program, it is far from being a user friendly application, which has fostered the development of different pre and post-processors (refered to as processors in the remainder part of the paper) which are available at different costs. Some of these processors are: Processing MODFLOW for Windows (PMWIN) (Chiang, 2001), UNCERT (Wingle et al., 1999), Groundwater Vistas (`www.groundwater-vistas.com`), Visual MODFLOW (`www.visual-modflow.com`) and the Groundwater Modelling System (`www.ems-i.com`). However, these processors can not be used within a GIS, and whenever GIS data need to be used to develop a groundwater flow model they need to be imported into these processors.

2.1 MODFLOW's inputs and outputs

MODFLOW's input has to be provided in different files in a very specific format. For a simple simulation five different files are needed, namely NAM, BAS, BCF,

PCG2 and OC. The NAM (NAMe) file is the main file used by MODFLOW as it instructs it where data related to a specific package are to be found. The basic (BAS) file provides data on boundary conditions (e.g. constant head, inactive or active cells) while the BCF (Block Centered Flow) file has data pertaining the number and type of layers to be modeled, row and column widths. The PCG2 (Hill, 1990) file has intructions for the Preconditioned Conjugate-Gradient solver method such as maximum number of inner and outer iterations per time step and convergence criterion. The Output Control (OC) file has information regarding the files on which heads and drawdowns are to be saved and if they are to be saved or printed. If a simulation with wells (extraction or injection), rivers and recharge is to be undertaken, additional files such as the Well (WEL), river (RIV), recharge (RCH) are needed as they provide information regarding location of wells and extraction rates; conductance, stage and elevation of rivers or aereal recharge distribution. All required documentation regarding the format of each file and array used by MODFLOW is provided in McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). The fact that data are available as GIS coverages from governmental agencies or vendors and that GIS are used to process and analyze georeferenced data makes them efficient tools to process the data required in a groundwater model.

2.2   Geographic Information Systems and MODFLOW

The spatial variability of the data required in groundwater modeling makes the use of GIS an evident step; unfortunately the GIS processors developed so far are not commonly used which can be explained by the fact that they are not available to download. Some authors such as Brodie (1999) have used a GIS to process all data required in a regional groundwater flow model and then import them into a MODFLOW processor; this requires exporting the data from the GIS, importing

it into the MODFLOW processor, running the simulation, exporting the resulting files from the processor and importing them into the GIS. This procedure makes it obvious that if data is being handled within a GIS it would also be efficient to run a groundwater simulation from within the GIS, which would not require importing and exporting data for each simulation. To avoid file transfers required by non-GIS processors, different authors have linked a GIS with MODFLOW: Orzol (1997) developed a MODFLOW processor which works with ARC-INFO through the use of FORTRAN and the Arc Macro Language (AML), Shapiro et al. (1997) developed a processor for MODFLOW using the Argus GIS. The GIS that have been linked with MODFLOW so far are proprietary software which are not as flexible as GRASS as it is not possible to access their source code.

3   The GRASS GIS

GRASS was originally developed in 1985–1995 at the U.S. Army Construction Engineering Research Laboratory (CERL) in Champaign, Illinois to support land management at military installations (Neteler and Mitasova, 2004). After CERL stopped its development in 1995, Baylor University continued GRASS' development and made available the version 4.2 in 1997. The development of GRASS is now in the hands of people who have collaborated on this Open Source project, which had made GRASS 6.0 possible in March, 2005 and which can be downloaded at GRASS' website (`http//grass.itc.it`). This latest version of GRASS provides tools for raster, vector and point analysis as well as three dimensional visualization and image processing.

The open source nature of GRASS allows it to be customized according to each user's needs. Schultz (1993) classified GIS as a function of their flexibility and ac-

cording to his classification, the GIS which ranked the highest was GRASS. He stated that its flexibility makes it a suitable GIS to be applied to the treatment of complex hydrological problems. GRASS flexibility resides in the accessibility of its code, which is written in ANSI C, avoiding the necessity of learning a different programming or GIS-specific macro language to write new modules. The accessibility of GRASS' code allows any user to modify or add modules to its official distribution. The advantage of this approach is that well documented modules can be added to the latest release of GRASS and eventually be part of the official distribution. This is the case for different modules such as `r.sun` (Súri and Hofierka, 2004) which computes radiation from a georeferenced DEM and `r.terraflow` (Arge et al., 2003) which is used for flow routing and flow accumulation in massive grids.

3.1 GRASS in hydrological modelling

The GRASS GIS provides powerful modules to analyze raster, vector and point data as well as satellite imagery. Its capabilities are not limited to the modules that form part of its official distribution, as external programs can be linked to it. GRASS provides different tools that can be used in hydrological modeling such as interpolation of point data through the `r.surf.rst` module (Mitasova and Mitas, 1993). In addition, the statistical package GSTAT (Pebesma and Cees, 1998) can be used within GRASS or as part of the R package (Pebesma, 2004; Ihaka and Gentleman, 1996) which also provides more tools for statistical analysis. The advantage of using R with GRASS is that statistical analysis of data stored both in the GIS database and in an external database such as PostgreSQL (Bivand, 2000) can be undertaken.

Different authors have used GRASS in hydrological modelling: Kunkel and Wendland (2002) used it to analyze the long-term average water balance in the German part of the Elbe river, Watson et al. (2000) used GRASS to investigate the influence of parameter mapping in predictions of water yield made by spatial models, while Krysanova et al. (1998) used GRASS to develop the watershed module SWIM, which integrates hydrology, vegetation, erosion and nitrogen dynamics at the watershed scale. The official GRASS distribution includes different modules for hydrological modelling such as `r.water.fea` (Vieux et al., 1990) which simulates storm water run-off using finite element analysis, `r.hydro.CASC2D` (Julien et al., 1995) which is a physically based raster hydrologic model. Additional hydrological models are SWAT (Arnold et al., 1993) and TOPMODEL (Beven et al., 1984), which can be compiled and run within GRASS.

The use of GRASS in groundwater modelling has been more limited but there are some examples available: Batelaan et al. (1993) developed a C program using GRASS' library functions in order to simulate a particular aquifer represented by a one layer model; they also wrote a FORTRAN program to simulate a three layer model which communicated with GRASS through a non-automated procedure; however, no attempt has been made of integrating GRASS with MODFLOW in order to develop large scale groundwater flow models.

4 GMTG implementation

The idea of integrating GRASS with a groundwater flow model originated from the fact that although GRASS has tools for hydrological modelling, this is not the case for groundwater flow models. The idea was to integrate an existing groundwater flow model with GRASS in order to take advantage of its data manipulation and

analysis capabilities.

GRASS is run under Linux and MODFLOW can be compiled on this operating system through the g77 FORTRAN compiler. The integration of both programs was required because of the strict format required by MODFLOW. Developing a groundwater flow model using the `r.ascii.out` module is tedious and error-prone as it implies transfering multiple files which have to be inserted in MODFLOW's required format. Through the `r.gmtg` module the available GRASS modules can be used to develop groundwater flow models instead of learning another software in which GIS data are imported to run a MODFLOW simulation and then exported after the simulation has been run. The module `r.gmtg` is run from the GRASS' command line and uses data stored in raster and sites (e.g. point data) maps together with data entered by the user. The data that have to be typed in by the user are data regarding the simulation (e.g. number of layers in the model, type of aquifer to model, number of stress periods, etc). The integration achieved with the `r.gmtg` module between GRASS and MODFLOW is illustrated in Figure 2, in which the GRASS database is enclosed by a dashed line; it also shows that once the simulation is finished, the module imports drawdowns and heads into GRASS as raster maps.

The parameters needed to run a groundwater simulation using `r.gmtg` are displayed when the user types `r.gmtg -help` from within GRASS. The way in which `r.gmtg` is used is as follows:

```
r.gmtg simulation=value units=value layers=value
aqtype=value[,value,...] stress=value length=value[,value,...]}
steps=value[,value,...] [tsmult}={name[,name,...]] region}=name[,name,...]
heads}=name[,name,...] [Sy=name[,name,...]] [T=name[,name,...]]
[K=name[,name,...]] [bottom=name[,name,...]] [vcond=name[,name,...]]
```
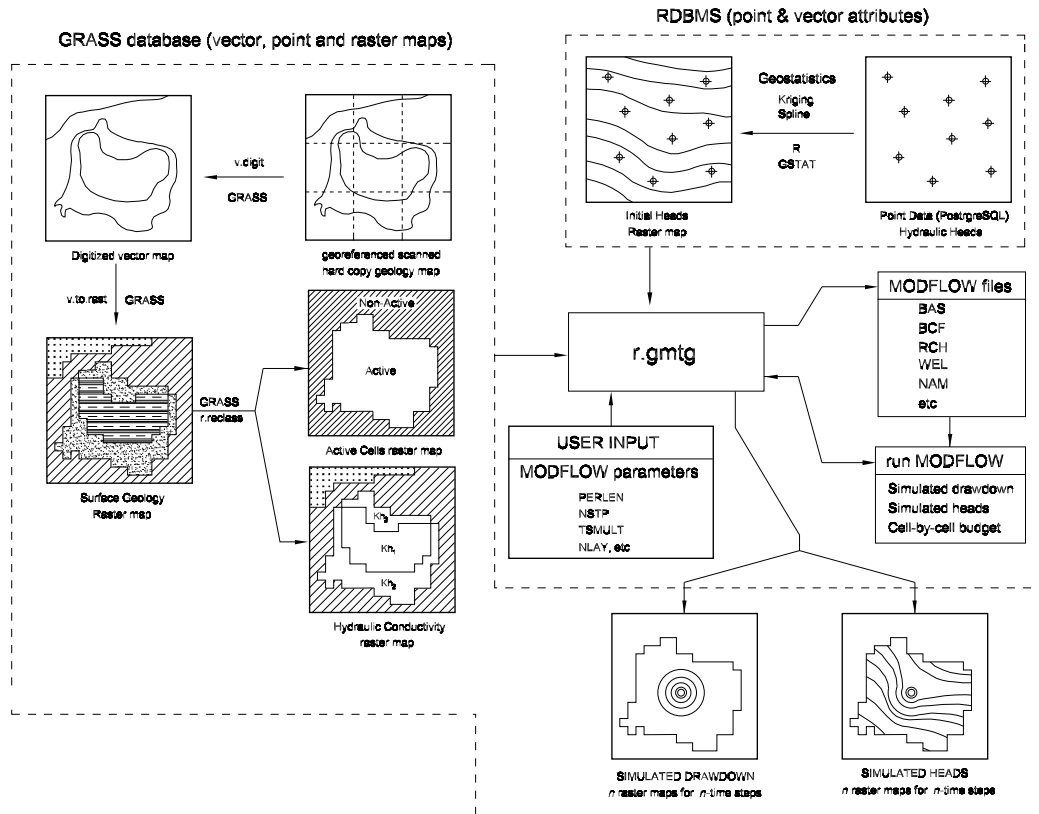
Fig. 2. Interaction of r.gmtg with GRASS and MODFLOW

```
[top=name[,name,...]] [Syb= name[,name,...]] [recharge=name[,name,...]]

[wells}= name[,name,...]] [river\_heads}=name] [river\_cond}=name]

[river\_elev= name] [drain= name[,name,...]] drawdownin=name headsin= name
```

In the previous statement, the parameters delimited by brackets are optional, depending on the type of simulation run. The parameters are explained in Table 1, which also shows the values and maps used to run the simulations presented subsequently and used to validate the r.gmtg module.

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Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1		Case 2
			Steady	Transient	
simulation	Type of simulation	0 = Transient 1 = Steady state	1	0	1
units	Time units	1 = Seconds 2 = minutes 3 = hours 4 = days	4	4	4

Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1 Steady	Case 1 Transient	Case 2
		5 = years			
layers	Number of layers in the model	int number	1	1	3
aqtype	Type of aquifer	0 = Confined 1 = Unconfined 2 = Variable with constant T 3 = Variable with variable T	1	1	1,3,3

Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1		Case 2
			Steady	Transient	
stress	Number of stress periods	int number	1	2	1
length	Length of each stress period	int number	1	240,120	1
steps	Number of time steps for each stress period	int number	1	12,6	1
tsmult	Time step multiplier for each stress period	float number	1	1,1	1
region	Name of raster map with active cells	string	boundaries	boundaries	active.1
					active.2
					active.3

Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1 Steady	Case 1 Transient	Case 2
heads	Name of raster map with initial heads	string	iheads	hd.lay1.stp1.tst1	iniheads.1
					iniheads.2
					iniheads.3
Sy	Name of existing raster map(s) with primary storage coefficient values	string		Sy	
T	Name of existing raster map(s) with Transmissivity. REQUIRED for CONFINED aquifers or VARIABLE confinment aquifers with CONSTANT T	string			

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Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1		Case 2
			Steady	Transient	
K	Name(s) of existing raster map(s) with Horizontal Conductivity. Required for UNCONFINED aquifers and VARIABLE confinment aquifers with VARIABLE T	string	H.conductivity	H.conductivity	hk.1
					hk.2
					hk.3
bottom	Name of an existing raster map with aquifer bottom. Required for unconfined and variable aquifers with variable T	string			top.2

Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1		Case 2
			Steady	Transient	
					top.3
					bot.3
top	Name of an existing raster map with Top of aquifer	string	top.2		top.3
vcond	Name of an existing raster map with Vertical conductance	string	vcond.1		vcond.2

Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1		Case 2
			Steady	Transient	
Syb	Name of an existing raster map with Secondary Storage Values	string			
recharge	Name of an existing raster map with recharge values	string	recharge.1	rch.1, rch.2	
wells	name of sites file(s) containing WELL data	string	cst.flux	wells,cst.flux	wells2
river_heads	Name of raster map with stage values for reaches	string			river.head
river_cond	Name of raster map containing conductance values for reaches	string			river.cond

Table 1: Parameters needed to run a simulation using r.gmtg

Parameter	Description	Value	Case 1 Steady	Case 1 Transient	Case 2
river_elev	Name of the raster map containing river-bed elevation values	string	river.bed		
drain	Name of site map(s) containing drain data	string			
drawdownin	Name of raster map for DRAWDOWN simulation values	string	dd	hdtr	ddtest
headsin	Name of raster map for HEAD simulation values	string	hd	hdtr	hdtest

The MODFLOW source code available at the USGS web site (http://water.usgs.gov/nrp/gwsoftware/modflow.html) required one modification as it prompts the user for a NAM file which specifies the packages used for the simulation as well as their location. This had to be changed in order for MODFLOW to automatically look for the .NAM file written by r.gmtg without requiring interaction from the user. The modified MODFLOW version is available at the GMTG's web site.

5 GMTG examples and validation

This section will use two cases to illustrate and validate the r.gmtg module. The cases considered provide different simulation conditions which might be faced whenever developing a regional groundwater flow model. These cases are: 1) Steady state and transient simulation of a one-layer unconfined aquifer and 2) Steady state simulation of a two aquifer system represented by three layers with a river on the upper most layer. Although these are simple models they prove that r.gmtg can be used for any type of groundwater flow simulation. The data required by each of these examples are enumerated on table 1 along with their respective description.

5.1 One layer unconfined aquifer

The first example consists of a steady state simulation of an unconfined aquifer with a constant head boundary at the north and a constant flux boundary at the south as illustrated in Figure 3.

This first example is divided in two parts: The first part consists of a steady-state model using a constant areal recharge. To clarify the data required to use the r.gmtg module refer to table 1. The example is run from within GRASS as follows:
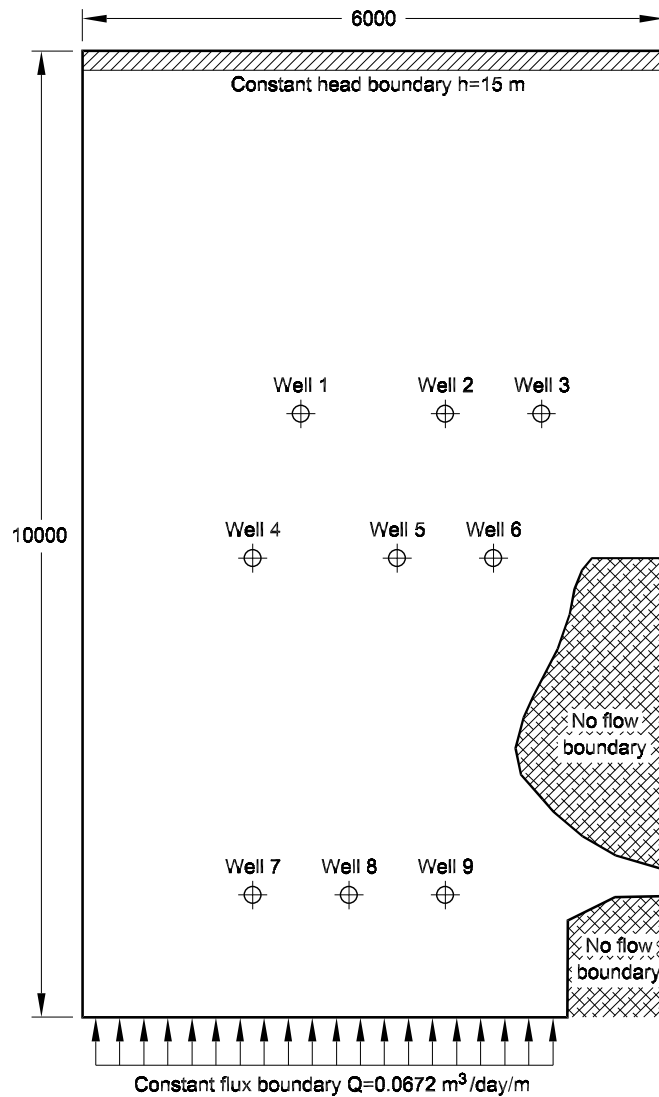
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Fig. 3. Modeling domain for the unconfined, one-layer model; adapted from Chiang (2001)

```
GRASS:˜ > r.gmtg simulation=1 units=4 layers=1 aqtype=1 stress=1
length=1 steps=1 tsmult=1 region=boundaries heads=initial.heads
K=H.conductivity bottom=bottom recharge=recharge wells=cst.flux
drawdownin=dd headsin=hd
```

Once MODFLOW has been run, the simulated head is saved on the raster map *hd.lay1.stp1.tst1* where *hd* is the name entered for the option headsin in r.gmtg (or dd for drawdown). The remaining parts of the file name are generated automati-

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cally to facilitate the task of reading the results of each simulation: hd.lay1.stp1.tst1 means that this map shows the head at layer 1, for stress period (stp) 1 at time step (tst) 1.

Transient simulation: The resultant heads from the steady state simulation are used as input in the transient simulation. Whenever transient simulations are undertaken, data for each stress period need to be specified. This applies to any stress applied in the modeling domain such as recharge and pumping rates. In this case there are two stress periods: Stress period one has a uniform areal recharge which is stored in the raster map rch.1; the second stress period has null recharge (0 m/day), a value that is stored in raster map rch.2. This is an important aspect, as if more than one stress period is used, data for each of them have to be entered even if extraction or recharge is equal to zero. The remainding data used for the transient simulation are shown in Table 1 and are used in the simulation as follows:

```
GRASS:~> r.gmt simulation=0 units=4 layers=1 aqtype=1 stress=2
length=240,120 steps=12,6 tsmult=1,1 region=boundaries
heads=hd.lay1.stp1.tst1 K=H.conductivity Sy=Sy bottom=bottom
recharge=rch.1,rch.2 wells=wells,cst.flux drawdownin=ddtr headsin=hdtr
```

In this case the resultant heads and drawdowns are saved on the raster files hdtr.lay1.stp1.tst1 and ddtr.lay1.stp1.tst1 respectively. It can be noted that for each stress period data for both recharge and wells are specified.

5.2   *Three layer aquifer*

This example is also taken from Chiang (2001) and comprises a two aquifer system with a clayey layer between them as well as constant head boundaries at both east
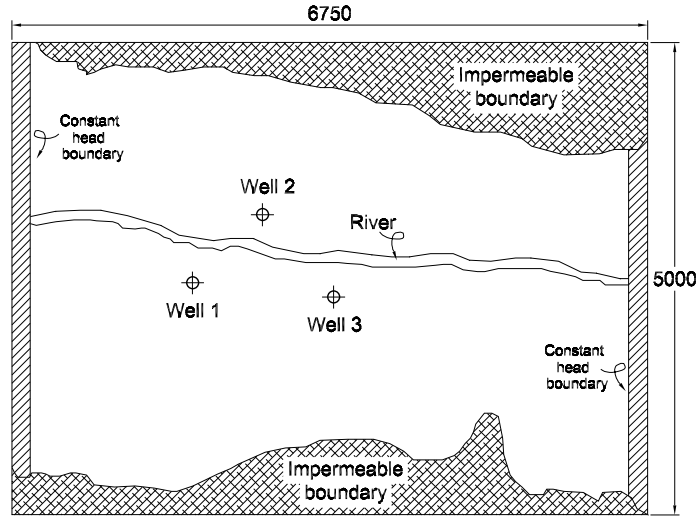
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Fig. 4. Modeling domain for the three layer model; adapted from Chiang (2001)

and west. The problem also includes a river which flows eastwards while three wells extract water from the confined aquifer as shown in Figure 4.

To simulate the river interaction with the aquifer system, data regarding location, conductance and stage of river are needed. The river conductance, which is obtained by using equation 1 can be computed with map algebra with the `r.mapcalc` module in order to determine its spatial variation on the modeling domain.

$$C_{riv} = \frac{K \times L \times W}{M} \tag{1}$$

Where C_{riv} is river conductance, K represents the hydraulic conductance of the riverbed sediment, M the thickness of the riverbed sediment, while L and W represent, respectively the length and width of the river within a cell. The simulation is run by typing the following at the GRASS' command line using the data of Table 1:

```
GRASS:~/tutorial2 > r.gmtg simulation=1 units=4 layers=3 aqtype=1,3,3
stress=1 length=1 steps=1 tsmult=1 region=active,active,active
heads=initial.heads,initial.heads,initial.heads K=hk.1,hk.2,hk.3
```

```
bottom=top.2,top.3,bot.3 top=top.2,top.3 vcond=vcond.1,vcond.2
wells=wells river_heads=river.head river_cond=river.cond
river_elev=river.bed headsin=hdtest drawdownin=ddtest
```

The resulting heads from this simulation are stored in the raster maps *hdtest.lay1.stp1.tst1, hdtest.lay2.stp1.tst1 and hdtest.lay3.stp1.tst1* as it is a steady state simulation with three layers; if more than one stress period or time step is used, stp1 and tst1 are automatically modified to facilitate the interpretation of each simulation, as shown in the previous example.

5.3   Validation

The two examples used in this paper illustrate that `r.gmtg` can be used to model both steady state and transient simulations as well as multilayer systems. To validate these results, they are compared with those obtained when PMWIN (Chiang, 2001) was used to solve the same problems. The simulations for the first case (unconfined aquifer for both steady state and transient simulations) obtained with `r.gmtg` are shown in Figure 5 while those obtained with PMWIN are in Figure 6.

The results shown in Figure 5 and 6 are very similar. To analyze in detail the difference between these simulations, an absolute difference map was created in order to visualize the areal distribution of differences between as shown in Figure 7. This figure illustrates that the difference between the two processors is caused by the use of different FORTRAN compilers and that the highest difference is near the right hand side on the maps which is caused by the use of different non-active areas.

The results of the simulation of the three layer steady state model (case 2) between r.gmtg and PMWIN are compared in Figure 8.
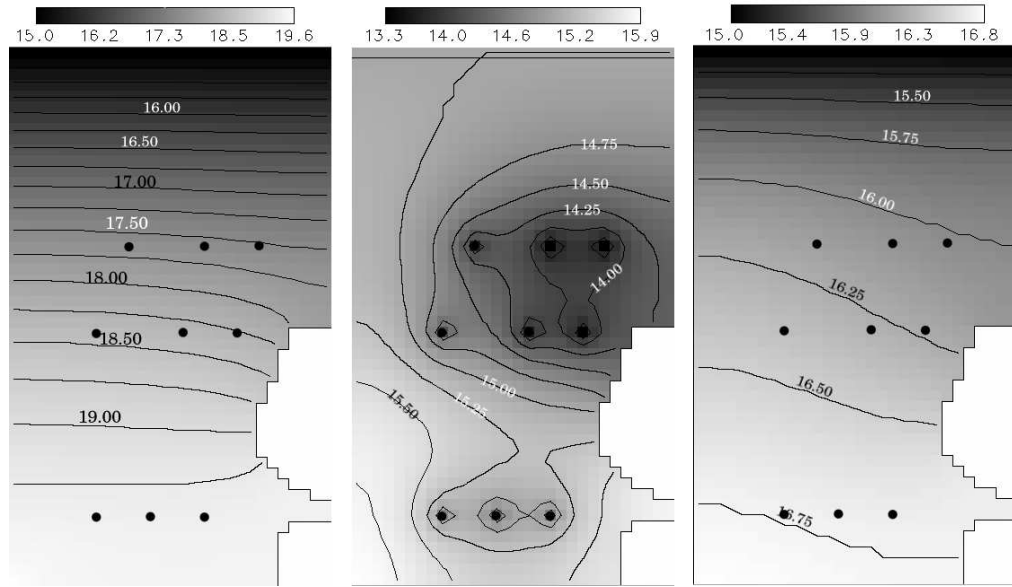
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(a) Steady state simulation heads   (b) Transient heads for stress period 1, time step 12   (c) Transient heads for stress period 2, time step 6

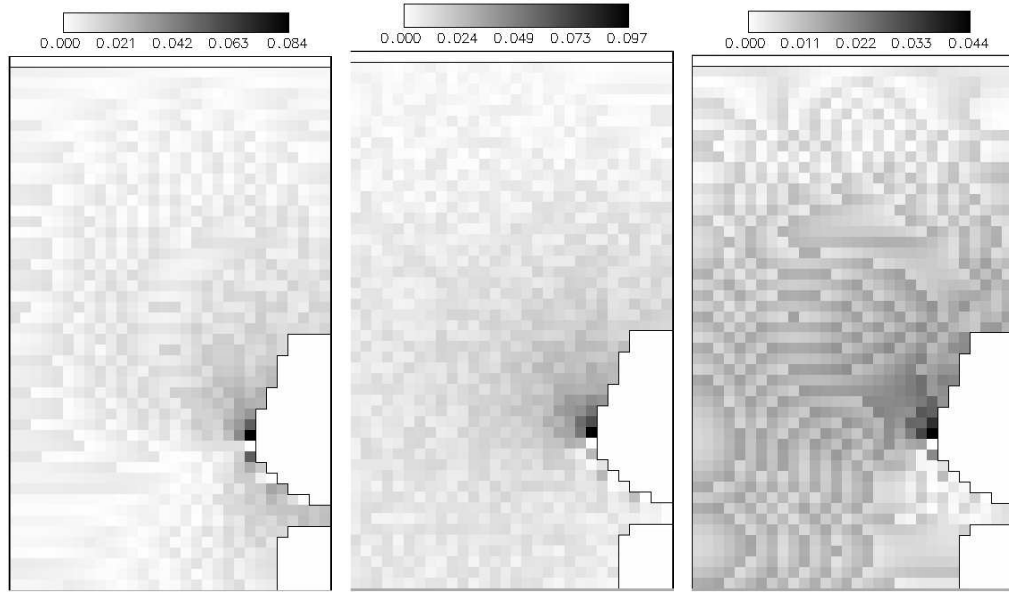Fig. 5. Simulation results obtained with GMTG for case 1
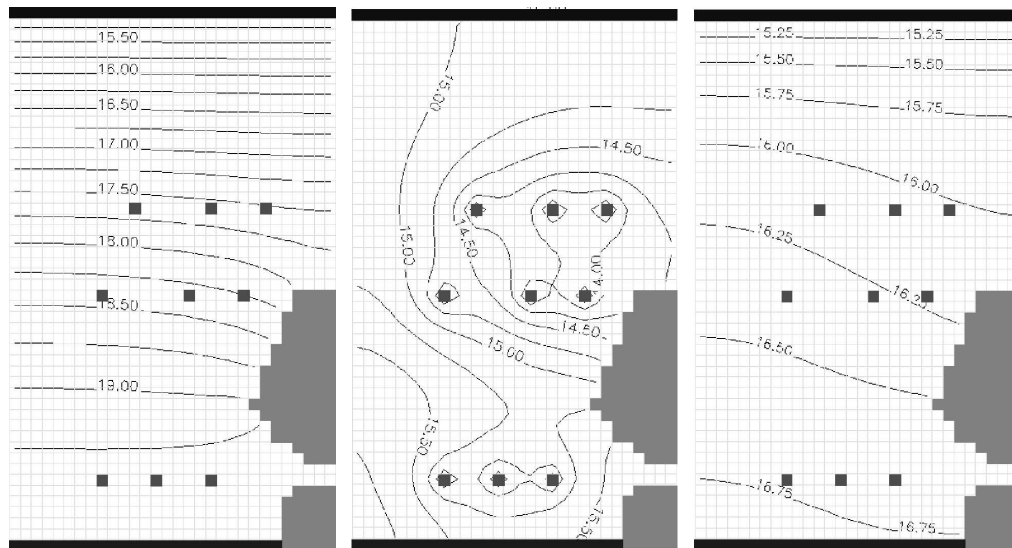
(a) Steady state simulation heads   (b) Transient heads for stress period 1, time step 12   (c) Transient heads for stress period 2, time step 6

Fig. 6. Simulation results obtained with PMWIN for case 1

6 Discussion

The results obtained with the `r.gmtg` module are the same as those obtained by using PMWIN, which proves that groundwater flow models can now be developed

(a) Steady state simulation heads (b) Transient heads for stress period 1, time step 12 (c) Transient heads for stress period 2, time step 6

Fig. 7. Absolute difference between the simulations obtained with GMTG and PMWIN
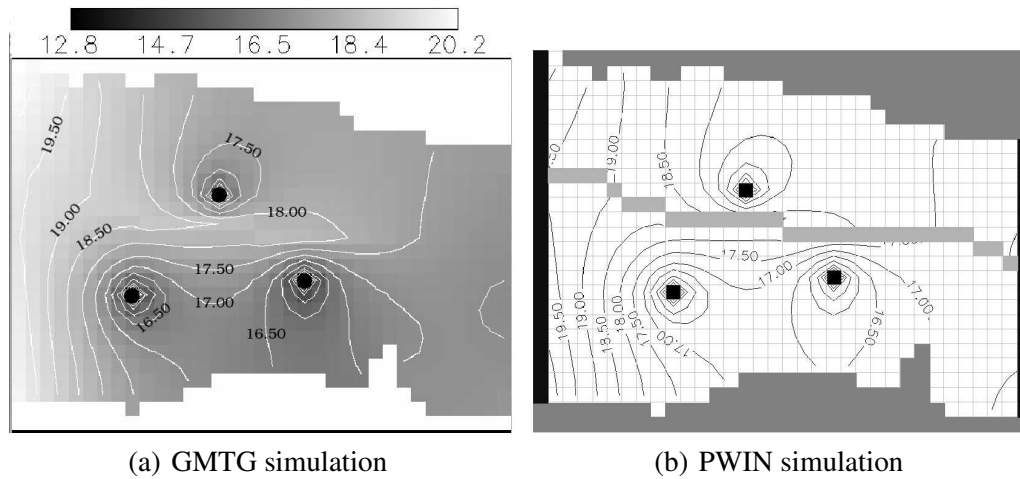
(a) GMTG simulation (b) PWIN simulation

Fig. 8. Simulation results for the steady-state, three layer model; heads in layer 1

within the GRASS GIS. One drawback of `r.gmtg` is that it uses GRASS' raster structure to read MODFLOW's output, which results in cells which have constant width (i.e. x and y directions) throughout the modeling domain. This limitation does not apply to the z direction, as variable height can be specified for each cell.

The `r.gmtg` module does not automatically compute the vertical conductance values required for 3-D modelling in MODFLOW, but it can be easily computed using
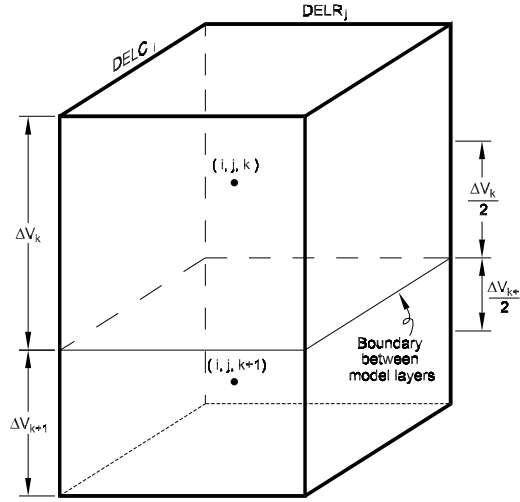
Fig. 9. Vertical conductance variables, adapted from McDonald and Harbaugh (1988)

the `r.mapcalc` module according to equation 2. The VCONT array is used to compute the vertical conductivity between two vertically-adjacent layers, considering their thickness and vertical conductivity, as illustrated in Figure 9.

$$VCONT_{(i,j,k+1/2)} = \frac{2}{\frac{\Delta V_k}{(K_z)_{i,j,k}} + \frac{\Delta V_{k+1}}{(K_z)_{i,j,k+1}}} \qquad (2)$$

Any type of raster map can be used as input for `r.gmtg`; however when a simulation with wells or drains is required, data have to be in a specific order. For wells, data should be in the following order:

```
Easting Northing Layer Flow ID
```

while for drains, the format is as follows:

```
Easting Northing Layer Elevation Conductance ID
```

It is worth noting that commercial MODFLOW processors provide access to more of MODFLOW's modules; however they are very expensive and the user has to import and export all the GIS-processed data. The `r.gmtg` module provides an accessible tool which: 1) Is available free of charge, 2) its open source nature pro-

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vides access to its code and 3) uses GIS data directly. This module is intended to take advantage of GRASS' capabilities to both manipulate and analize data, thus it is better suited for the simulation of regional groundwater flow models which are developed using georeferenced data. The simulation results, which are stored in GRASS' database can be queried on specific locations using coordinates, offering the possibility of storing the result of these queries in an external database (e.g. PostgreSQL) in order to compare the simulated values with those measured at observation wells.

The advantages of using the `r.gmtg` module can be summarized as:

- The Development of Digital Elevation Maps or thematic maps (e.g. surface geology or land cover) is possible through GRASS' interpolation and digitizing modules.
- 3-D visualization and animation is possible through the NVIZ module with which different layers can be simultaneously visualized (e.g. land cover superimposed on topography together with different groundwater table elevations and well locations).
- It provides easy access to data stored on Relational Database Management Systems.
- It can linked with other Open Source tools for different tasks such as R for statistical analysis.
- It provides a free groundwater flow modelling tool for users who can not afford the commercially available processors.

7 Conclusions

Geographic Information Systems are powerful tools which are used to handle geo-referenced data and can be used to develop models with high data requirements. The GRASS GIS is an open-source GIS to which different hydrological models have been linked or integrated because of its code accesibility. The decision of integrating MODFLOW with GRASS was taken on the grounds of portability and accesibility: both programs are open-source and portable, which in consequence allows any user to modify their source code; an aspect that is not possible in proprietary software. The `r.gmtg` module is also available at the GMTG web page (http://grass.gdf-hannover.de/twiki/bin/view/GRASS/JaimeCarrera) and accessible to any interested user. In order to take full advantage of the `r.gmtg` module the user should be familiar with the GRASS GIS; the advantage of Open Source projects such as GRASS is that they provide mailing lists for user support and tutorials. The interested reader is encouraged to explore GRASS' capabilities on its web site or consult Neteler and Mitasova (2004) in order to learn the use of GRASS. The examples used in this paper show that `r.gmtg` can be used to simulate steady-state and transient three dimensional groundwater flow for confined and/or unconfined aquifer systems, using GRASS' capabilities to both analyze and display data.

References

Arge, L., Chase, J. S., Halpin, P., Toma, L., Vitter, J. S., Urban, D., and Wickremesinghe, R. (2003). Efficient flow computation on massive grid terrain datasets. *Geoinformatica*, 7(4):283–313.

Arnold, J. G., Allen, P. M., and Bernhardt, G. (1993). A comprehensive surface-ground water flow model. *J. of Hydrology*, 142(1–4):47–69.

Batelaan, O., De Smedt, F., and Otero-Valle, M. (1993). Development and application of a groundwater model integrated in the GIS GRASS. In *HydroGIS 93: Application of Geographic Information Systems in Hydrology and Water Resources (Proceedings of the Vienna Conference, April, 1993)*, IAHS Publication No. 211, pages 580–589.

Beven, K. J., Kirkby, M. J., Schoffield, N., and Tagg, A. (1984). Testing a physically based flood forecasting model (TOPMODEL) for three uk catchments. *J. of Hydrology*, 69:119–143.

Biesheuvel, A. and Hemker, C. J. (1993). Groundwater modelling and GIS: integrating MICRO-FEM and ILWIS. In *HydroGIS 93: Application of Geographic Information Systems in Hydrology and Water Resources (Proceedings of the Vienna conference, April 1993)*, IAHS Publication 211.

Bivand, R. S. (2000). Using the R statistical data analysis language on GRASS 5.0 GIS database files. *Computers & Geosciences*, 26:1043–1052.

Brodie, R. S. (1999). Integrating GIS and RDBMS technologies during construction of a regional groundwater model. *Env. Modelling Software*, (14):119–128.

Chau, K. T., Sze, Y. L., Fung, M. K., and Wong, W. Y. (2004). Landslide hazard analysis for Hong Kong using landslide inventory and GIS. *Computers & Geosciences*, 30:429–443.

Chiang, W. H. (2001). *3-D groundwater modeling with PMWIN*. Springer Verlag.

Gurnell, A. M. and Montgomery, D. R. (2000). *Hydrological Applications of GIS*. Wiley.

Harbaugh, A. W. and McDonald, M. G. (1996). *User's documentation for MODFLOW-96 an update to the U.S. Geological Survey modular finite-difference groundwater flow model*. U.S. Geological Survey, Open-file report 96-485.

Herborg, L. M., Bentley, M. G., Clare, A. S., and Rushton, S. P. (2003). The spread of the Chinese mitten crab (Eriocheir sinensis) in Europe; the predictive value of an historical data set. *Hydrobiologia*, 503:21–28.

Hill, M. C. (1990). *Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations*. U.S. Geological Survey, Water Resources Investigations Report 90-4048.

Ihaka, R. and Gentleman, R. (1996). R: a language for data analysis and graphics. *J. of Computational and Graphical Statistics*, 26:299–314.

Julien, P. Y., Saghafian, B., and Ogden, F. L. (1995). Raster-based hydrological modeling of spatially-varied surface runoff. *Water Resources Bulletin*, 31(3):523–536.

Krysanova, V., Müller-Wohlfeil, D. I., and Becker, A. (1998). Development and test of a spatially distributed hydrological/water quality model for mesoscale watersheds. *Ecological Modelling*, 106:261–289.

Kunkel, R. and Wendland, F. (2002). The GROWA98 model for water balance analysis in large river basins - the river Elbe case study. *J. of Hydrology*, 259:152–162.

Lieste, R., Kovar, K., Verlouw, J. G. W., and Gan, J. B. S. (1993). Development of the GIS-based RIVM national groundwater model for the Netherlands. In *HydroGIS 93: Application of Geographic Information Systems in Hydrology and Water Resources (Proceedings of the Vienna Conference, April, 1993)*, IAHS

Publication No. 211, pages 641–652.

Lyon, J. G., editor (2003). *GIS for Water Resources and Watershed Management*. Taylor and Francis.

McDonald, M. G. and Harbaugh, A. W. (1988). *A modular, three dimensional finite difference groundwater flow model*. USGS Techniques of Water Resources Investigation Report.

Mitasova, H. and Mitas, L. (1993). Interpolation by regularized spline with tension: I. theory and implementation. *Math. Geol.*, 25:641–655.

Neteler, M. and Mitasova, H. (2004). *Open Source GIS: A GRASS GIS approach*. The Kluwer international series in engineering and computer science. Kluwer Academic Press, 2nd edition.

Orzol, L. L. (1997). *User's guide for MODTOOLS: Computer programs for translating data of MODFLOW and MODPATH into geographic information system files*. U. S. Geological Survey Open File Report 97-240.

Pebesma, E. J. (2004). Multivariable geostatistics in S: the gstat package. *Computers & Geosciences*, 30:683–691.

Pebesma, E. J. and Cees, G. W. (1998). GSTAT: a program for geostatistical modelling, prediction and simulation. *Computers & Geosciences*, 24(1):17–31.

Rushton, S. P., Lurz, P. W. W., Fuller, R., and Garson, P. J. (1997). Modelling the distributions of the red and grey squirrel at the landscape scale: A combined GIS and population dynamics approach. *J. of Applied Ecology*, 34:1137–1154.

Schultz, G. A. (1993). Application of GIS and remote sensing in hydrology. In *Application of Geographic Information Systems in Hydrology and Water Resources Management*, IAHS Publication No. 211.

Shapiro, A. M., Margollin, J., Dolev, S., and Ben-Israel, Y. (1997). *A graphical user interfacie for the U. S. Geological Survey Modular Three dimensional finite difference groundwater flow model (MODFLOW-96) using Argus Numerical En-*

vironments. U. S. Geological Survey Open File report 97-121.

Súri, M. and Hofierka, J. (2004). A new GIS-based solar radiation model and its application to photovoltaic assessments. *Transactions in GIS*, 8(2):175–190.

Vieux, B. E., Bralts, V. F., Segerling, L. J., and Wallace, R. B. (1990). Finite element watershed modeling: One dimensional elements. *J. of Wat. Res. Plann. and Manag.*, 116(6):803–819.

Waters, N. M. (1999). Transportation GIS: GIS-T. In Longley, P. A., Goodchild, M. F., Maguire, D. J., and Rhind, D. W., editors, *Geographical Information Systems: Management Issues and Applications*, pages 827–844. Wiley and Sons.

Watkins, D. W., McKinney, D. C., and Maidment, D. R. (1996). Use of geographic information systems in groundwater flow modeling. *J. of Wat. Res. Plann. and Manag.*, 122(2):88–96.

Watson, F. G. R., Grayson, R. B., Vertessy, R. A., and McMahon, T. A. (2000). Large scale distributed modelling and the utility of detailed ground data. In Gurnell, A. M. and Montgomery, D. R., editors, *Hydrological Applications of GIS*, pages 53–68. Wiley and Sons.

Wingle, W. L., Poeter, E. P., and McKenna, S. A. (1999). UNCERT: geostatistics, uncertainty analysis and contaminant transport modeling. *Computers & Geosciences*, 25:365–376.