FEMFLOW3D: A Finite-Element Program for the Simulation of Three-Dimensional Aquifers. Version 1.0

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FEMFLOW3D: A FINITE-ELEMENT PROGRAM FOR THE SIMULATION OF THREE-DIMENSIONAL AQUIFERS. Version 1.0

By T.J. Durbin *and* L.D. Bond

Abstract

This document describes a computer program that simulates three-dimensional ground-water systems using the finite-element method. The program was developed to simulate regional ground-water systems, but it can be applied to small-scale problems as well. This program can be used to simulate both confined and water-table aquifers.

The program simulates a linearized three-dimensional free-surface ground-water system with a fixed grid. *FEMFLOW3D* is applicable to the simulation of various free-surface ground-water systems for which the change in aquifer thickness is small relative to the overall aquifer thickness.

The finite-element method provides flexibility in the design of a geometric grid that represents the physical dimensions of an aquifer system. For example, features that can be well represented with a finite-element grid include irregular, random geographic and geologic features; irregular boundaries; and increased detail within localized areas of particular interest within the study area.

The structure of the computer program consists of a main program, which serves as a simple driver, and a set of subroutines in which the calculations are performed. The background, mathematical basis, structure, and inputs for each of the subroutines are described in the document where applicable. Each subroutine generally handles (1) a part of the mathematical calculations related to the finite-element method, (2) a specific feature of the hydrologic system, or (3) special features related to the management input or output data.

Hydrologic features that can be represented with the program include stream-aquifer interactions, phreatophytic evapotranspiration, highly permeable fault zones, land subsidence, and land-aquifer interactions associated with land-use activities. The program can also represent the primary features associated with complex irrigation systems, such as irrigated agriculture, and can calculate the ground-water recharge that results from these activities. Three boundary conditions, including specified-head boundaries, specified-flux boundaries, and variable-flux boundaries, can be represented with the program. The program also provides a method for identifying aquifer and river-bed parameters that can be used in the calibration of models.

This document also includes model validation, source code, and example input and output files. Model validation was performed using four test problems. For each test problem, the results of a model simulation with *FEMFLOW3D* were compared with either an analytic solution or the results of an independent numerical approach. The source code, written in the ANSI x3.9-1978 FORTRAN standard, and the complete input and output of an example problem are listed in the appendixes.

1.0 INTRODUCTION

This document describes the computer program *FEMFLOW3D*, which is a finite-element program for the simulation of three-dimensional aquifers. The document is divided into three principal sections: Section 3.0, which describes the mathematical basis of the program; Section 4.0, which describes simulations that have been made with *FEMFLOW3D* for problems that have a known solution and describes the comparison of the simulations with the known solution; and Section 5.0, which describes the input formats for the program *FEMFLOW3D*. The mathematical descriptions in Section 3.0 are more detailed than some readers may require, but these descriptions are necessary for the complete documentation of *FEMFLOW3D*. Most readers can skip Section 3.0 and can proceed directly to Section 5.0, which tells how to prepare the input files for *FEMFLOW3D*.

The program *FEMFLOW3D* simulates the three-dimensional flow of ground water. The program was developed to simulate regional ground-water systems but can also be applied to small-scale problems. The program can be used to simulate confined or water-table aquifers for problems at regional or smaller scales.

FEMFLOW3D uses an iterative procedure to simulate the hydraulic response of a three-dimensional water-table aquifer. However, the simulation of a water-table aquifer has been done by others using other approaches. The most commonly applied approach represents a ground-water system as a quasi three-dimensional system of two-dimensional aquifers connected hydraulically by leakage through interaquifer aquitards. To solve this problem, Bredehoeft and Pinder (1970) used the finite-difference method and Durbin (1978) used the finite-element method. Finite-difference algorithms for simulated quasi three-dimensional ground-water flow are documented by Trescott (1975) and Trescott and Larson (1977). In each of these methods, the free surface is represented by applying the Dupuit assumptions to the upper layer of a model. For the upper layer, transmissivity is a function of calculated head, and the storage coefficient is set to a value representing specific yield at the free surface.

In some fully three-dimensional representations of a ground-water system, the effect of the free surface can be approximated by keeping the geometry of the flow domain fixed while assigning a storage-coefficient value representing specific yield to the upper parts of the model grid. Using this approach, the large storage effect at the free surface is represented, but the nonlinear effects of the changed saturated thickness are not. Another approach uses fixed geometry to represent the free-surface problem as a saturated/unsaturated flow simulation. Freeze (1971) used the fixed geometry approach within a finite-difference approximation, and Frind and Verge (1978) used it within a finite-element approximation.

The effects of geometry changes in the flow domain can be represented by using a deforming model grid. Leake (1977) used this approach by eliminating or adding blocks to a finite-difference grid as the calculated heads within the aquifer changed with time. Leake demonstrated his algorithm for the two-dimensional x-z case, but the approach can be extended to the three-dimensional case. By

using this approach, the effects of storage changes at the free surface and the deformation of the flow domain are included. However, a more rigorous approach was taken by Neuman and Witherspoon (1971). Starting with the governing equation for ground-water flow and with a linearized partial differential equation describing the free-surface boundary condition, Neuman and Witherspoon developed a finite-element algorithm for the two-dimensional x-z case that uses a deforming grid.

The finite-element program *FEMFLOW3D* is based on the application of the work of Neuman and Witherspoon (1971) to the three-dimensional case with a fixed grid. Thus, the model simulates a linearized three-dimensional free-surface ground-water system. Neuman and Witherspoon (1971) uses this system in their analytical solution of the problem of pumping from a partially penetrating well within a three-dimensional free-surface aquifer. The use of a fixed grid within *FEMFLOW3D* disregards the effects of a change in aquifer thickness on ground-water flow. However, *FEMFLOW3D* does represent the effects of a free-surface boundary condition. For most free-surface ground-water systems, the free-surface effect is a more important phenomenon than is the saturated-thickness effect. Accordingly, *FEMFLOW3D* is applicable to the simulation of various free-surface ground-water systems, and it is particularly applicable to ground-water systems for which the change in aquifer thickness is small relative to the overall aquifer thickness.

2.0 GENERAL FEATURES OF *FEMFLOW3D*

The finite-element program *FEMFLOW3D* has several general features that aid the three-dimensional simulation of either regional or small-scale ground-water systems. These features include

1. Grid specification. Specification of the finite-element grid is done in terms of triangular prisms instead of tetrahedrons, although the internal model calculations are done using tetrahedral elements. Additionally, triangular prisms with zero-height edges can be used to represent particular hydrogeologic units that pinch out or can be used to make geographic changes in the vertical discretization of the grid.

2. Specified-head boundaries. Specified-head boundary conditions can be imposed with boundary heads that are either constant with time or vary with time. In the latter case, the boundary heads are specified in terms of tables representing the hydrograph of the boundary heads. Additionally, drainage nodes can be specified that allow discharge from the modeled flow domain, but that do not allow flow into the domain.

3. Specified-flux boundaries and internal source-sink terms. The specified-flux boundary conditions and internal sources-sink terms are defined in terms of a group of various data sets that can be combined in different configurations for each time step.

4. Variable-flux boundaries. The variable-flux boundary condition can be imposed to simulate time-variant boundary fluxes in response to changing boundary heads. This is a boundary condition that allows the finite volume of the modeled flow domain to be extended to infinity by attaching the analytical solution for a semi-infinite linear aquifer to the boundary of the flow domain.

5. River-aquifer simulation. To simulate river-aquifer interactions, riverflow is routed through a main channel and its tributaries. The exchange of water between the local river-channel reach and the ground-water system depends on the wetted width of the reach, flow depth, river-bed elevation, river-bed thickness, and river-bed hydraulic conductivity. Additionally, when water

seeps from the river reach to the ground-water system, the simulation allows a break in the hydraulic connection between the river and the ground-water system. The break occurs where the depth to the water table below the elevation of the river bed is greater than the thickness of the river bed. For this condition, the rate of ground-water recharge from the river is independent of the depth to the water table. This condition occurs when the hydraulic gradient from the river to the water table reaches unity in the vertical direction.

6. **Phreatophyte simulation.** The evapotranspiration of ground water from a shallow water table owing to phreatophytes can be simulated by specifying the maximum evapotranspiration rate and the extinction depth.

7. **Fault-zone simulation.** The effect of highly transmissive fault zones can be simulated without a representation in the finite-element grid, but poorly transmissive fault zones can be simulated only by an explicit representation in the finite-element grid. The representation of highly transmissive fault zones is done by specifying linkages between particular node pairs that allow the movement of water along the links, in addition to the movement of water through the aquifer continuum. These linkages can also be used as a convenient method for specifying the hydraulic condition in a well that pumps from multiple layers in the finite-element grid. The linkages distribute the discharge from individual layers to maintain nearly identical hydraulic heads in each layer, which represents the condition in a well casing where hydraulic heads typically are nearly uniform throughout the water column within the casing.

8. **Land-subsidence simulation.** The subsidence of the land surface as the result of aquifer compaction is simulated by specifying the elastic and inelastic specific storage of the fine-grained beds and by specifying the initial preconsolidation heads within the ground-water system. Accordingly, the elastic and inelastic release of stored water and the elastic uptake of water are simulated; correspondingly, the cumulative change in storage within an aquifer column is used to determine the cumulative change in the elevation of the land surface.

9. **Water-use specification.** Ground-water pumpage and recharge for an irrigated-agriculture system can conveniently be simulated. Input files consist of a data-management system for the storage and the retrieval of well-site data, ground-water pumpage data, irrigated-area data, crop-inventory data, and surface-water delivery data. The data is processed by an algorithm that calculates the consumption of water by crops and the recharge of ground-water that results from precipitation and the application of irrigation water. Data can be organized on the basis of geographic or political boundaries and are not restricted by the layout of the model grid.

10. **Parameter estimation.** The aquifer parameters for the model can be estimated using a weighted least-squared procedure. This procedure uses information on the expected value and variance of the expected value for hydraulic conductivity, specific storage, and specific yield, along with information on the measured ground-water levels and the variance of the measurements, to estimate the maximum likelihood values of hydraulic conductivity, specific storage, and specific yield.

3.0 DESCRIPTION OF *FEMFLOW3D*

The finite-element program *FEMFLOW3D* consists of the main program and a set of subroutines (fig. 1). The main program is a simple driver; the various subroutines perform the model calculations. The primary calculations are done in the subroutine *MODEL*. The FORTRAN source code for *FEMFLOW3D* is on the diskette in the pocket at the back of the report. The files that contain the source code have the extension .FOR. The source code for the program *FEMFLOW3D* is written in the ANSI x3.9-1978 FORTRAN standard. Two compiler specifications must be included when compiling the FORTRAN source code: (1) The compiler must accept "ENTRY" statements that have a different argument list than the argument list for the main subroutine call, and (2) the internal variables within the subroutines must be saved.

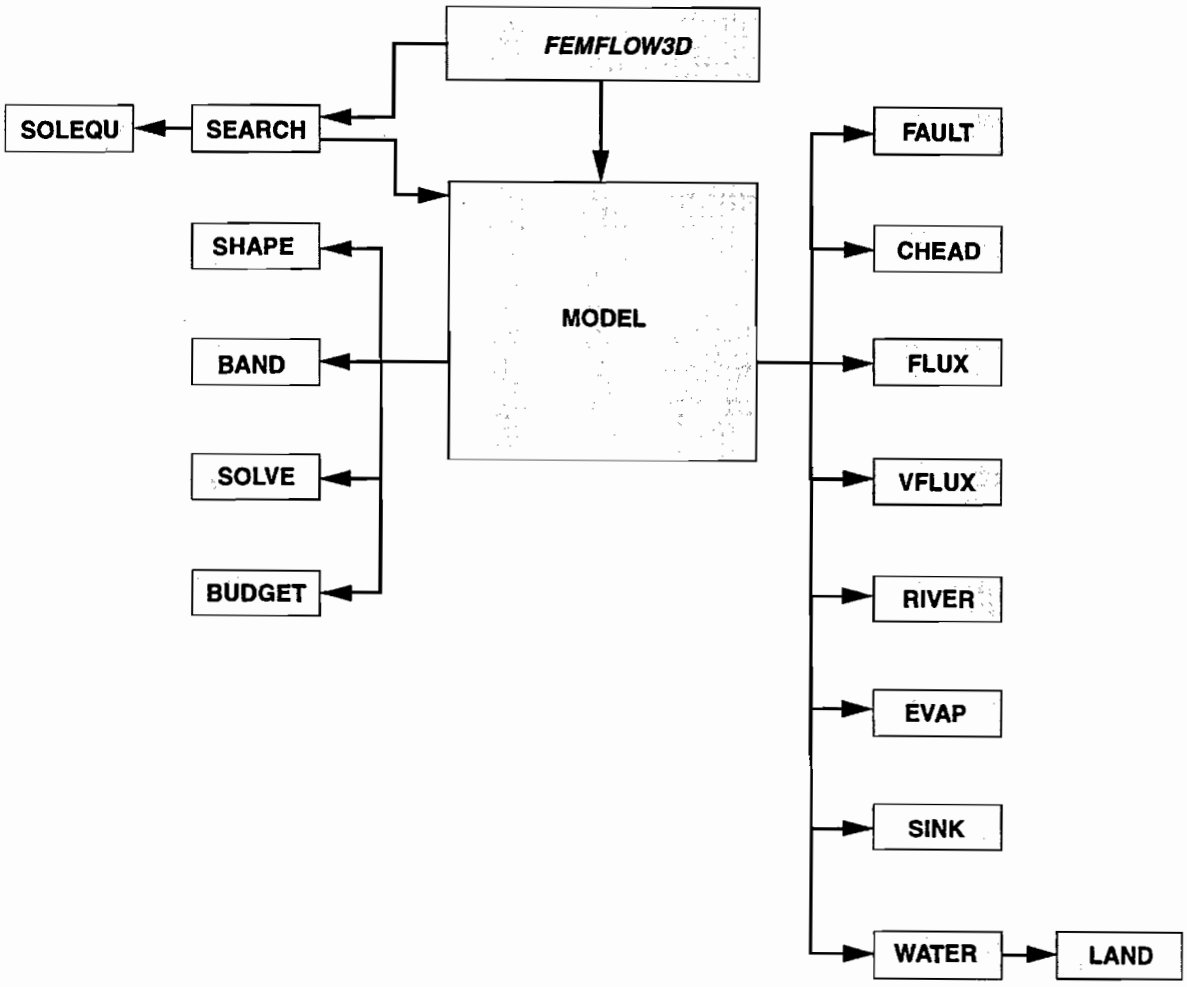


Figure 1. Structure of *FEMFLOW3D*.

3.1 Program *FEMFLOW3D*

3.1.1 Background

The finite-element program *FEMFLOW3D* derives its name from its main program called *FEMFLOW3D*. This main program is the driver program that makes calls only to the subroutines *MODEL* and *SEARCH*. Unless specified as the driver program, references to *FEMFLOW3D* refer to the finite-element program, including all of its subroutines.

3.1.2 Mathematical Basis

No calculations are done in the driver program, *FEMFLOW3D*.

3.1.3 Structure of Subroutine

The driver program, *FEMFLOW3D*, executes two alternative sets of subroutine calls. A call is determined by parameter estimation. Subroutine *MODEL* is structured into three basic blocks, *MODEL1*, *MODEL2*, and *MODEL3*. If parameter identification is not done, the driver program calls *MODEL1* and *MODEL3* in sequence, and then stops. If parameter identification is done, the driver program calls *MODEL1* and *SEARCH* in sequence and then calls *MODEL2* from subroutine *SEARCH*.

3.2 SUBROUTINE *MODEL*

3.2.1 Background

Subroutine *MODEL* is the central module of *FEMFLOW3D*. This subroutine controls data input for *FEMFLOW3D* and executes the principal calculations relating to the implementation of the finite-element method. Data are input below the primary entry point *MODEL1* either directly as read statements or indirectly as calls to the primary entry points of other subroutines. The finite-element calculations are executed below the secondary entry point *MODEL2* or *MODEL3*. These calculations include calculating volume and surface integrations, assembling elemental and global matrices, and solving a system of linear equations that yields the calculated hydraulic head for each time step. The progression of the calculations through time is controlled below the entry points *MODEL2* or *MODEL3*.

3.2.2 Mathematical Basis

3.2.2.1 Governing Equation

The calculations in subroutine *MODEL* are based on the three-dimensional equation of groundwater flow in the form

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - S_s\frac{\partial h}{\partial t} + W = 0, \qquad (3.2\text{-}1)$$

where

h is hydraulic head [L],
K_{xx} is the hydraulic conductivity in the x direction [L/t],
K_{yy} is the hydraulic conductivity in the y direction [L/t],
K_{zz} is the hydraulic conductivity in the z direction [L/t],
S_s is the specific storage [1/L],
W is the source injection rate per unit volume [L^3/t per L^3 or 1/t],
x is the coordinate in the x direction [L],
y is the coordinate in the y direction [L],
z is the coordinate in the z direction [L], which has the same datum as the hydraulic head, and
t is time [t].

The form of the governing equation assumes that the coordinate system is aligned with the principal components of the hydraulic conductivity tensor.

The governing equation is subject to the water-table boundary condition in the form

$$K_{xx} \frac{\partial h}{\partial x} n_x + K_{yy} \frac{\partial h}{\partial y} n_y + K_{zz} \frac{\partial h}{\partial z} n_z = - S_y \frac{\partial h_f}{\partial t} n_z \qquad (3.2\text{-}2)$$

and

$$h_f(x,y,t) = h(x,y,z,t)|_{\Gamma_F} \qquad (3.2\text{-}3)$$

where

n_x is the x component of the outward normal vector on the water-table surface Γ_F [dimensionless],
n_y is the y component [dimensionless],
n_z is the z component [dimensionless],
S_y is the specific yield [dimensionless],
h_f is the elevation of the water table [L],
Γ_F is the water-table surface [L^2],
t is time [t],

and the specific-flux boundary condition in the form

$$K_{xx} \frac{\partial h}{\partial x} n_x + K_{yy} \frac{\partial h}{\partial y} n_y + K_{zz} \frac{\partial h}{\partial z} n_z = q \qquad (3.2\text{-}4)$$

where q is the inward discharge normal to the boundary surface [L/t].

3.2.2.2 Finite-Element Approximation

In *FEMFLOW3D*, Equation 3.2-1 is solved using the Galerkin finite-element method described by Durbin and Berenbrock (1985). In this method, the exact continuous solution to Equation 3.2-1 is replaced by an approximate piecewise continuous solution. This piecewise continuous solution is defined by coefficient values specified at nodes in the model grid. Solution values between the nodes are calculated using piecewise continuous interpolation or basis functions that depend on the coefficients and are defined over the elements in the grid. *FEMFLOW3D* uses tetrahedral elements and linear interpolation functions.

Application of the Galerkin finite-element method to the spatial domain results in a system of ordinary differential equations in time. To solve this system of equations for each time step, the time derivative is approximated using a first-order, implicit, finite-difference scheme. Corresponding to the implicit approximation of the time derivative, the coefficients of the system of equations generated by the finite-element method are evaluated for each time step at the end of the new time step.

The coefficients of the system of equations are dependent, in part, on calculated hydraulic heads, causing the system of ordinary differential equations to be nonlinear. Specifically, nonlinearity results from (1) the use of the drainage node form of the specified-head boundary condition, (2) the representation of river-aquifer interactions, (3) the representation of evapotranspiration from ground water, and (4) the simulation of land subsidence. Because the nonlinearities are not severe, a solution to the nonlinear system of ordinary differential equations can be obtained by simple iteration, which is sometimes referred to as Picard iteration. At each iteration, a system of linear equations is generated using the hydraulic heads from the last iteration to evaluate the coefficients of the system of equations.

Application of Galerkin method.--To apply the finite-element method, the linear operator $L(\ )$ from Equation 3.2-1 is defined as

$$L(h') \equiv \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h'}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h'}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h'}{\partial z}\right) - S_s\frac{\partial h'}{\partial t} + W = 0. \qquad (3.2\text{-}5)$$

To solve $L(h) = O$, interpolating function is used in the form (Pinder and Gray, 1977)

$$h'(x,y,z,t) = \sum_{i=1}^{n} H_i(t)\phi_i(x,y,z), \tag{3.2-6}$$

where

h' is a series approximation to h [L],
H_i are the undetermined coefficients [L],
ϕ_i are linearly independent interpolating functions defined over the flow domain Ω [dimensionless],
n is the number of nodal points [dimensionless], and
Ω is the three-dimensional flow domain [L^3].

The series approximation to Equation 3.2-5 will provide an exact representation as n approaches infinity. For a finite series, however, the approximation will not satisfy exactly Equation 3.2-5 and a residual R will result. The residual is defined by

$$R(x,y,z,t) = L\left[\sum_{i=1}^{n} H_i(t)\phi_i(x,y,z)\right]. \tag{3.2-7}$$

If the trial solution was exact, the residual would vanish. For the trial solution, however, the average residual within the domain is forced to zero, in an average sense, through the selection of the undetermined coefficients H_i.

The undetermined coefficients are calculated by setting the weighted integrals of the residual to zero. In the Galerkin method (Pinder and Gray, 1977), the interpolating functions are used as weighting functions, that is, the inner product of the residual with each linearly interpolating function is set to zero, or

$$\int_{\Omega} L\left[\sum_{j=1}^{n} H_j(t)\phi_j(x,y,z)\right]\phi_i(x,y,z)d\Omega = 0 \tag{3.2-8}$$

$$for\ i = 1,2,...,n.$$

Using Equation 3.2-8 n equations can be solved for the n values of H_j.

System of ordinary differential equations.--To solve the system of ordinary differential equations, Equation 3.2-8 can be simplified. First, Equation 3.2-8 is expanded to obtain the system of n equations

$$\int_{\Omega} \left[\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial}{\partial x}\sum_{j=1}^{n} H_j\phi_j\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial}{\partial y}\sum_{j=1}^{n} H_j\phi_j\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial}{\partial z}\sum_{j=1}^{n} H_j\phi_j\right) - S_s\frac{\partial h'}{\partial t} + W \right] \phi_i d\Omega = 0 \qquad \text{for } i = 1,2,...,n. \tag{3.2-9}$$

Second, the second-order terms in Equation 3.2-9 are eliminated by applying Green's theorem (Pinder and Gray, 1977). By assuming that hydraulic conductivity is constant for each element and by recalling that H_j is a function of time only, the application of Green's theorem yields

$$\int_{\Omega}\sum_{j=1}^{n}\left(K_{xx}\frac{\partial\phi_i}{\partial x}\frac{\partial\phi_j}{\partial x} + K_{yy}\frac{\partial\phi_i}{\partial y}\frac{\partial\phi_j}{\partial y} + K_{zz}\frac{\partial\phi_i}{\partial z}\frac{\partial\phi_j}{\partial z}\right)H_j\, d\Omega + \int_{\Omega} S_s\phi_i\frac{\partial h'}{\partial t}d\Omega - \int_{\Omega} W\phi_i d\Omega - \int_{\Gamma_F}\left(K_{xx}\frac{\partial h'}{\partial x}n_x + K_{yy}\frac{\partial h'}{\partial y}n_y + K_{zz}\frac{\partial h'}{\partial z}n_z\right)\phi_i d\Gamma - \int_{\Gamma_R}\left(K_{xx}\frac{\partial h'}{\partial x}n_x + K_{yy}\frac{\partial h'}{\partial y}n_y + K_{zz}\frac{\partial h'}{\partial z}n_z\right)\phi_i d\Gamma = 0 \qquad \text{for } i = 1,2,...,n, \tag{3.2-10}$$

where

Γ is the overall boundary surface of the flow domain Ω [L^2],
Γ_F is the free-surface part of the boundary surface [L^2], and
Γ_R is the remaining part of the boundary surface [L^2].

The integral over the surface Γ_F represents the free-surface conditions on that boundary, and the integral over the surface Γ_R represents a specific-flux condition on that boundary.

Third, by substituting Equations 3.2-2 and 3.2.3 into the last term of Equation 3.2-10 and by replacing the partial derivatives of h with the general definition of the total derivative, the result is

$$\sum_{j=1}^{n} \int_{\Omega} \left(K_{xx} \frac{\partial \phi_i}{\partial x} \frac{\partial \phi_j}{\partial x} + K_{yy} \frac{\partial \phi_i}{\partial y} \frac{\partial \phi_j}{\partial y} + K_{zz} \frac{\partial \phi_i}{\partial z} \frac{\partial \phi_j}{\partial z} \right) H_j d\Omega + \sum_{j=1}^{n} \int_{\Omega} S_s \phi_i \phi_j \frac{dH_j}{dt} d\Omega - \int_{\Omega} W \phi_i d\Omega - \int_{\Gamma_R} q \phi_i d\Gamma + \sum_{j=1}^{n} \int_{\Gamma_F} S_y \phi_i \phi_j \frac{dH_j}{dt} n_z d\Gamma = 0 \qquad \text{for } i = 1,2,...,n, \tag{3.2-11}$$

where

q is the inward discharge normal to the surface Γ [L/t],
Γ is the overall boundary surface of the flow domain Ω [L^2], and
Γ_F is the free-surface part of the boundary surface [L^2].

In obtaining Equation 3.2-11 from 3.2-10, the boundary integral represented by the last term of Equation 3.2-10 is partitioned in the model domain for water-table surface.

The *n* equations of Equation 3.2-11 can be written in matrix form as

$$[A]\{H\} + [B]\left\{\frac{dH}{dt}\right\} - \{F\} = O. \tag{3.2-12}$$

The typical elements of the matrices *[A] and [B]* and the vector *{F}* are

$$A_{ij} = \int_{\Omega}\left(K_{xx}\frac{\partial\phi_i}{\partial x}\frac{\partial\phi_j}{\partial x} + K_{yy}\frac{\partial\phi_i}{\partial y}\frac{\partial\phi_j}{\partial y} + K_{zz}\frac{\partial\phi_i}{\partial z}\frac{\partial\phi_j}{\partial z}\right)d\Omega, \tag{3.2-13}$$

$$B_{ij} = \int_{\Omega} S_s\phi_i\phi_j d\Omega + \int_{\Gamma_F} S_y\phi_i\phi_j d\Gamma, \tag{3.2-14}$$

and

$$F_i = \int_{\Omega} W\phi_i d\Omega + \int_{\Gamma_R} q\phi_i d\Gamma, \tag{3.2-15}$$

which are referred to as the conductance matrix, the storage matrix, and the force vector, respectively.

3.2.2.3 Interpolating Function

To generate the set of algebraic equations represented by Equation 3.2-12, integrations of the interpolating functions must be carried out in the form

$$\int \frac{\partial \phi_i}{\partial x} \frac{\partial \phi_j}{\partial x} d\Omega,$$

$$\int \frac{\partial \phi_i}{\partial y} \frac{\partial \phi_j}{\partial y} d\Omega,$$

$$\int \frac{\partial \phi_i}{\partial z} \frac{\partial \phi_j}{\partial z} d\Omega,$$

$$\int \phi_i \phi_j d\Omega,$$

$$\int \phi_i d\Omega,$$

$$\int \phi_i \phi_j d\Gamma,$$

and

$$\int \phi_i d\Gamma.$$

To facilitate these integrations, the interpolating functions are defined separately for each element, but when combined produce the global-interpolating functions within the flow domain. The elemental interpolating functions used in this work are linear and are defined for tetrahedral elements within the interior of the flow domain and for triangular elements on the boundary surfaces of the flow domain.

Volume integrations.--Within a tetrahedral element, the trial solution (Equation 3.2-6) can be expressed as

$$h' = \sum_{i=1}^{4} H_i \phi_i^e \ , \tag{3.2-16}$$

where ϕ_i^e represent the elemental interpolating functions defined only within the element e. The interpolating functions for the node i are given by the relation (Zienkiewicz, 1977)

$$\phi_i^e = \frac{1}{6V} (a_i + b_i x + c_i y + d_i z), \tag{3.2-17}$$

where the coefficients of Equation 3.2-17 are given by the determinants

$$a_i = \begin{vmatrix} x_j & y_j & z_j \\ x_m & y_m & z_m \\ x_p & y_p & z_p \end{vmatrix}, \tag{3.2-18}$$

$$b_i = -\begin{vmatrix} 1 & y_j & z_j \\ 1 & y_m & z_m \\ 1 & y_p & z_p \end{vmatrix}, \tag{3.2-19}$$

$$c_i = -\begin{vmatrix} x_j & 1 & z_j \\ x_m & 1 & z_m \\ x_p & 1 & z_p \end{vmatrix}, \tag{3.2-20}$$

$$d_i = -\begin{vmatrix} x_j & y_j & 1 \\ x_m & y_m & 1 \\ x_p & y_p & 1 \end{vmatrix}, \tag{3.2-21}$$

$$6V = \begin{vmatrix} 1 & x_i & y_i & z_i \\ 1 & x_j & y_j & z_j \\ 1 & x_m & y_m & z_m \\ 1 & x_p & y_p & z_p \end{vmatrix}, \tag{3.2-22}$$

and where V is the volume of a tetrahedral element [L^3]. The indexes p, i, j, and m are the nodal numbers for a tetrahedral element. The ordering of nodal numbers must follow the right-hand rule, that is, the first three nodes (p, i, and j) are numbered in a counterclockwise manner when viewed from the last (m).

Integrations using derivatives of interpolating functions from Equations 3.2-17 through 3.2-18 are given by the relations (Zienkiewicz, 1977)

$$\int_e K_{xx} \frac{\partial \phi_i^e}{\partial x} \frac{\partial \phi_j^e}{\partial x} d\Omega = \frac{K_{xx}}{36V} b_i b_j , \tag{3.2-23}$$

$$\int_e K_{yy} \frac{\partial \phi_i^e}{\partial y} \frac{\partial \phi_j^e}{\partial y} d\Omega = \frac{K_{yy}}{36V} c_i c_j , \tag{3.2-24}$$

and

$$\int_e K_{zz} \frac{\partial \phi_i^e}{\partial z} \frac{\partial \phi_j^e}{\partial z} d\Omega = \frac{K_{zz}}{36V} d_i d_j . \tag{3.2-25}$$

Finally,

$$A_{ij}^e = \frac{1}{36V} (K_{xx} b_i b_j + K_{yy} c_i c_j + K_{zz} d_i d_j) , \tag{3.2-26}$$

where K_{xx}, K_{yy}, and K_{zz} are assumed constant for an element, and A_{ij}^e is the elemental contribution to matrix $[A^e]$ for i = 1,2,3,4 and j = 1,2,3,4 locally.

The matrix $[A]$ is obtained by summing the contribution from each node for each element matrix $[A^e]$. For example, if nodes i and j in the element nodal system correspond to nodes p and q in the global nodal system, the A_{ij}^e in the element stiffness matrix is added to A_{pq} in the global stiffness matrix. This procedure is repeated for each node in an element and for all elements in the domain Ω.

Integrations with only the interpolating function, and not their derivatives, are given by the relations (Zienkiewicz, 1977)

$$B_{ij}^e = \int_e S_s \phi_i^e \phi_j^e d\Omega = \frac{S_s V}{20} \quad for\ i \neq j \tag{3.2-27}$$

and

$$B_{ij}^e = \int_e S_s \phi_i^e \phi_j^e d\Omega = \frac{S_s V}{10} \quad for\ i = j, \tag{3.2-28}$$

where S_s is assumed constant for an element and B_{ij}^e is the elemental contribution to the matrix $[B^e]$ for i = 1,2,3,4 and j = 1,2,3,4 locally. The matrix $[B]$ is obtained by summing the contributions from each elemental matrix $[B^e]$, as described above for matrices $[A]$ and $[A^e]$.

Surface integrations.--On the free surface, it is necessary to perform integrations of the interpolating functions in the form

$$\int_e \phi_i^e \phi_j^e d\Gamma,$$

where the two-dimensional functions are now defined on the free surface. Where the flow domain is defined by an assemblage of tetrahedral elements, the free surface (and other boundary surfaces) can be defined by selected triangular faces of those tetrahedral elements that form the free surface. In other words, the free surface is defined by an assemblage of triangular elements representing the faces of those tetrahedral elements. Furthermore, if the free surface is assumed to be approximately horizontal, then the integrations can be carried out in the x-y plane according to the description below.

Within a triangular element, the approximate solution (Equation 3.2-6) can be expressed as

$$h' = \sum_{i=1}^{3} H_i \phi_i^e, \tag{3.2-29}$$

where ϕ_i^e represent the elemental interpolating functions defined only within the element e. The interpolating function for the node i is given by the relation (Zienkiewicz, 1977)

$$\phi_i^e = \frac{1}{2A}(a_i + b_i x + c_i y), \tag{3.2-30}$$

where

$$a_i = \begin{vmatrix} x_j & y_j \\ x_m & y_m \end{vmatrix}, \tag{3.2-31}$$

$$b_i = -\begin{vmatrix} 1 & y_j \\ 1 & y_m \end{vmatrix}, \tag{3.2-32}$$

$$c_i = -\begin{vmatrix} x_j & 1 \\ x_m & 1 \end{vmatrix}, \tag{3.2-33}$$

$$2A = \begin{vmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_m & y_m \end{vmatrix}, \tag{3.2-34}$$

and where A is the area of a triangular element [L^2]. The indexes i, j, and m are the nodal numbers for a triangular element. The ordering of nodal numbers must follow the right-hand rule, that is, the nodes are numbered in a counterclockwise direction when viewed from above the x-y plane.

Using Equations 3.2-30 through 3.2-34, integrations of the interpolating functions are given by the relations (Zienkiewicz, 1977)

$$B_{ij}^{e} = \int_{e} S_y \phi_i^e \phi_j^e d\Gamma = \frac{S_y}{12} A \quad for\ i \neq j \tag{3.2-35}$$

and

$$B_{ij}^{e} = \int_{e} S_y \phi_i^e \phi_j^e d\Gamma = \frac{S_y}{6} A \quad for\ i = j, \tag{3.2-36}$$

where S_y is assumed constant over an element and B_{ij}^{e} is the elemental contribution to matrix *[B]* for $i = 1,2,3$ and $j = 1,2,3$ locally. The matrix *[B]* is obtained by summing the contributions from each elemental matrix $[B^e]$, as described above for the matrices *[A]* and $[A^e]$.

3.2.2.4 Integration in Time

Although the matrices *[A]* and *[B]* and the vector *{F}* can now be evaluated, the system of ordinary differential equations must still be solved. To do this, the time derivative is approximated using the first-order, implicit, finite-difference scheme

$$[A]\{H_{t+\Delta t}\} + \frac{1}{\Delta t}[B]\{H_{t+\Delta t} - H_t\} - \{F\} = O, \tag{3.2-37}$$

which can be rearranged to obtain

$$\left([A] + \frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F\}, \tag{3.2-38}$$

where Δt is the time step [t]. By the implicit approximation of the time derivative, the matrices *[A]* and *[B]* and the vector *{F}* are evaluated at the new time step $t+\Delta t$.

3.2.2.5 Iterative Solution

Because the coefficients of the matrices *[A]* and *[B]* and the vector *{F}* are dependent, in part, on hydraulic head, Equation 3.2-38 represents a system of nonlinear algebraic equations. However, the nonlinearity introduced by head-dependent sources and sinks and by land subsidence is not severe. Therefore, the solution of Equation 3.2-38 can be obtained by a simple iterative procedure, in which, at the *k-th* iteration, Equation 3.2-38 takes the form

$$\left([A]^{(k-1)} + \frac{1}{\Delta t}[B]^{(k-1)}\right)\{H_{t+\Delta t}\}^{(k)} = \frac{1}{\Delta t}[B]^{(k-1)}\{H_t\} + \{F\}^{(k-1)}. \qquad (3.2\text{-}39)$$

At each iteration, the matrices *[A]* and *[B]* and the vector *{F}* are updated, and a solution is obtained the for new values of $\{H_{t+\Delta t}\}$ by the square-root or Cholesky method (Pinder and Gray, 1977). The process is repeated until the absolute difference between $\{H_{t+\Delta t}\}^{(k)}$ and $\{H_{t+\Delta t}\}^{(k-1)}$ at any particular node is less than some specified value. In most applications, convergence is obtained in two to five iterations.

3.2.3 Structure of Subroutine

3.2.3.1 General Structure

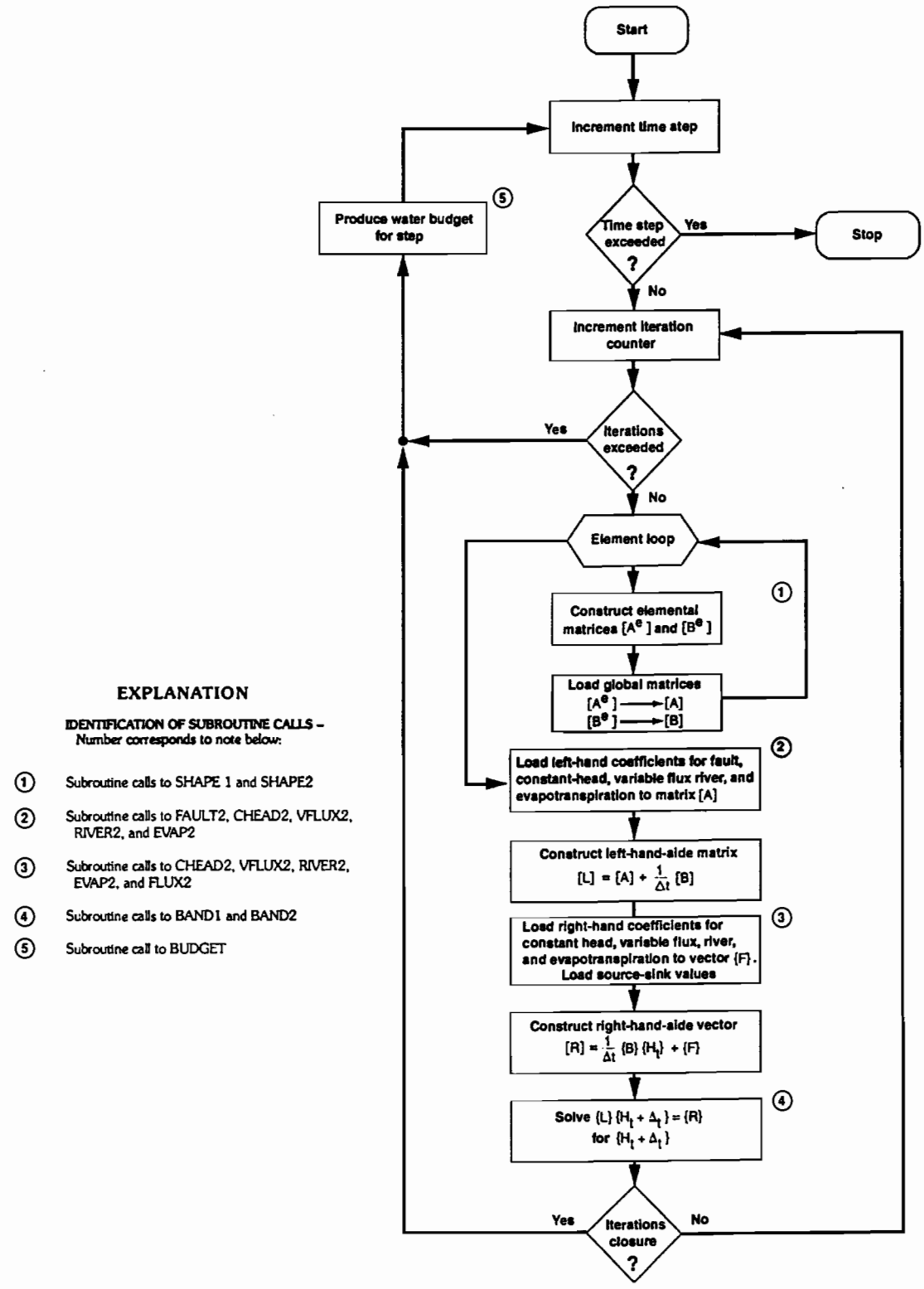
Subroutine *MODEL* is structured into two basic blocks. The first block, which is entered by a call to *MODEL1*, is for the input and display of data describing the ground-water problem to be solved. These data are entered by read statements within the *MODEL1* block and within the subroutine blocks *CHEAD1*, *FLUX1*, *RIVER1*, *EVAP1*, *VFLUX1*, *FAULT1*, *SINK1*, *WATER1*, and *SEARCH*, which are called in *MODEL1*. Within the first block, switches are set for the display of the input data and of the computational results.

Within the second block, which is entered by the call to *MODEL2*, the finite-element method is implemented (fig. 2). The finite-element calculations are organized into two computational loops. The outer loop is the time-step loop, and the inner loop is the iterative-solution loop, which relates to the solution method described in Section 3.2.2.5. For each time step, the iterative-solution loop is repeated until the solution converges. The closure criterion for convergence is that the calculated hydraulic heads change less than a specified value between two successive iterations. The actual closure criterion is

$$\max_i \quad |H_i^{(k)} - H_i^{(k-1)}| \leq \epsilon, \qquad (3.2\text{-}40)$$

where

H_i is the calculated hydraulic head at the node i [L],
k is the iteration counter [dimensionless], and
ϵ is the closure criterion [L].



EXPLANATION

IDENTIFICATION OF SUBROUTINE CALLS – Number corresponds to note below:

1. Subroutine calls to SHAPE 1 and SHAPE2
2. Subroutine calls to FAULT2, CHEAD2, VFLUX2, RIVER2, and EVAP2
3. Subroutine calls to CHEAD2, VFLUX2, RIVER2, EVAP2, and FLUX2
4. Subroutine calls to BAND1 and BAND2
5. Subroutine call to BUDGET

Figure 2. Structure of subroutine *MODEL*.

3.2.3.2 Compressed Storage

A compressed storage scheme is used in subroutine *MODEL* for the matrices *[A]* and *[B]*. Because these matrices are symmetric, the storage requirement can be reduced. It is necessary to store only the upper half or the lower half of a symmetric matrix. The half that is not stored can be reconstructed at any time from the relation

$$A_{ij} = A_{ji} , \tag{3.2-41}$$

which applies to any symmetric matrix. Besides being symmetric, the matrices *[A]* and *[B]* are banded. Because it is necessary to store only part of the matrices within the band of nonzero coefficients, minimizing the bands reduce the storage requirement for the matrices. The size of the bands is minimized when the nodes are numbered to minimize the numerical difference between the highest and lowest node within each element. Within a band, the element with the largest numerical difference between its highest and lowest nodes determines the size of the band. Within the finite-element grid, the band with largest size determines the storage requirement of the matrices for the model. Band size is usually minimized when the nodes are sequentially numbered in stacks on vertical planes across the shortest dimension of the grid.

Using matrix *[A]* as an example, figure 3 shows how the symmetric and the banded structure of matrices *[A]* and *[B]* can be used to reduce the storage requirements. As indicated on the figure, the diagonal of matrix *[A]* occurs in the compressed matrix *[A′]* as column 1. Accordingly, a column of matrix *[A]* occurs in the compressed matrix *[A′]* as a diagonal where the diagonal runs downward from the left.

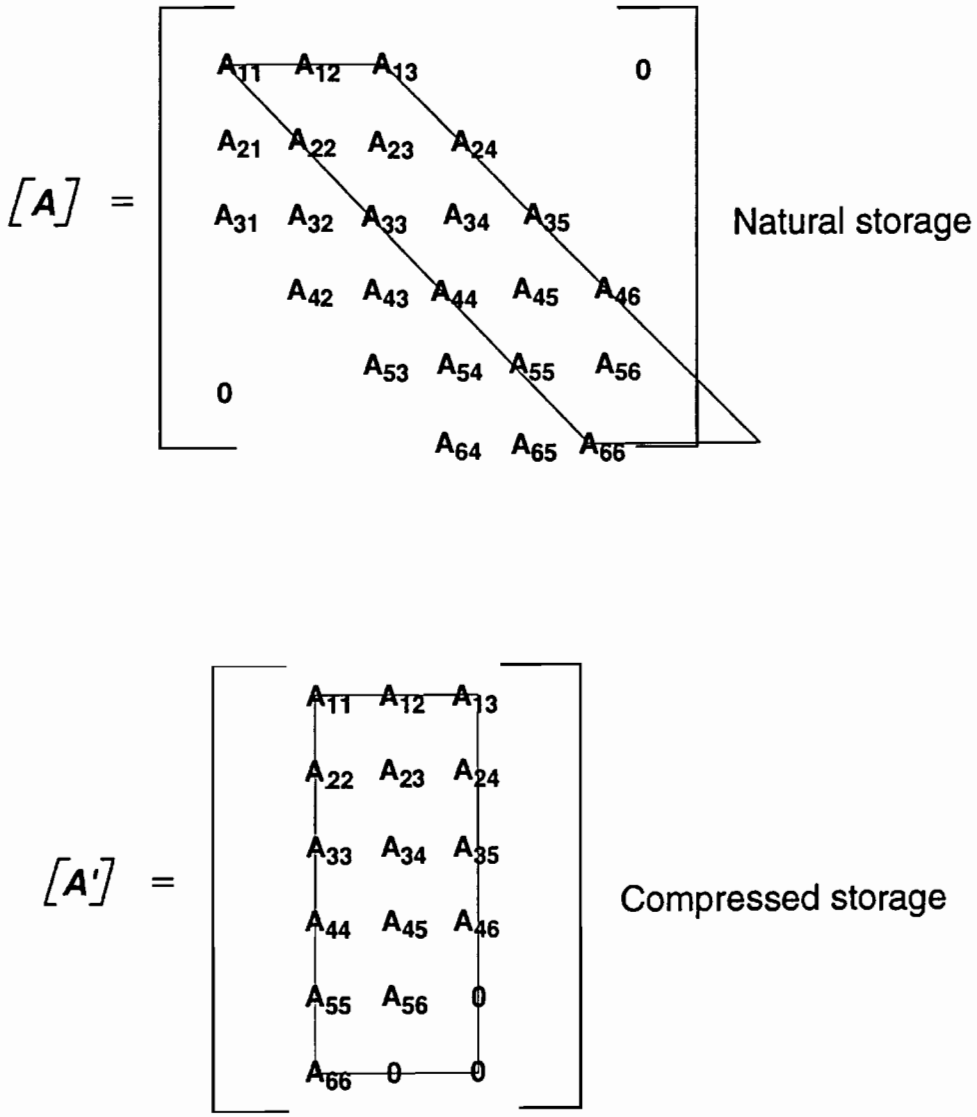


Figure 3. Compressed storage of matrix *[A]*.

3.2.3.3 Linear Problems

In some applications of *FEMFLOW3D*, the matrices *[A]* and *[B]*, do not change during simulation. This occurs when the coefficients of *[A]*, *[B]*, and *[F]* are independent of *{H}*, which means that Equation 3.2-38 is linear. This linear equation occurs when (1) the drainage-node form of the specified-head boundary condition is not used, (2) river-aquifer interactions are not simulated, (3) evapotranspiration from ground water is not simulated, and (4) land subsidence is not simulated. If each of these conditions is satisfied, the matrices *[A]* and *[B]* need to be constructed only once. Further, if the time step is constant, the upper triangularization of the matrix

$$\left([A] + \frac{1}{\Delta t}[B]\right),$$

which occurs in Equation 3.2-38, needs to be done only once in subroutine *BAND*. Accordingly, a switch can be set in subroutine *MODEL* to identify the problem as linear. In this case, the matrices *[A]* and *[B]* will be constructed only once, which will reduce the computational requirements of the application.

3.2.3.4 Finite-Element Grid

The finite-element grid defines the geometry of the ground-water system. The grid consists of a solid configuration of tetrahedrons. Because tetrahedrons are difficult solids with which to work, the actual grid is assembled from prismatic elements with a triangular cross section. The prismatic elements are oriented spatially with subhorizontal triangular faces and subvertical quadrilateral faces. Subroutine *MODEL* then automatically fits three tetrahedrons into each prismatic element (fig. 4). However, to allow flexibility in the construction of three-dimensional grids, the subroutine also accepts prismatic elements that contain edges of zero height (fig. 5). A prismatic element with one zero-height edge contains two tetrahedrons, and an element with two zero-height edges contains one. These special elements can be used to represent geologic features that taper to zero thickness or they can be used to include a vertically fine grid in zones of particular interest. Without these special elements, a vertical zone of fine gridding can be terminated only by carrying it to the edge of the grid.

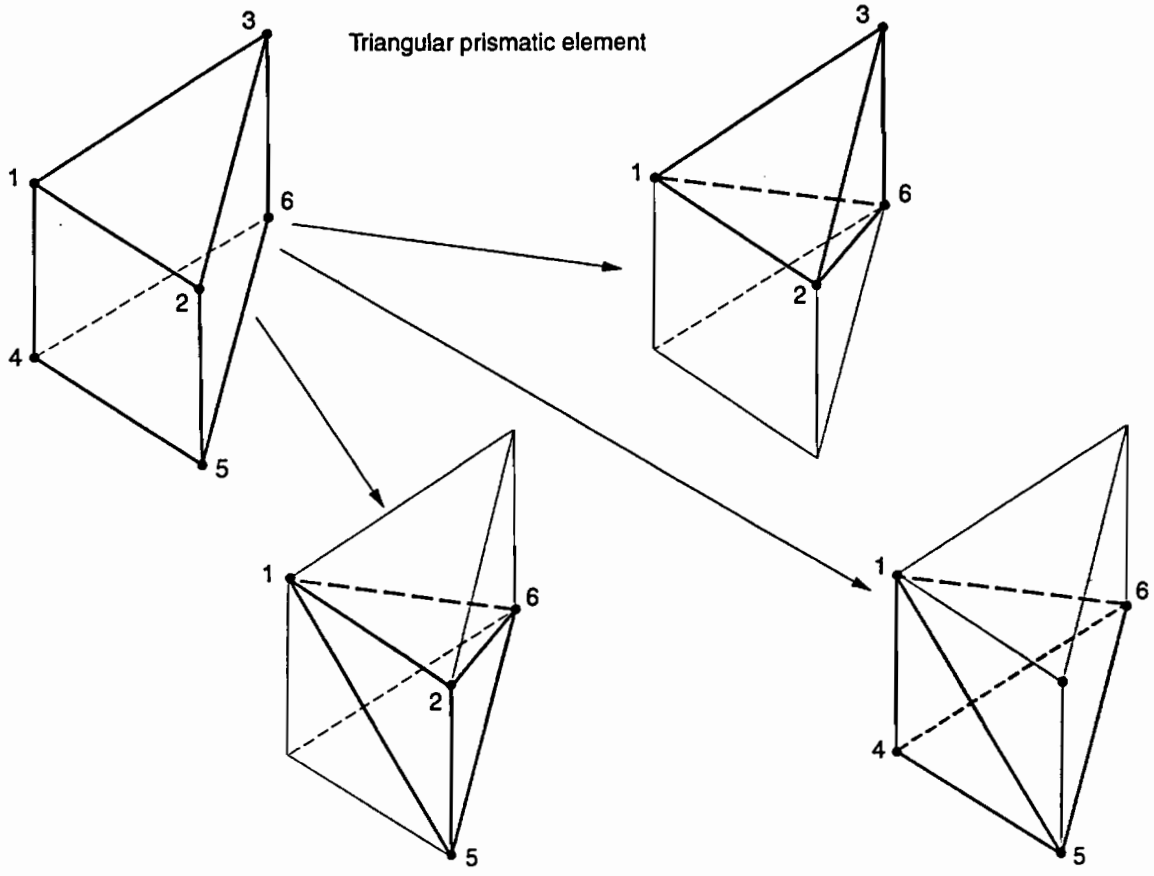


Figure 4. Disaggregation of triangular prismatic elements into tetrahedrons.

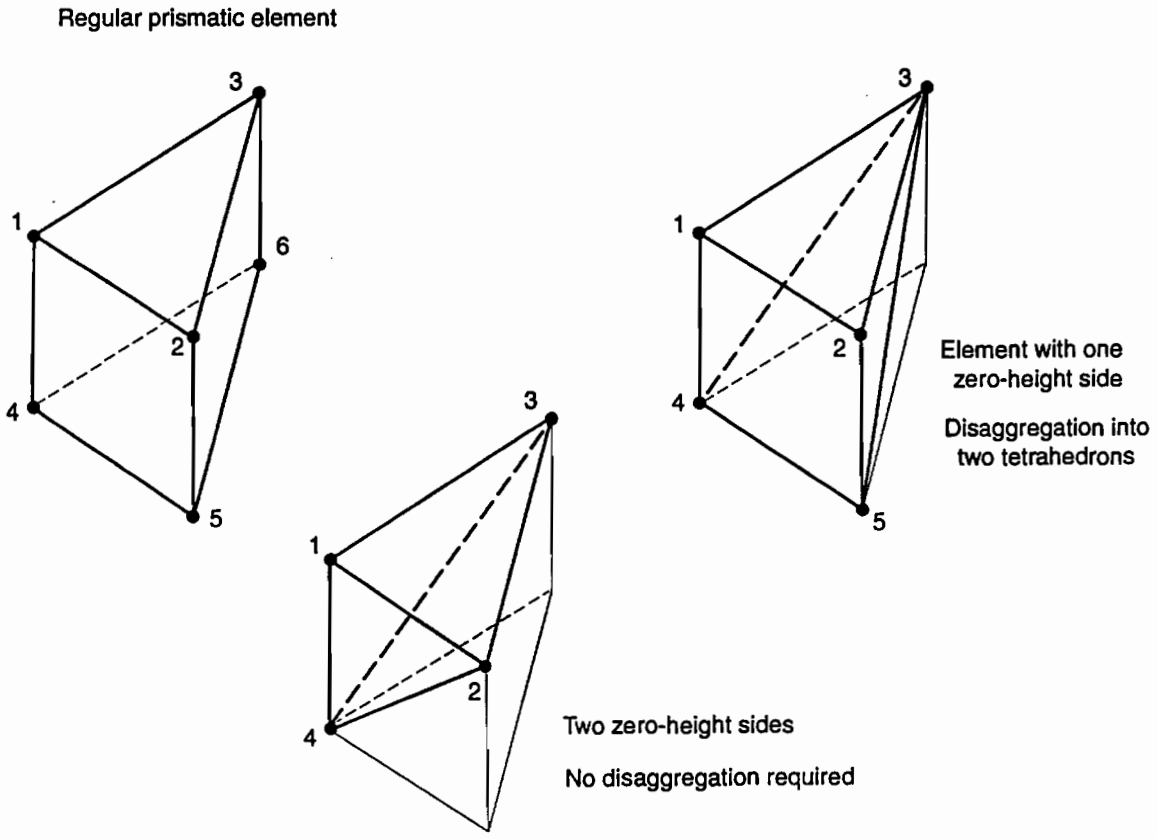


Figure 5. Triangular prisms with zero-height edges.

3.3 Subroutine *CHEAD*

3.3.1 Background

Subroutine *CHEAD* is used to represent specified-head boundary conditions, which can take three different forms. In the first form, unlimited discharge can occur into or from the ground-water system through the specified-head nodes. For example, this type of boundary condition is used with constantly flowing rivers that maintain a hydraulic connection to the water table. In the second form, unlimited discharge can occur from the ground-water system through specified-head nodes, but discharge into the ground-water system through the nodes is limited. This boundary condition is used when a water table periodically drops below a river or a lake. In the third form, unlimited discharge can occur from the ground-water system through specified-head nodes, but no discharge can occur into the ground-water system through the nodes. This boundary condition is used to represent drainage systems. Such a condition might exist where ground-water can discharge to a subsurface drain pipe. However, if water otherwise does not flow in the pipe, water cannot discharge from the pipe to the ground-water system.

The heads specified in the subroutine *CHEAD* either may be constant or may vary with time. A single head elevation for each specified-head node may be assigned for the entire simulation to represent invariant conditions, such as the elevation of a subsurface drain pipe. Alternatively, the head elevation for each specified-head node may vary in time in accordance with a specified hydrograph, which is input to the model as a table of hydraulic heads at specified times

3.3.2 Mathematical Basis

Discharge equation.--The equation for the discharge of water across the boundary surface owing to specified heads is

$$q_B(x,y,t) = \sum_{i=1}^{n} C_{Bi}(H_{Bi} - H_i)\ \delta(x - x_i)\ \delta\ (y - y_i)\ , \qquad (3.3\text{-}1)$$

where

q_B is the functional representation of ground-water discharges owing to the specified-head boundary condition [L/t],
C_{Bi} is a coefficient representing the leakance of the specified-head boundary condition for the node i [L^2/t],
H_{Bi} is the specified head for the node i [L],
H_i is the calculated hydraulic head for the node i,
x_i is the x coordinate for the node i [L],
y_i is the y coordinate for the node i [L],
δ is the Dirac delta function [1/L], and
n is the number of nodes [dimensionless],

and where the coordinate system locally is oriented within the plane of the boundary surface. For a drainage boundary condition in which the direction of flow across the boundary is outward, flow occurs only when H_i is greater than H_{Bi} in Equation 3.3-1.

The discharge q_B has a nonzero value at the specified-head nodes and a zero value elsewhere, where the discharge q_B is the discharge necessary to produce calculated hydraulic heads H_i at node i that are approximately equal to the boundary heads H_{Bi} at the node i. This relation between specified and calculated heads can be achieved if the coefficient C_{Bi} in Equation 3.3-1 is sufficiently large. The practical application of the specified-head boundary condition does not require the careful determination of values for the coefficient C_{Bi}. It is sufficient to choose a value that is large enough that H_i will be close to H_{Bi}. Nevertheless, the value should not be so large that the difference between H_i and B_{Bi} is lost in the precision of the calculations.

Substitution into force vector.--Equation 3.2-15 is an expression for F_i, which is the quantity representing the internal and boundary fluxes for the model domain. Correspondingly, Equation 3.3-1 is an expression for the boundary fluxes representing specified-head boundaries. Equation 3.2-15 and 3.3-1 can be combined into the form

$$F_i = F'_{Bi} + C_{Bi}(H_{Bi} - H_i) \tag{3.3-2}$$

where F'_{Bi} represents the internal and boundary fluxes associated with node i except for the boundary fluxes associated with the specified-head boundary conditions.

The right-hand side of Equation 3.3-2 includes the dependent variable {H} from Equation 3.2-38, which is the system of algebraic equations representing the heads {H} at the end of the current time step. With the substitution of Equation 3.3-2 for {F} in Equation 3.2-38, the dependent variable occurs on both the right-hand and left-hand side of Equation 3.2-38 in the form

$$\left([A]+\frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\}=\frac{1}{\Delta t}[B]\{H_t\}+\{F_B\}+\{C_B H_B\}-diag\{C_B\}\{H_{t+\Delta t}\} \tag{3.3-3}$$

or

$$\left([A]+\frac{1}{\Delta t}[B]+diag\{C_B\}\right)\{H_{t+\Delta t}\}=\frac{1}{\Delta t}[B]\{H_t\}+\{F_B\}+\{C_B H_B\} \tag{3.3-4}$$

where

$$\{C_B H_B\}=diag\{C_B\}\{H_B\}. \tag{3.3-5}$$

Equation 3.3-4 is equivalent to adding the quantities C_{Bi} to the diagonal of the left-hand martix

$$\left([A]+\frac{1}{\Delta t}[B]\right)$$

in Equation 3.2-38 and to adding the quantities $C_{Bi}\ H_{Bi}$ to the right hand vector

$$\frac{1}{\Delta t}[B]\{H_t\}+\{F\}.$$

3.3.3 Structure of Subroutine

Subroutine *CHEAD* is structured into three basic blocks. The first block, which is entered by a call to *CHEAD1*, is for the input and display of data for the identification of specified-head nodes in the finite-element grid and the particular form of the boundary condition. The second block, which is entered by a call to *CHEAD2*, creates the coefficients to be added to *diag[A]* and *{F}*, as described in Section 3.3.2. The third block, which is entered by a call to *CHEAD3*, calculates the actual ground-water discharge through each specified-head node.

In the third block of subroutine *CHEAD*, the discharge of ground water through individual nodes in the finite-element grid is calculated from the expression

$$\{Q_B\} = \{C_{BR}\} - \{C_{BL}\, H\}, \tag{3.3-6}$$

where an element of $\{Q_B\}$ is given by

$$Q_{Bi} = C_{BRi} - C_{BLi} H_i, \tag{3.3-7}$$

and where $\{Q_B\}$ is a vector of inward discharges [L^3/t]. The cumulative discharge through all specified-head nodes is given by

$$Q_B = \sum_{i=1}^{n} Q_{Bi}, \tag{3.3-8}$$

where

Q_B is the cumulative discharge [L^3/t], and
n is the number of nodes [dimensionless].

3.4 Subroutine *FLUX*

3.4.1 Background

Subroutine *FLUX* is used to specify values for the source-sink term W and the boundary-flux term q in Equation 3.2-15. In subroutine *FLUX*, the boundary-flux term is for the specified-flux boundary condition.

3.4.2 Mathematical Basis

Discharge equation.--The internal source-sink fluxes and the boundary fluxes are both represented by nodal values. Mathematically, the internal source-sink fluxes are given by the relation

$$W_P(x,y,z,t) = \sum_{i=1}^{n} Q_{Pi}(t)\ \delta(x-x_i)\ \delta\ (y-y_i)\ \delta\ (z-z_i), \qquad (3.4\text{-}1)$$

where

W_P is the functional representation of internal source-sink fluxes [1/t],
Q_P is the source-sink flux at the node i [L^3/t],
x_i is the x coordinate of the node i [L],
y_i is the y coordinate of the node i [L],
z_i is the z coordinate of the node i [L],
δ is the Dirac delta function [1/L], and
n is the number of nodes [dimensionless].

The discharge w_P has a nonzero value at nodes where source-sink fluxes occur and a zero value elsewhere.

Substitution into force vector.--Equation 3.2-15 is an expression for F_i, which is the quantity representing the internal and boundary fluxes for the model domain. Correspondingly, Equation 3.4-1 is an expression for the boundary fluxes representing specified fluxes. Equations 3.2-15 and 3.4-1 can be combined into the form:

$$F_i = F'_{Pi} + Q_{Pi}\ , \qquad (3.4\text{-}2)$$

where F'_{Pi} represents the internal and boundary fluxes associated with node i except for the boundary fluxes associated with the specified fluxes. With the substitution of Equation 3.4-2 for {F} in Equation 3.2-38, the resulting expression is

$$\left([A]+\frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\}=\frac{1}{\Delta t}[B]\{H_t\}+\{F'_P\}+Q_P. \qquad (3.4\text{-}3)$$

3.4.3 Structure of Subroutine

Subroutine *FLUX* is structured into two basic blocks. The first block, which is entered by a call to *FLUX1*, is for the input and display of data on nodal fluxes for either internal source-sink fluxes or boundary fluxes. The second block, which is entered by a call to *FLUX2*, combines data sets on nodal fluxes to produce the nodal fluxes for a particular time step.

The nodal fluxes are input to subroutine *FLUX* as a series of nodal-flux data sets. Then, the nodal fluxes for a particular time step are assigned to that time step by constructing a linear combination of the data sets in the form

$$\{Q_P\} = a_i \sum_{i=1}^{n} \{Q'_P\}_i \,, \tag{3.4-4}$$

where

$\{Q_P\}$ is the vector of combined nodal fluxes for the time step [L^3/t],
a_i is a multiplicative factor for the data set i [dimensionless],
n is the number of data sets [dimensionless], and
$\{Q'_P\}_i$ is the vector of nodal fluxes for the data set i [L^3/t].

Each data set represents a set of fluxes for each node. The flux for a particular node is the sum of the values from each data set multiplied by a factor for the data set, where the factor can be zero.

The cumulative discharge through all specified-flux nodes is given by

$$Q_P = \sum_{i=1}^{n} Q_{Pi} \,, \tag{3.4-5}$$

where

Q_P is the cumulative inward discharge [L^3/t], and
n is the number of nodes [dimensionless].

3.5 Subroutine *RIVER*

3.5.1 Background

Subroutine *RIVER* is used to simulate river-aquifer interactions. The simulation is performed by routing input inflows through a river network (or networks) that consists of a main river channel and tributary channels, while accounting for riverflow depletions and accretions owing to the exchange of water between the river and the ground-water system. Each river channel consists of a series of reaches associated with nodes in the model. In subroutine *RIVER*, the exchange of water is dependent on the river stage, river width, river-bed thickness, river-bed hydraulic conductivity, and ground-water levels at each node in the model.

Section 5.2.11 provides a detailed example of a representation of river networks in a model.

3.5.2 Mathematical Basis

Discharge equation.--The exchange of water between the river and the ground-water system has the general form

$$q_R\,(x,y,t) = \sum_{i=1}^{n} C_{Ri}\,(H_{Ri} - H_i)\;\delta\,(x-x_i)\;\delta(y-y_i), \qquad (3.5\text{-}1)$$

where

q_R is the functional representation of the exchange rate [L/t],
C_{Ri} is a coefficient representing the river-bed leakance associated with the node i [L^2/t],
H_{Ri} is the stage in the river reach for the node i [L],
H_i is the calculated hydraulic head for the node i [L],
x_i is the x coordinate of the node i [L],
y_i is the y coordinate of the node i [L],
δ is the Dirac delta function [dimensionless], and
n is the number of nodes [dimensionless].

The exchange rate q_R has a nonzero value at the river nodes and a zero value elsewhere.

The coefficient C_{Ri} in Equation 3.5-1 depends on several factors, as indicated in the expression

$$C_{Ri} = L_i W_i \frac{K_i'}{B_i'}, \tag{3.5-2}$$

where
L_i is the reach length associated with the node i [L],
W_i is the river width at node i [L],
K_i' is the vertical hydraulic conductivity of the river bed at node i [L/t], and
B_i' is the thickness of the river bed at node i [L].

Accordingly, the coefficient C_{Ri} is the product of the wetted area of the river reach $(L_i W_i)$ and the river-bed leakance $(K_i' B_i')$.

River width.--The river width, in turn, is given by the relation (Leopold and others, 1964, p. 214-241)

$$W_i = (\alpha_w Q_{Si})^{m_w}, \tag{3.5-3}$$

where
α_w is a coefficient for the river width $[(t/L^2)^{1/m_w}]$,
Q_{Si} is the river flow $[L^3/t]$, and
m_w is an exponent for the river width [dimensionless].

The values of α_w and m_w are the intercept and slope of the log-log width-flow relation for the river.

Alternatively, the river width can be specified as a table of widths and the corresponding flows. Then, the width for a particular flow can be obtained from the table by interpolation between the tabulated values.

River stage.--The river stage H_{Ri} in Equation 3.5-1 also depends on several factors, as indicated in the expression (Leopold and others, 1964, p. 214-241)

$$H_{Ri} = H_{Di} + (\alpha_D Q_{Si})^{m_D}, \tag{3.5-4}$$

where
H_{Ri} is the stage in the river reach at the node i [L],
H_{Di} is the river-bed elevation [L], which is measured from the same datum as H_i,
α_D is a coefficient for river depth $[(t/L^2)^{1/m_D}]$,
Q_{Si} is the river flow $[L^3/t]$, and
m_D is an exponent for the river depth [dimensionless].

The values of α_D and m_D are the intercept and slope of the log-log depth-flow relation for the river.

Alternatively, the river depth can be specified as a table of depths and the corresponding flows. Then, the depth for a particular discharge can be obtained from the table by interpolation between the tabulated values.

Substitution into force vector.--Equation 3.2-15 is an expression for F_i, which is the quantity representing the internal and boundary fluxes for the model domain. Correspondingly, Equation 3.5-1 is an expression for the boundary fluxes representing river nodes. Equations 3.2-15 and 3.5-1 can be combined into the form

$$F_i = F'_{Ri} + C_{Ri}\,(H_{Ri} - H_i)\,, \tag{3.5-5}$$

where F'_{Ri} represents the internal and boundary fluxes associated with node i except for the boundary fluxes associated with the river nodes.

The right-hand side of Equation 3.5-5 includes the dependent variable $\{H\}$ from Equation 3.2-38, which is the system of algebraic equations representing the heads $\{H\}$ at the end of the current time step. With the substitiution of Equation 3.5-5 for $\{F\}$ in Equation 3.2-38, the dependent variable occurs on both the right-hand and left-hand side of Equation 3.2-38 in the form

$$\left([A]+\frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\}=\frac{1}{\Delta t}[B]\{H_t\}+\{F'_R\}+\{C_R H_R\}-diag\{C_R\}\{H_{t+\Delta t}\} \tag{3.5-6}$$

or

$$\left([A]+\frac{1}{\Delta t}[B]\right)+diag\{C_R\}\{H_{t+\Delta t}\}=\frac{1}{\Delta t}[B]\{H_t\}+\{F'_R\}+\{C_R H_R\}, \tag{3.5-7}$$

where

$$\{C_R H_R\}=diag\{C_R\}\{H_R\}, \tag{3.5-8))}$$

Equation 3.5-7 is equivalent to adding the quantities C_{Ri} to the diagonal of the left-hand martrix

$$\left([A]+\frac{1}{\Delta t}[B]\right)$$

in Equation 3.2-38 and to adding the quantities $C_{Ri}\,H_{Ri}$ to the right hand vector

$$\frac{1}{\Delta t}[B]\{H_t\}+\{F\}.$$

Several different conditions determine the values of C_{Ri}. First, if water flows to the lower end of the reach associated with the node i in the finite-element grid, then C_{Ri} is given by Equation 3.5-2 where L_i is the entire length of the reach. Second, if water does not flow to the lower end of the reach, then C_{Ri} again is given by Equation 3.5-2, except that L_i is the wetted length of the reach. Third, if no flow occurs within the reach, then C_{Ri} equals zero. Finally, if the ground water at the node i is below the bottom of the river-bed thickness B', then C_{Ri} equals zero, but the coefficient F_i in Equation 3.2-15 is replaced by

$$F'_{Ri} + C_{Ri}[H_{Ri} - (H_{Di} - B_i')],$$

where

H_{Di}- B_i' is equal to the elevation of the base of the river bed material [L].

For this condition, the lefthand side of Equation 3.2-38 is unchanged. The length L_i is always the wetted length of the reach.

For this latter condition, the hydraulic connection between the river and the ground-water system is broken. The recharge rate to the ground-water system from the river is independent of the hydraulic heads in the ground-water system. For the condition of hydraulic disconnection, the seepage through the river-bed material depends on the head differential across the river-bed material. The head at the upper surface of the river-bed material is the river-surface elevation H_R. The head at the bottom surface of the river-bed material is defined by the assumption of unit hydraulic gradient from the bottom surface to the ground-water table. With that assumption, the head equals the water-table elevation plus the distance from the water table to the bottom surface. However, the sum of these quantities equals the elevation of the bottom surface of the bed materials H_{Di}-B_i.

3.5.3 Structure of Subroutine

Subroutine *RIVER* is structured into three basic blocks. The first block, which is entered by a call to *RIVER1*, is for the input and display of data for the specification of the river network, the physical properties of the river reaches, and the river inflow inputs. The second block, which is entered by a call to *RIVER2*, creates the coefficients to be added to *diag[A]* and *{F}*, as described in Section 3.5.2. The third block, which is entered by a call to *RIVER3*, calculates the components of the water budget for the river network, including the exchanges of water between the river network and the ground-water system.

In the third block, the exchange of water between the river and ground-water system is calculated from the expression

$$\{Q_R\} = \{C_{RR}\} - \{C_{RL}H\}, \tag{3.5-9}$$

where an element of $\{Q_R\}$ is given by

$$Q_{Ri} = C_{RRi} - C_{RLi}H_i, \tag{3.5-10}$$

and where $\{Q_R\}$ is a vector of inward discharges [L^3/t]. The cumulative discharge through all nodes is given by

$$Q_R = \sum_{i=1}^{n} Q_{Ri}, \tag{3.5-11}$$

where

Q_R is the cumulative inward discharge [L^3/t], and
n is the number of nodes [dimensionless].

3.6 Subroutine *EVAP*

3.6.1 Background

Subroutine *EVAP* is used to simulate the discharge of ground-water from a shallow water table owing to evapotranspiration from vegetated areas or evaporation from bare-soil areas. Simulation is done by assuming that the discharge is linearly related to the depth below the land surface to the water table. The linear relation holds until a maximum depth (extinction depth) is reached. If the water table drops below the extinction depth, evapotranspiration (or evaporation) ceases. In subroutine *EVAP*, the evapotranspiration rate depends on the local depth to the water table, the extinction depth, the potential evapotranspiration rate, and the size of the discharge area.

3.6.2 Mathematical Basis

Discharge equation.--The discharge of ground water from a shallow water table has the general form

$$q_E(x,y,t) = \sum_{i=1}^{n} C_{Ei} \, (H_{Ei} - H_i) \, \delta(x - x_i) \, \delta \, (y - y_i) \, , \tag{3.6-1}$$

where

q_E is the functional representation discharge of ground water [L/t],
C_{Ei} is a coefficient representing the evapotranspiration at the node i [L^2/t],
H_{Ei} is the extinction-depth elevation [L],
H_i is the calculated hydraulic head for the node i [L],
x_i is the x coordinate of the node i [L],
y_i is the y coordinate of the node i [L],
δ is the Dirac delta function [1/L], and
n is the number of nodes [dimensionless].

The discharge q_E has a nonzero value for nodes where ground-water discharge occurs and a zero value elsewhere.

The coefficient C_{Ei} in Equation 3.6-1 depends on several factors, as indicated in the expression

$$C_{Ei} = \frac{A_i E_{max}}{H_{Li} - H_{Ei}}, \tag{3.6-2}$$

where

A_i is the discharge area associated with node i [L^2],
E_{max} is the potential evapotranspiration rate per unit area [L/t],
H_{Li} is the land-surface elevation at the node i [L], and
H_{Ei} is the extinction-depth elevation at the node i [L], and is given by

$$H_{Ei} = H_{Li} - d_o, \tag{3.6-3}$$

where d_o is the extinction depth [L].

Substitution into force vector.--Equation 3.2-15 is an expression for F_i which is the quantity representing the internal and boundary fluxes for the model domain. Correspondingly, Equation 3.6-1 is an expression for the boundary fluxes representing evapotranspiration nodes. Equations 3.2-15 and 3.6-1 can be combined into the form

$$F_i = F'_{Ei} + C_{Ei}(H_{Ei} - H_i), \tag{3.6-4}$$

where F'_{Ei} represents the internal and boundary fluxes associated with node i except for the boundary fluxes associated with the evapotranspiration nodes.

The right-hand side of Equation 3.6-4 includes the dependent variable *{H}* from Equation 3.2-38, which is the system of algebraic equations representing the heads *{H}* at the end of the current time step. With the substitution of Equation 3.6-4 for *{F}* in Equation 3.2-38, the dependent variable occurs on both the right-hand and left-hand side of Equation 3.2-38 in the form

$$\left([A] + \frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F'_E\} + \{C_E H_E\} - diag\{C_E\}\{H_{t+\Delta t}\}\ , \qquad (3.6\text{-}5)$$

or

$$\left([A] + \frac{1}{\Delta t}[B] + diag\{C_E\}\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F'_E\} + \{C_E H_E\}\ , \qquad (3.6\text{-}6)$$

where

$$\{C_E H_E\} = diag\{C_E\}\{H_E\}\ . \qquad (3.6\text{-}7)$$

Equation 3.6.6 is equivalent to adding the quantities C_{Ei} to the diagonal of the left-hand martix

$$\left([A] + \frac{1}{\Delta t}[B]\right)$$

in Equation 3.2.38 and to adding the quantities $C_{Ei}\ H_{Ei}$ to the right hand vector

$$\frac{1}{\Delta t}[B]\{H_t\} + \{F\}\ .$$

Several different conditions can occur for values of C_{Ei}. First, if the calculated hydraulic head H_i is above the extinction depth and below the land surface, then C_{Ei} is given by Equation 3.6-2. Second, if the calculated hydraulic head H_i is below the extinction depth, then C_{Ei} equals zero, and no discharge occurs from the shallow water table. Third, if the calculated hydraulic head H_i is at or above the land surface, C_{Ei} is set to a large value to create a specified-head boundary condition with the land-surface elevation as the boundary head.

For this last condition, the discharge rate from a shallow water table is greater than the potential evapotranspiration rate and ground water seeps onto the land surface. The simulation assumes that the seepage onto the land surface is removed from further interaction with the ground-water system, which, for example, would occur if the seepage is collected into surface-water channels and then exits the geographic area of the ground-water system as surface-water outflow.

3.6.3 Structure of Subroutine

Subroutine *EVAP* is structured into three basic blocks. The first block, which is entered by a call to *EVAP1*, is for the input and display of data for the discharge of ground water by evapotranspiration, including data on the discharge area, extinction depth, and potential evapotranspiration rate. The second block, which is entered by a call to *EVAP2*, creates the coefficients to be added to *diag[A]* and *{F}*, as described in Section 3.6.2. The third block, which is entered by a call to *EVAP3*, calculates the ground-water discharge by evapotranspiration.

In the third block, the discharge of ground water by evapotranspiration is calculated from the relation

$$\{Q_E\} = \{C_{ER}\} - \{C_{EL}H\}\,, \tag{3.6-8}$$

where an element of $\{Q_E\}$ is given by

$$Q_{Ei} = C_{ERi} - C_{ELi}H_i\,, \tag{3.6-9}$$

and where $\{Q_E\}$ is a vector of inward discharges [L^3/t]. The cumulative discharge through all nodes is given by

$$Q_E = \sum_{i=1}^{n} Q_{Ei}\,, \tag{3.6-10}$$

where

Q_E is the cumulative inward discharge [L^3/t], and
n is the number of nodes [dimensionless].

3.7 Subroutine *VFLUX*

3.7.1 Background

Subroutine *VFLUX* is used to specify variable-flux boundary conditions. These conditions are for the boundary fluxes that would result if the modeled flow domain was extended outward a large distance from the actual boundary of the modeled flow domain. This is done by attaching the analytical solution for a semi-infinite linear ground-water system to the boundary of the modeled flow domain.

Section 5.2.13 provides a detailed example of a representation of variable-flux boundaries in a model.

3.7.2 Mathematical Basis

Discharge equation.--The exchange of water at the boundary of the modeled flow domain has the general form

$$q_V(x,y,t) = \sum_{i=1}^{n} [C_{Vi}(H_{Vi} - H_i) + Q_{Vi}' \, \delta(X-X_i) \, \delta(Y-Y_i)], \qquad (3.7\text{-}1)$$

where

- q_V is the functional representation of the exchange rate [L/t],
- C_{Vi} is a coefficient relating to the effect in the current time step owing to the head change for node i at the boundary in the current time step [L^2/t],
- H_{Vi} is the steady-state hydraulic head for node i [L],
- H_i is the calculated hydraulic head for node i for the current time step [L],
- Q_{Vi}' is the discharge across the boundary at node i in the current time step owing to head changes at the boundary in past time steps [L^3/t],
- x_i is the x coordinate of the node i [L],
- y_i is the y coordinate of the node i [L],
- δ is the Dirac delta function [1/L],
- n is the number of nodes [dimensionless],
- i is the node number [dimensionless],

and where the coordinate system is locally oriented within the plane of the boundary surface.

Equation 3.7-1 applies only if the simulation starts with a steady-state initial condition. This requirement eliminates the need for considering the time fluctuations of the boundary heads at time prior to t=0 in the simulation.

The coefficient C_{Vi} and the discharge Q_{Vi}' have nonzero values for nodes on the variable-flux boundaries and zero values elsewhere. Correspondingly, the exchange rate q_v has a nonzero value for nodes where both C_{Vi} and Q_{Vi}' have nonzero values.

The coefficient C_{Vi} for the effect in the current time step owing to the head change in the current time step is given by the relation

$$C_{Vi} = \frac{2}{\Delta t}\left[\frac{K_i B_i W_i}{\left(\frac{\pi K_i}{S_{si}}\right)^{1/2}}\right] \Delta t^{1/2}, \tag{3.7-2}$$

where

K_i is the hydraulic conductivity of the extended ground-water system for node i [L/t],
B_i is the thickness of the extended ground-water system for node i [L],
W_i is the width of the extended ground-water system for node i [L],
Δt is the time-step length [t],
S_{si} is the specific storage for the extended ground-water system for node i [1/L], and
i is the node number.

Semi-infinite aquifer.–Equation 3.7-2 is derived from the analytical solution for the discharge at $x = 0$ for a linear ground-water system that extends from $x = 0$ to $x = \infty$ (Carslaw and Jaeger, 1959). That solution is

$$q_{oi} = -\frac{K_i B_i W_i}{\left(\frac{\pi K_i t}{S_{si}}\right)^{1/2}} \Delta h_i, \tag{3.7-3}$$

where

q_{oi} is the instantaneous discharge rate [L^3/t], and
Δhi is a step change in the boundary head at $x = 0$ in the extended ground-water system for node i [L].

The discharge q_{oi} is positive for discharge from the extended ground-water system into the modeled flow domain.

Equation 3.7-3 can be integrated over a time step to get the average discharge rate within the time step. The integration of

$$Q_{oi} = -\frac{1}{\Delta t}\int_{t_1}^{t_2}\left[\frac{K_i B_i W_i}{\left(\frac{\pi K_i t}{S_{si}}\right)^{1/2}}\right]\Delta h_i dt \qquad (3.7\text{-}4)$$

yields

$$Q_{oi} = -\frac{2}{\Delta t}\left[\frac{K_i B_i W_i}{\left(\frac{\pi K_i}{S_{si}}\right)^{1/2}}\right]\Delta h_i (t_2^{1/2} - t_1^{1/2}), \qquad (3.7\text{-}5)$$

where

Q_{oi} is the average discharge during the period t_1 to t_2 [L^3/t],
t_1 is the time at the start of a step head change Δh_i [t],
t_2 is the time at the end of a step head change [t],

and where

$$\Delta t = t_2 - t_1. \qquad (3.7\text{-}6)$$

Equation 3.7-2 is obtained from Equation 3.7-5 by noting that the average discharge contribution for Δh of the current time step m coincides with $t_2 = \Delta t = t_m - t_{m-1}$ and $t_1 = 0$.

Discharge owing to current step.--Equation 3.7-5 can be rewritten in the form for a particular node i

$$Q_{oij} = C_{Vi}\,(-\Delta h_{ij}), \qquad (3.7\text{-}7)$$

where

j is the index for time step (dimensionless)

which corresponds to Equations 3.7-1 and 3.7-2, where

$$-\Delta h_{ij} = H_{Vij} - H_{ij}\,. \qquad (3.7\text{-}8)$$

Discharge owing to past steps. The discharge Q_{vi}' across the boundary for a particular node i in the current time step owing to head changes at the boundary for a particular node i in a past time step is derived from Equation 3.7-5 in the form

$$Q_v' = -\sum_{j=1}^{m-1} \frac{2}{\Delta t_m}\left[\frac{KBW}{\left(\frac{\pi K}{S_s}\right)^{1/2}}\right]\Delta h_j\left[(t_m - t_{j-1})^{1/2}\right. \\ \left. - (t_m - t_j)^{1/2} - (t_m - t_j)^{1/2} + (t_m - t_{j+1})^{1/2}\right], \tag{3.7-9}$$

where m is the index for the current time step [dimensionless] and the index i has been dropped for clarity from Q_v', K, B, W, S_s and Δh.

The indexes j and m refer to the time at the end of the indicated time step.

Equation 3.7-9 is based on the application of Equation 3.7-5 using the principal of superposition. Equation 3.7-9 is the solution for the case, where

$$\Delta h_i = 0 \text{ for } t < t_m - \Delta t_m$$
$$\Delta h_i = H_{vi} - H_i \text{ for } t_m - \Delta t \le t \le t_m$$
$$\Delta h_i = 0 \text{ for } t > t_m.$$

On the basis of this case, Δh_i is the change in head from the steady-state head.

Substitution into force vector.-- Equation 3.2-15 is an expression for F_i, which is the quantity representing the internal and boundary fluxes for the model domain. Correspondingly, Equation 3.7-1 is an expression for the boundary fluxes representing variable-flux nodes. Equations 3.2-15 and 3.7-1 can be combined into the form

$$F_i = F'_{vi} + C_{vi}(H_{vi} - H_i) + Q'_v, \tag{3.7-10}$$

where F'_{vi} represents the internal and boundary fluxes associated with node i except for the boundary fluxes associated with the variable-flux nodes.

The right-hand side of Equation 3.7-10 includes the dependent variable *{H}* from Equation 3.2-38, which is the system of algebraic equations representing the heads *{H}* at the end of the current time step. With the substitution of Equation 3.7-10 for *{F}* in Equation 3.2-38, the dependent variable occurs on both the right-hand and left-hand side of Equation 3.2-38 in the form

$$\left([A] + \frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F'_v\} + \{C_v H_v\} - diag\{C_v\}\{H_{t+\Delta t}\} \qquad (3.7\text{-}11)$$

$$\left([A] + \frac{1}{\Delta t}[B] + diag\{C_v\}\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F'_v\} + \{C_v H_v\} + Q'_v, \qquad (3.7\text{-}12)$$

where

$$\{C_v H_v\} = diag\{C_v\}\{H_v\}. \qquad (3.7\text{-}13)$$

Equation 3.7-12 is equivalent to adding the quantities C_{vi} to the diagonal of the left-hand matrix

$$\left([A] + \frac{1}{\Delta t}[B]\right)$$

in Equation 3.2-38 and to adding the quantities $C_{vi}\, H_{vi}$ to the right-hand vector

$$\frac{1}{\Delta t}[B]\{H_t\} + \{F\}.$$

3.7.3 Structure of Subroutine

Subroutine *VFLUX* is structured into two basic blocks. The first block, which is entered by a call to *VFLUX1*, is for the input and display of data for the variable-flux boundary condition, including data on the hydraulic conductivity, specific storage, aquifer thickness, and width of the extended ground-water system. The second block, which is entered by a call to *VFLUX2*, creates the coefficients to be added to *diag[A]* and *{F}*, as described in Section 3.7.2, and calculates the discharge of ground water through the individual nodes in the finite-element grid.

The discharge of ground water through the individual nodes is calculated from the expression

$$\{Q_v\} = \{C_{vR}\} - \{C_{VL}H\} + \{Q'_V\}, \tag{3.7-14}$$

where an element of $\{Q_V\}$ is given by

$$Q_{Vi} = C_{VRi} - C_{VLi}H_i + Q'_{Vi}, \tag{3.7-15}$$

where $\{Q_V\}$ is a vector of inward discharges [L^3/t]. The cumulative discharge through all variable-flux nodes is given by

$$Q_v = \sum_{i=1}^{n} Q_{vi}, \tag{3.7-16}$$

where

Q_V is the cumulative discharge [L^3/t], and
n is the number of nodes [dimensionless].

3.8 Subroutine *FAULT*

3.8.1 Background

Subroutine *FAULT* is used to simulate the effects of highly permeable features within the ground-water system, but without an explicit representation of the feature in the finite-element grid. An example of these features include fault zones, where ground water can easily move parallel to the fault plane and well casings perforated over a long depth interval, where ground water can easily move from one aquifer to another through the well casing. These features tend to short circuit the ground-water system by providing high-permeability paths for the movement of ground water through a range of lower permeability media that make up the bulk of the ground-water system.

Subroutine *FAULT* cannot simulate the effects of low-permeability fault zones. However, such hydrogeologic features can be simulated by the assigning low hydraulic-conductivity values to the elements that define the plane of the fault zone. The barrier effect of faults can also be simulated using this approach.

3.8.2 Mathematical Basis

Discharge equations.--The simulation of the effects of highly permeable features within a ground-water system is done in subroutine *FAULT* by allowing the direct exchange of water along a link from one node in the finite-element grid to another node. In this simulation, ground water will flow from one node to another node, where the outflow from the first node is equal to the inflow to the second node. The exchange of water between the node pairs, which can be described by Darcy's (1856) Law, is given by the relations

$$Q_{Fi} = C_{Fij} (H_j - H_i) \tag{3.8-1}$$

$$Q_{Fj} = C_{Fji} (H_j - H_i), \tag{3.8-2}$$

and

$$C_{fji} = - C_{fij} ,$$

where

Q_{Fi} is the outflow for node i [L^3/t],
C_{Fij} is a coefficient relating to the conductivity of the link between nodes i and j [L^2/t],
H_j is the hydraulic head at node j [L],
H_i is the hydraulic head at node i [L], and
Q_{Fj} is the inflow for node j [L^3/t].

The coefficient C_{Fij}, which relates to the conductivity of the link, is given by the expression

$$C_{Fij} = \frac{T_{ij}B_{ij}}{\Delta L_{ij}}, \tag{3.8-3}$$

where

T_{ij} is the transmissivity of the feature, parallel to the link of the node pair [L^2/t],
B_{ij} is the height or width of the part of the feature represented by the node pair [L], and
ΔL_{ij} is the distance between the node pairs that define the length of the feature [L].

Two examples representing faults and well casings, as well as the configuration of node pairs and their related parameters, are described in greater detail in Section 5.2.14.

If the highly permeably feature is a fault zone, a single layer of nodes defines the geometry of the fault plane. The coefficients ΔL_{ij} and B_{ij} describe the spatial relations between the nodes that define the fault plane. The transmissivity is the product of a unit thickness, normal to the plane of the fault, and the hydraulic conductivity of the fault zone, parallel to the fault node link. To represent both horizontal and vertical ground-water flow within a fault plane, two sets of fault links must be specified: one set links nodes in the horizontal direction, and the other set links nodes in the vertical direction.

If the highly permeable feature is a well casing, a single line of nodes defines the length of the casing perforations. The coefficient ΔL_{ij} is the distance between nodes in the line of nodes that represent the perforations, and the product of transmissivity times the width (diameter of the well) is the conductivity of the well casing to vertical flow.

Substitution into force vector.--Equation 3.2-15 is an expression for F_i, which is the quantity representing the internal and boundary fluxes for the model domain. Correspondingly, Equation 3.8-1 is an expression for the boundary fluxes representing fault nodes. Equations 3.2-15 and 3.8-1 can be combined into the form

$$F_i = F'_{Fi} + C_{Fij}(H_{Fi} - H_i) \tag{3.8-4}$$

and

$$F_j = F'_{Fj} + C_{Fji}(H_{Fj} - H_j), \tag{3.8-5}$$

where F'_{Fi} and F'_{Fj} represent the internal and boundary fluxes associated with nodes i and j except for the boundary fluxes associated with the fault nodes.

The right-hand side of Equations 3.8-4 and 3.8-5 include the dependent variable {H} from Equation 3.2-38, which is the system of algebraic equations representing the heads {H} at the end of the current time step. With the substitution of Equations 3.8-4 and 3.8-5 for {F} in Equation 3.2-38, the dependent variable occurs on both the right-hand and left-hand side of Equation 3.2-38 in the form

$$\left([A] + \frac{1}{\Delta t}[B]\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F'_F\} + \{C_F H_F\} - diag\{C_F\}\{H_{t+\Delta t}\} \tag{3.8-6}$$

$$\left([A] + \frac{1}{\Delta t}[B] + diag\{C_F\}\right)\{H_{t+\Delta t}\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F'_F\} + \{C_F H_F\} + Q'_v, \tag{3.8-7}$$

where

$$\{C_F H_F\} = diag\{C_F\}\{H_F\}. \tag{3.8-8}$$

Equation 3.8-7 is equivalent to adding C_{Fi} or C_{Fj} to the diagonal of the left-hand matrix

$$\left([A] + \frac{1}{\Delta t}[B]\right)$$

in Equation 3.2-38 and to adding the quantities $C_{Fi}\,H_{Fi}$ or $C_{Fj}\,H_{Fj}$ to the right-hand vector

$$\frac{1}{At}[B]\{H_t\} + \{F\}.$$

3.8.3 Structure of Subroutine

Subroutine *FAULT* is structured into three basic blocks. The first block, which is entered by a call to *FAULT1*, is for the input and display of data on the physical characteristics of the links between node pairs. The second block, which is entered by a call to *FAULT2*, creates the coefficients to be added to *[A]*, as described in Section 3.8.2. The third block, which is entered by a call to *FAULT3*, calculates the ground-water discharges through the links between node pairs.

Discharge through fault-node pairs is calculated using Equation 3.8-1 or 3.8-2. Cumulative discharge through fault-node pairs is given by

$$Q_F = \sum_{i=1}^{n} Q_{Fi} , \qquad (3.8\text{-}9)$$

where

Q_F is the cumulative discharge [L^3/t] and
n is the number of nodes [dimensionless].

However, the cumulative discharge is zero (or very close to zero) because each fault node pair has equal discharge in the opposite direction.

3.9 Subroutine *SINK*

3.9.1 Background

Subroutine *SINK* is used to simulate land subsidence that results from ground-water pumping. This subroutine is based on the interbed compaction model of Leake and Prudic (1988). Pumping causes storage depletion within the ground-water system, which is expressed in changes in the land-surface elevation. Those changes are temporary if the ground-water system is responding within the range of the elastic compressibility of the solid matrix. However, the changes are permanent if the ground-water system is responding within the range of inelastic compressibility of the solid matrix. An inelastic response occurs when the effective stress within the solid matrix of fine-grained hydrogeologic units exceeds the preconsolidation stress.

3.9.2 Mathematical Basis

Relation of subsidence to specific storage.--Changes in the elevation of the land surface (downward or upward) occur in response to changes in the effective stress. Effective stress is given by the relation (Terzaghi, 1925)

$$P' = P - U , \tag{3.9-1}$$

where

P' is the effective stress [M/Lt^2],
P is the overburden or geostatic pressure [M/Lt^2], and
U is the pore pressure [M/Lt^2].

If lowering the hydraulic head in the ground-water system does not change the geostatic pressure, which neglects the change in the buoyancy, the change in effective stress is then related only to the change in pore pressure, or

$$\Delta P' = - \gamma_w \Delta h, \tag{3.9-2}$$

where

$\Delta P'$ is the change in effective stress [M/Lt^2],
γ_w is the unit weight of water [M/L^2t^2], and
Δh is the change in hydraulic head [L].

Elastic compaction or expansion of the solid matrix is given by the relation (Riley, 1969; Helm, 1975)

$$\Delta B = \Delta h \, S'_{Ske} \, B_o \,, \tag{3.9-3}$$

where

ΔB is the elastic change in thickness of the ground-water system [L], which is also the change in the land-surface elevation,
S'_{Ske} is the elastic specific storage of the ground-water system [1/L], and
B_o is the initial thickness of the ground-water system [L].

The approximate inelastic compaction of the solid matrix, which occurs primarily within fine-grained interbeds of the ground-water system, is given by the relation (Helm, 1975)

$$\Delta B^* = \Delta h \, S'_{Skv} \, B_o \,, \tag{3.9-4}$$

where

ΔB^* is the inelastic change in thickness of interbeds [L], which is also the permanent change in the land-surface elevation, and
S'_{Skv} is the inelastic specific storage of the interbeds [1/L].

Equation 3.9-4 applies only when hydraulic head within the interbeds has gone below the previous lowest head or preconsolidation head. Furthermore, because significant time is required for a pressure change to propagate into an interbed, only some thickness intervals of an interbed may experience inelastic compaction.

The time required for a pressure change to propagate into an interbed is given by the relation (Riley, 1969)

$$\tau = \frac{S'_s \, B_o^2}{4K'}, \tag{3.9-5}$$

where

τ is the effective time constant for the interbed [t],
S'_s is the effective bulk specific storage for the interbed [1/L],
B_o is the initial thickness of the interbed [L], and
K' is the vertical hydraulic conductivity of the interbed [L/t].

The time constant τ is the time required for 93 percent of the pressure change to occur at the center of the interbed. If the specific storage S'_{Skv} is used for the specific storage S'_s in Equation 3.9-5, then the resulting time constant is the upper limit.

Discharge equation.--On the basis of Equations 3.9-3 and 3.9-4, the rate of flow per unit volume of water flowing into storage in compressible interbeds is given by (Leake and Prudic, 1988)

$$q_S^{t+\Delta t} = \frac{S_{Sk}^{t+\Delta t}}{\Delta t}\left(H^{t+\Delta t} - H_P^t\right) + \frac{S_{Ske}}{\Delta t}\left(H_P^t - H^t\right), \tag{3.9-6}$$

where

$$S_{Sk} = \begin{cases} S'_{Ske} \text{ for } H^t > H_P^{t-\Delta t} \\ S'_{Skv} \text{ for } H^t \le H_P^{t-\Delta t} \end{cases} \tag{3.9-7}$$

and

q_s is the rate of storage change per unit volume [L^3/t per L^3 or $^1/t$],
H is the calculated hydraulic head [L],
t is time [t],
H_P is the preconsolidation head [L], and
Δt is the time step in the simulation [t].

Modification of storage matrix and force vector.--The implementation of Equation 3.9-6 in the finite-element method requires the modification of Equation 3.2-38 to yield

$$\left([A] + \frac{(1-p)}{\Delta t}[B] + \frac{p}{\Delta t}[C]\right)\{H_{t+\Delta t}\} = \frac{(1-p)}{\Delta t}[B]\{H_t\} + \frac{p}{\Delta t}[C]\{H_{pt}\} + \frac{p}{\Delta t}[D]\{H_t - H_{pt}\} - \{F\}, \tag{3.9-8}$$

where p is the proportion of the local ground-water system that is occupied by interbeds [dimensionless]. When p equals zero, Equation 3.9-8 reduces to Equation 3.2-38.

Typical elements of *[C]* and *[D]* are

$$C_{ij} = \int_{\Omega} S'_{Sk}\phi_i\phi_j d\Omega, \tag{3.9-9}$$

where S'_{sk} is defined by Equation 3.9-7 and

$$D_{ij} = \int_{\Omega} S'_{Ske}\phi_i\phi_j d\Omega. \tag{3.9-10}$$

3.9.3 Structure of Subroutine

Subroutine *SINK* is structured into three basic blocks. The first block, which is entered by a call to *SINK1*, is for the input and display of data for the simulation of land subsidence. The input include data on the proportion of the local ground-water system occupied by interbeds, the elastic specific storage of the interbeds, and the inelastic specific storage. The second block, which is entered by a call to *SINK2*, is for constructing the elemental matrices for elastic and inelastic storage change within interbeds, where the elemental matrices correspond to the matrices *[C]* and *[D]*, as indicated in Equations 3.9-9 and 3.9-10. The third block is for the calculation of change in the land-surface elevation.

In the third block, the change in land-surface elevation is calculated from the relation

$$\Delta V_s = p \int_B [S'_{Sk}(H_{t+\Delta t} - H_p) + S'_{Ske}(H_p - H_t)]\, dz \,, \tag{3.9-11}$$

where

ΔV_s is the volume of storage change per unit area over the time interval Δt [L], and
B is the thickness of the ground-water system [L].

However,

$$\Delta B_s = \Delta V_s \,, \tag{3.9-12}$$

where ΔB_s is the change in the land-surface elevation [L].

Elastic and inelastic storage changes within interbeds are components of the water budget for the ground-water system. The rate of elastic storage change within interbeds is given by the relation

$$Q'_{Ske} = \int_\Omega p\, S'_{Ske} \frac{(H_p - H_t)}{\Delta t} d\Omega \,, \tag{3.9-13}$$

if H_p is between H_t and $H_{t+\Delta t}$, where Q'_{Ske} is the rate of elastic storage change [L^3/t] over the time interval. Otherwise,

$$Q'_{Ske} = \int_\Omega p\, S'_{Ske} \frac{(H_{t+\Delta t} - H_t)}{\Delta t} \Omega \,, \tag{3.9-14}$$

if H_p is less than $H_{t+\Delta t}$. The rate of inelastic storage change is given by

$$Q'_{Skv} = \int_\Omega p\, S'_{Skv} \frac{(H_{t+\Delta t} - H_p)}{\Delta t} d\Omega \,, \tag{3.9-15}$$

if H_p is between H_t and $H_{t+\Delta t}$, where Q'_{Ske} is the rate of inelastic storage change [L^3/t]. Otherwise,

$$Q'_{Skv} = 0 \,. \tag{3.9-16}$$

3.10 Subroutine *WATER*

3.10.1 Background

Subroutine *WATER* is used to simulate ground-water recharge and pumpage that result from the operation of an irrigated agricultural system. First, the subroutine distributes irrigation water from ground-water pumpage and surface-water deliveries to individual land parcels, which are referred to as user areas. Second, through a call to subroutine *LAND*, evapotranspiration and ground-water recharge are determined for each user area. Third, the ground-water recharge and ground-water pumpage are distributed to nodes within the finite-element grid.

An irrigated agricultural system, represented by data inputs to subroutine *WATER*, is shown in figure 6. The system consists of separate user areas that are irrigated either with surface water or ground water or both surface water and ground water. The system includes wells that directly deliver water for irrigation or that discharge into a canal system. In a typical application, the user areas represent aggregations of farms at a scale that is appropriate to the problem being simulated. However, user areas can also represent irrigated or nonirrigated parts of an urban area within the model boundary.

Data inputs to subroutine *WATER* specify the total acreage of crops and the soil characteristics within a user area and the precipitation on a user area. On the basis of these inputs, the actual evapotranspiration and the deep percolation of irrigation water are calculated within subroutine *LAND*. A representation of irrigation to a user area is shown in figure 7.

Recharge from a user area is calculated in subroutine *LAND*. Data inputs to subroutine *WATER* specify the nodes within the finite-element grid that represent the recharge from the user area. A representation of recharge to a user area is shown in figure 8. A user area that is arbitrarily distributed geographically in the finite-element grid will be connected with several nodes, depending on the geographic extent of the user area and the layout of the finite-element grid. The nodes and the proportion of user-area recharge for each node are specified by data inputs to subroutine *WATER*. Section 5.3.5 provides a description of the algorithm by which recharge is distributed to nodes in the finite-element grid.

Data inputs to subroutine *WATER* specify pumpage from individual wells. A representation of pumpage from a well is shown in figure 9. Additional data inputs specify the nodes within the finite-element grid that represent the location of a well. Pumpage for a well is distributed to six or more nodes, depending on the depth interval of the well screen. The nodes and the proportion of well pumpage for each node are specified by data inputs to subroutine *WATER*. Section 5.3.1 provides a description of the algorithm by which pumpage is distributed to nodes in the finite-element grid.

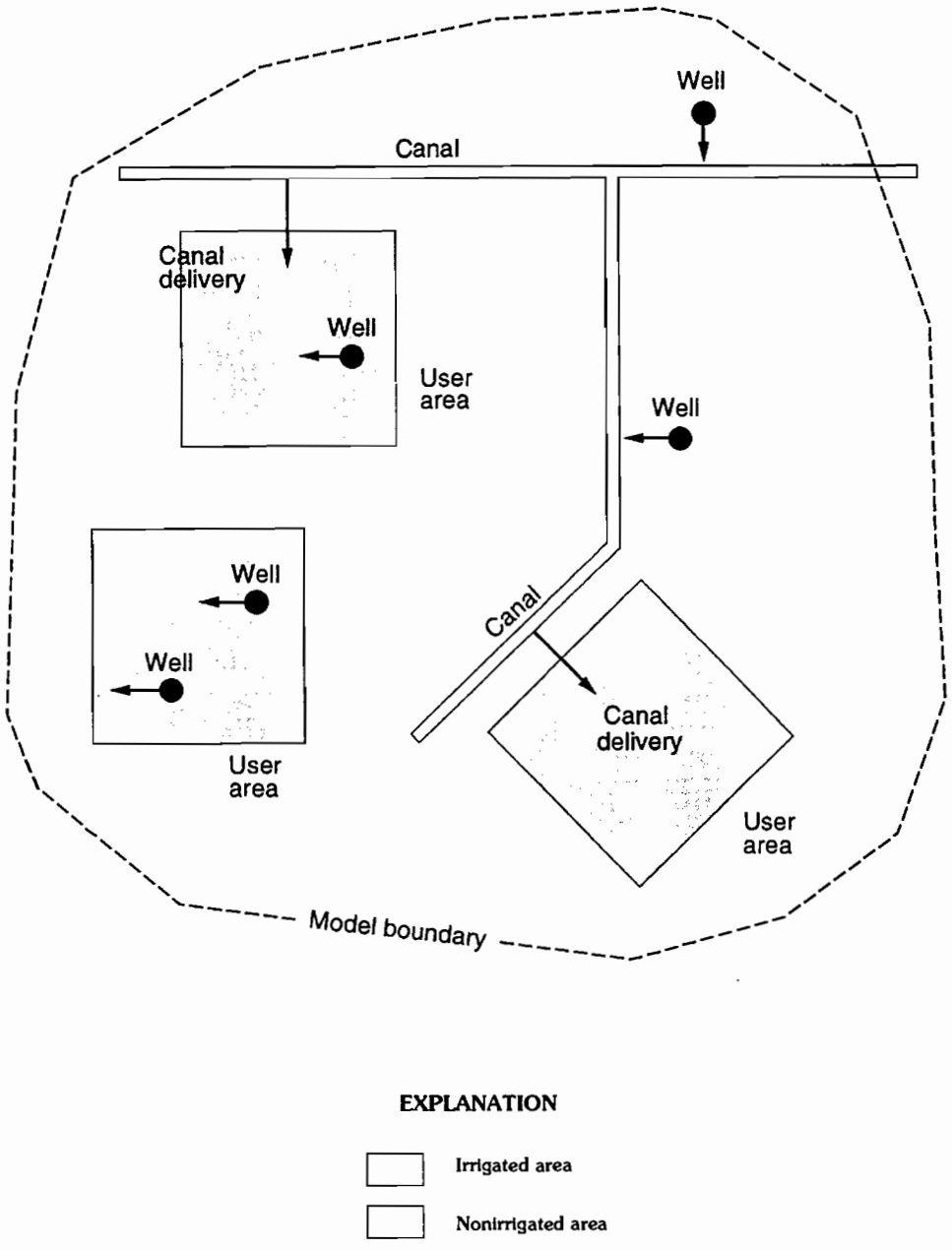


Figure 6. Representation of an irrigated agricultural system in subroutine *WATER*.

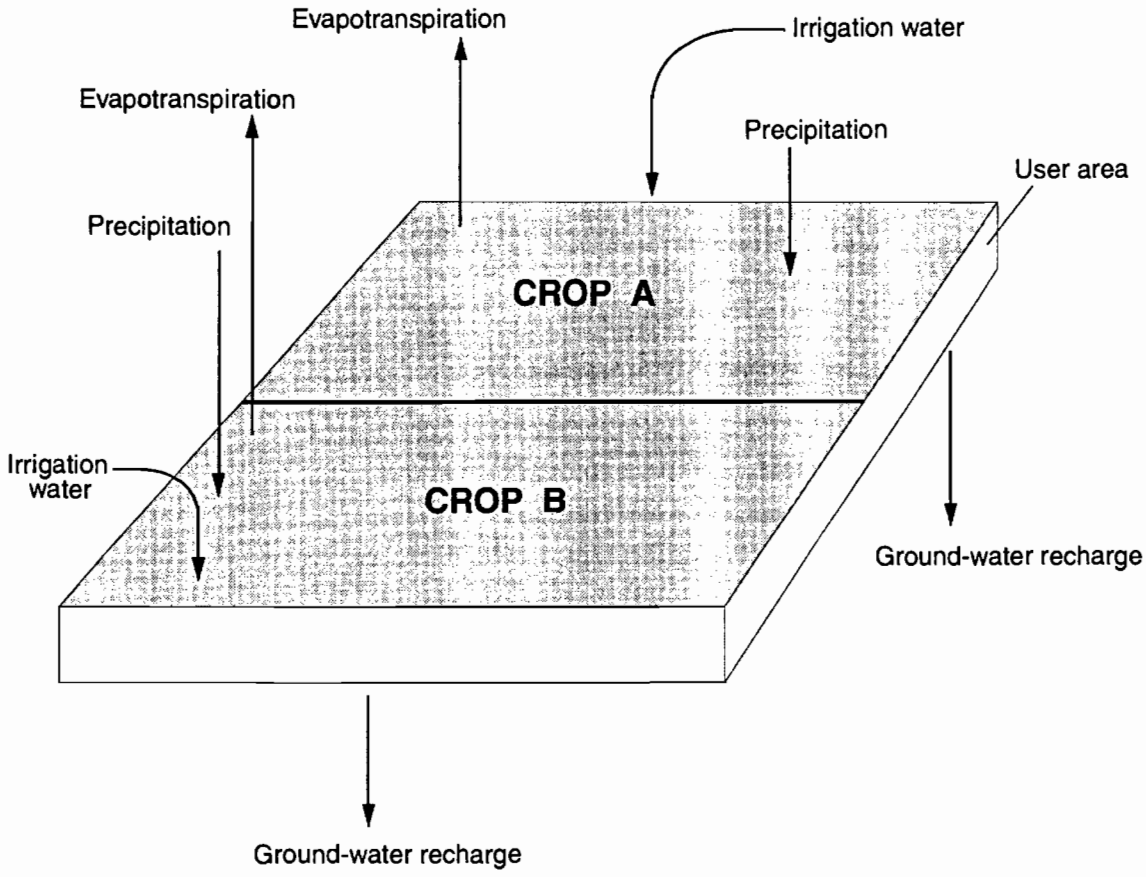


Figure 7. Representation of a user area in subroutine *WATER*.

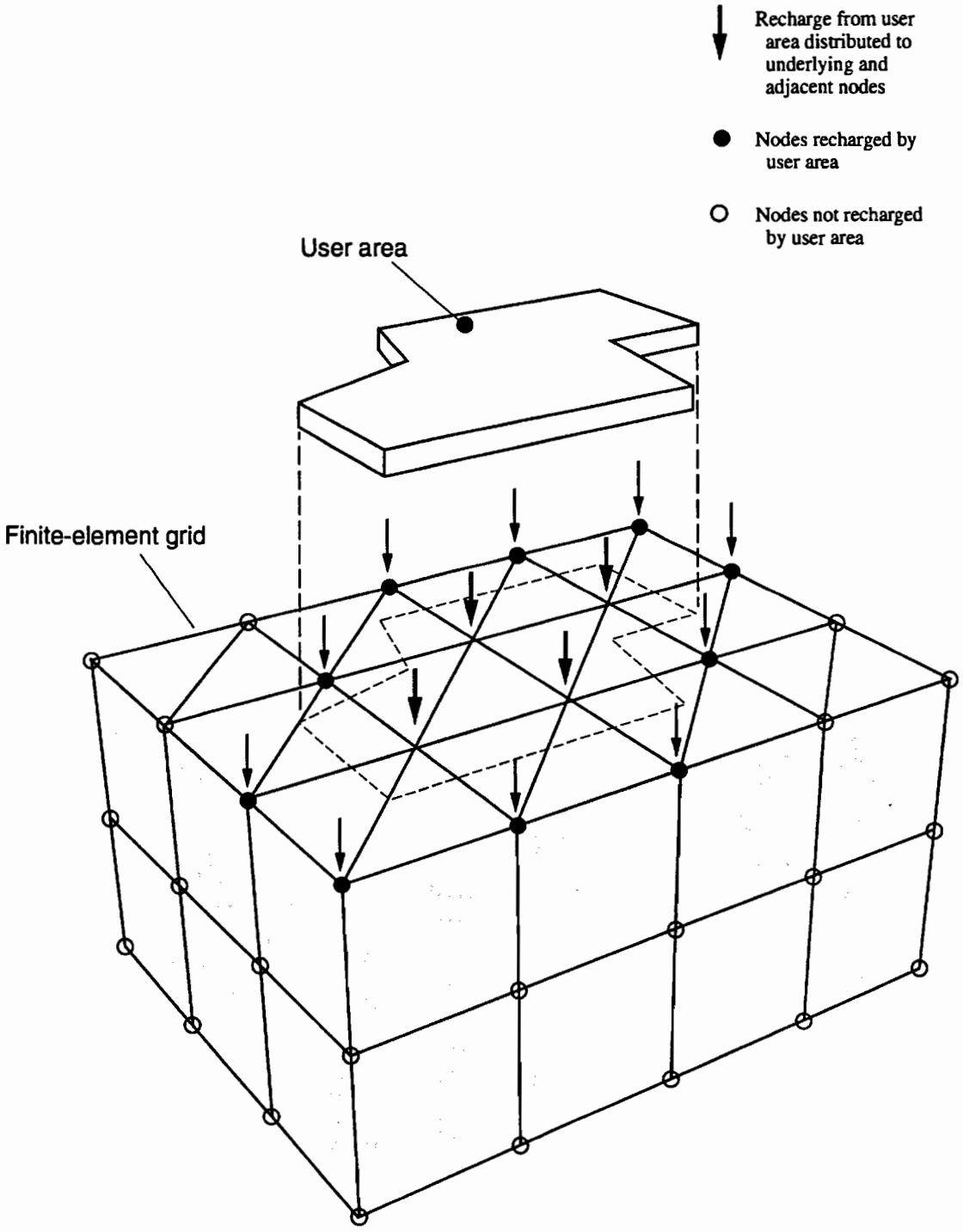


Figure 8. Representation of ground-water recharge in subroutine *WATER*.

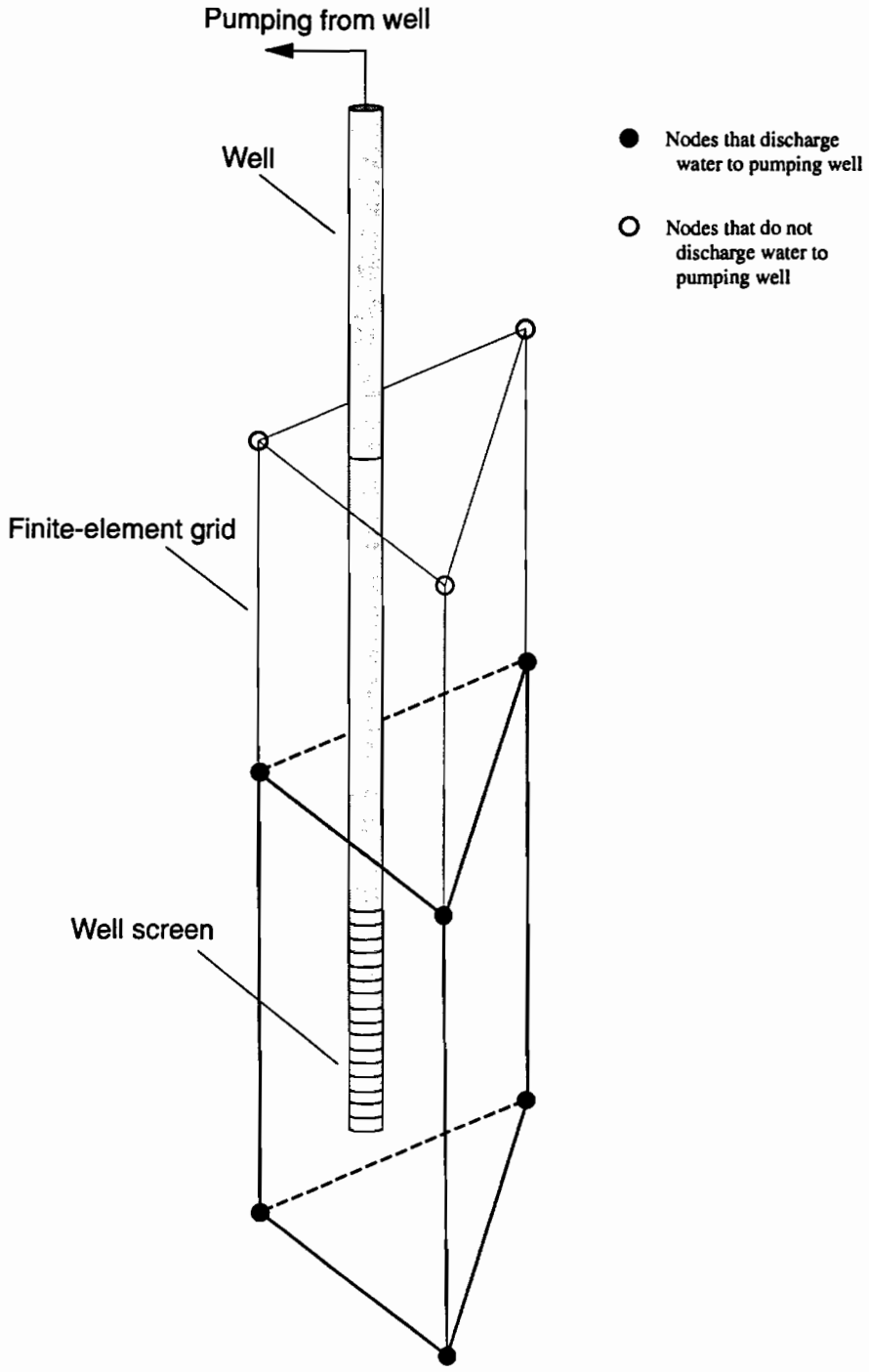


Figure 9. Representation of ground-water pumping in subroutine *WATER*.

3.10.2 Mathematical Basis

Subroutine *WATER* is based on the mass balance of water into and from a user area. That mass balance is given by the relation

$$Q_{sw} + Q_{Pump} - Q_{ET} - Q_{Rech} = Q_{Store}, \quad (3.10\text{-}1)$$

where

Q_{sw} is the surface-water delivery to a user area [L^3/t],
Q_{Pump} is the ground-water pumped to a user area [L^3/t],
Q_{ET} is the evapotranspiration from a user area [L^3/t],
Q_{Rech} is the ground-water recharge from the user area [L^3/t], and
Q_{Store} is the rate of change in soil-moisture storage [L^3/t].

3.10.3 Structure of Subroutine

Subroutine *WATER* is structured into two basic blocks. The first block, which is entered by a call to *WATER1*, is for the input and display of data for ground-water pumpage, surface-water deliveries, well locations, user-area boundaries, crop patterns, soil type, and potential evapotranspiration. The second block, which is entered by a call to *WATER2*, distributes ground-water pumpage and surface-water deliveries to the user areas, calculates the actual evapotranspiration through a call to subroutine *LAND*, and distributes ground-water pumpage and recharge to nodes in the finite-element grid.

In the first block, data representing the area to be modeled are organized into 15 files as follows:

1. **Well-site inventory.** The well-site inventory file contains information on the location and construction of wells and on the assignment of wells to particular user areas.

2. **Well-status codes.** The well-status code file contains information on the assignment of a well to a status group, which may change with time.

3. **Monthly well pumping.** The monthly pumping file contains information on monthly pumpage from individual wells.

4. **Well-pumping construction.** The pumping-construction file is used to set up a particular pumping scenario for a simulation. The pumping-construction file allows the user to set up a scenario by selecting pumpage listed in the monthly pumping file for individual wells or by selecting a pumpage value listed in the well-construction file for a group of wells.

5. **User inventory.** The user-inventory file contains information on the location and other characteristics of individual user areas.

6. **Monthly canal delivery.** The monthly delivery file contains information on monthly surface-water deliveries to individual user areas.

7. **Canal-delivery construction.** The canal-delivery construction file is used to set up a particular delivery scenario for a simulation. The canal-delivery construction file allows the user to set up a scenario by selecting delivery values from the monthly delivery file for individual user areas or by assigning a total delivery to a group of user areas with the same user-type code specified in the user-inventory file.

8. **Crop inventory.** The crop-inventory file contains information on the crops within individual user areas.

9. **Rooting depth.** The rooting-depth file contains information on the rooting depths of crops in the crop-inventory file.

10. **Monthly precipitation.** The monthly precipitation file contains monthly precipitation for a station. The precipitation station is assigned to user areas and adjusted by a factor in accordance with a specification in the user-inventory file.

11. **Monthly evapotranspiration.** The monthly evapotranspiration file contains information on the potential evapotranspiration for the crops in the crop-inventory file.

12. **Consumption construction.** The consumption-construction file is used to set up a particular evapotranspiration scenario for a simulation. The consumption-construction file allows the user to set up a scenario by selecting potential evapotranspiration values from the monthly evapotranspiration file and crop distribution from the crop-inventory file.

13. **Well-pumping destination.** The pumping-destination file identifies wells that pump into the surface-water distribution system. The identification is by the well-status code specified in the well-status code file.

14. **Recharge factor.** The recharge-factor file contains information on the proportion of deep percolation that becomes ground-water recharge. If the factor does not equal 1 for a particular area, only part of the deep percolation becomes ground-water recharge, and the remaining deep percolation is presumed to be removed from further interaction with the ground-water system. This would occur if part of the deep percolation entered an agricultural drainage system.

15. **Well exclusion.** The well-exclusion file identifies wells that are to be excluded from a simulation.

The relation of these 15 files to subroutine *WATER* and *LAND* is shown in figure 10.

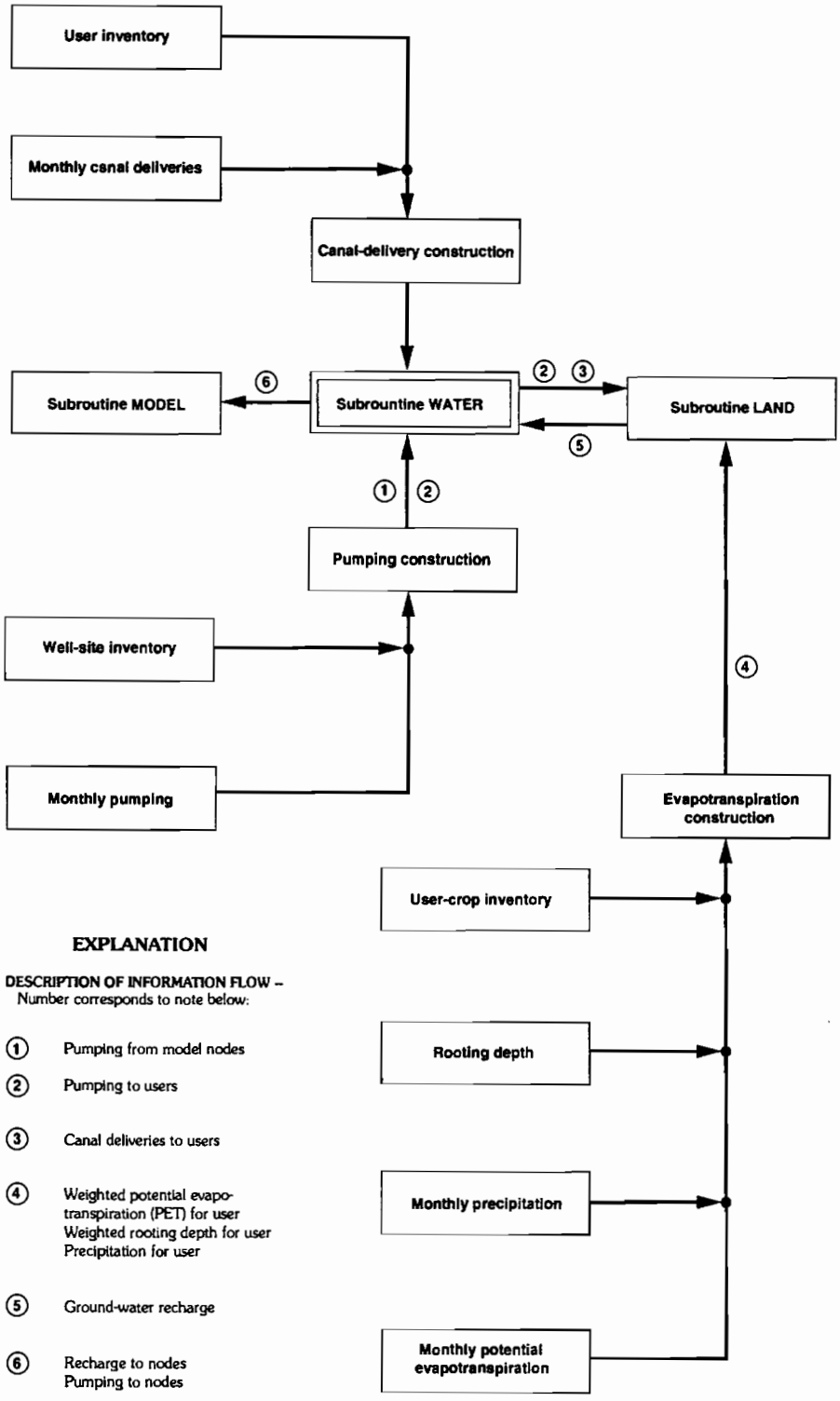


Figure 10. Files used in subroutine *WATER*.

In the second block of subroutine *WATER*, two vectors represent the distribution of ground-water recharge and pumpage to nodes within the finite-element grid. These vectors are $\{Q_R\}$ and $\{Q_P\}$ (ground-water recharge and the ground-water pumpage, respectively). Cumulative recharge and pumpage through all nodes are given by

$$Q_{WR} = \sum_{i=1}^{n} Q_{Ri} \qquad (3.10\text{-}2)$$

and

$$Q_{WP} = \sum_{i=1}^{n} Q_{Pi}\,, \qquad (3.10\text{-}3)$$

where

Q_{WR} is the cumulative recharge [L^3/t],
Q_{Ri} is the recharge at the node i [L^3/t],
Q_{WP} is the cumulative pumpage [L^3/t], and
Q_{Pi} is the pumpage at node i [L^3/t].

3.11 Subroutine *LAND*

3.11.1 Background

Subroutine *LAND* is used to calculate evapotranspiration and ground-water recharge that result from precipitation on cropped and noncropped areas and from irrigation applications on cropped areas.

3.11.2 Mathematical Basis

Evapotranspiration and ground-water recharge for a user area depend on the depth of water that infiltrates into soils. That infiltration, in turn, depends on (1) the acreage of the user area, (2) the effective precipitation on the user area, (3) the water delivered to the user area by surface-water deliveries and ground-water pumpage, (4) the delivery-system losses within a user area, and (5) the tailwater losses from fields.

3.11.2.1 Effective Precipitation

Effective precipitation is precipitation that infiltrates into the soil. In subroutine *LAND*, effective precipitation is calculated using a method by Jensen (1983) by which effective precipitation is the sum of increments of effective precipitation. In turn, the increments of effective precipitation are determined as a proportion of an increment of actual precipitation (table 1). The proportions range from 95 percent for the increment of precipitation less than 1 inch during a month to 5 percent for increments of precipitation of more than 7 inches during a month. This method of calculating effective precipitation is a simple approach that ignores much of the complexities of precipitation runoff.

Table 1. Effective precipitation based on increments of monthly rainfall

Precipitation increment range (inches)	Effective precipitation (percent)
0–1	95
1–2	90
2–3	82
3–4	65
4–5	45
5–6	25
6+	5

3.11.2.2 Infiltrated Water

Water that infiltrates the soil is given by the relation

$$Q_I = Q_{sw} + Q_{Pump} + A_u P_{Eff} - Q_{Tail} - Q_{Canal}, \quad (3.11\text{-}1)$$

where

Q_I is the rate of infiltration within the user area [L^3/t],
Q_{SW} is the surface-water deliveries into the user area [L^3/t],
Q_{Pump} is the ground-water pumpage within the user area [L^3/t],
A_u is the area of the user area [L^2],
P_{Eff} is the effective precipitation [L/t],
Q_{Tail} is the tailwater losses from field [L^3/t], and
Q_{Canal} is the conveyance loss within the user area [L^3/t].

The conveyance loss, in turn, is given by the relation

$$Q_{Canal} = Q_{SW} f_{Canal}, \quad (3.11\text{-}2)$$

where f_{Canal} is the proportion of surface-water deliveries that become conveyance losses [dimensionless]. The tailwater loss is given by the relation

$$Q_{Tail} = (Q_{sw} + Q_{Pump} - Q_{Canal}) f_{Tail}, \quad (3.11\text{-}3)$$

where f_{Tail} is the proportion of the water that is applied to a field that becomes tailwater [dimensionless].

3.11.2.3 Distribution of Infiltrated Water

The water that infiltrates the soil eventually can (1) be consumed by evapotranspiration, (2) be stored as soil moisture in the root zone, and (3) past the root zone, flow as deep percolation. This deep percolation, in turn, can recharge to the ground-water system and discharge to agricultural drains. The distribution of infiltrated water is calculated on the basis of a set of rules that depends primarily on the comparison of the infiltration rate and the potential evapotranspiration rate. The distribution is also calculated on the basis of the relation between actual evapotranspiration, potential evapotranspiration, and soil moisture (fig. 11).

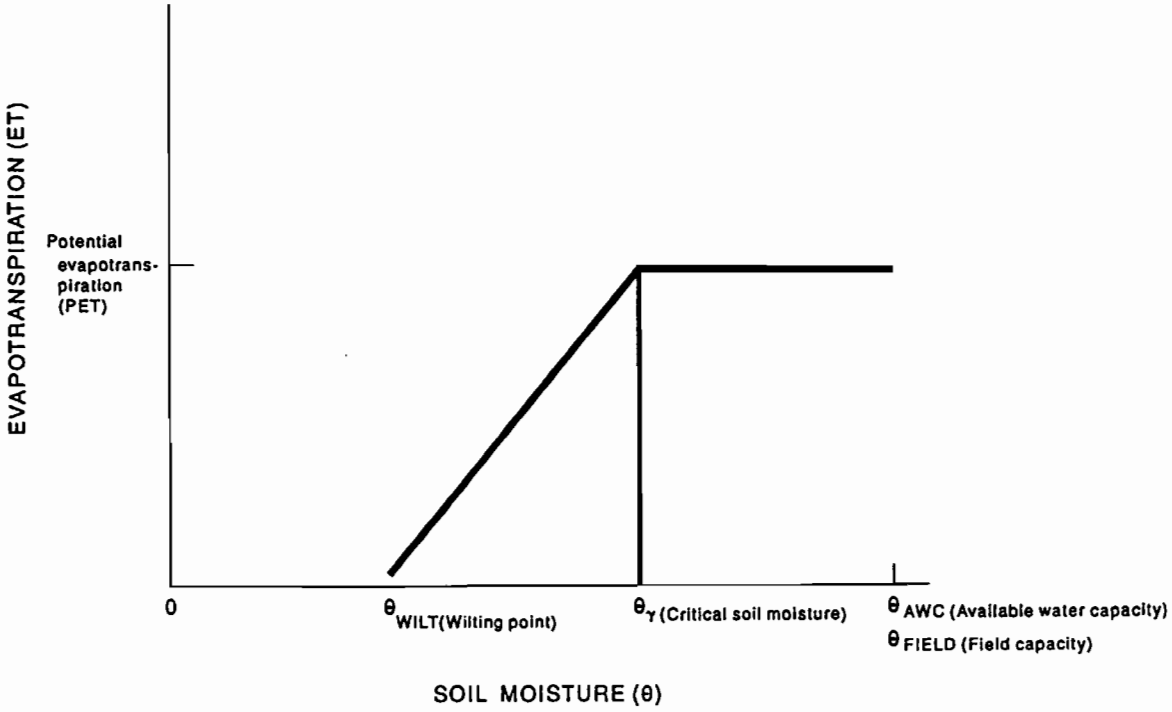


Figure 11. Relation between soil moisture and the evapotranspiration rate.

Actual evapotranspiration *(ET)* ranges from zero to a maximum value equal to the potential evapotranspiration *(PET)* for a range of volumetric soil moisture (θ), from the wilting point (θ_{Wilt}) to the field capacity (θ_{Field}) (fig. 11). The range for soil moisture can be expressed in terms of a scale that equals zero at the wilting point and equals available water capacity (θ_{AWC}) at the field capacity. *ET* increases linearly from a soil moisture equal to the wilting point to soil moisture equal to the critical soil moisture value ($\theta\gamma$). For higher soil moisture, *ET* continues to equal the *PET*. The distribution of infiltrated water is determined in subroutine *LAND* from rules that are triggered principally by the amount of infiltrated water relative to *PET*.

Infiltrated water greater than potential evapotranspiration.--If the infiltrated water is greater than or equal to the *PET*, then

$$\Delta\theta = \frac{(I - PET)}{R_d} \tag{3.11-4}$$

and

$$\theta_f = \theta_i + \Delta\theta\ , \tag{3.11-5}$$

unless θ_f is greater than θ_{AWC}. In which,

$$\theta_f = \theta_{AWC}\ , \tag{3.11-6}$$

$$\Delta\theta = \theta_{AWC} - \theta_i\ , \tag{3.11-7}$$

and

$$D = I - PET - (\theta_{awc} - \theta_i)\ R_d\ , \tag{3.11-8}$$

where

$\Delta\theta$	is the change in soil-moisture storage [dimensionless],
I	is the infiltrated water [L],
PET	is the potential evapotranspiration [L],
R_d	is the root-zone depth [L],
θ_f	is the final soil moisture [dimensionless],
θ_i	is the initial soil moisture at node i [dimensionless],
θ_{AWC}	is the available water capacity [dimensionless], and
D	is the deep percolation past the root zone [L].

Infiltrated water less than potential evapotranspiration.-- If the infiltrated water is less than the *PET*, then two conditions can occur relative to the *ET* rate (fig. 12). For the first condition, where the infiltrated water plus the stored soil moisture above $\theta\gamma$ is greater than or equal to the *PET*,

$$I + (\theta_i - \theta_\gamma)R_d \geq PET, \tag{3.11-9}$$

where

θ_γ is the soil moisture below which the actual evapotranspiration is less than the potential evapotranspiration,

then all *ET* will occur at the *PET* rate. For this condition,

$$\Delta\theta = \frac{(I - PET)}{R_d} \tag{3.11-10}$$

and

$$\theta_f = \theta_i + \Delta\theta\,. \tag{3.11-11}$$

For the second condition, where the infiltrated water plus the stored soil moisture above θ_γ is less than the *PET*, only some *ET* will occur at the *PET* rate, and an *ET* rate less than the *PET* rate will occur for part of the time period. If θ_i is greater than θ_γ,

$$\Delta t = 1 - \frac{[I + (\theta_i - \theta_\gamma)R_d]}{PET}\,, \tag{3.11-12}$$

Otherwise,

$$\Delta t = 1 - \frac{I}{PET}\,, \tag{3.11-13}$$

where Δt is the proportion of the time period for which the *ET* rate is less than the *PET* rate [dimensionless].

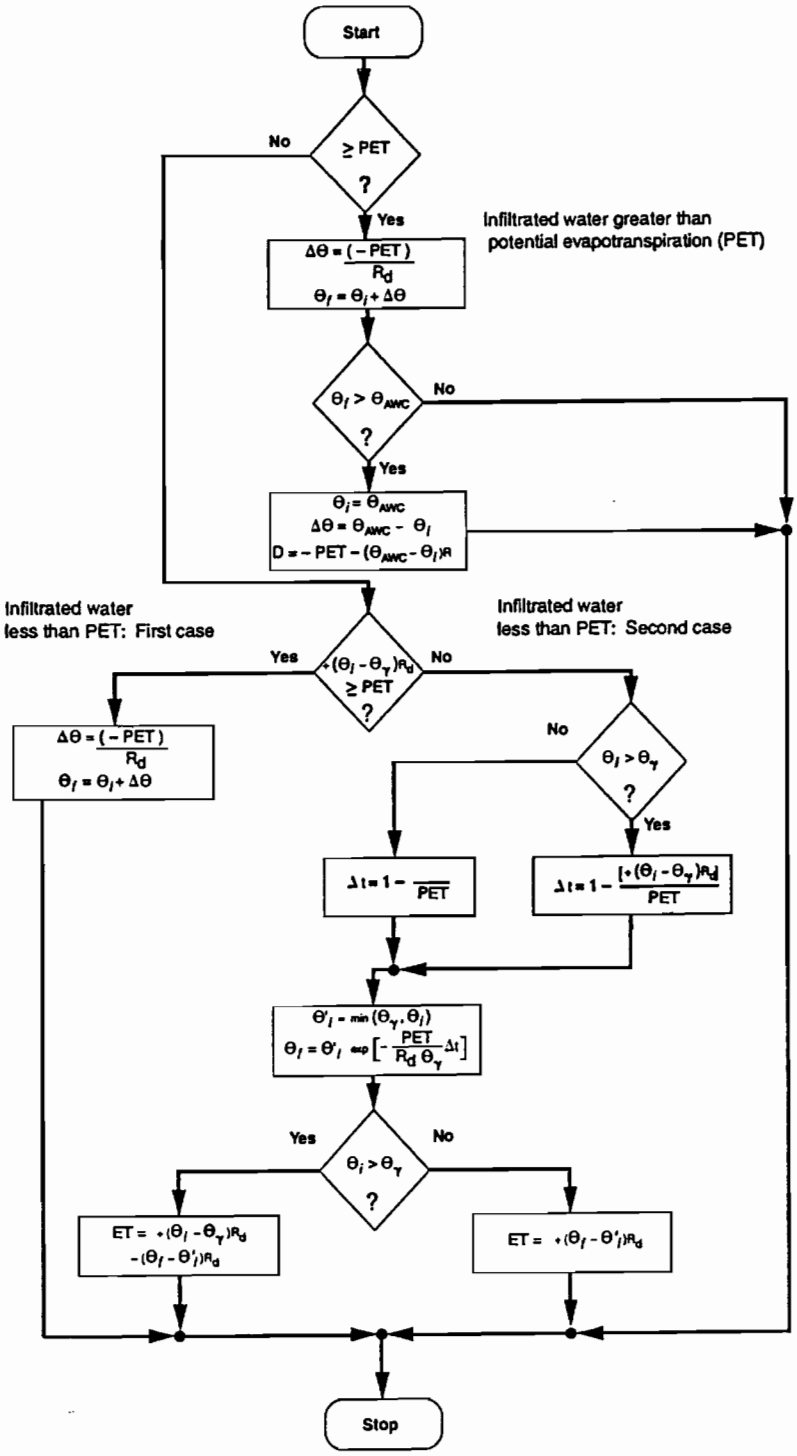


Figure 12. Calculations of evapotranspiration.

During this proportional time period Δt, the change in soil moisture with time is given by the ordinary differential equation

$$\frac{d\theta}{dt} = -\frac{ET}{R_d} = -\frac{1}{R_d}\left(\frac{\theta PET}{\theta_\gamma}\right), \tag{3.11-14}$$

which has the solution

$$\theta = \theta_i' \, exp\left[-\frac{PET}{R_d \theta_\gamma} t\right], \tag{3.11-15}$$

where

$$\theta_i' = min\,(\theta_\gamma, \theta_i), \tag{3.11-16}$$

and where, in Equations 3.11-14 and 3.11-15, the quantities ET and PET are expressed in depth per unit time.

The final soil moisture can be obtained from the relation

$$\theta_f = \theta_i' - \frac{1}{R_d} \int_o^{\Delta t} ET dt. \tag{3.11-17}$$

However, the *ET* rate is given by

$$ET = \theta \frac{PET}{\theta_\gamma}, \tag{3.11-18}$$

which can be substituted into Equation 3.11-17, along with Equation 3.11-15, to obtain

$$\theta_f = \theta_i' - \frac{PET\ \theta_i'}{R_d\ \theta_\gamma} \int_o^{\Delta t} exp\left[-\frac{PET}{R_d\ \theta_\gamma} t\right] dt, \tag{3.11-19}$$

which can be reduced to

$$\theta_f = \theta_i' \exp\left[-\frac{PET}{R_d\,\theta_r}\Delta t\right]. \tag{3.11-20}$$

Total *ET* during the time period is

$$ET = I + (\theta_i - \theta_r)\,R_d - (\theta_f - \theta_i')\,R_d, \tag{3.11-21}$$

if θ_i is greater than θ_r. Otherwise,

$$ET = I - (\theta_f - \theta_i')R_d. \tag{3.11-22}$$

3.11.2.4 Nonuniform Applications

Subroutine *LAND* assumes that irrigation water is not applied uniformly over a user area to represent this condition. The user area is divided into five water-application zones, where water application is different in each zone according to the uniformity coefficient. Zone 3 receives an average water application, zones 1 and 2 receive more than average applications, and zones 4 and 5 receive less than average applications. These different applications are given by the relation (Jensen, 1983)

$$I_Z = I\left|1 + \frac{5}{6}(1 - U_c)(3 - Z)\right|, \tag{3.11-23}$$

where

I_Z is the water application in the zone Z [L],
I is the average water application for all zones [L],
U_c is the uniformity coefficient [dimensionless], and
Z is the zone number [dimensionless].

Values in the uniformity coefficient can range from 0.4 to 1. When U_c equals 1, the applied water is distributed equally to each zone. When U_c equals 0.4, the application in zone 1 is 200 percent of the average application, and the application in zone 5 is zero. The value of U_c for a particular nonuniformity of irrigation can be solved with Equation 3.11-23, but the equation would need to be algebraically rearranged. Additionally, values would need to be specified for the average water application, the zone number, and the water application in the zone.

3.11.3 Structure of Subroutine

Subroutine *LAND* is structured into a single block and is entered by a call to *LAND*. A call is made from subroutine *WATER* for each user. Subroutine *LAND* returns the deep percolation of infiltrated water.

3.12 Subroutine *BUDGET*

3.12.1 Background

Subroutine *BUDGET* is used to produce a water budget for the ground-water system at each time step.

3.12.2 Mathematical Basis

The water budget for the ground-water system is given by the relation

$$\sum_{i=1}^{n} Q_i = \Delta S, \tag{3.12-1}$$

where

Q_i is a component of inflow or outflow for the ground-water system [L^3/t] and
ΔS is the rate of storage change within the ground-water system [L^3/t].

By expanding Equation 3.12-1, the inflows, the outflows, and the storage changes for the ground-water system are given by the expression

$$Q_P + Q_{WP} + Q_{WR} + Q_B + Q_E + Q_R + Q_V + Q_F = Q'_{Ske} + Q'_{Skv} + Q_{Ske}, \tag{3.12-2}$$

where

Q_P is the cumulative discharge through specified-flux nodes from subroutine *FLUX* [L^3/t],
Q_{WP} is the cumulative pumpage from subroutine *WATER* L^3/t],
Q_{WR} is the cumulative recharge from subroutine *WATER* [L^3/t],
Q_B is the cumulative discharge through specified-head nodes from subroutine *CHEAD* [L^3/t],
Q_E is the cumulative evapotranspiration from subroutine *EVAP* [L^3/t],
Q_R is the cumulative discharge through river nodes from subroutine *RIVER* [L^3/t],
Q_V is the cumulative discharge through variable-flux nodes from subroutine *VFLUX* [L^3/t],
Q_F is the cumulative net discharge through fault-node pairs from subroutine *FAULT* [L^3/t],
Q'_{Ske} is the rate of elastic storage change within interbeds from subroutine *SINK* [L^3/t],
Q'_{Skv} is the rate of inelastic storage change within interbeds from subroutine *SINK* [L^3/t], and
Q_{Ske} is the rate of elastic storage change within noninterbeds from subroutine *BUDGET* [L^3/t].

Within subroutine *BUDGET*, the rate of elastic storage change within noninterbeds is determined from the relation

$$Q_{Ske} = \int_{\Omega} (1-p) S_S \frac{\Delta h}{\Delta t} d\Omega + \int_{\Gamma} S_y \frac{\Delta h}{\Delta t} d\Gamma, \qquad (3.12\text{-}3)$$

where

p is the proportion of the local ground-water system that is occupied by interbeds [dimensionless],
S_s is the specific storage [1/L],
Δh is the average hydraulic-head change [L],
S_y is the specific yield at the water-table surface [dimensionless], and
Δt is the time interval [t].

Equation 3.12-3 is the complement to Equations 3.9-14 and 3.9-15, which relate to the rates of elastic and inelastic storage change within interbeds.

3.12.3 Structure of Subroutine

Subroutine *BUDGET* is structured into a single block and is entered by a call to *BUDGET*. Within that block, the rate of elastic storage change within the noninterbeds and the imbalance of the water budget are calculated and the water-budget components of Equation 3.12-2 are displayed. The water-budget imbalance is the difference between the right-hand and left-hand sides of Equation 3.12-2.

3.13 Subroutine *SHAPE*

3.13.1 Background

Subroutine *SHAPE* is used to construct the elemental matrices $[A^e]$ and $[B^e]$.

3.13.2 Mathematical Basis

The elemental matrices $[A^e]$ and $[B^e]$ are constructed using Equations 3.2-26, 3.2-27, 3.2-28, 3.2-35, and 3.2-36 in Section 3.2.2.3.

3.13.3 Structure of Subroutine

Subroutine *SHAPE* is structured into two basic blocks. The first block is entered by a call to *SHAPE1* and is used to construct the elemental matrices $[A^e]$ and $[B^e]$ using Equations 3.2-26, 3.2-27, and 3.2-28, which relate to volume integrations over tetrahedra elements. In the first block, the matrix $[B^e]$ relates to the specific storage of the ground-water system. The second block, which is entered by a call to *SHAPE2*, is used to construct the elemental matrix $[B^e]$ using Equations 3.2-35 and 3.2-36, which relate to surface integrations over triangular elements. In the second block, the matrix $[B^e]$ relates to the specific yield at the water table.

3.14 Subroutine *BAND*

3.14.1 Background

Subroutine *BAND* is used to solve the symmetric and banded system of linear algebraic equations that are represented by Equation 3.2-38. The left-hand side matrix of that system is

$$[L] = [A] + \frac{1}{\Delta t}[B], \tag{3.14-1}$$

the right-hand side vector is

$$\{R\} = \frac{1}{\Delta t}[B]\{H_t\} + \{F\}, \tag{3.14-2}$$

and the vector of unknowns is $\{H_{t+\Delta t}\}$. The resulting system of equations to be solved is

$$[L]\{H_{t+\Delta t}\} = \{R\}. \tag{3.14-3}$$

3.14.2 Mathematical Basis

The square-root or Cholesky method (Pinder and Gray, 1977, p. 22-23) is used to solve the system of linear equations. This method is based on the fact that, for the symmetric matrix $[L]$, the matrix $[\ell]$ exists such that

$$[L] = [\ell][\ell]^T, \tag{3.14-4}$$

where $[\ell]$ is a lower triangular matrix. A lower triangular matrix is a matrix with coefficients of zero above the diagonal. The general ability to factor a matrix into upper and lower triangular matrices is the essential scheme for solving systems of linear equations. The Cholesky method is one of many such schemes.

Derivation of solution.—Setting aside the problem of finding $[\ell]$, Equation 3.14-3 can be solved using a three-step derivation. First, Equation 3.14-4 can be substituted into Equation 3.14-3 to obtain

$$[\ell]\ [\ell]^T\ \{Ht+\Delta t\} = \{R\}. \tag{3.14-5}$$

However, an intermediate solution to Equation 3.14-5 can be defined as

$$[\ell]\{X\} = \{R\} \tag{3.14-6}$$

where $\{X\}$ is the intermediate solution. Second, because of the triangular structure of $[\ell]$, Equation 3.14-6 can be readily solved for $\{X\}$ by direct back substitution. However, Equation 3.14-6 can be substituted into Equation 3.14-5 to obtain

$$[\ell][\ell]^T\ \{H_{t+\Delta t}\} = [\ell]\{X\}. \tag{3.14-7}$$

Third, by premultiplying both sides of Equation 3.14-7 by $[\ell]^{-1}$, Equation 3.14-7 can be reduced to

$$[\ell]^T\ \{H_{t+\Delta t}\} = \{X\}. \tag{3.14-8}$$

Again, because of the triangular structure of $[\ell]^T$, Equation 3.14-8 can be solved for $\{H_{t+\Delta t}\}$ by direct back substitution.

Finding lower triangularization.--Returning to the problem of finding $[\ell]$, expressions for the coefficients of $[\ell]$ can be obtained first by writing expressions for the expansion of Equation 3.14-4 by the definition of matrix multiplication and then by solving for the coefficients $[\ell]$. The expansion of Equation 3.14-4 yields

$$L_{ij} = \ell_{j1}^2 + \ell_{j2}^2 + \ldots + \ell_{jj}^2 \tag{3.14-9}$$

on the diagonal and yields

$$L_{ij} = \ell_{i1}\ell_{j1} + \ell_{i2}\ell_{j2} + \ldots + \ell_{ij}\ell_{jj} \tag{3.14-10}$$

below the diagonal. Equations 3.14-9 and 3.14-10 can be arranged to obtain

$$\ell_{jj} = \left(L_{jj} - \sum_{k=1}^{j-1} \ell_{jk}^2 \right)^{1/2} \tag{3.14-11}$$

on the diagonal and

$$\ell_{ij} = \frac{\left(L_{ij} - \sum_{k=1}^{j-1} \ell_{ik}\ell_{jk} \right)}{\ell_{jj}} \tag{3.14-12}$$

below the diagonal. Equations 3.14-11 and 3.14-12 are used in subroutine *BAND* to extract the lower triangular matrix $[\ell]$ from the matrix $[L]$.

3.14.3 Structure of Subroutine

Subroutine *BAND* is structured into two basic blocks. The first block, which is entered by a call to *BAND1*, is for the lower triangularization of the matrix $[L]$. The second block, which is entered by a call to *BAND2*, is used to obtain $\{H_{t+\Delta t}\}$ using back substitution. $\{H_{t+\Delta t}\}$ is obtained first by solving for the intermediate solution $\{X\}$ using Equation 3.14-6 and then by solving for the solution $\{H_{t+\Delta t}\}$ using Equation 3.14-8.

For some ground-water problems, the matrix $[L]$ is identical for each time step of a simulation. This occurs when the governing equations are linear and the time-step length is the same in each time step. The governing equations are linear when the problem being simulated does not include drain nodes, ground-water evapotranspiration, stream-aquifer interactions, or land subsidence. For these conditions, the computational effort in solving Equation 3.14-3 can be reduced by performing the upper triangularization of $[L]$ once and by performing the back substitution at each time step.

3.15 Subroutine *SOLVE*

3.15.1 Background

Subroutine *SOLVE* is used to solve the system of linear algebraic equations that are represented by Equation 3.2-38. The left-hand side matrix of that system is

$$[L] \equiv [A] + \frac{1}{\Delta t}[B], \tag{3.15-1}$$

the right-hand side vector is

$$\{R\} \equiv \frac{1}{\Delta t}[B]\{H_t\} + \{F\}, \tag{3.15-2}$$

and the vector of unknowns is $\{H_{t+\Delta t}\}$. The system of equations to be solved is

$$[L]\{H_{t+\Delta t}\} = \{R\}. \tag{3.15-3}$$

3.15.2 Mathematical Basis

The point overrelaxation method is used to solve the system of linear equations. This method is based such that the matrix $[L]$ can be expressed as

$$[L] = [D] - [l] - [u], \tag{3.15-4}$$

where

$[D]$ is diagonal $\{L_{11}, L_{22}, \ldots, L_{nn}\}$,
$[l]$ is a lower triangular matrix, and
$[u]$ is a upper triangular matrix.

The entries of the matrices $[l]$ and $[u]$ are the negatives of the entries of $[L]$ below and above the main diagonal of $[L]$, respectively.

The substitution of Equation 3.15-4 into Equation 3.15-3 yields

$$([D]-[l]-[u])\{H\} = \{R\}, \tag{3.15-5}$$

where the time subscript $t+\Delta t$ has been dropped for simplicity. Equation 3.15-5 can be rearranged to obtain

$$[D]\{H\} = ([l]+[u])\ \{H\}+\{R\}. \tag{3.15-6}$$

Premultiplication of each term by $[D]^{-1}$ subsequently yields the expression

$$\{H\} = [D]^{-1}([l]+[u])\{H\}+[D]^{-1}\{R\}. \tag{3.15-7}$$

From Equation 3.15-7, H_i can be calculated iteratively given estimates H_j for $j \neq i$ using the algebraic expression

$$H_i^{(k+1)} = -\sum_{j=1}^{i-1}\left(\frac{L_{ij}}{L_{ii}}\right)H_j^{(k+1)} - \sum_{j=i+1}^{n}\left(\frac{L_{ij}}{L_{ii}}\right)H_j^{(k)} + \frac{R_i}{L_{ii}}, \tag{3.15-8}$$

where k is an iteration counter for each successive update of the vector $\{H\}$. In Equation 3.15-8, $H_i^{(k+1)}$ is calculated using the most current updated vector $\{H\}$.

The rate of convergence for the successive applications of Equation 3.15-8 can be slow; however, the rate can be accelerated by introducing the auxiliary vector $[\tilde{H}]$ in the form

$$L_{ii}\,\tilde{H}_i^{(k+1)} = -\sum_{j=1}^{i-1} L_{ij}H_j^{(k+1)} - \sum_{j=i+1}^{n} L_{ij}H_j^{(k)} + R_i. \tag{3.15-9}$$

Then, the quantity $H_i^{(k+1)}$ is a weighted mean of $H_i^{(k)}$ and $\tilde{H}_i^{(k+1)}$ in the form

$$H_i^{k+1} = (1-\omega)H_i^{(k)} + \omega\tilde{H}_i^{(k+1)}, \tag{3.15-10}$$

where ω is the overrelaxation factor for $1 \le \omega \le 2$.

Combining of Equations 3.15-9 and 3.15-10 yields the relation

$$H_i^{(k+1)} = H_i^{(k)} + \omega\left\{-\sum_{j=1}^{i-1}\left(\frac{L_{ij}}{L_{ii}}\right)H_j^{(k+1)} - \sum_{j=i+1}^{n}\left(\frac{L_{ij}}{L_{ii}}\right)H_j^{(k)} + \frac{R_i}{L_{ii}} - H_i^{(k)}\right\}. \tag{3.15-11}$$

Equation 3.15-11 is used iteratively in subroutine *SOLVE* to solve Equation 3.15-3. Iterations are continued until convergence is achieved, where convergence is defined by the relation

$$E^{(k+1)} = \max_i \left(|H_i^{(k+1)} - H_i^{(k)}| \right), \tag{3.15-12}$$

such that

$$\varepsilon^{k+1} \leq \varepsilon_{max}, \tag{3.15-13}$$

where ε_{max} is the closure criterion.

3.15.3 Structure of Subroutine

Subroutine *SOLVE* is structured into two basic blocks. The first block, which is entered by a call to *SOLVE1*, reads values for the relaxation factor, the closure criterion, and the maximum allowed number of iterations. The second block, which is entered by a call to *SOLVE2*, is for the iterative application of Equation 3.15-11.

3.16 Subroutine *SEARCH*

3.16.1 Background

Subroutine *SEARCH* is used to calibrate the ground-water model and to identify aquifer and river-bed parameters. The aquifer parameters are horizontal and vertical hydraulic conductivities, specific storage, and specific yield, and the river-bed parameters are river-bed hydraulic conductivities. Subroutine *SEARCH* also identifies parameter values for the aquifer and the river bed, such that the ground-water model best fits the measured ground-water levels and the available prior information on the aquifer and river-bed parameters. Prior parameter values are those developed outside the model calibration. To identify the set of parameter values that produce the best fit, two series of squared residuals are calculated within the subroutine. One series calculates the sum of weighted squared differences between the calculated and measured ground-water levels. The second series calculates the sum of weighted squared differences between the calculated and the prior parameter values. The best fit is defined as the set of parameter values that minimizes the combined sum of the measured and the simulated values.

The weighting within each of the sums of squared residuals is based on the uncertainty of the measured ground-water levels owing to measurement errors and to the lack of representativeness and on the uncertainty of previous estimates of the parameter values. Examples of measurement errors include mistakes in field measurements and uncertainty in the elevation of the land-surface measuring point. Examples of lack of representativeness include water-level measurements that are affected by nearby pumping and water-level measurements that are made in wells that are not representative of the conceptual basis of the ground-water model. Regardless of the source of uncertainty, the uncertainty of individual water-level measurements is expressed in terms of the standard deviation of the water-level measurements in subroutine *SEARCH*.

The uncertainty in the prior estimates of the parameter values is also expressed in terms of the standard deviation. However, the uncertainty of these estimates is expressed in log units, which represent the standard deviation of the log-transform of the parameter estimate. The sources of uncertainty in the prior estimates of parameter values include measurement errors and scale effects. Measurement errors can include errors in interpreting aquifer tests, boring logs, and other type of hydrologic information. Errors can occur when data are translated from one scale to another. For example, data from aquifer tests and boring logs, used to estimate parameter values, are essentially point data relative to the geographic scales represented in the model.

Model calibration is a technically complex procedure, and the structure of subroutine *SEARCH* is based, in part, on the assumption that the user understands the requirements for producing a valid model calibration. Because those requirements are beyond the scope of this report, the user is referred to Anderson and Woessner (1992) for direction on model calibration.

Subroutine *SEARCH* is used to identify aquifer parameters for the ground-water system using the Box-Kanemasu method of nonlinear least squares, which is a maximum a posteriori estimator (Beck and Arnold, 1977). This estimator uses prior information on the aquifer parameters and information on measurement errors. Inclusion of prior parameter information can reduce the variances of the parameter estimates.

Beck and Arnold (1977, p. 269-274) describe the Box-Kanemasu method in terms of a model that is linear in its parameters. However, ground-water models are nonlinear in their parameters and must be linearized to apply the method. This method identifies the sensitivity of the calculated water levels to the parameter values of the model. However, that sensitivity is dependent on particular parameter values, which is the phenomenon that makes ground-water models nonlinear in their parameters. A model is linearized by iteratively recalculating the sensitivities as the search for parameters proceeds.

The Box-Kanemasu method identifies parameter values that are not greatly different than the prior estimates of the parameters values and that reduce the difference between calculated water levels and measured water levels. The balance depends on the uncertainty in the measured water levels relative to the uncertainty in the prior estimates of the parameter values. For example, if the prior estimates of parameter values are highly certain, the method will identify parameter values that are not much different than the prior estimates but at the expense of allowing larger differences between calculated and measured water levels.

3.16.2 Mathematical Basis

3.16.2.1 Modified Box-Kanemasu Method

In subroutine *SEARCH*, aquifer and river-bed parameters are identified that minimize the weighted sum of squared deviations between measured and calculated water levels plus the weighted sum of squared deviations between the prior parameter values and the calibrated parameter rates. This parameter-identification problem is nonlinear, and an iterative process is needed to obtain a solution. Subroutine *SEARCH* uses a modified Box-Kanemasu iterative method.

Update the parameter estimates.—The Box-Kanemasu method (fig. 13) iteratively updates the initial estimate of the parameter vector for the *(k)* iteration by the relation (Beck and Arnold, 1977)

$$\{b\}^{(k)} = \{b\}^{(k-1)} + h^{(k)} \{\Delta b\}^{(k-1)}, \qquad (3.16\text{-}1)$$

where

$\{b\}$ is a $[n_p \times 1]$ vector of parameters [dimensionless],
k is an iteration counter,
h is a scaler interpolating factor [dimensionless],
$\{\Delta b\}$ is a $[n_p \times 1]$ vector of parameter changes [dimensionless], and
n_p is the number of parameters [dimensionless].

By this relation, the updated estimates equal the previous estimates plus scaled parameter changes. The scaling factor h is selected to optimize the improvement of the parameter estimates, where the optimal value of $h^{(k)}$ minimizes the sum of squared deviations.

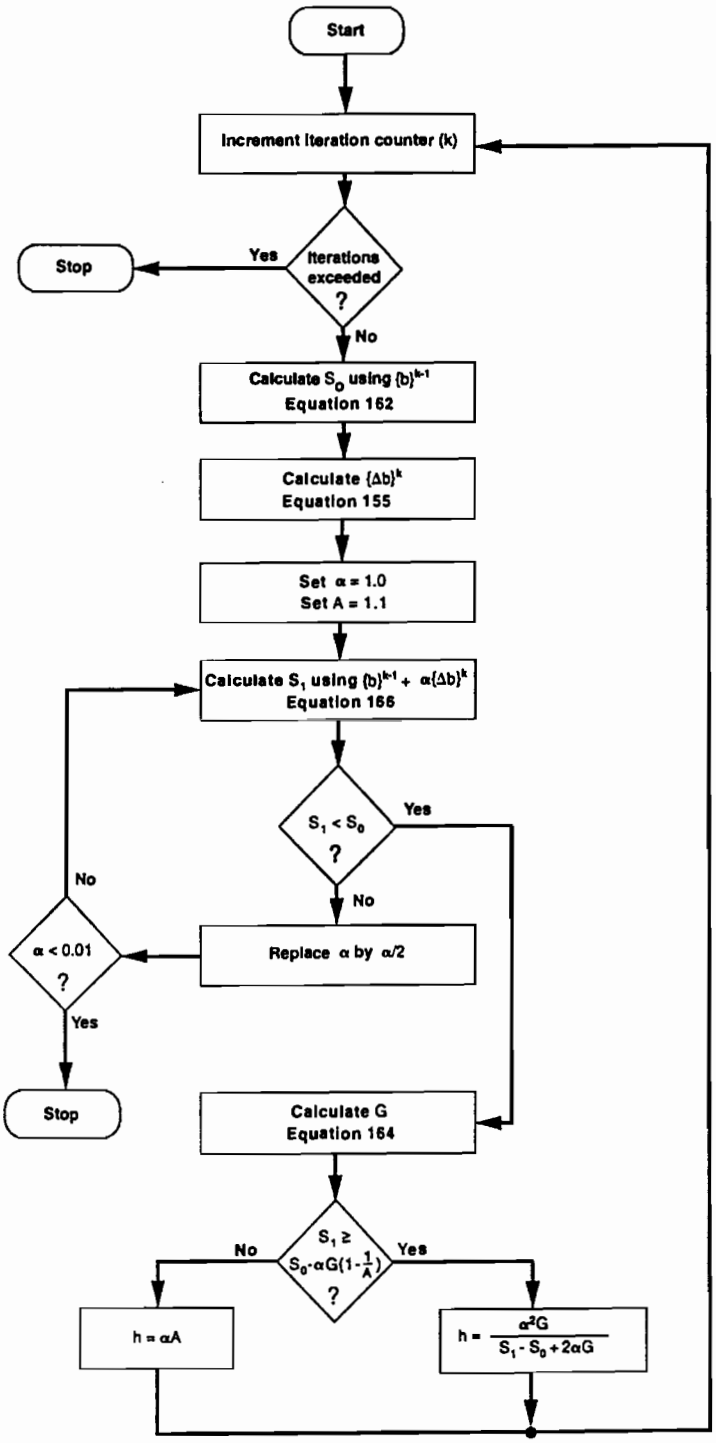


Figure 13. Parameter identification using the Box-Kanemasu method.

The vector of parameter changes is given by the relations (Beck and Arnold, 1977, Equations 6.6.6a and 6.6.6b)

$$\{\Delta b\}^{(k-1)} = [P]^{(k-1)} \left[[X]^{T(k-1)} [W] (\{Y\} - \{\eta\}^{(k-1)}) + [V](\{\mu\} - \{b\}^{(k-1)}) \right], \tag{3.16-2}$$

and

$$[P]^{-1(k-1)} \equiv [X]^{T(k-1)}[W][X]^{(k-1)} + [V], \tag{3.16-3}$$

where

$[X]$ is a $[n_o \times n_p]$ sensitivity matrix [L],
$[W]$ is the $[n_o \times n_o]$ inverse of the covariance matrix of the water-level measurement errors [$1/L^2$],
$\{Y\}$ is a $[n_o \times 1]$ vector of measured water levels [L],
$\{\eta\}$ is a $[n_o \times 1]$ vector of calculated water levels [L],
$[V]$ is the $[n_p \times n_p]$ inverse of the covariance matrix of the prior estimates of the aquifer parameters [dimensionless],
$\{\mu\}$ is the $[n_p \times 1]$ parameter vector from prior estimates [dimensionless],
n_o is the number of water-level measurements [dimensionless], and
n_p is the number of aquifer parameters [dimensionless].

A typical element of the sensitivity matrix is given by the relation

$$X_{ij} = \frac{\partial \eta_i}{\partial b_j}. \tag{3.16-4}$$

The elements of the sensitivity matrix are calculated by sequentially perturbing the parameter values to the model and calculating the resulting change in hydraulic heads.

Specification of uncertainty.--In subroutine *SEARCH*, the water-level-measurement error for a particular well is assumed to be independent of the measurement errors for another well. Accordingly, all off-diagonal terms of *[W]* equal zero. The diagonal of *[W]* is given by the relation

$$diag[W] = \left\{\frac{1}{\sigma_Y^2}\right\}, \tag{3.16-5}$$

where σ_Y^2 is the variance of the water-level measurement $[L^2]$. Likewise, the uncertainty in the prior estimate for a particular parameter is assumed to be independent of the uncertainty for another parameter. Accordingly, the off-diagonal terms of *[V]* all equal zero. The diagonal of *[V]* is given by the relation

$$diag[V] = \left\{\frac{1}{\sigma_b^2}\right\}, \tag{3.16-6}$$

where σ_b^2 is the variance of the prior parameter estimate [dimensionless].

Optimizing the scaling factor.--The factor h in Equation 3.16-1 is used to optimize parameter change $\{\Delta b\}$ at each iteration. This is done using the Box-Kanemasu method. This method is described in detail by Beck and Arnold (1977, p. 362-368). However, an overview of the method is given below.

The Box-Kanemasu method optimizes the parameter change $\{\Delta b\}$ at each iteration, finding the value of h that minimizes S by the relation (Beck and Arnold, 1977)

$$S = a_o + a_1 h + a_2 h^2 , \tag{3.16-7}$$

where a_o, a_1, and a_2 are coefficients of the quadratic equation.

This method approximates the weighted sum of squared deviations between measured and calculated water levels plus the weighted sum of squared deviations between the prior estimates and the estimates of the aquifer parameters.

The coefficient a_o is given by the relation

$$a_o = S_{o'} \tag{3.16-8}$$

where

$$S_o = (\{Y\} - \{\eta(\{b\})\})^T [W] (\{Y\} - \{\eta(\{b\})\}) + (\{\mu\} - \{b\})^T [V] (\{\mu\} - \{b\}). \tag{3.16-9}$$

The coefficient a_1 is given by the relation

$$a_1 = -2G, \tag{3.16-10}$$

where

$$G = [X]^T[W](\{Y\} - \{\eta(\{b\})\}) + [V](\{\mu\} - \{b\}). \tag{3.16-11}$$

The coefficient a_2 is given by the relation

$$a_2 = \frac{1}{\alpha} [S_1 - S_o + 2G\alpha], \tag{3.16-12}$$

where

$$S_1 = (\{Y\} - \{\eta(\{b\} + \alpha\{\Delta b\})\})^T[W](\{Y\} - \{\eta(\{b\} + \alpha\{\Delta b\})\}) + (\{\mu\} - \{b\}^T[V](\{\mu\} - \{b\}), \tag{3.16-13}$$

and where α is a parameter [dimensionless], which is small enough that S_1 is less than S_o.

The procedure by which h is obtained from Equations 3.16-7 to 3.16-13 is shown in figure 13. The iterations are required to find an appropriate value of the parameter α. Initially, the parameter α is set to the value 1.0 (fig. 13). However, if S_1 is not less than S_o, the parameter value is reduced progressively by one-half until S_1 is less than S_o.

3.16.2.2 Interface with Subroutine *MODEL*

Subroutine *SEARCH* passes a dimensionless parameter vector *{b}* to subroutine *MODEL*. The parameter values are determined from the relations

$$K_{xx}(j) = K^{o}_{xx}(j) exp[b(i)], \tag{3.16-14}$$

where

$K_{xx}(j)$ is the hydraulic conductivity of prismatic element j in the finite-element grid [L/t], which has been assigned to the parameter i,
$K^{o}_{xx}(j)$ is the initial value of $K_{xx}(j)$ [L/t],
$b(i)$ is the parameter with index i in the vector *{b}* [dimensionless], and
j is the element index [dimensionless].

Similar relations apply to K_{yy}, K_{zz}, S_s, S_y, and K_l. Accordingly, the parameter values are determined by the initial values of K_{yy}, K_{zz}, S_s, S_s, and K_l and a factor that multiplies these initial values.

Rather than directly adjusting the parameter values, an exponential function is used as a parameter multiplier. This approach was selected for three reasons. First, the use of a multiplier allows elemental parameters to be adjusted as a group, identified by the element index. For example, a multiplier can be useful when applied to a group of elements that represents a single geologic formation because it allows uniform adjustment. Second, the use of an exponential function prevents the selection of a negative multiplier, which would produce physically implausible values. Third, exponential values reflect the typical log-normal distribution of hydraulic conductivities measured in aquifer materials. Subroutine *SEARCH* assumes that the parameter *{b}* is distributed as a log-normal probability distribution. Accordingly, K_{xx} in Equation 3.16-14 is assumed to be distributed as a log-normal distribution. Additionally, the variance $\{\sigma_b^2\}$ in Equation 3.16-6 is the variance of *ln(b)*.

3.16.3 Structure of Subroutine

Subroutine *SEARCH* is structured into a single block, which is entered by a call to *SEARCH*. The first part of the block is for the input and display of information on the parameter identification problems, including information on prior parameter estimates and measured ground-water levels. In the second part of the block, an iterative search for parameter values is done. Within those iterations, the sensitivity matrix is constructed by making multiple calls to subroutine *MODEL2*. Equation 3.16-2 is then solved for $\{\Delta b\}$, and Equations 3.16-7 through 3.16-13 are used to identify h. Iterations are repeated until the sum of squared deviations cannot be improved further.

3.17 Subroutine *SOLEQU*

3.17.1 Background

Subroutine *SOLEQU* is used to solve the system of linear equations represented by Equation 3.16-2. The left-hand side matrix of that system is

$$[L] = [P], \tag{3.17-1}$$

the right-hand side vector is

$$\{R\} = [X]^T[W](\{Y\} - \{\eta\}), \tag{3.17-2}$$

and the vector of unknowns is $\{\Delta b\}$. The resulting system of equations to be solved is

$$[L]\{\Delta b\} = \{R\}. \tag{3.17-3}$$

3.17.2 Mathematical Basis

The Gauss elimination method is used to solve the system of linear equations. This method is based on the fact that the matrices $[\ell]$ and $[u]$ exist such that

$$[\ell]\,[u] = [L], \tag{3.17-4}$$

where

$[\ell]$ is a lower triangular matrix, and
$[u]$ is an upper triangular matrix.

A lower triangular matrix is a matrix with coefficients of zero above the diagonal, and an upper triangular matrix is a matrix with coefficients of zero below the diagonal. The general ability to factor a matrix into upper and lower triangular matrices is the essential idea of all elimination schemes for solving systems of linear equations. The Gauss method is one of many such elimination schemes.

Derivation of solution.--Setting aside the problem of finding $[\ell]$ and $[u]$, the solution to Equation 3.17-3 can be obtained using a three-step derivation. First, Equation 3.17-4 can be substituted into Equation 3.17-3 to obtain

$$[\ell][u]\{\Delta b\} = \{R\}. \tag{3.17-5}$$

However, an intermediate solution to Equation 3.17-5 is

$$[\ell]\{X\} = \{R\}, \tag{3.17-6}$$

where $\{X\}$ is the intermediate solution. Second, because of the triangular structure of $[\ell]$, Equation 3.17-6 can readily be solved for $\{X\}$ by direct back substitution. However, Equation 3.17-6 can be substituted into Equation 3.17-5 to obtain

$$[\ell][u]\,\{\Delta b\} = [\ell]\{X\}. \tag{3.17-7}$$

Third, by premultiplying Equation 3.17-7 by $[\ell]^{-1}$, Equation 3.17-7 can be reduced to

$$[u]\{\Delta b\} = \{X\}. \tag{3.17-8}$$

Again, because of the triangular structure of $[u]$, Equation 3.17-8 can be used to solve $\{\Delta b\}$ by direct back substitution.

Finding lower and upper triangularizations.--Returning to the problem of finding *[ℓ]* and *[u]*, expressions for the coefficients of *[ℓ]* and *[u]* can be obtained first by writing expressions to expand Equation 3.17-4 using matrix multiplication and then by solving for the coefficients of *[u]* and *[ℓ]*. The expansion of Equation 3.17-4 yields

$$L_{ij} = \sum_{k=1}^{m} \ell_{ik} u_{kj} \tag{3.17-9}$$

where

m = min (i,j).

By letting $u_{ii} = L_{ii}$, equation 3.17-9 can be rearranged to obtain

$$u_{ij} = L_{ij} - \sum_{k=1}^{i-1} \ell_{ii} u_{kj} \tag{3.17-10}$$

where $j \geq i$. As $u_{ii} = \ell_{ii}$, it is necessary that $\ell_{ii} = 1$; for $j \leq i$, ℓ_{ij} becomes

$$\ell_{ij} = \frac{L_{ij} - \sum_{k=1}^{j-1} \ell_{ik} u_{kj}}{u_{jj}}. \tag{3.17-11}$$

3.17.3 Structure of Subroutine

Subroutine *SOLEQU* is structured into a single block, which is entered by a call to *SOLEQU*. Within this block, the matrix *[L]* is factored into upper and lower triangular matrices using Equations 3.17-10 and 3.17-11. Then, the solution *{Δb}* is obtained by back substitution, which is done first by solving for the intermediate solution *{X}* using Equation 3.17-6 and then by solving for the solution *{Δb}* using Equation 3.17-8.

3.18 Subroutine *FMERGE*

3.18.1 Background

Subroutine *FMERGE* is used to construct input files from file segments. For example, the input file to subroutine *MODEL* includes data on the coordinates of the grid nodes, the specification of the nodes that makes up the grid elements, the aquifer parameter values, and other data. If the data on the nodal coordinates are in a particular file, the data on elements in a second file, the data on aquifer parameters in a third file, and the remaining data in a fourth file, subroutine *FMERGE* can be used to concatenate these files into the overall input file for subroutine *MODEL*. Likewise, subroutine *FMERGE* can be used to construct other input files.

3.18.2 Mathematical Basis

No calculations are done in subroutine *FMERGE*.

3.18.3 Structure of Subroutine

Subroutine *FMERGE* is structured into a single block. Within that block, the file segments are copied into the input file in a specified order. The file segments are not modified during this process.

4.0 MODEL VALIDATION

FEMFLOW3D was validated in four test problems using solutions obtained by independent methods:

1. Transient, confined, radial flow to a well (Theis, 1935).
2. Transient, unconfined, radial flow to a well (Neuman, 1974).
3. Transient, confined, linear flow to a ditch (Carslaw and Jaeger, 1959).
4. Transient compaction of an interbed owing to water-level changes (Leake and Prudic, 1988).

The following sections describe each of these four validation tests. Validation was done by simulating each test problem using *FEMFLOW3D* and then by comparing the results of the simulation with the results of the independent methods. For the first three test problems, the results of the independent method were obtained using analytical solutions (Theis, 1935; Neuman, 1974; Carslaw and Jaeger, 1959; respectively). For the fourth problem, the results of the independent method were obtained using another model (Leake and Prudic, 1988).

4.1 Transient, Confined, Radial Flow to a Well

4.1.1 Problem Description

For the first problem, *FEMFLOW3D* was used to simulate flow to a fully penetrating well in an infinite confined aquifer; the well was pumped at a constant rate. The simulation was then compared with the Theis (1935) analytical solution, which is described in Lohman (1979). This solution has the form

$$s = \frac{Q}{4\pi KB} W(u), \tag{4.1-1}$$

where

s is the drawdown in the aquifer at a specified time and distance from the well [L],
Q is the pumping rate [L^3/t],
K is the radial hydraulic conductivity of the aquifer [L/t],
B is the aquifer thickness [L],
$W()$ is the well function [dimensionless], and
u is a parameter [dimensionless].

The parameter u is given by the relation

$$u = \frac{r^2 S_s}{4Kt}, \tag{4.1-2}$$

where

r is the radial distance from the well [L],
t is the time since the start of pumping [t], and
S_s is the specific storage of the aquifer [1/L].

4.1.2 Model Simulation

The finite-element grid used for the first test problem (fig. 14) is radially symmetric and represents a 24-degree wedge. The radial length of the grid is approximately 21,600 ft, which is sufficient to avoid adverse boundary effects. The radius of the well is 1.0 ft, and the grid spacing in the radial direction increases by a factor of 1.1 with distance from the well. The vertical thickness of the grid is 100 ft.

This first test problem has one transient time-step period that is divided into 21 geometrically expanding time steps. The initial time step is 0.01 day in duration. The duration of each successive time step is expanded by a factor of 1.5. The total duration of the simulation is about 99.7 days.

The initial and boundary conditions for *FEMFLOW3D* are

1. For initial conditions everywhere, drawdown equals zero.

2. For the boundary condition at a radial distance from the well equal to 1.0 ft, flow toward the well equals the pumping rate for times greater than zero. (The well radius and the inward boundary of the finite-element grid are equal to 1.0 ft.)

3. For the boundary condition at a radial distance from the well equal to 21,600 ft (which is equal to the outward boundary of the finite-element grid), no flow occurs for all times.

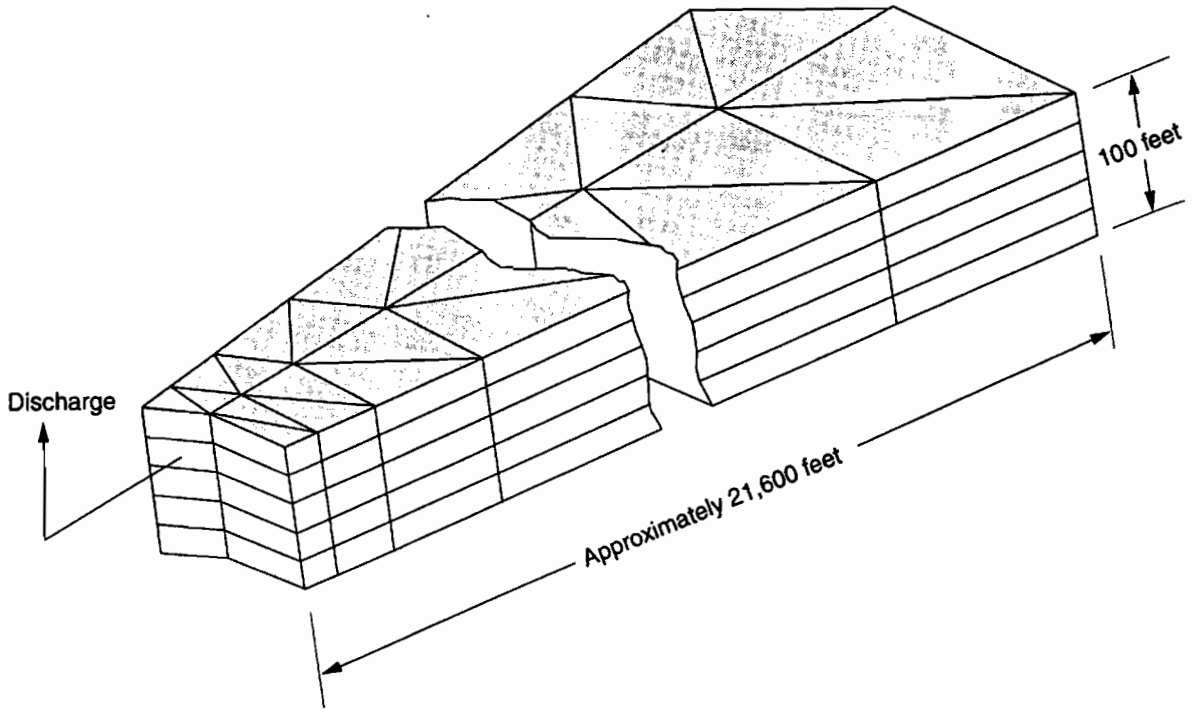


Figure 14. Finite-element grid for Theis problem.

The initial and boundary conditions for the Theis solution are

1. For initial conditions everywhere, drawdown equals zero.

2. For the boundary condition as the radial distance from the well approaches zero, flow toward the well equals the pumping rate for times greater than zero.

3. For the boundary condition as the radial distance from the well approaches infinity, drawdown equals zero for all times.

The hydraulic parameters used in *FEMFLOW3D* are

Hydraulic conductivity *(K)*	10.0 ft/d
Specific storage *(S)*	1.0×10^{-4} 1/ft
Aquifer thickness	100.0 ft
Pumping rate *(Q)*	0.25 ft^3/s

These parameters were also used in the Theis solution, except that the pumping rate was increased to represent the full circumference of the well, while the finite-element grid represents only a 24-degree wedge. Accordingly, the pumping rate is

Pumping rate *(Q)*	3.75 ft^3/s

The input and the output files for *FEMFLOW3D* are on the diskette in the pocket at the back of the report. The input files are THEIS.FLS and THEIS.IN. The output files are THEIS.OUT, THEIS.PLT and THEIS.BUD. The formats of the input files are described in Section 5.0.

4.1.3 Results

The results from the *FEMFLOW3D* simulation and from the Theis solution are shown on a plot of drawdown against $log_{10}(r^2/t)$ (fig. 15). The output file from *FEMFLOW3D* is listed in appendix B for two time steps. The parameter $log_{10}(r^2/t)$ allows various combinations of distance from the well and of elapsed time to be compared on a single graph. *FEMFLOW3D* can very closely replicate the results of the Theis solution for a range of distances and times (fig. 15).

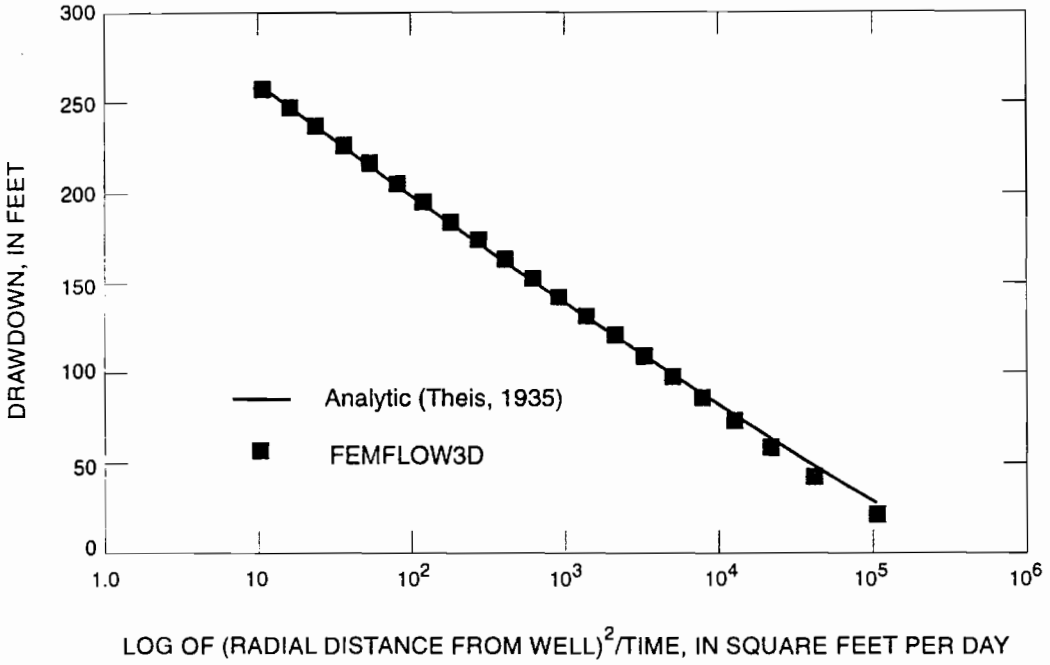


Figure 15. Comparison of *FEMFLOW3D* results with Theis solution.

4.2 Transient, Unconfined, Radial Flow to a Well

4.2.1 Problem Description

For the second test problem, *FEMFLOW3D* was used to simulate flow to a partially penetrating well in an infinite unconfined aquifer; the well was pumped at a constant rate. This problem simulated, in part, the release of stored ground water owing to changes in the position of the water table. The results of the *FEMFLOW3D* simulation were compared with the results of Neuman's (1974) analytical solution, which has the form

$$s = \frac{Q}{4\pi KB} W(\sigma, \beta, z_D, \ell_D, d_D, t_s), \tag{4.2-1}$$

where

- s is the drawdown at a specified time, radial distance from the well, and depth within the aquifer [L],
- Q is the pumping rate [L^3/t],
- K is the hydraulic conductivity of the aquifer [L/t],
- B is the thickness [L], and
- $W()$ is the well function [dimensionless].

The dimensionless parameters of the well function are

$$\sigma = \frac{S_s}{S_y}, \tag{4.2-2}$$

$$\beta = \frac{K_z}{K_r}\frac{r^2}{B^2}, \tag{4.2-3}$$

$$z_D = \frac{z}{r}, \tag{4.2-4}$$

$$\ell_D = \frac{\ell}{B}, \tag{4.2-5}$$

$$d_D = \frac{d}{B}, \tag{4.2-6}$$

and

$$t_s = \frac{KBt}{S_s r^2}, \tag{4.2-7}$$

where

- S_s is the specific storage of the aquifer [1/L],
- S_y is the specific yield [dimensionless],
- K_z is the vertical hydraulic conductivity [L/t],
- K_r is the radial hydraulic conductivity [L/t],
- r is the radial distance from the well to the observation point [L],
- z is the height above the bottom of the aquifer to the observation point [L],
- ℓ is the distance from the top of the aquifer to the bottom of the well perforations [L],
- d is the distance from the top of the aquifer to the top of the well perforations [L], and
- t is the elapsed time [t].

4.2.2 Model Simulation

The finite-element grid used for the second test problem (fig. 16) is radially symmetric and represents a 24-degree wedge. The radial length of the grid is 9,974 ft, which is sufficient to avoid adverse boundary effects. The radius of the well is 1.0 ft, and the grid spacing in the radial direction increases by a factor of 1.5 with distance from the well. The vertical thickness of the grid is 160 ft, which represents the initial saturated thickness of the aquifer. The well is perforated within the depth interval between 60 to 160 ft below the initial water-table position.

The second test problem has one transient time-step period that is divided into 21 geometrically expanding time steps. The initial time step is 0.01 day in duration, and the duration of each successive time step is expanded by a factor of 1.5. The total duration of the simulation is about 99.7 days.

The initial and boundary conditions for *FEMFLOW3D* are

1. For initial conditions everywhere, drawdown equals zero.

2. For the boundary condition at a radial distance from the well equal to 1.0 ft, flow toward the well equals the pumping rate for times greater than 0. (The well radius and the inward boundary of the finite-element grid are equal to 1.0 ft.)

3. For the boundary condition at a radial distance from the well equal to 9,974 ft (which is equal to the outward boundary of the finite-element grid), no flow occurs for all times.

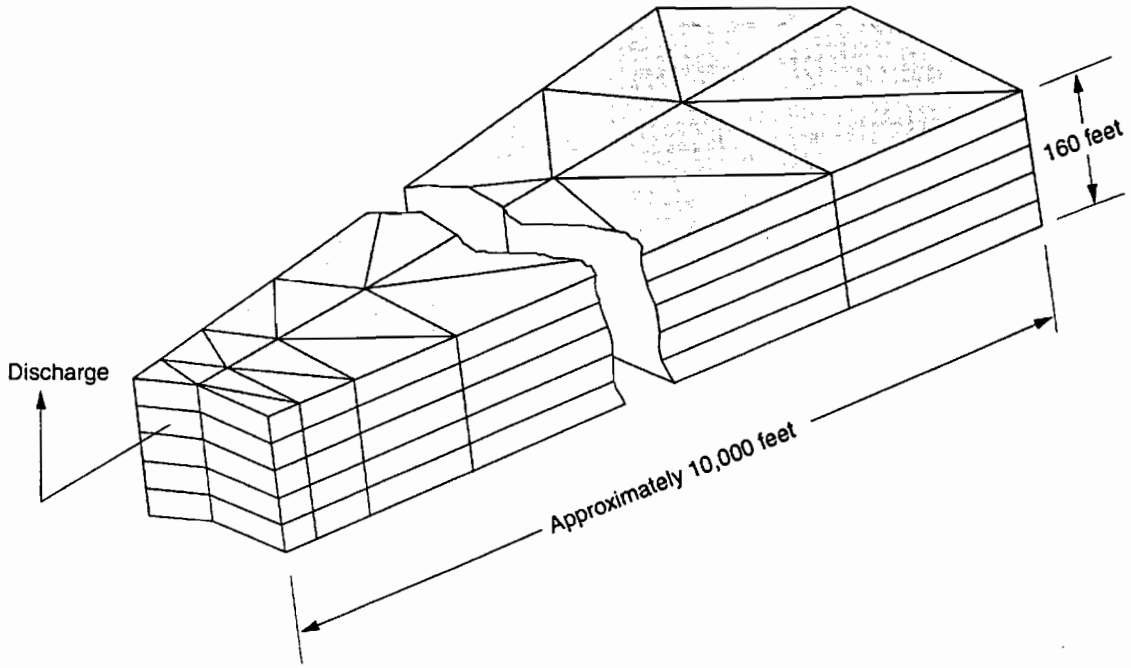


Figure 16. Finite-element grid for Neuman problem.

The initial and boundary conditions for the Neuman (1974) solution are

1. For initial conditions everywhere, drawdown equals zero.
2. For the boundary condition as the radial distance from the well approaches zero, flow toward well equals the pumping rate for times greater than zero.
3. For the boundary condition as the radial distance from the well approaches infinity, drawdown equals zero for all times.

The hydraulic parameters used in *FEMFLOW3D* are

Specific yield (S_y)	0.1 ft {dimensionless]
Specified storage (S_s)	1.0 x 10^{-6} ^{1}/ft
Radial hydraulic conductivity (K_r)	50.0 ft/d
Vertical hydraulic conductivity (K_z)	50.0 ft/d
Aquifer thickness (B)	160.0 ft
Depth to top of well perforations (d)	60.0 ft
Depth to bottom of well perforations (ℓ)	160.0 ft
Pumping rate (Q)	0.297 ft^3/s
Height above aquifer bottom to observation point (z)	0.0 ft

These parameters were also used in the Neuman solution, except that the pumping rate was increased to represent the full circumference of the area affected by the well, while the finite-element grid represents only a 24-degree wedge. Accordingly, the pumping rate is

Pumping rate (Q)	4.46 ft^3/s

The input and the output files for *FEMFLOW3D* are on the diskette in the pocket at the back of the report. The input files are NEUMAN.FLS and NEUMAN.IN. The output files are NEUMAN.OUT, NEUMAN.PLT, and NEUMAN.BUD. The formats of the input files are described in Section 5.0.

4.2.3 Results

The results of the *FEMFLOW3D* simulation and of the Neuman (1974) solution are shown on a plot of drawdown against $log_{10}(r^2/t)$ (fig. 17), This is the same type of plot used for the Theis test problem shown on figure 15. *FEMFLOW3D* can very closely replicate the results of the Neuman solution for a range of distances and times.

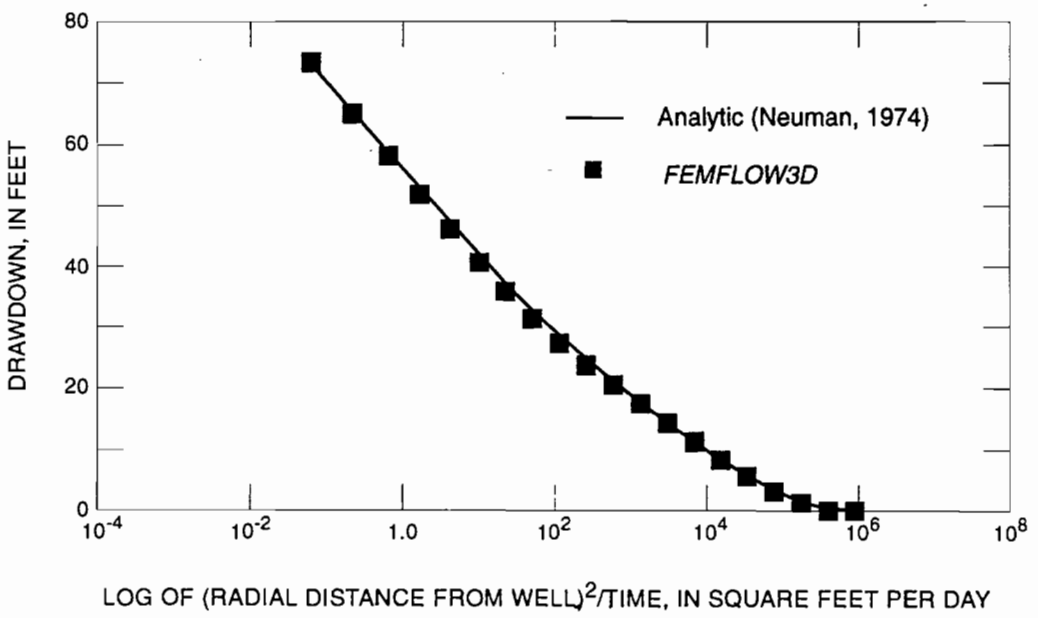


Figure 17. Comparison of *FEMFLOW3D* results with Neuman solution.

4.3 Transient, Confined, Linear Flow to a Ditch

4.3.1 Problem Description

For the third test problem, *FEMFLOW3D* was used to simulate flow to a fully penetrating ditch at the boundary of a semi-infinite aquifer as the result of a step change in the water level within the ditch. The simulation was then compared with the analytical solution of Carslaw and Jaeger (1959), which has the form

$$\Delta h = \Delta h_o \, erfc \left[\frac{x}{2\sqrt{\frac{Kt}{S_s}}} \right], \qquad \text{(4.3-1)}$$

where

- Δh is the change in hydraulic head in the aquifer at a specified time and distance from the ditch [L],
- Δh_o is the change in the water level in the ditch [L],
- K is the hydraulic conductivity of the aquifer [L/t],
- S_s is the specific storage of the aquifer [^{1}/L],
- x is the distance from the ditch [L], and
- t is the elapsed time [t].

4.3.2 Model Simulation

The finite-element grid for the third test problem is linear, with a length of 5,800 ft, a width of 40 ft, and a vertical thickness of 10 ft (fig. 18).

The third test problem has two time-step periods. Steady-state heads are calculated in the first period. The second transient time period is divided into 40 geometrically expanding time steps. The initial time step is 0.25 day in duration, and the duration of each succesive time step is expanded by a factor of 1.30. The total duration of the transient simulation is about 80 years.

The initial and boundary conditions for *FEMFLOW3D* are

1. For initial conditions everywhere, the change in hydraulic head equals zero.

2. For the boundary condition at the ditch (x equals zero), the change in hydraulic head equals the change in water level in the ditch for times greater than zero.

3. For the boundary condition at a distance of 5,800 ft from the ditch, the change in hydraulic head is calculated using a variable-flux boundary condition. (See Section 3.7 for a discussion of variable-flux boundary conditions.) This boundary condition has the effect of extending the finite-element grid to infinity, where the boundary condition at an infinite distance from the ditch is such that the change in hydraulic head equals zero for all times.

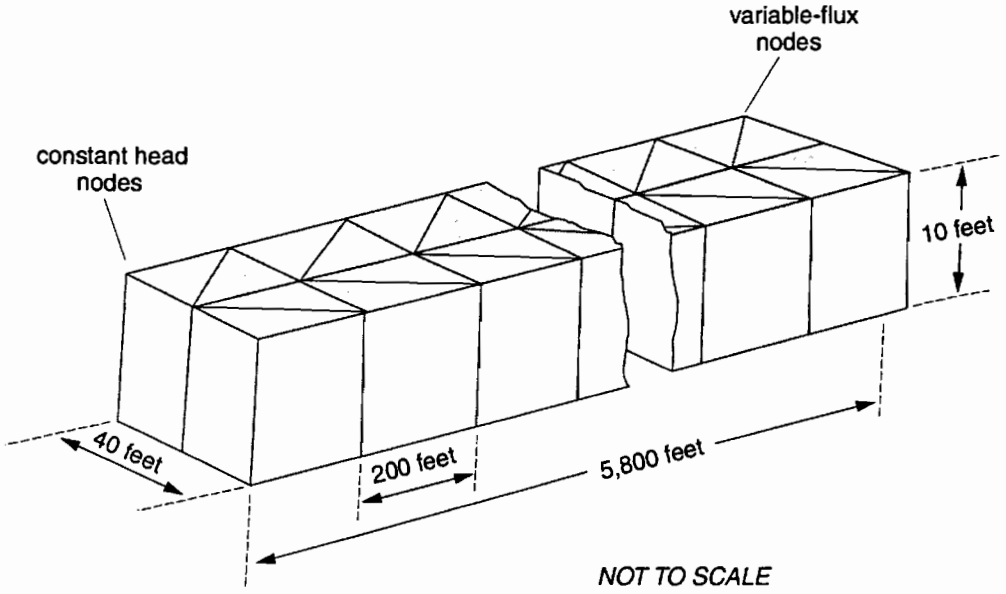


Figure 18. Finite-element grid for Carslaw and Jaeger problem.

The corresponding initial and boundary conditions for the Carslaw and Jaeger (1959) solution are

1. For initial conditions everywhere, the change in hydraulic head equals zero.

2. For the boundary condition at the ditch (x equals zero), the change in hydraulic head equals the change in water level in the ditch for times greater than zero.

3. For the boundary condition at an infinite distance from the ditch, the change in hydraulic head equals zero for all times.

The hydraulic parameters used in *FEMFLOW3D* are

Hydraulic conductivity *(K)*	100.0 ft/d
Specific storage *(S_s)*	1.0×10^{-3} 1/ft
Water-level step *(Δh_o)*	10.0 ft

These parameters were also used in the Carslaw and Jaeger (1959) solution.

The input and the output files for *FEMFLOW3D* are on the diskette in the pocket at the back of this report. The input files are CARSLAW.FLS and CARSLAW.IN. The output files are CARSLAW.OUT, CARSLAW.OUT, CARSLAW.PLT, and CARSLAW.BUD. The formats for the input files are described in Section 5.0.

4.3.3 Results

The results from the *FEMFLOW3D* simulation and the Carslaw and Jaeger (1959) solution are given in figure 19, which shows Δh against $log_{10}(t)$ for x equals 5,800 ft. These results indicate that the variable-flux boundary condition implemented in *FEMFLOW3D* replicates the effect of a semi-infinite aquifer. This boundary condition provides a practical alternative to extending the finite-element grid, where stresses reach the boundaries of the finite-element grid and the boundary condition cannot dependably be modeled as a specified-flux or specified-head boundary.

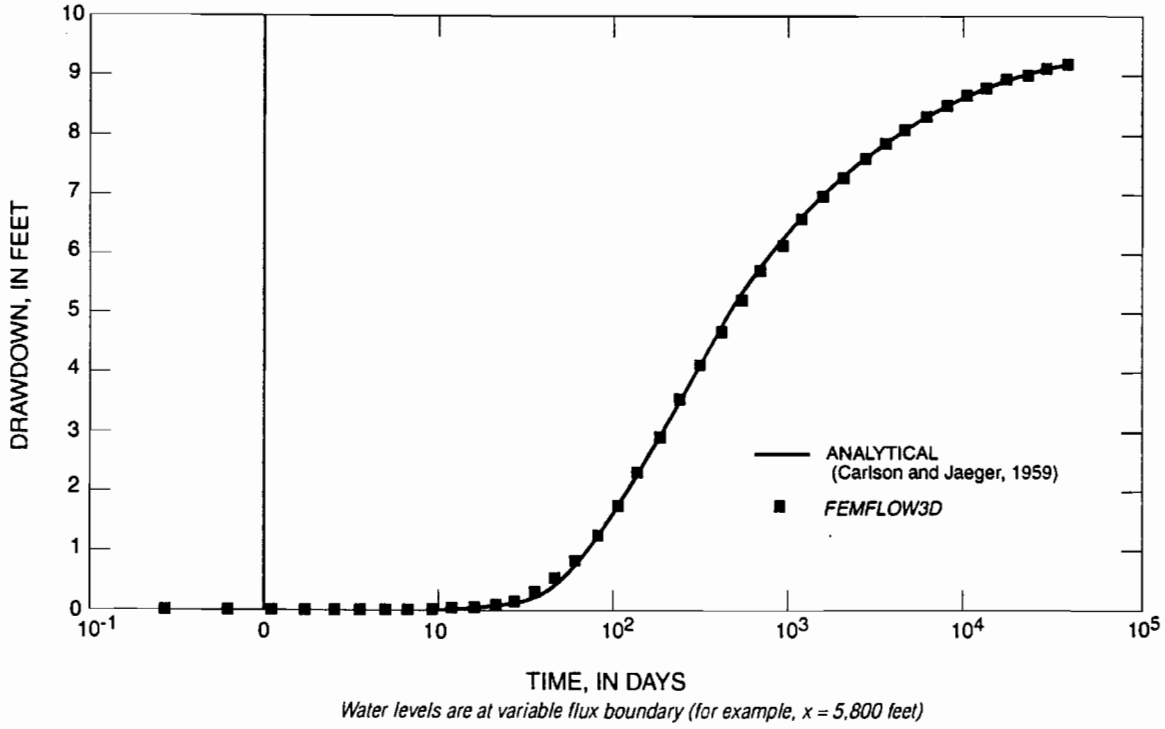


Figure 19. Comparison of *FEMFLOW3D* results with Carslaw and Jaeger solutions.

4.4 Transient Compaction Owing to Water-Level Changes

4.4.1 Problem Description

For the fourth test problem, *FEMFLOW3D* was used to simulate compaction of a compressible interbed owing to changes in the hydraulic head at the boundary of the interbed. This problem, which was taken from Leake and Prudic (1988), simulated the cumulative compaction of 100 identical interbeds. Hydraulic head at the boundaries of the interbeds was specified to decline linearly for 180 days to 10 ft below the starting value. Following the decline, the head recovered linearly for 180 days to the original value. Five successive cycles of declines and recoveries were simulated. The *FEMFLOW3D* simulation was then compared with the solution from the one-dimensional compaction model *COMPAC1* (Helm, 1975; 1984), which is described by Leake and Prudic (1988).

4.4.2 Model Simulation

The finite-element grid used for the fourth test problem (fig. 20) represents one-half of a single 10-foot thick interbed. The grid represents a column within the interbed with a thickness of 5 ft, a width of 10 ft, and a breadth of 10 ft. Each element in the grid has a thickness of 0.5 ft. It was assumed that the interbeds drain from above and below, because the test problem simulates drainage from the one-half interbed from above only. Therefore, the compaction of 100 identical interbeds was obtained by multiplying the compaction for one-half of an interbed by 200 (fig. 20).

The fourth test problem has one transient time-step period that is divided into 180 uniform time steps. Each time step is 10 days in duration. The total duration of the simulation is 1,800 days.

The initial and boundary conditions for *FEMFLOW3D* and *COMPAC1* are

1. For initial conditions everywhere, hydraulic heads and preconsolidation heads equal zero.

2. For the boundary condition at the top surface of the interbed, hydraulic heads are specified (fig. 21) for times greater than zero.

3. For the boundary condition at the center of the interbed, no-flow occurs for all times.

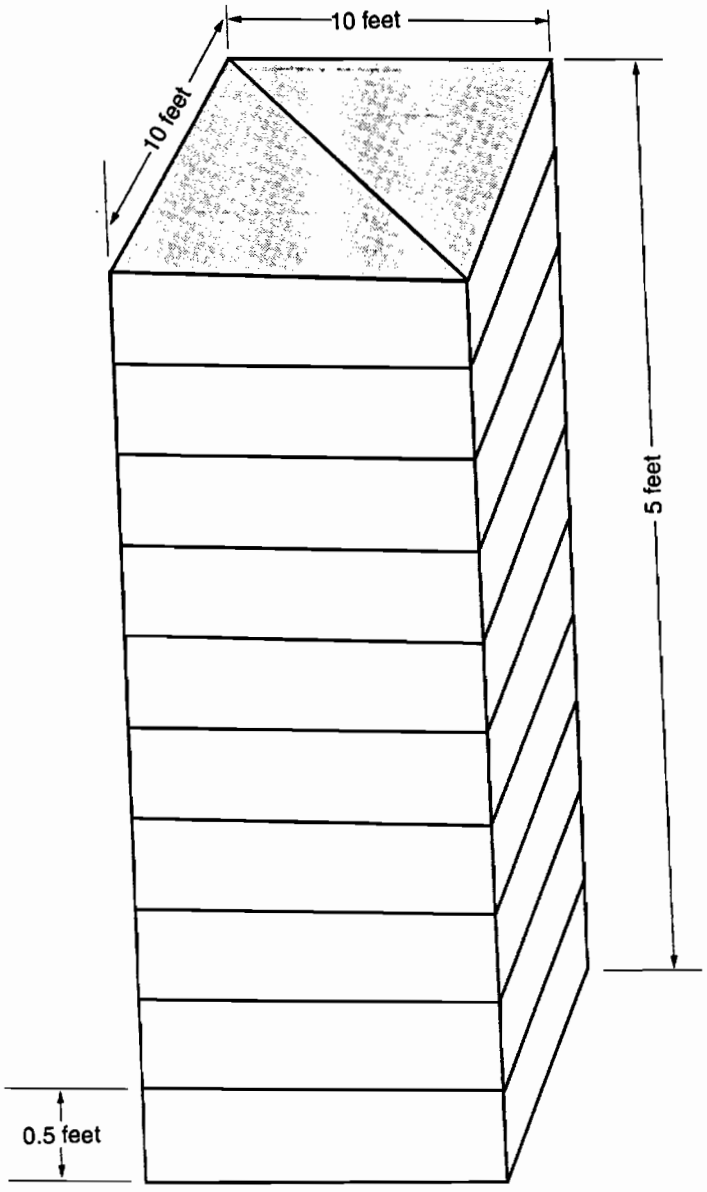


Figure 20. Finite-element grid for compaction problem.

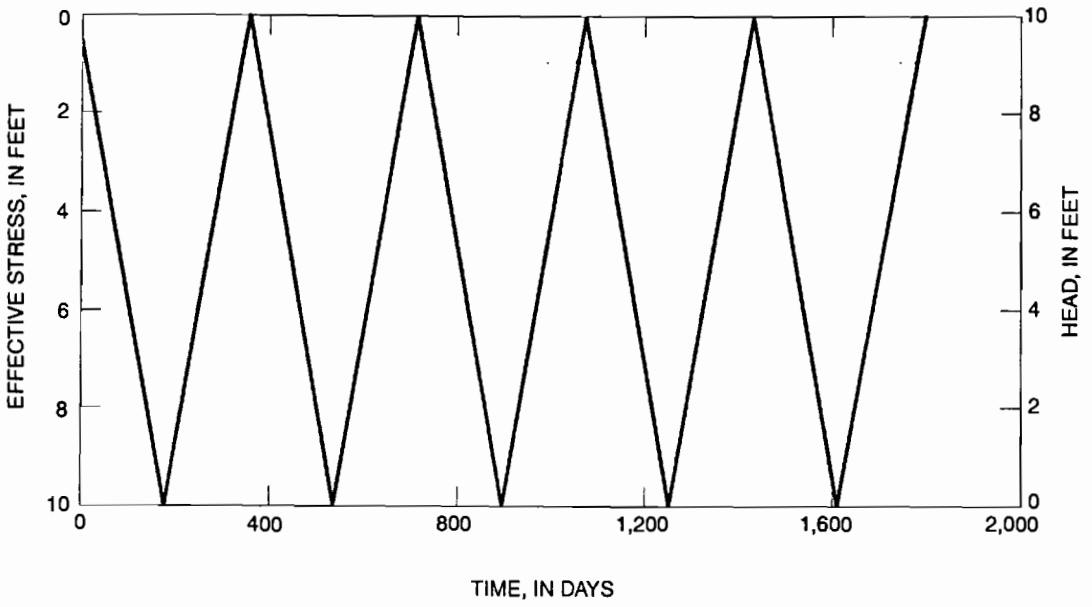


Figure 21. Boundary heads for compaction problem.

The hydraulic parameters for *FEMFLOW3D* and *COMPAC1* are

Vertical hydraulic conductivity (K_z)	2.7×10^{-6} ft/d
Elastic specific storage (S_{Ske})	1.0×10^{-6} ^{1}/ft
Inelastic specific storage (S_{Skv})	1.0×10^{-4} ^{1}/ft
Half-thickness of interbed ($B/2$)	5.0 ft

With these properties, the elastic and the inelastic time constraints (Equation 3.9-5) are 9 days and 900 days, respectively.

The input and the output files for *FEMFLOW3D* are on the diskette in the pocket at the back of the report. The input files are LEAKE.FLS and LEAKE.IN. The output files are LEAKE.OUT, LEAKE.PLT, and LEAKE.BUD. The formats for the input files are described in Section 5.0.

4.4.3 Results

The results from the *FEMFLOW3D* simulation and the results for *COMPAC1* (Leake and Prudic, 1988) are shown on a plot of cumulative compaction with time. *FEMFLOW3D* can very closely replicate the results of the one-dimensional compaction model *COMPAC1* (fig. 22).

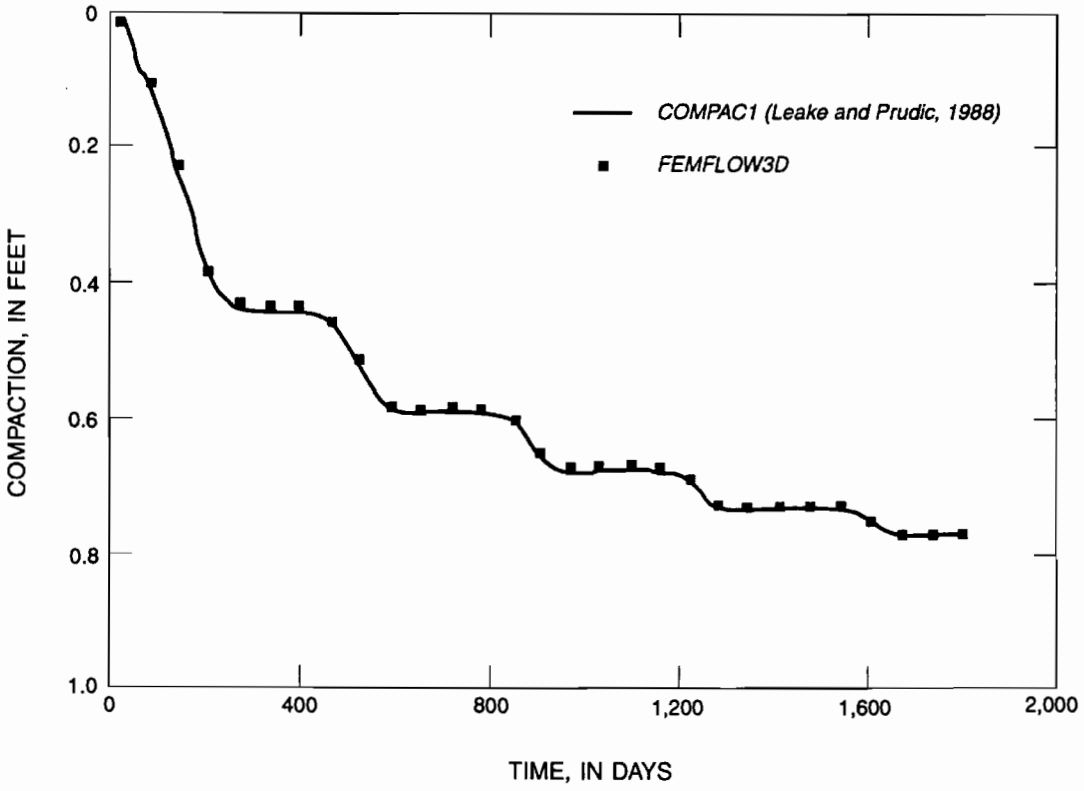


Figure 22. Comparison of *FEMFLOW3D* results with *COMPAC1* results.

5.0 INPUT FORMATS

The inputs to *FEMFLOW3D* are organized into four groups of files, with each group consisting of one or more files. These files are described in subsections 5.1 through 5.4. The first group is the file-specification file, which identifies the input and the output files for a simulation. The second group is the model-input file, which specifies the ground-water problem to be simulated, but excludes inputs relating to the simulation of an irrigated-agricultural system. The third group consists of the irrigated-agricultural system files, which describe the source and fate of irrigation water. The fourth group consists of the parameter-identification files, which specify the parameter identification problem to be solved.

Unless otherwise specified, all files and variables must be included in every simulation and must follow the order and the format specified in this section. Provisions for omitting unnecessary input for subroutines that are not used in any specific application are described in each of the subsections.

Section 5.0 concludes with a description of the procedure for specifying array dimensions (Section 5.5), which is a necessary step in using the program for any specific application.

5.1 File-Specification File

The file-specification file contains the names of input, output, and plot files for program *FEMFLOW3D*. For reference, each of these files has been assign a name, which is shown in parentheses in the text. Two input files are associated with subroutine *MODEL*; they specify the ground-water problem to be solved and the parameter indexes to be used in parameter identification. Five files provide output data for each simulation (MODEL.OUT, MODEL.PLT, MODEL.BUD, MODEL.FLX, AND MODEL.RIV). Fifteen input files are associated with subroutine *WATER*; they specify the source and use of irrigation water (WELL.DAT, WSTAT.DAT, PUMP.DAT, CPUMP.DAT, USER.DAT, DELIVER.DAT, CDELIVER.DAT, CROP.DAT, ROOT.DAT, PRECIP.DAT, PET.DAT, CCROP.DAT, HARDPAN.DAT, DESTIN.DAT, and EXCLUDE.DAT). Fifteen files provide output data related to subroutine *WATER* (WATER.OUT, WELL.OUT, PUMP.OUT, CPUMP.OUT, USER.OUT, DELIVER.OUT, CDELIVER.OUT, CROP.OUT, ROOT.OUT, PRECIP.OUT, PET.OUT, CCROP.OUT, HARDPAN.OUT, DESTIN.OUT, AND EXCLUDE.OUT). In addition to the parameter identification file (MODEL.IND), the file-specification file also contains the names of the other files needed for subroutine *SEARCH*, the input file SEARCH.DAT and the output file SEARCH.OUT.

FEMFLOW3D has a file-handing facility that allows each input file to be specified as a single file or as a series of file segments that are concatenated into a single input file. File names are specified for each input file and associated file segments. Subroutine *MERGE* performs the concatenation by copying the file segments into the input file.

The file names for a *FEMFLOW3D* simulation are listed sequentially in the file-specification file (FILES.DAT). *FEMFLOW3D* asks for the name of this file-specification file on the CRT screen prompt, and the file name is entered using the keyboard. *FEMFLOW3D* then reads the names for the input and the output files and opens those files. The format for the file-specification file are listed in the next section. (See table 2 for a formatted example of these inputs.)

Table 2. Example of inputs for file-specification file (Records 1 through 57 for FILES.DAT)

Record	Input records	Remarks
Input files for subroutine MODEL		
	FILE1	NFILE
	A60	I10
1	MODEL.DAT	12
	XFILE	If NFILE is greater than zero, the file segments that make up the input file are listed.
	A60	This example show 12 file segments for the MODEL input file.
2	STEP.DAT	
2	GRID.DAT	
2	AQUIFER.DAT	
2	HEAD.DAT	
2	CHEAD.DAT	
2	FLUX.DAT	
2	RIVER.DAT	
2	EVAP.DAT	
2	VFLUX.DAT	
2	FAULT.DAT	
2	SINK.DAT	
2	WATER.DAT	
Output files for subroutine MODEL		
	FILE20	
	A60	
3	RIVER.OUT	
	FILE2	
	A60	
4	MODEL.OUT	
	FILE3	
	A60	
5	MODEL.PLT	
	FILE4	
	A60	
6	MODEL.BUD	
	FILE6	
	A60	
7	MODEL.FLX	

Table 2. Example of inputs for file-specification file (Records 1 through 57 for FILES.DAT)--Continued

Record	Input records	Remarks
Input file for parameter-index file.		
	FILE5	NFILE
	A60	I10
8	MODEL.IND	0
		IF NFILE is zero, no file segments are listed and the record for XFILE is omitted.
Input files for subroutine WATER1		
	FILE2	NFILE
	A60	I10
10	WELL.DAT	0
	FILE29	NFILE
	A60	I10
12	WSTAT.DAT	0
	FILE3	NFILE
	A60	I10
14	PUMP.DAT	0
	FILE4	NFILE
	A60	I10
16	CPUMP.DAT	0
	FILE5	NFILE
	A60	I10
18	USER.DAT	0
	FILE6	NFILE
	A60	I10
20	DELIVER.DAT	0
	FILE7	NFILE
	A60	I10
22	CDELIVER.DAT	0
	FILE8	NFILE
	A60	I10
24	CROP.DAT	0

Table 2. Example of inputs for file-specification file (Records 1 through 57 for FILES.DAT)--Continued

Record	Input records	Remarks
Input files for subroutine WATER1--Continued		
	FILE9	NFILE
	A60	I10
26	ROOT.DAT	0
	FILE10	NFILE
	A60	I10
28	PRECIP.DAT	0
	FILE11	NFILE
	A60	I10
30	PET.DAT	0
	FILE12	NFILE
	A60	I10
32	CCROP.DAT	0
	FILE25	NFILE
	A60	I10
34	HARDPAN.DAT	0
	FILE27	NFILE
	A60	I10
36	DESTIN.DAT	0
	FILE30	NFILE
	A60	I10
38	EXCLUDE.DAT	0
Output files for subroutine WATER1		
	FILE13	
	A60	
40	WATER.OUT	
	FILE14	
	A60	
41	WELL.OUT	

Table 2. Example of inputs for file-specification file (Records 1 through 57 for FILES.DAT)--Continued

Record	Input records	Remarks
Output files for subroutine WATER1--Continued		
	FILE15	
	A60	
42	PUMP.OUT	
	FILE16	
	A60	
43	CPUMP.OUT	
	FILE17	
	A60	
44	USER.OUT	
	FILE18	
	A60	
45	DELIVER.OUT	
	FILE19	
	A60	
46	CDELIVER.OUT	
	FILE20	
	A60	
47	CROP.OUT	
	FILE21	
	A60	
48	ROOT.OUT	
	FILE22	
	A60	
49	PRECIP.OUT	
	FILE23	
	A60	
50	PET.OUT	
	FILE24	
	A60	
51	CCROP.OUT	

Table 2. Example of inputs for file-specification file (Records 1 through 57 for FILES.DAT)--Continued

Record	Input records	Remarks
Output files for subroutine WATER1--Continued		
	FILE26 A60	
52	HARDPAN.OUT	
	FILE28 A60	
53	DESTIN.OUT	
	FILE31 A60	
54	EXCLUDE.OUT	
Input file for parameter identification		
	FILE1 A60	NFILE I10
55	SEARCH.DAT	2 This example shows two file segments, SEARCH.PAR and LEVELS.DAT, which will be concatenated and copied into the file SEARCH.DAT.
	XFILE A60	
56	SEARCH.PAR	
56	LEVELS.DAT	
Output file for parameter identification		
	FILE2 A60	
57	SEARCH.OUT	

5.1.1 Files for Subroutine *MODEL*

Subroutine *MODEL* opens six files. These include two input files and four output files as follows:

Record	Columns	Format	Variable	Variable Description
1	1-60	A60	FILE1	Name of model-input file (MODEL.DAT).
	61-70	I10	NFILE	Number of file segments that make up the model-input file.
2	1-60	A60	XFILE(*i*)	Name of segment for model-input file.
3	1-60	A60	FILE20	Name of river-output file (MODEL.RIV).
4	1-60	A60	FILE2	Name of main output file (MODEL.OUT).
5	1-60	A60	FILE3	Name of model-plot output file (MODEL.PLT).
6	1-60	A60	FILE4	Name of water-budget output file (MODEL.BUD).
7	1-60	A60	FILE6	Name of flux-output file (MODEL.FLX).
8	1-60	A60	FILE5	Name of parameter-index input file (MODEL.IND).
	61-70	I10	NFILE	Number of file segments that make up the parameter-index file.
9	1-60	A60	XFILE(*i*)	Name of segment for parameter-index file.

Notes:

1. If NFILE is zero, file segments (XFILE) are omitted. If NFILE is greater than zero, the record for reading a file-segment name is repeated NFILE times. For example, for Records 1 and 2, Record 2 is repeated NFILE times as specified in Record 1. Accordingly, the NFILE files named in XFILE(*i*) are concatenated and copied into the file named in FILE1, and that file is opened.

2. If any of the model output files are not needed, it can be named "NUL" and no output file will be written.

3. The parameter index file (FILE5) can be specified as "NUL" if the *SEARCH* subroutine is not used and Record 9 is omitted.

4. The file names in parentheses in the "variable description" column indicate suggested file names only and may be named differently for each application.

5. Input files should be "write protected" because errors in constructing the file-specification file can result in writing to input files.

5.1.2 Files for Subroutine WATER

Subroutine *WATER* opens 30 files and their corresponding file segments. These files are listed below. The first 15 files are the input files, and the remaining 15 files are the output files. If subroutine *WATER* is not used, these files are omitted.

Record	Columns	Format	Variable	Variable Description
10	1-60	A60	FILE2	Name of well-site inventory file (WELL.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the well-site inventory file.
11	1-60	A60	XFILE(*i*)	Name of segment for well-site inventory file.
12	1-60	A60	FILE29	Name of well-status file (WSTAT.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the well-status file.
13	1-60	A60	XFILE(*i*)	Name of segment for well-status file.
14	1-60	A60	FILE3	Name of well-pumping file (PUMP.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the well-pumping file.
15	1-60	A60	XFILE(*i*)	Name of segment for well-pumping file.
16	1-60	A60	FILE4	Name of pumping-construction file (CPUMP.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the pumping-construction file.
17	1-60	A60	XFILE(*i*)	Name of segment for well-pumping file.
18	1-60	A60	FILE5	Name of water-user inventory file (USER.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the water-user inventory file.
19	1-60	A60	XFILE(*i*)	Name of segment for water-user inventory file.
20	1-60	A60	FILE6	Name of water-delivery file (DELIVER.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the water-delivery file.
21	1-60	A60	XFILE(*i*)	Name of segment for water-delivery file.
22	1-60	A60	FILE7	Name of delivery-construction file (CDELIVER.DAT).
	61-70	I10	NFILE	Number of segments that makes up the delivery-construction file.
23	1-60	A60	XFILE(*i*)	Name of segments for delivery-construction file.
24	1-60	A60	FILE8	Name of crop-inventory file (CROP.DAT).
	61-70	I10	NFILE	Number of segments that makes up the crop-inventory file.
25	1-60	A60	XFILE(*i*)	Name of segment for crop-inventory file.
26	1-60	A60	FILE9	Name of rooting-depth file (ROOT.DAT).
	61-70	I10	NFILE	Number of segments that makes up the rooting-depth file.
27	1-60	A60	XFILE(*i*)	Name of segment for rooting-depth file.
28	1-60	A60	FILE10	Name of precipitation file (PRECIP.DAT).
	61-70	I10	NFILE	Number of segments that makes up the precipitation file.
29	1-60	A60	XFILE(*i*)	Name of segment for precipitation file.

Record	Columns	Format	Variable	Variable Description
30	1-60	A60	FILE11	Name of potential evapotranspiration file (PET.DAT).
	61-70	I10	NFILE	Number of segments that makes up the potential evapotranspiration file.
31	1-60	A60	XFILE(*i*)	Name of segment for potential evapotranspiration file.
32	1-60	A60	FILE12	Name of crop-construction file (CCROP.DAT).
	61-70	I10	NFILE	Number of segments that makes up the crop-construction file.
33	1-60	A60	XFILE(*i*)	Name of segment for crop-construction file.
34	1-60	A60	FILE25	Name of recharge-fraction file (HARDPAN.DAT).
	61-70	I10	NFILE	Number of segments that makes up the recharge-fraction file.
35	1-60	A60	XFILE(*i*)	Name of segment for recharge-fraction file.
36	1-60	A60	FILE27	Name of pumping-destination file (DESTIN.DAT).
	61-70	I10	NFILE	Number of segments that makes up the pumping-destination file.
37	1-60	A60	XFILE(*i*)	Name of segment for the pumping-destination file.
38	1-60	A60	FILE30	Name of well-exclusion file (EXCLUDE.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the well-exclusion file.
39	1-60	A60	XFILE(*i*)	Name of segment for well-exclusion file.
40	1-60	A60	FILE13	Name of water-output file (WATER.OUT).
41	1-60	A60	FILE14	Name of well-site inventory output file (WELL.OUT).
42	1-60	A60	FILE15	Name of well-pumping output file (PUMP.OUT).
43	1-60	A60	FILE16	Name of pumping-construction output file (CPUMP.OUT).
44	1-60	A60	FILE17	Name of water-user inventory output file (USER.OUT).
45	1-60	A60	FILE18	Name of water-delivery output file (DELIVER.OUT).
46	1-60	A60	FILE19	Name of delivery-construction output file (CDELIVER.OUT).
47	1-60	A60	FILE20	Name of crop-inventory output file (CROP.OUT).
48	1-60	A60	FILE21	Name of rooting-depth output file (ROOT.OUT).
49	1-60	A60	FILE22	Name of precipitation output file (PRECIP.OUT).
50	1-60	A60	FILE23	Name of potential evapotranspiration output file (PET.OUT).
51	1-60	A60	FILE24	Name of crop-construction output file (CCROP.OUT).
52	1-60	A60	FILE26	Name of recharge-factor output file (HARDPAN.OUT).
53	1-60	A60	FILE28	Name of pumping-destination output file (DESTIN.OUT).
54	1-60	A60	FILE31	Name of well-exclusion output file (EXCLUDE.OUT)

Notes:

1. If NFILE is zero, file segments (XFILE) are omitted. IF NFILE is greater than zero, the record for reading a file-segment name is repeated NFILE times. For example, for Records 1 and 2, Record 2 is repeated NFILE times as specified in Record 1. Accordingly, the NFILE files named in XFILE(*i*) are concatenated and copied into the file named in FILE1, and that file is opened.

2. If subroutine *WATER* is not being used in the simulation, Records 10 through 54 can be omitted.

3. The file names in parentheses in the "variable description" column indicate suggested file names only and may be named differently for each application.

4. Input files should be "write protected" because errors in constructing the file-specification file can result in writing to input files.

5.1.3 Files for Subroutine *SEARCH*

Subroutine *SEARCH* opens two files, one input file and one output file. These files are listed below. If subroutine *SEARCH* is not used, these files can be omitted and not listed in the file-specification file.

Record	Columns	Format	Variable	Variable Description
55	1-60	A60	FILE1	Name of parameter-identification input file (SEARCH.DAT).
	61-70	I10	NFILE	Number of file segments that makes up the parameter-identification file.
56	1-60	A60	XFILE(*i*)	Name of segment for parameter-identification file.
57	1-60	A60	FILE2	Name of parameter-identification output file (SEARCH.OUT).

Notes:

1. If NFILE is zero, file segments (XFILE) are omitted. IF NFILE is greater than zero, the record for reading a file-segment name is repeated NFILE times. For example, for Records 1 and 2, Record 2 is repeated NFILE times as specified in Record 1. Accordingly, the NFILE files named in XFILE(*i*) are concatenated and copied into the file named in FILE1, and that file is opened.

2. If parameter identification is not done for a simulation, then FILE5 in Record 8 is named "NUL," NFILE equals zero, and Record 9 is omitted.

3. The file names in parentheses in the "variable description" column indicate suggested file names only and may be named differently for each application.

4. Input files should be "write protected" because errors in constructing the file-specification file can result in writing to input files.

The example of the files-specification file given in table 2 represents a model simulation that includes an irrigated agricultural system represented by the input files for subroutine *WATER*. Additionally, the example represents a model simulation in which model parameters are identified to fit calculated ground-water levels to measured water levels, as represented by the input files for subroutine *SEARCH*. In the example, only the input files for subroutine *MODEL* and subroutine *SEARCH* are represented by file segments that will be concatenated into the files MODEL.DAT and SEARCH.DAT. respectively. However, any of the other input files could be concatenated from model segments.

If a model simulation does not invoke the use of subroutine *WATER* or the use of subroutine *SEARCH* to perform parameter identification, some of the files in table 2 are not applicable, and the names of the inapplicable files can be deleted from the file-specification file. If subroutine *WATER* is not used, the input and the output files for subroutine *WATER* must be deleted. If parameter identification is not going to be done, the input and the output files for parameter identification must also be deleted. However, there must be a file name for the parameter-index file, with NUL used for the dummy-file name.

The input and the output files listed in the file-specification file may reside in any volume or directory of the computer. If a file is in a directory other than the directory from which *FEMFLOW3D* is executed, the path name for the file must be included.

5.2 Subroutine *MODEL* Input File

The model-input file (MODEL.DAT) contains specifications for the simulation parameters, time-step scheme, output frequency controls, matrix solution options, the finite-element grid, aquifer parameters, initial conditions, constant-head boundary conditions, internal sources and sinks, stream-aquifer parameters, groundwater evapotranspiration, variable-flux boundary conditions, fault conditions, subsidence parameters, and controls for the use of the subroutine *WATER*.

5.2.1 Simulation Parameters (*MODEL*)

The simulation parameters represent switches that select basic options in *FEMFLOW3D* for use in a simulation. These inputs are listed below. (See table 3 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1-78	A78	TITLE	Title of simulation.
2	1-10	I10	MAXKNS	Maximum number of time steps.
	11-20	I10	IDELT	Switch for type of time-step scheme.
	21-30	I10	NITER	Maximum number of iterations.
	31-40	F10.0	CLOSE	Closure criterion for iterations [ft].
	41-50	I10	ISKIP	Switch for skipping updates when a problem is linear.
	51-60	I10	IFIT	Switch for doing parameter identification.
	61-70	I10	ISS	Switch for calculating steady-state heads in the first time step.
	71-80	I10	ISOLVE	Switch for selecting solution method.

Table 3. Example of inputs for simulation parameters (Records 1 and 2 for MODEL.DAT)

Record **Input records**

```
         TITLE
         A78

1        FEMFLOW3D - Western Basin - Run 1

             MAXKNS     IDELT     NITER     CLOSE     ISKIP     IFIT      ISS     ISOLVE
               I10       I10       I10      F10.0      I10       I10       I10       I10

2                9         2        10      0.01          0         1         1         1
```

Notes:

1. One of two time-step schemes can be selected by setting the switch IDELT. If IDELT equals 1, a scheme with geometrically expanding time steps is selected. If IDELT equals 2, a scheme with integer-multiple time steps is selected. If subroutine *WATER* is used in the simulation, IDELT must equal 2.

2. The maximum number of iterations NITER should equal 1 if (1) the finite-element grid is fixed over time, (2) the "drainage-node" form of the specified-head boundary condition is not used, (3) stream-aquifer interactions are not simulated, (4) evapotranspiration is not simulated, and (5) land subsidence is not simulated. Otherwise, NITER should equal about 10.

3. The closure criterion CLOSE is the maximum absolute difference in calculated hydraulic heads between two iterations (see discussion in Section 3.2.2.5). CLOSE should equal about 0.05 to 0.005 ft.

4. The switch ISKIP must equal zero (no skipping) if the simulation is nonlinear or has unequal time steps. ISKIP can equal one (skipping) if the simulation is linear and has equal time steps, as discussed in Section 3.2.3.3

5. The switch IFIT is for selecting parameter identification. If IFIT equals 1, parameter identification is performed; if IFIT equals zero, it is not performed.

6. The switch ISS is for selecting a steady state for the first time step. If ISS equals 1, then the calculated heads for the first time step are the steady-state heads, and the transient-state simulation starts with the second time step. In this case, the specified initial conditions are not used. If ISS equals zero, then the transient-state simulation starts with the first time step. In this case, the specified initial conditions are used.

7. If ISOLVE equals 1, the direct solution method is used and no other input is needed. If ISOLVE equals 2, the iterative solution method is used and Record 8 (Section 5.2.4) must be included.

5.2.2 Time-Step Scheme (*MODEL*)

The inputs for the time-step scheme describe the discretization of time within the simulation. One of two types of time-step schemes can be selected. These inputs are listed below. (See table 4 for formatted examples of these inputs.)

Record	Columns	Format	Variable	Variable Description
3	1-10	I10	NSTART	Number of time-step periods.
4	1-10	I10	KNS1	First time step of period.
	11-20	I10	KNS2	Last time step of period.
	21-30	F10.0	DELT0	Initial time step for period [days].
	31-40	F10.0	FDELT	Factor for expansion of time steps during period [dimensionless].
5	1-10	F10.0	DELT0	Basic time step [days].
6	1-10	I10		Time step (for reference only).
	11-20	I10	ICMO1(i)	Start of time step in integer multiples of DELT0.
	21-30	I10	ICMO2(i)	End of time step in integer multiples of DELT0.

Table 4. Examples of inputs for alternative time-step schemes (Records 3 through 6 for MODEL.DAT)

Record	Input records				Remarks
Example for IDELT = 1 and MAXKNS = 50:					
	NSTART				
	I10				
3	9				
	KNS1	KNS2	DELT0	FDELT	
	I10	I10	F10.0	F10.0	
4	1	10	0.05	1.2	Expanding time steps.
4	11	50	0.31	1.0	Constant time steps.
Example for IDELT = 2, ISS= 0, and MAXKNS = 8:					Steady-state conditions are not calculated.
	DELT0				
	F10.0				
5	30.4				
	time step	ICMO1	ICMO2		
	I10	I10	I10		
6	1	1	3		Start transient time steps.
6	2	4	6		
6	3	7	9		
6	4	10	12		
6	5	13	15		
6	6	15	18		
6	7	19	21		
6	8	22	24		
Example for IDELT = 2 ISS = 1, and MAXKNS = 9:					Steady-state initial condition.
	DELT0				
	F10.0				
5	30.4				
	time step	ICMO1	ICMO2		
	I10	I10	I10		
6	1	1	12		Start steady-state time step.
6	2	1	3		Proceed to transient time steps.
6	3	4	6		
6	4	7	9		
6	5	10	12		
6	6	13	15		
6	7	16	18		
6	8	19	21		
6	9	22	24		

Notes:

1. If IDELT in Record 2 equals 1, omit Records 5 and 6. If IDELT equals 2, omit Records 3 and 4.

2. If IDELT equals 1, repeat Record 4 NSTART times.

3. If IDELT equals 2 and subroutine *WATER* is used in the simulation, DELT0 must equal 1/12 year in days (30.42 days).

4. If IDELT equals 2, repeat Record 6 MAXKNS times, where MAXKNS appears in Record 2. Time steps are integer multiples of DELT0 and are based on the specifications of ICMO1(*i*) and ICMO2(*i*).

Examples of three alternative time-step schemes are given in table 4. If subroutine *WATER* is not used, either the geometrically expanding time-step scheme, where IDELT = 1, or the integer-multiple time-step scheme, where IDELT = 3, may be used. If subroutine *WATER* is used, the integer-multiple time-step scheme, where IDELT = 2, must be used.

The first example is for IDELT = 1 and MAXKNS = 50. For this example, two time-step periods were used (NSTART = 2). For the first period, there were 10 time steps (KNS1 = 1 and KNS2 = 10), where the initial time step was 5 days (DELT0 = 0.05), and the time-step length was increased by a factor of 1.2 for each following step (FDELT = 1.2). For the second period, there were 40 time steps (KNS1 = 11 and KNS2 = 50), where the initial time step for the period was 31 days (DELT0 = 0.31), and the time-step length was constant for each following time step (FDELT = 1.0).

The second example is for IDELT = 2, ISS = 0, and MAXKNS = 8. The basic time step for this example was 30.4 days, (DELT0 = 30.4, which is the standard time step used in subroutine *WATER* for the input of water-use and other data. However, the time steps used in the ground-water model are integer multiples of the basic time step. For the second example, each of the eight time steps were three basic time steps in length. The first time step included basic time steps 1 through 3 (ICMO1 = 4 and ICMO2 = 6). In the second example, each time step was equal in length; however, by selecting different values of ICMO1 and ICMO2, each step can vary in length, as needed.

The third example is for IDELT = 2, ISS = 1, and MAXKNS = 9. For this example, the time-step schemes for steps 2 through 9 were the same time-step schemes used for steps 1 through 8 for the second example. For the third example, however, time step 1 represented the steady-state condition, and the initial steady-state conditions were calculated using pumpage and ground-water recharge for basic steps 1 through 12 (ICMO1 = 1 and ICMO2 = 12).

The interactions between subroutines *WATER* and *MODEL* are controlled by the time-step schemes. Subroutine *WATER* assumes that the basic time-step is 1 month (DELT0 = 30.4 days), and all data inputs are specified for particular years and months. Within the time-step loop of subroutine *MODEL*, subroutine *WATER* is called for each time step, which is an integer multiple of the basic time step of 1 month. Subroutine *WATER* calculates average pumpage and ground-water recharge for the time step on the basis of a 1-month time step within subroutine *WATER*. Consequently, when subroutine *WATER* is used, *FEMFLOW3D* operates on two time-step schemes: the 1-month time step in subroutine *WATER* and the integer-multiple time step in subroutine *MODEL*.

Subroutine *WATER* operates on an 1-month time step. The other subroutines operate on the time step specified in the time-step scheme input, whether IDELT = 1 or IDELT = 2, and include subroutines for specified-head boundaries, stream-aquifer interactions, ground-water evapotranspiration, variable-flux boundaries, fault effects, and land subsidence. All data inputs for these subroutines must correspond to the time steps in subroutine *MODEL*.

5.2.3 Output Controls (*MODEL*)

The inputs for output controls determine the frequency of time-step outputs. These inputs are listed below. (See table 5 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
7	1-10	I10	NPRINT	Frequency of output to the river model output file, the model output file, and the water-budget file.
	11-20	I10	NPLOT	Frequency of output to model plot file.
	21-30	I10	NFLUX	Frequency of output to model flux file.

Table 5. Example of inputs for output frequency controls (Record 7 for MODEL.DAT)

Record	Input records		
	NPRINT	NPLOT	NFLUX
	I10	I10	I10
7	10	1	5

Notes:

1. NPRINT specifies the time-step frequency that the calculated heads and other information are written to the model output file.
2. NPLOT specifies the time-step frequency that the calculated heads are written to the model plot file.
3. NFLUX specifies the time-step frequency that the inflow to and outflow from each node are written to the model flux file.

5.2.4 Matrix Solution Parameters *(SOLVE)*

The matrix solution parameters define the maximum number of iterations, the relaxation factor, and the closure criterion for the iterative solution method. These inputs are listed below. (See table 6 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
8	1-10	I10	NITER	Maximum number of iterations.
	11-20	F10.0	OMEGA	Relaxation factor.
	21-30	F10.0	CLOSE	Closure criterion [ft].

Notes:

1. If the switch ISOLVE in Record 2 equals 1, Record 8 is omitted and the direct solution method is used.
2. The run time for *FEMFLOW3D* is minimized when OMEGA, the relaxation factor, is assigned a value between 1.2 and 1.7.

Table 6. Example of inputs for the matrix solution parameters (Record 8 for MODEL.DAT)

Record	Input records			Remarks
	NITER	OMEGA	CLOSE	
	I10	F10.0	F10.0	
8	500	1.7	0.001	If the switch ISOLVE in Record 2 equals 1, Record 8 is omitted and the direct solution method is used.

5.2.5 Finite-Element Grid Coordinates (*MODEL*)

The inputs of the finite-element coordinate define the three-dimensional position of the nodes within the grid. These inputs are listed below. (See table 7 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
9	1-10	I10	NN	Number of nodes.
	11-20	I10	NE	Number of prismatic elements.
10	1-10	F10.0	FACX	Multiplication factor for x coordinates [dimensionless]
	11-20	F10.0	FACY	Multiplication factor for y coordinates [dimensionless].
	21-30	F10.0	FACZ	Multiplication factor for z coordinates [dimensionless].
	31-40	I10	IECHO1	Switch for echo of node coordinates.
11	1-10	I10		Node number (for reference only).
	11-20	F10.0	X(i)	X coordinate of node [ft].
	21-30	F10.0	Y(i)	Y coordinate of node [ft].
	31-40	F10.0	Z(i)	Z coordinate of node [ft].

Table 7. Example of inputs for finite-element grid coordinates (Records 9 through 11 for MODEL.DAT)

Record	Input records			
	NN	NE		
	I10	I10		
9	698	946		
	FACX	FACY	FACZ	IECHO1
	F10.0	F10.0	F10.0	I10
10	1.0	1.0	1.0	0
	node number	X	Y	Z
		F10.0	F10.0	F10.0
11	1	1212153.	427015.	0
11	2	1212153.	427015.	-45
11	3	1212718.	428532.	0
11	4	1212718.	428532.	-50
11	5	1213313.	430068.	0
11	6	1213313.	430068.	-50
11	7	1213843.	431569.	0
11	8	1213843.	431569.	-50
11	9	1214298.	432775.	0
11	10	1214298.	432775.	-45
11	11	1217064.	441786.	0
11	12	1217064.	441786.	-60
11	13	1217064.	441786.	-104
11	14	1217064.	441786.	-180
11	15	1217551.	443443.	0
11	16	1217551.	443443.	-60
11	17	1217551.	443443.	-104
11	18	1217551.	443443.	-180
11	19	1217732.	444098.	0
11	20	1217732.	444098.	-60
11	21	1217732.	444098.	-104
11	22	1217732.	444098.	-125
11	23	1217886.	444598.	0
11	24	1217886.	444598.	-60
11	25	1217886.	444598.	-104
11	26	1217886.	444598.	-125

Notes:

1. If the switch IECHO1 equals 1, displays occur. If the switch equals zero, no display occurs.
2. Record 11 is repeated for NN nodes.

5.2.6 Finite-Element Grid Incidences (*MODEL*)

The inputs of the finite-element grid incidences describe the definition of elements with regard to nodes. These inputs are listed below. (See table 8 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
12	1-10	I10	IECHO2	Switch for display of incidences for prismatic elements.
	11-20	I10	IECHO3	Switch for display of incidences for tetrahedral elements.
13	1-10	I10		Element number (for reference only).
	11-70	6I10	IPRISM(*i*)	Node incidences for a prismatic element.

Table 8. Example of inputs for the finite-element grid incidences (Records 12 and 13 for MODEL.DAT)

Record Input records

```
            IECHO2     IECHO3
              I10        I10

12              1          1

Regular prismatic elements have six node incidences:

    element number     IPRISM     IPRISM     IPRISM     IPRISM     IPRISM     IPRISM
                         I10        I10        I10        I10        I10        I10

13              1         11         45         15         12         46         16
13              2         15         45         49         16         46         50
13              3         49         19         15         50         20         16
13              4         49         53         19         50         54         20
13              5         19         53         23         20         54         24
13              6         53         57         23         54         58         24
13              7         23         57         27         24         58         28
13              8         27         57         61         28         58         62
13              9         41         75         45         42         76         46
13             10         75         49         45         76         50         46
13             11         75         77         49         76         78         50

Elements can also be irregular to represent geologic features that pinch out.
For example, elements with one zero-height side have five node incidences:

    element number     IPRISM     IPRISM     IPRISM     IPRISM     IPRISM     IPRISM
                         I10        I10        I10        I10        I10        I10

15            203        645        641        667        646        642          0

Element with two zero-height sides have four node incidences:

    element number     IPRISM     IPRISM     IPRISM     IPRISM     IPRISM     IPRISM
                         I10        I10        I10        I10        I10        I10

13            204        641        638        667        642          0          0
```

Notes:

1. Record 13 identifies the six nodes that define a prismatic element. The nodes are numbered counterclockwise around the top and then counterclockwise around the bottom.

2. Zero-height edges are identified by a node number of zero. For one zero-height edge, the zero-node number must be listed as the sixth node incidence in Record 13. For two zero-height edges, the zero-node number must be listed as the fifth and sixth node incidences in Record 13.

3. Record 13 is repeated for each element specified by NE.

5.2.7 Aquifer Parameters (*MODEL*)

The inputs for aquifer parameters describe the hydraulic properties of the ground-water system. These inputs are listed below. (See table 9 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
14	1-10	F10.0	FACKXX	Multiplication factor for hydraulic conductivity in the *x* direction [dimensionless].
	11-20	F10.0	FACKYY	Multiplication factor for hydraulic conductivity in the *y* direction [dimensionless].
	21-30	F10.0	FACKZZ	Multiplication factor for hydraulic conductivity in the *z* direction [dimensionless].
	31-40	F10.0	FACSS	Multiplication factor for specific storage [dimensionless].
	41-50	F10.0	FACSY	Multiplication factor for specific yield [dimensionless].
	51-60	I10	IECHO4	Switch for display of aquifer parameters.
	61-70	I10	IECHO5	Switch for display of parameter indexes.
15	1-10	I10		Element number (for reference only).
	11-20	F10.0	KXX0	Initial value of hydraulic conductivity in *x* direction [ft/d].
	21-30	F10.0	KYY0(*i*)	Initial value of hydraulic conductivity in *y* direction [ft/d].
	31-40	F10.0	KZZ0(*i*)	Initial value of hydraulic conductivity in *z* direction [ft/d].
	41-50	F10.0	SS0(*i*)	Initial specific storage [1/ft].
	51-60	F10.0	SY0(*i*)	Initial specific yield [dimensionless].
	61-70	I10	ITOP	Flag to identify prismatic elements that make up the top of grid.

Table 9. Example of inputs for aquifer parameters (Records 14 and 15 for MODEL.DAT)

Record	Input records						
	FACKXX	FACKYY	FACKZZ	FACSS	FACSY	IECHO4	IECHO5
	F10.0	F10.0	F10.0	F10.0	F10.0	I10	I10
14	1.0	1.0	1.0	1.0	1.0	1	1
	element number	KXX0	KYY0	KZZ0	SS0	SY0	ITOP
		F10.0	F10.0	F10.0	F10.0	F10.0	I10
15	1	4.35E+01	4.35E+01	1.20E-02	4.11E-04	7.14E-02	1
15	2	2.86E+01	2.86E+01	2.10E-01	4.34E-05	0.00E+00	0
15	3	6.19E+01	6.19E+01	3.19E-01	4.34E-05	0.00E+00	0
15	4	4.29E+01	4.29E+01	1.19E-02	4.11E-04	7.08E-02	1
15	5	2.84E+01	2.84E+01	2.10E-01	4.34E-05	0.00E+00	0
15	6	6.18E+01	6.18E+01	3.19E-01	4.34E-05	0.00E+00	0
15	7	4.38E+01	4.38E+01	1.20E-02	4.11E-04	7.18E-02	1
15	8	2.80E+01	2.80E+01	2.09E-01	4.34E-05	0.00E+00	0
15	9	6.18E+01	6.18E+01	3.19E-01	4.34E-05	0.00E+00	0
15	10	4.15E+01	4.15E+01	1.18E-02	4.11E-04	6.94E-02	1
15	11	2.71E+01	2.71E+01	2.08E-01	4.34E-05	0.00E+00	0
15	12	6.13E+01	6.13E+01	3.18E-01	4.34E-05	0.00E+00	0
15	13	4.48E+01	4.48E+01	1.21E-02	4.11E-04	7.29E-02	1
15	14	2.73E+01	2.73E+01	2.08E-01	4.34E-05	0.00E+00	0
15	15	6.13E+01	6.13E+01	3.18E-01	4.34E-05	0.00E+00	0
15	16	4.38E+01	4.38E+01	1.20E-02	4.11E-04	7.18E-02	1
15	17	2.73E+01	2.73E+01	2.08E-01	4.34E-05	0.00E+00	0
15	18	6.12E+01	6.12E+01	3.18E-01	4.34E-05	0.00E+00	0

Notes:

1. Record 15 is repeated for each element specified by NE in Record 9.
2. If the switches IECHO4 or IECHO5 equal 1, then displays occur. If the switches equal zero, no displays occur.
3. The flag ITOP equals 1 for elements that form the water table; otherwise, ITOP equals zero. If a water-table condition is not being simulated, ITOP equals zero everywhere.
4. Values for initial specific yield SY0(i) are needed only for elements with ITOP equals 1.
5. Initial aquifer-parameter values are modified during the calibration process, if parameter identification is going to be done. Otherwise, the initial values are maintained throughout the simulation.

5.2.8 Initial Hydraulic Heads (*MODEL*)

The inputs for initial hydraulic head describe initial conditions for the simulation. These inputs are listed below. (See table 10 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
16	1-10	I10	IECHO6	Switch for display of initial hydraulic heads.
17	1-50	5F10.0	H0(*i*)	Initial hydraulic heads [ft].

Notes:

1. Record 17 is repeated for each node, specified by NN in Record 9, until NN values of H0(*i*) are input.
2. If the switch IECHO6 equals 1, a display occurs. If IECHO6 equals zero, no displays occur.

Table 10. Example of inputs for initial hydraulic heads (Records 16 and 17 for MODEL.DAT)

Record	Input records					Remarks
	IECHO6					
	I10					
16	1					
	H0	H0	H0	H0	H0	
	F10.0	F10.0	F10.0	F10.0	F10.0	(5F10.0)
						The file lists an initial head for each node in the model. If a calculation for steady-state heads is included in the simulation, initial heads may be set to zero or any arbitrary value.
17	5.0	5.0	5.0	5.0	5.0	
17	5.0	5.0	5.0	5.0	5.0	
17	5.0	5.0	5.0	5.0	5.0	
17	5.0	5.0	5.0	5.0	5.0	
17	5.0	5.0	5.0	5.0	5.0	
17	5.0	5.0	5.0	5.0	5.0	
17	32.4	32.2	31.1	31.0	29.9	
17	30.1	29.9	30.1	30.8	30.8	
17	13.7	13.7	13.6	13.6	12.4	
17	12.4	11.8	11.8	12.7	12.7	
17	12.0	12.0	13.2	13.1	12.0	
17	12.0	12.4	12.4	12.0	12.0	
17	12.1	12.1	11.9	11.9	39.0	
17	38.8	38.3	37.9	37.2	36.7	
17	36.6	36.2	36.6	36.7	15.4	
17	15.4	14.6	14.6	15.2	15.2	
17	14.6	14.6	15.2	15.2	14.3	
17	14.3	15.1	15.1	14.9	14.9	
17	15.0	15.0	43.4	41.8	42.4	
17	40.2	40.3	37.9	38.2	36.7	
17	36.1	34.4	34.0	25.1	22.7	
17	22.2	22.7	21.3	21.3	20.9	
17	20.9	21.5	21.5	20.8	20.8	
17	20.8	20.8	20.5	20.5	20.0	
17	20.0	19.8	19.8	36.3	35.2	
17	35.2	34.2	33.8	33.1	32.1	
17	32.0	32.3	28.1	24.6	24.3	
17	25.5	31.1	24.1	23.5	23.5	
17	23.6	26.2	26.2	24.1	24.1	
17	27.2	27.2	24.5	24.5	26.6	
17	26.6	24.6	24.6	32.5	31.7	
17	31.3	31.2	30.0	30.0	31.2	
17	29.8	29.7	29.6	31.1	36.1	

5.2.9 Specified-Head Boundary Condition (*CHEAD*)

The inputs for specified-head boundary conditions describe, in part, how the simulation relates to conditions outside the modeled volume. These inputs are listed below. (See table 11 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
18	1-10	I10	NCHN	Number of specified-head nodes.
	11-20	I10	IECHO1	Switch for display of inputs.
	21-30	I10	IECHO2	Switch for display of fluxes through specified-head nodes.
19	1-10	I10	CHNODE(i)	Identity of specified-head node.
	11-20	F10.0	CHEAD0(*i*)	Specified head [ft].
	21-30	F10.0	K(*i*)	Hydraulic conductivity of membrane [ft/d].
	31-40	F10.0	B(*i*)	Thickness of membrane [ft].
	41-50	F10.0	AREA(*i*)	Area of membrane that is associated with node [ft^2].
	51-60	I10	TYPE(i)	Switch for type of specified-head node.
	61-70	I10	TABLE(*i*)	Identity of table of specified heads.
20	1-10	I10	NTABLE	Number of tables of specified heads.
21	1-10	I10	NPT(*i*)	Number of entries in a table.
22	1-10	F10.0	TTAB(*i,j*)	Time for entry in table [days].
	11-20	F10.0	CHTAB(*i,j*)	Specified head for entry in table [ft].

Table 11. Example of inputs for specified-head boundary conditions (Records 18 through 22 for MODEL.DAT)

Record	Input records							Remarks
	NCHN	IECHO1	IECHO2					
	I10	I10	I10					
18	15	1	1					
	CHNODE	CHEAD0	K	B	AREA	TYPE	TABLE	
	I10	F10.0	F10.0	F10.0	F10.0	I10	I10	
19	321	130.	0.001	100.	3.0E+07	0		Lake
19	325	130.	0.001	100.	3.0E+07	0		Lake
19	393	130.	0.001	100.	3.0E+07	0		Lake
19	397	130.	0.001	100.	3.0E+07	0		Lake
19	65	154.	40.	20.	1.5E+06	1	1	River
19	93	152.	40.	20.	1.5E+06	1	1	River
19	125	149.	40.	20.	1.5E+06	1	1	River
19	161	145.	40.	20.	1.5E+06	1	1	River
19	193	136.	40.	20.	1.5E+06	1	1	River
19	229	129.	40.	20.	1.5E+06	1	1	River
19	261	125.	40.	20.	1.5E+06	1	1	River
19	237	130.	10.	2640.	1.0E+05	2	2	Subsurface drain
19	241	131.	10.	2640.	1.0E+05	2	2	Subsurface drain
19	269	126.	10.	2640.	1.0E+05	2	2	Subsurface drain
19	273	127.	10.	2640.	1.0E+05	2	2	Subsurface drain
	NTABLE							
	I10							
20	2							
	NPT							
	I10							
21	9							
	TTAB	CHTAB						
	F10.0	F10.0						
22	0.00	3.03						Changes in river
22	365.25	3.15						stage
22	730.50	0.55						
22	1095.75	1.59						
22	1461.00	3.68						
22	1826.25	1.65						
22	2191.50	0.12						
22	2556.75	-0.90						
22	2922.00	2.19						
	NPT							
	I10							
21	9							
	TTAB	CHTAB						
	F10.0	F10.0						
22	0.00	-5.00						Depth of drain
22	365.25	-5.00						below land
22	730.50	-5.00						surface
22	1095.75	-5.00						
22	1461.00	-5.00						
22	1826.25	-5.00						
22	2191.50	-5.00						
22	2556.75	-5.00						
22	2922.00	-5.00						

Notes:

1. If NCHN equals zero, then Records 19 through 22 are omitted.

2. If the switches IECH01 and IECH02 equal 1, displays occur. If the switches equal zero, then no displays occur.

3. If the switch TYPE(i) equals zero, unlimited discharge can occur in either direction through the specified-head nodes. This boundary condition represents constantly flowing rivers with a hydraulic connection to the water table. If the switch equals 1, unlimited discharge can occur from the model domain through the specified-head nodes, and only limited discharge can occur into the model domain, where the maximum inward discharge is discharge that occurs with a unit hydraulic gradient through the membrane. This second boundary condition represents rivers or lakes with a limited capacity for recharging the ground-water system. If the switch equals 2, unlimited discharge can occur from the model domain through the specified-head nodes, but no discharge can occur into the model domain. This third boundary condition is used to represent drainage systems.

4. Record 19 is repeated for each specified-head node (NCHN times).

5. If NTABLE equals zero, Records 21 and 22 are omitted.

6. Record 22 is repeated for NPT(i) table entries. Records 21 and 22 are repeated for NTABLE tables as a group.

5.2.10 Internal and Boundary Fluxes (*FLUX*)

The inputs for internal and boundary fluxes describe the flux sources and sinks within and on the boundaries of the modeled volume. These inputs are listed below. (See table 12 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
23	1-10	I10	NQSET	Number of data sets of node fluxes.
	11-20	I10	MAXKNS	Number of time steps.
	21-30	F10.0	FACQ	Multiplication factor for node fluxes [dimensionless].
	31-40	I10	IECHO1	Switch for display of input fluxes.
	41-50	I10	IECHO2	Switch for display of time-step fluxes.
24	1-10	I10	NQ	Number of node-flux values in data set.
25	1-10	I10	QNODE(i)	Identity of node in data set.
	11-20	F10.0	QSET(i,j)	Flux through node [ft^3/s].
26	1-10	I10		Time step (for reference only).
	11-60	5F10.0	FACSET(i,j)	Multiplication factor for data set and time step.

Table 12. Example of inputs for internal and boundary fluxes (Records 23 through 26 for MODEL.DAT)

Record	Input records						Remarks
	NQSET	MAXKNS	FACQ	IECHO1	IECHO2		
	I10	I10	F10.0	I10	I10		
23	2	9	1.0	1	1		
	NQ						
	I10						
24	2						
	QNODE	QSET					
	I10	F10.0					
25	483	1.32E+00					
25	565	1.32E+00					
	NQ						
	I10						
24	3						
	QNODE	QSET					
	I10	F10.0					
25	483	1.32E+00					
25	565	1.32E+00					
25	587	1.32E+00					
	time step	FACSET	FACSET	FACSET	FACSET	FACSET	
		F10.0	F10.0	F10.0	F10.0	F10.0	
							The format of 5F10.0 allows as many as five multiplication factors (FACSET) for the data sets (NQSET) to be listed per line.
							In this example, only two data sets are specified, and only two corresponding FACSETs are shown.
26	1	1.00	1.00				
26	2	1.00	1.00				
26	3	1.00	1.10				
26	4	1.00	1.20				
26	5	1.00	1.30				
26	6	1.00	1.40				
26	7	1.00	1.50				
26	8	1.00	1.60				
26	9	1.00	1.70				

Notes:

1. If NQSET equals zero, Records 24 through 26 are omitted.

2. If the switches IECHO1 and IECHO2 equal 1, displays occur. If the switches equal zero, no displays occur.

3. The value of MAXKNS in Record 23 must be greater than or equal to the value of MAXKNS in Record 2.

4. Record 25 is repeated for each node-flux value in the data set (NQ times). Records 24 and 25 are repeated for each data set (NQSET times) as a group.

5. Record 26 is repeated until NQSET values of FACSET(i,j) have been entered, and Record 26 is repeated for MAXKNS time steps.

5.2.11 River-Aquifer Interactions (*RIVER*)

The inputs for river-aquifer interactions determine the ground-water recharge and discharge that results from or produces riverflow within a network of river channels. Each river channel consists of a series of reaches associated with nodes in the model. These inputs are listed below. (See table 13 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
27	1-10	I10	NRCH	Number of river channel reaches.
	11-20	I10	NINF	Number of river inflow input locations.
	21-30	I10	NSTEP	Number of time steps.
	31-40	I10	IECHO1	Switch for display of river parameters.
	41-50	I10	IECH02	Switch for display of river inflows.
	51-60	I10	IECHO3	Switch for display of riverflow routing.
28	1-10	F10.0	AD	Depth coefficient [$(t/L^2)^{m_D}$].
	11-20	F10.0	BD	Depth exponent [dimensionless].
	21-30	F10.0	AW	Width coefficient [$(t/L^2)^{m_w}$].
	31-40	F10.0	BW	Width exponent [dimensionless].
29	1-10	I10	NRN(i)	Number of nodes for the reaches of the river channel.
	11-20	F10.0	KFACT	Multiplication factor for river-bed hydraulic conductivity [dimensionless].
30	1-10	I10	RNODE(i,j)	Identity of node for the reach of the river channel.
	11-20	F10.0	HBED(i,j)	Elevation of river bed at the node [ft].
	21-30	F10.0	LENGTH(i,j)	Length of reach of the river channel at the node [ft].
	31-40	F10.0	KBED(i,j)	Hydraulic conductivity of river bed at node [ft/d].
	41-50	F10.0	BBED(i,j)	Thickness of river bed at node [ft].
	51-60	I10	JOIN(i,j)	Identifier for river channel to be joined at this node.
	61-70	I10	SET(i,j)	Identifier for river inflow data set to be used at this river node.
	71-80	I10	ITABLE(i,j)	Identifier for table of the cross-sectional geometry of the reach to be used for this river node.
	81-90	I10	INDRIV(i,j)	Parameter identification index for assignment of hydraulic conductivity of the river bed.
31	1-10	I10	NTABLE	Number of reach-geometry tables.
32	1-10	I10	NPT(i)	Number of entries in reach-geometry table.
33	1-10	F10.0	QTAB(i,j)	Riverflow [ft^3/s].
	11-20	F10.0	WTAB(i,j)	Width of riverflow [ft].
	21-30	F10.0	DTAB(i,j)	Depth of flow at lowest point on cross section of the reach [ft].
34	1-10	F10.0	RFACT	Multiplication factor for riverflow inputs [dimensionless].
35	1-50	5F10.0	QIN(i,j)	River inflow input (ft^3/s).

Table 13. Example of inputs for river-aquifer interactions (Records 27 through 35 for MODEL.DAT)

Record	Input records									Remarks
	NRCH	NINF	NSTEP	IECHO1	IECHO2	IECHO3				
	I10	I10	I10	I10	I10	I10				
27	3	5	10	1	1	1				
	AD	BD	AW	BW						
	F10.0	F10.0	F10.0	F10.0						
28	5.0	0.4	20.0	0.5						
	NRN	KFACT								
	I10	F10.0								
29	3	1.0								Channel 1
	RNODE	HBED	LENGTH	KBED	BBED	JOIN	SET	ITABLE	INDRIV	
	I10	F10.0	F10.0	F10.0	F10.0	I10	I10	I10	I10	
30	10	100.0	4000.0	2.0	5.0	0	1	0	18	
30	12	90.0	4000.0	2.0	5.0	0	0	0	18	
30	14	80.0	4000.0	2.0	5.0	0	2	0	18	
	NRN	KFACT								
	I10	F10.0								
29	2	1.0								Channel 2
	RNODE	HBED	LENGTH	KBED	BBED	JOIN	SET	ITABLE	INDRIV	
	I10	F10.0	F10.0	F10.0	F10.0	I10	I10	I10	I10	
30	30	110.0	2000.0	3.0	10.0	0	4	0	19	
30	28	100.0	2000.0	3.0	10.0	0	0	0	19	
	NRN	KFACT								
	I10	F10.0								
29	4	1.0								Channel 3
	RNODE	HBED	LENGTH	KBED	BBED	JOIN	SET	ITABLE	INDRIV	
	I10	F10.0	F10.0	F10.0	F10.0	I10	I10	I10	I10	
30	50	110.0	3000.0	2.0	5.0	0	3	1	20	
30	52	100.0	3000.0	2.0	5.0	0	0	2	20	
30	54	90.0	3000.0	2.0	5.0	2	0	2	20	
30	56	80.0	3000.0	2.0	5.0	0	5	2	20	
	NTABLE									
	I10									
31	2									

Table 13. Example of inputs for river-aquifer interactions (Records 27 through 35 for MODEL.DAT)--Continued

Record	Input records					Remarks
	NPT					
	I10					
32	5					
	QTAB	WTAB	DTAB			
	F10.0	F10.0	F10.0			
33	0.000	0.000	0.000			
	0.116	5.549	0.185			
	3.169	19.164	0.640			
	51.416	54.479	1.819			
	780.869	114.605	4.879			
	NPT					
	I10					
32	5					
	QTAB	WTAB	DTAB			
	F10.0	F10.0	F10.0			
33	0.000	0.000	0.000			
	0.052	4.772	0.159			
	1.569	17.150	0.573			
	26.158	49.254	1.645			
	402.788	109.228	4.426			
	RFACT					
	F10.0					
34	1.00					
	QIN	QIN	QIN	QIN	QIN	
	F10.0	F10.0	F10.0	F10.0	F10.0	(5F10.0)
35	37.472	266.579	140.913	30.334	46.358	
35	33.000	26.300	15.500	15.000	50.873	
	RFACT					
	F10.0					
34	1.00					
	QIN	QIN	QIN	QIN	QIN	
	F10.0	F10.0	F10.0	F10.0	F10.0	(5F10.0)
35	5.479	6.587	4.420	6.164	5.871	
35	4.017	1.952	0.000	0.000	0.000	

Table 13. Example of inputs for river-aquifer interactions (Records 27 through 35 for MODEL.DAT)–Continued

Record	Input records					Remarks
	RFACT F10.0					
34	1.00					
	QIN F10.0	QIN F10.0	QIN F10.0	QIN F10.0	QIN F10.0	(5F10.0)
35	62.000	193.189	126.457	82.000	75.849	
35	59.000	71.000	67.000	49.000	18.000	
	RFACT F10.0					
34	1.00					
	QIN F10.0	QIN F10.0	QIN F10.0	QIN F10.0	QIN F10.0	(5F10.0)
35	55.382	81.000	77.000	49.000	46.000	
35	20.000	2.000	19.000	25.000	39.843	
	RFACT F10.0					
34	1.00					
	QIN F10.0	QIN F10.0	QIN F10.0	QIN F10.0	QIN F10.0	(5F10.0)
35	4.958	2.098	2.420	0.699	3.562	
35	6.184	0.309	0.000	0.781	0.813	

Notes:

1. If NRCH equals zero, then Records 28 through 35 are omitted.

2. If the switches IEHCO1, IECHO2, and IECHO3 equal 1, then displays occur. If the switches equal zero, then no displays occur.

3. Two options specify the relations between the geometry of a reach and the flow in the river at the reach. If ITABLE (*i,j*) in Record 30 equals zero, the coefficients in Record 28 are used for the reach. The coefficients and exponents in Record 28 are described in Section 3.5.2. If these coefficients are applied to all of the reaches of the river, NTABLE in Record 31 equals zero and Records 32 and 33 are omitted. Otherwise, a table number is assigned to the river reach in Record 30 and a reach-geometry table is used. The reach-geometry table is specified in Records 32 and 33. If a reach-geometry table is specified for all reaches in a river, the coefficients and exponents in Record 28 are set equal to zero.

4. Record 30 is repeated for NRN(*i*) river nodes in a reach. Then, Records 29 and 30 are repeated for NRCH river reaches as a group.

5. The river nodes RNODE(*i,j*) in Record 30 must not be shared. In other words, a node in the finite-element grid that is assigned to a node reach within any channel reach cannot also be assigned to another node reach within any channel reach.

6. INDRIV in Record 30 corresponds to the global parameters within the subroutine *SEARCH*, described in Section 5.4.

7. If NTABLE equals zero, then Records 32 and 33 are omitted.

8. Record 33 is repeated for each entry in the reach-geometry table [NPT(*i*) times], and Records 32 and 33 are repeated for each reach-geometry table (NTABLE times) as a group.

9. Record 35 is repeated for each time step until NSTEP values of QIN(*i,j*) are input. Record 34 and 35 are repeated for each river inflow input location (NINF times) as a group.

An example of inputs for a layout of a river system is given in table 13. This example is based on the layout shown in figure 23, which includes three channels that make up two separate river systems. The first system includes channel 1; the second system includes channels 2 and 3, where channel 2 is tributary to channel 3. Lateral inflows occur at five locations. Inflow inputs 1 and 2 occur within channel 1, inflow input 4 occurs within channel reach 2, and inflow inputs 3 and 5 occur within channel 3. Each channel is divided into node reaches: channel 1 has three node reaches, channel 2 has two node reaches, and channel 3 has four node reaches.

The ordering of channel reaches in the input data set (table 13) must follow specific ordering rules. Within subroutine *RIVER*, the routing of riverflow is done in a specific order for each channel and then for each node reach. Riverflow is routed down channels in order. If a channel is tributary to another channel, flow must be routed down the tributary channel before flow is routed down the receiving channel. Therefore, the ordering rule specifies that a channel tributary to another channel must appear in the input data set prior (but not necessarily just prior) to the receiving channel. If a channel is not tributary, the input data set can be in any order. In the example in table 13, flow must be routed down channel 2 before channel 3. However, channel 1, which receives no tributary flow, could have been listed anywhere in the order.

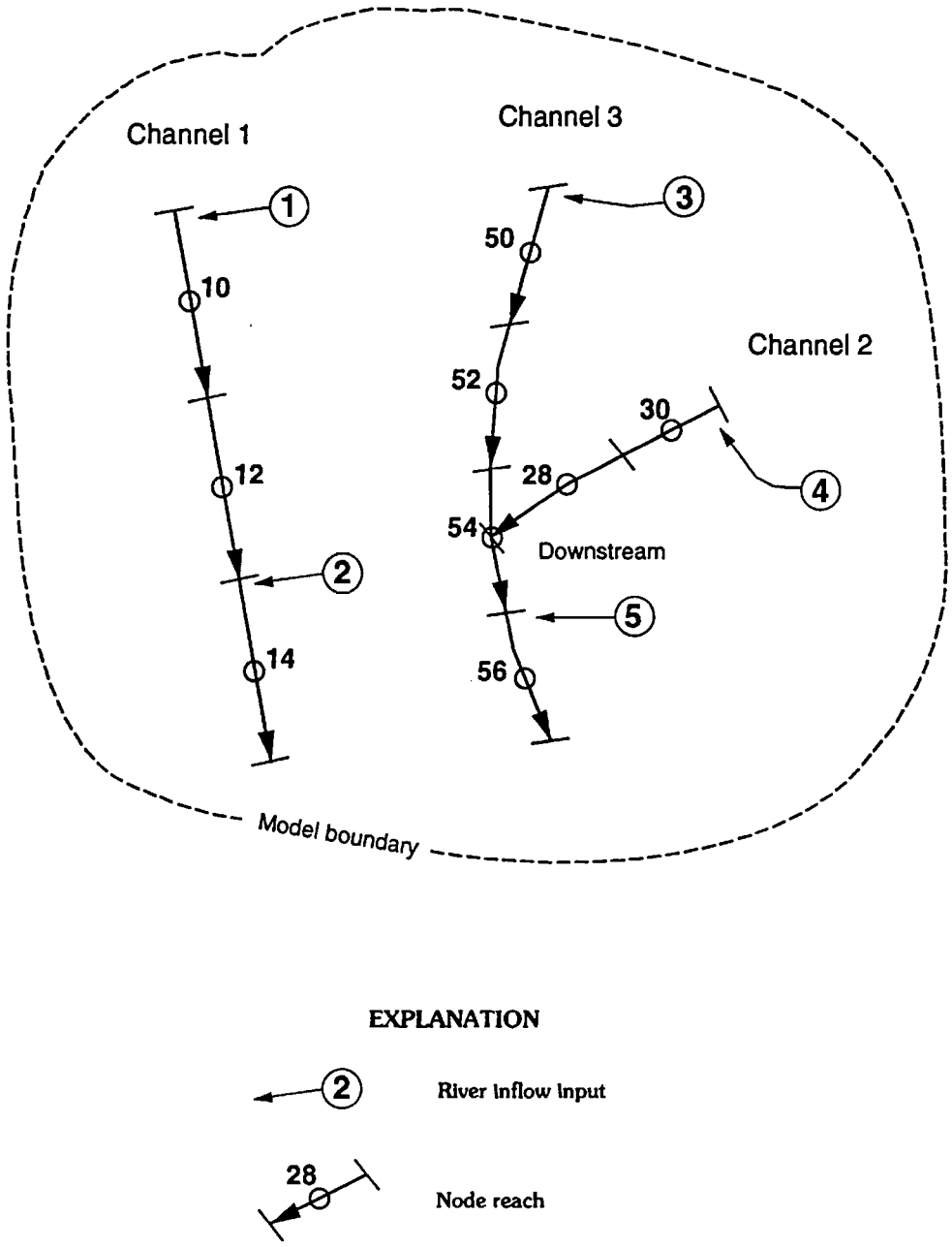


Figure 23. Representation of river network for river-aquifer interaction.

Two alternatives can be used for specifying reach geometry. In channels 1 and 2, the exponential relations for riverflow depth and width (Record 28) are used for each of the node reaches, and ITABLE in Record 30 is set to zero. In channel 3, tabulated values of width and depth are used. ITABLE in Record 30 is set to 1 for the first node reach in channel 3. The other three node reaches in channel 3 use table 2. Records 32 and 33 specify the reach geometry.

5.2.12 Ground-Water Evapotranspiration (*EVAP*)

The inputs for ground-water evapotranspiration describe the consumption of ground water by phreatophytes or by bare-soil evaporation. These inputs are listed below. (See table 14 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
36	1-10	I10	NETN	Number of evapotranspiration nodes.
	11-20	I10	MAXKNS	Number of time steps.
	21-30	I10	IECH01	Switch for display of inputs.
	31-40	I10	IECH02	Switch for display of discharges from evapotranspiration nodes.
37	1-10	I10	ETNODE(*i*)	Identity of evapotranspiration node.
	11-20	F10.0	ETAREA(*i*)	Area of evapotranspiration for node [acres].
	21-30	F10.0	LAND(*i*)	Land-surface elevation at node [ft].
	31-40	F10.0	DELH0(*i*)	Extinction depth for node [ft].
	41-50	F10.0	ETMAX(*i*)	Maximum evapotranspiration rate for node [ft/yr].
38	1-10	I10		Number of time step (for reference only).
	11-20	F10.0	FACSET(*i*)	Multiplication factor of maximum evapotranspiration for time step [dimensionless].

Table 14. Example of inputs for ground-water evapotranspiration (Records 36 through 38 for MODEL.DAT)

Record	Input records				
	NETN	MAXKNS	IECHO1	IECHO2	
	I10	I10	I10	I10	
36	6	24	1	1	
	ETNODE	ETAREA	LAND	DELH0	ETMAX
	I10	F10.0	F10.0	F10.0	F10.0
37	49	62.0	10.0	15.0	3.15
37	57	62.0	10.0	15.0	3.15
37	77	45.0	12.5	15.0	3.15
37	85	121.0	12.5	15.0	3.15
37	108	44.0	19.5	15.0	3.15
37	116	44.0	19.5	15.0	3.15
	time step	FACSET			
		F10.0			
38	1	0.99			
38	2	0.69			
38	3	0.50			
38	4	0.51			
38	5	0.61			
38	6	0.86			
38	7	1.07			
38	8	1.27			
38	9	1.38			
38	10	1.49			
38	11	1.44			
38	12	1.19			
38	13	0.99			
38	14	0.69			
38	15	0.50			
38	16	0.51			
38	17	0.61			
38	18	0.86			
38	19	1.07			
38	20	1.27			
38	21	1.38			
38	22	1.49			
38	23	1.44			
38	24	1.19			

Notes:

1. If NETN equals zero, Records 37 and 38 are omitted.
2. If the switches IECHO1 and IECHO2 equal 1, displays occur. If the switches equal zero, no displays occur.
3. The number of time steps MAXKNS in Record 36 must be greater than or equal to MAXKNS in Record 2.
4. Record 37 is repeated for each evapotranspiration node (NETN times).
5. Record 38 is repeated for each time step (MAXKNS times).

5.2.13 Variable-Flux Boundary Conditions (*VFLUX*)

The inputs for variable-flux boundary conditions describe, in part, how the simulation relates to conditions outside the modeled volume. These inputs are listed below. (See table 15 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
39	1-10	I10	NVFB	Number of variable-flux nodes.
	11-20	I10	IECH01	Switch for display of inputs.
	21-30	I10	IECH02	Switch for display of discharges through variable-flux nodes.
40	1-10	I10	VFNODE(*i*)	Identity of variable-flux node.
	11-20	F10.0	K(*i*)	Hydraulic conductivity of the extended ground-water system [ft/d].
	21-30	F10.0	SS(*i*)	Specific storage of the extended ground-water system [^{1}/ft].
	31-40	F10.0	WIDTH(*i*)	Width of extended ground-water system for node [ft].
	41-50	F10.0	HEIGHT(*i*)	Height of extended ground-water system for node [ft].

Table 15. Example of inputs for variable-flux boundary conditions (Records 39 and 40 for MODEL.DAT)

Record	Input records				
	NVFB	IECHO1	IECHO2		
	I10	I10	I10		
39	6	1	1		
	VFNODE	K	SS	WIDTH	HEIGHT
	I10	F10.0	F10.0	F10.0	F10.0
40	5	33.0	1.0E-05	5280.0	80.0
40	9	33.0	1.0E-05	5280.0	85.0
40	13	33.0	1.0E-05	5280.0	90.0
40	17	33.0	1.0E-05	5280.0	95.0
40	21	33.0	1.0E-05	5280.0	100.0
40	25	33.0	1.0E-05	5280.0	105.0

Notes:

1. If NVFB equals zero, Record 40 is omitted.
2. If the switches IECH01 and IECH02 equal 1, displays occur. If the switches equal zero, no displays occur.
3. Record 40 is repeated for each variable-flux node (NVFB times).

An example of the layout of variable-flux boundaries is shown in figure 24. For this boundary condition, an extended ground-water system is associated with a node on the boundary surface (VFNODE). The extended ground-water system has a finite width (WIDTH) and height (HEIGHT), but it extends an infinite distance away from the boundary surface.

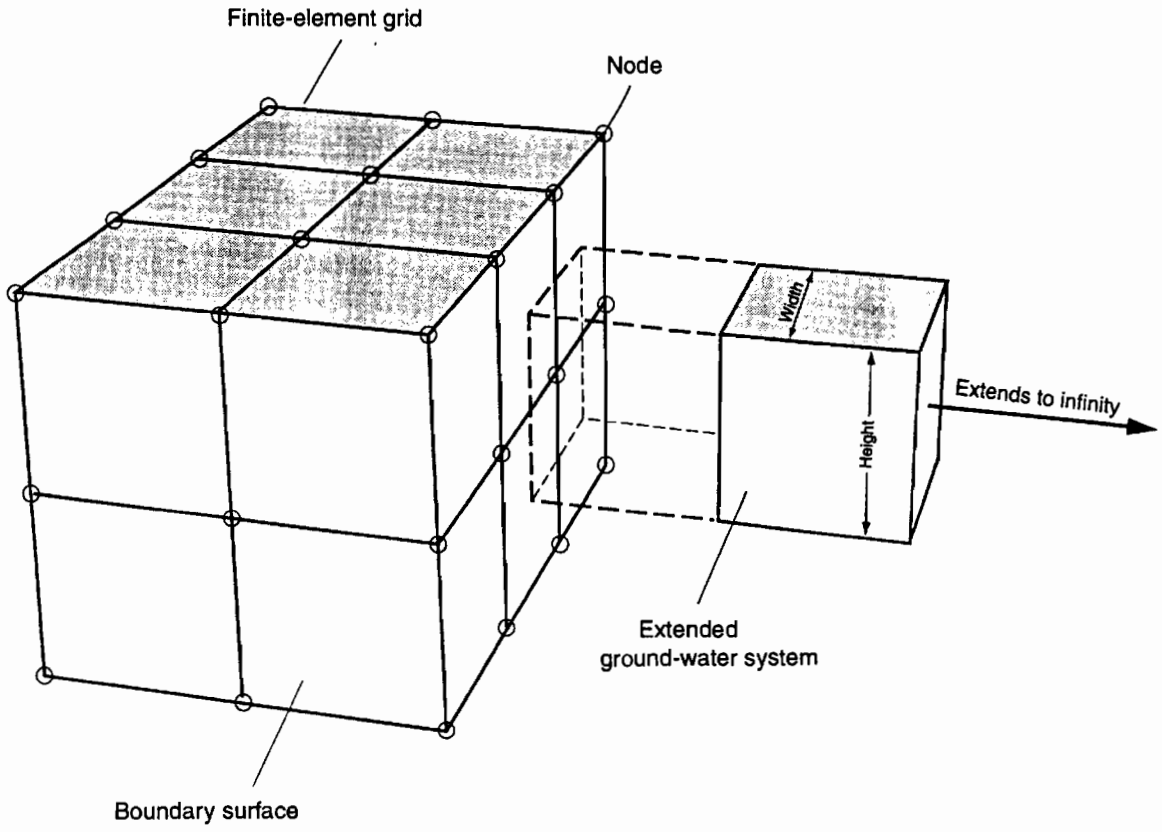


Figure 24. Representation of variable-flux boundary condition.

In the expected application of the variable-flux boundary condition, the width and height of the extended ground-water system extends one-half the distance from the associated node to the adjacent nodes on the boundary surfaces. Each node on the boundary surface has an extended ground-water system with a height and width such that the entire boundary surface is included. The sum of the end areas of the extended ground-water systems should equal the total area of the boundary surface.

5.2.14 Fault Internal Condition (*FAULT*)

The inputs for fault internal conditions represent the flow of ground water through highly transmissive features, such as fault zones or well casings. These inputs are listed below. (See table 16 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
41	1-10	I10	NFN	Number of node pairs.
	11-20	I10	IECH01	Switch for display of inputs.
	21-30	I10	IECH02	Switch for display of discharges between node pairs.
42	1-10	I10	FNODE1(i,j)	First node of node pair.
	11-20	I10	FNODE2(i,j)	Second node of node pair.
	21-30	F10.0	TRAN(i)	Transmissivity of feature for node pair parallel to node link, which is the connecting line between the node pair [ft^2/d].
	31-40	F10.0	LENGTH(i)	Length of node link [ft].
	41-50	F10.0	HEIGHT(i)	Height or width of the part of the feature represented by the node pair [ft].

Table 16. Example of inputs for fault internal conditions (Records 41 and 42 for MODEL.DAT)

Record **Input records**

```
Example for fault link:

                NFN     IECHO1     IECHO2
                I10        I10        I10

 41               2          1          1

           FNODE1     FNODE2       TRAN     LENGTH     HEIGHT
              I10        I10      F10.0      F10.0      F10.0

 42            51         61     1000.0      400.0      500.0
 42            41         42     1000.0      500.0      400.0


Example for well link

                NFN     IECHO1     IECHO2
                I10        I10        I10

 41               2          1          1

           FNODE1     FNODE2       TRAN     LENGTH     HEIGHT
              I10        I10      F10.0      F10.0      F10.0

 42            30         31   2.0E+06      500.0        1.0
 42            31         32   2.0E+06      500.0        1.0
```

Notes:

1. If NFN equals zero, Record 42 is omitted.

2. If the switches IECH01 equal 1, displays occur. If the switches equal zero, no displays occur.

3. Record 42 is repeated for each node pair (NFN times).

4. If the highly permeable feature is a fault, two sets of fault links must be specified to represent both horizontal and vertical ground-water flow within a fault plane: one set links nodes in the horizontal direction, and the other set links nodes in the vertical direction. Each set of fault links should separately represent the total area of the fault surface.

5. If the highly permeable feature is a well casing, the product of transmissivity times the width (diameter of the well) is the conductivity of the well casing to vertical flow.

The node-pair links allow the representation of ground-water flow through a highly permeable feature, where the feature can transmit significantly more water than the adjacent aquifer continuum.

Two examples of inputs for the layout of the fault internal conditions are given in table 16. The examples are based on the layouts shown in figure 25. The first example is for fault links and the second example is for well links (figs. 25*A* and 25*B*, respectively).

In the example for fault links, a single layer of nodes define the geometry of the fault plane. The height of the fault link extends one-half the distance above and below the line between the two nodes that define the link to the adjacent node pairs on the fault surface.

In the first example, two fault links are represented (NFN = 2); the fault links link nodes 51 and 61 (FNODE1 = 51 and FNODE2 = 61) and nodes 41 and 42 (FNODE1 = 41 and FNODE2 = 42). The height of the first fault link is 500 ft (HEIGHT = 500.0) and the length is 400 ft (LENGTH = 400.0). The transmissivity of the fault link is 1,000 ft^2/d (TRAN = 1000.0). This transmissivity represents the product of a unit thickness normal to the plane of the fault and the hydraulic conductivity of the fault zone parallel to the fault node link. If the thickness of a fault is 2 ft, the hydraulic conductivity that corresponds to the transmissivity would be 500 ft/d.

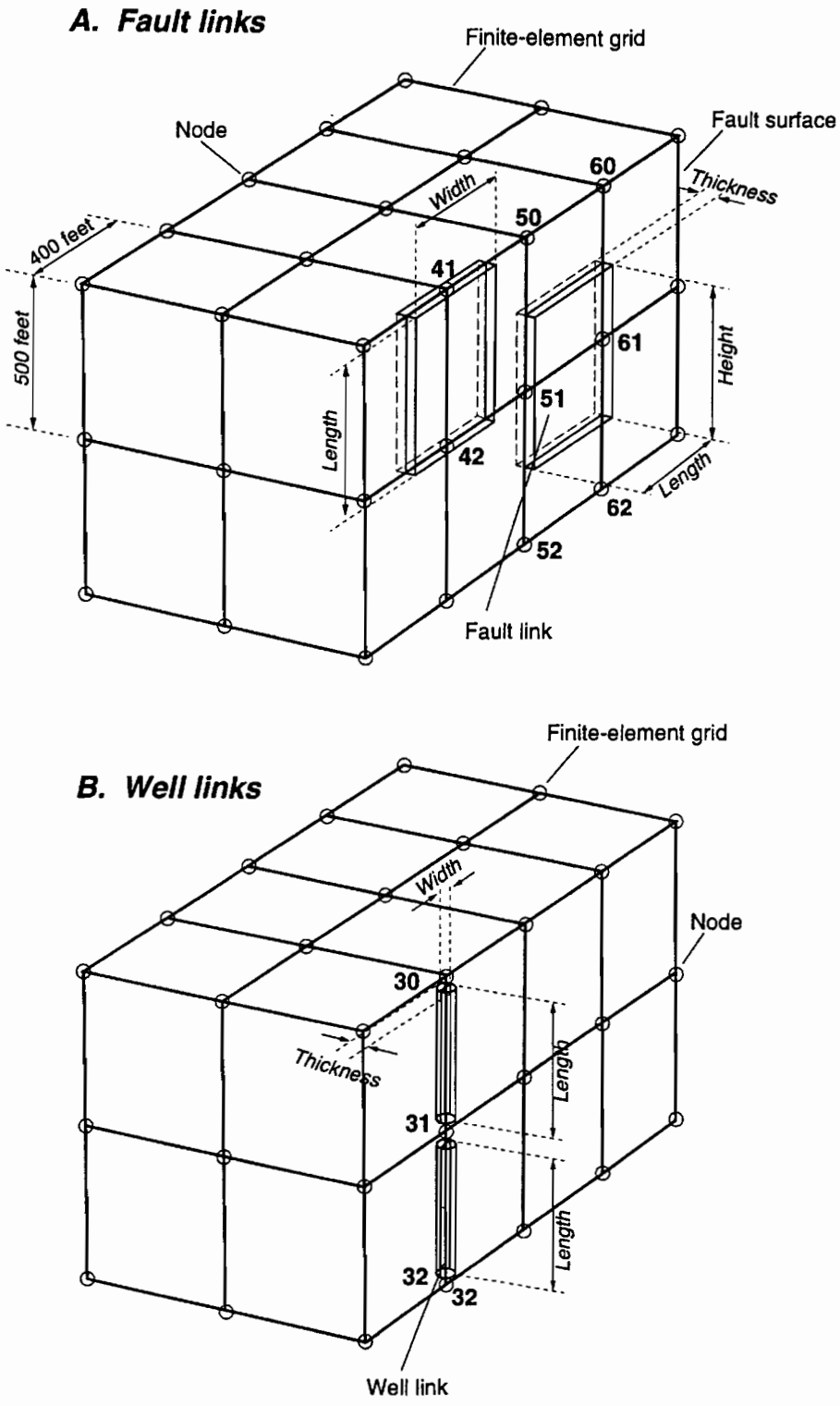


Figure 25. Representation of fault internal condition.

In the first example, the first fault link is oriented horizontally, and the second fault is oriented vertically (fig. 25A). In both examples, the length of the fault link is the length between the two nodes that define the link. However, the connecting line is horizontal in the first example and vertical in the second. In the first example, the height is a vertical dimension of the fault link normal to the line between the two nodes that define the link. In the second example, the width is a horizontal dimension. In both examples, transmissivity represents the resistance to flow between the node pairs.

In the second example, the highly permeable feature is represented by a well casing in which a single line of nodes define the length of the casing perforations. A well link represents the preferential flow of ground water through a well casing. For a well that is perforated within different layers of the finite-element grid, well links can be used to represent hydraulic head that is nearly equal throughout a well casing, and hydraulic head within the ground-water system that is nearly equal adjacent to the perforated interval of the well.

In the second example, two well links are represented (NFN = 2), the well links link nodes 30 and 31 (FNODE1 = 30 and FNODE2 = 31) and nodes 31 and 32 (FNODE1 = 31, and FNODE2 = 32). The width of the well links is 1 ft (WIDTH = 1.0) and the length is 500 ft (LENGTH = 500.0). The transmissivity of the well links is 2.0E+06 ft^2/d. This represents a transmissivity that is large enough so that the differential in hydraulic head across the well link is small. If the well was pumping at 2 ft^3/s, the transmissivity would produce a differential of 0.086 ft, where the head differential equals the pumping rate divided by the transmissivity using a consistent set of dimensional units.

5.2.15 Land Subsidence (*SINK*)

The inputs for land subsidence describe the simulation of land subsidence owing to water-level declines. These inputs are listed below. (See table 17 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
43	1-10	I10	ISIN	Switch for simulating land subsidence.
	11-20	I10	IECH01	Switch for display of aquifer parameters.
	21-30	I10	IECH02	Switch for display of initial preconsolidation heads.
	31-40	I10	IECH03	Switch for display of preconsolidation heads at end of time step.
	41-50	I10	IECH04	Switch for display of element columns.
	51-60	I10	IECH05	Switch for display of land subsidence for each element column.
44	1-10	F10.0	FACSKE	Multiplication factor for elastic specific storage of interbeds [dimensionless].
	11-20	F10.0	FACSKV	Multiplication factor for inelastic specific storage of interbeds [dimensionless].
	21-30	F10.0	FACPOR	Multiplication factor for proportion of element occupied by interbeds [dimensionless].
45	1-10	I10		Element number (for reference only).
	11-20	F10.0	SSKE(*i*)	Elastic specific storage for interbeds [^{1}/ft].
	21-30	F10.0	SSKV(*i*)	Inelastic specific storage for interbeds [^{1}/ft].
	31-40	F10.0	POR(*i*)	Proportion of prismatic element occupied by interbeds [dimensionless].
46	1-50	5F10.0	HP(*i*)	Initial preconsolidation heads [ft].
47	1-10	I10	NCOL	Number of element columns.
	11-20	I10	NSTACK	Maximum number of elements in element column.
48	1-10	I10		Number of element column (for reference only).
	11-60	5I10	COL(*i,j*)	Identification of elements in an element column.

Table 17. Example of inputs for land subsidence (Records 43 through 48 for MODEL.DAT)

Record	Input records						Remarks
	ISINK	IECHO1	IECHO2	IECHO3	IECHO4	IECHO5	
	I10	I10	I10	I10	I10	I10	
43	1	1	1	1	1	1	
	FACSKE	FACSKV	FACPOR				
	F10.0	F10.0	F10.0				
44	1.0	1.0	1.0				
	element number	SSKE	SSKV	POR			
		F10.0	F10.0	F10.0			
45	1	1.0E-06	5.51E-05	1.0			
45	2	1.0E-06	5.51E-05	1.0			
45	3	1.0E-06	5.51E-05	1.0			
45	4	1.0E-06	5.51E-05	1.0			
45	5	1.0E-06	5.51E-05	1.0			
45	6	1.0E-06	5.51E-05	1.0			
45	7	1.0E-06	5.51E-05	1.0			
45	8	1.0E-06	5.51E-05	1.0			
45	9	1.0E-06	5.51E-05	1.0			
45	10	1.0E-06	5.51E-05	1.0			
45	11	1.0E-06	5.51E-05	1.0			
45	12	1.0E-06	5.51E-05	1.0			
45	13	1.0E-06	5.51E-05	1.0			
45	14	1.0E-06	5.51E-05	1.0			
45	15	1.0E-06	5.51E-05	1.0			
45	16	1.0E-06	5.51E-05	1.0			
45	17	1.0E-06	5.51E-05	1.0			
45	18	1.0E-06	5.51E-05	1.0			
45	19	1.0E-06	5.51E-05	1.0			
45	20	1.0E-06	5.51E-05	1.0			
	HP	HP	HP	HP	HP		
	F10.0	F10.0	F10.0	F10.0	F10.0		(5F10.0)
	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0	0.0		
46	0.0	0.0	0.0	0.0			
	NCOL	NSTACK					
	I10	I10					
47	2	10					
	element number	COL	COL	COL	COL	COL	
		I10	I10	I10	I10	I10	(5I10)
48	1	1	3	5	7	9	
		11	13	15	17	19	
48	2	2	4	6	8	10	
		12	14	16	18	20	

Notes:

1. If the switch ISINK equals zero, Records 44 through 48 are omitted.
2. If the switches IECH01, IECH02, IECH03, IECHO4, and IECH05 equal 1, displays occur. If the switches equal zero, no displays occur.
3. Record 45 is repeated for each prismatic element (NE times), where NE is defined in Record 9.
4. Record 46 is repeated for each node until NN values have been entered, where NN is defined in Record 9.
5. Record 48 is repeated for each element in the element column until NSTACK elements in a column have been input. If a particular column has less than NSTACK elements, zeros are entered until NSTACK elements in a column have been input.
6. Record 48 is repeated for each element column. NSTACK elements for a column are input, then a new record is started and the elements for the next column are input.

5.2.16 Controls of an Irrigated System (*WATER*)

The inputs for control of an irrigated system set switches for the output of inputs to subroutine *WATER*. These inputs are listed below. (See table 18 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
49	1-10	I10	ICONT	Switch for use of subroutine *WATER*.
50	1-10	I10	IOUT1	Switch for display of well inventory (WELL.OUT).
	11-20	I10	IOUT2	Switch for display of monthly pumping (PUMP.OUT).
	21-30	I10	IOUT3	Switch for display of pumping construction (CPUMP.OUT).
	31-40	I10	IOUT4	Switch for display of user inventory (USER.OUT).
	41-50	I10	IOUT5	Switch for display of monthly deliveries (DELIVERY.OUT).
	51-60	I10	IOUT6	Switch for display of delivery construction (CDELIVER.OUT).
51	1-10	I10	IOUT7	Switch for display of crop inventory (CROP.OUT).
	11-20	I10	IOUT8	Switch for display of rooting depth (ROOT.OUT).
	21-30	I10	IOUT9	Switch for display of monthly precipitation (PRECIP.OUT).
	31-40	I10	IOUT10	Switch for display of monthly potential evapotranspiration (PET.OUT).
	41-50	I10	IOUT11	Switch for display of crop and weather construction (CCROP.OUT).
	51-60	I10	IOUT12	Switch for display of recharge factors (HARDPAN.OUT).
52	1-10	I10	IOUT13	Switch for display of pumping destinations (DESTIN.OUT).
	11-20	I10	IOUT14	Switch for display of well exclusions (EXCLUDE.OUT).

Table 18. Example of inputs for output controls for irrigation system data used in subroutine WATER (Records 49 through 52 for MODEL.DAT)

Record	Input records					
	ICONT					
	I10					
49	1					
	IOUT1	IOUT2	IOUT3	IOUT4	IOUT5	IOUT6
	I10	I10	I10	I10	I10	I10
50	1	1	1	1	1	1
	IOUT7	IOUT8	IOUT9	IOUT10	IOUT11	IOUT12
	I10	I10	I10	I10	I10	I10
51	1	1	1	1	1	1
	IOUT13	IOUT14				
	I10	I10				
52	1	1				

Notes:

1. If subroutine *WATER* is not used, ICONT in Record 49 is zero, and Records 50 through 52 are omitted.
2. If the switches IECHO1 through IECHO14 equal 1, displays occur. If the switches equal zero, no displays occur.
3. File names in parentheses in the "variable description" column indicate suggested file names only.

5.3 Subroutine *WATER* Input Files

The subroutine *WATER* input files contain the description of the irrigated-agricultural system. The formats of the 15 input files include fields that are not used directly by subroutine *WATER* and are for reference only. Those fields are included to allow storage of more complete data on the irrigated-agricultural system, where that data would be available for other purposes. The fields that are used by subroutine *WATER* are indicated by the occurrence of a variable name.

The file names shown in parentheses in the tables and text are suggested file names only and may be named differently for each application. The file names for subroutine *WATER* used in this report are WELL.DAT, WSTAT.DAT, PUMP.DAT, CPUMP.DAT, USER.DAT, DELIVER.DAT, CDELIVER.DAT, CROP.DAT, ROOT.DAT, PRECIP.DAT, PET.DAT, CCROP.DAT, DESTIN.DAT, RECHARGE.DAT, and EXCLUDE.DAT).

5.3.1 Well-Site Inventory File (WELL.DAT)

The inputs for well-site inventory describe well characteristics. These inputs are listed below. (See table 19 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=A).
	3-14	A12	WNUM(*i*)	Well number.
	16-35	A20		Local well name (for reference only).
	38-40	A3		Township (for reference only).
	41-43	A3		Range (for reference only).
	44-45	I2		Section (for reference only).
	46	A1		40-acre parcel (for reference only).
	47-48	I2		Sequence number (for reference only).
	49-50	A2		Well type (for reference only).
	53-70	A18		Account number (for reference only).
	72-80	I9		Meter number (for reference only).
2	1	A1	LINE	Record type (=B).
	3-14	A12	WNUM(*i*)	Well number.
	22-30	I9	WNODE(*i,j*)	Pumpage node number.
	32-40	F9.0	WFACT(*i,j*)	Pumpage proportion for node [dimensionless].
3	1	A1	LINE	Record type (=D).
	3-14	A12	WNUM(*i*)	Well number.
	22-30	F9.0	WCAP(*i*)	Well capacity [gal/min].
	32-40	I9		Data estimate code (well capacity) (for reference only.)
	42-50	F9.0		Land-surface elevation [ft] (for reference only).
	52-60	F9.0		Well-casing length [ft] (for reference only).
	62-70	F9.0		Well depth [ft] (for reference only).
	72-80	I9		Data estimate code (well depth) (for reference only).
4	1	A1		Record type (=X) (for reference only).
	3-14	A12		Well number (for reference only).
	23-30	F9.0		Top of perforation [ft] (for reference only).
	33-40	F9.0		Bottom of perforation [ft] (for reference only).
5	1	A1		Record type (=*Y*) (for reference only).
	3-14	A12		Well number (for reference only).
	22-40	F19.0		*X* California coordinate [ft] (for reference only).
	42-60	F19.0		*Y* California coordinate [ft] (for reference only).

Table 19. Example of inputs for well-site inventory file (WELL.DAT)

Record	Input records

```
        L                          township, range,
        I                  local   section, parcel,
        N                  well    and sequence
        E    WNUM          name    number
        A1    A12          A20     A3

1       A  MIS001          WELL 1 7N/34W-34B1

        L
        I
        N
        E    WNUM               WNODE     WFACT
        A1    A12                 I9      F9.0

2       B  MIS001                 447     0.137
        B  MIS001                 448     0.119
        B  MIS001                 449     0.001
        B  MIS001                 452     0.266
        B  MIS001                 453     0.230
        B  MIS001                 454     0.001
        B  MIS001                 488     0.096
        B  MIS001                 489     0.083
        B  MIS001                 490     0.000

        L
        I                                    data     land-     well-              data
        N                                estimate  surface    casing      well  estimate
        E    WNUM               WCAP        code elevation    length     depth      code
        A1    A12               F9.0          I9      F9.0      F9.0      F9.0        I9

3       D  MIS001            2500.0           0     102.0     192.0     192.0         0

        L
        I
        N    well              top of    bottom of
        E  number          perforation  perforation
        A1    A12               F9.0         F9.0

4       X  MIS001                97.0     192.0

        L
        I
        N    well                  X California        Y California
        E  number                    coordinate          coordinate
        A1    A12                         F19.0               F19.0

5       Y  MIS001                    1264625.0           428812.5
```

Notes:

1. Record 2 is repeated for each node associated with the well. Record 4 is repeated for each perforation interval in a well. If there are no perforation data available, Record 4 is omitted. Records 1 through 5 are repeated as a group for each well.

2. For each well, WFACT(i,j) in Record 2 must sum to 1.

3. In Record 3, data estimate codes are optional and can be used to reference data sources.

The distribution of the pumpage from a well to nodes in the finite-element grid depends on the location of the well and the depth interval of the well screen or perforations. Pumpage for a well that is screened entirely within one element, as shown in figure 26, is distributed proportionally to each of the six nodes that define that element. Two pumpage distributions occur: one distribution is horizontal and one distribution is vertical.

The geometry for the horizontal distribution is shown in figure 26. For the horizontal distribution, the proportion of pumpage assigned to node i is given by the relation

$$p_i = \frac{a_i}{b_i}, \tag{5.3-1}$$

where

p_i is the pumpage proportion for node i [dimensionless],
a_i is the perpendicular distance from the side opposite node i to the well [L], and
b_i is the perpendicular distance from the side opposite node i to node i [L].

The proportions for the nodes j and k are given by similar relations. The sum of the proportions for the three nodes, i, j, and k will equal 1.0.

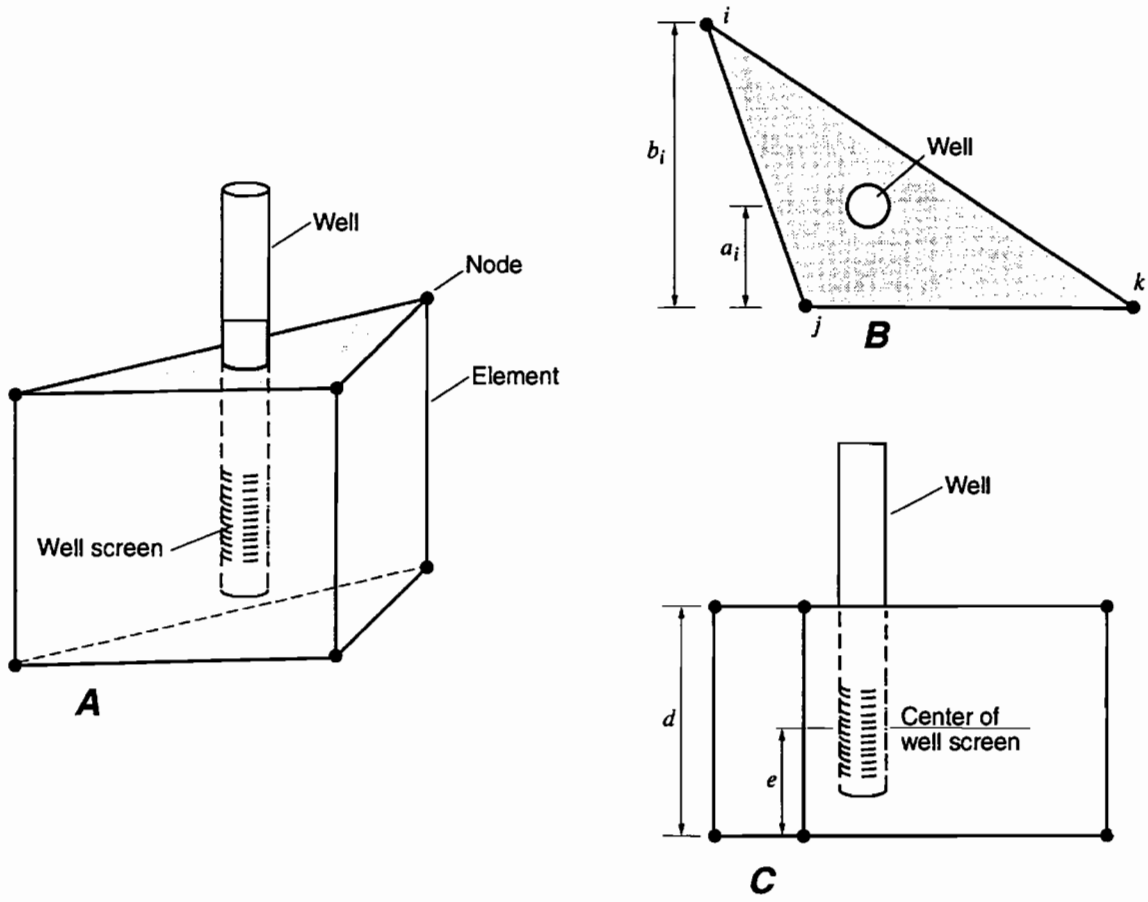


Figure 26. Distribution of pumping from wells to nodes in finite-element grid.

The geometry for the vertical distribution is shown in figure 26. For the vertical distribution, the proportion of pumpage assigned to the top of the element is given by the relation

$$p_T = \frac{e}{d}, \tag{5.3-2}$$

where

p_T is the pumpage proportion for the top of the element [dimensionless],
e is the distance from the bottom of the element to the center of the well screen [L], and
d is the height of the element [L].

The proportion of pumpage assigned to the bottom of the element is given by the relation

$$p_B = 1 - p_T \tag{5.3-3}$$

where p_B is the pumpage proportion for the bottom of the element [dimensionless]. The sum of these proportions will equal 1.0.

The horizontal and vertical distribution of pumpage must be combined. Using node i as an example, the combined proportion is given by the relation

$$P_i = p_i p_T \tag{5.3-4}$$

where P_i is the combined proportion [dimensionless]. The proportions for the other nodes that define the top and bottom of the element are similar.

5.3.2 Well-Status File (WSTAT.DAT)

The inputs for well status specify the pumping period of wells by well-status code and the assignment of user areas to wells. These inputs are as listed below. (See table 20 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=C).
	3-14	A12	WNUM(i)	Well number.
	22-30	I9	WSTAT(i,j)	Well-status code.
	34-35	I2	BSM0(i,j)	Beginning month for well-status change.
	37-40	I4	BSYR(i,j)	Beginning year for well-status change.
	44-45	I2	ESM0(i,j)	Ending month for well-status change.
	47-50	I4	ESYR(i,j)	Ending year for well-status change.
	53-60	A8	WUSER(i)	User Number.

Notes:

1. Record 1 is repeated when the user number for a well changes, the well status changes, or a new beginning and ending period occurs.

Table 20. Example of inputs for well-status file (WSTAT.DAT)

```
Record  Input records
        L
        I
        N
        E  WNUM                 WSTAT BSMO BSYR ESMO ESYR  WUSER
        A1 A12                    I9   I2   I4   I2   I4  A8

1       C  MIS001                 26   10 1941   09 1994  MISSION
1       C  MIS002                 26   10 1941   09 1994  MISSION
1       C  MIS003                 26   10 1941   09 1994  MISSION
```

The purpose of the well-status file is to assign each well to a group, to identify the construction and abandonment date for each well, and to identify the user area irrigated by each well. The grouping of wells i based on the well-status code. The purpose of the well-status code is to assign pumping values to wells as a group. (Well capacity is assigned to each well in the well-inventory file.)

Generally, wells are grouped into ownership or water-use categories. For example, individual group: might include municipal wells for a city, private wells within an irrigation district, and district-owned wells within an irrigation district. For example, a well-status code would be assigned to each group using three different codes to identify the municipal, private, and district-owned wells. The well status for a well can change over time, which is indicated by multiple records for the well in the well-status file. For example, a well might initially be privately owned and then converted to a district-owned well.

The well-status codes are arbitrary two-digit integers. The codes are for identification purposes and do not need to follow a particular sequence.

Wells pump to a user area for direct irrigation use or to a canal system for eventual delivery for irrigation use. The user area for direct irrigation use is identified in the well-status file. The user area for a well can change over time, which is indicated by multiple records for the well in the well-status file. A change in user area can occur with a change in the user-area boundary. For example, the boundary of a user area changes when an urban area expands into an area that was previously an agricultural area.

The date of a change in the well-status code or the user area irrigated by the well is specified in the well-status file. For wells with multiple records, the dates should represent a continuous span of time from th first record to the last record. The construction date for the well is the begin date in the first record. The abandonment date is the date in the last record, unless the well continues to be used through the end of the simulation period. In the latter case, the end date is the end date for the simulation.

5.3.3 Monthly Well-Pumping File (PUMP.DAT)

The inputs for monthly pumpage specify the monthly pumpage for individual wells. These inputs are listed below. (See table 21 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=F).
	3-14	A12	XWNUM	Well number.
	24-25	I2	PDMO(*i*)	Month of monthly well-pumping record.
	27-30	I4	PDYR(*i*)	Year of monthly well-pumping record.
	32-40	F9.0	QPUMP(*i*)	Pumpage [acre-ft/mo].
	42-50	I9		Data source code (for reference only).

Notes:

1. Record 1 is repeated, listing sequentially the monthly pumpage for a well. Record 1 is then repeated for each well.

2. At least one record must be entered, but the pumpage value may be set to zero.

Table 21. Example of inputs for monthly well-pumping file (PUMP.DAT)

Record **Input records**

```
        L
        I
        N
        E  XWNUM              PDMO PDYR     QPUMP
        A1 A12                  I2   I4      F9.0

1       F  MIS001                1 1973      26.3
1       F  MIS001                2 1973      40.8
1       F  MIS001                3 1973      23.8
1       F  MIS001                4 1973       0.1
1       F  MIS001                5 1973      53.0
1       F  MIS001                6 1973     221.7
1       F  MIS001                7 1973     192.2
1       F  MIS001                8 1973     188.4
1       F  MIS001                9 1973     214.5
1       F  MIS001               10 1973     163.5
1       F  MIS001               11 1973      98.7
1       F  MIS001               12 1973       4.1
1       F  MIS001                1 1973      22.6
1       F  MIS001                2 1973       7.8
1       F  MIS001                3 1973     147.7
1       F  MIS001                4 1973     198.2
1       F  MIS001                5 1973     227.4
1       F  MIS001                6 1973     242.9
```

5.3.4 Pumping-Construction File (CPUMP.DAT)

The inputs for pumping construction specify the pumping scenario for a simulation. These inputs are listed below. (See table 22 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=G).
	4-5	I2	PCMO(*i*)	Month of pumping-construction record.
	7-10	I4	PCYR(*i*)	Year of pumping-construction record.
2	1	A1	LINE	Record type (=H).
	3-10	I8	PSCODE(*i,j*)	Well-status code.
	12-20	I9	PDFILE(*i,j*)	Data-file code.
	22-30	F9.0	RPUMP(*i,j*)	Pumpage [acre-ft/mo].
	34-35	I2	PUMO(*i,j*)	Month of record from monthly well-pumping file to use.
	37-40	I4	PUYR(*i,j*)	Year of record from monthly well-pumping file to use.
	42-50	F9.0	PFACT(*i,j*)	Adjustment factor for pumpage [dimensionless].

Table 22. Example of inputs for pumping-construction file (CPUMP.DAT)

Record	Input records						
	L						
	I						
	N						
	E	PCMO	PCYR				
	A1	I2	I4				
1	G	08	1973				
	L						
	I						
	N						
	E	PSCODE	PDFILE	RPUMP	PUMO	PUYR	PFACT
		I8	I9	F9.0	I2	I4	F9.0
2	H	18	0	2000.0	00	0000	1.0
2	H	26	1	0.0	08	1973	1.0
2	H	40	1	0.0	08	1983	0.7

Notes:

1. Record 2 is repeated for each active well-status code. Records 1 and 2 are repeated as a group for each month. Pumpage is entered if the data-file code (PDFILE) equals zero. If the data-file code equals 1, pumpage is not entered in CPUMP.DAT, and pumpage for individual wells is entered into the monthly well-pumping file (PUMP.DAT) instead.

The purpose of the pumping-construction file is to specify a pumping scenario for a simulation. For each month in the simulation, the pumpage is specified for each well-status code. The pumpage for a status code can be specified by three alternative approaches. For the first approach, if monthly pumping data for individual wells are not available for a particular month, the total pumpage for all wells within the status-code groups can be specified and the total pumpage is distributed to the individual wells in proportion to the well capacity of individual wells. For the second approach, if monthly pumping data are available for the particular month, that monthly pumping data can be used to specify the pumpage for individual wells. For the third approach, if monthly pumping data are available for a different month, that monthly pumping data can be used to specify the pumpage for the individual wells.

Examples of these three alternative approaches are given in table 22 for August 1973 (PCMO = 08 and PCYR = 1973). For the first approach [status code 18 (PSCODE = 18)], monthly pumping data were not available (PDFILE = 0) so a total for pumpage of 2,000 acre-ft was distributed to the wells (RPUMP = 2000.0). For the second approach [status code 26 (PSCODE = 26)], monthly pumping data were available (PDFILE = 1), thus monthly pumping for the current month was used (PUMO = 08 and PUYR = 1973). For the third approach [status code 40 (PSCODE = 40)], monthly pumping data were not available (PDFILE = 1) for August 1983 (PUMO = 08 and PUYR = 1983). These data were used for August 1973. However, pumpage for August 1983 was multiplied by a factor of 0.7 (PFACT = 0.7) to represent the pumpage for August 1973.

5.3.5 User-Area-Inventory File (USER.DAT)

The inputs for the user-area inventory describe the user area characteristics. These inputs are listed below. (See table 23 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=I).
	3-10	A8	UNUM(*i*)	User number.
	12-20	I9	UTYPE(*i*)	User-type code.
	22-30	I9		Ditch-tender district number (for reference only).
2	1	A1	LINE	Record type (=Z).
	3-10	A8	UNUM(*i*)	User number.
	12-20	I9	IMO	Month of year for delivery adjustment.
	22-30	F9.0	PORDEL(*i,j*)	Proportion of delivery used for irrigation during specified month of year [dimensionless].
3	1	A1	LINE	Record type (=R).
	3-10	A8	UNUM(*i*)	User number.
	12-20	F9.0	AWC(*i*)	Available water capacity [dimensionless].
	22-30	F9.0	GAMMA(*i*)	Critical soil moisture [dimensionless].
	32-40	F9.0	UCOEF(*i*)	Uniformity coefficient [dimensionless].
	42-50	F9.0	THETA0(*i*)	Initial soil moisture [dimensionless].
	52-60	F9.0	RFACT(*i*)	Precipitation adjustment factor [dimensionless].
	62-70	F9.0	CLOSS(*i*)	Canal-loss coefficient [dimensionless].
	72-80	F9.0	TAILF(*i*)	Tailwater coefficient [dimensionless].
4	1	A1	LINE	Record type (=J).
	3-10	A8	UNUM(*i*)	User number.
	12-20	F9.0	AREA(*i,j*)	Irrigated acreage of user area [acres].
	24-25	I2	BAMO(*i,j*)	Begin month.
	27-30	I4	BAYR(*i,j*)	Begin year.
	34-35	I2	EAMO(*i,j*)	End month.
	37-40	I4	EAYR(*i,j*)	End year.
5	1	A1	LINE	Record type (=K).
	3-10	A8	UNUM(*i*)	User number.
	12-20	I9	UNODE(*i,j,k*)	Recharge node number.
	22-30	F9.0	UFACT(*i,j,k*)	Recharge proportion for node [dimensionless].

Table 23. Example of inputs for user-area inventory file (USER.DAT)

Record	Input records								
	L								
	I								
	N								
	E	UNUM	UTYPE						
	A1	A8	I9						
1	I	WESTID01	36						
	L								
	I								
	N								
	E	UNUM	IMO	PORDEL					
	A1	A8	I9	F9.0					
2	Z	WESTID01	1	1.00					
2	Z	WESTID01	2	1.00					
2	Z	WESTID01	3	1.00					
2	Z	WESTID01	4	1.00					
2	Z	WESTID01	5	1.00					
2	Z	WESTID01	6	1.00					
2	Z	WESTID01	7	1.00					
2	Z	WESTID01	8	1.00					
2	Z	WESTID01	9	1.00					
2	Z	WESTID01	10	1.00					
2	Z	WESTID01	11	1.00					
2	Z	WESTID01	12	1.00					
	L								
	I								
	N								
	E	UNUM	AWC	GAMMA	UCOEF	THETA0	RFACT	CLOSS	TAILF
	A1	A8	F9.0	F9.0	F9.0	F9.0	F9.0	F9.0	F9.0
3	R	WESTID01	0.1211	0.50	0.88	0.00	1.1707	0.05	0.10
	L								
	I								
	N								
	E	UNUM	AREA	BAMO	BAYR	EAMO	EAYR		
	A1	A8	F9.0	I2	I4	I2	I4		
4	J	WESTID01	1458.4	10	1961	9	1962		
	L								
	I								
	N								
	E	UNUM	UNODE	UFACT					
	A1	A8	I9	F9.0					
5	K	WESTID01	351	0.0064					
5	K	WESTID01	354	0.1072					
5	K	WESTID01	358	0.0289					
5	K	WESTID01	362	0.0019					
5	K	WESTID01	394	0.2279					
5	K	WESTID01	397	0.4423					
5	K	WESTID01	401	0.0968					

Table 23. Example of inputs for user-area inventory file (USER.DAT)–Continued

Record	Input records						
5	K	WESTID01	405	0.0016			
5	K	WESTID01	438	0.0551			
5	K	WESTID01	441	0.0310			
5	K	WESTID01	445	0.0008			
	L						
	I						
	N						
	E	UNUM	AREA	BAMO	BAYR	EAMO	EAYR
	A1	A8	F9.0	I2	I4	I2	I4
4	J	WESTID01	1399.7	10	1962	9	1963
	L						
	I						
	N						
	E	UNUM	UNODE	UFACT			
	A1	A8	I9	F9.0			
5	K	WESTID01	351	0.0064			
5	K	WESTID01	354	0.1072			
5	K	WESTID01	358	0.0289			
5	K	WESTID01	362	0.0019			
5	K	WESTID01	394	0.2279			
5	K	WESTID01	397	0.4423			
5	K	WESTID01	401	0.0968			
5	K	WESTID01	405	0.0016			
5	K	WESTID01	438	0.0551			
5	K	WESTID01	441	0.0310			
5	K	WESTID01	445	0.0008			

Notes:

1. Record 2 is repeated 12 times for each user, once for each month in a calendar year. If PORDEL is equal to 1.0, the total amount of water listed in the pumpage and delivery files assigned to a user area is used in the calculation of recharge for a user area. If PORDEL is less than 1.0, the total amount of water is adjusted by this proportion in the calculation of recharge.

2. Record 4 is repeated for each change in acreage of user area.

3. Record 5 is repeated for each node with each change in area. For a particular user the sum of the recharge proportions (UFACT) in Record 5 must equal 1.

The variables IMO and PORDEL in Record 2 can reduce the total amount of water used for irrigation within a user area on a monthly basis. For example, in an urban area, water supplies generally are used for landscape irrigation and indoor use. The disposal of water used indoors determines the value assigned to PORDEL. If the water used indoors is discharged to septic tanks, the water contributes to ground-water recharge for the area, and PORDEL equals 1.0 for all 12 months of the year. However, if water used indoors is routed to a treatment plant and then discharged to a river, this part of the urban water supply is not applied to the land, and thus, should not be used to calculate ground-water recharge for the area. If wastewater is discharged outside of the user area, the value assigned to PORDEL is less than 1.0, and a different value for PORDEL can be assigned to each month to reflect the usual monthly variation in the proportion of water used indoors and outdoors.

The distribution of the recharge from a user to the nodes in the finite-element grid depends on the intersection of the user area with the elements in the top surface of the grid. The intersection of a user area with an element is shown in figure 27. The recharge within the intersected area is distributed to the three nodes that define the top surface of the element that is intersected. The proportion of recharge from an intersected area to the total recharge from a user is equal to the proportion of irrigated acreage within the intersected area to the total irrigated acreage within the user area.

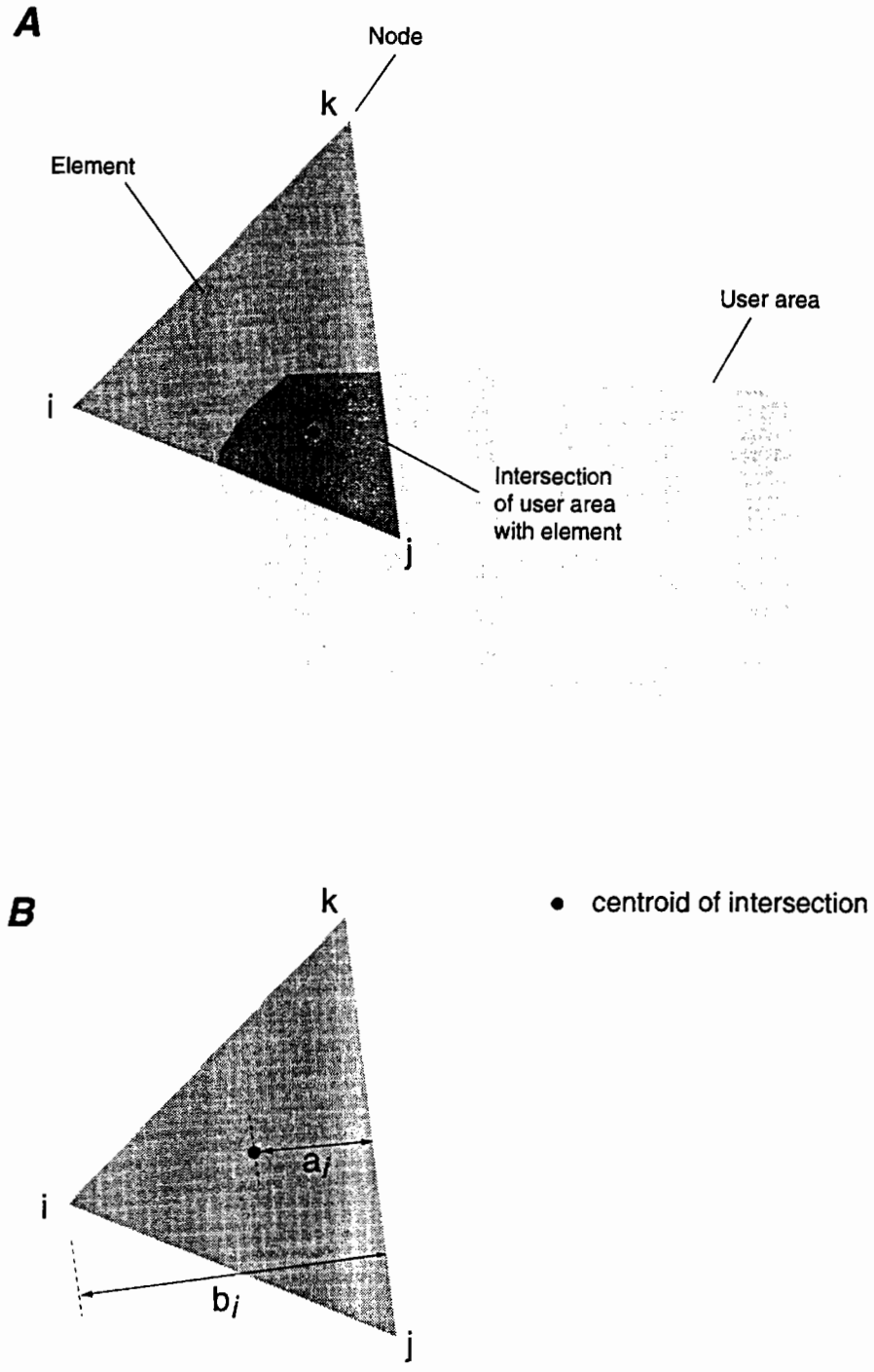


Figure 27. Distribution of recharge from user area to nodes in the finite-element grid.

The proportions of recharge to the nodes are obtained by considering the centroid of the intersected area. The geometry for the distribution of recharge from an intersected area to the node is shown in figure 27B. The proportion of recharge that is assigned to node i is given by the relation

$$r_i = \frac{a_i}{b_i}, \tag{5.3-5}$$

where

r_i is the recharge proportion for the node i for an intersected area [dimensionless],
a_i is the perpendicular distance from the side opposite node i to the centroid [L], and
b_i is the perpendicular distance from the side opposite node i to node i [L].

The proportions for the nodes j and k are given by similar relations. The sum of these proportions equals 1.0 for each intersection.

To calculate the recharge proportion (UFACT) for each node assigned recharge for the user area (UNODE), the recharge proportions from each intersected area must be weighted and summed for each node according to the expression

$$R_i = \sum_{I=1}^{n} r_i \frac{A_I}{A}, \tag{5.3-6}$$

where

R_i is the recharge proportion for the node i for the user area [dimensionless],
A_I is the irrigated acreage of the intersected area I [L^2], and
A is the irrigated acreage of the user area [L^2].

The sum of the proportions of the nodes assigned to the user area equals 1.0 for each user area in the model.

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The purpose of the delivery-construction file is to specify a canal-delivery scenario for a simulation. For each month in the simulation, the canal delivery is specified for each user-type code. The canal delivery for a user-type code can be specified using three alternative approaches. For the first approach, if monthly delivery data for individual user areas are not available for a particular month, the total delivery for all user areas within a user-type group can be specified, and the total delivery is distributed to individual user areas in proportion to the acreage of individual user areas. For the second approach, if monthly delivery data are available for the particular month, that monthly delivery data can be used to specify the deliveries for individual user areas. For the third approach, if monthly delivery data are available for a different month, that monthly delivery data can be used to specify the deliveries to individual user areas.

Examples of these three approaches are given in table 25 for August 1973 (DCMO = 08 and DCYR = 1973). For the first approach [user-type code 28 (UTCODE = 28)], monthly delivery data were not available (DDFILE = 0), and a total delivery of 2,000 acre-ft was distributed to the user areas (RDEL = 2000.0). For the second approach [user-type code 36 (UTCODE = 36)], monthly delivery data were available (DDFILE = 1), and the monthly deliveries for the current month were used (DUMO = 08 and DUYR = 1973). For the third approach [user-type code 50 (UTCODE = 50)], monthly delivery data were available (DDFILE = 1) for August 1983 (DUMO = 08 and DUYR = 1983), and those data were used for August 1973. However, the deliveries for August 1983 were multiplied by a factor of 0.7 (DFACT = 0.7) to represent the deliveries for August 1973.

5.3.8 Crop-Inventory File (CROP.DAT)

The inputs for crop inventory specify the crops for each user area. These inputs are listed below. (See table 26 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=P).
	3-10	A8	XUNUM	User number.
	17-20	I4	INYR(*i,j*)	Year of crop inventory record.
	22-30	I9	INCODE(*i,j*)	Crop code.
	32-50	A19		Crop name (for reference only).
	52-60	F9.0	INPOR(*i,j*)	Crop proportion [dimensionless].

Notes:

1. Record 1 is repeated for each user area, year of record, and crop type. If the proportion in a user area for a crop type is zero, omit that record.

Table 26. Example of inputs for crop-inventory file (CROP.DAT)

Record	Input records					
	L					
	I					
	N					
	E	XUNUM	INYR	INCODE	crop name	INPOR
	A1	A8	I4	I9	A19	F9.0
1	P	WESTID01	1942	13	LETTUCE	0.649
1	P	WESTID01	1942	10	COLE CROPS	0.248
1	P	WESTID01	1942	21	TRUCK (MISC)	0.103
1	P	WESTID01	1953	13	LETTUCE	0.667
1	P	WESTID01	1953	10	COLE CROPS	0.228
1	P	WESTID01	1953	21	TRUCK (MISC)	0.101
1	P	WESTID01	1966	6	FIELD (MISC)	0.477
1	P	WESTID01	1966	13	LETTUCE	0.275
1	P	WESTID01	1966	10	COLE CROPS	0.248
1	P	WESTID01	1977	05	DRY BEANS	0.921
1	P	WESTID01	1977	20	FLOWERS	0.066
1	P	WESTID01	1977	30	URBAN LANDSCAPE	0.004
1	P	WESTID01	1977	10	COLE CROPS	0.009
1	P	WESTID01	1984	5	DRY BEANS	0.886
1	P	WESTID01	1984	26	CITRUS	0.099
1	P	WESTID01	1984	6	FIELD (MISC)	0.008
1	P	WESTID01	1984	10	COLE CROPS	0.007
1	P	WESTID02	1942	29	PASTURE	1.000
1	P	WESTID02	1953	29	PASTURE	1.000
1	P	WESTID02	1966	29	PASTURE	1.000
1	P	WESTID02	1977	29	PASTURE	1.000
1	P	WESTID02	1984	9	GREEN BEANS	0.966
1	P	WESTID02	1984	29	PASTURE	0.034

5.3.9 Rooting-Depth File (ROOT.DAT)

The inputs for rooting depth specify the rooting depth for individual crops. These inputs are listed below. (See table 27 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=W).
	3-10	I8	CCODE(*i*)	Crop code.
	12-30	A19		Crop name (for reference only.
	32-40	F9.0	ROOT(*i*)	Rooting depth [inches].

Notes:

1. Record 1 is repeated for each crop.

Table 27. Example of inputs for rooting-depth file (ROOT.DAT)

Record	Input records

```
        L
        I
        N
        E    CCODE crop name                ROOT
        A1   I8    A19                      F9.0

1       W        1 FLAX                     48
1       W        2 SUGAR BEETS              66
1       W        3 CORN                     36
1       W        4 SUDAN                    72
1       W        5 DRY BEANS                42
1       W        6 FIELD (MISC)             42
1       W        7 ARTICHOKES               54
1       W        8 ASPARAGUS               120
1       W        9 GREEN BEANS              36
1       W       10 COLE CROPS               24
1       W       11 SWEET CORN               36
1       W       12 CARROTS                  36
1       W       13 CELERY                   12
1       W       14 LETTUCE                  18
1       W       15 PUMPKINS                 72
1       W       16 GARLIC                   12
1       W       17 POTATOES                 48
1       W       18 SPINACH                  24
1       W       19 TOMATOES                 48
1       W       20 FLOWERS                  42
1       W       21 TRUCK (MISC)             42
1       W       22 STRAWBERRIES             42
1       W       23 BROCCOLI                 24
1       W       24 CABBAGE                  24
1       W       25 CAULIFLOWER              24
1       W       26 CITRUS                   18
1       W       27 DECIDUOUS TREES          72
1       W       28 GRAIN                    48
1       W       29 PASTURE                  36
1       W       30 URBAN LANDSCAPE          24
1       W       31 NON-IRRIG GRAIN          48
1       W       32 NON-IRRIG PASTURE       120
1       W       33 NATIVE VEGETATION        24
```

5.3.10 Monthly-Precipitation File (PRECIP.DAT)

The inputs for monthly precipitation specify the monthly precipitation on user areas. These inputs are listed below. (See table 28 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=U).
	6-9	I4	XYR	Year of precipitation record.
	10-15	F6.0	RAIN(*i*)	January precipitation [inches].
	16-21	F6.0	RAIN(*i*)	February precipitation [inches].
	22-27	F6.0	RAIN(*i*)	March precipitation [inches].
	28-33	F6.0	RAIN(*i*)	April precipitation [inches].
	34-39	F6.0	RAIN(*i*)	May precipitation [inches].
	40-45	F6.0	RAIN(*i*)	June precipitation [inches].
	46-51	F6.0	RAIN(*i*)	July precipitation [inches].
	52-57	F6.0	RAIN(*i*)	August precipitation [inches].
	58-63	F6.0	RAIN(*i*)	September precipitation [inches].
	64-69	F6.0	RAIN(*i*)	October precipitation [inches].
	70-75	F6.0	RAIN(*i*)	November precipitation [inches].
	76-81	F6.0	RAIN(*i*)	December precipitation [inches].

Notes:

1. Record 1 is repeated for each year of record.

Table 28. Example of inputs for monthly precipitation file (PRECIP.DAT)

Record **Input records**

```
        L
        I
        N     XYR  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN  RAIN
        E          jan   feb   mar   apr   may   jun   jul   aug   sep   oct   nov   dec
        A1     I4  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0  F6.0

1       U    1975  0.19  3.88  5.82  0.92  0.00  0.00  0.00  0.00  0.00  0.53  0.36  0.16
1       U    1976  0.00  4.68  1.40  1.31  0.03  0.16  0.02  0.57  2.67  0.53  0.80  0.89
1       U    1977  1.87  0.12  1.95  0.01  2.54  0.00  0.00  0.00  0.01  0.00  0.15  3.22
1       U    1978  6.81  8.27  7.92  2.92  0.00  0.00  0.00  0.00  1.43  0.00  1.31  1.14
1       U    1979  4.78  3.08  4.37  0.03  0.09  0.00  0.00  0.00  0.29  0.62  0.50  2.67
1       U    1980  3.69  6.34  1.96  0.65  0.11  0.00  0.02  0.00  0.00  0.00  0.00  1.14
1       U    1981  3.24  2.88  5.98  0.40  0.00  0.00  0.00  0.00  0.00  0.53  0.81  0.89
1       U    1982  2.66  0.77  4.59  2.45  0.00  0.02  0.00  0.00  0.35  1.40  3.11  1.64
1       U    1983  8.43  6.61  6.73  3.55  0.37  0.06  0.00  0.53  0.03  0.52  2.37  3.46
1       U    1984  0.06  0.38  0.52  0.63  0.00  0.00  0.00  0.18  0.07  0.25  2.50  4.63
1       U    1985  0.69  0.85  1.28  0.00  0.00  0.00  0.00  0.00  0.01  0.57  5.06  0.70
1       U    1986  1.93  4.84  5.06  0.27  0.00  0.00  0.00  0.00  0.75  0.00  2.01  0.94
1       U    1987  2.15  1.72  4.00  0.33  0.09  0.04  0.00  0.00  0.00  1.49  0.81  4.63
1       U    1988  1.85  2.28  0.19  2.67  0.12  0.21  0.00  0.00  0.00  0.00  0.77  3.08
1       U    1989  0.46  0.58  0.37  0.20  0.26  0.00  0.00  0.00  0.64  0.28  0.33  0.00
1       U    1990  2.87  1.70  0.44  0.44  0.58  0.01  0.00  0.00  0.05  0.00  0.22  0.82
1       U    1991  1.26  2.17 11.63  0.38  0.00  0.02  0.03  0.04  0.01  0.00  0.00  0.00
1       U    1992  2.69  7.06  2.31  0.01  0.00  0.02  0.06  0.00  0.00  0.49  0.00  3.63
1       U    1993  6.36  5.66  3.16  0.02  0.12  0.11  0.00  0.00  0.00  0.25  0.86  1.75
1       U    1994  1.82  4.47  2.40  0.84  0.74  0.00  0.00  0.00  0.03  0.63  2.38  0.99
```

5.3.11 Monthly Potential Evapotranspiration File (PET.DAT)

The inputs for monthly potential evapotranspiration (PET) specify the monthly PET for each crop. These inputs are listed below. (See table 29 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=V).
	3-4	I2	XCODE	Crop code.
	6-9	I4	XYR	Year of potential evapotranspiration.
	10-15	F6.0	PET(*i,j*)	January PET [inches].
	16-21	F6.0	PET(*i,j*)	February PET [inches].
	22-27	F6.0	PET(*i,j*)	March PET [inches].
	28-33	F6.0	PET(*i,j*)	April PET [inches].
	34-39	F6.0	PET(*i,j*)	May PET [inches].
	40-45	F6.0	PET(*i,j*)	June PET [inches].
	46-51	F6.0	PET(*i,j*)	July PET [inches].
	52-57	F6.0	PET(*i,j*)	August PET [inches].
	58-63	F6.0	PET(*i,j*)	September PET [inches].
	64-69	F6.0	PET(*i,j*)	October PET [inches].
	70-75	F6.0	PET(*i,j*)	November PET [inches].
	76-81	F6.0	PET(*i,j*)	December PET [inches].

Notes:

1. Record 1 is repeated for each year of record and for each crop, and is entered by crop and then by year for the crop.

Table 29. Example of inputs for monthly potential evapotranspiration file (PET.DAT)

Record	Input records														
	LINE	XCOORDE	XYR	PET jan	PET feb	PET mar	PET apr	PET may	PET jun	PET jul	PET aug	PET sep	PET oct	PET nov	PET dec
	A1	I2	I4	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0	F6.0
1	V	1	1971	1.64	2.61	3.37	4.27	2.30	0.28	1.12	0.83	0.76	0.48	0.75	0.67
1	V	1	1972	1.82	1.96	3.82	5.35	2.95	0.29	0.95	0.81	0.59	0.38	0.41	0.54
1	V	1	1973	1.29	1.57	3.55	6.07	3.10	0.30	0.92	0.81	0.69	0.37	0.72	0.54
1	V	1	1974	1.19	2.47	3.05	4.31	3.16	0.33	0.91	0.83	0.64	0.50	0.53	0.70
1	V	1	1975	1.49	2.20	3.78	4.10	3.37	0.31	0.86	0.81	0.56	0.41	0.70	0.74
1	V	1	1976	1.90	3.08	4.93	4.96	3.64	0.37	0.96	0.74	0.56	0.38	0.70	0.97
1	V	1	1977	1.01	2.67	4.57	6.49	2.26	0.31	0.95	0.77	0.55	0.38	0.68	0.44
1	V	1	1978	0.79	1.73	3.26	4.09	3.53	0.31	0.86	0.76	0.65	0.55	0.80	0.89
1	V	1	1979	1.40	1.17	2.52	3.90	3.42	0.28	0.90	0.70	0.58	0.29	0.35	0.63
1	V	1	1980	1.04	1.63	4.63	4.16	2.64	0.25	0.83	0.75	0.60	0.45	0.72	0.69
1	V	2	1971	1.64	2.61	0.32	0.47	6.38	9.40	11.95	9.23	8.29	1.80	0.75	0.67
1	V	2	1972	1.82	1.96	0.36	0.59	8.20	9.60	10.08	9.00	6.47	1.43	0.41	0.54
1	V	2	1973	1.29	1.57	0.33	0.68	8.60	10.00	9.79	9.00	7.57	1.41	0.72	0.54
1	V	2	1974	1.19	2.47	0.29	0.48	8.78	11.07	9.75	9.21	6.96	1.91	0.53	0.70
1	V	2	1975	1.49	2.20	0.35	0.46	9.37	10.34	9.15	8.97	6.08	1.55	0.70	0.74
1	V	2	1976	1.90	3.08	0.46	0.55	10.11	12.20	10.20	8.25	6.06	1.43	0.70	0.97
1	V	2	1977	1.01	2.67	0.43	0.72	6.29	10.21	10.13	8.55	5.95	1.43	0.68	0.44
1	V	2	1978	0.79	1.73	0.31	0.45	9.81	10.29	9.16	8.39	7.04	2.09	0.80	0.89
1	V	2	1979	1.40	1.17	0.24	0.43	9.49	9.31	9.56	7.81	6.30	1.08	0.35	0.63
1	V	2	1980	1.04	1.63	0.43	0.46	7.34	8.45	8.80	8.37	6.56	1.72	0.72	0.69
1	V	3	1971	1.64	2.61	0.32	0.47	0.57	2.91	10.96	7.48	1.44	0.48	0.75	0.67
1	V	3	1972	1.82	1.96	0.36	0.59	0.74	2.98	9.24	7.29	1.12	0.38	0.41	0.54
1	V	3	1973	1.29	1.57	0.33	0.68	0.77	3.10	8.98	7.29	1.31	0.37	0.72	0.54
1	V	3	1974	1.19	2.47	0.29	0.48	0.79	3.43	8.94	7.46	1.21	0.50	0.53	0.70
1	V	3	1975	1.49	2.20	0.35	0.46	0.84	3.21	8.39	7.27	1.05	0.41	0.70	0.74
1	V	3	1976	1.90	3.08	0.46	0.55	0.91	3.78	9.35	6.68	1.05	0.38	0.70	0.97
1	V	3	1977	1.01	2.67	0.43	0.72	0.57	3.17	9.28	6.93	1.03	0.38	0.68	0.44
1	V	3	1978	0.79	1.73	0.31	0.45	0.88	3.19	8.40	6.80	1.22	0.55	0.80	0.89
1	V	3	1979	1.40	1.17	0.24	0.43	0.85	2.89	8.76	6.33	1.09	0.29	0.35	0.63
1	V	3	1980	1.04	1.63	0.43	0.46	0.66	2.62	8.07	6.78	1.14	0.45	0.72	0.69

5.3.12 Crop-Construction and Weather-Construction File (CCROP.DAT)

The inputs for the crop-construction and weather-construction file specify a crop and weather scenario for a simulation. This file selects data from the crop-inventory file, the monthly precipitation file, and the monthly potential evapotranspiration file and assigns these data to each month in the simulation. These inputs are listed below. (See table 30 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1	A1	LINE	Record type (=S).
	4-5	I2	CCMO(*i*)	Month of crop- and weather-construction record.
	7-10	I4	CCYR(*i*)	Year of crop- and weather-construction record.
2	1	A1	LINE	Record type (=T).
	3-10	I8	ETCODE(*i,j*)	User-type code.
	17-20	I4	CUYR(*i,j*)	Year of record from crop inventory file to use for crops.
24-25	I2	EUMO(*i,j*)		Month of record from precipitation and potential evapotranspi- ration files to use for weather.
	27-30	I4	EUYR(*i,j*)	Year of record from precipitation and potential evapotranspi- ration files to use for weather.

Notes:

1. Record 2 is repeated for each user-type code. Records 1 and 2 are repeated as a group for each month.

Table 30. Example of inputs for crop-construction and weather-construction file (CCROP.DAT)

Record	Input records
	L
	I
	N
	E CCMO CCYR
	A1 I2 I4
1	S 10 1941
	L
	I
	N
	E ETCODE CUYR EUMO EUYR
	A1 I8 I4 I2 I4
2	T 18 1942 10 1941
2	T 25 1942 10 1941
2	T 26 1942 10 1941
2	T 27 1942 10 1941
2	T 28 1942 10 1941
2	T 31 1942 10 1941
2	T 32 1942 10 1941
2	T 33 1942 10 1941
2	T 34 1942 10 1941
2	T 35 1942 10 1941
2	T 36 1942 10 1941
2	T 40 1942 10 1941
2	T 50 1942 10 1941
	L
	I
	N
	E CCMO CCYR
	A1 I2 I4
1	S 11 1941
	L
	I
	N
	E ETCODE CUYR EUMO EUYR
	A1 I8 I4 I2 I4
2	T 18 1942 11 1941
2	T 25 1942 11 1941
2	T 26 1942 11 1941
2	T 27 1942 11 1941
2	T 28 1942 11 1941
2	T 31 1942 11 1941
2	T 32 1942 11 1941
2	T 33 1942 11 1941
2	T 34 1942 11 1941
2	T 35 1942 11 1941
2	T 36 1942 11 1941
2	T 40 1942 11 1941
2	T 50 1942 11 1941

5.3.13 Recharge-Proportions File (HARDPAN.DAT)

The inputs for the recharge-proportion file specify what proportion of deep percolation becomes ground-water recharge. These inputs are listed below. (See table 31 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1-50	5F10.0	RDEEP(*i*)	Proportion of deep percolation that becomes ground-water recharge [dimensionless].

Notes:

1. Record 1 is repeated until a value for each node in the finite-element grid has been entered. The number of nodes is specified by NN in Record 9 of the input file for subroutine *MODEL*.

Table 31. Example of inputs for recharge-proportions file (HARDPAN.DAT)

Record	Input records					Remarks
	RDEEP F10.0	RDEEP F10.0	RDEEP F10.0	RDEEP F10.0	RDEEP F10.0	(5F10.0) The file lists a recharge proportion for each node in the model. If there is no hardpan present, the proportion is equal to 1.00.
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	0.75	1.00	1.00	1.00	0.50	
1	1.00	1.00	1.00	0.50	1.00	
1	1.00	1.00	0.50	1.00	1.00	
1	1.00	0.50	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	0.75	1.00	
1	1.00	1.00	0.50	1.00	1.00	
1	1.00	0.50	1.00	1.00	1.00	
1	0.50	1.00	1.00	1.00	0.50	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	1.00	1.00	
1	1.00	1.00	1.00	0.75	1.00	
1	1.00	1.00	0.50	1.00	1.00	
1	1.00	0.50	1.00	1.00	1.00	
1	0.50	1.00	1.00	1.00	0.50	
1	1.00	1.00	1.00	0.50	1.00	

5.3.14 Pumping-Destination File (DESTIN.DAT)

The inputs for the pumping-destination file specify that pumpage from wells within a group, indicated by the well-status code, is discharged into the canal system, rather than used directly for irrigation. These inputs are listed below. (See table 32 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1-10	I10	NPOUT	Number of groups of wells that do not pump to user.
2	1-10	I10	POUT(*i*)	Identity of well-status code for each group of wells.

Notes:

1. Record 2 is repeated for NPOUT groups of wells.

Table 32. Example of inputs for pumping-destination file (DESTIN.DAT)

Record	Input records
	NPOUT
	I10
1	3
	POUT
	I10
2	45
2	46
2	47

5.3.15 Well-Exclusion File (EXCLUDE.DAT)

The inputs for the well-exclusion file specify that pumpage from an indicated well is excluded from the simulation. These inputs are listed below. (See table 33 for a formatted example for these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1-10	I10	NEXC	Number of wells to be excluded.
2	1-12	A12	EWNUM(*i*)	Name of well to be excluded.

Notes:

1. Record 2 is repeated for NEXC well names.

Table 33. Example of inputs for well-exclusion file (EXCLUDE.DAT)

Record	Input records
	NEXC
	I10
1	3
	EWNUM
	A12
2	T15R03S15C01
2	T15R04S02Q02
2	T15R04S32H01

5.4 Subroutine *Search* Input Files

The parameter-identification files contain the description of the parameter-identification problem to be solved. The parameter-index file (MODEL.IND) contains specification for the assignment of aquifer parameters to global parameters within subroutine *SEARCH*, which is described in Section 3.16.2.2. The assignment of parameter indexes for the hydraulic conductivity of the river bed is specified by the variable INDRIV in the river-aquifer interactions file (RIVER). The parameter-search file (SEARCH.DAT) configures the parameter-identification problem that is to be solved. If a simulation does not require parameter identification, the parameter-search file can be omitted. In this case, IFIT in Record 2 of the model input (described in Section 5.2.1) must equal zero, and the parameter-index file in the file specification file (described in Section 5.1) is named "NUL."

5.4.1 Parameter-Index File (MODEL.IND)

The inputs for the parameter-index file describe the association of parameters with the hydraulic properties of elements. These inputs are listed below. (See table 34 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1-10	I10		Element number (for reference only).
	11-20	I10	INDKXX	Parameter index for the hydraulic conductivity in the *x* direction of the element.
	21-30	I10	INDKYY	Parameter index for the hydraulic conductivity in the *y* direction of the element.
	31-40	I10	INDKZZ	Parameter index for the hydraulic conductivity in the *z* direction of the element.
	41-50	I10	INDSS	Parameter index for the specific storage of the element.
	51-60	I10	INDSY	Parameter index for assignment of specific yield to element of the parameter vector.

Notes:

1. Record 1 is repeated for the number of prismatic elements (NE times), where NE is given in Record 9 of the model-input file.

2. More than one aquifer-parameter value can be assigned to a single parameter index, which allows aquifer-parameter values within a three-dimensional block of the ground-water system to be adjusted as a group by the same proportion during the parameter-identification procedure.

Table 34. Example of inputs for parameter-index file (MODEL.IND)

Record	Input records					
	element number	INDKXX	INDKYY	INDKZZ	INDSS	INDSY
	I10	I10	I10	I10	I10	I10
1	1	4	4	23	42	61
1	2	4	4	23	42	61
1	3	1	1	20	39	58
1	4	1	1	20	39	58
1	5	1	1	20	39	58
1	6	1	1	20	39	58
1	7	4	4	23	42	61
1	8	4	4	23	42	61
1	9	4	4	23	42	61
1	10	4	4	23	42	61
1	11	4	4	23	42	61
1	12	1	1	20	39	58
1	13	1	1	20	39	58
1	14	1	1	20	39	58
1	15	1	1	20	39	58
1	16	4	4	23	42	61
1	17	4	4	23	42	61
1	18	5	5	24	43	62
1	19	5	5	24	43	62
1	20	5	5	24	43	62
1	21	1	1	20	39	58
1	22	1	1	20	39	58
1	23	1	1	20	39	58
1	24	1	1	20	39	58
1	25	4	4	23	42	61
1	26	4	4	23	42	61
1	27	5	5	24	43	62
1	28	5	5	24	43	62
1	29	5	5	24	43	62
1	30	5	5	24	43	62
1	31	5	5	24	43	62
1	32	1	1	20	39	58
1	33	1	1	20	39	58
1	34	1	1	20	39	58
1	35	1	1	20	39	58
1	36	4	4	23	42	61
1	37	6	6	25	44	63
1	38	5	5	24	43	62
1	39	5	5	24	43	62
1	40	5	5	24	43	62
1	41	5	5	24	43	62
1	42	5	5	24	43	62
1	43	5	5	24	43	62

5.4.2 Parameter-Search File (SEARCH.DAT)

The inputs for the parameter-search file specify the parameter-identification problem to be solved. These inputs are listed below. (See table 35 for a formatted example of these inputs.)

Record	Columns	Format	Variable	Variable Description
1	1-10	I10	NGBL	Number of global parameters.
	11-20	I10	NPAR	Number of active parameters.
	21-30	I10	NITER	Number of iterations in parameter-identification process.
	31-40	F10.0	PFACT	Perturbation factor for calculating the finite-difference approximation for sensitivity matrix.
	41-50	I10	IOLS	Switch for doing an ordinary nonlinear least-squares.
2	1-10	I10		Global parameter number (for reference only).
	11-20	F10.0	PARAM0(*i*)	Parameter value for global parameter [dimensionless].
	21-30	F10.0	IPARAM(*i*)	Active parameter corresponding to global parameter.
3	11-20	F10.0	PARAM(*i*)	Initial value for active parameter [dimensionless].
	21-30	F10.0	UPAR(*i*)	Prior estimate of mean value for parameter [dimensionless].
	31-40	F10.0	VPAR(*i*)	Prior estimate of standard deviation for the estimate of mean value for parameter [dimensionless].
4	1-10	I10	NOBS	Number of water-level observations.
5	1-10	I10	STEP(*i*)	Time step in simulation that corresponds to the measured water level [dimensionless].
	11-20	I10	NODE1(*i*)	First node number.
	21-30	F10.0	WEIGHT1(*i*)	First node weighting factor.
	31-40	I10	NODE2(*i*)	Second node number.
	41-50	F10.0	WEIGHT2(*i*)	Second node weighting factor.
	51-60	I10	NODE3(*i*)	Third node number.
	61-70	F10.0	WEIGHT3(*i*)	Third node weighting factor.
	71-80	F10.0	WLM(*i*)	Water-level measurement [ft].
	81-90	F10.0	WOBS(*i*)	Standard deviation of error in water-level measurement [ft].
	93-104	A12		Well name (for reference only).

Notes:

1. Record 2 is repeated for each of the global parameters (NGBL times).
2. Record 3 is repeated for each active parameter (NPAR times).
3. Record 5 is repeated for NOBS water-level measurements.
4. The number of global parameters (NGBL) must correspond with the number of parameter indexes in the parameter index file. Accordingly, NGBL must equal the total number of aquifer-parameter block assignments made.
5. The number of active parameters (NPAR) is the number of parameters that will be adjusted during parameter-identification process. NPAR must be less than or equal to NGBL.
6. The perturbation factor PFACT is the natural log of the factor by which the aquifer parameters in subroutine *MODEL* are to be perturbed.
7. The switch IOLS equals zero if the MAP least-squares method is to be used. The switch equals 1 if the ordinary nonlinear least squares method is to be used.

8. The active parameter correspondence IPARAM equals zero, if the global parameter is not being adjusted. Otherwise, IPARAM is less than or equal to NPAR. More than one global parameter can be assigned to the same active parameter.

9. The prior estimate of the mean value for the parameter UPAR is entered in terms of the natural log of the mean.

10. The prior estimate of the standard deviation for the estimates of the mean VPAR is entered in terms of the standardization of the natural logs.

11. Each well selected for use in the calibration can be located within a stack of one or more finite elements as described in Section 5.3.1, Well-Site Inventory File. In the horizontal plane, three nodes within the stack of elements will most closely correspond to the screened interval of the well. These three nodes form a horizontal triangle around the well screen. Variables NODE1(*i*), NODE2(*i*), and NODE3(*i*) identify these three nodes for each well. The model first calculates water levels for each node. The weighting factor for each node is given by the relation

$$w_i = \frac{a_i}{b_i},$$

where

w_i is the weighting factor for the node,
a_i is the perpendicular distance from the side opposite the node *i* to the well [L], and
b_i is the perpendicular distance from the side opposite node *i* to node *i* [L].

Table 35. Example of inputs for parameter-search file (SEARCH.DAT)

Record	Input records				
	NGBL I10	NPAR I10	NITER I10	PFACT F10.0	IOLS I10
1	20	3	2	0.05	0
	global parameter number	PARAMO F10.0	IPARAM F10.0		
2	1	0	1		
2	2	0	1		
2	3	0	2		
2	4	0	2		
2	5	0	3		
2	6	0	3		
2	7	0	0		
2	8	0	0		
2	9	0	0		
2	10	0	0		
2	11	0	0		
2	12	0	0		
2	13	0	0		
2	14	0	0		
2	15	0	0		
2	16	0	0		
2	17	0	0		
2	18	0	0		
2	19	0	0		
2	20	0	0		
	active parameter number	PARAM F10.0	UPAR F10.0	VPAR F10.0	
3	1	0	0	0.0063	
3	2	0	0	0.0063	
3	3	0	0	0.0063	
	NOBS I10				
4	1318				

Table 35. Example of inputs for parameter-search file (SEARCH.DAT)--Continued

Record	Input records									
	STEP I10	NODE1 I10	WEIGHT1 F10.0	NODE2 I10	WEIGHT2 F10.0	NODE3 I10	WEIGHT3 F10.0	WLM F10.0	WOBS F10.0	well name A12
5	1	226	0.263	269	0.577	229	0.160	53.0	5.0	T16R04S06C01
5	2	226	0.263	269	0.577	229	0.160	51.2	5.0	T16R04S06C01
5	3	226	0.263	269	0.577	229	0.160	51.5	5.0	T16R04S06C01
5	4	226	0.263	269	0.577	229	0.160	51.8	5.0	T16R04S06C01
5	5	226	0.263	269	0.577	229	0.160	52.1	5.0	T16R04S06C01
5	6	226	0.263	269	0.577	229	0.160	52.3	5.0	T16R04S06C01
5	7	226	0.263	269	0.577	229	0.160	52.0	5.0	T16R04S06C01
5	8	226	0.263	269	0.577	229	0.160	52.0	5.0	T16R04S06C01
5	1	136	0.453	179	0.186	139	0.361	64.6	5.0	T17R04S23C01
5	2	136	0.453	179	0.186	139	0.361	63.5	5.0	T17R04S23C01
5	3	136	0.453	179	0.186	139	0.361	64.2	5.0	T17R04S23C01
5	4	136	0.453	179	0.186	139	0.361	65.6	5.0	T17R04S23C01
5	5	136	0.453	179	0.186	139	0.361	65.3	5.0	T17R04S23C01
5	6	136	0.453	179	0.186	139	0.361	65.8	5.0	T17R04S23C01
5	7	136	0.453	179	0.186	139	0.361	66.1	5.0	T17R04S23C01
5	8	136	0.453	179	0.186	139	0.361	66.2	5.0	T17R04S23C01

5.5 Specifying Array Dimensions for Problem Size

The dimensions of arrays in the *FEMFLOW3D* must be set to accommodate a particular problem size. The dimensions are set by editing two files, each containing a PARAMETER statement. These files are included in appropriate subroutines by INCLUDE statements, where the parameters within the PARAMETER statement are the dimensions of arrays.

The file PARAM.FOR contains the PARAMETER statement that dimensions the size of the finite-element problem to be solved. These arrays are those associated with the finite-element solution, specified-head boundaries, specified-flux boundaries, internal fluxes, stream-aquifer interactions, ground-water evapotranspiration, variable-flux boundaries, fault internal conditions, and land subsidence. However, the PARAMETER statement in file PARAM.FOR does not dimension the size of the irrigated-agricultural problem to be solved.

The parameter value in the PARAMETER statement should be set as follows:

Parameter	Definition
MAXNN	Maximum number of nodes in the finite-element grid. The value of MAXNN equals the number of nodes.
MAXNE	Maximum number of prismatic elements in the finite-element grid. The value of MAXNE equals the number of elements.
MAXNE2	Maximum number of tetrahedral elements in the finite-element grid. The number of tetrahedral elements is never larger than three times the number of prismatic elements. Therefore, the value of MAXNE2 equals three times the value of MAXNE. However, if some of the prismatic elements have zero-height edges, the number of tetrahedral elements will be smaller.
MAXNB	Maximum half-band width. The value of MAXNB is determined by the pattern by which nodes in the finite-element grid are assigned numbers. The half-band width more specifically is determined by the element in the grid that has the maximum difference between the node numbers that define the element. Therefore, the value of MAXNB equals that maximum difference plus 1.
MAXSTP	Maximum number of time steps in the simulation. The value of MAXSTP equals the number of time steps.
MAXFLS	Maximum number of file segments that are concatenated into an input file. The value of MAXFLS equals the maximum number of file segments for an input file. However, the value of MAXFLS equals 1 if no file segments are concatenated.
MAXCOL	Maximum number of element columns. The value of MAXCOL equals the maximum number of element columns specified in the input file for land subsidence. The number of columns is never larger than the number of elements in the top surface of the grid. The value of MAXCOL equals 1 if land subsidence is not simulated.
MAXNUM	Maximum number of elements in a column. The value of MAXNUM equals the maximum number of element layers specified in the input file for land subsidence. The number of elements in a column is never larger than the number of element layers in the grid. The value of MAXNUM equals 1 if land subsidence is not simulated.
MAXCHN	Maximum number of specified-head nodes. The value of MAXCHN equals the number of specified-head nodes. However, the value of MAXCHN equals 1 if specified-head nodes are not simulated.

MAXTAB	Maximum number of entries in specified-head tables. The specified-head tables define hydrographs of heads for the specified-head nodes. The entries in the tables are the points that define the hydrographs. Therefore, the value of MAXTAB equals the number of entries in the table with the largest number entries. However, the value of MAXTAB equals 1 if tables are not used.
MAXSET	Maximum number of flux data sets. The specified-flux data sets define the fluxes at nodes. To represent temporal changes in the spatial distribution of fluxes, multiple data sets can be used. Therefore, the value of MAXSET equals the number of data sets. However, the value of MAXSET equals 1 if no specified-flux nodes are simulated.
MAXRCH	Maximum number of river channels. A river system is represented by a network of tributary river channels. The value of MAXRCH equals the number of separate channels in the network. However, the value of MAXRCH equals 1 if river-aquifer interactions are not simulated.
MAXRIV	Maximum number of node reaches in a river channel. Each river channel is divided into reaches, each associated with a node in the finite-element grid. The value of MAXRIV equals the number of node reaches in the channel having the most node reaches. However, the value of MAXRIV equals 1 if river-aquifer interactions are not simulated.
MAXINF	Maximum number of inflow locations within the river system. These are locations where inflows are specified for each time step. The value of MAXINF equals the number of these inflows. However, the value of MAXINF equals zero if river-aquifer interactions are not simulated.
MAXSEC	Maximum number of tables of stream-channel geometry. The stage-discharge and width-discharge relations for a node reach can be represented by tabulations of the relations. The value of MAXSEC equals the number of these relations. However, the value of MAXSEC equals 1 if river-aquifer relations are not simulated or if tabulated relations are not used.
MAXPTS	Maximum number of points in a table of river-channel geometry. The channel-geometry tables define stage-discharge and width-discharge relations for node reaches. The entries in the table are the points that define the relations. Therefore, the value of MAXPTS equals the number of entries in the table with the largest number of entries. However, the value of MAXPTS equals 1 if river-aquifer interactions are not simulated or if tabulated relations are not used.
MAXETN	Maximum number of evapotranspiration nodes. The value of MAXETN equals the number of evapotranspiration nodes. Value of MAXETN equals 1 if ground-water evapotranspiration is not simulated.
MAXVFB	Maximum number of variable-flux nodes. The value of MAXVFB equals the number of variable-flux nodes. However, the value of MAXVFB equals 1 if variable-flux boundaries are not simulated.
MAXFLN	Maximum number of fault links. The value of MAXFLN equals the number of fault links. However, the value of MAXFLN equals 1 if fault links are not simulated.
MAXPAR	Maximum number of parameter in the parameter-identification problem. The value of MAXPAR equals the number of parameters. However, the value of MAXPAR equals 1 if parameter identification is not done.
MAXWL	Maximum number of measured water levels in the parameter-identification problem. The value of MAXWL equals the number of measured water levels. However, the value of MAXWL equals 1 if parameter identification is not done.

The file PARAM2.FOR contains the PARAMETER statement that dimensions the size of the irrigated-agriculture problem to be solved. If an irrigated-agricultural system is not simulated, the parameter values all equal 1. Otherwise, the parameter values in the PARAMETER statement should be set as follows:

MAXWEL	Maximum number of wells. The value of MAXWEL equals the number of wells.
MAXWST	Maximum number of well-status changes. The status of a well changes if the user area for the well changes or if the group category of the well changes. These changes in well status are reflected by multiple records in the well-status file. The value of MAXWST equals the maximum number of records for an individual well.
MAXWND	Maximum number of well nodes. Each well is associated with a set of nodes. The value of MAXWND equals the number of nodes associated with the well with the largest number of nodes.
MAXWSQ	Maximum number of records in the monthly pumping file. The value of MAXWSQ equals the total monthly pumpage for all wells and all months.
MAXPCE	Maximum number of well-status codes. Well-status codes are established for specified well groups. The value of MAXPCE is the number of different well-status codes.
MAXUSE	Maximum number of user areas. The value of MAXUSE equals the number of user areas.
MAXUST	Maximum number of user-area changes. The acreage within a user area can be changed with time. The value of MAXUST equals the maximum number of acreage change for an individual user area.
MAXUND	Maximum number of user-area nodes. Each user area is associated with a set of nodes, which can change with time. The value of MAXUND equals the number of nodes associated with the user area with the largest number of nodes.
MAXUSQ	Maximum number of monthly canal-delivery values. The value of MAXUSQ equals the total number of monthly delivery values for all user areas and all months.
MAXDCE	Maximum number of user-type codes. User-type codes are established for specified user-area groups. The value of MAXDCE is the number of different user-type codes.
MAXCON	Maximum number of months in construction files. The pumping-construction, delivery-construction, and crop-construction files specify pumpage, canal deliveries, crops, and weather representing a particular simulation scenario. The construction files specify these conditions for each month in the simulation. The value of MAXCON is the number of months in a construction file.
MAXCRP	Maximum number of crops. The value of MAXCRP is the number of crops.
MAXREC	Maximum number of crop inventory records per user.

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