

# AnAqSim: Analytic Element Modeling Software for Multi-Aquifer, Transient Flow

reviewed by Charles McLane

## Introduction

Analytic element method (AEM) groundwater flow models, first developed in the early 1980s, have made great advances over the past decade. Their power and ease of use place them among the first tools that a hydrogeologist or engineer may wish to apply when the need arises to develop a rapid and cost-effective answer to a question regarding a groundwater flow system. AEM models are capable of simulating both confined or water table aquifers, and heterogeneities such as zones of differing hydraulic conductivity or differing model base elevation (e.g., bedrock). Newer AEM models permit multiple aquifer layers, transient simulations, and analysis of saltwater interface boundaries. Each hydrologic feature or “element” is represented by a precise analytic mathematical solution, with those element solutions being superimposed (added together) to form more complex solutions.

Model set up is quick. No construction of a complex computational grid or mesh is required. In addition, the tight integration of model post-processing tools in many AEM models supports a rapid run-display-change-rerun cycle that allows the modeler to focus on the model concepts and interpretation, and not on the mechanics of model modification.

A new AEM model called AnAqSim applies a new theoretical approach based on model domains to incorporate many of these powerful AEM features. AnAqSim was developed by Dr. Charles Fitts of Fitts Geosolutions and is available on the web site <http://www.AnAqSim.com>.

## How We Tested

### Test Computers

AnAqSim version 2011-2 (released August 20, 2011) was reviewed and tested on a Dell Precision T5500

workstation with dual hexacore Xeon CPUs (2.4 MHz) and 12 GB RAM running Windows 7; and in Windows XP emulation mode (VMWare Fusion v 3.1.3) on a MacBook Pro (Intel Core 2 Duo; 2.33 GHz; 3 GB RAM; Mac OS X 10.5.8). Minor graphics artifacts in several of the AnAqSim windows on the MacBook Pro when running in XP emulation mode (apparently caused by conflicts with the VMWare display drivers) were eliminated by turning off hardware acceleration in the Windows XP Display Settings control panel.

The current version of AnAqSim is Windows XP and Windows 7 compliant, and runs in 32-bit mode. A 64-bit version, which will permit the execution of larger models (i.e., a greater number of element coefficient matrix equations) is being developed.

### Installation

The AnAqSim installation file (~91 MB) was downloaded from the Fitts Geosolutions web site and installed in less than 10 min. Microsoft.net library is automatically downloaded and installed if needed. System requirements, as stated in the User Guide are: (1) Windows XP, Windows 7 (32 or 64 bit); (2) At least 250 MB of available disk space; and (3) At least 1 GB memory—more memory is needed for larger problems.

License activation is performed by emailing to Fitts Geosolutions the Site Code generated by AnAqSim following installation; the Site Key to activate the license is returned to the user in an email reply. AnAqSim can be uninstalled using the standard Windows installation manager interface. It is necessary to uninstall each previous version of AnAqSim before installing a newer updated version.

### Test Example Problems

The review tested the software by running test problems provided on the AnAqSim web site, completing the tutorial described in the User Guide, and working with data from three reviewer-generated test problems, as described briefly below.

1. *AnAqSim check problems*: Dr. Fitts provides on the AnAqSim web site descriptions of, and model input

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files for, a series of check problems that demonstrate AnAqSim solution accuracy. The problems included checks for confined and unconfined, single-layer and multi-layer models; recharge from above and leakage from below an aquifer layer; three-dimensional (3D) particle tracking; formation of a saltwater interface in a coastal aquifer model; and checks against known analytical model solutions (e.g., a model problem from an AEM textbook and a transient match to the well-known Theis equation).

2. *AnAqSim Tutorial*: The AnAqSim Tutorial, presented in the User Guide, is built around a small watershed, with known hydrologic boundaries, a stream running through the center to an outlet point on the boundary, and a well field pumping near the river.
3. *Flow to a well in a horizontally anisotropic aquifer*: The reviewer developed a test problem for a fully-penetrating well pumping in a horizontally anisotropic unconfined aquifer.
4. *Saltwater interface response to pumping*: The reviewer developed a test problem in which a shallow partially penetrating supply well is pumped at some distance above a saltwater interface that forms the lower boundary of a freshwater lens aquifer.
5. *Aquifer test data analysis for a multi-layer aquifer system*: The reviewer developed a test problem in which AnAqSim is used to estimate aquifer properties by fitting drawdown data from a pumping test in an aquifer system consisting of three aquifer zones separated by two intervening aquitards.

## What We Found

### User Interface

The user interface consists of two main views: Data View and Plot View, controlled by a Switch View tab. In Data View the user can enter and edit input data in data grids (spreadsheet-like tables) in the upper portion of the window, while in the lower portion of the window a Run Log displays a variety of text information including files recently opened and closed, solver iterations during a run, status and error messages, and information regarding the status of the user's AnAqSim license. Plot View displays a map of the current model elements and simulation output (contours, pathlines, etc.), as well as a Plot View Menu that contains functions related to the plot including view zoom controls, a tool for digitizing model features, and a Plot File menu that allows graphics output in various file formats. At the left of the Plot View window is a dashboard of collapsible and expandable model output fields that allow the user to inspect the results of a simulation by moving the mouse cursor over the model space. Values displayed include cursor x, y location, hydraulic head, saturated thickness, and groundwater flow velocity and direction.

Modeling operations, while involving a moderately large number of steps as in most modeling environments, are controlled in AnAqSim in a manner that is relatively

logical and well laid out. Models are developed and executed, graphic results are generated, and post-processing analyses are conducted using the features of primarily three menus: Model Input, Plot Input, and Analysis.

1. The Model Input menu allows the user to specify basic model parameters such as solver settings and time step settings, number and types of solution domains (confined, unconfined, saltwater interface, etc.), hydrologic feature elements within those domains (wells, rivers, etc.), boundary condition settings, and areas of recharge over the model domain and/or leakage between model layers.
2. The Plot Input menu allows the user to set the model view and solution space window, and to define what model output graphics to display and how to display them (e.g., water level contours, flow pathlines, and flow vectors).
3. The Analysis menu contains a valuable collection of post-processing and analysis tools that are described in the Capabilities section below.

To facilitate model construction, AnAqSim has a digitizing capability that allows use of the mouse to draw in the model window a line or polyline for a particular feature or boundary. The coordinate list of that line is captured and placed in an internal clipboard from which it can be pasted into the coordinates cell of the corresponding element data grid. While the user interface for model setup does not make extensive use of standard Windows features such as data entry dialog boxes or point-and-click drawing and editing of model elements, it is clean and functional, and has the added benefit of allowing the user to easily access, review and edit the underlying model database. Also, for certain data entry cells, the user is presented with a list of previously entered features from which to select; this avoids unnecessary typing for long feature and variable names and prevents possible typographical errors.

The software does not have a comprehensive model data viewer mode where data for all elements and model settings can be viewed in a single concise summary, nor does the current version write out a "data echo" file summarizing all model input parameters. However, model data and settings entered in the various data grids is stored in a single XML file that can be examined fairly readily using the standard Windows Notepad application or, for a more organized and readable viewing experience, via the free Microsoft XML Notepad application.

### Capabilities and Performance

AnAqSim uses a variation of the AEM that divides the modeled region into subdomains (called "domains" in AnAqSim), each enclosed by its own boundary with its own definition of aquifer parameters and its own separate AEM model (Fitts 2010). A variety of line boundary conditions are available in AnAqSim; each formed by a polyline that can be easily configured to accurately match a boundary or hydrologic feature. The

line boundary condition is approximated using linesink elements similar to those described by Jankovic and Barnes (1999).

Each subdomain model is written in terms of two-dimensional (2D) functions, but 3D flow may be simulated using multiple levels in a model (up to five layers). In multilevel models, the resistance to vertical flow is accounted for in the vertical leakage between levels. Multiple levels (subdomains stacked vertically and leaking vertically to each other) can abut an area with subdomains in just a single level. This allows the model to focus layering and computational effort in the area of interest, with a simpler single-level model for distant areas. AnAqSim uses multi-quadric interpolator functions to simulate spatially variable area source/sinks, seepage and storage (Strack and Jankovic 1999; Fitts 2010).

AnAqSim provides transient simulation capabilities by using finite difference time steps as suggested by Haitjema and Strack (1985). The transient term in the flow equations is handled in essentially the same manner as it is in finite difference programs like MODFLOW.

There is a limit to the application of AnAqSim where the system of equations gets so large that it takes too long to solve in a reasonable time. That limit on present standard personal computers is probably in the range of 5000 to 10,000 equations. For situations with more equations than this, a numerical method like finite differences or finite elements may be a better choice. The shift to 64-bit systems will allow larger systems of equations, with computation time still being an issue for very large models, but rapidly evolving computing power will likely ease these limits with time.

AnAqSim allows import of basemap files to facilitate the layout and construction of a model. The software does not currently have the capability of exporting data files of simulation results (e.g., gridded contour data, pathline points, flow vectors) to external visualization or plotting software. Graphic depictions of model results can be saved in a number of formats including (BMP, JPG, PNG, PDF, DWG, DXF, and others).

The Analysis menu offers a large number of post-processing analysis tools that allow the user to examine model results in data list and chart formats including checks on boundary conditions; pumping and constant head well discharges; river reach fluxes; various model conditions along a transect line of the modeler's choosing including steady-state heads along the transect, transient heads along the transect, fluxes through the transect, and saltwater interface location along the transect; comparison of model results to user-specified calibration targets; and simulated hydrographs displaying either head or drawdown vs. time at one or more user-specified observation points in the model.

### Results of Test Problem Evaluation

1. *AnAqSim check problems*: All check problems ran with no difficulties. These data files, in addition to illustrating and checking AnAqSim features and solution accuracy, serve as guides for a new user

regarding how to set up a variety of simple AnAqSim models.

2. *AnAqSim Tutorial*: The tutorial begins with a one-level (layer) steady model of a small watershed adjacent to a lake. Groundwater discharges to the stream running down the center of the watershed and to a portion of the lakeshore boundary. A pumping well is then placed in the center area of the watershed near the stream. More complex geology near the well field area is incorporated by drawing a large polygon centered on the well, creating three levels (layers), and assigning them differing hydraulic properties. The model is then converted from steady to transient to examine drawdown through time at the pumping well. Display and control of contours, pathlines, and flow vectors are presented. The tutorial introduces many of the AnAqSim tools available for checking simulated conditions on boundaries and near wells and streams to determine that a valid solution has been obtained. This tutorial gives a good introduction to many of the capabilities of AnAqSim.
3. *Flow to a well in a horizontally anisotropic aquifer*: A single-layer unconfined domain (with impermeable base = 0 foot) was set up with  $K1 = 80$  ft/d oriented N45E, and  $K2 = 20$  ft/d oriented perpendicular to  $K1$ . This created a horizontal anisotropy  $K1/K2$  of 4:1. The western boundary was set at a constant head of 125 feet; eastern boundary was set at 100 feet; north and south boundaries were no-flow. A pumping well with a discharge of 40,100 ft<sup>3</sup>/d (300,000 gpd) was placed in the eastern portion of the flow field. Model solve time was less than 2 s. Particle paths delineating the capture zone of the well are oriented at an angle to hydraulic head contours due to the horizontal anisotropy (Figure 1). No problems were encountered during the model development or execution.
4. *Saltwater interface response to pumping*: To test AnAqSim's saltwater interface capability, a circular island model was set up with radius of 8000 feet, aquifer thickness of 500 feet, hydraulic conductivity of 150 ft/d and a sea-level constant head boundary (0.5 feet msl) around the entire coastline. In the center of the island a circular multilevel domain with radius 1000 feet was created to represent the well field area. A shallow well, extracting 100,000 ft<sup>3</sup>/d (750,000 gpd) was placed in Level 1 representing sandy material ( $Kh = 150$  ft/d,  $Kv = 30$  ft/d). Level 2 represented a silty clay zone ( $Kh = 30$  ft/d,  $Kv = 5$  ft/d) between the well screen and the deeper sand zone (Level 3) in which the saltwater interface was located. Model solve time was approximately 20 s. The AnAqSim Analysis tool "Graph Conditions Along a Line" was used to plot the saltwater interface location for non-pumping and pumping conditions (Figure 2a and 2b). No problems were encountered during the model development or execution. Care must be taken in saltwater interface models in areas where saltwater thickness may go to zero within a portion of an interface domain.

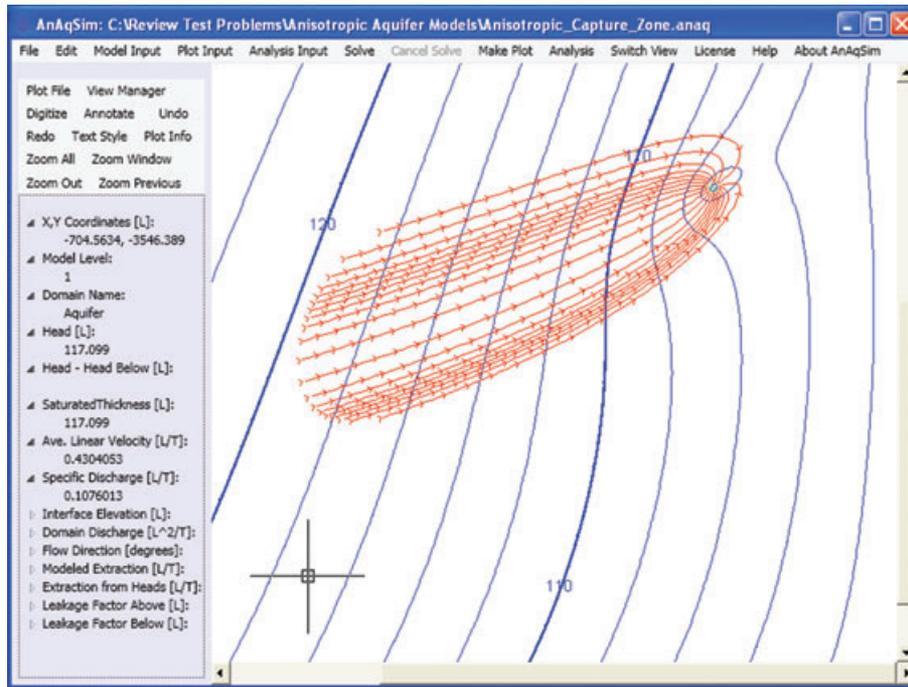


Figure 1. Capture zone for pumping well in unconfined aquifer with 4:1 horizontal anisotropy.

5. *Aquifer test data analysis for a multi-layer aquifer system:* As a test of both its transient and multilevel domain capabilities, AnAqSim was used to analyze data from a pumping test in a multi-aquifer system. In the field test, water was extracted at a constant rate for greater than 48 h from a mid-level aquifer zone that was separated from overlying and underlying aquifer zones by respective aquitard units. Test data were

measured from observation wells in all three aquifer zones. A five-level radial model (radius 20,000 feet) was set up with Levels 1, 3, and 5 representing the upper, middle, and lower aquifers, respectively; with Levels 2 and 4 representing the aquitards. In this example, transient drawdown data was recorded in AnAqSim at observation wells located in each aquifer unit at a radial distance of 150 feet from

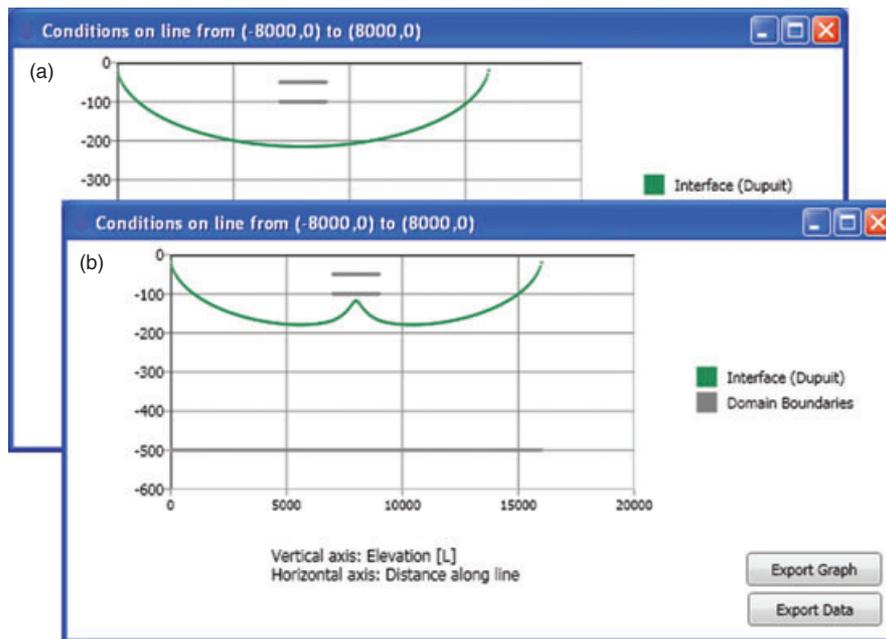


Figure 2. Saltwater interface location simulated by AnAqSim in freshwater lens aquifer for (a) pre-pumping conditions, and (b) with pumping from shallow zone at 750,000 gpd above a silty clay layer that separates the well screen from the deeper zone in which the interface resides.

the pumping well (corresponding to one set of field observation well locations). Hydraulic conductivity and storage values were adjusted in aquifer and aquitard domains to achieve acceptable matches with measured drawdown data. The AnAqSim Analysis tool “Graph Drawdown Hydrographs” was used to plot simulation results and measured data which can be read into AnAqSim as part of the matching process (Figure 3). Simulation of 12 timesteps at a step multiplier of 1.2 required approximately 30 s on the T5500 (100 s on the MacBook Pro) per complete drawdown simulation. Multiple simulations were required to arrive at an acceptable set of aquifer and aquitard parameters.

### Software Documentation and Help System

The User Guide (112 pages) is very thorough, beginning with an overview of the subdomain analytic element method on which AnAqSim is based; walking the user through a clearly explained and illustrated tutorial; and then clearly and methodically stepping through the various menus, tools, and features of the software with diagrams to illustrate key concepts. The AnAqSim software Help system is well written, with a search system that returns numerous related and helpful sections in response to a typical search.

### Software Support

Questions directed to technical support are answered quickly and thoroughly by the author. While the website states that anyone with a valid current license to AnAqSim is entitled to support to ensure that AnAqSim is functioning properly on your system, the reviewer found that support consistently exceeds this baseline, and is very helpful in properly applying the software.

### What We Liked

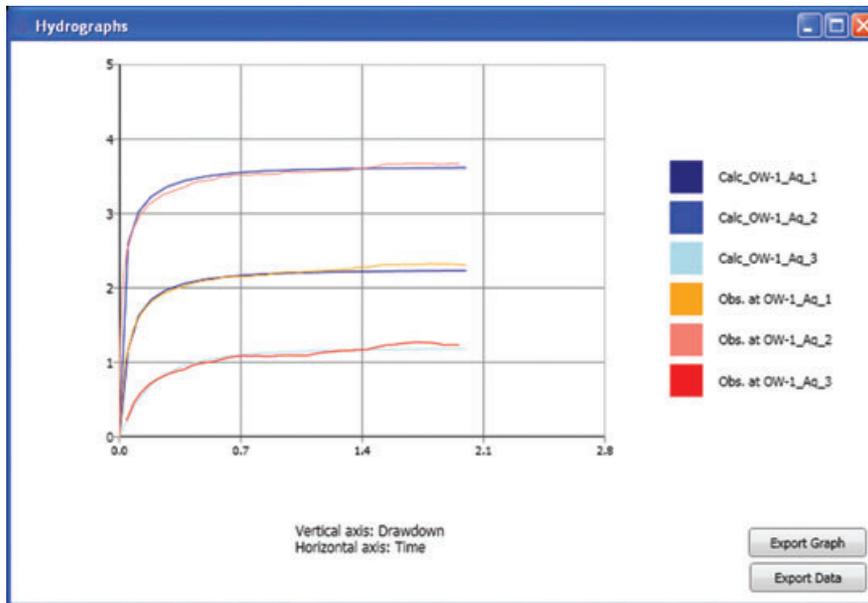
Here is what we liked about AnAqSim:

- Powerful capabilities (multi-layer, anisotropy, transient, etc.) with the rapid model development and scale-independent accuracy of the analytic element method.
- Import of complex basemap graphics (color, polylines, patterns, air photos, etc.) to facilitate AEM model construction.
- Analysis tools for post-processing model results (contours, particle tracking, flow vector plots, numerous graphs and charts, data listings).
- Tech support.
- Price.

### What We Did Not Like

Here are some areas in which AnAqSim could be improved:

- With the exception of certain lists containing domain or boundary feature names, the data entry system places the burden for coordinating all required input data on the modeler. Input dialog boxes that present the user with all required data for a feature, or warning messages for certain missing data prior to execution would be helpful.
- Lack of on-screen point-click-drag editing of model elements and objects.
- Limitation of approximately 5000 equations in current 32-bit version of AnAqSim can limit its application in certain instances.
- Occasional lack of convergence; sometimes difficult to track down source of problem especially for saltwater interface solutions.



**Figure 3. AnAqSim calculated transient drawdown curves matched against test data to estimate aquifer and aquitard hydraulic conductivity and storage coefficient values (system consists of middle aquifer zone that was pumped, separated by aquitards from upper and lower aquifer zones; observation wells in upper, middle, and lower aquifer zones).**

## Overall

Overall AnAqSim provides a new analytic element modeling tool that combines a wide range of capabilities; an ease-of-use factor that, while not at the simple end of the spectrum, is certainly commensurate with the rewards of added capabilities and worth the learning curve; a suite of post-processing and analysis tools that is rich and well thought out to assist the groundwater analyst in understanding the model results; and a price-point that ensures its value. In its inaugural configuration it is a highly useful and powerful analysis tool that, with the addition of a few more features and enhancements, will round out its already outstanding functionality.

## Rankings

The reviewer ranked the software's capability, reliability, ease of use, and technical support on a scale of 1 (worst) to 5 (best):

Capability: 4.0

Reliability: 4.2

Ease of use: 3.8

Tech support: 5.0

## How to Obtain the Software

The software can be downloaded from the vendor's web site at <http://www.AnAqSim.com>. One level of license allows simultaneous use on up to two computers (1 year for \$235; 4 years for \$545), while another allows

simultaneous use on up to six computers for 4 years for \$1090. Discounts are available for previous license holders of TWODAN or AnAqSim, and for academics. The full AnAqSim software may be examined for a 1-week free trial.

## Our Mission

The goal of Software Spotlight is to help readers identify well-written, intuitive, and useful software. Independent reviewers from government, industry, and academia try out full working versions of software packages and provide readers with a concise summary of their experiences and opinions regarding the capability, stability, and ease of use of these packages.

## References

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