

The groundwater modeling tool for GRASS (GMTG): Open source groundwater flow modeling[☆]

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Received 6 April 2005; received in revised form 22 June 2005; accepted 24 June 2005

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 cannot afford the commercially available processors and/or to those who wish to develop their models within a GIS.

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Keywords: MODFLOW; GRASS; Geographic Information Systems; Groundwater modeling

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

[☆]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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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 Montgomery (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 Fig. 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 groundwater 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 proprietary 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). The idea behind GMTG was to develop a free tool for users who cannot afford the commercial MODFLOW processors or even commercial compilers. Accordingly, GMTG supports MODFLOW-96 as this is the latest version which can be compiled with the `g77` compiler. The `g77` compiler is the most recent FORTRAN compiler available for free from the Internet (<http://gcc.gnu.org/>).

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 confinement with both constant and variable transmissivity 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 areal 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

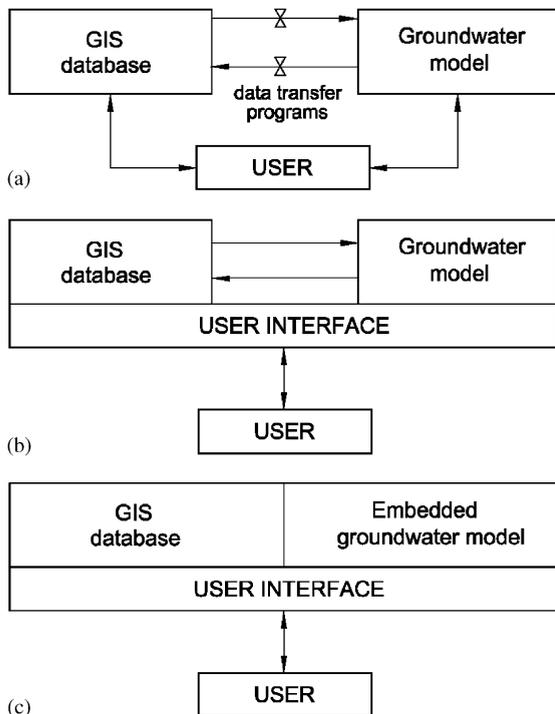


Fig. 1. Interaction of GIS with modeling software, adapted from Watkins et al. (1996).

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 (referred 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 Modeling System (www.ems-i.com). However, these processors cannot 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 Block Centered Flow (BCF) file has data pertaining the number and type of layers to be modeled, row and column widths. The PCG2 (Hill, 1990) file has instructions 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 areal 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 US 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 according 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 modeling

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 modeling: 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 modeling such as `r.water.fea` (Vieux et al., 1990) which simulates storm water run-off using finite element analysis and `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 modeling 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 modeling, 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 transferring 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 Fig. 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,...]]
[top = name[,name,...]] [Syb =
name[,name,...]]
[recharge = name[,name,...]]
```

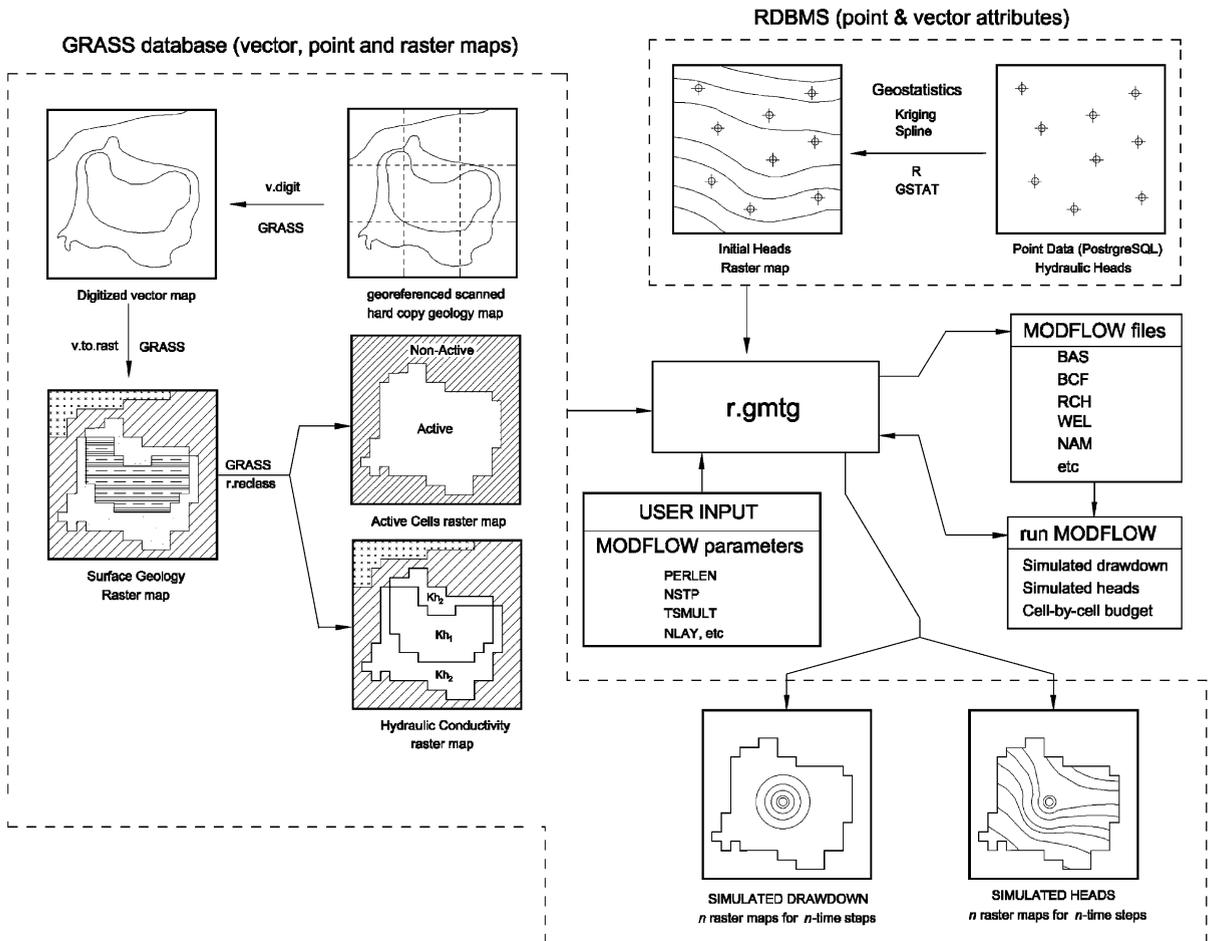


Fig. 2. Interaction of *r.gmtg* with GRASS and MODFLOW.

```
[wells = name[,name,...]]
[river_heads = name] [river_cond = name]
[river_elev = name] [drain =
name[,name,...]] drawdownin = name
headsins = 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.

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 Fig. 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:

```
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

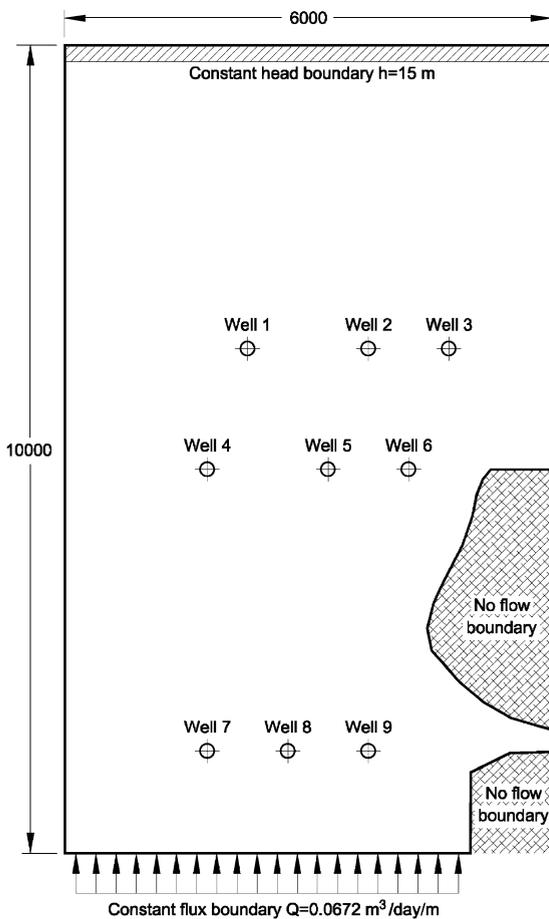


Fig. 3. Modeling domain for the unconfined, one-layer model; adapted from Chiang (2001).

name entered for the option `headsin` in `r.gmtg` (or `dd` for drawdown). The remaining parts of the file name are generated automatically 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 remaining data used for the transient simulation are shown in Table 1 and are used in the simulation as follows:

```
GRASS: ~> r.gmtg 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 and west. The problem also includes a river which flows eastwards while three wells extract water from the confined aquifer as shown in Fig. 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 Eq. (1) can be computed with map algebra through the `r.mapcalc` module in order to determine its spatial variation on the modeling domain.

$$C_{riv} = \frac{K \times L \times W}{M}, \quad (1)$$

where C_{riv} is river conductance, K represents the hydraulic conductance of the riverbed sediment, M the

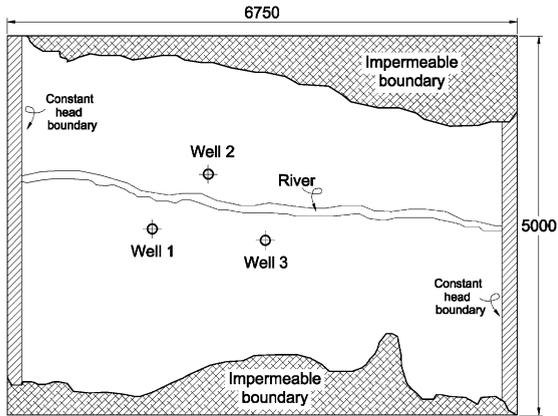


Fig. 4. Modeling domain for the three layer model; adapted from Chiang (2001).

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.1,active.2, active.3
heads = iniheads.1, iniheads.2,
iniheads.3 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 Fig. 5 while those obtained with PMWIN are in Fig. 6.

The results shown in Figs. 5 and 6 are very similar and map algebra was used to analyze in detail the difference between these simulations, which yielded a percentage difference less than .009%. The difference between the heads computed by GMTG and PMWIN is caused by the use of different FORTRAN compilers.

The results of the simulation of the three layer steady state model (case 2) between *r.gmtg* and PMWIN are compared in Fig. 7.

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 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 fact that the grid cannot be refined at specific points is not considered a serious drawback of the module, as most of the regional groundwater flow models developed so far have used a uniform grid size of up to 1 km. To overcome this problem a finer grid can be applied to the modeling domain.

The *r.gmtg* module does not automatically compute the vertical conductance values required for 3-D modeling in MODFLOW, but they can be easily computed using the *r.mapcalc* module according to Eq. (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 Fig. 8.

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

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.

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

Parameter	Description	Value	Case 1		Case 2	
			Steady	Transient	Steady	Transient
Simulation	Type of simulation	0 = Transient 1 = Steady state	1	0	1	1
Units	Time units	1 = Seconds 2 = minutes 3 = hours 4 = days 5 = years	4	4	4	4
Layers aqtype	Number of layers in the model Type of aquifer	int number 0 = Confined 1 = Unconfined 2 = Variable with constant <i>T</i> 3 =	1 1	1 1	3 1,3,3	
Stress Length Steps tsmult Region	Number of stress periods Length of each stress period Number of time steps for each stress period Time step multiplier for each stress period Name of raster map with active cells	Variable with variable <i>T</i> int number int number int number float number string	1 1 1 1 boundaries	2 240,120 12.6 1,1 boundaries	1 1 1 1 active.1 active.2 active.3	
Heads	Name of raster map with initial heads hd.lay1.stp1.tst1	string iniheads.1	ihheads			iniheads.2 iniheads.3
Sy T	Name of existing raster map(s) with primary storage coefficient values Name of existing raster map(s) with Transmissivity. REQUIRED for CONFINED aquifers or VARIABLE confinement aquifers with CONSTANT <i>T</i>	string string		Sy		

		H.conductivity	H.conductivity	H.conductivity
K	Name(s) of existing raster map(s) with Horizontal Conductivity. Required for UNCONFINED aquifers and VARIABLE confinement aquifers with VARIABLE T	string	hk.1	hk.1
Bottom	Name of an existing raster map with aquifer bottom. Required for unconfined and variable aquifers with variable T	string	hk.2 hk.3 top.2	hk.2 hk.3 top.2
Top	Name of an existing raster map with Top of aquifer	string	top.3 bot.3 top.2 top.3	top.3 bot.3 top.2 top.3
vcond	Name of an existing raster map with Vertical conductance	string	vcond.1 vcond.2	vcond.1 vcond.2
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
river_heads	Name of raster map with stage values for reaches	string		wells2
river_cond	Name of raster map containing conductance values for reaches	string		river.head
river_elev	Name of the raster map containing river-bed elevation values	string		river.cond
Drain	Name of site map(s) containing drain data	string		river.bed
Drawdownin	Name of raster map for DRAWDOWN simulation values	string	dd	ddtest
Headstin	Name of raster map for HEAD simulation values	string	hd	hdtest

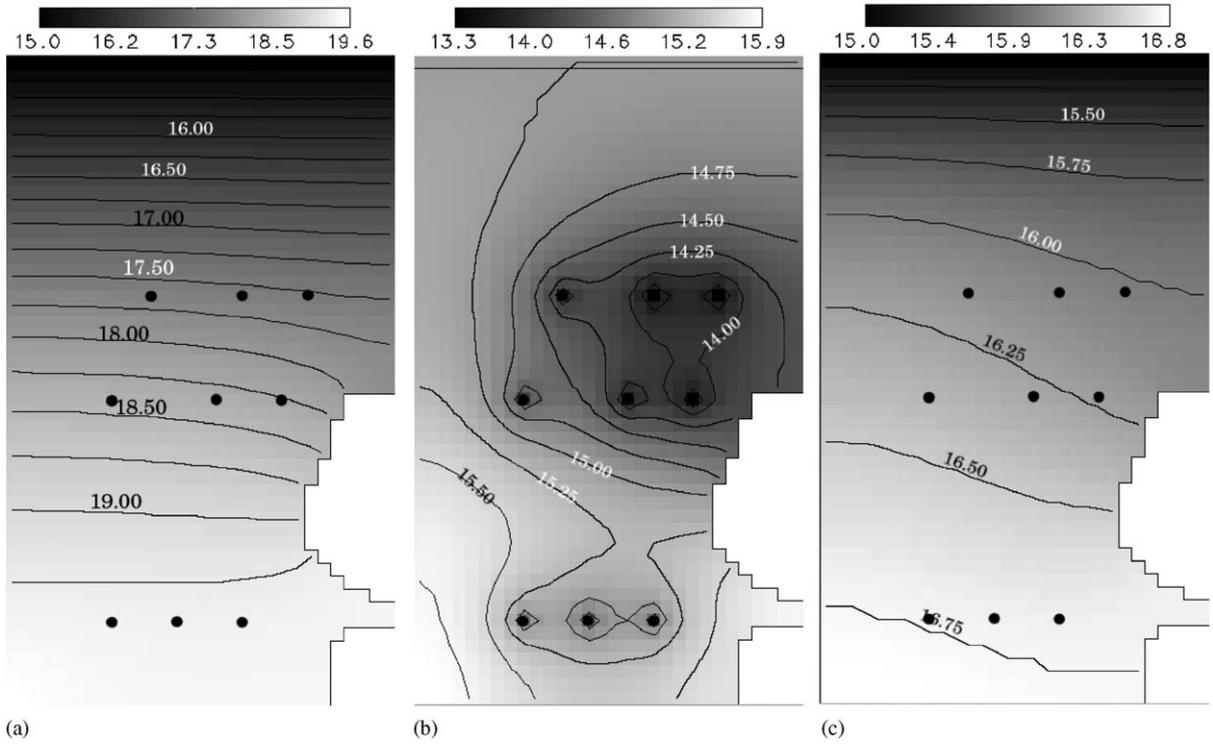


Fig. 5. Simulated heads obtained with GMTG for case 1: (a) steady state simulation heads; (b) transient heads for stress period 1, time step 12; and (c) transient heads for stress period 2, time step 6.

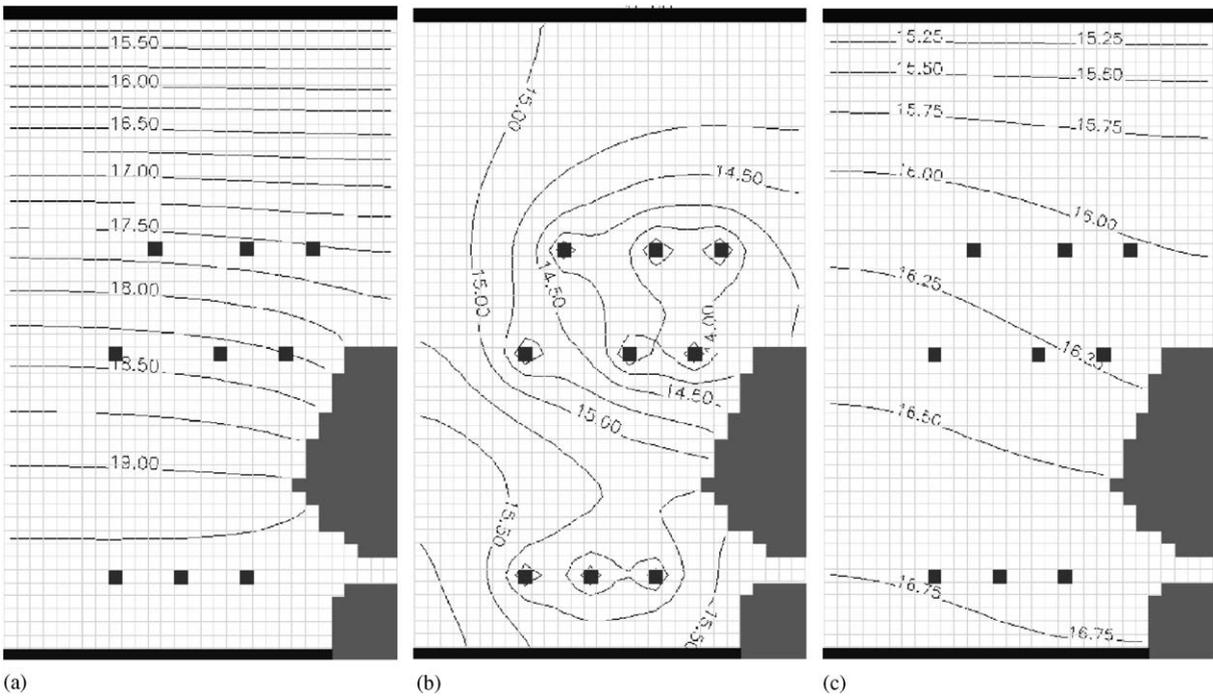


Fig. 6. Simulated heads obtained with PMWIN for case 1: (a) steady state simulation heads; (b) transient heads for stress period 1, time step 12; and (c) transient heads for stress period 12, time step 6.

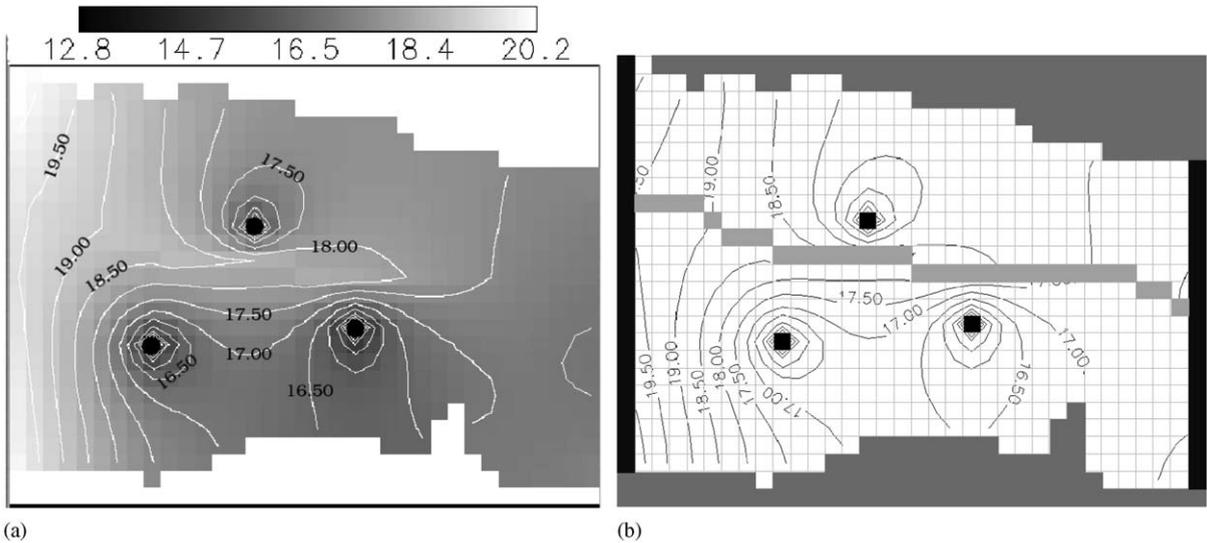


Fig. 7. Simulation results for the steady-state, three layer model; heads in layer 1: (a) GMTG simulation; (b) PWIN simulation.

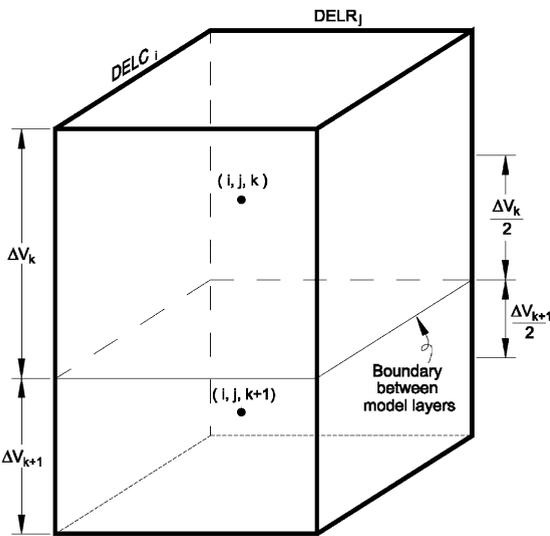


Fig. 8. Vertical conductance variables, adapted from McDonald and Harbaugh (1988).

The `r.gmtg` module provides an accessible tool which: (1) Is available free of charge, (2) its open source nature provides access to its code and (3) uses GIS data directly. This module is intended to take advantage of GRASS' capabilities to both manipulate and analyze 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 be linked with other Open Source tools for different tasks such as R for statistical analysis.
- It provides a free groundwater flow modeling tool for users who cannot afford the commercially available processors.

7. Conclusions

Geographic Information Systems are powerful tools which are used to handle georeferenced 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 accessibility. The decision of integrating MODFLOW with GRASS was taken on the grounds of portability and accessibility: 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.

Acknowledgements

Financial support by the Mexican Council for Science and Technology (CONACyT) and NSERC are acknowledged.

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