GroundWaterTutor: An Interactive Computer Module for Understanding Groundwater Flow and Transport

Andrew T. Banks and Mary C. Hill

I. Introduction

Teaching subsurface transport concepts has been approached in many ways, yet none of the existing methods were found to satisfy both of two important goals: emphasize basic flow and transport concepts, and provide a solid foundation for simulating more complex systems. For example, Li and Liu (2003) satisfies the first goal, but used a model with limited capabilities that does not prepare students well for models they are likely to use in practice. Vallochi et al (2015) introduces users to sophisticated and common models (i.e. MODFLOW and MODPATH), challenging the user with a very interesting problem, including wetlands, a river, and pumping. However, less emphasis is placed on underlying basic concepts, such as how hydraulic properties, recharge and pumping interact. Understanding the practical manifestations of what are fundamentally mathematical relationships is vital to using models as effective decision making tools.

Researchers at the University of Kansas have recently developed *GroundWaterTutor*, a freely available interactive computer module for groundwater education. *GroundWaterTutor* provides a simple, interactive environment for students to learn how key modeling parameters affect hydraulic heads and the flow of tracer particles. Students are presented with options to explore the effects of confined and unconfined conditions, heterogeneity, anisotropy, time-discretization, areal recharge, and pumping rates, which allows for a wide range of scenarios to be investigated within the context of a simple problem that emphasizes basic principals. Interactive visualizations illustrate the resulting hydraulic heads, as well as the transport of tracer particles from three origination sites.

The *GroundWaterTutor* graphical interface is constructed with the U.S. Geological Survey programs MODFLOW 2005 (Harbaugh et al, 2005), MODPATH 6 (Pollock et al, 2016) and a small library of MATLAB support code. MODFLOW is based on a finite differencing approximation of the groundwater flow equation, and is used by *GroundWaterTutor* to simulate hydraulic heads. MODPATH is a post-processor which is used by *GroundWaterTutor* to simulate advection based particle trajectories based on models of groundwater flow produced by MODFLOW.

The graphical interface was developed with MATLAB 2015, and provides the capability to create input files for MODFLOW and MODPATH, execute the models and visualize model results. A small library of support code was developed to translate user input from the graphical interface into text files readable by MODFLOW and MODPATH.

II. Features

The *GroundWaterTutor* module starts with default parameter sets, providing a helpful starting point for users to vary inputs and systematically investigate the changes in model output.

Five tabs along the top margin of the main interface window can be explored by users. Each tab contains information about the model under construction. The zoom, pan and rotate toolbar can be used to manipulate how the model input is displayed. A compass showing the four cardinal directions can be seen in the bottom left of all tabs. The compass reorients as the model object is rotated. A brief explanation of each tab and relevant details about the model is provided in the following sections

A. Boundary Conditions

The "Boundary Conditions" tab provides the first view of the model aquifer to users. In this model, neither the boundary conditions nor the spatial discretization of the model domain can be changed. The model spatial discretization consists of 30 columns by 20 rows, uniformly spaced, extending 650 m in the x-direction (E-W), and 300 m in the y-direction (N-S). No flow boundary conditions are enforced along the North and South. Constant head boundary conditions are enforced along the East and West , yielding a regional hydraulic gradient of dh/dx=0.03.

B. Initial Conditions

The "Initial Conditions" tab shows information about the initial guess for hydraulic heads input used in the MODFLOW BAS6 package. Here the user may specify the two elevation of the aquifer using the slider bar, or manual input features in the top center of the window. Adjusting the top elevation will affect whether the aquifer is under confined or unconfined conditions. The initial hydraulic heads cannot be changed by the user.

C. Parameters

The "Parameters" Tab (shown in Figure 1) provides the user with visualizations of the parameter fields used in the MODFLOW LPF package, and MODPATH MPSIM package. A dropdown menu allows users to select which parameter field is displayed. These include hydraulic conductivity, specific storage, specific yield and porosity. A slider bar and manual edit box can be used to scale the selected parameter. The spatial distribution of a given parameter is forced to be homogenous and isotropic. The exception to this is Hydraulic conductivity. Anisotropy can be introduced

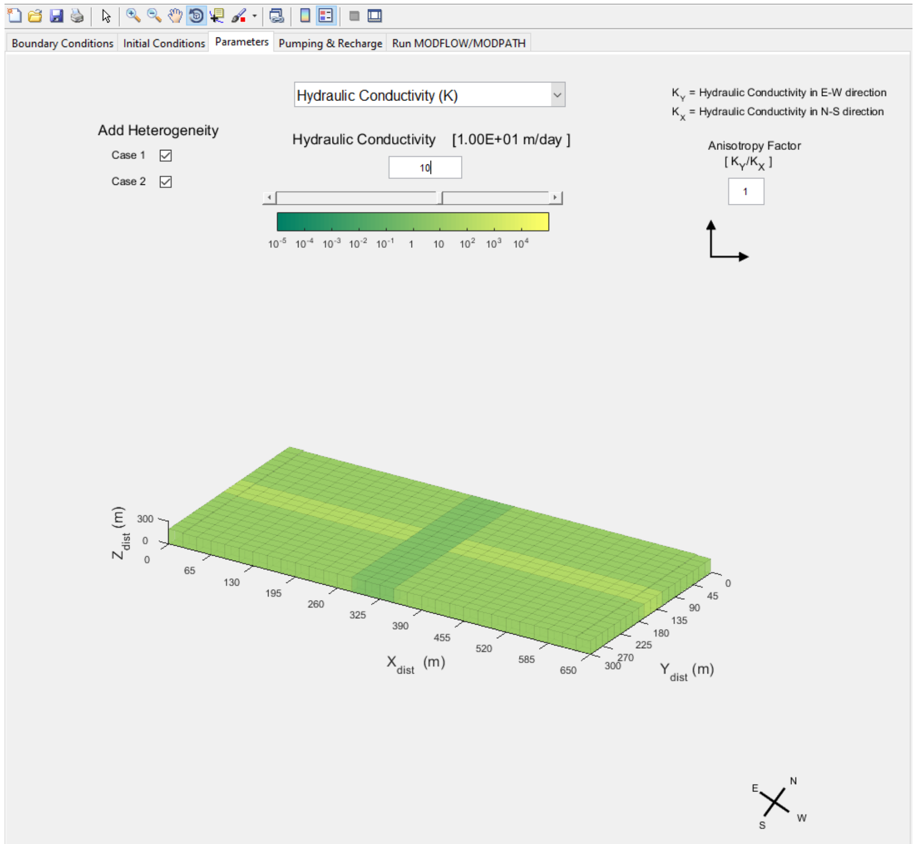

Fig. 1. **Parameters Tab in the *GroundWaterTutor* interface input window. High and Low K zones shown.**

to the hydraulic conductivities using the manual edit box on the right side of the window. Checkboxes allow the user to introduce limited heterogeneity into the hydraulic conductivity field. The "case 1" checkbox introduces three-cell wide stripe of high hydraulic conductivities running E-W, which are 10 times greater than the baseline values. Similarly, the "case 2" checkbox adds 3-cell wide stripe of low hydraulic conductivities running N-S, which are 10 times smaller than the base line values. If both "case 1" and "case 2" checkboxes are selected, the high and low hydraulic conductivity stripes will be superimposed.

D. Pumping and Recharge

The "Pumping and Recharge" tab provides the user with visualizations of the source fields used by the MODFLOW WEL and RCH packages. A dropdown menu allows the user to toggle between a display of uniform surface recharge, and discharge from a single pumping well, centered in the western half of the model. A slider bar and manual edit box can be used to scale the selected source term.

E. Run MODFLOW/MODPATH

The "Run MODFLOW/MODPATH" tab provides the user with a summary of the model. The saturated thickness of the aquifer is shown be default. Checkboxes allow the user to toggle between views of the boundary conditions, location and discharge rate for the pumping well, and the initial position of three clusters of tracer particles. Here the user can modify the time discretization used in the MODFLOW DIS package. The number of transient stress periods and the length of each stress period (in days) can be specified using manual edit boxes.

To account for the physically implausible initial hydraulic head distribution provided to users, a steady-state solution is specified automatically by "GroundWaterTutor". This steady state solution is then used as the initial guess for the first transient stress period.

III. Model Output

After MODFLOW and MODPATH have successfully terminated, a new interface window will appear alongside the main interface window. This window features two tabs. A description of each tab is provided in the following sections.

A. Hydraulic Head

The Hydraulic Head tab provides users with a visualization of the simulated hydraulic heads returned by MODFLOW. A slider bar can be used to specify the time at which hydraulic heads will be displayed. The stress period type is shown, along with an indication of whether aquifer conditions are confined or unconfined.

B. Particle Tracking

The "Particle Tracking" tab provides users with a visualization of the time-dependent position of tracer particles

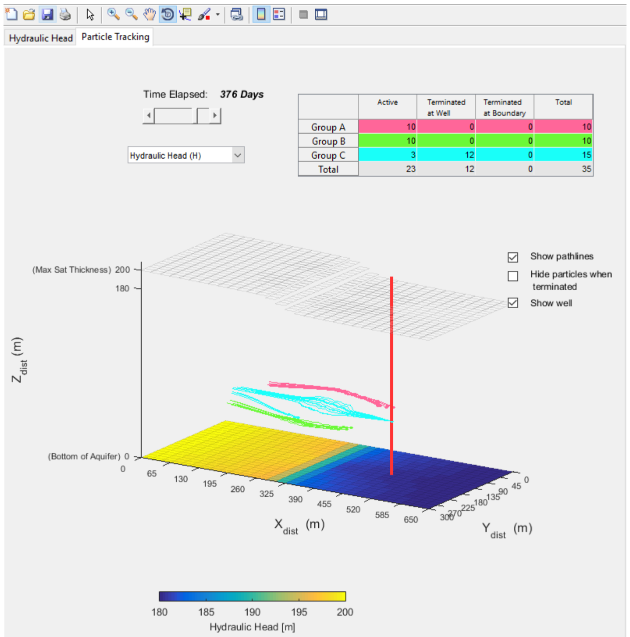

Fig. 2. **Particle Tracking Tab in the *GroundWaterTutor* interface output window. Particle pathlines and location of pumping well shown.**

(shown in Figure 2). A slider bar can be used to specify the time at which particle positions are displayed. The drawdown menu below can be used to toggle whether hydraulic head or hydraulic conductivities are displayed on the bottom surface of the model object. These features are useful for illustrating the effects of heterogeneous hydraulic conductivities on hydraulic gradients and resulting particle trajectories.

A table displays the status of each cluster of particles. The “Active” column indicated how many particles from each group are still eligible to move throughout the model domain. These particles have not been terminated at a model boundary or a strong sink (e.g. pumping well). The “Terminated at Well” column indicates how many particles from each group have been captured by the well. The total number of particles in each cluster remains fixed, which is indicated in the “Total” column of the table. Three checkboxes along the right side of the window provide the ability to: (1) Display the pathline taken by each particle up to the specified time, (2) Hide particle and pathlines when they are terminated at the well, and to (3) Display the location of the well.

[t]

IV. Accompanying Exercise

A sample set of exercises to accompany *GroundWaterTutor* is provided. The first exercises lead students through incremental changes that build basic insights into what Darcy’s Law, constant-head boundary conditions, and defined areal recharge mean in practice. Implications for simulated heads and particle transport are emphasized. Students are then asked to solve a simple problem – How much pumping is available for crop irrigation without capturing too much contamination? Finally, the exercises use a separate web applet developed at the University of Illinois with which they can explore the effects of urban and agricultural development on groundwater resources (Valocchi et al., 2015). Classroom trials suggest that these programs complement each other nicely. Feedback from students has been positive, with 80 % of students indicating increased comprehension.

V. Limitations

Users are required to have administrative privileges to a computer with a windows operating system. In theory *GroundWaterTutor* can be used on MacOS or Linux operating systems, however users will be required to manually compile MODFLOW 2005 and MODPATH 6 into standalone executables suitable for the respective operating system. This will be a challenging process for typical users. *GroundWaterTutor* has not been tested on MacOS or Linux systems.

The interface does not perform extensive parameter checking, allowing users to potentially enter physically implausible parameter combinations.

VI. How to Obtain the Software

GroundWaterTutor is distributed as a set of standalone executables, which can be acquired for free at https://github.com/andrewtbanks/GroundWaterTutor.

References

[1] Hu, Y., Valocchi, A. J., Lindgren, S. A., Ramos, E. A. and Byrd, R. A. (2015), Groundwater Modeling with MODFLOW as a Web Application. Groundwater, 53: 834-835. doi:10.1111/gwat.1272

[2] Li, S., Liu, Q. (2003). Interactive Groundwater (IGW): An innovative digital laboratory for groundwater education and research. Computer Applications in Engineering Education,11(4), 179-202. doi:10.1002/cae.10052