Chapter 2 - Introduction to GFLOW

Introduction

GFLOW is a complete groundwater flow modeling software package which combines the following programs:

- GFLOW1 — A single layer Dupuit-Forschheimer groundwater flow model, based on the analytic element method, with imbedded 3-dimensional features, transient wells and conjunctive solution of surface water - ground water interactions
- GAEP — A geographic preprocessor for model creation and modification
- TABLET — A supplemental digitizing program
- GFPRINT — A graphics postprocessor which allows graphical results from GFLOW1 to be printed on a wide variety of devices and exported to other programs as PCX or DXF files

This chapter first introduces the new user to the Analytic Element Method (AEM), and then describes the two main programs in the GFLOW package, GAEP and GFLOW1. These sections are intended as background information, describing briefly the philosophy and capabilities of GFLOW. It is recommended that the new user first read Chapter 2 and then proceed into Chapter 3, the GFLOW Tutorial.

The Analytic Element Method

The analytic element method, developed in the 1980s by Otto Strack (Strack and Haitjema 1981) represents hydrologic features by "analytic elements", each of which has an analytic solution. A detailed description of the analytic element method may be found in (Strack, 1989), while a brief description follows. A model is constructed by arranging elements which describe the boundary conditions for groundwater flow in the domain of interest. For example, a stream which represents a boundary condition for groundwater flow may be represented as a network of line sink elements. The modeling program solves for the (a priori unknown) strength of each feature, e.g. the inflow or outflow rate of each line sink. Once the strengths of all elements are known, the head or groundwater discharge may be determined analytically at any point in the flow domain.

Analytic elements have been developed which represent a wide variety of hydrologic features in two and three dimensions (Strack and Haitjema 1981, Haitjema 1985, Strack 1989). While many different element types are supported in analytic element method programs, very often a basic but useful model can be constructed with a few basic elements such as "wells", "line sinks", and "sink disks", which are supported by GAEP.

Well elements are used to represent the effect of a well on an infinite groundwater flow domain. Wells are usually entered as "discharge-specified" features; for example one would specify the location, radius and pumping rate of a well. The AEM groundwater flow modeling program uses the parameters to determine the influence of the well at any point in the flow domain.

Line sink elements are used to represent the effect of a linear discharge (or recharge) feature, such as a portion of a surface stream, on the groundwater flow domain. Line sinks can be thought of as discrete linear segments of a stream, each of which extracts water at a constant rate. In most cases, the modeler does not know the seepage rate into or out of a stream segment, but he knows the average elevation of water in the channel. A stream may be modeled as a network of "head-specified" line sinks with different heads. The modeling program determines the line sink discharges given information about all elements in the model. The modeler determines the number of line sinks to be used to represent a given stream reach based upon the nearness of the reach to the study region and the desired resolution of the solution.

Circular sink disks can be used to represent the effect of an areal recharge feature, for instance a lake or wetland, on the flow domain. These elements can be used as "discharge-specified" features for adding areal recharge, or as "head-specified" features to simulate lakes and wetlands of known head.

GAEP - The Geographic Analytic Element Preprocessor

Modelers who are familiar with the finite difference and finite element methods for groundwater flow modeling are familiar with input preprocessors. The preprocessor simplifies model generation by automating the discretization of boundary conditions and aquifer property data into model cells. These preprocessors are unnecessary when modeling with analytic element method programs like GFLOW1, because the analytic element method does not break the aquifer domain into cells but models boundary conditions, wells and aquifer inhomogeneities as distinct features, or "elements". This allows for fairly straightforward procedures for data management, as compared to traditional numerical models.

Most analytic element groundwater modelers prepare models by sketching elements on a topographic map and estimating their attributes (elevations, changes in permeability, etc.). Element locations are then digitized using a digitizer or an overlaid grid. If the modeler determines during the modeling process that a feature should be removed from the model or that additional model detail is necessary, he must return to the digitizing step to assemble the refined model. The repetitive process of returning to maps and digitizing is time-consuming and can discourage modelers from evaluating a wide variety of model scenarios.

The direct correlation between analytic elements and hydrologic features on maps may be exploited by the development of computer-aided tools for model preparation. A digital mapping tool, GAEP (Geographic Analytic Element Preprocessor), is provided as part of GFLOW. GAEP provides tools for digitizing maps with no regard to the ultimate model requirements. Creation and modification of elements from these digital maps is performed on the modeler's computer screen using a mouse. Providing the modeler with the ability to quickly modify the element layout allows the modeler to examine numerous model scenarios, improving his understanding of the groundwater flow field.

GAEP removes the time-consuming process of returning to topographic maps at each step in a modeling effort. Geographic data sets (in the form of digital maps), can be developed in a single digitizing step. Creation of digital maps can be accomplished without regard to any eventual model details and may be performed by a non-modeler. Once a digital map for a region has been produced, it can be re-used for other projects.

Role of the Preprocessor GAEP

When building a groundwater flow model, the modeler needs to know the boundary conditions controlling flow, such as the locations of surface hydrologic features and their elevations. A common source for hydrographic information is the $7^1/_2$ minute (1:24,000 series) topographic maps available from the U.S. Geological Survey. These maps locate surface water features and give reasonable information about their average water levels. Using surface water elevations as piezometric head boundary conditions assumes that the surface water feature is in full communication with groundwater. Modelers must evaluate this assumption as part of the modeling process. In addition to hydrography already delineated on the maps, the locations of pumping and injection wells and points of observed static water levels can be located and plotted on these maps.

GAEP provides facilities for digitizing and editing digital maps of hydrography. These maps include hydrologic features such as streams, wells and lakes and simple "background " map features such as roads and political boundaries for orientation. When complete, the digital map is used to create and manage input files which define the aquifer properties and boundary conditions needed by the AEM modeling program.

The Modeling Process Using Digital Maps

Analytic element modelers often work in a stepwise fashion, first defining a "rough" model of regional flow using only a few elements, then adding detail where required to understand flow within a detailed study region. GAEP allows the modeler to build and edit analytic elements for the model region directly on his computer screen without the use of maps and digitizer at each step in the modeling process.

A facility for generating analytic elements directly from digital maps allows the modeler to work exclusively on modeling once a digital map is available. The improvements in speed and flexibility in the creation and refinement of the element layout makes it possible for the modeler to perform numerous modeling scenarios. The modeler's understanding of groundwater flow in his study region is improved by the analysis of a variety of scenarios for hypothesis testing.

Digital map generation and verification is a routine procedure which does not need to be performed by a hydrologist. It may be avoided altogether by the use of prepared digital maps purchased from Haitjema Software, LLC. In any case, the modeler need not be involved. Digital maps can be re-used on other projects in a geographic region. Since many modelers already possess base map information such as road and building locations in CAD or GIS systems, GAEP supports the direct importation of Drawing Interchange Format (DXF) files for base maps.

<u>Program GFLOW1</u>

GFLOW1 is a single aquifer steady state groundwater flow model based on the *analytic element method*. In general, GFLOW1 adopts the *Dupuit-Forchheimer* assumption; ignoring resistance to vertical flow in the aquifer. Yet, in addition to the horizontal groundwater flow velocities, GFLOW1 also calculates (approximate) vertical flow velocities, supporting streamline tracing in three dimensions!

In zones of confined flow (horizontal parallel aquifer boundaries) the user may locally include a complete three-dimensional solution to a partially penetrating well and, or a three-dimensional solution to a sink disc. Locally, the user may also include "transient wells", based upon Theis' solution, to simulate periodic pumping activities.

Conjunctive Groundwater and Surface Water Solutions

An important feature of GFLOW1 is its capability to solve groundwater flow and surface water flow conjunctively. Both solutions are steady state (average conditions). This feature greatly improves the realism with which GFLOW1 handles boundary conditions, at least when compared to traditional models that do not include stream flow solutions. During the groundwater solution procedure GFLOW1 limits infiltration rates of surface waters based on maximum possible leakage rates through a resistance layer underneath the surface water, or if not present, based on the maximum steady state infiltration rate into the aquifer. During conjunctive surface water and groundwater flow solutions, stream flow is estimated based on groundwater inflow, while losing surface water features have infiltration rates limited by surface water availability.

Interactive Graphics

GFLOW1 is advanced in its interactive graphics features. Stream flow can be plotted with the stream width proportional to the flow. Losing or percolating surface water features can be highlighted on the screen. Data related to analytic elements such as line sinks, sink discs, wells, and inhomogeneity domains, can be inspected and modified graphically by use of a mouse cursor and key strokes selected from a menu. Plots of piezometric contours can be annotated by contour labels (point and shoot method) and text strings. Errors in the boundary conditions can be displayed graphically with line width proportional to the percent error. Differences between modeled and observed heads can be displayed by use of triangles whose size is proportional to the difference and whose color and orientation indicates whether the modeled head is higher or lower than observed. Any graphics screen can be reproduced on a printing device (over 100 printers supported) by simply pressing <F7> which calls up a menu driven printing utility GFPRINT. When printing is completed (or the printing file archived) the user is returned to the graphics screen in GFLOW1 as he or she left it. For most printers various resolutions black and white and color graphics are supported. In addition, grids for contouring, element layout, and 3-D streamlines can be written to SURFER compatible files for creating 3-D visualizations.

Analytic Elements in GFLOW1 and Their Use

The following analytic elements are supported in GFLOW1:

- Steady state wells (2D)
- Transient wells (2D)
- Partially penetrating wells (3D)
- Line sinks (2D)
- Sink Discs (2D)
- Sink Discs (3D)
- Line doublet strings (2D)
- Uniform flow (2D)

A brief explanation of their use in GFLOW1 follows. More detailed information about these analytic elements is found in the GFLOW1 reference manual. Some additional background information is found in appendix A.

Steady state wells

Wells may be discharge or head specified. Discharge specified wells are most common: municipal wells, industrial wells, irrigation wells, etc. Head specified wells may be used to model dewatering systems or contaminant recovery systems with waterlevel control switches.

Transient wells

These are discharge specified only and are based on Theis' equation. They are useful to simulate pumping tests, or periodic pumping scenarios. If not used properly, transient wells may corrupt the conditions set at nearby boundary conditions, see the reference manual for details.

Partially penetrating wells

These wells may be discharge specified or head specified. They should only be used in areas of confined flow. The user may specify the radius and the elevations of the start and end of the well screen. A fully three-dimensional flow solution is generated by this analytic element.

Line sinks

Line sinks may be discharge or head specified. Discharge specified line sinks are useful for modeling French Drains with a known pumping rate. Head specified line sinks are used to model rivers, creeks, canals, and lakes. When modeling lakes or large (wide) rivers, the line sinks are situated along the lake or river boundary. Line sinks may be given a width and resistance for flow between the surface water feature and the aquifer (e.g. due to a clay or silt layer). Line sinks used to model a stream and its tributaries may also be entered as strings (stream features) and are organized in GFLOW1 into stream networks. The (steady state) stream flow and groundwater flow problem are then solved conjunctively by GFLOW1. Stream flow can be represented graphically by plotting the stream width proportional to the stream flow. GFLOW1 also allows for spreadsheet files to be written which contain all relevant information for a stream reach (stream flow, base flow, infiltration per line sink, specified stream levels, heads underneath the stream, etc.).

Sink discs (2D)

May be discharge or head specified. Discharge specified sink discs may be used to add local recharge to the top of the aquifer or model local leakage at the bottom of the aquifer into or out of a lower aquifer (which is not in the model). Head specified sink discs may be used to model small lakes or wetlands.

Sink Discs (3D)

A three-dimensional version of the two-dimensional sink disc. Should only be used in zones of confined flow. These three-dimensional sink discs are useful to test the adequacy of the Dupuit-Forchheimer solution for areal and local infiltration or leakage.

Line Doublet strings

Line doublet strings are used to model closed domains with different hydraulic conductivity, porosity, and areal recharge rate due to precipitation. These inhomogeneity zones are useful for modeling, for instance, channel deposits near streams which often have both a higher hydraulic conductivity (gravely formations) and receive more areal recharge than the regional aquifer. Inhomogeneity domains may be nested, but cannot have common boundaries.

Uniform flow

Uniform flow may be useful for simple conceptual models whereby the uniform flow approximates the regional flow generated by remote boundary conditions and areal recharge due to precipitation. Uniform flow, in general, is not used in complete regional models, in which nearfield hydrological features are surrounded by farfield features, see also appendix A.