

The modular finite-difference ground-water flow model (MODFLOW) developed by the U.S. Geological Survey (USGS) is a computer program for simulating common features in ground-water systems (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The program was constructed in the early 1980's and has continually evolved since then with development of many new packages and related programs for ground-water studies. Currently, MODFLOW is the most widely used program in the world for simulating ground-water flow. The popularity of the program is attributed to the following factors:

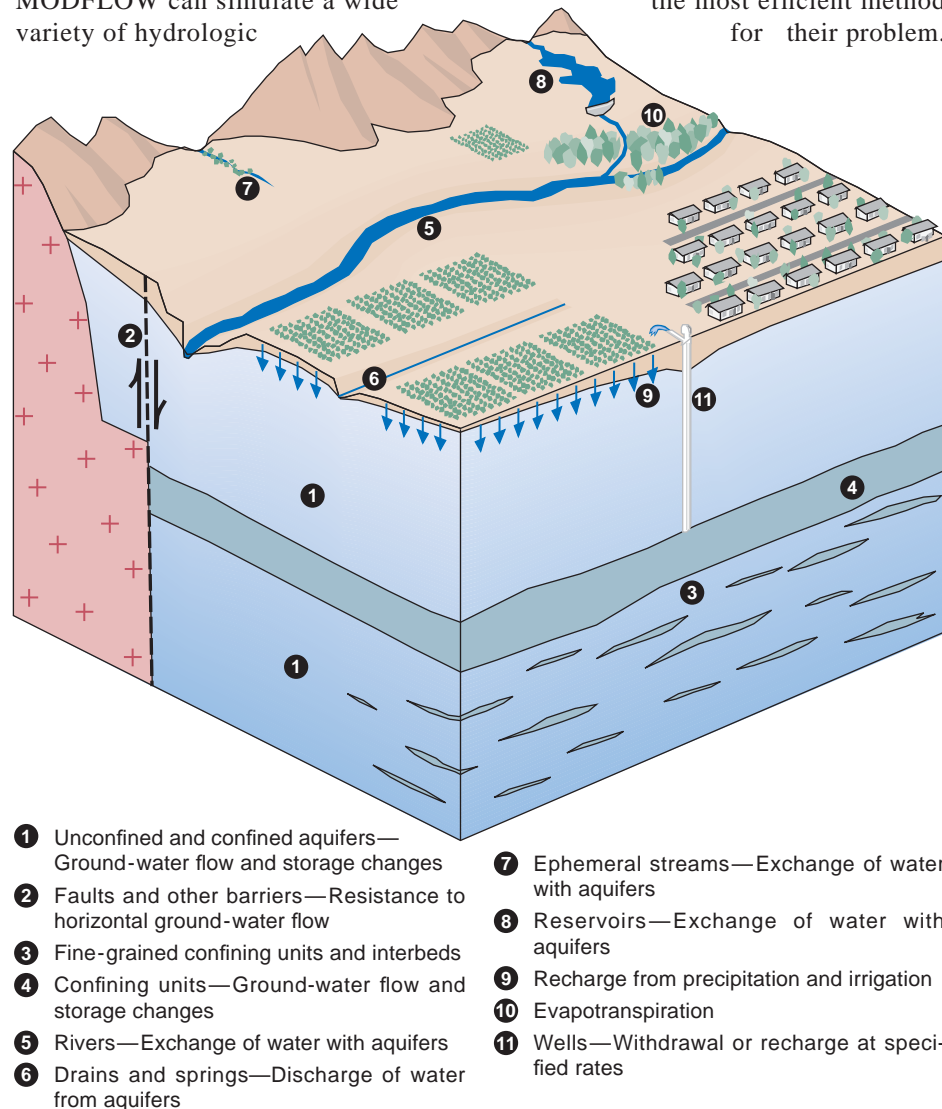
- The finite-difference method used by MODFLOW is relatively easy to understand and apply to a wide variety of real-world conditions.
- MODFLOW works on many different computer systems ranging from per-sonal computers to super computers.
- MODFLOW can be applied as a one-dimensional, two-dimensional, or quasi-or full three-dimensional model.
- Each simulation feature of MODFLOW has been extensively tested.
- Data input instructions and theory are well documented.
- The modular program design of MODFLOW allows for new simulation features to be added with relative ease.
- A wide variety of computer programs written by the USGS, other federal agencies, and private companies are available to analyze field data and construct input data sets for MODFLOW.
- A wide variety of programs are available to read output from MODFLOW and graphically present model results in ways that are easily understood.
- MODFLOW has been accepted in many court cases in the United States as a legitimate approach to analysis of ground-water systems.

This publication outlines the major features of MODFLOW and several related programs and gives information on obtaining programs and documentation.

Simulation Capabilities of MODFLOW

MODFLOW is designed to simulate aquifer systems in which (1) saturated-flow conditions exist, (2) Darcy's Law applies, (3) the density of ground water is constant, and (4) the principal directions of horizontal hydraulic conductivity or transmissivity do not vary within the system. These conditions are met for many aquifer systems for which there is an interest in analysis of ground-water flow and contaminant movement. For these systems, MODFLOW can simulate a wide variety of hydrologic

features and processes (fig. 1). Steady-state and transient flow can be simulated in unconfined aquifers, confined aquifers, and confining units. A variety of features and processes such as rivers, streams, drains, springs, reservoirs, wells, evapotranspiration, and recharge from precipitation and irrigation also can be simulated. At least four different solution methods have been implemented for solving the finite-difference equations that MODFLOW constructs. The availability of different solution approaches allows model users to select the most efficient method for their problem.



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| <ul style="list-style-type: none"> ① Unconfined and confined aquifers—Ground-water flow and storage changes ② Faults and other barriers—Resistance to horizontal ground-water flow ③ Fine-grained confining units and interbeds ④ Confining units—Ground-water flow and storage changes ⑤ Rivers—Exchange of water with aquifers ⑥ Drains and springs—Discharge of water from aquifers | <ul style="list-style-type: none"> ⑦ Ephemeral streams—Exchange of water with aquifers ⑧ Reservoirs—Exchange of water with aquifers ⑨ Recharge from precipitation and irrigation ⑩ Evapotranspiration ⑪ Wells—Withdrawal or recharge at specified rates |
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Figure 1. Features of an aquifer system that can be simulated by MODFLOW.

Application of MODFLOW

MODFLOW simulates ground-water flow in aquifer systems using the finite-difference method. In this method, an aquifer system is divided into rectangular blocks by a grid (fig. 2). The grid of blocks is organized by rows, columns, and layers, and each block is commonly called a “cell.”

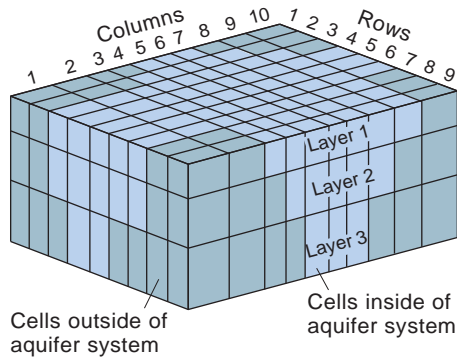


Figure 2. Example of model grid for simulating three-dimensional ground-water flow.

Model Input

For each cell within the volume of the aquifer system, the user must specify aquifer properties. Also, the user specifies information relating to wells, rivers, and other inflow and outflow features for cells corresponding to the location of the features. For example, if the interaction between a river and an aquifer system is simulated, then for each cell traversed by the river, input information includes layer, row, and column indices; river stage; and hydraulic properties of the river bed.

Model Output

MODFLOW uses the input to construct and solve equations of ground-water flow in the aquifer system. The solution consists of head (ground-water level) at every cell in the aquifer system (except for cells where head was specified as known in the input data sets) at intervals called “time steps.” The head can be printed and (or) saved on a computer storage device for any time step. Hydrologists commonly use water levels from a model layer to construct contour maps for comparison with similar maps drawn from field data. They also compare computed water levels at

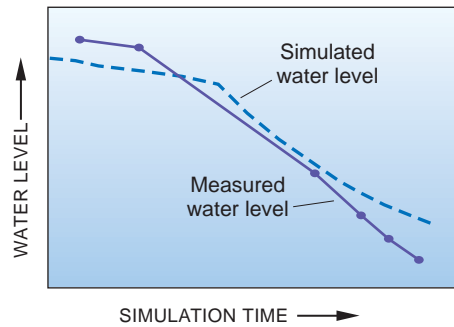


Figure 3. Example comparison of computed and measured water levels.

individual cells with measured water levels from wells at corresponding locations to determine model error (fig. 3). The process of adjusting the model input values to reduce the model error is referred to as model calibration.

In addition to water levels, MODFLOW prints a water budget for the entire aquifer system. The budget lists inflow to and outflow from the aquifer system for all hydrologic features that add or remove water.

Other program output consists of flow rates for each model cell. MODFLOW can write the flow rates onto a computer storage device for any hydrologic feature in a simulation. These cell-by-cell flow rates commonly are read by post-processing programs for detailed analysis of the simulated ground-water system.

Inverse Modeling with MODFLOW

In conventional or “forward modeling,” model parameters (such as aquifer properties) are specified and water levels and flow quantities are computed (fig. 4). For most aquifer systems, however, more information is available from field data on water levels, flows, and advective transport or ground-water age than on input

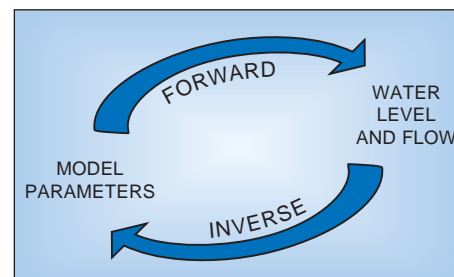


Figure 4. Forward and inverse approaches to modeling.

parameters. Typically, input parameters are adjusted during model calibration using a trial-and-error process. This calibration process can yield acceptable agreement between computed model results and field data but is time consuming, may not produce parameter values that result in the best fit of field data, and does not result in quantitative estimates of uncertainty in model results and estimated parameter values.

Inverse modeling is a more formal approach to model calibration that includes automatic parameter adjustment in order to match field data. Program MODFLOWP (pronounced MOD•FLOW•P) is the USGS version of MODFLOW that includes automatic parameter estimation (Hill, 1992). MODFLOWP uses a weighted least-squares objective function as a measure of how well model results agree with field measurements. Weights are used to reflect reliability of individual measurements. Parameters that can be estimated by MODFLOWP include transmissivity; hydraulic conductivity; storage coefficient; vertical leakage; vertical and horizontal anisotropy; hydraulic conductance between aquifer systems and rivers, drains and other features; areal recharge; maximum evapotranspiration; pumping; and water levels at constant-head boundaries. Measured or externally estimated information on parameters also can be included. Parameter values that minimize the objective function (fig. 5) are calculated by MODFLOWP using the modified Gauss-Newton method or the conjugate-direction method. The resulting parameter values are “best-fit” in that they provide the closest match between measured and simulated heads and flows, as measured by the objective function. The task of the modeler is to evaluate how well these calculated values represent the physical system being simulated.

Model output includes estimates of parameters and statistics relating to the parameter estimates. The statistics can be used to quantify the reliability of the resulting model, suggest changes in model construction, and compare results of models constructed in different ways. Post-processors can be used to calculate confidence intervals on predicted heads and flows to depict prediction uncertainty. To effectively use MODFLOWP, an understanding of principles of ground-water flow and basic statistics is needed.

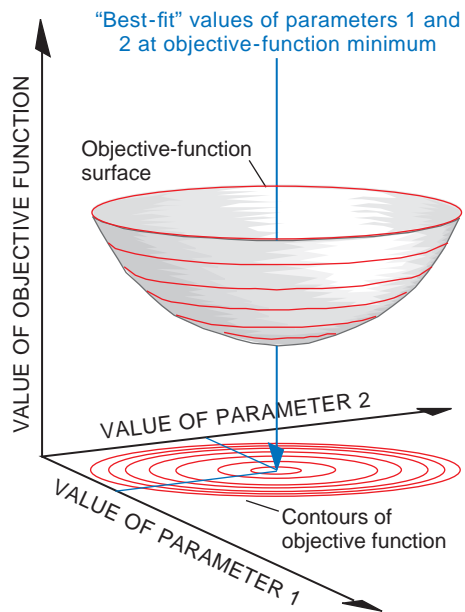


Figure 5. Example of an objective function and "best-fit" parameter values for a linear problem with two parameters.

Particle Tracking with MODPATH

Many studies require information such as the average rate of movement of ground water and contaminants. Also, information often is needed on the recharge or capture areas for water discharging to wells, springs, stream reaches, and other features. Although MODFLOW does not compute this information directly, simulation with MODFLOW provides basic information needed for such analyses. The particle-tracking program, MODPATH, is a post-processing program for MODFLOW to estimate flow paths (fig. 6) and times of travel in ground-water systems. An accompanying program, MODPATH-PLOT, displays particle paths, contours, and model features.

MODPATH can be used for studies of steady-state and transient flows. Common applications include studies of paths and time of travel of contaminant movement (fig. 7); and source (recharge) areas of wells, springs, rivers, and other features.

MODPATH can place particles at specified locations or generate starting locations of arrays of particles in selected regions. Particles can be tracked forward from starting locations to calculate where water is going or backwards to map where it came from. Multiple particle-release times can be used to simulate "plumes" of contamination.

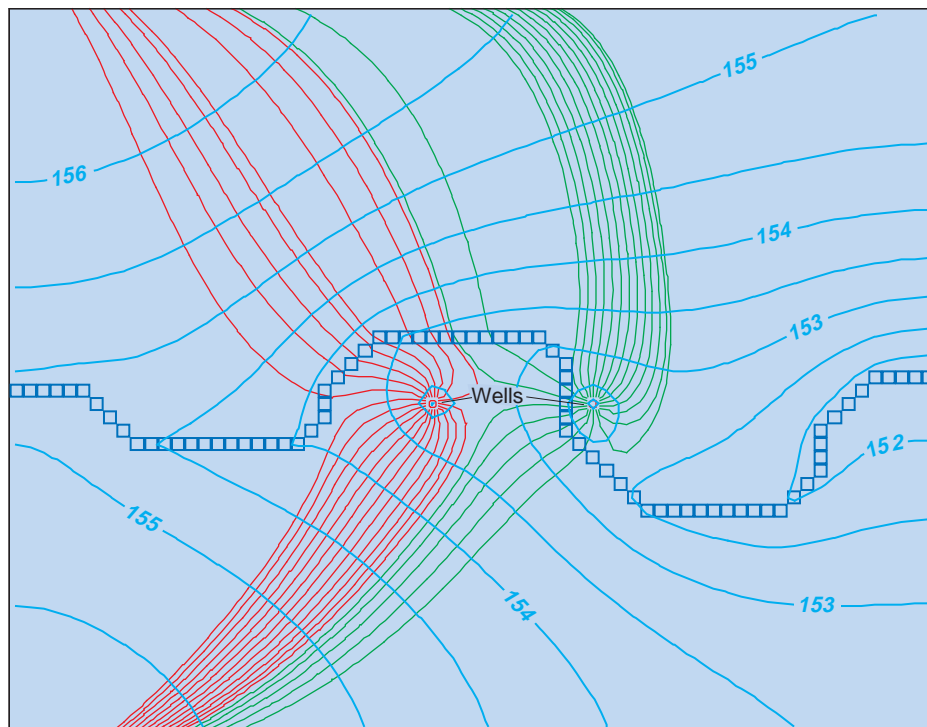


Figure 6. Flow paths of particles discharging at two wells. Pathlines were computed by MODPATH and are denoted by red and green lines. Blue squares are river cells and light blue lines are contours of water levels, in feet above sea level, computed by MODFLOW.

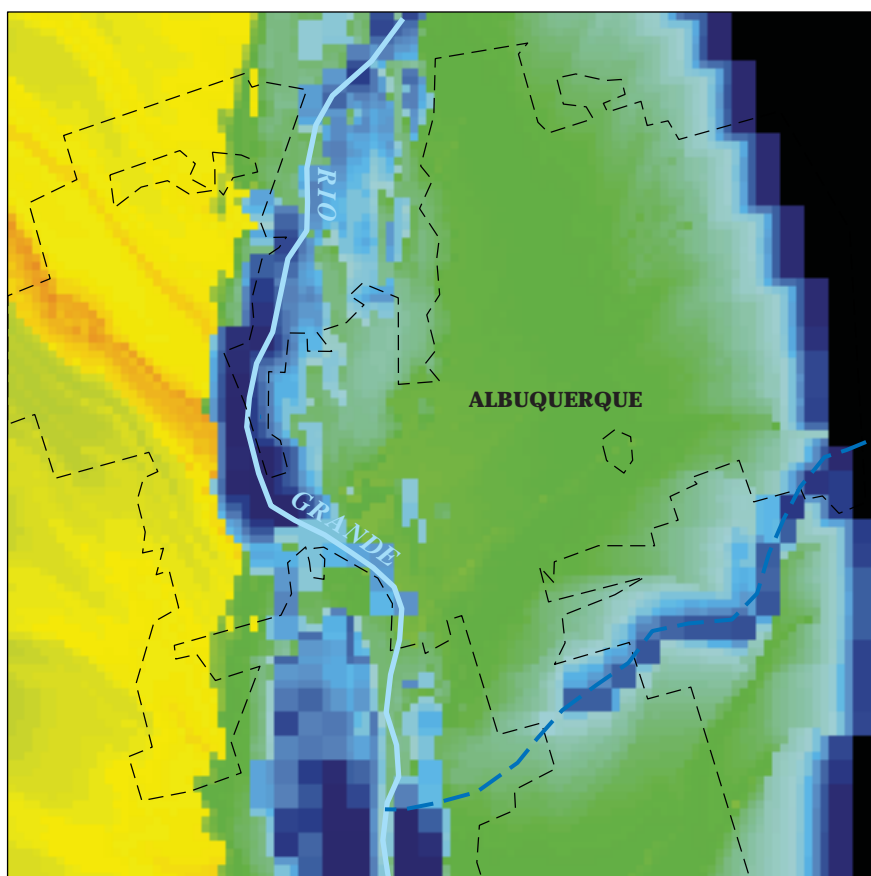
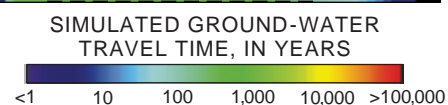


Figure 7. Application of particle tracking to estimate ground-water travel time.



Solute Transport with MOC3D

To evaluate or remediate contaminated aquifers, it is important to be able to compute the concentration of dissolved chemicals. Hydrologists and water managers need to know how contaminants will spread in the future, or how the concentration distributions will respond to changes in the flow field that might arise from new water-supply stresses, remediation efforts, or other management activities.

MOC3D is a solute-transport program that is integrated with MODFLOW and has the capability to calculate changes in concentration (fig. 8) of a single solute as affected by processes of advection, dispersion, diffusion, fluid sources, decay, and retardation. In addition to input data requirements for MODFLOW, the user must also define porosity, thickness, dispersivity, initial concentrations, and source-fluid concentrations. Model output includes the calculated concentration distribution in space and time.

MOC3D is based on a particle-tracking method coupled with an explicit finite-difference procedure. This numerical technique is optimal for advection-dominated problems.

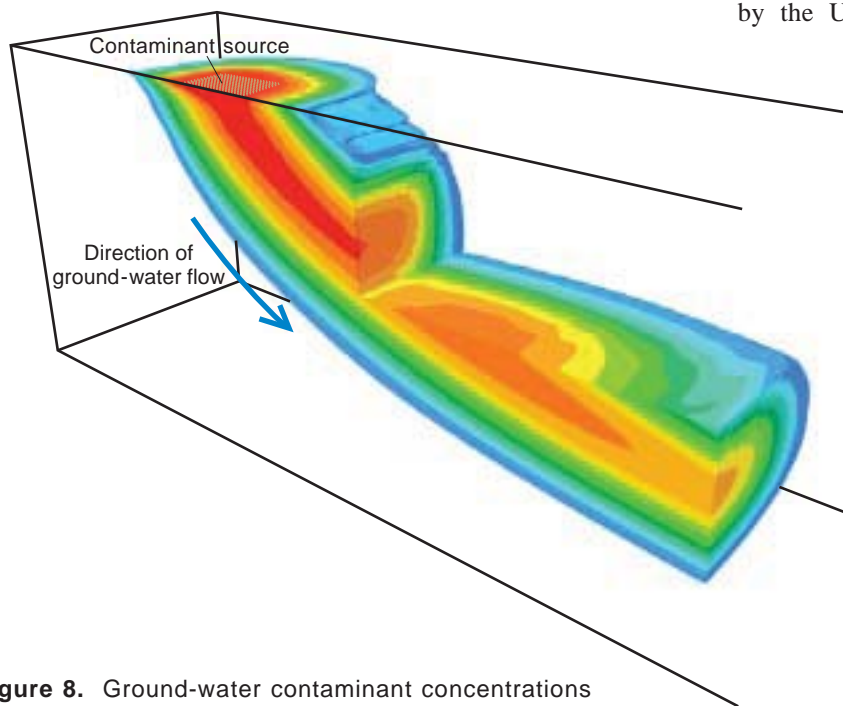


Figure 8. Ground-water contaminant concentrations computed by MOC3D. Colors represent different concentration ranges, with highest contaminant concentrations in red and lowest concentrations in blue.

Alternative numerical methods are planned to broaden the range of types of field problems for accurate and efficient application of the model.

How to Obtain Ground-Water Model Programs, Documentation, and Additional Information

Additional references for USGS computer programs for ground-water simulation are given by Appel and Reilly (1994). Many of the programs including MODFLOW, MODFLOWP, MODPATH, and MOC3D are available from the USGS at no cost at World Wide Web site <http://water.usgs.gov/software/>. The site includes links to download program source code and compiled versions for some computers. Also, some of the programs are available by anonymous ftp from Internet site [water.usgs.gov](http://water.usgs.gov/pub/software/ground_water/) in the directory [pub/software/ground_water/](http://water.usgs.gov/pub/software/ground_water/).

The MODFLOW program obtained from the USGS includes most simulation capabilities currently documented by the USGS. Added features for MODFLOW have been documented in separate reports. A bibliography of the documentation reports is included with copies of MODFLOW distributed by the USGS.

Reports documenting USGS model programs can be purchased from [U.S. Geological Survey Branch of Information Services](http://www.water.usgs.gov) Box 25286 Denver, CO 80225-0286

For information on local USGS studies and research applications of the MODFLOW family of computer programs, contact the USGS state representative for the area of interest. A list of state representatives is available from the World Wide Web site <http://water.usgs.gov/public/wrd011.html/>.

—S.A. Leake

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