A METHOD OF CONVERTING NO-FLOW CELLS TO VARIABLE-HEAD CELLS FOR THE U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL

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CONVERSION FACTORS

Multiply	By	To obtain
foot	0.3048	meter
foot per day	0.3048	meter per day
square foot	0.09290	square meter
cubic foot	0.02832	cubic meter
cubic foot per day	0.02832	cubic meter per day
gallon per minute	3.785	liter per minute

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ABSTRACT

The U.S. Geological Survey Modular Ground-Water Flow Model, commonly referred to as MODFLOW, simulates ground-water flow through porous media using the finite-difference method. The region being modeled is divided into a grid of cells, and each cell is defined to be either no-flow, variable-head, or constant-head. The model calculates a value for head at all variable-head cells whereas head at constant-head cells is specified by the user. Cells are designated as no-flow cells if they contain impermeable material or are unsaturated, and accordingly the flow of water is not simulated in such cells.

As originally published, MODFLOW could simulate the desaturation of variable-head model cells, which resulted in their conversion to no-flow cells, but could not simulate the resaturation of cells. That is, a no-flow cell could not be converted to variable head. However, such conversion is desirable in many situations. For example, one might wish to simulate pumping that desaturates some cells followed by the recovery of water levels after pumping is stopped. An option that allows cells to convert from no-flow to variable-head has been added to the model. In this option, a cell is converted to variable head based on the head at neighboring cells. The option is written in FORTRAN 77 and is fully compatible with the existing model. This report documents the new option, including a description of the concepts, detailed input instructions, and a listing of the code. Example problems illustrate the practical applications of the option. Although solution of the modified flow equations can be difficult for the model solvers, the example problems show that it is possible to solve a variety of complex problems.

INTRODUCTION

The U.S. Geological Survey developed a three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1988) commonly known as MODFLOW. In the model, the continuous derivatives in the ground-water flow equation are replaced with finite-difference approximations at points called nodes. Surrounding each node is a cell in which the hydraulic properties, such as hydraulic conductivity and storage coefficient, are defined. The result is a set of N equations containing N values of unknown head, where N is the number of nodes. The time derivative is approximated by the backward difference method (McDonald and Harbaugh, 1988, p. 2-16). The program solves for unknown head at each node at the end of each time interval.

The finite-difference flow equation for a model cell (i,j,k), where i, j, and k are row, column, and layer grid indexes respectively (McDonald and Harbaugh, 1988, p. 2-26), is:

$$
\begin{aligned}
& CV_{i,j,k-\frac{1}{2}}\, h^m_{i,j,k-1} + CC_{i-\frac{1}{2},j,k}\, h^m_{i-1,j,k} + CR_{i,j-\frac{1}{2},k}\, h^m_{i,j-1,k} \\
& + (-CV_{i,j,k-\frac{1}{2}} - CC_{i-\frac{1}{2},j,k} - CR_{i,j-\frac{1}{2},k} \\
& \quad - CR_{i,j+\frac{1}{2},k} - CC_{i+\frac{1}{2},j,k} - CV_{i,j,k+\frac{1}{2}} + HCOF_{i,j,k})h^m_{i,j,k} \\
& + CR_{i,j+\frac{1}{2},k}\, h^m_{i,j+1,k} + CC_{i+\frac{1}{2},j,k}\, h^m_{i+1,j,k} + CV_{i,j,k+\frac{1}{2}}\, h^m_{i,j,k+1} \\
& = RHS_{i,j,k}. \qquad (1)
\end{aligned}
$$

Hydraulic head is designated by h. The equation is written for each time step in a simulation, and the m superscript designates the time step number. The HCOF and RHS coefficients incorporate storage and external stress terms. The CR, CC, and CV coefficients are conductances. Conductance is a combination of several parameters from Darcy's law describing one-dimensional, steady-state flow occurring in a volume of porous material. Darcy's law states that flow through a block of porous material is the product of conductance and the head difference along the flow path. The terms in equation (1) involving conductance specify the flow between the node for which the equation is being written and its six neighboring nodes.

A model cell can be one of three types: constant-head, variable-head, and no-flow. A variable-head cell is one in which the head varies and for which an equation is formulated. A constant-head cell is one for which, because the head is known and constant, an equation in terms of the head is not needed. However, the flow equation for a variable-head cell adjacent to a constant-head cell contains terms representing flow to or from the constant-head cell. A no-flow cell is one that represents a portion of the region in which there can be no movement of water. Such cells either contain impermeable material or are unsaturated. At no-flow cells, no equation is formulated, and the flow equation for a variable-head cell adjacent to a no-flow cell does not contain terms representing flow from the no-flow cell. The user initially defines a type for each cell by assigning values to the model array, IBOUND.

As part of the simulation of unconfined aquifers and aquifers that can convert between confined and unconfined, MODFLOW can change a variable-head cell to a no-flow cell. The conductance of unconfined cells and cells that can convert between confined and unconfined depends on the saturated thickness, and MODFLOW calculates the saturated thickness for these cells throughout the simulation. If the saturated thickness becomes zero, MODFLOW converts the cell to no flow (McDonald and Harbaugh, 1988, p. 5-10). This conversion is termed "drying" the cell.

The original MODFLOW does not allow a cell to be converted from no flow to variable head, which is termed "wetting" a cell. A new option to allow wetting of cells has been added to MODFLOW. Based on head in surrounding cells, the new model option will attempt to wet cells that are dry. The user can specify the cells for which wetting is attempted.

There are numerous situations for which the wetting capability is useful. An example is the recovery of water levels when wells are turned off. Another example is the mounding that can occur when irrigation is applied to the surface above an aquifer; the mound could rise into a previously dry model layer. The wetting capability also is useful in situations where cells incorrectly go dry (convert to no flow) as part of the iterative solution process. During the solution process, heads may temporarily decrease to less than their final values, which may cause cells to go dry. The new wetting capability allows such cells to convert back to wet.

MODFLOW was designed in a modular fashion so that it would be easy to modify (McDonald and Harbaugh, 1988, p. 1-2). The program code was divided into modules, and the modules were grouped by function into packages. All modules dealing with internal aquifer flow, which includes flow between cells and flow into storage, are grouped into a package called the Block-Centered Flow (BCF) Package. To allow for future revision, each package was given a version number. The BCF Package documented by McDonald and Harbaugh (1988) is version 1 and is designated BCF1. The new wetting option was implemented by creating a replacement package for BCF1. The new package is BCF version 2, or BCF2. BCF2 is similar to BCF1; many of the modules are unchanged. All of the previous functionality is provided in addition to the new wetting capability. BCF2 is written in the FORTRAN 77 programming language (American National Standards Institute, 1978).

The remainder of this report describes the implementation of the BCF2 Package and how to use it. Several example problems are provided to illustrate its use. This report is intended to be used as a supplement to McDonald and Harbaugh (1988).

CONCEPTUALIZATION AND IMPLEMENTATION

The BCF2 Package is identical to the BCF1 Package except for the wetting and drying of cells. In particular, the BCF2 Package calculates vertical and horizontal conductance, storage terms, and vertical flow through a partially saturated zone exactly as done by the BCF1 Package (McDonald and Harbaugh, 1988, Ch. 5). Accordingly, this report discusses only the wetting and drying of cells.

For cells that are unconfined or can potentially become unconfined, the BCF1 Package calculates transmissivity as the product of hydraulic conductivity and saturated thickness. In equation form, transmissivity, TR, is calculated as (McDonald and Harbaugh, 1988, p. 5-9):

$$TR = (TOP - BOT)\,HY \quad \text{for } h \geq TOP \tag{2a}$$

$$TR = (h - BOT)\,HY \quad \text{for } TOP > h > BOT \tag{2b}$$

$$TR = 0 \quad \text{for } h \leq BOT \tag{2c}$$

where

HY is the hydraulic conductivity of a cell,
TOP is the elevation of the top of the cell, and
BOT is the elevation of the bottom of the cell.

The transmissivity values for cells are then used to calculate conductances (CR and CC) between cells as required for equation (1). Note that if horizontal anisotropy exists, hydraulic conductivity, and thus transmissivity, will be different in the row and column directions. Although transmissivity varies with saturated thickness, vertical conductance is a constant until a cell becomes dry, at which point vertical conductance is changed to zero.

As defined by equation (2), the value of head is part of the calculation of transmissivity. The head is unknown, however, until equation (1) is solved. To resolve this conflict, McDonald and Harbaugh (1988) take advantage of the fact that iterative solvers are used to solve the equations for head at each cell. Iterative solvers successively improve an approximation of the correct solution until the approximation is sufficiently accurate. Each approximation is called an iteration, and the solver is said to converge toward the correct answer. When calculating transmissivity according to equation (2) for a new iteration, the head from the previous iteration is used. As the solver converges toward an acceptable solution, the head from the previous iteration will be nearly equal to the head for the new iteration. Thus, if all works well, the transmissivity will be accurate by the time convergence is reached.

In BCF1, a cell becomes dry whenever transmissivity as defined by equation (2c) is zero. That is, a cell becomes dry when head is below the bottom elevation. When a cell becomes dry, IBOUND is set to 0 (which indicates no flow), all conductances to the cell are set to zero, and head is set to a large value so it will serve as a visual indicator of the conversion in printouts. The conversion is irreversible in BCF1. BCF2 is identical to BCF1, except that cells can be wetted.

In BCF2, a dry cell can become wet if the head from the previous iteration in a neighboring cell is greater than or equal to the turn-on threshold. The turn-on threshold is

TURNON = BOT + THRESH

where

THRESH is a user-specified constant called the wetting threshold.

The user has two options to select which neighboring cells are checked to see if the turn-on threshold has been reached. One option is to check the cell immediately below the dry cell and the four horizontally adjacent cells. The second option is to check only the cell immediately below the dry cell. This option is useful when there are relatively large head differences between adjacent horizontal cells, which means that head in a neighboring horizontal cell is a poor indicator of when a cell should become wet.

Only variable-head cells either immediately below or horizontally adjacent to a dry cell can cause the cell to become wet. That is, if the neighboring cell is either no flow or constant head, then that cell is not checked to see if the turn-on threshold has been reached. The reason for excluding constant-head cells from causing a dry cell to become wet is to avoid unnecessarily repeating the evaluations of whether a dry cell should become wet. If the head in a constant-head cell is high enough to cause a neighboring cell to be wet, then this neighboring cell should be wet during the entire simulation. The user can make this determination prior to running the model and can define the cell to be either wet or dry as appropriate.

When a cell is wetted, IBOUND for the cell is set to 1 (which indicates a variable-head cell), vertical conductances are set to their original values, and head at the cell is set either to

$$h = BOT + WETFCT\ (hn - BOT) \tag{3a}$$

or

$$h = BOT + WETFCT\ (THRESH) \tag{3b}$$

where

hn is the head at the neighboring cell that causes the cell to wet, and
WETFCT is a user-specified constant called the wetting factor.

The user must select between equations (3a) and (3b); the rationale for making a selection will be discussed later in this report.

Although the head that is assigned to a cell that becomes wet might exceed the wetting threshold for a neighboring cell, a neighboring cell cannot become wet as a result of a cell that has become wet in the same iteration. If this were allowed, a single wetted cell might cause the entire model to become wet in one iteration.

Once a cell becomes wet, transmissivity and horizontal conductances are calculated as they are for any variable-head cell, which is the same as done in the BCF1 Package. The head in a wetted cell will then be recalculated in subsequent iterations and time steps according to equation (1). A wetted cell can become dry again.

In transient simulations, the head from the previous time step, HOLD, is a part of the storage calculation (McDonald and Harbaugh, 1988, p. 5-24). For cells that become wet after becoming dry in an earlier time step, the value of HOLD that will produce the correct flow to storage is the bottom elevation. As a fundamental part of the finite-difference method for simulating the time derivative in the ground-water flow equation, MODFLOW begins each time step by setting HOLD equal to head from the end of the previous time step (McDonald and Harbaugh, 1988, pp. 2-16 and 3-2). Because the value for head at dry cells is set to a user-specified value when a cell becomes dry, the BCF2 Package must set HOLD equal to the bottom elevation at the beginning of each time step for dry cells that have the potential to become wet. To do this, a new module named BCF2AD has been added to the BCF Package.

The user should be aware of the possibility that non-unique solutions can result from the method used to wet cells. Consider a steady-state problem in which two simulations are made--the first simulation has starting heads below the final values and the second has starting heads above the final values. Heads in the first simulation may rise above the bottom of some dry cells and yet remain below the turn-on threshold. These cells would remain dry. In the second simulation, head may stay above the bottom in these same cells, so they would stay wet. Thus, there would be more variable-head cells in the second simulation even though both simulations satisfy the prescribed conditions for wetting and drying cells.

PROBLEMS WITH SOLVER CONVERGENCE

The method of wetting and drying cells can cause problems with the convergence of the iterative solvers used in MODFLOW. Convergence problems can occur in MODFLOW even without the wetting capability, but problems are more likely to occur when the wetting capability is used. Symptoms of a problem are slow convergence or divergence combined with the frequent wetting and drying of the same cells. It is normal for the same cell to convert between wet and dry several times during the convergence process, but frequent conversions are an indication of problems. The user can detect this situation by examining the model printout; a message is printed each time a cell converts.

The convergence problems result from several factors. The primary factor is that equations (1) and (2) together form a nonlinear set of equations, but they are being solved through the use of solvers designed to solve linear equations. In particular, if the head from the previous iteration is poor, then the determination of which cells are wet and dry and the transmissivity of the wet cells will be incorrect. The overall change to the system of simultaneous equations that occurs when many cells change between wet and dry can be another cause of instability. The solvers perform differently depending on how many equations are being solved and on the values for conductances in each equation; the wetting and drying process changes both of these.

Another cause for instability is inaccuracy in the determination of when cells should become wet. While it is logical that the head at neighboring cells is a good qualitative indicator of when to wet a cell, there is no guarantee that a cell that is wetted by the described methodology should actually be wet. That is, the decision to make a cell wet should be viewed as a tentative decision. Subsequent iterations will show if the decision is correct. If head in a wetted cell drops below its bottom elevation, the cell will become dry again. It is possible for a cell to repeatedly cycle between wet and dry.

A poor estimate of initial head at wetted cells can also cause instability. Although the initial head estimate does not impact the final answer provided that convergence is reached, poor estimates can slow or prevent convergence by causing incorrect heads to be calculated at nearby cells.

The user of BCF2 has a number of ways to control solution instability.

1. The user specifies individual cells for which the wetting capability is active (see parameter WETDRY in "Input Instructions" section), which makes it possible to avoid the possibility of wetting dry cells that the user knows should never become wet.

2. The user specifies the wetting threshold for each wettable cell and which neighboring cells are checked to see if the wetting threshold has been reached (see parameter WETDRY in "Input Instructions" section).

3. The choice between using equation 3a or 3b to define the initial estimate of head at wetted cells is specified by the user.

4. The wetting factor used in 3a and 3b is specified by the user.

5. In steady-state simulations, initial conditions can be adjusted to improve stability.

For cells that can become wet, the most influential factors for controlling instability are the wetting threshold and the choice of which neighboring cells are checked to determine if the wetting threshold has been reached. The higher the threshold, the more stable the solution. Unfortunately, the wetting threshold can have a significant impact on the accuracy of the solution; the higher the wetting threshold, the less accurate the solution because cells that should become wet might stay dry. Thus the user may have to make a tradeoff between accuracy and stability.

The choice between equation (3a) and (3b) to define the initial head at wetted cells can impact solution stability. Equation (3a) is thought to be the most realistic because it varies the estimate of the head at a wetted cell according to the head at the cell that causes the cell to become wet. Equation (3b) bases its estimate of initial head on the wetting threshold. Equation (3a) can promote instability, however, when the iterative solvers are generally calculating head changes that are higher than optimum. In that situation, equation (3b) can have a stabilizing effect. Both equations also include the wetting factor, WETFCT, which can be used to increase or decrease the estimate of head at a wetted cell.

Adjustments of the wetting threshold, the choice between equations (3a) and (3b), and wetting factor must be made on a trial and error basis. After adjusting any of these, the user should examine the output to see if a stable solution has been obtained and if acceptable determinations of which cells are wet and dry have been made.

For steady-state simulations, benefit can be gained by making an effort to set initial conditions as close as possible to final conditions. Of course the final heads are not known prior to running the simulation because the purpose of running a simulation is to solve for heads; however, it is often possible to make a good estimate of final heads. By using good estimates of initial head and the boundary array (IBOUND), which indicates which cells initially are wet and dry, conversions of cells between wet and dry can be minimized. Note that for transient simulations, there is no flexibility to adjust initial conditions; initial conditions must be set to accurately reflect conditions at the start of the simulation.

Up to this point, it has been implied that the wetting of cells is tested for at the start of every iteration. Although performing this test every iteration would appear to promote the most rapid solution, solution speed can sometimes be improved by limiting the iterations at which the wetting can occur. The reason is that the wetting of cells sometimes produces erroneous head changes in neighboring cells during the succeeding iteration, which would cause erroneous conversions of those cells. These erroneous conversions can be prevented by waiting a few iterations until heads have had a chance to adjust before testing for additional conversions. Accordingly, the ability to specify when wetting can be attempted has been incorporated into BCF2. In particular, the user can specify the iteration interval, IWETIT, for attempting to wet cells. That is, every IWETIT iterations starting from the beginning of each time step, BCF2 attempts to wet cells. At iterations for which no wetting is allowed, cells may still convert to dry. When setting IWETIT greater than one, there is some risk that cells may be prevented from correctly converting to wet. If the solution for a time step is obtained in less than IWETIT iterations, then there will be no check during that time step to see if cells should convert to wet. The potential for this problem is greatest in transient simulations, which frequently require only a few iterations for a time step.

The last way for controlling oscillation is through the choice of the solver and adjustments of that solver. Three methods of iterative solution are available for MODFLOW. The Slice-Successive Overrelaxation (SOR) method (McDonald and Harbaugh, 1988, Ch. 13), the Strongly Implicit Procedure (SIP) method (McDonald and Harbaugh, 1988, Ch. 12), and the the Preconditioned Conjugate-Gradient (PCG) method (Kuiper, 1987, and Hill, 1990). SIP and PCG have been used successfully with BCF2. PCG appears to be the best. The SOR method is generally not practical for use with BCF2. Each solver implementation has input parameters that can affect the convergence efficiency. The reader should refer to the documentation of the solvers for specific information on the ways to adjust them.

Users of the PCG solvers should be aware that both of these solvers make use of a dual-iteration methodology, which can be useful in controlling oscillation of cells between wet and dry. Hill (1990) describes the iteration methodology using the terms "inner" and "outer" iterations. An outer iteration is a model iteration as described by McDonald and Harbaugh (1988, p. 2-20). For each outer iteration, the PCG solver can perform multiple iterations, called inner iterations. During successive inner iterations, PCG improves the calculated head assuming that all parameters in the flow equation are constant. In particular, cells cannot change between wet and dry during inner iterations. Thus, PCG's inner iterations serve a similar purpose to that of the IWETIT iteration interval, and generally there is no need to use an IWETIT value other than 1 when using PCG. Note that IWETIT applies to outer iterations in PCG; the BCF2 Package has no control over inner iterations. Note also that the BCF2 iteration interval controls only the wetting of cells and does not have an impact on the other head-dependent formulations such as transmissivity and the resulting conductances within the BCF2 Package or any other model package. No head-dependent formulations occur in any packages during PCG inner iterations.

In an unstable problem in which many cells are erratically converting between wet and dry, the solvers can have numerical problems that cause them to abort. In particular, small clusters of cells isolated from the rest of the cells by no-flow cells can cause division by zero in the solvers. In addition, the PCG2 solver (Hill, 1990) may calculate a Cholesky matrix that is not diagonally dominant, which will cause the solver to abort. In some cases setting the value of PCG2 parameter RELAX in the range of 0.97 to 0.99 prevents zero divide and non-diagonally dominant matrix errors.

APPLICABILITY AND LIMITATIONS

The BCF2 Package makes it possible to simulate situations in which a water table rises into unsaturated model layers. A typical application of this capability is in the simulation of the recovery of over-stressed aquifers either through artificial recharge or the reduction of stress. The need for the wetting capability increases as the need for vertical detail of head distribution increases. High-accuracy simulations of vertical head gradients are required for such purposes as tracking the flow of contaminants, especially when significant vertical heterogeneity exists or when stresses partially penetrate an aquifer. To obtain accuracy of vertical head requires many model layers, which implies that each layer will be thin. The thinner the model layer, the more likely it is that cells will require conversions between wet and dry.

Another benefit of the wetting capability is improved simulation of declining water tables. Although the BCF1 Package can simulate the drying of cells when water levels decrease, there is a risk of drying cells that should not become dry. This can happen when an iterative solver overshoots the correct value during an iteration, which is not unusual for iterative solvers. The wetting capability of BCF2 allows such cells to become wet again in later iterations.

Although the BCF2 Package has the ability to simulate a variety of situations, there are limitations to its use. The primary limitation has already been discussed; there may be instabilities in the solution process that prevent solution or cause solution to require excessive computational time. To minimize solution problems, the user can choose from the SIP and PCG solvers, can adjust the solvers, and can adjust the data that controls the wetting process. All of the adjustments must be done through trial and error. Once a solver produces an answer, the user must examine the results to determine if the answer is acceptable. The budget error should be examined as well as which cells are wet and dry. Although the wetting threshold might have to be higher than one would like, the answers produced are probably more accurate than would otherwise be produced without the wetting capability.

A second limitation of BCF2 results from the method of drying cells. All stresses are removed when a cell becomes dry even though it might be more appropriate to move the stress to another location. For example, if a cell that contains a well goes dry, the pumpage will be eliminated. If the well owner would likely deepen the well rather than stop pumping water, a more appropriate action would be to move the pumpage to a deeper cell. Further, the removal of stresses when cells go dry can cause cells to repeatedly convert between wet and dry. In the example of a drying cell that contains a well, the elimination of the pumpage might then allow the cell to become wet again; this cycle could repeat indefinitely. Note that the Recharge (RCH) Package (McDonald and Harbaugh, 1988, Ch. 7) has an option to deal with this problem; it can allow recharge to pass through dry cells to the highest constant-head or variable-head cell. Likewise, this capability of the Recharge Package could be used to simulate wells whose pumpage is automatically moved to the next lower layer when a layer goes dry. Some situations may require new methods for simulating stresses; the modular design of MODFLOW makes it possible to easily add new capabilities.

A similar problem can result in transient simulations, which involve flow from storage. If a cell dries, the flow from storage at that time step is lost. Large volumes of water could be lost, causing an inaccurate simulation. For example, it is possible to specify large time steps such that the head in a cell drops from the top of the cell to the bottom in one time step. In this situation, all of the unconfined storage, which is generally a large quantity, would be lost. The solution to this problem is to use time steps that are small enough to allow most of a cell's water to be taken from storage before the cell converts to dry. However, small time steps can cause additional problems. Small time steps result in large rates of flow from storage when a cell becomes wet because flow from storage is dependent on the inverse of time-step length. The flow to storage can result in head in the wetted cell being only slightly above the bottom of the cell. The small saturated thickness results in a low transmissivity that can restrict the flow entering the cell from adjacent cells enough to cause the cell to convert to dry again. Also, the large flow to storage caused by wetting a cell can cause the solvers to over-compensate and reduce head enough to dry the cell. Thus, small time steps can result in repeated conversions between wet and dry. If small time steps are required, a larger wetting threshold may be necessary to avoid the oscillation between wet and dry.

A third limitation is the way vertical conductance converts when a cell changes between dry and wet. When dry, conductance is zero; when wet, conductance is a constant. If a confining layer exists between layers as assumed by McDonald and Harbaugh (1988, p. 5-30), this makes sense. That is, if the confining bed is the primary restriction to vertical flow, then the lowering of the water table in the aquifer above the confining unit will not change the vertical conductance very much because the confining unit is not changed by the aquifer's desaturation. When there is no confining layer as would be the situation when a single aquifer is being simulated by multiple model layers, the changing water level would have a significant impact on vertical conductance. A more accurate representation would be to vary vertical conductance with saturated thickness. To reduce the error, more layers can be used.

Another limitation also involves vertical flow. Vertical flow between two cells is limited when the lower cell is not confined (McDonald and Harbaugh, 1988, p. 5-19). This is appropriate for simulating perched conditions that can occur when there is recharge to the upper cell and there is a low-conductivity material between the two cells or the upper cell has lower hydraulic conductivity than the lower cell. A stress in the lower cell can cause the head to drop below the top without drying the upper cell.

When vertical flow is limited, vertical flow is calculated as saturated thickness of the upper cell times the vertical conductance. Thus, flow is not dependent on the head in the lower cell. A problem can occur if flow is limited between two cells that are simulating the same aquifer. That is, it is possible for a perched water table to form in the model when heads are declining even though there is no low conductivity material between the cells that could cause the perched condition. Although this would not happen if model heads were declining smoothly from the top down, it can happen if heads in a lower cell drop below its top during the iterative convergence process while the cell above is still wet. Once the perched condition is established, it can stay even though it does not make hydrologic sense because the vertical flow limitation prevents head from dropping as low as it should drop. Thus the user should examine model heads to see if there are cells having incorrectly perched conditions.

The final limitation involves the difficulty of preparing data for the BCF2 Package. The user is faced with a major effort to prepare the input data for a typical multi-layer problem that requires the wetting capability. Errors are a likelihood given the amount of data, and errors probably will be difficult to trace. Inconsistent top and bottom elevations and other incorrect data can cause convergence problems in addition to the convergence problems that are inherent in the model formulations. When faced with a model that will not converge, it is difficult to determine whether there is a fundamental stability problem or bad data somewhere in the input files. It is often helpful to make a series of increasingly complex models rather than starting off with the "full-blown" model. For example, a complex water-table aquifer system might be simulated initially as a single unconfined aquifer even though the final model will simulate the aquifer with a sequence of model layers, some of which will use the wetting capability. This makes it possible to get the basic model operational and obtain some knowledge of the values for aquifer parameters before dealing with the problems of the wetting and drying of cells.

INPUT INSTRUCTIONS

Most of the data required by the BCF2 Package are the same as for the BCF1 Package. These data consist primarily of arrays that are used to calculate conductance and storage terms for each layer. The required arrays can include transmissivity, hydraulic conductivity, specific yield, confined storage coefficient, vertical leakance, aquifer bottom elevation, and aquifer top elevation. The specific arrays required depend on the options that are used as indicated by the layer-type code, LAYCON. The reader is referred to McDonald and Harbaugh (1988, p. 5-30) for a detailed description of these data.

A small amount of data is required for the wetting capability in addition to that required by the BCF1 Package. The additional data are a flag indicating if the wetting capability is to be used, the wetting threshold, the wetting factor, and the iteration interval for attempting to wet cells. The only additional array is WETDRY, which must be specified for each wettable layer. If the wetting capability is enabled, all layers for which transmissivity varies with saturated thickness, which is indicated by a LAYCON value of 1 or 3, are wettable.

Because BCF2 is designed as a replacement for BCF1, input is read using the same unit number, which is specified in IUNIT(1). Refer to McDonald and Harbaugh (1988, p. 3-25) for a description of the use of unit numbers in MODFLOW. The data must be in the specified order. The data are read once at the start of the simulation.

BCF2AL

1. Data:	ISS	IBCFCB	HDRY	IWDFLG	WETFCT	IWETIT	IHDWET
Format:	I10	I10	F10.0	I10	F10.0	I10	I10

2. Data: LAYCON(NLAY) (Maximum of 80 layers)
   Format: 40I2
   (If there are 40 or fewer layers, use one record; otherwise, use two records.)

3. Data: TRPY(NLAY)
   Module: U1DREL

4. Data: DELR(NCOL)
   Module: U1DREL

5. Data: DELC(NROW)
   Module: U1DREL

A subset of the following two-dimensional arrays is used to describe each layer. The arrays needed for each layer depend on the layer-type code (LAYCON), whether the simulation is transient (ISS = 0) or steady state (ISS not 0), and if the wetting capability is active (IWDFLG not 0). If an array is not needed, it must be omitted. In no situation will all arrays be required. The required arrays (items 6-13) for layer 1 are read first; then the arrays for layer 2, etc.

IF THE SIMULATION IS TRANSIENT (ISS = 0)

6. Data: sf1(NCOL,NROW)
   Module: U2DREL

IF THE LAYER-TYPE CODE (LAYCON) is 0 or 2

7. Data: Tran(NCOL,NROW)
   Module: U2DREL

IF THE LAYER-TYPE CODE (LAYCON) IS 1 OR 3

8. Data: HY(NCOL,NROW)
   Module: U2DREL

9. Data: BOT(NCOL,NROW)
   Module: U2DREL

IF NOT THE BOTTOM LAYER

10. Data: Vcont(NCOL,NROW)
    Module: U2DREL

IF THE SIMULATION IS TRANSIENT (ISS = 0) AND THE LAYER-TYPE CODE (LAYCON) IS 2 OR 3

11. Data: sf2(NCOL,NROW)
    Module: U2DREL

IF THE LAYER-TYPE CODE (LAYCON) IS 2 OR 3

12. Data: TOP(NCOL,NROW)
    Module: U2DREL

IF THE LAYER-TYPE CODE (LAYCON) IS 1 OR 3 AND THE WETTING CAPABILITY IS ACTIVE (IWDFLG IS NOT 0)

13. Data: WETDRY(NCOL,NROW)
    Module: U2DREL

Explanation of Parameters Used in Input Instructions

ISS is the steady-state flag

If ISS is not 0, the simulation is steady state.

If ISS = 0, the simulation is transient.

IBCFCB is a flag and a unit number.

If IBCFCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL (see Output Control in McDonald and Harbaugh [1988, p. 4-15]) is set; the terms which are saved will include cell-by-cell storage terms, cell-by-cell constant-head flows, and cell-by-cell flow between adjacent cells.

If IBCFCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IBCFCB < 0, flow for each constant-head cell will be printed in the listing file whenever ICBCFL is set; cell-by-cell storage terms and cell-by-cell flow between adjacent cells will not be recorded or printed.

HDRY is the head that is assigned to cells that are converted to dry during a simulation. Although this value plays no role in the model calculations, it is useful as an indicator when looking at the resulting heads that are output from the model. HDRY is thus similar to HNOFLO in the Basic Package, which is the value assigned to cells that are no-flow cells at the start of a model simulation.

IWDFLG is a flag that determines if the wetting capability is active.

If IWDFLG = 0, the wetting capability is inactive.

If IWDFLG is not 0, the wetting capability is active.

WETFCT is a factor that is included in the calculation of the head that is initially established at a cell when it is converted from dry to wet. (See IHDWET.)

IWETIT is the iteration interval for attempting to wet cells. Wetting is attempted every IWETIT iterations. If using the PCG solver (Hill, 1990), this applies to outer iterations, not inner iterations. If IWETIT is 0, it is changed to 1.

IHDWET is a flag that determines which equation is used to calculate the initial head at cells that become wet:

If IHDWET = 0, equation (3a) is used:

$$h = BOT + WETFCT\ (hn - BOT),$$

If IHDWET is not 0, equation (3b) is used:

$$h = BOT + WETFCT\ (THRESH).$$

LAYCON is the layer-type table. Each element holds the code for the respective layer. Read one value for each layer. There is a limit of 80 layers. If there are 40 or fewer layers, use one record; otherwise, use two records. Leave unused elements in a record blank.

0 - confined -- Transmissivity and storage coefficient of the layer are constant for the entire simulation.

1 - unconfined -- Transmissivity of the layer varies. It is calculated from the saturated thickness and hydraulic conductivity. The storage coefficient is constant. This type code is valid only for layer 1.

2 - confined/unconfined -- Transmissivity of the layer is constant. The storage coefficient may alternate between confined and unconfined values. Vertical flow from above is limited if the layer desaturates.

3 - confined/unconfined -- Transmissivity of the layer varies. It is calculated from the saturated thickness and hydraulic conductivity. The storage coefficient may alternate between confined and unconfined values. Vertical flow from above is limited if the aquifer desaturates.

TRPY is a one-dimensional array containing an anisotropy factor for each layer. It is the ratio of transmissivity or hydraulic conductivity (whichever is being used) along a column to transmissivity or hydraulic conductivity along a row. Set to 1.0 for isotropic conditions. This is a single array with one value per layer. Do not read an array for each layer; include only one array control record for the entire array. If the value is the same for all layers, the entire array can be specified by setting LOCAT to 0 and setting CNSTNT to the value that applies to all layers.

DELR is the cell width along rows. Read one value for each of the NCOL columns. This is a single array with one value for each column.

DELC is the cell width along columns. Read one value for each of the NROW rows. This is a single array with one value for each row.

sf1 is the primary storage coefficient. Read only for a transient simulation (steady-state flag, ISS, is 0). For LAYCON equal to 1, sf1 will always be specific yield, while for LAYCON equal to 2 or 3, sf1 will always be confined storage coefficient. For LAYCON equal to 0, sf1 would normally be confined storage coefficient; however, a LAYCON value of 0 can also be used to simulate water-table conditions where drawdowns are expected to remain everywhere a small fraction of the saturated thickness, and where there is no layer above, or flow from above is negligible. In this case, specific yield values would be entered for sf1.

Tran is the transmissivity along rows. Tran is multiplied by TRPY to obtain transmissivity along columns. Read only for layers where LAYCON is 0 or 2.

HY is the hydraulic conductivity along rows. HY is multiplied by TRPY to obtain hydraulic conductivity along columns. Read only for layers where LAYCON is 1 or 3.

BOT is the elevation of the aquifer bottom. Read only for layers where LAYCON is 1 or 3.

Vcont is the vertical hydraulic conductivity divided by the thickness from a layer to the layer below. The value for a cell is the hydraulic conductivity divided by thickness for the material between the node in that cell and the node in the cell below. Because there is not a layer beneath the bottom layer, Vcont cannot be specified for the bottom layer.

sf2 is the secondary storage coefficient. Read only for layers where LAYCON is 2 or 3 and only if the simulation is transient (steady-state flag, ISS, is 0). The secondary storage coefficient is always specific yield.

TOP is the elevation of the aquifer top. Read only for layers where LAYCON is 2 or 3.

WETDRY is a combination of the wetting threshold and a flag to indicate which neighboring cells can cause a cell to become wet. If WETDRY < 0, only the cell below a dry cell can cause the cell to become wet. If WETDRY > 0, the cell below a dry cell and the four horizontally adjacent cells can cause a cell to become wet. If WETDRY is 0, the cell cannot be wetted. The absolute value of WETDRY is the wetting threshold. When the sum of BOT and the absolute value of WETDRY at a dry cell is equaled or exceeded by the head at an adjacent cell, the cell is wetted. Read only if LAYCON is 1 or 3 and IWDFLG is not 0.

EXAMPLE PROBLEMS

Example problems were posed to illustrate the practical applications of the BCF2 option. Although solution of the modified flow equations can be difficult for the model solvers, the example problems show that it is possible to solve a variety of complex problems.

Problem 1 -- Simulation of a Two-Layer Aquifer System in which the Top Layer Converts Between Wet and Dry

In an aquifer system where two aquifers are separated by a confining bed, large pumpage withdrawals from the bottom aquifer can desaturate parts of the upper aquifer. If pumpage is discontinued, resaturation of the upper aquifer can occur. This problem demonstrates the capability of the BCF2 Package to successfully simulate this common hydrologic situation which is difficult or impossible to simulate with the original BCF1 Package. If both aquifers were simulated by one model layer using BCF1, the effect of the confining bed on vertical flow could not be simulated. Also, the transmissivity would not be correctly calculated as a function of saturated thickness. The changes in hydraulic conductivity between the confining bed and the aquifers could not be distinctly represented. If each aquifer were simulated by a separate model layer using BCF1, there would be solution difficulties. When simulating declining heads, too many cells might convert to dry; when simulating rising heads, dry cells could not convert to wet.

Conceptual Model

A hypothetical aquifer system consists of two aquifers separated by a confining unit (fig. 1). No-flow boundaries surround the system on all sides, except that the lower aquifer discharges to a stream along the right side of the area. Recharge from precipitation is applied evenly over the entire area. The stream penetrates the lower aquifer; in the region above the stream, the upper aquifer and confining unit are missing. Under natural conditions, recharge flows through the system to the stream. Under

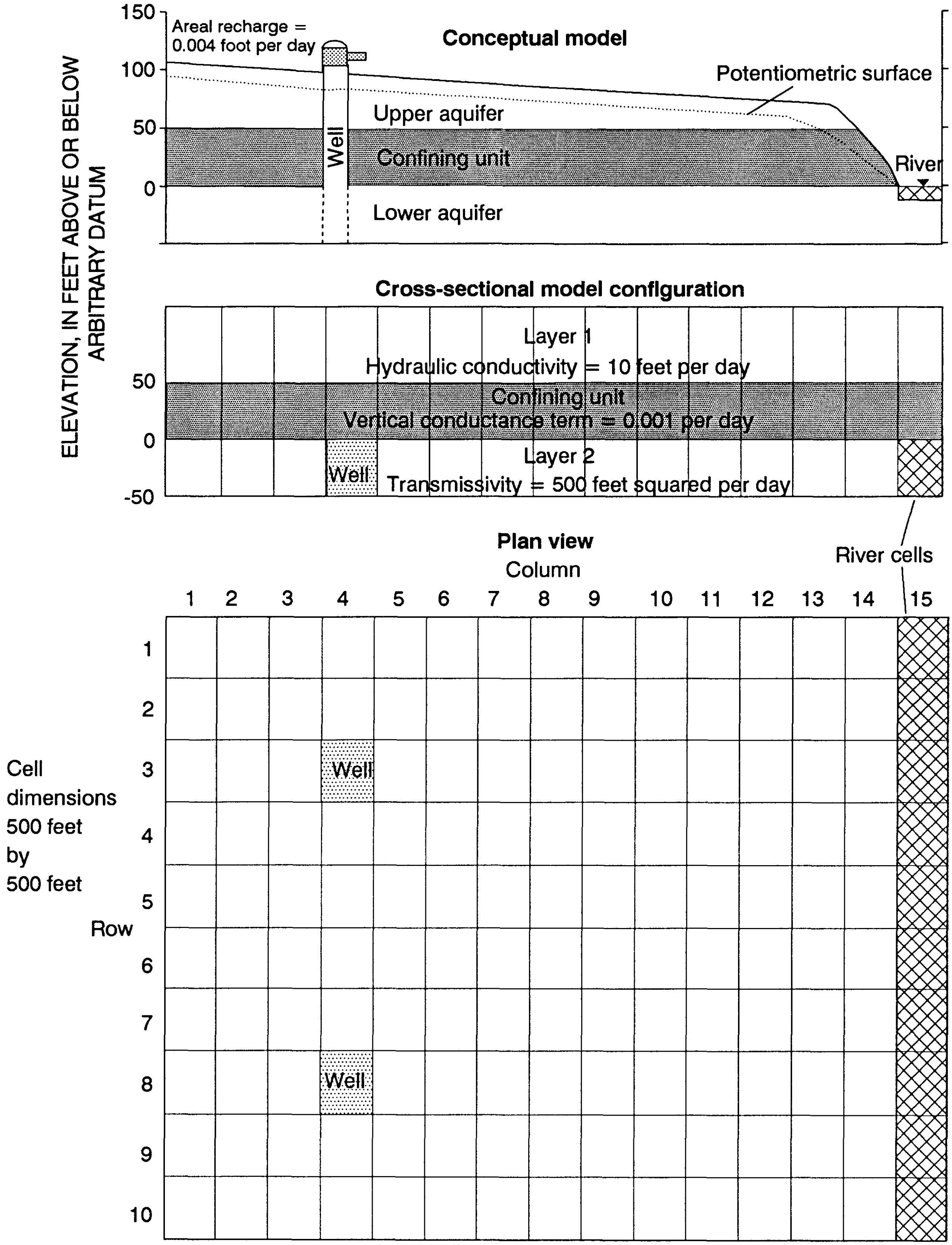

Figure 1.--Hydrogeology, model grid, and model boundary conditions for Problem 1.

stressed conditions, two wells withdraw water from the lower aquifer. If enough water is pumped, cells in the upper aquifer will desaturate. Removal of the stresses will then cause the desaturated areas to resaturate.

Modeling Approach

The model consists of two layers--one for each aquifer. Because horizontal flow in the confining bed is small compared to horizontal flow in the aquifers and storage is not a factor in steady-state simulations, the confining bed is not treated as a separate layer. The effect of the confining bed is incorporated in the value for vertical hydraulic conductivity divided by thickness between aquifer layers (McDonald and Harbaugh, 1988, p. 5-16). Note that if storage in the confining bed were significant, transient simulations would require that the confining layer be simulated using one or more layers. A uniform horizontal grid of 10 rows and 15 columns is used. Aquifer parameters are specified as shown in Figure 1.

Simulation Results

Two steady-state solutions were obtained to simulate natural conditions and pumping conditions. The two solutions are designed to demonstrate the ability of the BCF2 Package to handle a broad range of possibilities for cells converting between wet and dry in the top aquifer. When solving for natural conditions, the top aquifer initially is specified as being entirely dry and many cells must convert to wet. When solving for pumping conditions, the top aquifer is initially specified to be under natural conditions and many cells must convert to dry.

The steady-state solutions were obtained through a single simulation consisting of two stress periods. The first stress period simulates natural conditions and the second period simulates the addition of pumping wells. The simulation is declared to be steady state, so no storage values are specified and each stress period requires only a single time step to produce a steady-state result. The PCG2 Package is used to solve the flow equations for the simulations. The complete output from the model simulation is provided in Table 1.

In the process of simulating this problem, several trial simulations were made using different values for the WETDRY parameter. The absolute value of the WETDRY parameter is the wetting threshold, and the sign of the WETDRY parameter indicates which neighboring cells can cause a cell to become wet. Determination of the WETDRY parameter often requires considerable effort. The user may have to make multiple test runs trying different values in different areas of the model. On the right side of the model, the WETDRY parameter (table 1) is negative in order to cause a cell to become wet only when head in the layer below exceeds the wetting threshold. This was done to avoid incorrectly converting dry cells to wet because of the large head differences between adjacent horizontal cells. For example, the simulation of natural conditions (Stress Period 1) shows cells in column 14 of layer 1 being dry, which is reasonable based on the head below these cells. That is, the head in column 14 of layer 2 is over 20 feet below the bottom of layer 1. However, the head in column 13 of layer 1 is 21 feet above the bottom of the aquifer, which means that, if head in adjacent horizontal cells is allowed to wet cells, column 14 would convert to wet. Thus, it is not readily apparent whether column 14 should be wet or dry. The trial simulations showed that, when horizontal wetting is allowed, column 14 repeatedly oscillates between wet and dry, indicating that column 14 should be dry. If horizontal wetting is used, oscillation between wet and dry can be prevented by raising the wetting threshold, but this also can prevent some cells that should be partly saturated from converting to wet.

On the left side of the model, horizontal head changes between adjacent cells generally are small, so head in the neighboring horizontal cells is a good indicator of whether or not a dry cell should become wet. Therefore, positive WETDRY parameters are used in most of this area to allow wetting to occur either from the cell below or from horizontally adjacent cells. Near the well, the horizontal head gradients under pumping conditions also are relatively large; consequently, a negative WETDRY parameter was used at the cells above the well. This prevents these cells from incorrectly becoming

Table 1.--Model output for problem 1

```
                    U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER MODEL

Valley aquifer with 2 sand layers separated by silt.  Stress period 1 is natural conditions.  Stress period 2 adds wells.
   2 LAYERS        10 ROWS        15 COLUMNS
  2 STRESS PERIOD(S) IN SIMULATION
MODEL TIME UNIT IS DAYS

I/O UNITS:
ELEMENT OF IUNIT:  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
        I/O UNIT: 11 12  0 14  0  0  0 18  0  0  0 20 19  0  0  0  0  0  0  0  0  0  0  0

BAS1 -- BASIC MODEL PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT  5
ARRAYS RHS AND BUFF WILL SHARE MEMORY.
START HEAD WILL NOT BE SAVED -- DRAWDOWN CANNOT BE CALCULATED
    2583 ELEMENTS IN X ARRAY ARE USED BY BAS
    2583 ELEMENTS OF X ARRAY USED OUT OF  650000

BCF2 -- BLOCK-CENTERED FLOW PACKAGE, VERSION 2, 7/1/91 INPUT READ FROM UNIT 11
STEADY-STATE SIMULATION
CELL-BY-CELL FLOWS WILL BE RECORDED ON UNIT 30
HEAD AT CELLS THAT CONVERT TO DRY=   777.77
WETTING CAPABILITY IS ACTIVE
WETTING FACTOR=   1.00000     WETTING ITERATION INTERVAL=   1
FLAG THAT SPECIFIES THE EQUATION TO USE FOR HEAD AT WETTED CELLS=   0
     LAYER  AQUIFER TYPE
     ------------------
        1         1
        2         0
     602 ELEMENTS IN X ARRAY ARE USED BY BCF
    3185 ELEMENTS OF X ARRAY USED OUT OF  650000
```

Table 1.--Model output for problem 1--Continued

```
WEL1 -- WELL PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM 12
MAXIMUM OF    2 WELLS
CELL-BY-CELL FLOWS WILL BE RECORDED ON UNIT 30
       8 ELEMENTS IN X ARRAY ARE USED FOR WELLS
    3193 ELEMENTS OF X ARRAY USED OUT OF  650000

RCH1 -- RECHARGE PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 18
OPTION 3 -- RECHARGE TO HIGHEST ACTIVE NODE IN EACH VERTICAL COLUMN
CELL-BY-CELL FLOW TERMS WILL BE RECORDED ON UNIT 30
     150 ELEMENTS OF X ARRAY USED FOR RECHARGE
    3343 ELEMENTS OF X ARRAY USED OUT OF  650000

RIV1 -- RIVER PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 14
MAXIMUM OF   10 RIVER NODES
CELL-BY-CELL FLOWS WILL BE RECORDED ON UNIT 30
      60 ELEMENTS IN X ARRAY ARE USED FOR RIVERS
    3403 ELEMENTS OF X ARRAY USED OUT OF  650000

PCG2 -- CONJUGATE GRADIENT SOLUTION PACKAGE, VERSION 2, 5/1/88
MAXIMUM OF  40 CALLS OF SOLUTION ROUTINE
MAXIMUM OF  20 INTERNAL ITERATIONS PER CALL TO SOLUTION ROUTINE
MATRIX PRECONDITIONING TYPE :    1
   7600 ELEMENTS IN X ARRAY ARE USED BY PCG
  11003 ELEMENTS OF X ARRAY USED OUT OF 650000


Valley aquifer with 2 sand layers separated by silt.  Stress period 1 is natural conditions.  Stress period 2 adds wells.

                                                BOUNDARY ARRAY =            0 FOR LAYER  1
                                                BOUNDARY ARRAY =            1 FOR LAYER  2

AQUIFER HEAD WILL BE SET TO  999.99     AT ALL NO-FLOW NODES (IBOUND=0).
```

Table 1.--Model output for problem 1--Continued

```
                                        INITIAL HEAD =  0.0000000     FOR LAYER  1

                                        INITIAL HEAD =  0.0000000     FOR LAYER  2

HEAD PRINT FORMAT IS FORMAT NUMBER  -4    DRAWDOWN PRINT FORMAT IS FORMAT NUMBER  -4

HEADS WILL BE SAVED ON UNIT 50    DRAWDOWNS WILL BE SAVED ON UNIT 50

OUTPUT CONTROL IS SPECIFIED EVERY TIME STEP

                              COLUMN TO ROW ANISOTROPY =   1.000000

                                                  DELR =   500.0000

                                                  DELC =   500.0000

                                 HYD. COND. ALONG ROWS =   10.00000     FOR LAYER  1

                                                BOTTOM =   50.00000     FOR LAYER  1

                              VERT HYD COND /THICKNESS =  0.9999999E-03 FOR LAYER  1
```

Table 1.--Model output for problem 1--Continued

WETDRY PARAMETER FOR LAYER 1 WILL BE READ ON UNIT 11 USING FORMAT: (15f4.0)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
2	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
3	2.	2.	2.	-2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
4	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
5	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
6	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
7	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
8	2.	2.	2.	-2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
9	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.
10	2.	2.	2.	2.	2.	2.	2.	2.	-2.	-2.	-2.	-2.	-2.	-2.	-2.

TRANSMIS. ALONG ROWS = 500.0000 FOR LAYER 2

Table 1.--Model output for problem 1--Continued

```
                                SOLUTION BY THE CONJUGATE-GRADIENT METHOD
                                ------------------------------------------

                      MAXIMUM NUMBER OF CALLS TO PCG ROUTINE =        40
                          MAXIMUM ITERATIONS PER CALL TO PCG =        20
                                 MATRIX PRECONDITIONING TYPE =         1
          RELAXATION FACTOR (ONLY USED WITH PRECOND. TYPE 1) =   0.10000E+01
   PARAMETER OF POLYMOMIAL PRECOND. = 2 (2) OR IS CALCULATED :         2
                           HEAD CHANGE CRITERION FOR CLOSURE =   0.10000E-02
                       RESIDUAL CHANGE CRITERION FOR CLOSURE =   0.10000E+04
              PCG HEAD AND RESIDUAL CHANGE PRINTOUT INTERVAL =         1
              ALL PRINTING FROM THE SOLVER IS SUPPRESSED (1) =         1
FOR NPCOND=1, DO (0) OR DO NOT (1) RECALC. CHOL. DIAG. EACH OUTER ITER. =         0


                              STRESS PERIOD NO.    1, LENGTH =   1.000000
                              ----------------------------------------------

                              NUMBER OF TIME STEPS =     1

                               MULTIPLIER FOR DELT =     1.000

                             INITIAL TIME STEP SIZE =   1.000000

      0 WELLS

                                              RECHARGE =  0.4000000E-02
```

Table 1.--Model output for problem 1--Continued

10 RIVER REACHES

LAYER	ROW	COL	STAGE	CONDUCTANCE	BOTTOM ELEVATION	RIVER REACH
2	1	15	0.0000	0.1000E+05	-5.000	1
2	2	15	0.0000	0.1000E+05	-5.000	2
2	3	15	0.0000	0.1000E+05	-5.000	3
2	4	15	0.0000	0.1000E+05	-5.000	4
2	5	15	0.0000	0.1000E+05	-5.000	5
2	6	15	0.0000	0.1000E+05	-5.000	6
2	7	15	0.0000	0.1000E+05	-5.000	7
2	8	15	0.0000	0.1000E+05	-5.000	8
2	9	15	0.0000	0.1000E+05	-5.000	9
2	10	15	0.0000	0.1000E+05	-5.000	10

```
CELL CONVERSIONS FOR ITERATION=  2  LAYER= 1  TIME STEP=  1  STRESS PERIOD=  1      (ROW,COL)
 WET(  1,  1)   WET(  1,  2)   WET(  1,  3)   WET(  1,  4)   WET(  1,  5)   WET(  1,  6)   WET(  1,  7)   WET(  1,  8)
 WET(  1,  9)   WET(  1, 10)   WET(  1, 11)   WET(  1, 12)   WET(  1, 13)   WET(  2,  1)   WET(  2,  2)   WET(  2,  3)
 WET(  2,  4)   WET(  2,  5)   WET(  2,  6)   WET(  2,  7)   WET(  2,  8)   WET(  2,  9)   WET(  2, 10)   WET(  2, 11)
 WET(  2, 12)   WET(  2, 13)   WET(  3,  1)   WET(  3,  2)   WET(  3,  3)   WET(  3,  4)   WET(  3,  5)   WET(  3,  6)
 WET(  3,  7)   WET(  3,  8)   WET(  3,  9)   WET(  3, 10)   WET(  3, 11)   WET(  3, 12)   WET(  3, 13)   WET(  4,  1)
 WET(  4,  2)   WET(  4,  3)   WET(  4,  4)   WET(  4,  5)   WET(  4,  6)   WET(  4,  7)   WET(  4,  8)   WET(  4,  9)
 WET(  4, 10)   WET(  4, 11)   WET(  4, 12)   WET(  4, 13)   WET(  5,  1)   WET(  5,  2)   WET(  5,  3)   WET(  5,  4)
 WET(  5,  5)   WET(  5,  6)   WET(  5,  7)   WET(  5,  8)   WET(  5,  9)   WET(  5, 10)   WET(  5, 11)   WET(  5, 12)
 WET(  5, 13)   WET(  6,  1)   WET(  6,  2)   WET(  6,  3)   WET(  6,  4)   WET(  6,  5)   WET(  6,  6)   WET(  6,  7)
 WET(  6,  8)   WET(  6,  9)   WET(  6, 10)   WET(  6, 11)   WET(  6, 12)   WET(  6, 13)   WET(  7,  1)   WET(  7,  2)
 WET(  7,  3)   WET(  7,  4)   WET(  7,  5)   WET(  7,  6)   WET(  7,  7)   WET(  7,  8)   WET(  7,  9)   WET(  7, 10)
 WET(  7, 11)   WET(  7, 12)   WET(  7, 13)   WET(  8,  1)   WET(  8,  2)   WET(  8,  3)   WET(  8,  4)   WET(  8,  5)
 WET(  8,  6)   WET(  8,  7)   WET(  8,  8)   WET(  8,  9)   WET(  8, 10)   WET(  8, 11)   WET(  8, 12)   WET(  8, 13)
 WET(  9,  1)   WET(  9,  2)   WET(  9,  3)   WET(  9,  4)   WET(  9,  5)   WET(  9,  6)   WET(  9,  7)   WET(  9,  8)
 WET(  9,  9)   WET(  9, 10)   WET(  9, 11)   WET(  9, 12)   WET(  9, 13)   WET( 10,  1)   WET( 10,  2)   WET( 10,  3)
 WET( 10,  4)   WET( 10,  5)   WET( 10,  6)   WET( 10,  7)   WET( 10,  8)   WET( 10,  9)   WET( 10, 10)   WET( 10, 11)
 WET( 10, 12)   WET( 10, 13)
```

Table 1.--Model output for problem 1--Continued

```
   8 CALLS TO PCG ROUTINE FOR TIME STEP   1 IN STRESS PERIOD  1
  95 TOTAL ITERATIONS

HEAD/DRAWDOWN PRINTOUT FLAG = 1     TOTAL BUDGET PRINTOUT FLAG = 1     CELL-BY-CELL FLOW TERM FLAG = 0

OUTPUT FLAGS FOR ALL LAYERS ARE THE SAME:
  HEAD    DRAWDOWN  HEAD  DRAWDOWN
PRINTOUT  PRINTOUT  SAVE    SAVE
----------------------------------
    1         0       0       0
```

HEAD IN LAYER 1 AT END OF TIME STEP 1 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.77	102.77	93.33	82.39	71.06	999.99	999.99
2	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
3	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
4	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
5	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
6	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
7	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99

Table 1.--Model output for problem 1--Continued

8	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
9	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99
10	138.94	138.23	136.79	134.61	131.65	127.87	123.19	117.53	110.78	102.77	93.33	82.39	71.06	999.99	999.99

HEAD IN LAYER 2 AT END OF TIME STEP 1 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
2	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
3	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
4	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
5	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
6	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
7	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
8	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
9	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50
10	137.46	136.72	135.24	132.97	129.89	125.92	120.98	114.93	107.58	98.63	87.60	73.72	55.50	29.50	1.50

Table 1.--Model output for problem 1--Continued

```
                VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD  1
                -----------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3                          RATES FOR THIS TIME STEP      L**3/T
     ------------------                                    ------------------------

           IN:                                                   IN:
           ---                                                   ---
             STORAGE =   0.00000                                   STORAGE =   0.00000
       CONSTANT HEAD =   0.00000                             CONSTANT HEAD =   0.00000
               WELLS =   0.00000                                     WELLS =   0.00000
            RECHARGE =   0.15000E+06                              RECHARGE =   0.15000E+06
       RIVER LEAKAGE =   0.00000                             RIVER LEAKAGE =   0.00000

            TOTAL IN =   0.15000E+06                              TOTAL IN =   0.15000E+06

          OUT:                                                  OUT:
          ----                                                  ----
             STORAGE =   0.00000                                   STORAGE =   0.00000
       CONSTANT HEAD =   0.00000                             CONSTANT HEAD =   0.00000
               WELLS =   0.00000                                     WELLS =   0.00000
            RECHARGE =   0.00000                                  RECHARGE =   0.00000
       RIVER LEAKAGE =   0.15000E+06                         RIVER LEAKAGE =   0.15000E+06

           TOTAL OUT =   0.15000E+06                             TOTAL OUT =   0.15000E+06

            IN - OUT =  -1.8437                                   IN - OUT =  -1.8437

 PERCENT DISCREPANCY =             0.00              PERCENT DISCREPANCY =             0.00
```

Table 1.--Model output for problem 1--Continued

TIME SUMMARY AT END OF TIME STEP 1 IN STRESS PERIOD 1

	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	86400.0	1440.00	24.0000	1.00000	0.273785E-02
STRESS PERIOD TIME	86400.0	1440.00	24.0000	1.00000	0.273785E-02
TOTAL SIMULATION TIME	86400.0	1440.00	24.0000	1.00000	0.273785E-02

wet. It is also possible to use a larger positive wetting threshold to prevent these cells from incorrectly becoming wet.

Validation of Results

There is no known analytical solution for this problem. Several simulations using the BCF1 Package were made to show that the BCF2 results are valid. To do these, initial heads were set so that all cells were active, preventing the need to wet cells. In steady-state simulations, problems occurred because of the drying of too many cells. Therefore, a transient simulation was used to avoid the likelihood for cells to dry unnecessarily. With initial heads of 140 feet and all cells active, the natural and stressed conditions could be simulated in two successive stress periods in much the same way as done in the BCF2 simulation. Each stress period lasted 90,000 days, had 20 time steps, and a time step multiplier of 1.1. The specific yield for layer 1 was 0.2. By the end of the last time step, heads were essentially at steady state.

There were differences between the results from the BCF2 simulation and the transient BCF1 simulation. Cells in column 10 of layer 1 at the end of stress period 2 were dry in the BCF2 simulation and wet in the BCF1 simulation. The result is that heads in the BCF1 simulation are as much as 1 foot lower than heads in the BCF2 simulation. Analysis shows that the differences between the BCF1 and BCF2 simulations are not caused by errors in the BCF2 code. In fact, a transient BCF2 simulation was made that reproduced the BCF1 results exactly. Rather, the differences are caused by the non-unique solutions that can result from the method of solving the nonlinear equations as described previously. The cells in column 10 went dry in the BCF2 simulation because of overshoot in the iterative convergence process. Once they went dry, heads did not go high enough to cause these cells to rewet. In the steady-state BCF2 simulation, the head in column 10 of layer 2 was about 0.8 foot above the bottom of layer 1; the wetting threshold was 2 feet. The effects of flow from storage minimized the overshoot in the BCF1 transient simulation, allowing the cells in column 10 to stay wet. These simulations show that, with the specified wetting criteria, a range of solutions is possible, depending on numerical subtleties of the solution process. The range of uncertainty can be minimized by using a smaller wetting threshold, but this is at the risk of causing instability in the solution process.

Problem 2 -- Simulation of a Water-Table Mound in Resulting from Local Recharge

Localized recharge to a water-table aquifer results in formation of a ground-water mound. For example, a ground-water mound may form in response to recharge from infiltration ponds commonly used to artificially replenish aquifers or to remove contamination by filtration through a soil column. If the aquifer has low vertical hydraulic conductivity or contains interspersed zones of low hydraulic conductivity, it may be necessary to simulate the aquifer using multiple model layers in which the mound crosses more than one layer. The BCF1 Package could not be used for such a simulation because cells cannot change from no-flow to variable head, and the simulated mound could not build up into previously dry layers. The following hypothetical problem was posed to evaluate the capability of the BCF2 Package to simulate mounding of the water table through multiple model layers.

Conceptual Model

The conceptual model consists of a rectangular, unconfined aquifer overlain by a thick unsaturated zone (fig. 2). The horizontal hydraulic conductivity is 5 feet per day and vertical hydraulic conductivity is 0.25 feet per day. A leaking pond recharges the aquifer, resulting in the formation of a ground-water mound. The pond covers approximately 6 acres and pond leakage is 12,500 cubic feet per day (65 gallons per minute). The specific yield is 20 percent. The water table is flat prior to the creation of the recharge pond. The flat water table is the result of a uniform constant-head boundary that surrounds the aquifer.

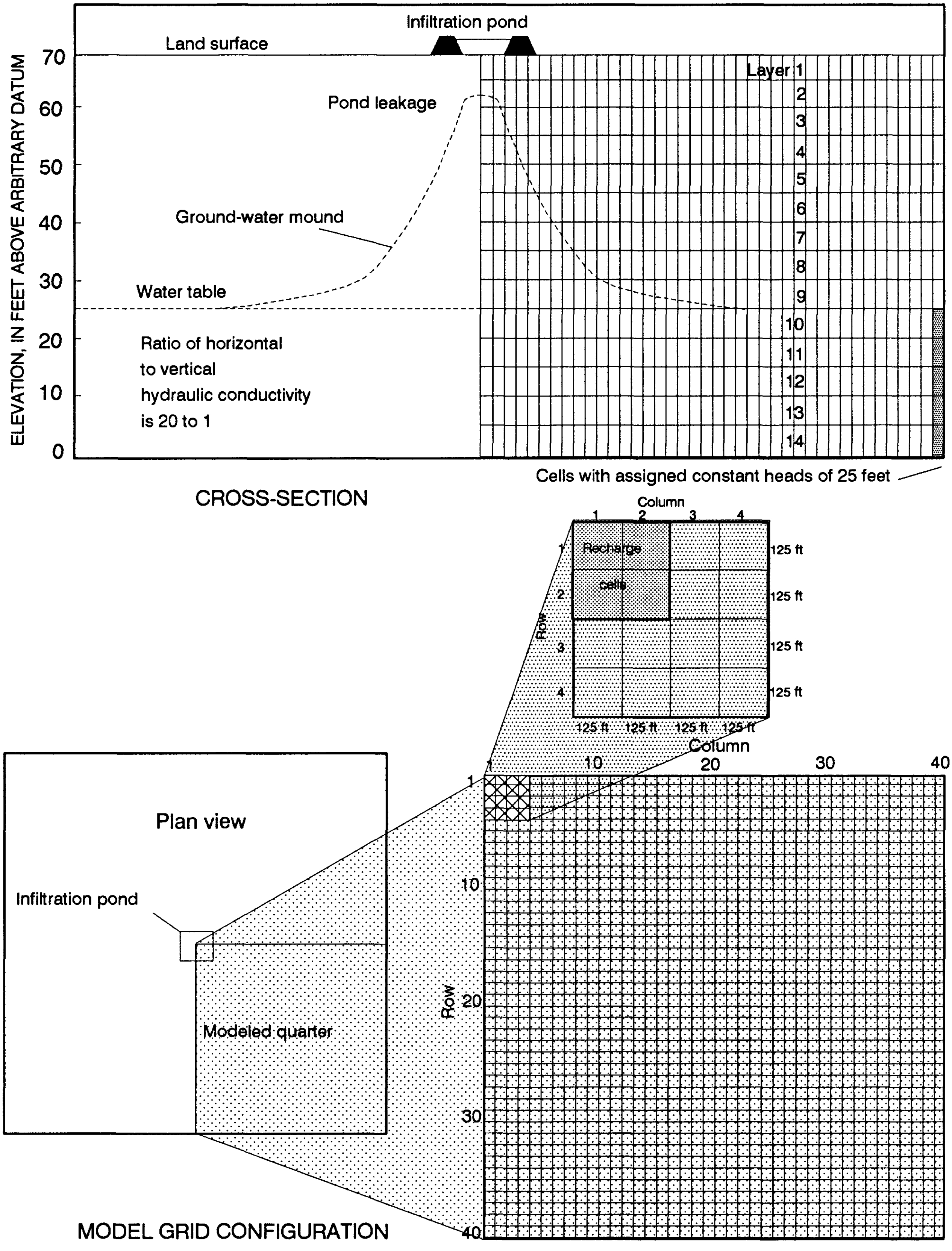

Figure 2.--Hydrogeology, model grid, and model boundary conditions for problem 2.

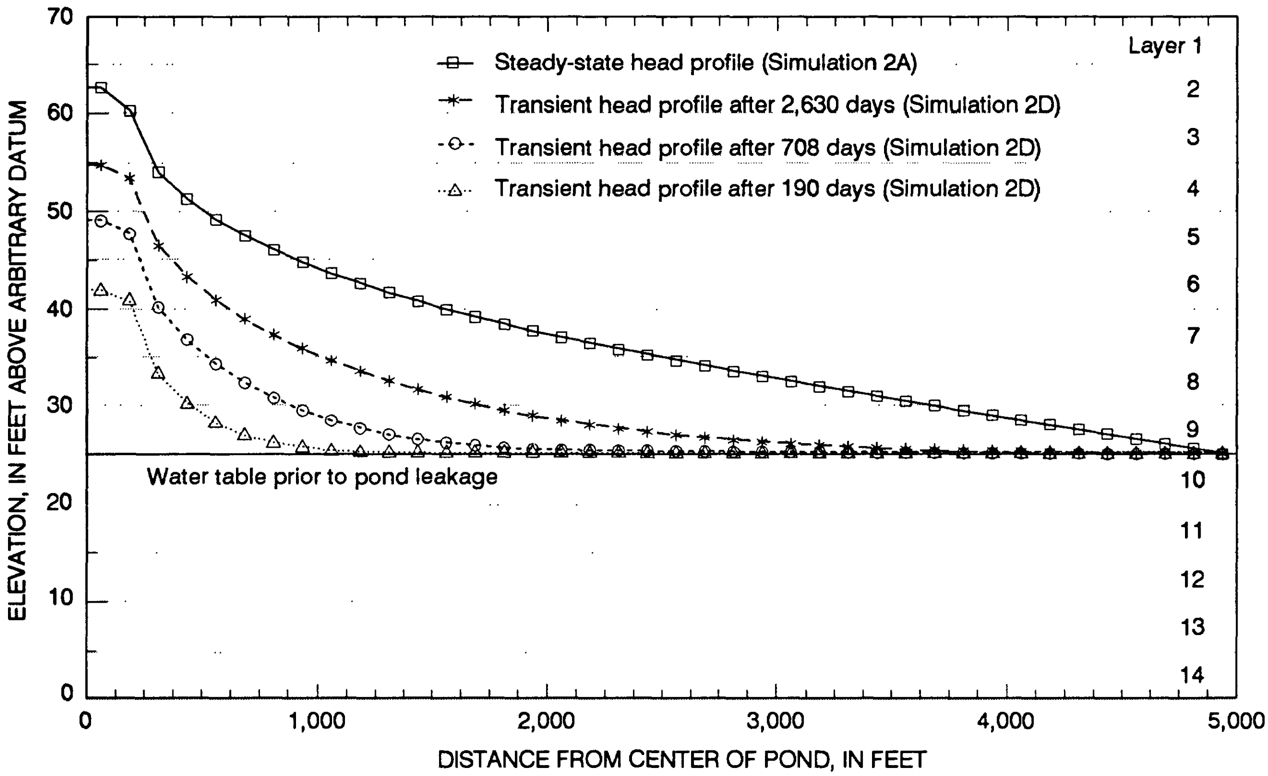

Figure 3.--Simulated head profiles beneath a leaking pond after 190 days, 708 days, 2,630 days, and at steady state conditions.

steepness of the head gradient and the grid discretization, the head difference between adjacent horizontal cells is generally much larger than the head difference between adjacent vertical cells along the mound. For example, the cell at layer 4, row 3, column 4 is supposed to be dry even though the head in the horizontally adjacent cell in column 3 is 1.4 feet above the bottom of the layer. The vertical head difference between cells in this part of the model is much less; the difference between the head at the cell in layer 4, row 3, column 3 and the cell below is only 0.05 foot. Thus, the neighboring cell to the right is repeatedly and incorrectly converted to wet during the solution process if horizontal wetting is used with a wetting threshold of 0.5 foot. The larger wetting threshold and wetting-iteration interval used in Simulation 2B allow convergence to occur, but only after many iterations. In this simulation, head in adjacent vertical cells is the best indicator of when a dry cell should become wet.

Both simulations gave similar results with minor differences in which cells were wet. For example, Simulation 2A has one wet cell in layer two while Simulation 2B has three wet cells in layer 2. However there were 244 less wet cells for Simulation 2B. This is because the higher wetting threshold of Simulation 2B prevented some cells from wetting that would have wetted with a lower threshold. Head differences between the two solutions generally were 0.05 foot or less with the exception of head at a few cells near the areas where the two simulations differed in which cells were wet. Head differences of about 0.1 foot were noted in these cells. The volumetric budget error for both solutions was zero.

A SIP solution to the steady-state ground-water mounding problem, Simulation 2C, was also obtained. In this simulation, cells were activated by comparison only to head in underlying cells. Wetting and SIP solver parameters were adjusted to minimize the required iterations (table 2). The wetting iteration interval was experimentally set at 11 iterations. The wetting threshold and wetting factor were set at 0.5 foot and 1.0, respectively. The solution met the head-change criterion for closure in 827 iterations, resulting in a budget error of 0.04 percent. This simulation took much more computer time than either PCG2 simulation. There were 43 less wet cells than in Simulation 2A. Heads matched Simulation 2A within 0.05 foot.

Modeling Approach

Because of the symmetry, heads are identical in each quadrant of the aquifer, and there is no flow between quadrants; therefore, only one quarter of the system needs to be simulated. The problem is simulated using a grid of 40 rows, 40 columns, and 14 layers (fig. 2). A uniform horizontal grid spacing of 125 feet is used, and each layer is 5 feet thick. The pond is in the upper left corner of the grid. The boundaries along row 1 and column 1 are no-flow as a result of the symmetry. A constant-head boundary of 25 feet is specified along row 40 and column 40 for layers 10-14; a no-flow boundary is assigned along row 40 and column 40 for layers 1-9. Without the recharge from the pond, layers 1-9 are dry, and the head in all the cells of layers 10-14 is 25 feet.

Recharge from the pond is applied to the horizontal area encompassed by rows 1 through 2 and columns 1 through 2. Recharge option 3 (McDonald and Harbaugh, 1988, p. 7-2) is used so that recharge will penetrate through inactive cells down to the water table. The recharge rate of 0.05 foot per day simulates leakage of 3,125 cubic feet per day (16.2 gallons per minute) through one quarter of the pond bottom, a simulated area of 62,500 square feet.

Simulation Results

Steady-state and transient simulations were made to demonstrate the capability of the BCF2 Package to simulate the formation of the mound. Solution of the flow equations was attempted using both the PCG2 solver and the SIP solver. Also, several combinations of the BCF2 parameters that affect stability of the wetting process were used. Wetting and solver parameters are shown in table 2 for comparison.

Table 2. -- Wetting and solver input data for Problem 2 simulations

Parameter	Simulation 2A	Simulation 2B	Simulation 2C
WETDRY (feet)	-0.5	1.5	-0.5
Equation used for calculating head at a cell that is wetted	3a	3a	3b
Wetting factor (WETFCT)	0.5	0.5	1.0
Wetting iteration interval (IWETIT)	1	2	11
Solver	PCG2	PCG2	SIP
Head-change closure criterion (feet)	0.001	0.001	0.00001
PCG residual closure criterion (cubic feet)	1000.	1000.	N/A
PCG maximum inner iterations	20	20	N/A
SIP WSEED	N/A	N/A	0.002

For the steady-state problem, the least computational time was required when using the PCG2 solver. Reasonable solutions to the ground-water mounding problem were obtained in two steady-state PCG2 simulations. In the first simulation, Simulation 2A, dry cells were converted to wet by comparison of the wetting threshold to head only in underlying cells, which is indicated by a negative WETDRY parameter. The wetting-iteration interval was 1 and the WETDRY parameter was -0.5 foot, which means that the wetting threshold is 10 percent of the thickness of a cell. Solution was achieved in 11 outer iterations and 179 total iterations. Figure 3 shows results from Simulation 2A.

In the second PCG2 simulation, Simulation 2B, wetting of cells was based on comparison to heads both in horizontally adjacent and underlying cells (WETDRY parameter is positive). A wetting-iteration interval of 2 and a WETDRY parameter of 1.5 feet were used in order to prevent continued oscillation between wet and dry for some cells. Solution was obtained in 23 outer iterations and 420 total iterations.

The use of horizontal wetting resulted in additional iterations for the second simulation and the need to change wetting parameters. Due to the

A steady-state SIP solution in which cells were activated by comparison of the wetting threshold to heads in horizontally adjacent and underlying cells could not be obtained despite experimental variation of WSEED and the wetting iteration interval. Chaotic wetting and drying of cells caused the simulation to terminate with divide-by-zero errors due to isolated groups of active cells.

The formation of the ground-water mound was simulated over time with a transient simulation, Simulation 2D. The transient simulation was run for one stress period with a length of 500,000 days. The stress period was divided into 50 time steps with a time-step multiplier of 1.3. The first time step was 0.3 days, and the last time step was 115,000 days. Transient simulations used a specific yield of 20 percent and a confined storage coefficient of 0.001. The PCG2 solver was used and cells were activated by comparison of the wetting threshold to heads in underlying cells. The head-change criterion for closure was 0.001 foot and the residual-change criterion was 10,000 cubic feet, the wetting threshold was 0.5 foot, the wetting factor was 0.5, and the wetting-iteration interval was 1. Figure 3 shows simulated water-table heads along row 1 at several times during the transient simulation.

Steady-state conditions were reached at the end of the transient simulation as indicated by storage flow terms being zero. Simulation 2D had 43 less wet cells at the end than did Simulation 2A. Heads at the end of Simulation 2D were within 0.02 foot of the heads in Simulation 2A. The volumetric budget error at the end of the stress period was 0.02 percent.

Validation of Results

The ground-water mounding problem is nonlinear, precluding comparison to an analytical solution. The steady-state solution from Simulation 2A was compared to two BCF1 simulations to show that the solution was reasonable.

The mounding problem theoretically can be simulated by the BCF1 Package in steady state if initial heads are above the final heads. That is, BCF1 could cause cells above the top of the mound to dry up provided that, as described earlier, heads did not temporarily drop too low during the convergence process. Several unsuccessful steady-state simulations were made to try to reproduce the BCF2 results. For these simulations, initial heads were specified as 65 feet for layers 1 through 9 and 25 feet for layers 10 through 14. The result was that too many cells went dry. In early iterations, heads dropped over the entire region so that all cells dried up in layers 1 through 5 even at the center of the mound. In later iterations, heads at the center of the mound rose again, but there was no way to rewet the dried cells. No amount of adjustment using SIP or PCG2 could avoid this problem.

Another approach at using BCF1 to simulate this problem at steady state was successful. A transient simulation was used so that the mound could form slowly over time. This produced the desired result of allowing heads to drop faster at the fringes of the mound than at the center. The steady-state solution was approximated by running the transient simulation for a 900,000-day stress period.

The successful BCF1 simulation, Simulation 2E, consisted of one stress period divided into 20 time steps with a time-step multiplier of 1.5. All cells in layers 2 through 14 initially were active and fully saturated; starting heads of 65 feet and 25 feet were assigned to all cells in layers 1-9 and 10-14, respectively. Cells were permitted to drain to a steady-state distribution of heads using the same recharge, grid configuration, and boundary conditions as used in the BCF2 simulations. The PCG2 solver was used in the simulation. PCG2 parameters included a head-change criterion for closure of 0.001 foot, residual closure criterion of 1,000 cubic feet per day and a maximum of 20 inner iterations for each outer iteration. In the last time step, essentially no water was moving in or out of storage. The overall volumetric budget error was -0.01 percent.

Comparison of Simulations 2A and 2E indicates that the steady-state heads match within 0.12 foot. Heads in Simulation 2E are slightly lower than in Simulation 2A because Simulation 2E has 159 more wet cells than Simulation 2A. For example, there are four wet cells in layer 2 in

Simulation 2E and one wet cell in Simulation 2A. This reflects the fact that the BCF1 solution was obtained by draining the system rather than raising heads. In Simulation 2A, heads below those dry cells that were wet in Simulation 2E are above the bottom of the dry cells, but not by more than the wetting threshold. Thus, the cells do not become wet. Both solutions are reasonable, but the differences point out the lack of uniqueness that results from the method of solving the nonlinear equations.

A steady-state BCF1 simulation with only one layer, Simulation 2F, was also run to help evaluate whether the steady-state BCF2 solution was reasonable. With the exception of the layering configuration and associated anisotropy, all other input parameters were the same as in the BCF2 simulations. The one-layer steady-state solution was by the SIP solver.

Figure 4 compares the head from Simulations 2F, 2E, and 2A. For Simulations 2A and 2E, head is the water-table head (head in the highest variable-head cell at a horizontal location). Heads in Simulation 2F are similar to but lower than water-table heads in the multi-layer simulations (Simulations 2A and 2E) because vertical resistance to flow is not being simulated in Simulation 2F. The vertically averaged head from all the cells at row 1, column 1 in Simulation 2A is 0.71 feet greater than the head in Simulation 2F. These results indicate that the BCF2 simulations provide a reasonable solution to the nonlinear, layered, ground-water mounding problem.

The steady-state and transient simulations of Problem 2 show that the BCF2 Package can successfully simulate the multiple-layer formation of a ground-water mound in a water-table aquifer. In many ways, Problem 2 simulates a very simple aquifer system compared to typical real-world systems. For example, boundary conditions would normally be more complex with the regional water table resulting from areal recharge flowing to natural discharge points. Also, additional stresses would normally be part of the system. However, the simplicity of the aquifer system does not reduce the complexity of the simulation regarding the wetting of cells. That is, this simulation is a difficult test of the cell-wetting capability of the BCF2 Package. In fact, typical simulations using the wetting

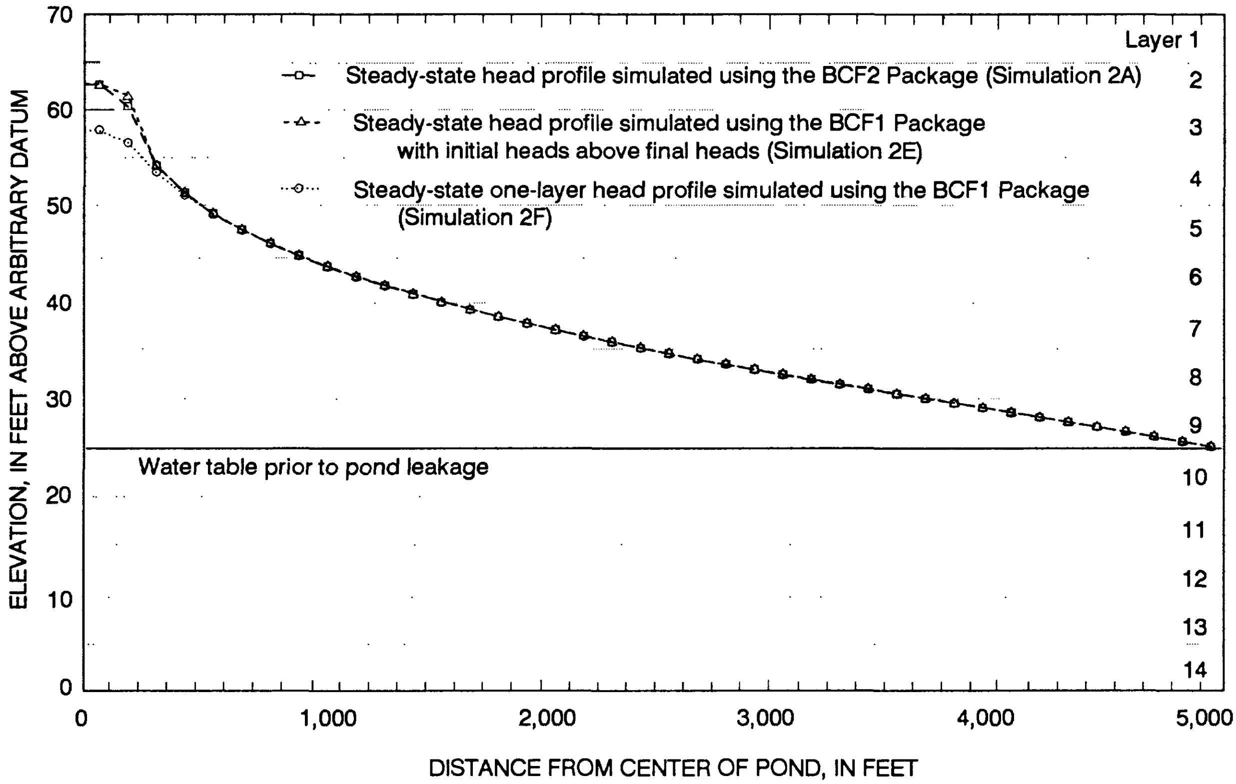

Figure 4.--Steady-state head profiles simulated using the BCF2 Package and BCF1 Package [one BCF1 simulation with initial heads higher than final heads and a one-layer BCF1 simulation].

capability probably will not involve a water table crossing so many model layers. For many purposes, this system could be simulated realistically with less layers. The large number of layers was used in order to test the BCF2 Package. With the water table crossing eight layers, there is a high possibility of repeated wetting and drying of cells. Yet stable solutions were obtained after moderate effort was used in selecting the various parameters that affect solution stability.

Problem 3 -- Simulation of a Perched Water Table

Contrasts in vertical hydraulic conductivity within the unsaturated zone can provide a mechanism for the formation of perched ground-water tables. The formation of these bodies in a previously unsaturated zone is difficult to simulate with the BCF1 Package because cells cannot change from no-flow to variable-head conditions. A problem was posed to evaluate the capability of the BCF2 Package to simulate formation of a perched water table. This problem has practical application in the simulation of recharge going to a deeper aquifer system.

Conceptual Model

The conceptual model is rectangular and consists of three geohydrologic units. The upper and lower units have higher hydraulic conductivities than the middle unit (fig. 5). There is a regional water table in which the head is below the bottom of unit 2. Natural recharge occurs over the entire area at a rate of 0.001 foot per day. This recharge can percolate through the two upper units without the formation of a water table above unit 2 because the vertical hydraulic conductivity of this middle unit is 0.002 foot per day.

Recharge at a rate of 0.01 foot per day from a pond covering 6 acres causes a perched ground-water body to form in the top two units. The total pond leakage is about 2,360 cubic feet per day (12 gallons per minute). The perched water table spreads out over an area much larger than the area

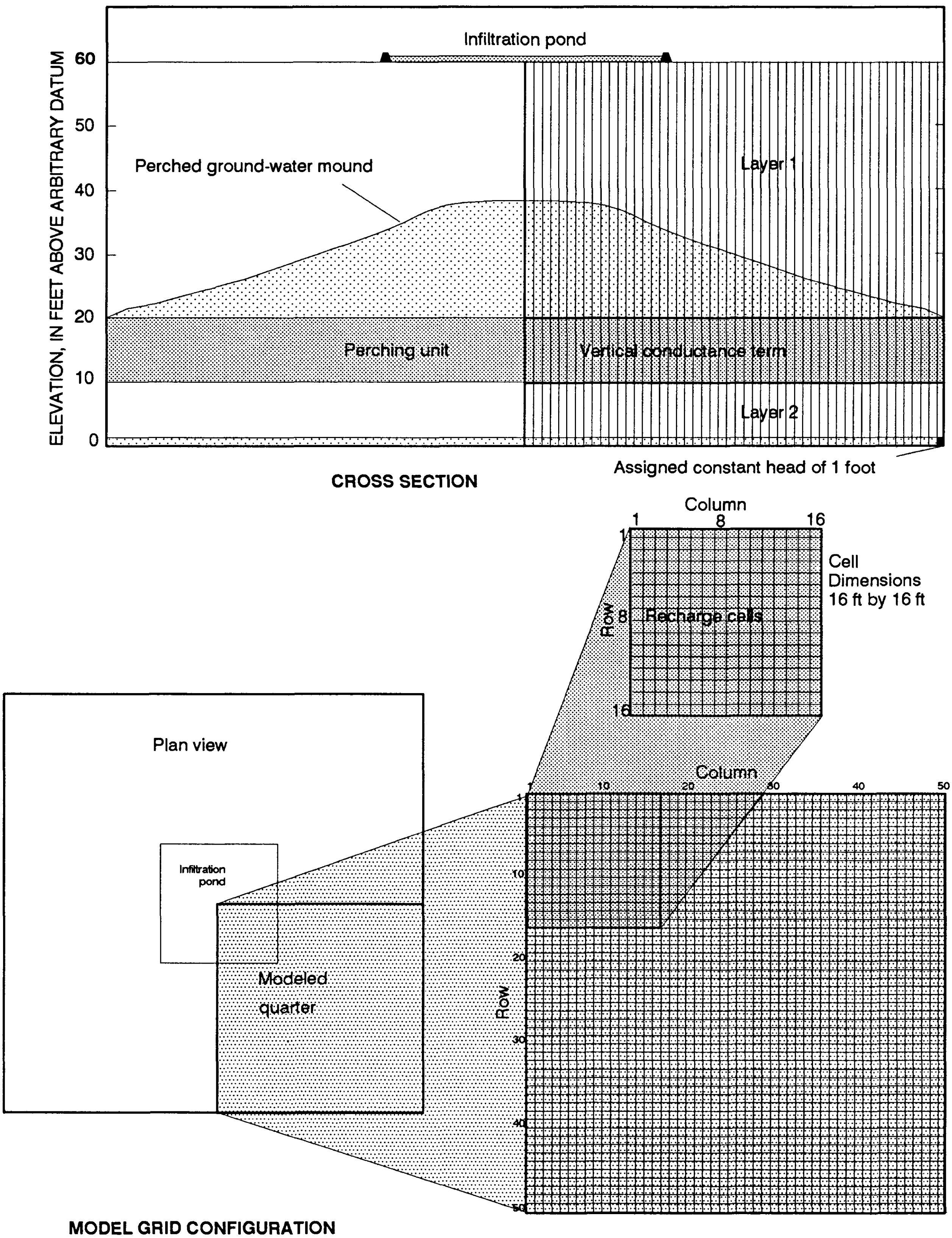

Figure 5.--Hydrogeology, model grid, and model boundary conditions for problem 3.

covered by the pond. This has an impact on the distribution of recharge to the lower unit.

Modeling Approach

Because of the rectangular symmetry of the system, there is no flow between quadrants. Therefore, only one quarter of the system must be simulated. The problem is simulated using a grid of 50 rows, 50 columns, and 2 units. A uniform grid spacing of 16 feet is used. The recharge pond is in the upper left corner of the grid; the quarter of the pond that is simulated occupies a square area that is 16 rows long and 16 columns wide. The boundaries along row 1 and along column 1 are no-flow boundaries as a result of the symmetry.

Model layer 1 simulates geohydrologic unit 1 and is assigned a hydraulic conductivity of 5 feet per day. The bottom of layer 1 is at an elevation of 20 feet.

Geohydrologic unit 3 is simulated as model layer 2. This layer is simulated as a confined/unconfined layer with constant transmissivity (layer-type 2, McDonald and Harbaugh, p. 5-34). The top and bottom of layer 2 are set at 10 and 0 feet, respectively. Because the head in this unit is always below the top of the unit, the flow from above is limited as described by McDonald and Harbaugh (p. 5-19). Thus, there is no direct hydraulic connection between the perched layer and the lower layer, but the perched heads have a direct impact on the recharge into the lower layer. The purpose of the simulation is to show that the distribution of recharge from the perched system can be estimated by using the BCF2 Package to simulate the perched water table. All cells in layer 2 are assigned a constant head of 1 foot because there is no need to simulate heads in this layer for the purpose of estimating recharge.

Geohydrologic layer 2 is not simulated as a separate model layer because it is assumed that horizontal flow and storage affects are negligible. This layer is represented by the value for VCONT (vertical hydraulic conductivity divided by thickness) between model layers 1 and 2. Assuming the vertical hydraulic conductivity is 0.002 foot per day and the thickness is 10 feet, VCONT is 0.0002 per day.

In areas not covered by the pond, recharge is applied areally at a rate of 0.001 foot per day to simulate natural recharge. Recharge option 3 (McDonald and Harbaugh, 1988, p. 7-2) is used so that recharge will penetrate through inactive cells to the water table. A recharge rate of 0.01 foot per day is applied to the area covered by the pond.

Simulation Results

Steady-state and transient simulations were made to demonstrate the capability of the BCF2 Package to simulate the formation of a perched water table. Solutions of the flow equation were obtained using the SIP solver and the PCG2 solver. Both solvers gave good solutions, but SIP was the most efficient. The SIP results are presented in the rest of this discussion.

The steady-state simulation produced the long-term head distribution resulting from the pond recharge. Initial head in layer 1 under the pond was set at 21 feet. All other cells in layer 1 initially were specified as no-flow cells. Wetting and SIP solver parameters were adjusted to obtain a solution. The wetting-iteration interval, WETDRY parameter, and wetting factor were set at 2 iterations, 1.0 foot, and 0.5, respectively. The WETDRY parameter was positive to indicate that horizontally adjacent cells could cause dry cells to become wet. This was the only way for cells in layer 1 to become wet because heads in layer 2 were always below the bottom of layer 1. The head-change criterion for closure was set at 0.001 foot. The adjusted WSEED value was 0.0015.

Steady-state heads along row 1 in layer 1 ranged from 29.92 feet in cell 1,1,1 to 20.78 feet in cell 1,1,40 (fig. 6). The volumetric budget error was 0.03 percent, and the solution met the head-change criterion for closure in 101 iterations.

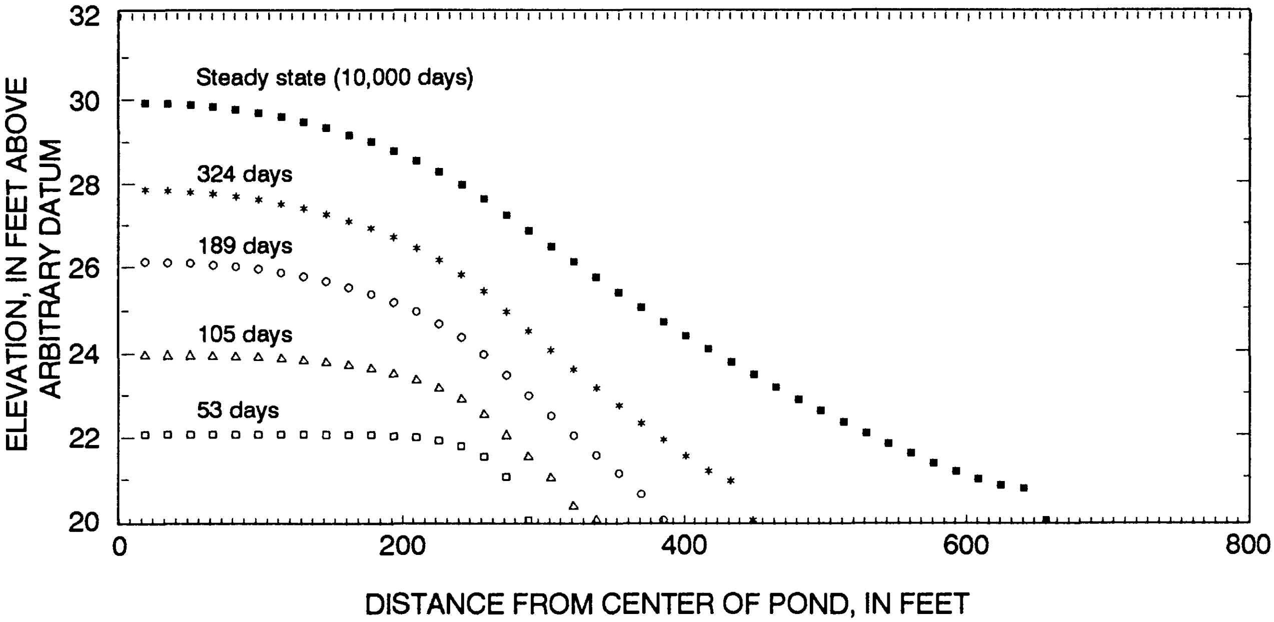

Figure 6.--Simulated perched water-table profiles after 53 days, 105 days 189 days, 324 days, and at steady-state conditions.

The formation of the perched water table was simulated over time in a transient simulation. The transient simulation was run for one stress period with a length of 10,000 days. The stress period was divided into 60 time steps with a time-step multiplier of 1.1. The specific yield was 20 percent. The wetting-iteration interval and wetting factor were experimentally set at 1 iteration and 0.1, respectively. The WETDRY parameter was 1.3 feet in the square area defined by rows 1-18 and columns 1-18, and everywhere else WETDRY was 1 foot. Initially, WETDRY was set to 1 foot everywhere, but this resulted in instability in early time. This may have been caused by the steeper head gradients that occur in early time as the mound began to form. Also, as described earlier, small time steps can contribute to instability due to the resulting large rates of flow from storage. The adjusted WSEED value was 0.0001. Initial heads of 20.01 feet were set at the cells below the pond. All other cells in layer 1 initially were no flow.

Transient heads along row 1 of layer 1 are shown in figure 6 at times of 53 days, 105 days, 189 days, and 324 days. The volumetric budget error was zero. After 10,000 days, heads essentially were at steady state because flow into storage was zero. Heads at the end of the transient simulation matched the heads from the steady-state simulation within 0.02 foot.

Validation of Results

The perched water-table problem is nonlinear, precluding comparison to an analytical solution. Comparison of the steady-state and transient solutions indicated that the BCF2 simulations reasonably solved the problem. The steady-state BCF2 solution also was compared to a transient BCF1 simulation to determine whether the solution was reasonable.

The BCF1 transient solution to the perched water-table problem was simulated by permitting cells to drain to a steady-state configuration. All cells in layer 1 initially were active with a starting head of 30 feet. SIP solver parameters were the same as those used in the BCF2 solutions. The simulation was run for 10,000 days, using 100 time steps and a time-step multiplier of 1.1. The volumetric budget error at the end of the 10,000 days was zero.

The steady-state heads were very similar in the two simulations, but the BCF1 steady-state heads were as much as 0.6 foot lower than the BCF2 steady-state heads near the edges of the perched water table. In the BCF1 simulation, the heads were draining from high initial values while in the the BCF2 simulation, heads rose from low initial values. Thus, some cells remained wet in the BCF1 simulation that did not become wet in the BCF2 simulation because the wetting threshold was not exceeded. The larger extent of the water table in the BCF1 simulation caused the slightly lower heads.

MODULE DOCUMENTATION

The design of the BCF2 Package closely follows the design of the BCF1 Package. Several of the BCF2 modules are identical to BCF1 modules, and the replaced modules are very similar in function and structure to the previous modules. There is one new module, BCF2AD. The unchanged modules have not been given new names. That is, the unchanged modules retain the revision level "1" in their names. Accordingly, the BCF2 Package consists of the following modules: BCF2AL, BCF2RP, BCF2AD, BCF2FM, BCF1BD, SBCF2N, SBCF2H, SBCF1C, SBCF1B, SBCF1F. This report contains documentation for all of the new modules. Refer to McDonald and Harbaugh (1988, Ch. 5) for documentation of unchanged modules.

In the model program, each package is assigned a file unit on which to read input data. The file unit for the BCF2 Package is assumed to be the same input unit that is used by the BCF1 Package, which is the first element in the IUNIT array [IUNIT(1)]. Because the BCF2 Package contains all of the functionality of the BCF1 Package, there is no need to retain the BCF1 Package as a separate package in the model program.

The MAIN program must be modified to call the BCF2 Package. There are 5 calls to BCF2 Package modules -- BCF2AL, BCF2RP, BCF2AD, BCF2FM, and BCF1BD. The call to module BCF1BD should not be changed from what it is in the original MAIN program (McDonald and Harbaugh, 1988, p. 3-32). Make the following changes to the MAIN program:

Replace the BCF1AL call statement with the following:

```
      IF(IUNIT(1).GT.0) CALL BCF2AL(ISUM,LENX,LCSC1,LCHY,
     1      LCBOT,LCTOP,LCSC2,LCTRPY,IUNIT(1),ISS,
     2      NCOL,NROW,NLAY,IOUT,IBCFCB,LCWETD,IWDFLG,LCCVWD,
     3      WETFCT,IWETIT,IHDWET,HDRY)
```

Replace the BCF1RP call statement with the following:

```
      IF(IUNIT(1).GT.0) CALL BCF2RP(X(LCIBOU),X(LCHNEW),X(LCSC1),
     1           X(LCHY),X(LCCR),X(LCCC),X(LCCV),X(LCDELR),
     2      X(LCDELC),X(LCBOT),X(LCTOP),X(LCSC2),X(LCTRPY),IUNIT(1),
     3      ISS,NCOL,NROW,NLAY,NODES,IOUT,X(LCWETD),IWDFLG,X(LCCVWD))
```

Replace the BCF1FM call statement with the following:

```
      IF(IUNIT(1).GT.0) CALL BCF2FM(X(LCHCOF),X(LCRHS),X(LCHOLD),
     1          X(LCSC1),X(LCHNEW),X(LCIBOU),X(LCCR),X(LCCC),X(LCCV),
     2          X(LCHY),X(LCTRPY),X(LCBOT),X(LCTOP),X(LCSC2),
     3          X(LCDELR),X(LCDELC),DELT,ISS,KKITER,KKSTP,KKPER,NCOL,
     4          NROW,NLAY,IOUT,X(LCWETD),IWDFLG,X(LCCVWD),WETFCT,
     5          IWETIT,IHDWET,HDRY)
```

Add a new call statement for the BCF2AD module immediately following the statement that calls module BAS1AD:

```
      IF(IUNIT(1).GT.0) CALL BCF2AD(X(LCIBOU),X(LCHOLD),X(LCBOT),
     1             X(LCWETD),IWDFLG,ISS,NCOL,NROW,NLAY)
```

Narrative for Module BCF2AL

This module allocates space for data arrays for the BCF2 Package.

1. Print a message identifying the package

2. Read and print the steady-state flag ISS and the cell-by-cell flow-term unit and flag (IBCFCB). Cell-by-cell flow terms for the BCF Package are flow to the right, flow forward, flow down, inflow from storage, and flow from constant heads. Read and print HDRY, which is the value for head that is assigned at cells that convert to dry (no flow). Also read and print the flag that determines if the wetting capability is active (IWDFLG), and read the wetting parameters WETFCT (wetting factor), IWETIT (wetting iteration interval), and IHDWET (flag that determines which equation is used to calculate the initial estimate of head at a wetted cell). If wetting is active, print the wetting parameters.

3. Stop the simulation if there are more than 80 layers.

4. Read the layer-type codes (LAYCON) and print the title for the table of layer-type codes.

   0 = confined
   1 = unconfined
   2 = confined/unconfined but transmissivity is constant
   3 = confined/unconfined with transmissivity dependent on head

5. Loop through layers printing the layer-type codes and counting the layers that require TOP and BOT arrays. Initialize the counters KT and KB in which the numbers of layers needing the TOP and BOT arrays are accumulated.

   (a) Only the top layer can be unconfined. If a layer other than the top layer is unconfined (layer type 1), print an error message and STOP.

   (b) If the layer type is one or three, add one to KB, which counts the number BOT arrays.

   (c) If the layer type is two or three, add one to KT, which counts the number of TOP arrays.

6. Compute the number of cells in the entire grid and in one layer.

7. Allocate space for the following arrays:

SC1	Primary storage capacity (only if transient);
SC2	Secondary storage capacity (only if transient);
TRPY	Horizontal anisotropy factor;
BOT	Bottom elevation of cells;

HY	Hydraulic conductivity;
TOP	Top elevation of cells;
WETD	Wetting threshold (only when wetting is active); and
CVWD	Initial values of vertical conductance (only when wetting is active).

8. Print the amount of space used by the BCF Package.

9. RETURN.

ISS is the steady-state flag. If it is set (ISS not 0), the simulation is steady state (storage is not considered).

IBCFCB is a flag and a unit number for saving cell-by-cell flow data.

If IBCFCB > 0, it is the unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set.

If IBCFCB = 0, cell-by-cell flow terms will not be printed or recorded.

If IBCFCB < 0, flow from constant-head cells will be printed whenever ICBCFL is set.

HDRY is the head that is assigned to cells that convert to dry.

LAYCON is a layer-type code (one for each layer).

0 - confined
1 - unconfined
2 - confined/unconfined but transmissivity is constant
3 - confined/unconfined

TOP is the elevation of the top of cells (one value for each cell in a layer).

BOT is the elevation of the bottom of cells (one value for each cell in a layer).

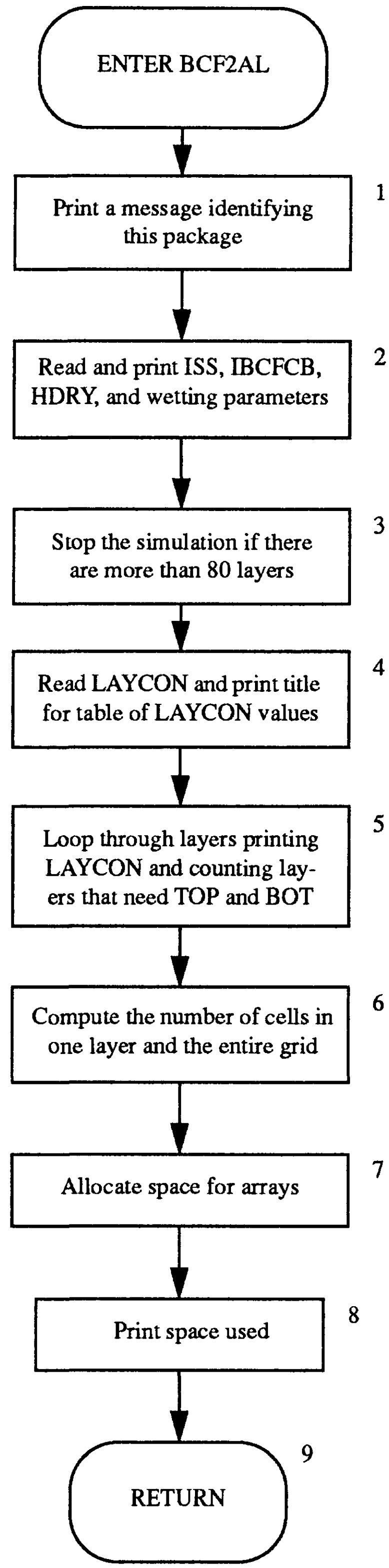

Figure 7. -- Flow chart for module BCF2AL.

```
      SUBROUTINE BCF2AL(ISUM,LENX,LCSC1,LCHY,LCBOT,LCTOP,LCSC2,LCTRPY,
     1  IN,ISS,NCOL,NROW,NLAY,IOUT,IBCFCB,LCWETD,IWDFLG,LCCVWD,
     2  WETFCT,IWETIT,IHDWET,HDRY)
C
C-----VERSION 1435 14MAY1991 BCF2AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR BLOCK-CENTERED FLOW PACKAGE, VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      COMMON /FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
C
C1------IDENTIFY PACKAGE
      WRITE(IOUT,1)IN
    1 FORMAT(1H0,'BCF2 -- BLOCK-CENTERED FLOW PACKAGE, VERSION 2',
     1', 7/1/91',' INPUT READ FROM UNIT',I3)
C
C2------READ AND PRINT ISS (STEADY-STATE FLAG), IBCFCB (FLAG FOR
C2------PRINTING OR UNIT# FOR RECORDING CELL-BY-CELL FLOW TERMS),
C2------HDRY (HEAD AT CELLS THAT CONVERT TO DRY), AND WETTING PARAMETERS
      READ(IN,2) ISS,IBCFCB,HDRY,IWDFLG,WETFCT,IWETIT,IHDWET
    2 FORMAT(2I10,F10.0,I10,F10.0,2I10)
      IF(ISS.EQ.0) WRITE(IOUT,3)
    3 FORMAT(1X,'TRANSIENT SIMULATION')
      IF(ISS.NE.0) WRITE(IOUT,4)
    4 FORMAT(1X,'STEADY-STATE SIMULATION')
      IF(IBCFCB.GT.0) WRITE(IOUT,9) IBCFCB
    9 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE RECORDED ON UNIT',I3)
IF(IBCFCB.LT.0) WRITE(IOUT,88)
   88 FORMAT(1X,'CONSTANT HEAD CELL-BY-CELL FLOWS WILL BE PRINTED')
      WRITE(IOUT,89) HDRY
   89 FORMAT(1X,'HEAD AT CELLS THAT CONVERT TO DRY=',G13.5)
      IF(IWDFLG.NE.0) GO TO 35
      WRITE(IOUT,31)
   31 FORMAT(1X,'WETTING CAPABILITY IS NOT ACTIVE')
      GO TO 39
C
   35 WRITE(IOUT,36)
   36 FORMAT(1X,'WETTING CAPABILITY IS ACTIVE')
      IF(IWETIT.LE.0) IWETIT=1
      WRITE(IOUT,37)WETFCT,IWETIT
   37 FORMAT(1X,'WETTING FACTOR=',F10.5,
     1     '      WETTING ITERATION INTERVAL=',I4)
      WRITE(IOUT,38)IHDWET
   38 FORMAT(1X,'FLAG THAT SPECIFIES THE EQUATION TO USE FOR HEAD AT WET
     1TED CELLS=',I4)
C
C3------STOP THE SIMULATION IF THERE ARE MORE THAN 80 LAYERS
   39 IF(NLAY.LE.80) GO TO 50
      WRITE(IOUT,11)
   11 FORMAT(1H0,'YOU HAVE SPECIFIED MORE THAN 80 MODEL LAYERS'/1X,
     1 'SPACE IS RESERVED FOR A MAXIMUM OF 80 LAYERS IN ARRAY LAYCON')
```

```
      STOP
C
C4------READ LAYCON & PRINT TITLE FOR LAYCON TABLE
   50 READ(IN,51) (LAYCON(I),I=1,NLAY)
   51 FORMAT(40I2)
      WRITE(IOUT,52)
   52 FORMAT(1X,5X,'LAYER  AQUIFER TYPE',/1X,5X,19('-'))
C
C5------LOOP THROUGH LAYERS PRINTING THE LAYER-TYPE CODE AND COUNTING
C5------LAYERS THAT NEED TOP & BOT ARRAYS
      NBOT=0
      NTOP=0
      DO 100 I=1,NLAY
      L=LAYCON(I)
      WRITE(IOUT,7) I,L
    7 FORMAT(1X,I9,I10)
C
C5A-----ONLY THE TOP LAYER CAN BE UNCONFINED(LAYCON=1).
      IF(L.NE.1 .OR. I.EQ.1) GO TO 70
      WRITE(IOUT,8)
    8 FORMAT(1H0,'AQUIFER TYPE 1 IS ONLY ALLOWED IN TOP LAYER')
      STOP
C
C5B-----LAYER TYPES 1 AND 3 NEED A BOTTOM. ADD 1 TO KB.
   70 IF(L.EQ.1 .OR. L.EQ.3) NBOT=NBOT+1
C
C5C-----LAYER TYPES 2 AND 3 NEED A TOP. ADD 1 TO KT.
      IF(L.EQ.2 .OR. L.EQ.3) NTOP=NTOP+1
  100 CONTINUE
C
C
C
C6------COMPUTE THE NUMBER OF CELLS IN THE ENTIRE GRID AND IN ONE LAYER
      NRC=NROW*NCOL
      ISIZ=NRC*NLAY
C
C7------ALLOCATE SPACE FOR ARRAYS.
      ISOLD=ISUM
      LCSC1=ISUM
      IF(ISS.EQ.0) ISUM=ISUM+ISIZ
      LCSC2=ISUM
      IF(ISS.EQ.0) ISUM=ISUM+NRC*NTOP
      LCTRPY=ISUM
      ISUM=ISUM+NLAY
      LCBOT=ISUM
      ISUM=ISUM+NRC*NBOT
      LCHY=ISUM
      ISUM=ISUM+NRC*NBOT
      LCTOP=ISUM
      ISUM=ISUM+NRC*NTOP
      LCWETD=ISUM
      IF(IWDFLG.NE.0)ISUM=ISUM+NRC*NBOT
      LCCVWD=ISUM
      IF(IWDFLG.NE.0)ISUM=ISUM+NRC*(NLAY-1)
```

```
C
C8------PRINT THE AMOUNT OF SPACE USED BY THE BCF PACKAGE.
      ISP=ISUM-ISOLD
      WRITE(IOUT,101) ISP
  101 FORMAT(1X,I8,' ELEMENTS IN X ARRAY ARE USED BY BCF')
      ISUM1=ISUM-1
      WRITE(IOUT,102) ISUM1,LENX
  102 FORMAT(1X,I8,' ELEMENTS OF X ARRAY USED OUT OF',I8)
      IF(ISUM1.GT.LENX) WRITE(IOUT,103)
  103 FORMAT(1X,'   ***X ARRAY MUST BE DIMENSIONED LARGER***')
C
C9------RETURN
      RETURN
      END
```

List of Variables for Module BCF2AL

Variable	Range	Definition
HDRY	Package	When a cell converts to dry, HNEW is set equal to HDRY.
I	Module	Index
IBCFCB	Package	Flag and a unit number. > 0, unit number on which cell-by-cell flow terms will be recorded whenever ICBCFL is set. = 0, cell-by-cell flow terms will not be printed or recorded. < 0, flow from each constant-head cell will be printed whenever ICBCFL is set.
IHDWET	Package	Flag indicating which equation to use for calculating the head at a cell that has just converted from dry to wet.
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output.
ISIZ	Module	Number of cells in the grid.
ISOLD	Module	Value of ISUM upon entry to this module.
ISP	Module	Number of elements in the X array allocated by this module.
ISS	Package	Steady-state flag. = 0, simulation is transient not 0, simulation is steady state.
ISUM	Global	Element number of the lowest element in the X array that has not yet been allocated. When space is allocated in the X array, the size of the allocation is added to ISUM.
ISUM1	Module	ISUM-1
IWDFLG	Package	Flag indicating if wetting capability is active.
IWETIT	Package	Iteration interval for attempting to wet cells.
L	Module	Temporary equivalent of LAYCON(I).
LAYCON	Package	DIMENSION (80) Layer-type code: 0 -- Layer is strictly confined. 1 -- Layer is strictly unconfined. 2 -- Layer is convertible between confined and unconfined (saturated thickness is constant). 3 -- Layer is convertible between confined and unconfined (saturated thickness varies).
LCBOT	Package	Location in the X array of the first element of array BOT.
LCCVWD	Package	Location in the X array of the first element of array CVWD.
LCHY	Package	Location in the X array of the first element of array HY.
LCSC1	Package	Location in the X array of the first element of array SC1.
LCSC2	Package	Location in the X array of the first element of array SC2.
LCTOP	Package	Location in the X array of the first element of array TOP.
LCTRPY	Package	Location in the X array of the first element of array TRPY.
LCWETD	Package	Location in the X array of the first element of array WETDRY.

LENX	Global	Number of elements in the X array. This should always be equal to the dimension of X specified in the MAIN program.
NBOT	Module	Counter for the number of layers that need elevation of the bottom and conductance divided by thickness arrays.
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NRC	Module	Number of cells in a layer.
NROW	Global	Number of rows in the grid.
NTOP	Module	Counter for the number of layers that need elevation of the top and (if transient) secondary storage capacity arrays.
WETFCT	Package	A factor that is included in the calculation of the head that is established at a cell that has just converted from dry to wet.

Narrative for Module BCF2RP

This module reads transmissivity along rows, hydraulic conductivity along rows, storage coefficients, vertical conductance, elevation of top of cells, elevation of bottom of cells, and wetting threshold. It also calls SBCF2N to calculate parameters that are constant throughout a simulation.

1. Call utility module U1DREL to read TRPY, DELR, and DELC which have one value for each layer, column, and row, respectively. TRPY is the ratio of transmissivity (or hydraulic conductivity) along columns to transmissivity (or hydraulic conductivity) along rows for each layer.

2. For each layer, call utility module U2DREL to read the properties of the porous medium. The data requirements for each layer are determined by the layer-type code.

   (a) Find the one-dimensional array subscripts for the first element of a layer within the multi-layer arrays.

   (b) If the simulation is transient (ISS = 0), read the primary storage coefficient.

   (c) For constant transmissivity layers (LAYCON = 0 or 2), read the transmissivity.

   (d) For variable transmissivity layers (LAYCON = 1 or 3), read the hydraulic conductivity and elevation of the bottom of cells.

   (e) Read vertical hydraulic conductivity divided by thickness (VCONT). For a given layer, VCONT represents the material between the nodes in that layer and the nodes in the next lower layer. Therefore, no VCONT array is read for the lowest layer in the grid.

   (f) If the simulation is transient and the layer-type code is two or three, read the secondary storage coefficient (specific yield).

   (g) Read the elevation of the top of cells if the layer-type code is two or three.

   (h) Read the wetting threshold if the layer-type code is one or three.

3. Call SBCF2N to calculate conductance and storage terms that are constant during the simulation. Also, check that branch conductances agree with boundaries specified in the IBOUND array. Save vertical conductance if the wetting capability is active.

4. RETURN.

DELR is the grid spacing in the row direction.

DELC is the grid spacing in the column direction.

TRPY is the ratio of transmissivity in the column direction to transmissivity in the row direction.

LAYCON is a layer-type code (one for each layer).

0 - confined
1 - unconfined
2 - confined/unconfined but transmissivity is constant
3 - confined/unconfined

VCONT is vertical hydraulic conductivity divided by distance between the node in one layer and the node in the layer below (one value for each cell in a layer).

WETDRY is the wetting threshold (one value for each cell in a layer).

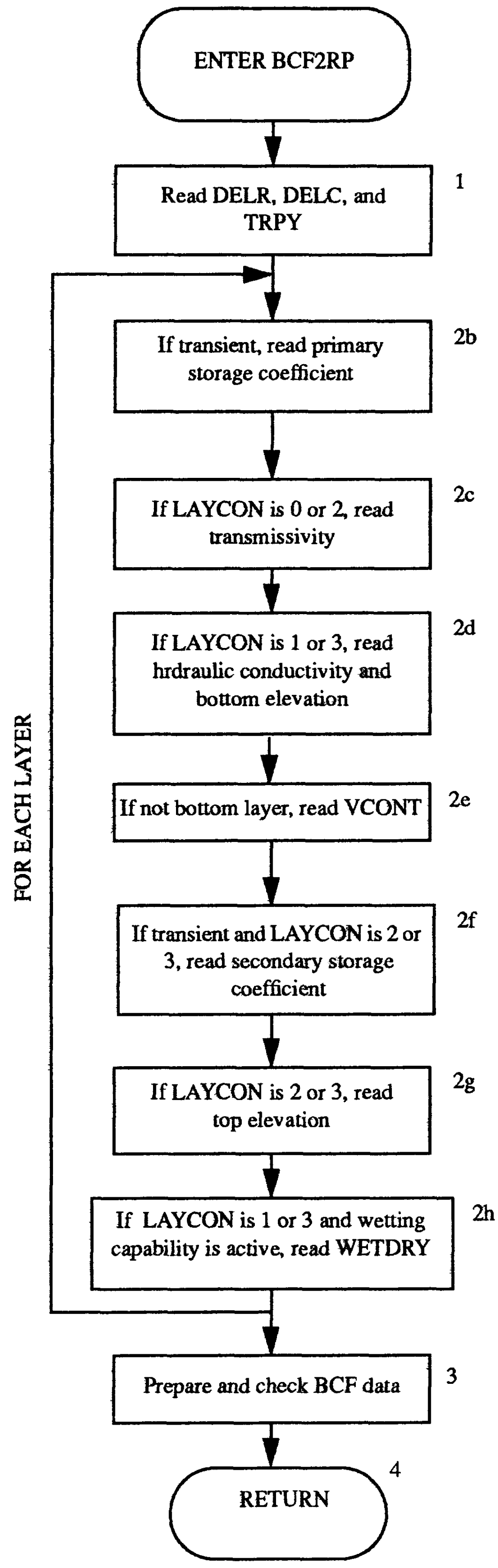

Figure 8. -- Flow chart for module BCF2RP.

```
      SUBROUTINE BCF2RP(IBOUND,HNEW,SC1,HY,CR,CC,CV,DELR,DELC,BOT,TOP,
     1 SC2,TRPY,IN,ISS,NCOL,NROW,NLAY,NODES,IOUT,WETDRY,IWDFLG,CVWD)
C
C-----VERSION 1275 6JUNE1991 BCF2RP
C     ******************************************************************
C     READ AND INITIALIZE DATA FOR BLOCK-CENTERED FLOW PACKAGE,
C     VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      CHARACTER*4 ANAME
      DOUBLE PRECISION HNEW
C
      DIMENSION HNEW(NODES),SC1(NODES),HY(NODES),CR(NODES),CC(NODES),
     1          CV(NODES),ANAME(6,11),DELR(NCOL),DELC(NROW),BOT(NODES),
     1          TOP(NODES),SC2(NODES),TRPY(NLAY),IBOUND(NODES),
     1          WETDRY(NODES),CVWD(NODES)
C
      COMMON /FLWCOM/LAYCON(80)
C
      DATA ANAME(1,1),ANAME(2,1),ANAME(3,1),ANAME(4,1),ANAME(5,1),
     1  ANAME(6,1) /'    ','PRIM','ARY ','STOR','AGE ','COEF'/
      DATA ANAME(1,2),ANAME(2,2),ANAME(3,2),ANAME(4,2),ANAME(5,2),
     1  ANAME(6,2) /'    ','TRAN','SMIS','. AL','ONG ','ROWS'/
      DATA ANAME(1,3),ANAME(2,3),ANAME(3,3),ANAME(4,3),ANAME(5,3),
     1  ANAME(6,3) /'   H','YD. ','COND','. AL','ONG ','ROWS'/
      DATA ANAME(1,4),ANAME(2,4),ANAME(3,4),ANAME(4,4),ANAME(5,4),
     1  ANAME(6,4) /'VERT',' HYD',' CON','D /T','HICK','NESS'/
      DATA ANAME(1,5),ANAME(2,5),ANAME(3,5),ANAME(4,5),ANAME(5,5),
     1  ANAME(6,5) /'    ','    ','    ','    ','  BO','TTOM'/
      DATA ANAME(1,6),ANAME(2,6),ANAME(3,6),ANAME(4,6),ANAME(5,6),
     1  ANAME(6,6) /'    ','    ','    ','    ','    ',' TOP'/
      DATA ANAME(1,7),ANAME(2,7),ANAME(3,7),ANAME(4,7),ANAME(5,7),
     1  ANAME(6,7) /'  SE','COND','ARY ','STOR','AGE ','COEF'/
      DATA ANAME(1,8),ANAME(2,8),ANAME(3,8),ANAME(4,8),ANAME(5,8),
     1  ANAME(6,8) /'COLU','MN T','O RO','W AN','ISOT','ROPY'/
      DATA ANAME(1,9),ANAME(2,9),ANAME(3,9),ANAME(4,9),ANAME(5,9),
     1  ANAME(6,9) /'    ','    ','    ','    ','    ','DELR'/
      DATA ANAME(1,10),ANAME(2,10),ANAME(3,10),ANAME(4,10),ANAME(5,10),
     1  ANAME(6,10) /'    ','    ','    ','    ','    ','DELC'/
      DATA ANAME(1,11),ANAME(2,11),ANAME(3,11),ANAME(4,11),ANAME(5,11),
     1  ANAME(6,11) /'    ','    ','WETD','RY P','ARAM','ETER'/
C     ------------------------------------------------------------------
C
C1------CALCULATE NUMBER OF NODES IN A LAYER AND READ TRPY,DELR,DELC
      NIJ=NCOL*NROW
C
      CALL U1DREL(TRPY,ANAME(1,8),NLAY,IN,IOUT)
      CALL U1DREL(DELR,ANAME(1,9),NCOL,IN,IOUT)
      CALL U1DREL(DELC,ANAME(1,10),NROW,IN,IOUT)
C
C2------READ ALL PARAMETERS FOR EACH LAYER
      KT=0
```

```
      KB=0
      DO 200 K=1,NLAY
      KK=K
C
C2A-----FIND ADDRESS OF EACH LAYER IN THREE DIMENSION ARRAYS.
      IF(LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) KB=KB+1
      IF(LAYCON(K).EQ.2 .OR. LAYCON(K).EQ.3) KT=KT+1
      LOC=1+(K-1)*NIJ
      LOCB=1+(KB-1)*NIJ
      LOCT=1+(KT-1)*NIJ
C
C2B-----READ PRIMARY STORAGE COEFFICIENT INTO ARRAY SC1 IF TRANSIENT
      IF(ISS.EQ.0)CALL U2DREL(SC1(LOC),ANAME(1,1),NROW,NCOL,KK,IN,IOUT)
C
C2C-----READ TRANSMISSIVITY INTO ARRAY CC IF LAYER TYPE IS 0 OR 2
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.1) GO TO 100
      CALL U2DREL(CC(LOC),ANAME(1,2),NROW,NCOL,KK,IN,IOUT)
      GO TO 110
C
C2D-----READ HYDRAULIC CONDUCTIVITY(HY) AND BOTTOM ELEVATION(BOT)
C2D-----IF LAYER TYPE IS 1 OR 3
  100 CALL U2DREL(HY(LOCB),ANAME(1,3),NROW,NCOL,KK,IN,IOUT)
      CALL U2DREL(BOT(LOCB),ANAME(1,5),NROW,NCOL,KK,IN,IOUT)
C
C2E-----READ VERTICAL HYCOND/THICK INTO ARRAY CV IF NOT BOTTOM LAYER
C2E----- READ AS HYCOND/THICKNESS -- CONVERTED TO CONDUCTANCE LATER
  110 IF(K.EQ.NLAY) GO TO 120
      CALL U2DREL(CV(LOC),ANAME(1,4),NROW,NCOL,KK,IN,IOUT)
C
C2F-----READ SECONDARY STORAGE COEFFICIENT INTO ARRAY SC2 IF TRANSIENT
C2F-----AND LAYER TYPE IS 2 OR 3
  120 IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.2) GO TO 130
      IF(ISS.EQ.0)CALL U2DREL(SC2(LOCT),ANAME(1,7),NROW,NCOL,KK,IN,IOUT)
C
C2G-----READ TOP ELEVATION(TOP) IF LAYER TYPE IS 2 OR 3
      CALL U2DREL(TOP(LOCT),ANAME(1,6),NROW,NCOL,KK,IN,IOUT)
C
C2H-----READ WETDRY CODES IF LAYER TYPE IS 1 OR 3 AND WETTING
C2H-----CAPABILITY HAS BEEN INVOKED (IWDFLG NOT 0)
  130 IF(LAYCON(K).NE.3.AND.LAYCON(K).NE.1)GO TO 200
      IF(IWDFLG.EQ.0)GO TO 200
      CALL U2DREL(WETDRY(LOCB),ANAME(1,11),NROW,NCOL,KK,IN,IOUT)
  200 CONTINUE
C
C3------PREPARE AND CHECK BCF DATA
      CALL SBCF2N(HNEW,IBOUND,SC1,SC2,CR,CC,CV,HY,TRPY,DELR,DELC,ISS,
     1          NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,CVWD)
C
C4------RETURN
      RETURN
      END
```

List of Variables for Module BCF2RP

Variable	Range	Definition
ANAME	Module	DIMENSION (6,11), Labels for printout of input arrays.
BOT	Package	DIMENSION (NODES), Elevation of the aquifer bottom. Although BOT is dimensioned to the size of the grid, space exists only for layers in which saturated thickness is calculated.
CC	Global	DIMENSION (NODES), Conductance in the column direction.
CR	Global	DIMENSION (NODES), Conductance in the row direction.
CV	Global	DIMENSION (NODES), Conductance in the vertical direction. Although CV is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
CVWD	Package	DIMENSION (NODES), Conductance in the vertical direction. When a wet cell converts to dry, CV is set equal to 0. When a dry cell converts to wet, CV is set equal to CVWD. Although CVWD is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains the width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains the width of column J.
HNEW	Global	DIMENSION (NODES), Most recent estimate of head in each cell.
HY	Package	DIMENSION (NODES), Hydraulic conductivity in the row direction for each cell. Although HY is dimensioned to the size of the grid, space exists only for layers in which saturated thickness is calculated.
IBOUND	Global	DIMENSION (NODES), Status of each cell: < 0, constant-head cell = 0, no-flow cell > 0, variable-head cell
IN	Package	Primary unit number from which input for this package will be read.
IOUT	Global	Primary unit number for all printed output.
ISS	Package	Steady-state flag. = 0, simulation is transient not 0, simulation is steady state.
IWDFLG	Package	Flag indicating if wetting capability is active.
K	Module	Index for layers.
KB	Module	Index for layer within BOT, HY, and WETDRY arrays.
KK	Module	Temporary variable set equal to K. KK is used as an actual argument in subroutine calls to avoid using the DO loop variable K as an argument, which causes problems with some compilers.
KT	Module	Index for layer within TOP and (if transient) SC2 arrays.
LAYCON	Package	DIMENSION (80) Layer-type code: 0 -- Layer is strictly confined. 1 -- Layer is strictly unconfined. 2 -- Layer is convertible between confined and unconfined (transmissivity is constant). 3 -- Layer is convertible between confined and unconfined (transmissivity varies).

LOC	Module	Pointer used to point to different layers in conductance arrays.
LOCB	Module	Pointer used to point to different layers in BOT, HY, and WETDRY arrays.
LOCT	Module	Pointer used to point to different layers in TOP and SC2 arrays.
NCOL	Global	Number of columns in the grid.
NIJ	Module	Number of cells in a layer.
NLAY	Global	Number of layers in the grid.
NODES	Global	Number of cells (nodes) in the finite-difference grid.
NROW	Global	Number of rows in the grid.
SC1	Package	DIMENSION (NODES), Primary storage capacity.
SC2	Package	DIMENSION (NODES), Secondary storage capacity. Although SC2 is dimensioned to the size of the grid, space exists only for layers that can convert between confined and unconfined.
TOP	Package	DIMENSION (NODES), Elevation of the aquifer top. Although TOP is dimensioned to the size of the grid, space exists only for layers that can convert between confined and unconfined.
TRPY	Package	DIMENSION (NLAY), Ratio of transmissivity (or hydraulic conductivity) in the column direction to transmissivity (or hydraulic conductivity) in the row direction.
WETDRY	Package	DIMENSION (NODES), Wetting threshold. Although WETDRY is dimensioned to the size of the grid, space exists only for layers that have the potential for converting from dry to wet.

Narrative for Module BCF2AD

At the beginning of each time step, this module sets head from the previous time step (HOLD) equal to the bottom elevation (BOT) for any cells that are dry and have the potential for converting to wet. This is necessary in order to compute correct storage terms for these cells.

1. Return if steady-state simulation or if the wetting capability is inactive.

2. Loop through all layers to check for dry cells that can become wet.

    (a) Keep track of the layer index for wettable layers (layers with layer-type code 1 or 3). Loop through the cells in wettable layers and skip non-wettable layers.

    (b) Skip cells that are currently wet (IBOUND not 0) or not wettable (WETDRY = 0).

    (c) Set HOLD = BOT.

3. RETURN.

LAYCON is a layer-type code (one for each layer).

0 - confined
1 - unconfined
2 - confined/unconfined but transmissivity is constant
3 - confined/unconfined

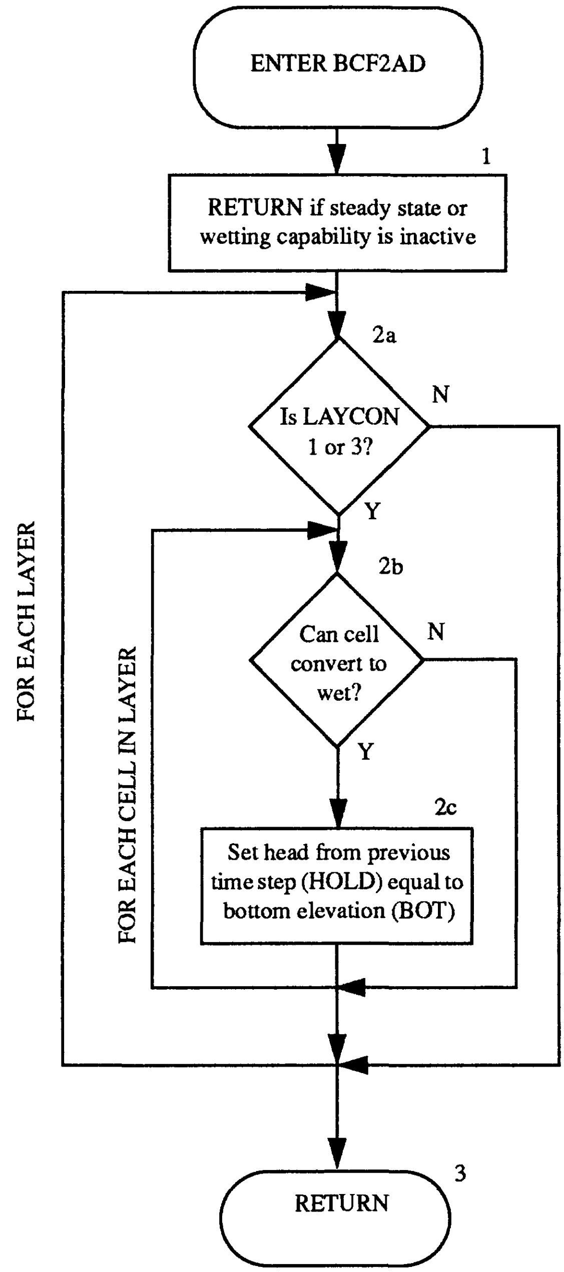

Figure 9. -- Flow chart for module BCF2AD.

```
      SUBROUTINE BCF2AD(IBOUND,HOLD,BOT,WETDRY,IWDFLG,ISS,
     1                  NCOL,NROW,NLAY)
C
C-----VERSION 1434 14MAY1991 BCF2AD
C     ******************************************************************
C     SET HOLD TO BOT WHENEVER A WETTABLE CELL IS DRY
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
C
      DIMENSION IBOUND(NCOL,NROW,NLAY),HOLD(NCOL,NROW,NLAY),
     1          BOT(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY)
C
      COMMON /FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
C
C1------RETURN IF STEADY STATE OR IF NOT USING WETTING CAPABILITY
      IF(IWDFLG.EQ.0 .OR. ISS.NE.0) RETURN
C
C2------LOOP THROUGH ALL LAYERS TO SET HOLD=BOT IF A WETTABLE CELL IS DRY
      KB=0
      DO 100 K=1,NLAY
C
C2A-----SKIP LAYERS THAT CANNOT CONVERT BETWEEN WET AND DRY
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.1) GO TO 100
      KB=KB+1
      DO 90 I=1,NROW
      DO 90 J=1,NCOL
C
C2B-----SKIP CELLS THAT ARE CURRENTLY WET OR ARE NOT WETTABLE
      IF(IBOUND(J,I,K).NE.0) GO TO 90
      IF(WETDRY(J,I,KB).EQ.0.) GO TO 90
C
C2C-----SET HOLD=BOT
      HOLD(J,I,K)=BOT(J,I,KB)
   90 CONTINUE
  100 CONTINUE
C
C3-----RETURN
      RETURN
      END
```

List of Variables for Module BCF2AD

BOT	Package	DIMENSION (NCOL,NROW,NLAY), Elevation of the aquifer bottom. Although BOT is dimensioned to the size of the grid, space exists only for layers for which saturated thickness is calculated.
HOLD	Global	DIMENSION (NCOL,NROW,NLAY), Head at the start of the current time step.
I	Module	Index for rows.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell: < 0, constant-head cell = 0, no-flow cell > 0, variable-head cell
ISS	Package	Steady-state flag. = 0, simulation is transient not 0, simulation is steady state.
IWDFLG	Package	Flag indicating if wetting capability is active.
J	Module	Index for columns.
K	Module	Index for layers.
KB	Module	Index for layer within WETDRY array.
LAYCON	Package	DIMENSION (80) Layer-type code: 0 -- Layer is strictly confined. 1 -- Layer is strictly unconfined. 2 -- Layer is convertible between confined and unconfined (saturated thickness is constant). 3 -- Layer is convertible between confined and unconfined (saturated thickness varies).
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
WETDRY	Package	DIMENSION (NCOL,NROW,NLAY), Wetting threshold. Although WETDRY is dimensioned to the size of the grid, space exists only for layers that have the potential for converting from dry to wet.

Narrative for Module BCF2FM

This module calculates branch conductances if they are not constant throughout the simulation, adds storage terms to the HCOF and RHS accumulators, and adds terms to RHS that correct for overestimation of flow down into partially saturated cells.

1. For each layer in which transmissivity varies with head (LAYCON = 1 or 3), call module SBCF2H to calculate branch conductances.

2. If the simulation is transient, calculate storage terms for each layer. Steps 3-5 comprise the storage calculations. If the simulation is steady state, go to Step 6.

3. Determine if the layer is convertible between confined and unconfined.

4. If the layer is not convertible (LAYCON = 0 or 1), use primary storage capacity to calculate storage terms and add them to the right hand side (RHS) and h-coefficient (HCOF) terms.

5. If the layer is convertible (LAYCON = 2 or 3), then use head at the beginning of the time step (HOLD) to determine the storage factor at the beginning of the time step (SOLD). Use the latest estimate of head at the end of the time step (HNEW) to determine the storage factor at the end of the time step (SNEW). Note that the term "storage factor" as used in BCF2FM refers to storage capacity divided by time step length. Use SOLD and SNEW to calculate storage terms and add them to RHS and HCOF.

6. For each layer, determine if correction terms are needed for vertical flow down into a partially saturated layer (Steps 7-8).

7. If the layer is partially saturated and there is flow from above, calculate the vertical flow correction terms and add them to RHS (program comment C7D). This vertical flow correction is incorporated jointly in RHS and HCOF in the original model (McDonald and Harbaugh, 1988, p. 5-23 and 5-59). In BCF2, the correction is being made through RHS alone in order to avoid the possibility of producing a matrix that is not diagonally dominant. A non-diagonally dominant matrix causes problems with the Preconditioned Conjugate-Gradient Package, version 2 (Hill, 1990, p. 15). Implementing the correction through RHS alone is essentially equivalent to the former method. The method using both RHS and HCOF is an implicit representation of the correction while the method using only RHS is an explicit representation.

8. If this layer is not the bottom layer and the layer below is partially saturated, calculate the correction terms and add them to RHS.

9. RETURN.

LAYCON is a layer-type code
(one for each layer).

0 - confined
1 - unconfined
2 - confined/unconfined but transmissivity is constant
3 - confined/unconfined

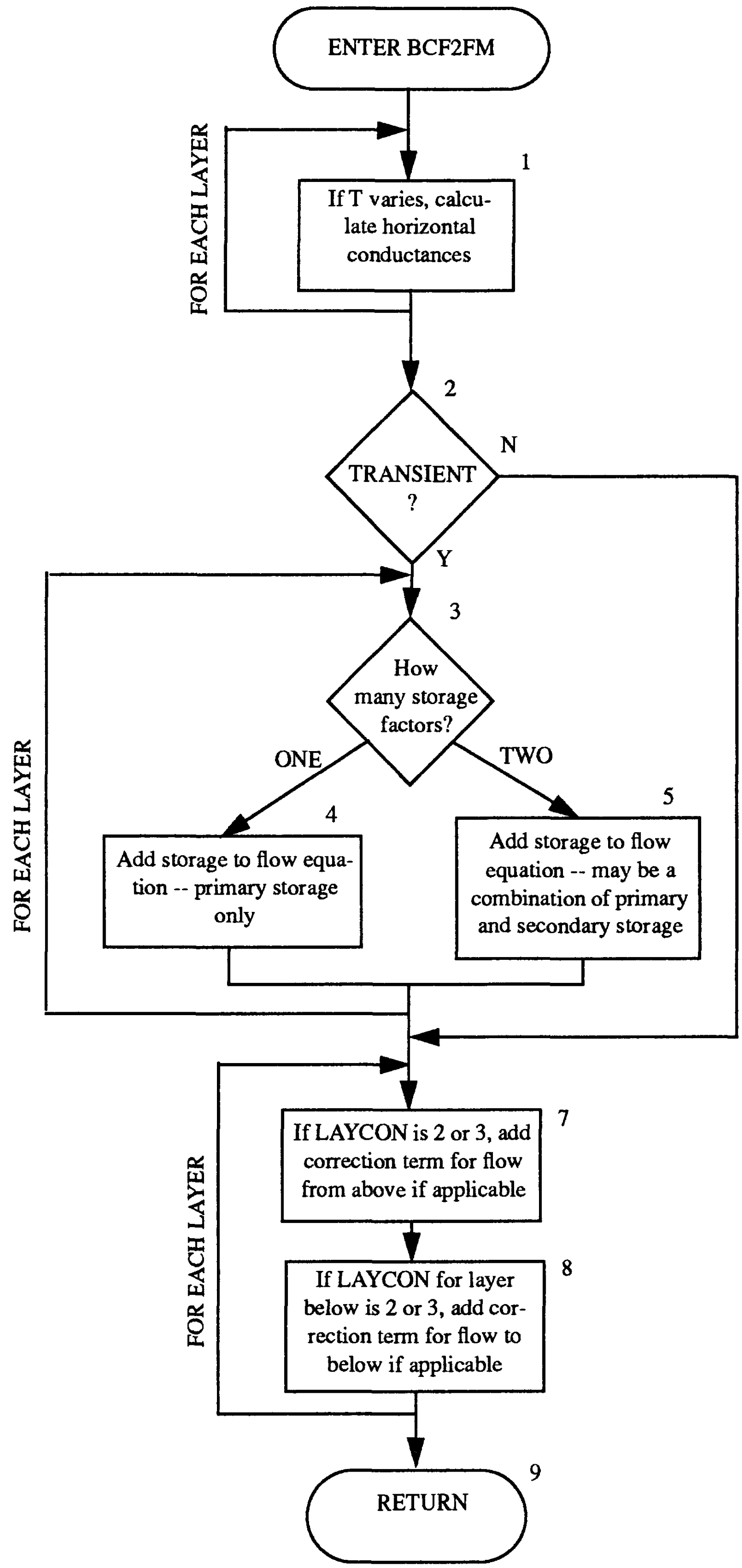

Figure 10. -- Flow chart for module BCF2FM.

```
      SUBROUTINE BCF2FM(HCOF,RHS,HOLD,SC1,HNEW,IBOUND,CR,CC,CV,HY,TRPY,
     1                 BOT,TOP,SC2,DELR,DELC,DELT,ISS,KITER,KSTP,KPER,
     2                 NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,CVWD,
     3                 WETFCT,IWETIT,IHDWET,HDRY)
C-----VERSION 1104 5MAY1991 BCF2FM
C     ******************************************************************
C     ADD LEAKAGE CORRECTION AND STORAGE TO HCOF AND RHS, AND CALCULATE
C     CONDUCTANCE AS REQUIRED, VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION HCOF(NCOL,NROW,NLAY),RHS(NCOL,NROW,NLAY),
     1    HOLD(NCOL,NROW,NLAY),SC1(NCOL,NROW,NLAY),HNEW(NCOL,NROW,NLAY),
     2    IBOUND(NCOL,NROW,NLAY),CR(NCOL,NROW,NLAY),
     3    CC(NCOL,NROW,NLAY),CV(NCOL,NROW,NLAY),HY(NCOL,NROW,NLAY),
     4    TRPY(NLAY),BOT(NCOL,NROW,NLAY),TOP(NCOL,NROW,NLAY),DELR(NCOL),
     5    DELC(NROW),SC2(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY),
     6    CVWD(NCOL,NROW,NLAY)
C
      COMMON /FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
      KB=0
      KT=0
C
C1------FOR EACH LAYER: IF T VARIES CALCULATE HORIZONTAL CONDUCTANCES
      DO 100 K=1,NLAY
      KK=K
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.2) KT=KT+1
C
C1A-----IF LAYER TYPE IS NOT 1 OR 3 THEN SKIP THIS LAYER.
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.1) GO TO 100
      KB=KB+1
C
C1B-----FOR LAYER TYPES 1 & 3 CALL SBCF2H TO CALCULATE
C1B-----HORIZONTAL CONDUCTANCES.
      CALL SBCF2H(HNEW,IBOUND,CR,CC,CV,HY,TRPY,DELR,DELC,BOT,TOP,
     1  KK,KB,KT,KITER,KSTP,KPER,NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,
     2  CVWD,WETFCT,IWETIT,IHDWET,HDRY)
  100 CONTINUE
C
C2------IF THE SIMULATION IS TRANSIENT ADD STORAGE TO HCOF AND RHS
      IF(ISS.NE.0) GO TO 201
      TLED=1./DELT
      KT=0
      DO 200 K=1,NLAY
C
C3------SEE IF THIS LAYER IS CONVERTIBLE OR NON-CONVERTIBLE.
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.2) GO TO 150
```

```
C4------NON-CONVERTIBLE LAYER, SO USE PRIMARY STORAGE
      DO 140 I=1,NROW
      DO 140 J=1,NCOL
      IF(IBOUND(J,I,K).LE.0) GO TO 140
      RHO=SC1(J,I,K)*TLED
      HCOF(J,I,K)=HCOF(J,I,K)-RHO
      RHS(J,I,K)=RHS(J,I,K)-RHO*HOLD(J,I,K)
  140 CONTINUE
      GO TO 200
C
C5------A CONVERTIBLE LAYER, SO CHECK OLD AND NEW HEADS TO DETERMINE
C5------WHEN TO USE PRIMARY AND SECONDARY STORAGE
  150 KT=KT+1
      DO 180 I=1,NROW
      DO 180 J=1,NCOL
C
C5A-----IF THE CELL IS EXTERNAL THEN SKIP IT.
      IF(IBOUND(J,I,K).LE.0) GO TO 180
      TP=TOP(J,I,KT)
      RHO2=SC2(J,I,KT)*TLED
      RHO1=SC1(J,I,K)*TLED
C
C5B-----FIND STORAGE FACTOR AT START OF TIME STEP.
      SOLD=RHO2
      IF(HOLD(J,I,K).GT.TP) SOLD=RHO1
C
C5C-----FIND STORAGE FACTOR AT END OF TIME STEP.
      HTMP=HNEW(J,I,K)
      SNEW=RHO2
      IF(HTMP.GT.TP) SNEW=RHO1
C
C5D-----ADD STORAGE TERMS TO RHS AND HCOF.
      HCOF(J,I,K)=HCOF(J,I,K)-SNEW
      RHS(J,I,K)=RHS(J,I,K) - SOLD*(HOLD(J,I,K)-TP) - SNEW*TP
C
  180 CONTINUE
C
  200 CONTINUE
C
C6------FOR EACH LAYER DETERMINE IF CORRECTION TERMS ARE NEEDED FOR
C6------FLOW DOWN INTO PARTIALLY SATURATED LAYERS.
  201 KT=0
      DO 300 K=1,NLAY
C
C7------SEE IF CORRECTION IS NEEDED FOR LEAKAGE FROM ABOVE.
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.2) GO TO 250
      KT=KT+1
      IF(K.EQ.1) GO TO 250
C
C7A-----FOR EACH CELL MAKE THE CORRECTION IF NEEDED.
      DO 220 I=1,NROW
      DO 220 J=1,NCOL
C
```

```
C7B-----IF THE CELL IS EXTERNAL(IBOUND<=0) THEN SKIP IT.
      IF(IBOUND(J,I,K).LE.0) GO TO 220
      HTMP=HNEW(J,I,K)
C
C7C-----IF HEAD IS ABOVE TOP THEN CORRECTION NOT NEEDED
      IF(HTMP.GE.TOP(J,I,KT)) GO TO 220
C
C7D-----WITH HEAD BELOW TOP ADD CORRECTION TERMS TO RHS.
      RHS(J,I,K)=RHS(J,I,K) + CV(J,I,K-1)*(TOP(J,I,KT)-HTMP)
  220 CONTINUE
C
C8------SEE IF THIS LAYER MAY NEED CORRECTION FOR LEAKAGE TO BELOW.
  250 IF(K.EQ.NLAY) GO TO 300
      IF(LAYCON(K+1).NE.3 .AND. LAYCON(K+1).NE.2) GO TO 300
      KTT=KT+1
C
C8A-----FOR EACH CELL MAKE THE CORRECTION IF NEEDED.
      DO 280 I=1,NROW
      DO 280 J=1,NCOL
C
C8B-----IF CELL IS EXTERNAL (IBOUND<=0) THEN SKIP IT.
      IF(IBOUND(J,I,K).LE.0) GO TO 280
C
C8C-----IF HEAD IN THE LOWER CELL IS LESS THAN TOP ADD CORRECTION
C8C-----TERM TO RHS.
      HTMP=HNEW(J,I,K+1)
      IF(HTMP.LT.TOP(J,I,KTT)) RHS(J,I,K)=RHS(J,I,K)
     1                        - CV(J,I,K)*(TOP(J,I,KTT)-HTMP)
  280 CONTINUE
  300 CONTINUE
C
C9------RETURN
      RETURN
      END
```

List of Variables for Module BCF2FM

Variable	Range	Definition
BOT	Package	DIMENSION (NCOL,NROW,NLAY), Elevation of the aquifer bottom. Although BOT is dimensioned to the size of the grid, space exists only for layers for which saturated thickness is calculated.
CC	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the column direction.
CR	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the row direction.
CV	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the vertical direction. Although CV is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
CVWD	Package	DIMENSION (NCOL,NROW,NLAY), Conductance in the vertical direction. When a wet cell converts to dry, CV is set equal to 0. When a dry cell converts to wet, CV is set equal to CVWD. Although CVWD is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains the width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains the width of column J.
DELT	GLOBAL	Length of the current time step.
HCOF	Global	DIMENSION (NCOL,NROW,NLAY), Coefficient of head in the finite-difference equation.
HDRY	Package	When a cell converts to dry, HNEW is set equal to HDRY.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell.
HOLD	Global	DIMENSION (NCOL,NROW,NLAY), Head at the start of the current time step.
HTMP	Module	Temporary single precision equivalent of HNEW(J,I,K).
HY	Package	DIMENSION (NCOL,NROW,NLAY), Hydraulic conductivity in the row direction for each cell. Although HY is dimensioned to the size of the grid, space exists only for layers in which saturated thickness is calculated.
I	Module	Index for rows.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell: < 0, constant-head cell = 0, no-flow cell > 0, variable-head cell
IHDWET	Package	Flag indicating which equation to use for calculating the head at a cell that has just converted from dry to wet.
IOUT	Global	Primary unit number for all printed output.
ISS	Package	Steady-state flag. = 0, simulation is transient not 0, simulation is steady state.
IWDFLG	Package	Flag indicating if wetting capability is active.
IWETIT	Package	Iteration interval for attempting to wet cells.
J	Module	Index for columns.
K	Module	Index for layers.

KB	Module	Index for layer within BOT, HY, and WETDRY arrays.
KITER	Global	Iteration counter. KITER=1 at the start of each time step.
KK	Module	Temporary variable set equal to K. KK is used as an actual argument in subroutine calls to avoid using the DO loop variable K as an argument, which causes problems with some compilers.
KPER	Global	Stress period counter.
KSTP	Global	Time step counter. KSTP=1 at the start of each stress period.
KT	Module	Index for layer within TOP and (if transient) SC2 arrays.
KTT	Module	Index to TOP array of layer immediately below layer K.
LAYCON	Package	DIMENSION (80) Layer-type code: 0 -- Layer is strictly confined. 1 -- Layer is strictly unconfined. 2 -- Layer is convertible between confined and unconfined (transmissivity is constant). 3 -- Layer is convertible between confined and unconfined (transmissivity varies).
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
RHO	Module	Storage capacity divided by time step length for strictly confined or strictly unconfined layers.
RHO1	Module	Confined storage capacity divided by time step length for convertible layers.
RHO2	Module	Unconfined storage capacity divided by time step length for convertible layers.
RHS	Global	DIMENSION (NCOL,NROW,NLAY), Right-hand side of finite-difference equation.
SC1	Package	DIMENSION (NCOL,NROW,NLAY), Primary storage capacity.
SC2	Package	DIMENSION (NCOL,NROW,NLAY), Secondary storage capacity. Although SC2 is dimensioned to the size of the grid, space exists only for cells that can convert between confined and unconfined.
SNEW	Module	Storage capacity divided by time step length at the end of the time step for convertible layers.
SOLD	Module	Storage capacity divided by time step length at the start of the time step for convertible layers.
TLED	Module	1/DELT.
TOP	Package	DIMENSION (NCOL,NROW,NLAY), Elevation of the aquifer top. Although TOP is dimensioned to the size of the grid, space exists only for cells that can convert between confined and unconfined.
TP	Module	Temporary equivalent of TOP(J,I,KT).
TRPY	Package	DIMENSION (NLAY), Ratio of transmissivity (or hydraulic conductivity) in the column direction to transmissivity (or hydraulic conductivity) in the row direction.
WETDRY	Package	DIMENSION (NCOL,NROW,NLAY), Wetting threshold. Although WETDRY is dimensioned to the size of the grid, space exists only for layers that have the potential for converting from dry to wet.

WETFCT Package A factor that is included in the calculation of the head that is established at a cell that has just converted from dry to wet.

Narrative for Module SBCF2N

This module insures that the transmissive properties of each cell agree with the codes specified in the boundary array (IBOUND). In addition, this module calculates parameters that remain constant throughout a simulation: horizontal-branch conductance in layers where transmissivity is constant, vertical conductance, and storage capacity for layers that cannot convert between confined and unconfined.

The array IBOUND indicates the status of every cell in the grid as shown:

IBOUND Value	Cell Status
zero	inactive
positive	variable head
negative	constant head

Module SBCF2N sets vertical conductance (CV) and transmissivity equal to zero for cells in which IBOUND is 0, and it sets IBOUND equal to 0 at cells in which all transmissive parameters are 0. IBOUND values are read by the BAS1RP module. Module SBCF2N is called by module BCF2RP, and SBCF2N calls module SBCF1C to calculate conductance for layers that have constant transmissivity.

1. Multiply vertical leakance (VCONT) by cell area to obtain vertical conductance.

2. If the wetting capability is activated, save vertical conductance (CV) as variable CVWD. At a dry cell, CV will be set to 0; at a wet cell, CV will be set to CVWD.

3. If IBOUND is 0, set vertical conductance and transmissivity to 0.

4. Insure that each active cell (variable head or constant head) has at least one non-zero transmissive parameter. Convert any cell that does not have at least one non-zero transmissive parameter to no flow. The specific tests for non-zero transmissive parameters depends on the layer-type code and if the wetting capability is active. Loop through each layer to determine the layer type.

    (a) The layer has constant transmissivity. Loop through each cell in the layer looking for cells in which transmissive parameters are all zero; transmissive parameters are horizontal transmissivity and vertical conductance. If all of these are 0 for an active cell, set IBOUND to 0, set HNEW to 888.88, and print a message.

    (b) The layer has variable transmissivity. Loop through each cell in the layer looking for cells in which transmissive parameters are all zero; transmissive parameters are horizontal hydraulic conductivity and vertical conductance.

(1) If the wetting capability is active for a cell, check to see if CVWD above or below is non zero. The test for non-zero CVWD is performed even if the cell is initially dry because the cell could convert to wet at a later time, and this would be senseless if all transmissive terms were zero.

(2) For active cells in which the wetting capability is not active, check to see if CV above or below is non zero.

(3) For cells in which CV or CVWD above and below are zero, check to see if hydraulic conductivity is zero.

(4) Hydraulic conductivity and vertical conductance above and below are all zero, so convert the cell to no flow. Set IBOUND to 0, set HNEW to 888.88, and print a message. Also, if the wetting capability is active, set WETDRY to 0 so that the cell is never allowed to become wet.

5. Call module SBCF1C to calculate conductance for layers that have constant transmissivity.

6. If a transient simulation, loop through each layer and calculate storage capacity as the product of storage coefficient and cell area.

   (a) Calculate primary storage capacity for all layers.

   (b) For layers that can convert between confined and unconfined, calculate secondary storage capacity.

7. RETURN.

LAYCON is a layer-type code (one for each layer).

0 - confined
1 - unconfined
2 - confined/unconfined but transmissivity is constant
3 - confined/unconfined

VCONT is vertical hydraulic conductivity divided by the thickness between nodes in a layer and the layer below.

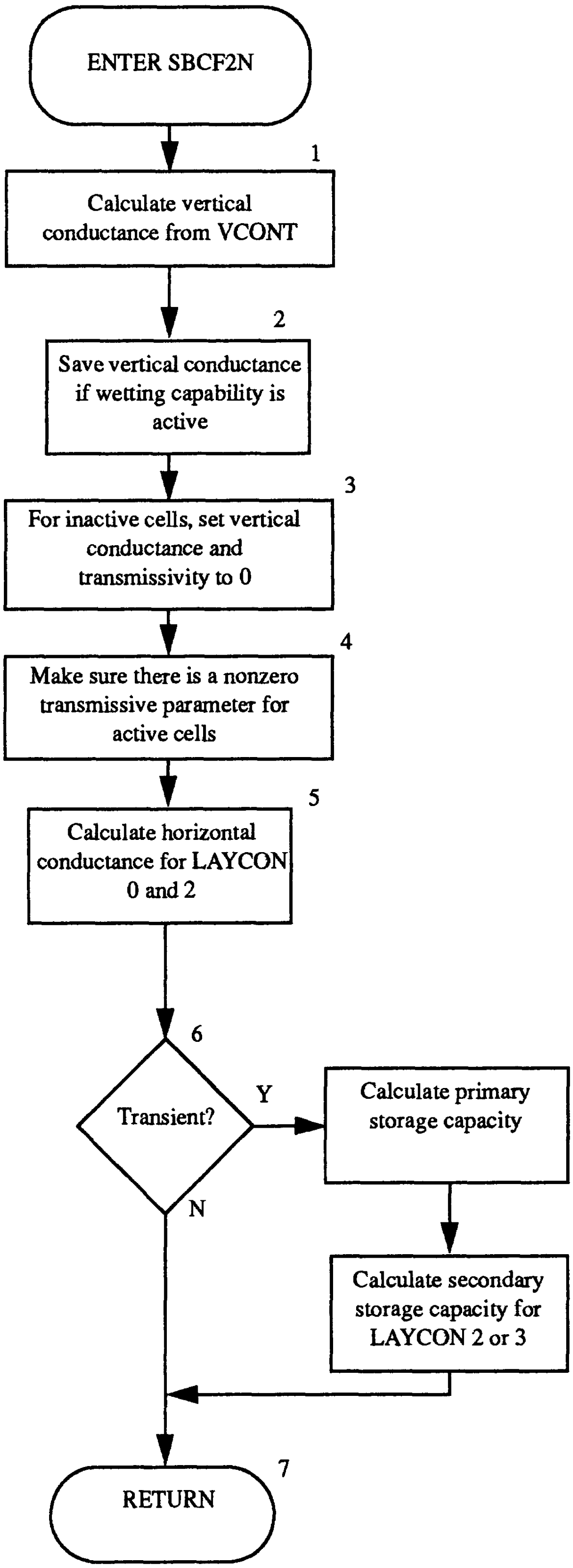

Figure 11. -- Flow chart for module SBCF2N.

```
      SUBROUTINE SBCF2N(HNEW,IBOUND,SC1,SC2,CR,CC,CV,HY,TRPY,DELR,DELC,
     1    ISS,NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,CVWD)
C
C-----VERSION 1107 5MAY1991 SBCF2N
C
C     ******************************************************************
C     INITIALIZE AND CHECK BCF DATA, VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
C
      DOUBLE PRECISION HNEW,HCNV
C
      DIMENSION HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY)
     1     ,SC1(NCOL,NROW,NLAY),CR(NCOL,NROW,NLAY)
     2     ,CC(NCOL,NROW,NLAY),CV(NCOL,NROW,NLAY)
     3     ,HY(NCOL,NROW,NLAY),TRPY(NLAY),DELR(NCOL),DELC(NROW)
     4     ,SC2(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY)
     5     ,CVWD(NCOL,NROW,NLAY)
C
      COMMON /FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
C
C1------MULTIPLY VERTICAL LEAKANCE BY AREA TO MAKE CONDUCTANCE
      IF(NLAY.EQ.1) GO TO 20
      K1=NLAY-1
      DO 10 K=1,K1
      DO 10 I=1,NROW
      DO 10 J=1,NCOL
      CV(J,I,K)=CV(J,I,K)*DELR(J)*DELC(I)
   10 CONTINUE
C
C2------IF WETTING CAPABILITY IS ACTIVATED, SAVE CV IN CVWD FOR USE WHEN
C2------WETTING CELLS.
      IF(IWDFLG.EQ.0) GO TO 20
      DO 15 K=1,K1
      DO 15 I=1,NROW
      DO 15 J=1,NCOL
      CVWD(J,I,K)=CV(J,I,K)
   15 CONTINUE
C
C3------IF IBOUND=0, SET CV=0 AND CC=0.
   20 DO 30 K=1,NLAY
      DO 30 I=1,NROW
      DO 30 J=1,NCOL
      IF(IBOUND(J,I,K).NE.0) GO TO 30
      IF(K.NE.NLAY) CV(J,I,K)=0.
      IF(K.NE.1) CV(J,I,K-1)=0.
      CC(J,I,K)=0.
   30 CONTINUE
C
C4------INSURE THAT EACH ACTIVE CELL HAS AT LEAST ONE NON-ZERO
```

```
C4------TRANSMISSIVE PARAMETER.
      HCNV=888.88
      KB=0
      DO 60 K=1,NLAY
      IF(LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) GO TO 50
C
C4A-----WHEN LAYER TYPE IS 0 OR 2, TRANSMISSIVITY OR CV MUST BE NONZERO
      DO 45 I=1,NROW
      DO 45 J=1,NCOL
      IF(IBOUND(J,I,K).EQ.0) GO TO 45
      IF(CC(J,I,K).NE.0.) GO TO 45
      IF(K.EQ.NLAY) GO TO 41
      IF(CV(J,I,K).NE.0.) GO TO 45
   41 IF(K.EQ.1) GO TO 42
      IF(CV(J,I,K-1).NE.0.) GO TO 45
   42 IBOUND(J,I,K)=0
      HNEW(J,I,K)=HCNV
      WRITE(IOUT,43) K,I,J
   43 FORMAT(1X,'NODE (LAYER,ROW,COL)',3I4,
     1      ' ELIMINATED BECAUSE ALL CONDUCTANCES TO NODE ARE 0')
   45 CONTINUE
      GO TO 60
C
C4B-----WHEN LAYER TYPE IS 1 OR 3, HY OR CV MUST BE NONZERO
   50 KB=KB+1
      DO 59 I=1,NROW
      DO 59 J=1,NCOL
C
C4B1----IF WETTING CAPABILITY IS ACTIVE, CHECK CVWD
      IF(IWDFLG.EQ.0) GO TO 55
      IF(WETDRY(J,I,KB).EQ.0.) GO TO 55
      IF(K.EQ.NLAY) GO TO 51
      IF(CVWD(J,I,K).NE.0.) GO TO 59
   51 IF(K.EQ.1) GO TO 57
      IF(CV(J,I,K-1).NE.0.) GO TO 59
C
C4B2----WETTING CAPABILITY IS INACTIVE, SO CHECK CV AT ACTIVE CELLS
   55 IF(IBOUND(J,I,K).EQ.0) GO TO 59
      IF(K.EQ.NLAY) GO TO 56
      IF(CV(J,I,K).NE.0.) GO TO 59
   56 IF(K.EQ.1) GO TO 57
      IF(CV(J,I,K-1).NE.0.) GO TO 59
C
C4B3----CHECK HYDRAULIC CONDUCTIVITY
   57 IF(HY(J,I,KB).NE.0.) GO TO 59
C
C4B4----HY AND CV ARE ALL 0, SO CONVERT CELL TO NO FLOW
      IBOUND(J,I,K)=0
      HNEW(J,I,K)=HCNV
      IF(IWDFLG.NE.0) WETDRY(J,I,KB)=0.
      WRITE(IOUT,43) K,I,J
   59 CONTINUE
   60 CONTINUE
C
```

```
C5------CALCULATE HOR. CONDUCTANCE(CR AND CC) FOR CONSTANT T LAYERS
      DO 70 K=1,NLAY
      KK=K
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.1) GO TO 70
      CALL SBCF1C(CR,CC,TRPY,DELR,DELC,KK,NCOL,NROW,NLAY)
   70 CONTINUE
C
C6------IF TRANSIENT, LOOP THROUGH LAYERS AND CALCULATE STORAGE CAPACITY
      IF(ISS.NE.0) GO TO 100
      KT=0
      DO 90 K=1,NLAY
C
C6A-----MULTIPLY PRIMARY STORAGE COEFFICIENT BY DELR & DELC TO GET
C6A-----PRIMARY STORAGE CAPACITY
      DO 80 I=1,NROW
      DO 80 J=1,NCOL
      SC1(J,I,K)=SC1(J,I,K)*DELR(J)*DELC(I)
   80 CONTINUE
C
C6B-----IF LAYER IS CONF/UNCONF MULTIPLY SECONDARY STORAGE COEFFICIENT
C6B-----BY DELR AND DELC TO GET SECONDARY STORAGE CAPACITY(SC2).
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.2) GO TO 90
      KT=KT+1
      DO 85 I=1,NROW
      DO 85 J=1,NCOL
      SC2(J,I,KT)=SC2(J,I,KT)*DELR(J)*DELC(I)
   85 CONTINUE
   90 CONTINUE
C
C7------RETURN
  100 RETURN
      END
```

List of Variables for Module SBCF2N

Variable	Range	Definition
CC	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the column direction.
CR	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the row direction.
CV	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the vertical direction. Although CV is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
CVWD	Package	DIMENSION (NCOL,NROW,NLAY), Conductance in the vertical direction. When a wet cell converts to dry, CV is set equal to 0. When a dry cell converts to wet, CV is set equal to CVWD. Although CVWD is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains the width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains the width of column J.
HCNV	Module	Value of head used to indicate that a cell has been converted to no flow because all conductances to that cell are 0.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell.
HY	Package	DIMENSION (NCOL,NROW,NLAY), Hydraulic conductivity in the row direction for each cell. Although HY is dimensioned to the size of the grid, space exists only for layers in which saturated thickness is calculated.
I	Module	Index for rows.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell: < 0, constant-head cell = 0, no-flow cell > 0, variable-head cell
IOUT	Global	Primary unit number for all printed output.
ISS	Package	Steady-state flag. = 0, simulation is transient not 0, simulation is steady state.
IWDFLG	Package	Flag indicating if wetting capability is active.
J	Module	Index for columns.
K	Module	Index for layers.
K1	Module	NLAY-1
KB	Module	Index for layer within HY and WETDRY arrays.
KK	Module	Temporary variable set equal to K. KK is used as an actual argument in subroutine calls to avoid using the DO loop variable K as an argument, which causes problems for some compilers.
KT	Module	Index for layer within SC2 array.

LAYCON	Package	DIMENSION (80) Layer-type code: 0 -- Layer is strictly confined. 1 -- Layer is strictly unconfined. 2 -- Layer is convertible between confined and unconfined (transmissivity is constant). 3 -- Layer is convertible between confined and unconfined (transmissivity varies).
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
SC1	Package	DIMENSION (NCOL,NROW,NLAY), Primary storage capacity.
SC2	Package	DIMENSION (NCOL,NROW,NLAY), Secondary storage capacity. Although SC2 is dimensioned to the size of the grid, space exists only for cells that can convert between confined and unconfined.
TRPY	Package	DIMENSION (NLAY), Ratio of transmissivity (or hydraulic conductivity) in the column direction to transmissivity (or hydraulic conductivity) in the row direction.
WETDRY	Package	DIMENSION (NCOL,NROW,NLAY), Wetting threshold. Although WETDRY is dimensioned to the size of the grid, space exists only for layers that have the potential for converting from dry to wet.

Narrative for Module SBCF2H

Module SBCF2H calculates the horizontal-branch conductances for a layer in which the transmissivity is a function of head. It does this by calculating transmissivity for each cell as saturated thickness times hydraulic conductivity. Then it calls module SBCF1C to calculate the conductances from transmissivity of cells. As part of saturated thickness calculations, module SBCF2H determines if dry cells should become wet or if wet cells should become dry. Module BCF2FM calls SBCF2H for each type 1 or type 3 layer at each iteration.

1. Loop through each cell in the layer, and calculate transmissivity at each active cell. Before starting, initialize several variables. NCNVRT keeps track of the number of cells that have converted between wet and dry since the last line was printed telling which cells have converted. A line of output may list up to 8 cell conversions. IHDCNV controls the printing of the cell conversion heading; this heading is printed the first time a line of cell conversions is printed. ITFLG is 0 if the attempt to wet cells should be made this iteration, which means that the wetting capability is active and the current iteration is an even multiple of the wetting iteration interval (IWETIT).

2. If the cell is active, go to the saturated thickness calculation.

3. When the cell is inactive, check for the possibility of wetting. A cell has the potential for converting to wet only if ITFLG is zero. Also, the wetting threshold must be non zero. If these conditions are not met, go to the code that sets transmissivity to zero. If these conditions are met, calculate the turn-on threshold, TURNON, and continue the process of determining whether the cell should be converted to wet.

    (a) Check the cell below the inactive cell to see if it is variable head and if the wetting threshold has been reached. If so, go to the code that converts the cell to wet. Note that a constant head cell cannot cause another cell to become wet.

    (b) If the wetting threshold is negative, do not make any further attempts to wet the cell; the cell remains dry, and transmissivity will be set to zero. If the wetting threshold is positive, check the four horizontal neighbors to see if the turn-on threshold is reached. Neighboring cells that have converted to wet during the current iteration are not allowed to cause a cell to convert to wet. This is implemented by temporarily setting IBOUND to 30000 in Step 4 when a cell becomes wet. That is, neighboring cells having IBOUND of 30000 are not checked to see if the turn-on threshold is reached. If the turn-on threshold is reached, go to the code that converts the cell to wet.

    (c) The cell will stay dry. Set transmissivity to 0, and go to the end of the cell loop.

4. The cell becomes wet. Set initial head according to the flag IHDWET, set vertical conductance to CVWD, and set IBOUND to 30000. IBOUND will later be set to 1, but it is momentarily set to a high value as a flag to indicate cells that have been converted to wet this iteration. The flag is used in Step 3b to prevent a newly converted cell from causing other cells to convert. This could otherwise cause a chain reaction.

   (a) Save the information about which cell has converted to wet so that it can be printed. When eight conversions between wet and dry have been accumulated, print a line listing those cells.

5. Calculate saturated thickness. If LAYCON is 3, saturated thickness has a maximum value of TOP-BOT.

6. Check to see if saturated thickness is less than 0.

   (a) Saturated thickness is greater than 0; calculate transmissivity as saturated thickness times hydraulic conductivity. Store transmissivity temporarily in CC. Go to the end of the cell loop.

   (b) Saturated thickness is less than or equal to 0; convert the cell to no flow and save information flagging which cell has converted to dry. When eight conversions between wet and dry have been accumulated, print a line listing those cells. If the cell is not constant head, set IBOUND, CC (transmissivity), and CV to 0. If the cell is constant head, stop the simulation.

7. Transmissivity has been calculated for all cells. If there is a partially filled line of output of cell conversions, print the line.

8. Convert IBOUND values of 30000 to 1.

9. Call module SBCF1C to calculate conductance from transmissivity.

10. RETURN.

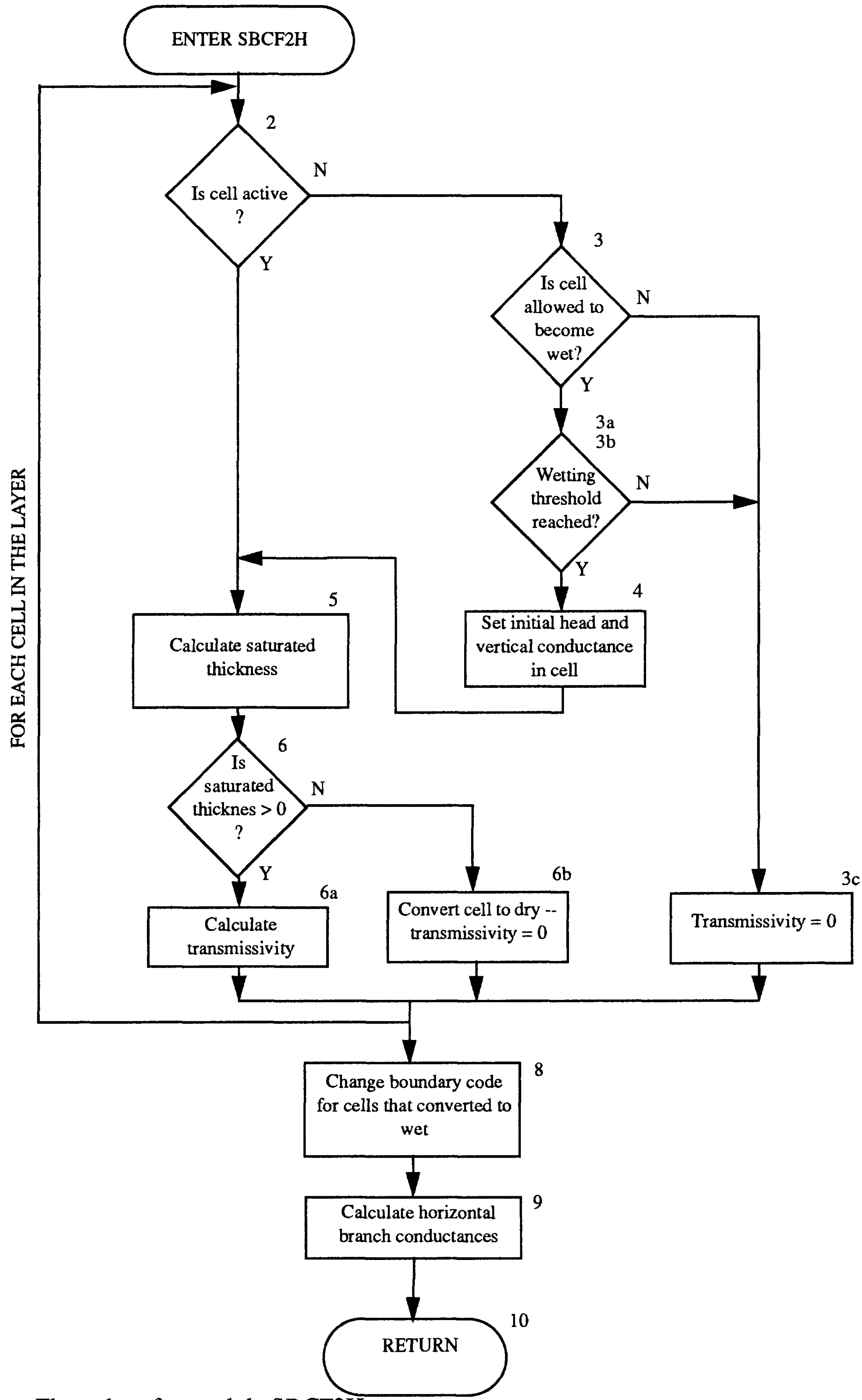

Figure 12. -- Flow chart for module SBCF2H.

```
      SUBROUTINE SBCF2H(HNEW,IBOUND,CR,CC,CV,HY,TRPY,DELR,DELC
     1,BOT,TOP,K,KB,KT,KITER,KSTP,KPER,NCOL,NROW,NLAY,IOUT
     2,WETDRY,IWDFLG,CVWD,WETFCT,IWETIT,IHDWET,HDRY)
C-----VERSION 1345 23MAY1991 SBCF2H
C
C     ******************************************************************
C     COMPUTE CONDUCTANCE FOR ONE LAYER FROM SATURATED THICKNESS AND
C     HYDRAULIC CONDUCTIVITY, VERSION 2
C     ******************************************************************
C
C      SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY)
     1,CR(NCOL,NROW,NLAY), CC(NCOL,NROW,NLAY), CV(NCOL,NROW,NLAY)
     2,HY(NCOL,NROW,NLAY), TRPY(NLAY), DELR(NCOL), DELC(NROW)
     3,BOT(NCOL,NROW,NLAY),TOP(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY)
     4,CVWD(NCOL,NROW,NLAY)
      CHARACTER*4 ACNVRT
      DIMENSION ICNVRT(8),JCNVRT(8),ACNVRT(8)
C
      COMMON /FLWCOM/LAYCON(80)
C     ------------------------------------------------------------------
C
C1------LOOP THROUGH EACH CELL IN LAYER AND CALCULATE TRANSMISSIVITY AT
C1------EACH ACTIVE CELL.
      NCNVRT=0
      IHDCNV=0
      ITFLG=1
      IF(IWDFLG.NE.0) ITFLG=MOD(KITER,IWETIT)
      DO 200 I=1,NROW
      DO 200 J=1,NCOL
C
C2------IF CELL IS ACTIVE, THEN SKIP TO CODE THAT CALCULATES SATURATED
C2------THICKNESS.
      IF(IBOUND(J,I,K).NE.0) GO TO 20
C
C3------DETERMINE IF THE CELL CAN CONVERT BETWEEN CONFINED AND
C3------UNCONFINED.  IF NOT, SKIP TO CODE THAT SETS TRANSMISSIVITY TO 0.
      IF(ITFLG.NE.0) GO TO 6
      IF(WETDRY(J,I,KB).EQ.0.0)GO TO 6
      WD=WETDRY(J,I,KB)
      IF(WD.LT.0.) WD=-WD
      TURNON=BOT(J,I,KB)+WD
C
C3A-----CHECK HEAD IN CELL BELOW TO SEE IF WETTING THRESHOLD HAS BEEN
C3A-----REACHED.
      IF(K.EQ.NLAY)GO TO 2
      HTMP=HNEW(J,I,K+1)
      IF(IBOUND(J,I,K+1).GT.0.AND.HTMP.GE.TURNON)GO TO 9
C
C3B-----CHECK HEAD IN ADJACENT HORIZONTAL CELLS TO SEE IF WETTING
```

```
C3B-----THRESHOLD HAS BEEN REACHED.
    2 IF(WETDRY(J,I,KB).LT.0.) GO TO 6
      IF(J.EQ.1)GO TO 3
      HTMP=HNEW(J-1,I,K)
      IF(IBOUND(J-1,I,K).GT.0.AND.IBOUND(J-1,I,K).NE.30000.AND.
     1                           HTMP.GE.TURNON)GO TO 9
    3 IF(J.EQ.NCOL)GO TO 4
      HTMP=HNEW(J+1,I,K)
      IF(IBOUND(J+1,I,K).GT.0.AND.HTMP.GE.TURNON)GO TO 9
    4 IF(I.EQ.1)GO TO 5
      HTMP=HNEW(J,I-1,K)
      IF(IBOUND(J,I-1,K).GT.0.AND.IBOUND(J,I-1,K).NE.30000.AND.
     1                            HTMP.GE.TURNON)GO TO 9
    5 IF(I.EQ.NROW)GO TO 6
      HTMP=HNEW(J,I+1,K)
      IF(IBOUND(J,I+1,K).GT.0.AND.HTMP.GE.TURNON)GO TO 9
C
C3C-----CELL IS DRY AND STAYS DRY.  SET TRANSMISSIVITY TO 0 AND SKIP
C3C-----TO THE NEXT CELL.
    6 CC(J,I,K)=0.
      GO TO 200
C
C4------CELL BECOMES WET.  SET INITIAL HEAD AND VERTICAL CONDUCTANCE.
    9 IF(IHDWET.NE.0) HNEW(J,I,K)=BOT(J,I,KB)+WETFCT*WD
      IF(IHDWET.EQ.0) HNEW(J,I,K)=BOT(J,I,KB)+WETFCT*(HTMP-BOT(J,I,KB))
      IF(K.EQ.NLAY) GO TO 12
      IF(IBOUND(J,I,K+1).NE.0) CV(J,I,K)= CVWD(J,I,K)
   12 IF(K.EQ.1) GO TO 14
      IF(IBOUND(J,I,K-1).NE.0) CV(J,I,K-1)= CVWD(J,I,K-1)
   14 IBOUND(J,I,K)=30000
C
C4A-----PRINT MESSAGE SAYING CELL HAS BEEN CONVERTED TO WET.
      NCNVRT=NCNVRT+1
      ICNVRT(NCNVRT)=I
      JCNVRT(NCNVRT)=J
      ACNVRT(NCNVRT)=' WET'
      IF(NCNVRT.LT.8) GO TO 20
         IF(IHDCNV.EQ.0) WRITE(IOUT,17) KITER,K,KSTP,KPER
   17    FORMAT(1H0,'CELL CONVERSIONS FOR ITERATION=',I3,'  LAYER=',
     1    I2,'  TIME STEP=',I3,'  STRESS PERIOD=',I3,'      (ROW,COL)')
         IHDCNV=1
         WRITE(IOUT,18) (ACNVRT(L),ICNVRT(L),JCNVRT(L),L=1,NCNVRT)
   18    FORMAT(1X,8(A4,'(',I3,',',I3,')   '))
         NCNVRT=0
C
C5------CALCULATE SATURATED THICKNESS.
   20 HD=HNEW(J,I,K)
      IF(LAYCON(K).EQ.1) GO TO 50
      IF(HD.GT.TOP(J,I,KT)) HD=TOP(J,I,KT)
   50 THCK=HD-BOT(J,I,KB)
C
C6------CHECK TO SEE IF SATURATED THICKNESS IS GREATER THAN ZERO.
      IF(THCK.LE.0.) GO TO 100
C
```

```
C6A-----IF SATURATED THICKNESS>0 THEN TRANSMISSIVITY IS HYDRAULIC
C6A-----CONDUCTIVITY TIMES SATURATED THICKNESS.
      CC(J,I,K)=THCK*HY(J,I,KB)
      GO TO 200
C
C6B-----WHEN SATURATED THICKNESS < 0, PRINT A MESSAGE AND SET
C6B-----TRANSMISSIVITY, IBOUND, AND VERTICAL CONDUCTANCE =0
  100 NCNVRT=NCNVRT+1
      ICNVRT(NCNVRT)=I
      JCNVRT(NCNVRT)=J
      ACNVRT(NCNVRT)=' DRY'
      IF(NCNVRT.LT.8) GO TO 150
         IF(IHDCNV.EQ.0) WRITE(IOUT,17) KITER,K,KSTP,KPER
         IHDCNV=1
         WRITE(IOUT,18) (ACNVRT(L),ICNVRT(L),JCNVRT(L),L=1,NCNVRT)
         NCNVRT=0
  150 HNEW(J,I,K)=HDRY
      CC(J,I,K)=0.
      IF(IBOUND(J,I,K).GE.0) GO TO 160
         WRITE(IOUT,151)
  151    FORMAT(1H0,'CONSTANT-HEAD CELL WENT DRY -- SIMULATION ABORTED')
         WRITE(IOUT,152) K,I,J,KITER,KSTP,KPER
  152    FORMAT(1X,'LAYER=',I2,'   ROW=',I3,'   COLUMN=',I3,
     1     '   ITERATION=',I3,'   TIME STEP=',I3,'   STRESS PERIOD=',I3)
         STOP
  160 IBOUND(J,I,K)=0
      IF(K.LT.NLAY) CV(J,I,K)=0.
      IF(K.GT.1) CV(J,I,K-1)=0.
  200 CONTINUE
C
C7------PRINT ANY REMAINING CELL CONVERSIONS NOT YET PRINTED
      IF(NCNVRT.EQ.0) GO TO 203
         IF(IHDCNV.EQ.0) WRITE(IOUT,17) KITER,K,KSTP,KPER
         IHDCNV=1
         WRITE(IOUT,18) (ACNVRT(L),ICNVRT(L),JCNVRT(L),L=1,NCNVRT)
         NCNVRT=0
C
C8------CHANGE IBOUND VALUE FOR CELLS THAT CONVERTED TO WET THIS
C8------ITERATION FROM 30000 to 1.
  203 IF(IWDFLG.EQ.0) GO TO 210
      DO 205 I=1,NROW
      DO 205 J=1,NCOL
      IF(IBOUND(J,I,K).EQ.30000) IBOUND(J,I,K)=1
  205 CONTINUE
C
C9------COMPUTE HORIZONTAL BRANCH CONDUCTANCES FROM TRANSMISSIVITY.
  210 CALL SBCF1C(CR,CC,TRPY,DELR,DELC,K,NCOL,NROW,NLAY)
C
C10-----RETURN
      RETURN
      END
```

List of Variables for Module SBCF2H

Variable	Range	Definition
ACNVRT	Module	DIMENSION (8), Contains "DRY" or "WET" for up to eight cells that have converted between wet and dry.
BOT	Package	DIMENSION (NCOL,NROW,NLAY), Elevation of the aquifer bottom. Although BOT is dimensioned to the size of the grid, space exists onlfor cells for which saturated thickness is calculated.
CC	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the column direction. This array is also used to temporarily hold saturated thickness.
CR	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the row direction.
CV	Global	DIMENSION (NCOL,NROW,NLAY), Conductance in the vertical direction. Although CV is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
CVWD	Package	DIMENSION (NCOL,NROW,NLAY), Conductance in the vertical direction. When a wet cell converts to dry, CV is set equal to 0. When a dry cell converts to wet, CV is set equal to CVWD. Although CVWD is dimensioned to the size of the grid, space exists only for NLAY-1 layers.
DELC	Global	DIMENSION (NROW), Cell dimension in the column direction. DELC(I) contains the width of row I.
DELR	Global	DIMENSION (NCOL), Cell dimension in the row direction. DELR(J) contains the width of column J.
HD	Module	Single precision equivalent of HNEW(J,I,K).
HDRY	Package	When a cell converts to dry, HNEW is set equal to HDRY.
HNEW	Global	DIMENSION (NCOL,NROW,NLAY), Most recent estimate of head in each cell.
HTMP	Module	Temporary single precision equivalent of HNEW.
I	Module	Index for rows.
IBOUND	Global	DIMENSION (NCOL,NROW,NLAY), Status of each cell: < 0, constant-head cell = 0, no-flow cell > 0, variable-head cell
ICNVRT	Module	DIMENSION (8), Row index for up to eight cells that have converted between wet and dry.
IHDCNV	Module	Flag indicating if any cell conversion information has been printed.
IHDWET	Package	Flag indicating which equation to use for calculating the head at a cell that has just converted from dry to wet.
IOUT	Global	Primary unit number for all printed output.
ITFLG	Module	Flag indicating if the current iteration is one in which cells are allowed to convert from dry to wet.
IWDFLG	Package	Flag indicating if wetting capability is active.
IWETIT	Package	Iteration interval for attempting to wet cells.
J	Module	Index for columns.
JCNVRT	Module	DIMENSION (8), Column index for up to eight cells that have converted between wet and dry.
K	Module	Index for layers.

KB	Module	Index for layer within BOT, HY, and WETDRY arrays.
KITER	Global	Iteration counter. KITER=1 at the start of each time step.
KPER	Global	Stress period counter.
KSTP	Global	Time step counter. KSTP=1 at the start of each stress period.
KT	Module	Index for layer within TOP array.
L	Module	Index for printing cell conversion information.
LAYCON	Package	DIMENSION (80) Layer-type code: 0 -- Layer is strictly confined. 1 -- Layer is strictly unconfined. 2 -- Layer is convertible between confined and unconfined (transmissivity is constant). 3 -- Layer is convertible between confined and unconfined (transmissivity varies).
NCNVRT	Module	Counter for number of cells that have converted between wet and dry since a line of conversion information has been printed.
NCOL	Global	Number of columns in the grid.
NLAY	Global	Number of layers in the grid.
NROW	Global	Number of rows in the grid.
THCK	Module	Saturated thickness.
TOP	Package	DIMENSION (NCOL,NROW,NLAY), Elevation of the aquifer top. Although TOP is dimensioned to the size of the grid, space exists only for cells that can convert between confined and unconfined.
TRPY	Package	DIMENSION (NLAY), Ratio of transmissivity (or hydraulic conductivity) in the column direction to transmissivity (or hydraulic conductivity) in the row direction.
TURNON	Module	Turn-on threshold.
WD	Module	The absolute value of WETDRY(J,I,KB).
WETDRY	Package	DIMENSION (NCOL,NROW,NLAY), Wetting threshold. Although WETDRY is dimensioned to the size of the grid, space exists only for layers that have the potential for converting from dry to wet.
WETFCT	Package	A factor that is included in the calculation of the head that is established at a cell that has just converted from dry to wet.

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