
APPENDIX A GROUNDWATER MODEL DOCUMENTATION

APPENDIX A
GROUNDWATER MODEL DOCUMENTATION

A.1 BACKGROUND AND THEORY

The three-dimensional movement of groundwater through a porous aquifer under constant density conditions is described using the following partial-differential equation

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t}$$

where

K_{xx} , K_{yy} , and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are parallel to the major axes of hydraulic conductivity (L/t);

h is the potentiometric head (L);

W is a volumetric flux per unit volume and represents sources/sinks of water (t^{-1});

S_s is the specific storage of the porous material (L^{-1}); and

t is time (t).

For a complete derivation of the above equation and a detailed theoretical summary of the MODFLOW model see McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). The SSA groundwater model developed for this study uses MODFLOW96 (Harbaugh and McDonald, 1996), supplemented with a lake package to simulate the aquifer interaction with the Salton Sea. The lake package theory is included in Section A.4.

A.2 COMPUTER IMPLEMENTATION

The mathematical equation given above is solved using finite-difference techniques and implemented in a computer program. Documentation of the computer program and a users manual can be found in McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996). Documentation of the computer program and a users manual for the lake package is included in Section A.4. Documentation, a users manual, and copies of the model MODFLOW96 can be downloaded free of charge from the Internet at

the following USGS address: <http://water.usgs.gov/software/modflow-96.html>. A USGS Summary of MODFLOW is also included in Section A.4

A.3 SSA SEEPAGE MODEL CALIBRATION

This section presents additional figures and tables documenting the groundwater calibration, including plots of simulated and measured water levels and an analysis of the model error, which were only briefly summarized in the main body of the report.

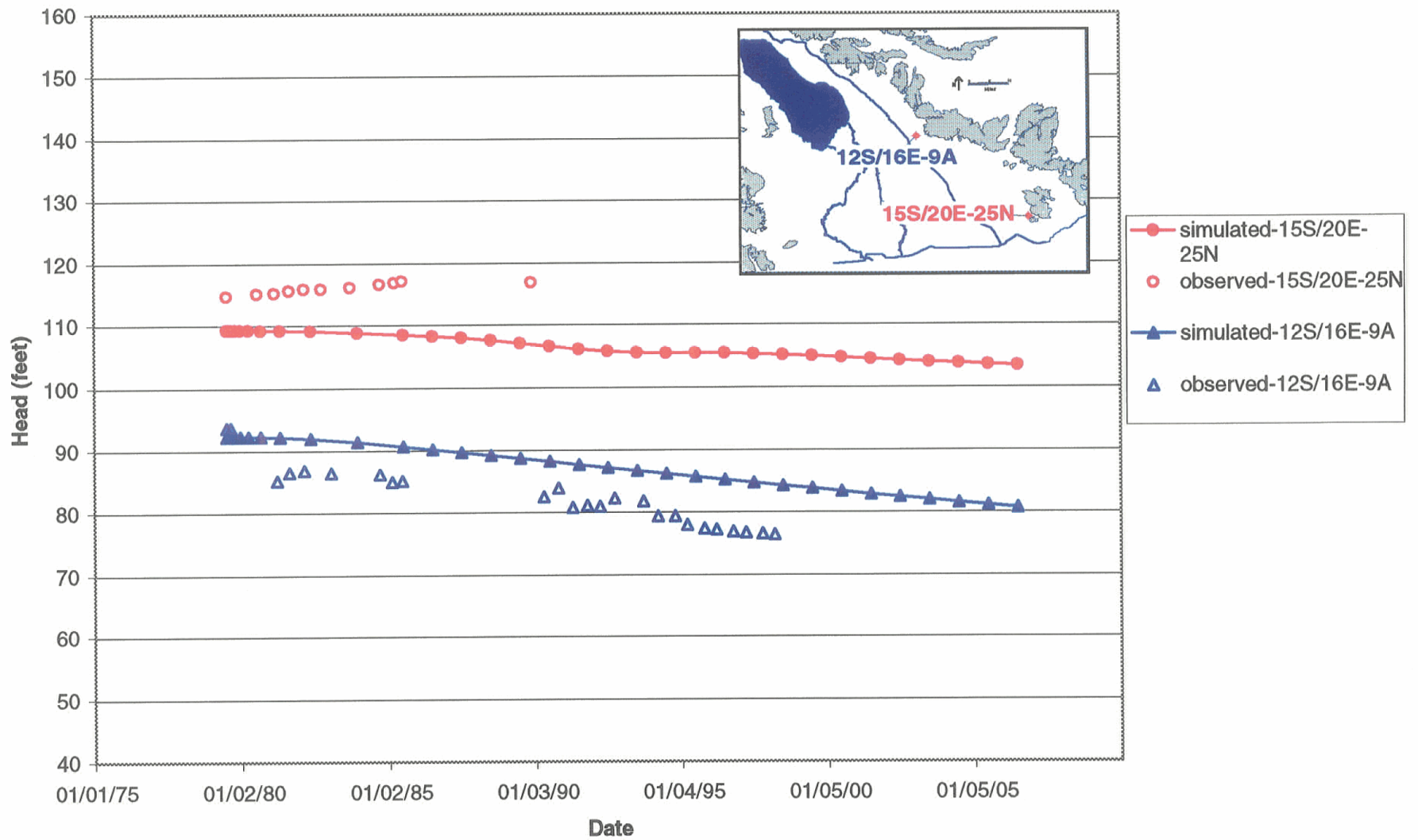


Figure A-1. Hydrographs showing Simulated and Observed Water Levels in Wells 15S20E25N and 12S16E9A

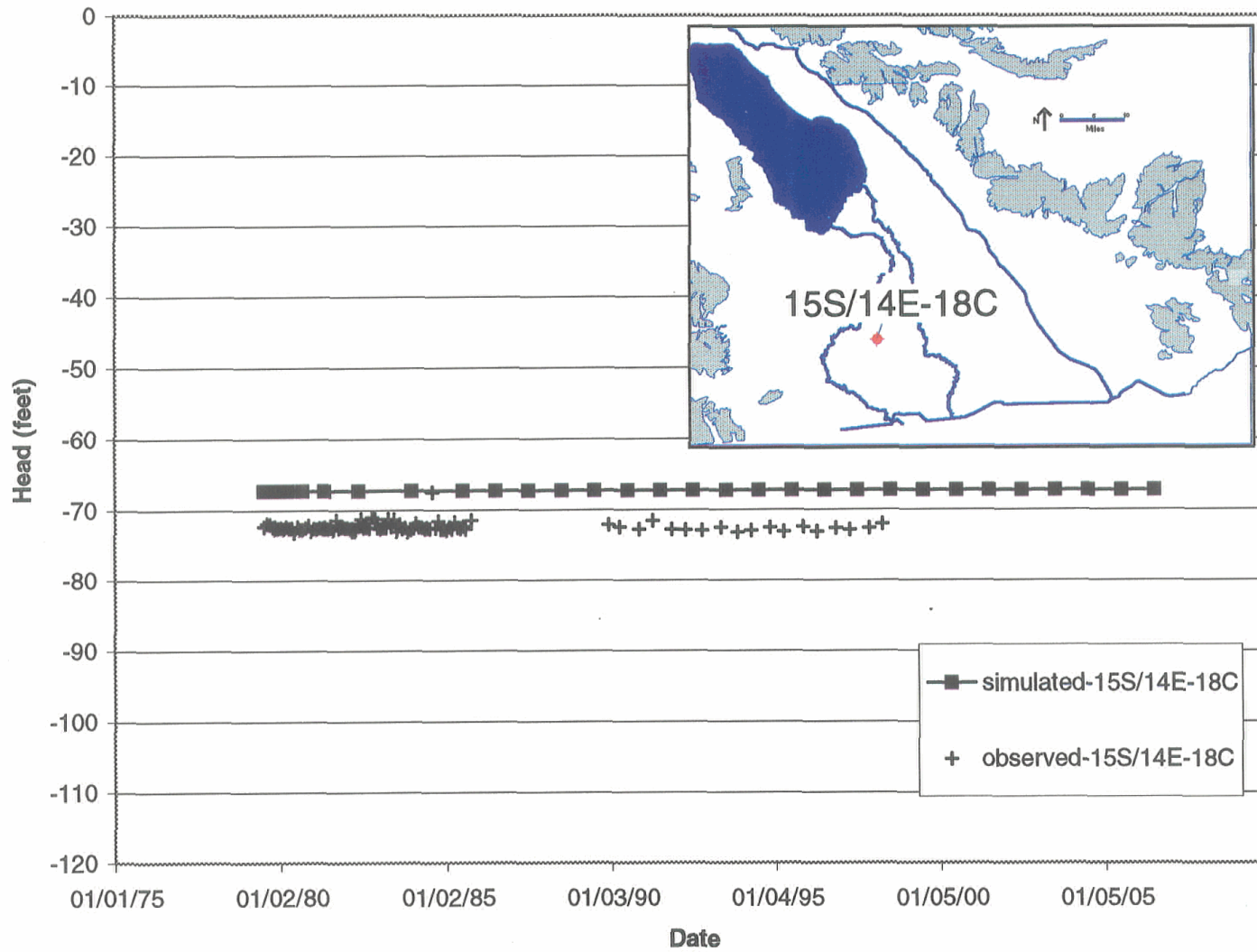


Figure A-2 . Hydrographs showing Simulated and Observed Water Levels in Well 15S14E18C

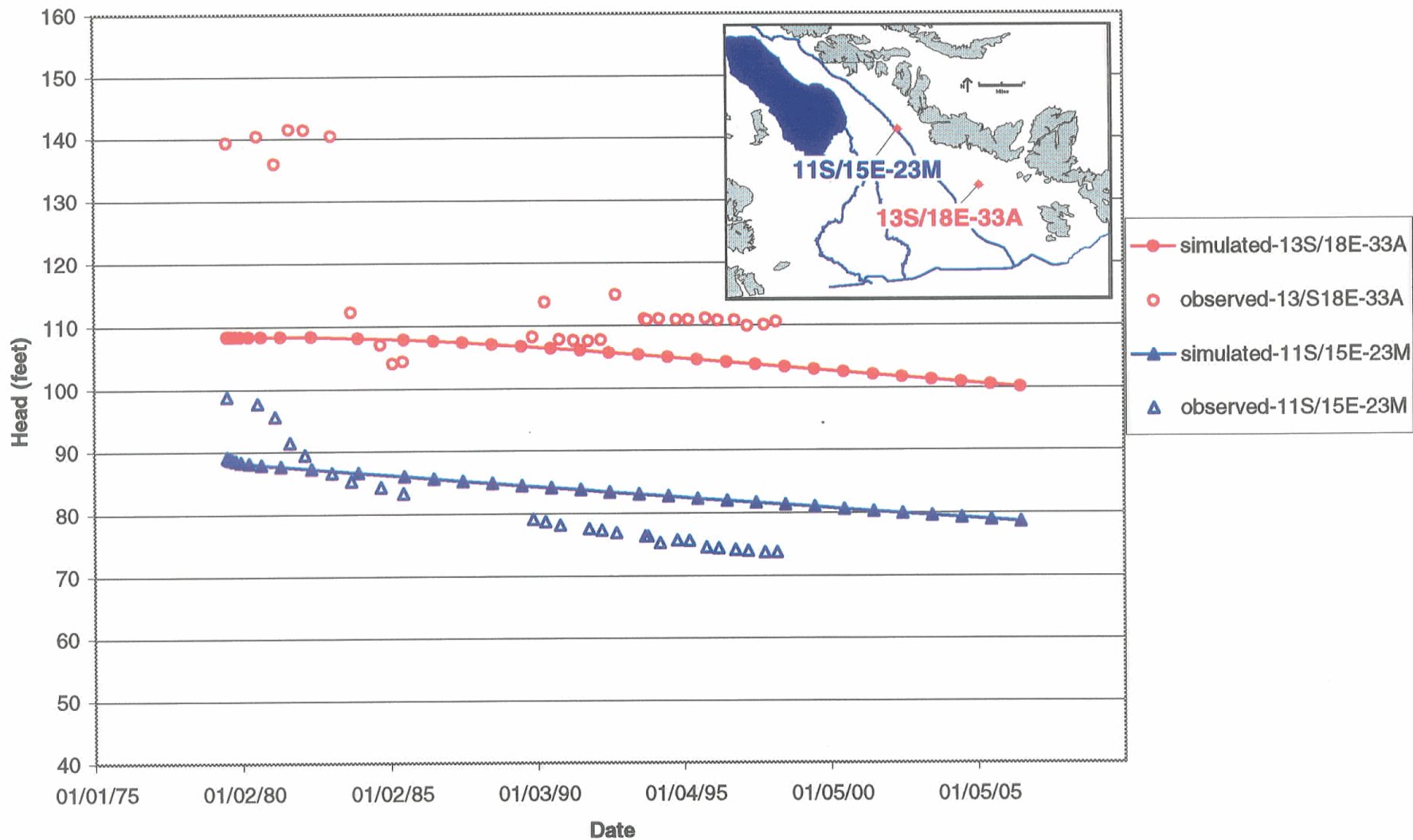


Figure A-3 . Hydrographs showing Simulated and Observed Water Levels in Wells 13S/18E-33A and 11S/15E-23M

A.4 SSA SEEPAGE MODEL SUPPORTING DOCUMENTATION

Section A.4.1 provides supporting documentation on the theory of the MODFLOW lake package. Section A.4.2 provides supporting documentation for the MODFLOW lake package users manual. See also Appendix B for model execution instructions. Section A.4.3 provides a USGS summary of MODFLOW, including an extensive reference list and historical overview of the model development.

THIS PAGE INTENTIONALLY LEFT BLANK

Section A.4.1

A Lake Package for MODFLOW

A STUDY ON SEEPAGE AND SUBSURFACE INFLOWS
TO SALTON SEA AND ADJACENT WETLANDS

THIS PAGE INTENTIONALLY LEFT BLANK

A Lake Package for MODFLOW

Gregory W. Council
HSI GeoTrans
1080 Holcomb Bridge Rd, Building 200 Suite 305
Roswell, GA 30076.

ABSTRACT

A new package was developed for simulating lake-groundwater interaction with MODFLOW. This Lake package calculates lake level fluctuations resulting from simulated environmental stresses. Four simulation modes are provided: 1) steady-state mode to compute the lake stage in equilibrium with ground-water head, 2) transient mode to compute stage as a function of time, 3) specified-stage mode with the stage held constant during stress periods, and 4) specified-stage mode with stage varying linearly during stress periods. The Lake package is also linked to the Streamflow Routing package to simulate lake-stream interaction. General equations of stream outflow as a function of lake stage are used. This Lake package provides a broader range of features than previously-documented lake and reservoir packages.

The Lake package is effective because it allows a MODFLOW user to treat lake stage as an unknown variable, it adjusts a lake's area (the number of wetted cells) and flow budget as the stage changes, and it automatically updates the flow into connected streams. With the Lake package, a single model can be used to predict the effect of a groundwater stress (e.g. a pumping well or mine) on aquifer heads and nearby lake levels.

The package has been applied at a proposed underground mine site in northern Wisconsin. Transient and steady-state simulations were used to predict lake level decline at four lakes in response to mine operation.

INTRODUCTION

Numerical models of groundwater and surface water flow help us understand environmental systems, identify the important parameters affecting flow, and predict responses to various types of development (e.g. drilling a well to remove groundwater from an aquifer, installing a control structure on a lake, or dewatering the underground workings of a mine). Traditionally, separate models have been used to analyze surface water and groundwater resources. However, it is often important to recognize that the interaction between surface water and groundwater requires a model that incorporates both components. A change in groundwater head can affect the water level in overlying lakes and vice-versa, because of flow through

permeable lakebeds. The surface water and groundwater systems are thus coupled, and a model that analyzes both systems simultaneously is often desirable.

Figure 1 depicts a lake and its volumetric budget components. The various inflows and outflows are used to determine the stage (water elevation) of the lake. In order to properly model the lake, all of the volumetric components must be accounted for. In many applications, many of the lake budget components will vary as the (potentially unknown) lake stage changes. The Lake package for MODFLOW (LAK2 Version 2.2) handles the lake-groundwater and lake-stream interactions including allowances for lake expansion and contraction, multiple inflow and outflow streams, and user-specified stage-outflow relationships. The user can choose to have the model calculate the steady-state or transient lake stage, or the stage can be specified as a linear function of time.

The Lake package was developed as part of a broad study of the environmental effects of a proposed mine in Northern Wisconsin (Foth & Van Dyke, 1995). As part of the regulatory permitting process, a MODFLOW model was developed to determine the effect of proposed mining on groundwater and surface water in the vicinity of the mine. Using the Lake package, the model predicts the amount of decline in lake stage at four lakes of interest at the site. That study demonstrates the package's utility and is discussed in greater detail later in this paper.

DEVELOPMENT HISTORY

MODFLOW and Standard Packages

The MODFLOW program solves (via iterative approximations) the groundwater flow equation, which is a combination of the continuity equation and Darcy's Law:

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} \quad (1)$$

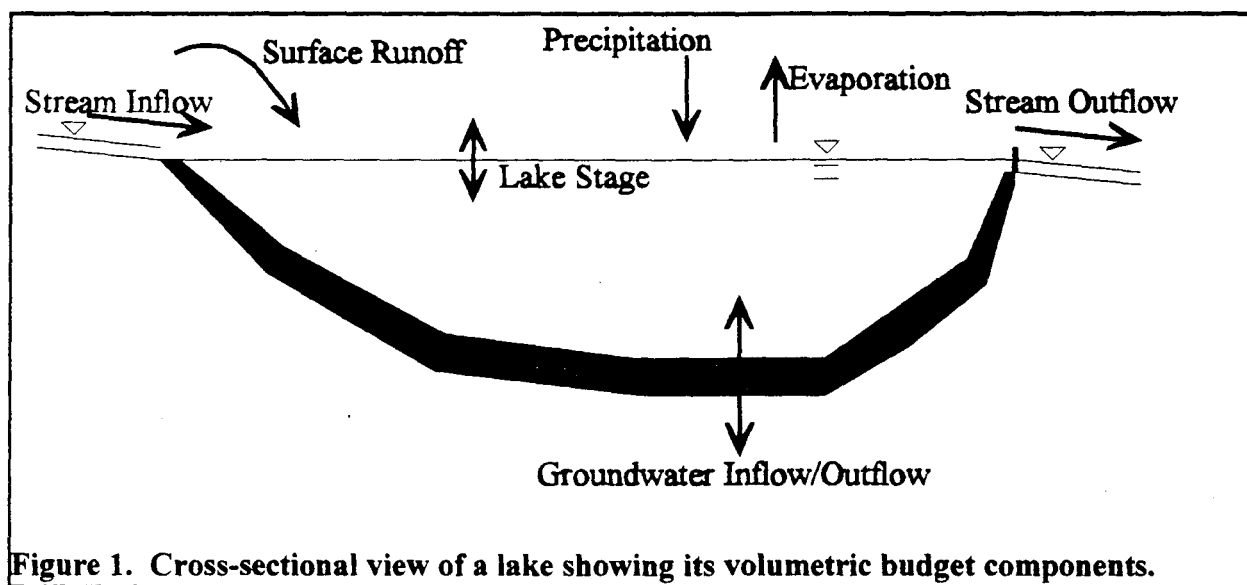


Figure 1. Cross-sectional view of a lake showing its volumetric budget components.

In equation (1) the dependent variable, h , is potentiometric head [L], a function of space and time. The independent variables are the spatially variable hydraulic conductivity (K_x , K_y , and K_z) [L/T] and specific storage (S_s) [L^{-1}] fields. Together with initial conditions for head and various boundary conditions, MODFLOW uses a discretized, algebraic form of equation (1) to solve for the potentiometric head at every model cell at time steps within each simulated period.

Boundary conditions allowed by MODFLOW include the specified-head, specified-flux, and head-dependent flux types. Boundary conditions are specified in MODFLOW through its various packages, or modules, including: Recharge (RCH), Well (WEL), River (RIV), Drain (DRN), and Evapotranspiration (EVT). Another package was later added for streamflow routing (STR1, revised to STR2, Prudic, 1989).

Packages to Simulate Lake-Groundwater Interaction

At least two previously-documented packages have been written to simulate lakes with MODFLOW: the Reservoir package (RES1), and the original Lake package (LAK1). The Reservoir package (RES1, Fenske et al., 1996) works like the River (RIV) package, but allows for a specified, linearly-varying (in time) lake stage. The known stage is used to determine the number of cells that are covered by the lake at each time step, and to determine the amount of flow to and from the groundwater. The RES1 package was not designed to calculate the stage in response to environmental stresses, and it is not connected to the Streamflow Routing package.

The original Lake package (LAK1) developed by Xiangxue Cheng and Mary Anderson (Cheng, 1994, Cheng and Anderson, 1993) includes many of the functions in the newer LAK2 package. In providing boundary conditions for equation (1), LAK1 also behaves like the River package (RIV). Additionally, it calculates lake stage as a transient response to evaporation, precipitation, surface runoff, streamflow, and groundwater flux. The LAK1 package handles lake-stream interaction with a modified version of the original Streamflow Routing package (STR1). The package does not provide for steady-state solution of lake stage, and requires the use of Manning's equation to calculate flow from a lake to an adjoining stream, based on the stage in the lake.

The new Lake package (LAK2) described here includes all of the capabilities of the RES1 and LAK1 packages, and includes new features that were desired for modeling the proposed mine site in northern Wisconsin. First, computation of steady-state lake stage is possible, using a modified version of Newton's method. The steady-state lake stage represents the stage at which lake inflow (from precipitation on the lake, overland runoff, stream inflow, and groundwater flux) is balanced by lake outflow (to streams, groundwater, and the atmosphere via evaporation). Also, the relationship describing stream outflow has been made very general, to accommodate a wide variety of stage-outfall relationships. The LAK2 package is a completely new code, which improves the input file structure, output options, and memory requirements of the LAK1 package. It is easy to connect to MODFLOW, seamlessly connecting with the current Streamflow Routing package (STR2) for stream-lake interaction.

Other Lake-Groundwater Models

Lake packages for other groundwater flow models have previously been developed, as documented in Cheng and Anderson, 1993. Additionally, fully integrated surface-water and groundwater models have been and are being developed that vary in terms of capabilities and complexity (see Yan and Smith, 1994, for example).

LAKE PACKAGE DESIGN

The LAK2 Lake package provides two major functions: 1) it formulates boundary conditions for the system of equations MODFLOW uses to solve equation (1), and 2) it computes lake-wide budget and stage information. These two functions are related through the lakebed hydraulic conductance, which controls the degree of lake-groundwater interaction.

Groundwater Flow Boundary Condition

The head-dependent flux boundary formulation used by the Lake package is very similar to that used in the River (RIV) package, which specifies the flux through the lakebed or riverbed as a function of stage, head in the connected cells, and the lakebed or riverbed conductance. With the Lake package, the conductance at each cell is either specified in the input file or calculated by the program from the specified lakebed geometry and hydraulic conductivity.

As with the River package, flow from a lake to the groundwater is limited when the head in a cell falls below the lakebed bottom. Also, if the stage of a lake is below the top of the lakebed, the lake cell is dry and seepage into the groundwater is cut off for that cell.

Lake Volumetric Balance and Stage Computation

Once head values are obtained by MODFLOW, subroutines in the Lake package sum the inflows and outflows which can be used to update the lake stage. Simple volumetric equations are applied to update stage in steady-state and transient modes.

Steady-state stage. To solve for steady-state lake stage, the following volumetric-balance equation is applied (all flow terms have units of L^3/T):

$$Q_P + Q_{RO} + Q_{STRIN} = Q_{GW}(S) + Q_E(S) + Q_{STROUT}(S) \quad (2)$$

In equation (2), which simply states that lake inflow equals lake outflow, the three terms on the right-hand-side are each a function of the lake stage, S . The total flux to the groundwater (Q_{GW}) is the sum of each lake cell's individual flux. The evaporative flux, Q_E is computed as the product of the user-specified evaporation rate and the "wetted" lake area, which includes only those cells with a lakebed top elevation below the lake stage. The total stream outflow, Q_{STROUT} is the sum of any number of individual stream outflows, each computed (as a function of stage) with user-specified outflow relationships. The computed stream outflows are also assigned as the inflow terms for specified segments of the Streamflow Routing package.

The left-hand-side of equation (2) contains inflows that are independent of lake stage. The precipitation inflow, Q_P is the product of the user-specified precipitation rate and the total

lake area (when full). The runoff inflow, Q_{RO} , is specified by the user in the input file. The total stream inflow, Q_{STRIN} , is the sum of outflows from all stream reaches that are tributary to the lake, contained in the *ARTRIB* variable of the Streamflow Routing package.

When steady-state mode is specified for a lake, the steady-state stage is computed after each head solution approximation. In this manner, the stage remains in balance with successive approximations of groundwater head until the head solution converges. An efficient solution method, based on Newton's method is used to calculate steady-state stage in an iterative fashion. In this process, the derivative of outflow with respect to lake stage is calculated, which indicates the direction and approximate magnitude of stage change necessary to maintain a steady-state balance. Modifications to Newton's method allow for potential discontinuities in the outflow vs. stage relationship. Iteration stops when the lake stage is within a specified tolerance of the exact solution. The number of cells representing the lake may change as the stage is updated.

Transient stage. In transient mode, the stage is updated at every timestep, increasing when inflows exceed outflows and decreasing when outflows exceed inflows. For the first timestep, MODFLOW solves for potentiometric head, with the lake boundary conditions formulated using the specified initial lake stage. After the head solution is complete, lake inflows and outflows are summed to determine the volume change for the lake, ΔV during the timestep of length Δt :

$$\Delta V = (Q_P + Q_{RO} + Q_{STRIN} - Q_{GW} - Q_E - Q_{STROUT})\Delta t \quad (3)$$

This volume change is added to the original volume to obtain the volume for the next timestep. The stage is then set by an iterative method (similar to that used for the steady-state stage solver) to a value that gives the appropriate volume. The number of cells representing the lake may change in this process.

Output options. The Lake package has many output options to aid in the interpretation of results. The status of each lake can be listed in a table in the main output file at the end of each simulation period. These tables include computed or specified stage, lake wetted area and water volume, all of the terms of equations (2) and (3), the total of all inflows and outflows, and the net flow (or steady-state volumetric balance error). Additionally, the stage and/or flow terms can be saved to a separate output file after each timestep, for easy loading into post-processing software or spreadsheets. Cell-by-cell flows between the lake and groundwater can be printed in the main output file or saved in MODFLOW's binary format for post-processing and linking to other programs (such as particle tracking and solute transport programs).

Code Testing

Several tests were performed on the Lake package to ensure that it correctly formulates the groundwater equations and properly calculates lake stage. For two test problems (Cheng and Anderson, 1993 and Cheng, 1994), the results of the LAK2 package were identical to those of LAK1. The steady-state and transient stage solvers were tested against hand calculations of

volumetric balance for various test problems, and simulations were conducted to verify that the groundwater equations were being formulated in a manner identical to that used by the River (RIV) package.

EXAMPLE APPLICATION

A flow model using the Lake package was used to simulate lake-groundwater interaction near a proposed underground zinc and copper mine site located approximately 5 miles south of Crandon, Wisconsin. The 169 row, 137 column model extends over 57 square miles with cell widths ranging from 30 to 300 meters (100 to 1000 feet). Vertically, the model is discretized into seven layers that vary in thickness to follow the geologic stratigraphy. The upper four layers contain glacial till, glacial outwash, and lacustrine sediments. The lower three layers represent bedrock with differing degrees of weathering. The orebody to be mined is located in the bedrock layers.

The model was set up to predict what would happen once the mine goes into operation. As a result of mine dewatering, water would be removed from the bedrock system leading to a decrease in aquifer head and a decline in water levels in overlying lakes and streams. The model was used to predict the location and magnitude of groundwater drawdown, and the amount of lake stage decline at the nearest four lakes. These lakes are connected directly to the saturated groundwater, with no significant unsaturated zone beneath them.

The project's environmental impact report (Foth & Van Dyke, 1995) contains detailed discussions of the entire modeling process and the extensive field tests used to establish approximate ranges for model parameter values. This paper only touches on a small part of the ongoing modeling effort, concentrating on the simulated lakes.

Model Calibration

Before predictive simulations were performed, reasonable values for model/system parameters (such as aquifer hydraulic conductivity, lakebed conductivities, and other boundary conditions) were chosen. The selected parameter values resulted in a model that closely matched observed heads, lake levels, and streamflows. This process of calibration to past and current conditions was critical to producing meaningful predictions. Several calibration time frames were chosen to eliminate as much parameter uncertainty as practicable. For example, a seven-year transient simulation was conducted to determine how well the model could replicate water levels observed during a prolonged drought. With the most reasonable values assigned to model parameters, simulated lake levels closely followed the observed pattern of lake stage changes, as shown for one of the lakes in Figure 2.

Model Predictions

Once calibration quality was within the project's pre-defined goals, steady-state and transient predictive simulations were performed to estimate the hydrological effects of the proposed mine. Dewatering in the mine was simulated using MODFLOW's Drain (DRN) package.

In steady-state, the rate of mine inflow would be replaced by increased inflow from, or decreased outflow to, the various water bodies comprising the groundwater model's boundary conditions. A decrease in groundwater levels would affect the surface water components: wetlands, streams, and lakes. The predicted amounts of steady-state lake stage decline and stream outflow decline are listed in Table 1. The stage declines were markedly less at Little Sand Lake, Duck Lake, and Deep Hole Lake, than at Skunk Lake because lower-conductivity lacustrine deposits underlie the first three lakes, and beaver dams on the outgoing streams of these lakes play an important part in controlling lake stage.

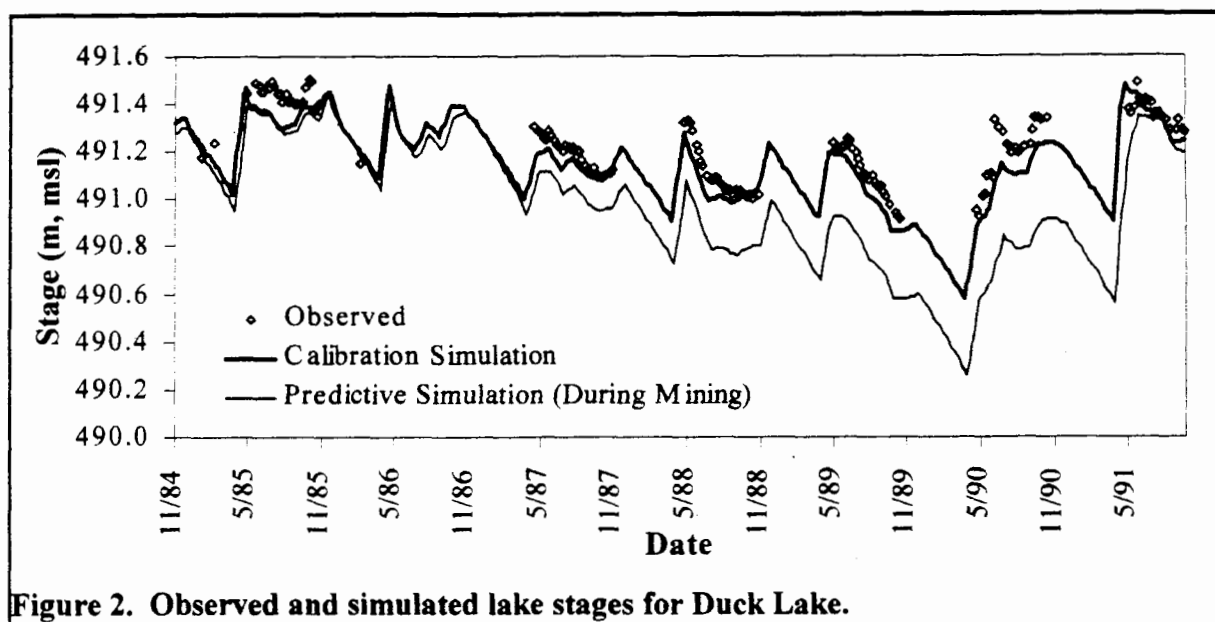


Figure 2. Observed and simulated lake stages for Duck Lake.

Lake Name	Stage Before Mining (m, msl)	Stage During Mining (m, msl)	Stage Decline (m)	Stream Outflow Before Mining (m ³ /d)	Stream Outflow During Mining (m ³ /d)	Stream Outflow Reduction (m ³ /d)
Deep Hole	489.430	489.417	0.012	493	354	139
Duck	491.319	491.277	0.043	61	12	48
Little Sand	485.132	485.120	0.012	1752	1005	746
Skunk	486.939	486.464	0.475	0	0	0

Transient simulations were used to predict the combined effect of mining operations and a natural drought. In Figure 2, the bottom line shows model-predicted lake stages during a drought that occurs well into the mining process (for this series, the date refers only to the precipitation/evaporation data used—the mine was not actually in operation during that period).

CONCLUSIONS

The LAK2 Lake package provides for the simulation of lakes with MODFLOW, effectively simulating lake-groundwater interaction. The package provides methods for computing the steady-state or transient lake stage, and integrates seamlessly with the Streamflow Routing package. LAK2 provides a broad range of features and capabilities that builds on those offered by the previously-documented packages RES1 and LAK1.

A demonstration of the usefulness of the Lake package is provided by the proposed mine site example. In steady-state and transient simulations, the Lake package predicts the lake level decline that would occur as a result of operating the underground mine.

ACKNOWLEDGMENTS

The LAK2 Lake package code development and the Crandon project modeling study were funded by the Crandon Mining Company and the Nicolet Minerals Company through their consultant, Foth & Van Dyke.

REFERENCES

- Cheng, X. and M.P. Anderson, 1993. Numerical simulation of ground-water interaction with lakes allowing for fluctuating lake levels. *Ground Water*. v. 31:6, pp. 929-933.
- Cheng, X., 1994. Numerical Analysis of Groundwater and Lake Systems with Application to the Trout River Basin, Vilas County, Wisconsin. Ph.D. Thesis, University of Wisconsin-Madison.
- Fenske, J.P., S.A. Leake, and D.E. Prudic, 1996. Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW), US Geological Survey Open-File Report 96-364.
- Foth & Van Dyke, 1995. Environmental Impact Report for the Crandon Project. Submitted to the Wisconsin Department of Natural Resources in Madison and the US Corps of Engineers in St. Paul, MN.
- McDonald, M.G. and A.W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Book 6, Ch. A1 of Techniques of Water-Resources Investigations of the U.S. Geological Survey.
- Prudic, D.E., 1989. Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model, US Geological Survey Open-File Report 88-729.
- Yan, J., and K.R. Smith, 1994. Simulation of integrated surface water and ground water systems — model formulation, *Water Resources Bulletin*, Vol. 30, No. 5, pp. 879-890.

Section A.4.2

INPUT INSTRUCTIONS

Lake Package for MODFLOW, Version 2.2

THIS PAGE INTENTIONALLY LEFT BLANK

INPUT INSTRUCTIONS
Lake Package for MODFLOW, Version 2.2
GeoTrans, May 1996
Greg Council

IDENTIFICATION LINE

/*LAK2.2
format: exactly as shown

SIMULATION DATA

NLAKES ILKCBC ILKOUT IECHO NSUBSTEPS
format: 5I10

NAME ISIMMODE STSTAGE ITERLAKE CONVCRIT (one line for each lake)
e)
format: A10, I10, F10.0, I10, F10.0

PHYSICAL DATA
(one set for each lake)

NODES NSTRIN NSTROUT STAGEMX ICONDOP
format: 3I10, F10.0, I10

ISEGIN (one line for each inflow stream)
format: I10

ISEGOUT NRATEQ |
one set |
format: 2I10 |
for each |

outflow |
CUTOFF CONST ELEV EXPNT (one line for each rating equation) |
stream |
format: 4F10.0 (sorted by CUTOFF, descending) |

ILAY IROW ICOL TOP BOT AREA COND (one line for each lake node)
)
format: 3I10, 4F10.0

STRESS PERIOD DATA
(one set for each stress period)

ITMP

format: I10

PRECIP EVAP RUNOFF DRYRCH IOUTOP STAGE (one line each lake if
ITMP >=0)

format: 4F10.0, I10, F10.0

VARIABLE DESCRIPTIONS

NLAKES: Number of lakes
 ILKCBC: >0 Cell-by-cell unit number, <=0 Do not save cell-by-cell
 ILKOUT: >0 Stage/Budget unit number, <=0 Do not write stage/budget
 t records
 IECHO: <0 No input echoing, 0 Summary of input, >0 Full echoing
 of input
 NSUBSTEPS: Number of sub-time-steps for simulating lakes in transien
 t mode

NAME: Name (ID) of lake (10 characters)
 ISIMMODE: Simulation Mode:
 0 Fixed Stage, 1 Interpolated stage, 2 Steady-state, 3 Tr
 ansient
 STSTAGE: Starting Stage (not required for ISIMMODE = 0)
 ITERLAKE: Max iterations for stage solver (ISIMMODE = 2 or 3)
 CONVCRIT: Stage solver termination criteria (change in stage in 1 i
 teration,
 ISIMMODE = 2 or 3)

NODES: Number of lake nodes
 NSTRIN: Number of inflow streams
 NSTROUT: Number of outflow streams
 STAGEMX: Maximum lake stage
 ICONDOP: <=0 Hydraulic conductivity input, >0 Conductance input

ISEGIN: Inflow stream segment (from streamflow routing package)
 ISEGOUT: Outflow stream segment (from streamflow routing package)
 NRATEQ: Number of equations used to define stage-discharge relati
 onship

CUTOFF: Lower stage limit of rating equation

CONST: Rating equation constant
 ELEV: Rating equation reference (outfall) elevation
 EXPNT: Rating equation exponent

$$\text{Outflow} = \text{CONST} * (\text{STAGE} - \text{ELEV})^{\text{EXPNT}} \quad (\text{Above CUTOFF})$$

ILAY: Lake node model layer (0 for top active layer)
 IROW: Lake node model row
 ICOL: Lake node model column
 TOP: Lakebed top elevation
 BOT: Lakebed bottom elevation
 AREA: Lake node area
 COND: Lakebed hydraulic conductivity or conductance (see ICONDO P above)

ITMP: <0 Use information from last stress period, >=0 read new information

PRECIP: Total area flow rate (L/T multiplied by total lake area, positive = inflow to lake, e.g. precipitation rate)

EVAP: Wetted area flow rate (L/T multiplied by wetted lake area

negative = outflow from lake, e.g. evaporation rate)

RUNOFF: Fixed lake inflow (L³/T, positive = inflow to lake, e.g. runoff)

DRYRCH: Recharge rate applied to groundwater beneath dry lake cells (L/T)

IOUTOP: Output option, constructed as follows:

0 = no output

+1 = print cell-by-cell flows in main output file

+2 = print lake budget information in main output file

le

+4 = write stage to stage/budget output file

+8 = write flows (& stage) to stage/budget output file

le

(e.g. 6 to print lake budget in main output file, write stage record

to stage/budget output file)

STAGE: If ISIMMODE = 0, lake stage for the stress period

If ISIMMODE = 1, final lake stage for the stress period

Ignored for ISIMMODE = 2 or 3

A STUDY ON SEEPAGE AND SUBSURFACE INFLOWS
TO SALTON SEA AND ADJACENT WETLANDS

THIS PAGE INTENTIONALLY LEFT BLANK

Section A.4.3

USGS Report

Water Resources Applications Software

Summary of MODFLOW

A STUDY ON SEEPAGE AND SUBSURFACE INFLOWS
TO SALTON SEA AND ADJACENT WETLANDS

THIS PAGE INTENTIONALLY LEFT BLANK

USGS REPORT

Water Resources Applications Software

Summary of MODFLOW

NAME

modflow - Modular three-dimensional finite-difference ground-water flow model

ABSTRACT

MODFLOW is a three-dimensional finite-difference ground-water flow model. It has a modular structure that allows it to be easily modified to adapt the code for a particular application. Many new capabilities have been added to the original model. This version includes all the major capabilities that were documented as of September 1996.

MODFLOW simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axes and the anisotropy ratio between horizontal coordinate directions is fixed in any one layer), and the storage coefficient may be heterogeneous. The model requires input of the ratio of vertical hydraulic conductivity to distance between vertically adjacent block centers. Specified head and specified flux boundaries can be simulated as can a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block. MODFLOW is currently the most used numerical model in the U.S. Geological Survey for ground-water flow problems. An efficient contouring program is available (Harbaugh, 1990) to visualize heads and drawdowns output by the model.

METHOD

The ground-water flow equation is solved using the finite-difference approximation. The flow region is considered to be subdivided into blocks in which the medium properties are assumed to be uniform. The plan view rectangular discretization results from a grid of

mutually perpendicular lines that may be variably spaced. The vertical direction zones of varying thickness are transformed into a set of parallel "layers". Several solvers are provided for solving the associated matrix problem; the user can choose the best solver for the particular problem. Mass balances are computed for each time step and as a cumulative volume from each source and type of discharge.

HISTORY

Version 2.6 1996/09/20 - Added Reservoir package (RES1) as documented in U.S. Geological Survey Open-File Report 96-364. Problem fixed for IBS package. Although subsidence is only meant to be active for layers in which $IBQ > 0$, sometimes MODFLOW performed subsidence calculations when $IBQ < 0$. Note that this was a problem only if negative IBQ values were specified. That is, the code has always worked correctly for $IBQ = 0$ and $IBQ > 0$.

Version 2.5 1995/06/23 - Added direct solution package (DE45).

Version 2.4 1995/06/15 - Added transient leakage package (TLK1).

Version 93/08/30 - Release with PCG2, BCF3, STR1, HFB1, ISB1, CHD1, and GFD1 additions.

Version 87/07/24 - Fortran 77 version published in U.S. Geological Survey Techniques of Water-Resources Investigations 6-A1.

Version 83/12/28 - Fortran 66 version published in U.S. Geological Survey Open-File Report 83-875.

DATA REQUIREMENTS

In order to use MODFLOW, initial conditions, hydraulic properties, and stresses must be specified for every model cell in the finite-difference grid.

OUTPUT OPTIONS

Primary output is head, which can be written to the listing file or into a separate file. Other output includes the complete listing of all input data, drawdown, and budget data. Budget data are printed as a summary in the listing file, and detailed budget data for all model cells can be written into a separate file.

SYSTEM REQUIREMENTS

MODFLOW-88 is written in Fortran 77 with the following extensions: use of variable names longer than 6 characters and the CARRIAGECONTROL option in OPEN statements. By default, the software is dimensioned for use with models having up to 90,000 cells. MODFLOW-88 uses preallocated files, which means that the file names are not assigned by Fortran OPEN statements. Instead, the compiler or operating system must provide a way to open the files. Example script files are provided to illustrate this procedure. Generally, the program is easily installed on most computer systems. The code has been used on UNIX-based computers and DOS-based 386 or greater computers having a math coprocessor and 4 mb of memory.

PACKAGES

This version of MODFLOW includes the following packages:

- BAS1 -- Basic Package
- BCF3 -- Version 3 of Block-Centered Flow Package

RIV1 -- River Package
 DRN1 -- Drain Package
 WEL1 -- Well Package
 GHB1 -- General Head Boundary Package
 RCH1 -- Recharge Package
 EVT1 -- Evapotranspiration Package
 SIP1 -- Strongly Implicit Procedure Package
 SOR1 -- Slice Successive Over-Relaxation Package
 UTL1 -- Utility Package
 PCG2 -- Version 2 of Preconditioned Conjugate Gradient Package
 STR1 -- Stream Package
 IBS1 -- Interbed-Storage Package
 CHD1 -- Time-Variant Specified-Head Package
 GFD1 -- General Finite Difference Flow Package
 HFB1 -- Horizontal Flow Barrier Package
 TLK1 -- Transient Leakage Package
 DE45 -- Direct solver
 RES1 -- Reservoir Package

The user must specify values for the appropriate IUNIT array element to include packages not in the original model. The IUNIT array is interpreted according to the following table:

BCF3 -- IUNIT(1) -- same IUNIT as used for BCF1 because BCF3
 replaces BCF1
 TLK1 -- IUNIT(6)
 DE45 -- IUNIT(10)
 PCG2 -- IUNIT(13)
 GFD1 -- IUNIT(14)
 HFB1 -- IUNIT(16)
 RES1 -- IUNIT(17)
 STR1 -- IUNIT(18)
 IBS1 -- IUNIT(19)
 CHD1 -- IUNIT(20)

The input unit for the Basic Package is unit 5, which is defined by the assignment of variable INBAS in the MAIN program.

DEPENDENCIES AMONG PACKAGES

As documented in Open-File Report (OFR) 94-59, the Transient Leakage (TLK) Package does not simulate flow through a confining unit at any horizontal grid location at which a cell on either side of the confining unit is dry. When this situation occurs as a result of initial conditions, the user can determine if this is appropriate before making a simulation. However, a cell can go dry at any time during a simulation when using the water-table or convertible layer options in the Block-Centered Flow (BCF) Package. When a cell goes dry on either side of a confining unit, the transient leakage through the confining unit immediately becomes zero at that horizontal location. Users should check simulations to see if cells on either side of a confining unit are going dry at any time during a simulation and determine if it is acceptable for the transient leakage to switch to zero. Further complications can result when using the wetting capabilities of version 2 of the BCF Package. If dry cells convert to wet so that cells on both sides of a confining unit are wet, then transient leakage calculations will be started; however, the equations will not be properly formulated to simulate the previous conditions, so the transient flow will not be correct. Thus, the wetting capability should not be used for any model layers that connect to a confining unit that is being simulated with the

TLK Package.

The Time-Variant Specified-Head (CHD) Package can potentially cause the TLK Package to operate incorrectly if the CHD Package is being used to specify constant heads at cells on either side of a confining unit. The TLK Package relies on initial head as defined by the Basic Package to setup initial parameters. If the data for the CHD Package define initial heads (i.e., head for the first time step of the simulation) on either side of a confining unit to be different than defined by the Basic Package, the transient leakage calculations will be incorrect. To avoid this conflict, do not use the CHD Package to define constant head cells on either side of a confining unit, or be sure that the initial head in the Basic Package exactly matches the initial head defined by the CHD Package.

DOCUMENTATION

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Version 2 of Preconditioned Conjugate Gradient Package is documented in:

Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.

The Stream Package is documented in:

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

The Interbed-Storage and Time-Variant Specified-Head Packages are documented in:

Leake, S.A., and Prudic, D.E., 1988, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 88-482, 80 p.

The General Finite Difference Flow Package is documented in:

Harbaugh, A.W., 1992, A generalized finite-difference formulation for the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-494, 60 p.

The Version 2 of the Block-Centered Flow Package is documented in:

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1992, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-536, 99 p. The BCF3 Package is documented in three pieces. It builds on two previous versions of the Block-Centered Flow (BCF) Package. Documentation for the BCF1 Package describes the fundamental

function of all BCF Packages. This documentation is contained in the basic model documentation (McDonald and Harbaugh, 1988). BCF2 documentation describes the addition of the capability to convert dry cells to wet:

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1992, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-536, 99 p.

BCF3 documentation describes the addition of alternate interblock transmissivities. The BCF3 code includes the capabilities of BCF1 and BCF2:

Goode, D.J., and Appel, C.E., 1992, Finite-difference interblock transmissivity for unconfined aquifers and for aquifers having smoothly varying transmissivity: U.S. Geological Survey Water-Resources Investigations Report 92-4124, 79 p.

The HFBI Package is documented in:

Hsieh, P.A., and Freckleton, J.R., 1993, Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 92-477, 32 p.

The Transient-Leakage Package (TLK1) is documented in:

Leake, S.A., Leahy, P.P., and Navoy, A.S., 1994, Documentation of a computer program to simulate transient leakage from confining units using the modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-59, 70 p.

The DE45 Package is documented in:

Harbaugh, A.W., 1995, Direct solution package based on alternating diagonal ordering for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 95-288, 46 p.

The RES1 Package is documented in:

Fenske, J.P., Leake, S.A., and Prudic, D.E., 1996, Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW): U.S. Geological Survey Open-File Report 96-364, 51 p.

RELATED DOCUMENTATION

Harbaugh, A.W., 1990, A simple contouring program for gridded data: U.S. Geological Survey Open-File Report 90-144, 37 p.

REFERENCES

MODFLOW is widely used in the USGS and throughout the world.

Belitz, K., and Phillips, S.P., 1993, Numerical simulation of ground-water flow in the central part of the western San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 2396, 69 p.

Prince, K.R., Franke, O.L., and Reilly, T.E., 1988, Quantitative

assessment of the shallow ground-water flow system associated with Connetquot Brook, Long Island, New York: U.S. Geological Survey Water-Supply Paper 2309, 28 p.

TRAINING

Modeling of Ground-Water Flow Using Finite-Difference Methods (GW2096TC), offered annually at the USGS National Training Center.

Advanced Finite-Difference Modeling of Ground-Water Flow (GW3099TC), offered annually at the USGS National Training Center.

CONTACTS

Operation:

U.S. Geological Survey
Office of Ground Water
Arlen Harbaugh
411 National Center
Reston, VA 20192

harbaugh@usgs.gov

Distribution:

U.S. Geological Survey
Hydrologic Analysis Software Support Program
437 National Center
Reston, VA 20192

h2osoft@usgs.gov

Official versions of U.S. Geological Survey water-resources analysis software are available for electronic retrieval via the World Wide Web (WWW) at:

<http://water.usgs.gov/software/>

and via anonymous File Transfer Protocol (FTP) from:

[water.usgs.gov \(path: /pub/software\)](ftp://water.usgs.gov/pub/software).

The WWW page and anonymous FTP directory from which the MODFLOW software can be retrieved are, respectively:

<http://water.usgs.gov/software/modflow.html>

--and--

[/pub/software/ground_water/modflow](ftp://pub/software/ground_water/modflow)

If you would like to obtain the price of and (or) order paper copies of USGS reports, contact the USGS Branch of Information Services at:

U.S. Geological Survey
Branch of Information Services
Denver Federal Center, Box 25286
Denver CO 80225-0286

To inquire about Open-File Reports or Water-Resources Investigations Reports:

Tel: 303-202-4210; Fax 303-202-4695

To inquire about other USGS reports:

Tel: 303-202-4700; Fax 303-202-4693

A.5 REFERENCES

Cheng, X. and M.P. Anderson

1993 Numerical simulation of ground-water interaction with lakes allowing for fluctuating lake levels. *Ground Water*. v. 31:6, pp. 929-933.

Fenske, J.P., S.A. Leake, and D.E. Prudic

1996 Documentation of a computer program (RES1) to simulate leakage from reservoirs using the modular finite-difference ground-water flow model (MODFLOW), US Geological Survey Open-File Report 96-364.

Harbaugh, A.W., and McDonald, M.G.

1996 User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

McDonald, M.G. and A.W. Harbaugh

1988 A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Book 6, Ch. A1 of *Techniques of Water-Resources Investigations of the U.S. Geological Survey*.

Prudic, D.E.

1989 Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model, US Geological Survey Open-File Report 88-729.

Yan, J., and K.R. Smith

1994 Simulation of integrated surface water and ground water systems — model formulation, *Water Resources Bulletin*, Vol. 30, No. 5, pp. 879-890.

THIS PAGE INTENTIONALLY LEFT BLANK