

HYDRUS: Software for Flow and Transport Modeling in Variably Saturated Media

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Introduction

HYDRUS is a software program for solving Richards equation for water flow and the advection-dispersion equation for heat and solute transport in variably saturated subsurface media. Variably saturated zones are fundamental to understanding many aspects of hydrology, including infiltration, soil moisture storage, evaporation, plant water uptake, groundwater recharge, runoff, and erosion. More and more studies are now focusing on the integrated water cycle, and the consideration of water, heat, and solute exchanges between groundwater and surface water must include both saturated and unsaturated zones.

HYDRUS uses the finite-element (FE) method to simulate one-, two- or three-dimensional movement of water, heat, and multiple solutes in unsaturated, partially saturated, or fully saturated porous media. There are two main variants of HYDRUS: (1) HYDRUS-1D that has existed as a Windows-based code since 1998 (the latest version 4.0 was released in 2007); and (2) HYDRUS-2D/3D that is a combination of HYDRUS-2D (1999 to 2007) and HYDRUS-3D (2006 to 2007). The most recent version of HYDRUS-2D/3D is 1.11 released in February 2010. HYDRUS-1D is free and its source code is open. It was first developed by Šimůnek et al. (1998) for academic purposes. But HYDRUS-2D/3D is a commercial product developed by PC-Progress Company (<http://www.pc-progress.com>). Both HYDRUS-1D and HYDRUS-2D/3D can be downloaded directly online. However, HYDRUS-2D/3D only runs in demo mode until it is activated following a license purchase from the software vendor.

HYDRUS comes with a graphical user interface (GUI) that runs under the Microsoft Windows operating system. It can be used in either the 32-bit or 64-bit version of Windows XP or higher. The minimum requirement to run the HYDRUS software with the GUI includes an ×86 CPU (Intel or AMD) at 1 GHz or faster, 512 MB RAM, a graphics card with a resolution of 1024 × 768 pixels, and 10 GB total hard disk capacity with about 500 MB reserved for installation. The software vendor's website, <http://www.pc-progress.com>, provides a comprehensive coverage of HYDRUS, including download and purchase information, version history, application examples, and instructional materials.

How We Tested

The latest version 1.11 of HYDRUS-2D/3D (referred to as HYDRUS hereafter) is reviewed. The installation package was downloaded online and installed by one reviewer on a laptop PC with a 1.7 GHz Intel Celeron M CPU, 1.5 GB RAM, and Intel GMA4500 integrated graphics card, running Windows 7. The other reviewer had it installed on a Dell laptop with a 1.4 GHz Intel Core-2 Duo CPU, 3.0 GB RAM, and Intel GMA 4500 integrated graphics card, running Windows Vista SP2. The installation package was first self-extracted to a temporary folder. The setup process in itself took less than a minute. By default the program was installed to "C:\Program Files\PC-Progress\HYDRUS 1.xx". After full installation the main program occupied about 45 MB of hard disk space while examples occupied another 100 MB.

During the installation, no conflicts between HYDRUS and other software applications occurred. No other system component (e.g., Microsoft .Net) was needed. Moreover, no other plug-in or auxiliary program was installed. After purchasing a software license, the user will be provided authorization codes by the software vendor to activate the installed software. The reviewers tested the software by working with a three-dimensional example installed along with the software and a customized application with more complexity.

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What We Found

Documentation and Technical Support

The installation folder contains two HYDRUS manuals in PDF format. The first is a user manual that contains detailed instructions on how to use the HYDRUS software through its GUI, while the second is a technical manual that presents the theoretical background and technical details about the conceptual model and numerical method. Both manuals are comprehensive and useful. Besides these two manuals, a help file in chm format is also provided. The user could either open it or find it through the “Help” menu. This document provides a more simplified explanation about the GUI and the basic theories used in HYDRUS. This is useful for quick references during model construction.

The reviewers found the tutorials on the developer’s website to be particularly helpful, especially for those who are first exposed to HYDRUS. A series of video tutorials showing how to construct a HYDRUS model using the GUI is also available online (<http://www.pc-progress.com/en/Default.aspx?h3d-tutorials>). It would take approximately 4 h to finish the video tutorial course. The video course provides a good overview on the basic steps of constructing a FE model, including, defining

the model geometry, generating the FE mesh, assigning domain properties, setting up the initial and boundary conditions, and displaying simulation output.

GUI, Data Import and Management

The GUI of HYDRUS is organized into three panels under the main menu and tool bars (Figure 1). The left panel is a navigation bar with three tabs at the bottom: Data, View, and Sections. Dynamic navigation trees associated with these tabs provide convenient data access and display options to lead users through all model building steps in HYDRUS. The middle panel is a view window associated with six tabs: Geometry, FE-Mesh, Domain Property, Initial Condition, Boundary Condition, and Results. Also, data and view options in the navigation bar are organized into six groups closely corresponding with the six tabs associated with the view window. This arrangement of the GUI makes it easier to navigate through six common steps of model pre- and post-processing. The right panel is an edit bar. It displays the details of a list of edit commands. For example, when the “Boundary Conditions” tab is selected in the view window, the “Boundary Conditions” group of the dynamic navigation trees in the navigation bar expands automatically. At the same time, the edit bar

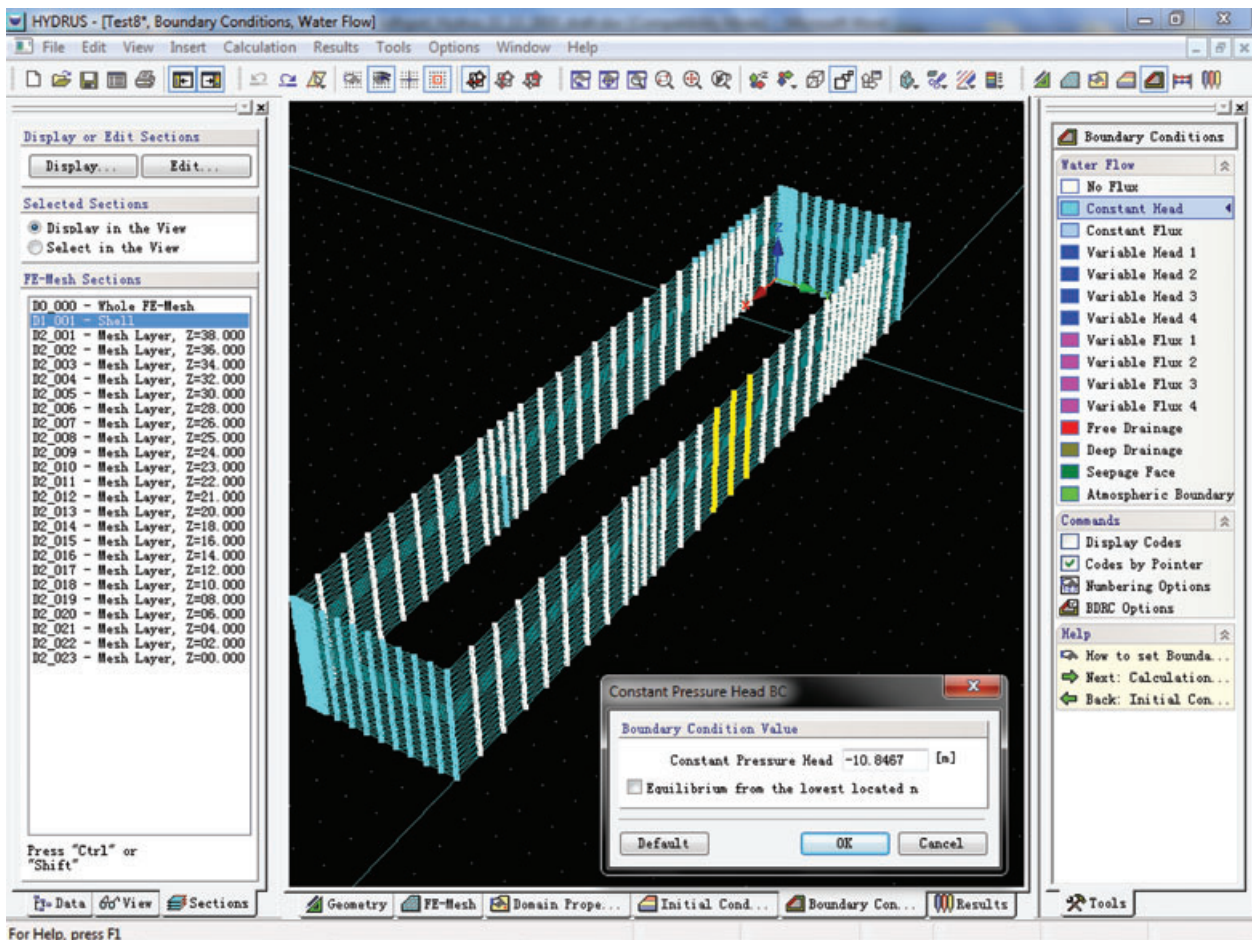


Figure 1. A screen capture of the input window for HYDRUS. The input window is divided into three panels with a navigation bar on the left, a view window in the middle, and an edit bar on the right.

changes to reveal the commands for a list of recommended boundary types. Click on any boundary type and the edit bar will automatically update to show options for that boundary condition. This seems a more user-friendly design than popping up dialog boxes with available options. Reviewers felt quite comfortable with the GUI after only some brief experimentation.

The third tab of the navigation bar in the left panel is “Sections” whose function is to divide complex objects (models) into simpler parts (i.e., sections). Clicking on the “Sections” tab will show a list of sections associated with the FE mesh. By default, a whole FE mesh is one section. New sections can be added, deleted, and edited. The reviewers found the “Sections” tool a convenient way to manage a large number of elements. For example, to set boundary or initial conditions to a certain group of elements, the user just needs to select these elements associated with a particular section in the navigation bar, and then click on the “Boundary Condition” tab in the view window, choose all, set the condition in the edit bar, and then repeat this procedure in the “Initial Condition” tab.

Each problem to be solved by HYDRUS is referred to as a “Project.” By default, when HYDRUS is started, it will automatically reload the project opened in the last HYDRUS session. But if no project was opened when last exiting HYDRUS, a dialog will pop up to guide the user through basic model building steps: choosing a model type, setting up time discretization and print options, and specifying iterative solution criteria as well as other basic input information. All the data and information pertinent to a particular project are organized and managed by the “Project Manger.” The reviewers found this data-management approach convenient and straightforward.

The data import and export capability appears to be rather limited with the GUI. Users can either import or export data through text files with a default file extension [.txt]. However, though the user manual has explained the format of such .txt files, the reviewers found it almost impossible to have data exchange between HYDRUS and geographic information system tools such as ArcGIS. In addition, users cannot import a graphics base map to guide the spatial discretization when setting up the model grid, a feature commonly available to other model GUIs.

Run time and software performance

After finishing the FE model construction, the user can run the simulation code through “*menu-> calculation-> calculate current project*”. A DOS command window will pop up showing the calculation details. In a HYDRUS-1D project, input data are saved into ASCII files, and the simulation is carried out by a console application. In HYDRUS-2D/3D, the preprocessing is also carried out by the GUI, however, the input data are not saved into ASCII files, rather they are saved into .DLL files. The simulation is also carried out by a console application named H3D.exe. The run time of a simulation project depends on the physical complexity and iteration criteria. The reviewed cases involving both a developer’s

tutorial and an actual example took more than half an hour to complete. During the calculation, the program was stable, and no error occurred. It is noteworthy that the recommended computer configuration by the developer is a 3.0 GHz CPU and 2.0 GB RAM and graphics card with OpenGL hardware acceleration. The systems used by both reviewers are below that configuration. Still, the software performance was adequate.

Output

The output of HYDRUS simulation can be displayed directly through the GUI. Three-dimensional distributed fields such as pressure head, water content, velocity, concentration, and temperature are shown as contour maps through the “Result” tab of the view window (Figure 2). Meanwhile, in the edit bar, tools are provided for creating cross-section plots. Users might either save the onscreen plot as a graphical image, or export the raw data to text files. This is an improvement in HYDRUS-2D/3D over HYDRUS-1D which only allows the results to be exported to bitmap files in low resolution. In HYDRUS-2D/3D, the results can be exported as .txt files with x , y coordinates. Users can choose to do post-processing with the exported data in other graphic programs. HYDRUS also provides animations to show the flow or solute transport process. The animations can be exported to .avi files in six types of video encoding.

What We Liked

HYDRUS appears to be a versatile modeling system with a well-designed GUI for water flow, solute, and heat transport simulation in variably saturated media. The reviewers especially like several features available in the GUI. The project manager and step-by-step guidance can be very helpful to users, in particular, beginners. The overall GUI design is intuitive and various options are arranged logically into groups corresponding with model construction steps. The edit bar is changed from the menu-dialog style that is popular in many other programs into an integrated panel with colorful icons. Reviewers also thought that the output module is impressive for its intuitive representation by animations and multiple types of graphics. The “Sections” tool provides a convenient way to access and edit a group of elements simultaneously. The reviewers also very much liked the video tutorial course available on the software vendor’s website. This course allows users to learn about almost all of the options available to HYDRUS.

Another useful and convenient feature of HYDRUS is the integrated inverse modeling capability that can be used to optimize input parameters during model calibration. The GUI can be used to define the objective functions and the soil properties to be optimized, and to enter observed head and concentration data directly. While it is more common nowadays to use a simulation code in conjunction with a model-independent inverse parameter estimation package such as PEST or UCODE for model calibration purposes, integrating forward and

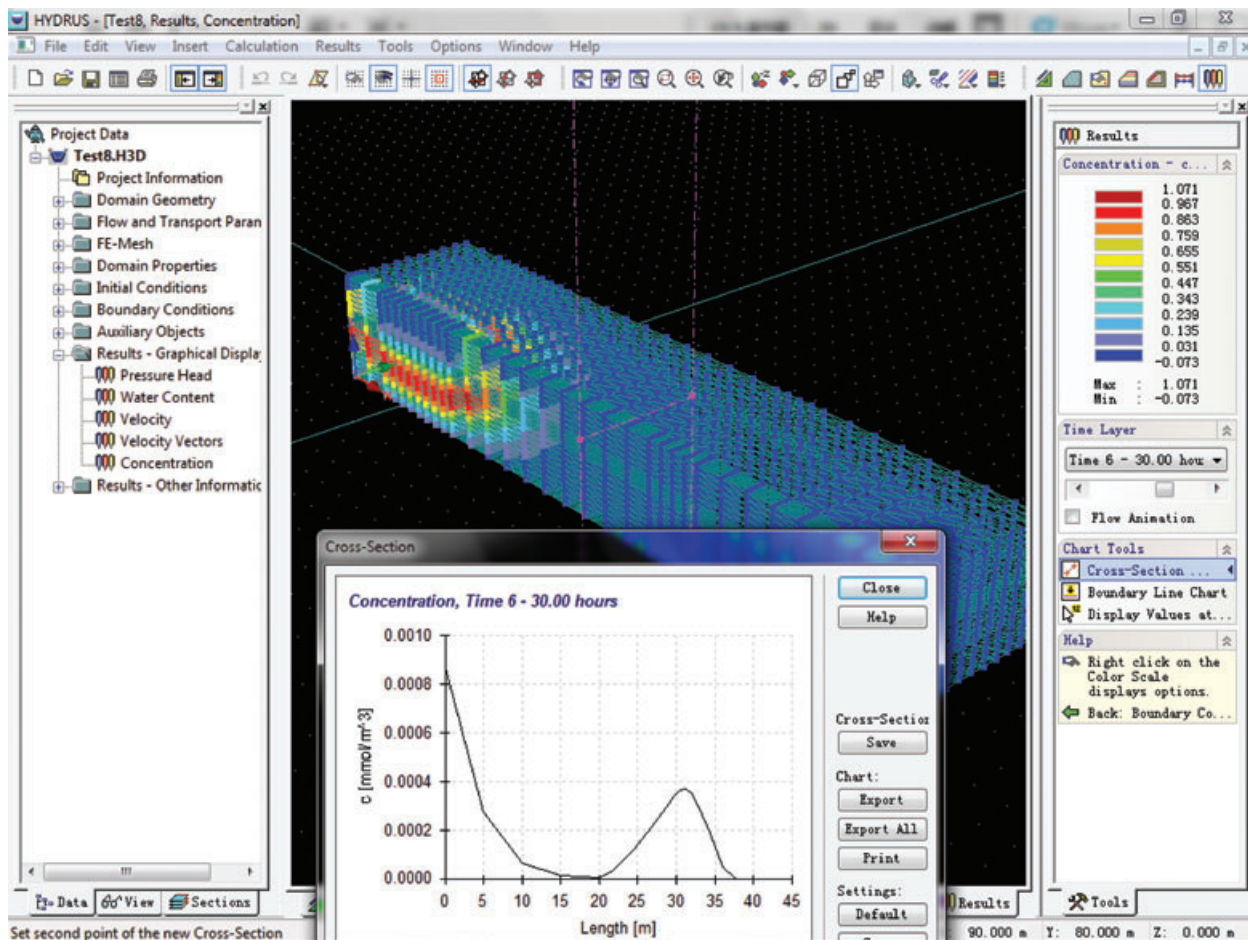


Figure 2. An output screen capture for HYDRUS. Shown in the plot is a calculated concentration distribution in 3D as well as a breakthrough curve at an observation location.

inverse modeling functionalities in a single code has its own benefits.

Although not related to HYDRUS-2D/3D directly, it is noteworthy that the software developer has also released a HYDRUS-1D package for the United States Geological Survey (USGS) groundwater flow model, MODFLOW. This appears to be a useful and practical tool for integrating the unsaturated zone with saturated zone flow modeling.

What We Did Not Like

Data exchange with external files and programs needs to be enhanced in future versions of HYDRUS. Current versions appear to be only capable of importing data files exported by HYDRUS itself. This can significantly limit the application of HYDRUS to more complex field problems. Moreover, while HYDRUS supports animation export to .avi files, reviewers found it difficult, if not impossible, to export graphs to high resolution images. As a result, simulation results may need to be saved as text files and post-processed with external graphic programs for publication-quality plots.

By default, program files and example files are installed to different folders. The default installation

folders change under different versions of the Windows operating system. While this is a minor issue, it could cause some confusion among users. Another minor issue concerns the icons in the tool bars and in other panels, which are not very intuitive.

Finally, while the HYDRUS series of codes have had a long history of development and successful applications to many field problems (Šimůnek et al. 2008), the core numerical solution technique has not progressed much beyond the classic Galerkin-type FE method. By using upstream weighting to curb numerical oscillation, the transport solution is vulnerable to significant numerical dispersion if spatial discretization cannot be made sufficiently fine due to computational efficiency considerations.

Overall

Overall, the two reviewers are favorably impressed by HYDRUS as a versatile modeling platform with a long, proven track record and a well-designed GUI for flow and transport under variably saturated conditions. Although some features need to be enhanced, the software appears to be stable, efficient, and easy-to-use. HYDRUS would be a good choice for any researchers or environmental

engineers interested in subsurface flow, transport, and remediation where variably saturated conditions must be considered.

Ranking

The reviewers ranked the software's capability, reliability, ease of use, and technical support on a scale of 1 (worst) to 5 (best). The following rankings are the average of two sets of scores from both reviewers:

Capability: 4.5

Reliability: 4.2

Ease of use: 4.5

Technical support: 4.8 (a series of online video tutorials)

How to Obtain the Software

Those interested in obtaining the free HYDRUS-1D software or purchasing the commercial HYDRUS-2D/3D can visit the software developer's website at <http://www.pc-progress.com>. The current prices for HYDRUS-2D/3D licenses range from 600 euro (\$780 USD)

for "2D-lite" to 1800 euro (\$2400 USD) for "3D Standard."

References

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Šimůnek, J., M.Th. van Genuchten, and M. Šejna. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes, *Vodose Zone Journal* 7, no. 2: 587–600.

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