MODIFICATIONS TO THE DIFFUSION ANALOGY SURFACE-WATER FLOW MODEL (DAFLOW) FOR COUPLING TO THE MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL (MODFLOW)

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LIST OF SYMBOLS

A	cross-sectional area of flow
A0	cross-sectional area at zero flow
A1	hydraulic-geometry coefficient for area
A2	hydraulic-geometry exponent for area
A_1,A_2	cross-sectional area downstream and upstream of wave, Respectively
B_e	elevation of streambed as it crosses the aquifer cell
B_t	thickness of the streambed
C	celerity of moving wave
D_f	wave dispersion coefficient
D_L	diffusive length scale
g	acceleration of gravity
H_d	head of aquifer in the cell
K	conveyance
K_c	hydraulic conductivity of the streambed
L	length of stream reach in communication with the aquifer
L_a	distance traveled by a wave during one time step
n	Mannings resistance coefficient
Q	discharge
Q_c	channel forming discharge
Q_s	flow under steady uniform flow conditions
Q_1,Q_2	discharge downstream and upstream of wave, respectively
S_{ep}	flow from the aquifer to the stream as seepage
S_f	friction slope in channel flow
S_o	slope of channel bed
T	time
U	velocity
W	top width of channel
W1	hydraulic-geometry coefficient for width
W2	hydraulic-geometry exponent for width
x	distance coordinate, north to south, for MODFLOW
X	distance coordinate, along the channel
y	distance coordinate, west to east, for MODFLOW
Y	depth of flow
z	vertical distance coordinate, for MODFLOW
Δt	time increment
Δx	incremental distance along x coordinate

CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot/second (ft/s)	0.3048	meter/second (m/s)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

ADDITIONAL ABBREVIATIONS

cal	calorie

ACRONYMS

DAFLOW	Diffusion Analogy Flow Model
FTP	File Transfer Protocol
GW	Ground water
MODFLOW	Modular Finite Difference Ground-Water Flow Model
SW	Surface Water

Modifications to the Diffusion Analogy Surface-Water Flow Model (DAFLOW) for Coupling to the Modular Finite-Difference Ground-Water Flow Model (MODFLOW)

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Abstract

Surface-water and ground-water computer models are widely used to simulate flow for evaluating and managing water resources. Simulation of the surface-water/ground-water interaction is, however, less well developed. To facilitate the simulation of this interaction, the surface-water flow model (DAFLOW) has been coupled to the modular, finite-difference, ground-water flow model (MODFLOW).

The DAFLOW model routes flows through a system of inter-connected one-dimensional channels and subdivides the system into a series of branches, with each branch divided into a number of subreaches. MODFLOW simulates ground-water flow through a three-dimensional grid of cells. The models are coupled by adding an exchange between each subreach and a specified ground-water cell, with the amount of flow from the stream to ground water being limited to the available streamflow. The water exchange for each subreach is computed on the basis of the stream-aquifer head difference, the streambed thickness, stream width, and streambed hydraulic conductivity.

Three example applications are provided to assess the accuracy of the solutions and demonstrate the use of the combined models.

INTRODUCTION

Computer models that simulate ground-water (GW) and surface-water (SW) flow are widely used to evaluate and manage ground- and surface-water resources. The MODFLOW model (Harbaugh and McDonald, 1996; McDonald and Harbaugh, 1988) simulates three-dimensional GW flow and includes the effects of many steady-state or transient processes, such as areal recharge, rivers, drains, evapotranspiration, and pumpage. The DAFLOW model, Jobson (1989) simulates one-dimensional flow through a system of interconnected channels by solving the diffusive-wave form of the flow equations. DAFLOW subdivides the stream system into a series of branches, with each branch divided into a number of subreaches. It is designed to simulate flow in upland stream systems where flow reversals do not occur and backwater conditions are not severe. If these two conditions are satisfied, DAFLOW can be applied with reasonable accuracy using minimal field data.

This report describes the coupling of MODFLOW and DAFLOW. Although other methods of simulating surface-water interaction have been previously incorporated within MODFLOW (McDonald and Harbaugh, 1988; Prudic, 1989; and Swain and Wexler, 1993), DAFLOW provides a highly stable solution scheme that is simple to run and requires a minimum of field data and calibration. This report does not, however, attempt to compare the different approaches, so potential users of the coupled MODFLOW and DAFLOW models should also evaluate these other approaches in order to choose the best approach for their particular problem.

To facilitate coupling the models, the DAFLOW code was separated into subroutines that are consistent with the modular structure of MODFLOW. These subroutines were structured such that multiple DAFLOW time steps can be run iteratively within a MODFLOW time step. DAFLOW was also modified to allow subreaches to go dry so that it will be possible to simulate streams from which the entire flow seeps into the ground.

MODFLOW is divided into a main program and a series of independent sets of subroutines called packages, which allows additional capabilities to be easily incorporated. To couple DAFLOW to MODFLOW, a group of subroutines was written that incorporates DAFLOW as a MODFLOW package. These additional subroutines calculate the water exchange between the SW and GW systems.

This report: (1) gives a brief conceptualization of routing streamflow and a summary of the theory of the DAFLOW model, (2) describes the mechanics of computing the leakage to the aquifer, (3) documents the modifications to the DAFLOW model needed for it to be coupled to the MODFLOW package, (4) describes the calls necessary to couple MODFLOW and DAFLOW, (5) describes the input files necessary to run DAFLOW with MODFLOW, as well as the output files, and (6) presents three example applications.

All U.S. Geological Survey (USGS) hydrologic analysis software is available for electronic retrieval by means of either the World Wide Web (WWW) at http://water.usgs.gov/software or by anonymous File Transfer Protocol (FTP) from water.usgs.gov in pub/software/surface_water directory.

CONCEPTUALIZATION OF ROUTING STREAMFLOWS

The differential equations derived by Saint-Venant (1871) for one-dimensional, unsteady flow are the basis for the diffusion analogy method used by DAFLOW. Assuming no lateral inflow, the Saint-Venant equations for channel flow are the continuity of mass equation:

$$\frac{\partial Q}{\partial X} + \frac{\partial A}{\partial t} = 0 , \qquad (1)$$

and the continuity of momentum equation:

$$\frac{1}{g}\frac{\partial U}{\partial t} + \frac{U \partial U}{g \partial X} + \frac{\partial Y}{\partial X} + S_f - S_o = 0 , \qquad (2)$$

in which Q is discharge, X is distance along the channel, A is the cross-sectional area of flow, t is time, g is the acceleration of gravity, U is velocity, Y is depth, S_f is the friction slope, and S_o is the streambed slope.

DAFLOW approximates the flow distribution in a stream as reaches of steady uniform flow separated by transitions of unsteady flow as illustrated in figure 1. The transitions are considered to be regions of uniformly progressive flow, as defined by Chow (1959, p 528). This type of flow has a stable wave profile that does not change shape as it moves down the channel. One common type of uniformly progressive flow, which approximates most flood waves in natural channels, is the monoclinal rising wave (Chow, 1959, p 528). Kleitz (1877) developed the mathematical principle of uniformly progressive waves, but it was Seddon (1900) and Wilkinson (1945) who showed it to be applicable to actual rivers. Wilkinson found that the mid-point of the rise or fall in stages were best suited for determining the velocity of an observed wave.

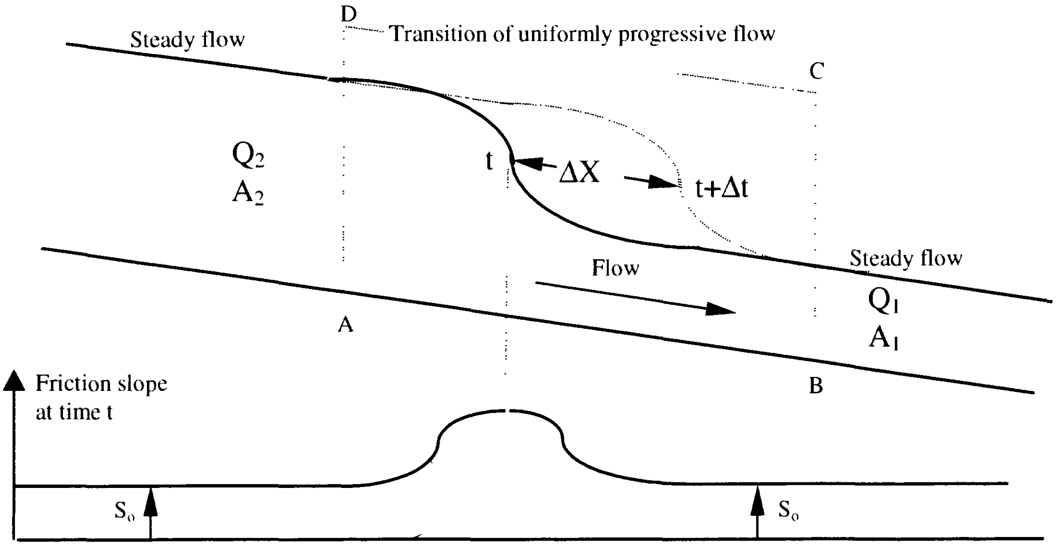

Figure 1. Schematic showing steady uniform flow subreaches connected by a transition of uniformly progressive flow.

By considering the flow into and out of the control volume ABCD (figure 1), it is shown that:

$$Q_2\Delta t - Q_1\Delta t = (A_2 - A_1)\Delta x \,,$$

or

$$C = \frac{\Delta X}{\Delta t} = \frac{Q_2 - Q_1}{A_2 - A_1} \Rightarrow \frac{\partial Q}{\partial A} \,, \qquad (3)$$

in which C is the speed of the moving wave, or celerity, Q_1 and Q_2 are the discharge downstream and upstream of the wave, respectively, and A_1 and A_2 are the cross-sectional areas downstream and upstream of the wave, respectively.

For the unsteady portion of the flow (the transition) it can be seen that the rate of change of depth with distance has a maximum absolute value at the inflection point and approaches zero both upstream and downstream of the wave. The shape of the curve representing the rate of change of depth with distance in the transition can often be approximated as a Normal probability density function.

Ignoring the first two terms (the acceleration terms) of the momentum equation (2) the friction slope can be approximated as:

$$S_f = S_o - \frac{\partial Y}{\partial X} = S_o - \frac{1}{W}\frac{\partial A}{\partial X} \,. \qquad (4)$$

in which W is the top width of the channel. The last form of the equation is strictly valid only for a prismatic channel. The friction slope is equal to the streambed slope in each steady flow reach and is a maximum at the inflection point as illustrated on figure 1.

The friction slope is often estimated by using an empirical equation of the type:

$$S_f = \frac{Q^2}{K^2}, \qquad (5)$$

in which K is the conveyance, which is often computed from an equation of the Manning type:

$$K = \frac{1.49}{n} \frac{A^{5/3}}{W^{2/3}}, \qquad (6)$$

in which n is the Manning roughness coefficient and W, the top width, has been substituted for the more correct wetted perimeter. Equation 6 is expressed in the English system of units; in metric units the constant 1.49 is replaced with 1.0. Equation 5 is often expressed in terms of the streambed slope (S_o) rather than S_f in which case the computed discharge is considered to be the flow that would occur under steady uniform conditions (Q_s). Substituting equation 5 into equation 4:

$$\frac{Q^2}{K^2} = \frac{Q_s^2}{K^2} - \frac{1}{W}\frac{\partial A}{\partial X}.$$

Multiplying both sides by K^2 and completing the squares by adding $\left(\frac{K^2}{2WQ_s}\frac{\partial A}{\partial X}\right)^2$ to each side:

$$Q^2 + \left(\frac{K^2}{2WQ_s}\frac{\partial A}{\partial X}\right)^2 = Q_s^2 - 2Q_s\frac{K^2}{2WQ_s}\frac{\partial A}{\partial X} + \left(\frac{K^2}{2WQ_s}\frac{\partial A}{\partial X}\right)^2.$$

Solving for discharge (Q) and ignoring the second term on the left side, because it involves the square of a derivative, an equation for the unsteady discharge in the transition region is obtained, which is based on the diffusive wave form of the momentum equation:

$$Q = Q_s - \frac{K^2}{2WQ_s}\frac{\partial A}{\partial X} = Q_s - D_f\frac{\partial A}{\partial X}, \qquad (7)$$

in which D_f is a wave-diffusion coefficient defined as:

$$D_f = \frac{K^2}{2WQ_s} = \frac{Q}{2WS_o}. \qquad (8)$$

The second form of equation 8 is obtained by approximating K^2 as $Q \cdot Q_s/S_o$.

As shown by Jobson (1989, p. 6) equation 7 can be substituted into the continuity equation (1) to produce the diffusive wave form of the flow equation:

$$\frac{\partial Q_s}{\partial t} + C\frac{\partial Q_s}{\partial X} - D_f\frac{\partial^2 Q_s}{\partial X^2} = 0. \qquad (9)$$

The actual solution procedure used by DAFLOW is as follows. At the beginning of each time step the flow along the stream is represented as a series of steady uniform flow reaches, called waves, separated by shocks that are transition zones of zero length. During a time step, these shocks would naturally diffuse according to equation 9, so at the end of the time step they should look similar to that shown on figure 1. The diffusive length scale (D_L) (Carslaw and Jaeger, 1959),

$$D_L = \sqrt{2D_f\Delta t}, \qquad (10)$$

is a measure of the distance that the shocks diffuse during the time step. At the beginning of each time step each shock is replaced by two shocks that are a distance of $2D_L$ apart. This maintains a series of steady flow subreaches separated by shocks, and accounts for the diffusion of the waves. The discharge in the wave between the two new shocks is computed such that the volume of water in the wave is identical to what existed in the space before the mass was redistributed, by adding the shock. Within the wave, where steady uniform conditions exist, there is a unique relation between the flow area and discharge.

If the diffusion of mass around the shock obeys equation 9 with a constant value of D_f, the variation of water mass with distance from the shock follows a Normal probability distribution function. It can be easily shown that the mean and variance of the water-mass distribution after splitting a single shock into two shocks connected by a steady flow wave is identical to that of the Normal probability distribution, if the shocks are a distance of $2D_L$ apart. Jobson (1989) further shows that the theoretical distribution of mass described by equation 9 can be closely approximated by repetitively breaking a single shock into two shocks a distance of $2D_L$ apart. Once the mass of water is redistributed to account for the diffusion, the shocks are moved to new locations by computing their wave speeds from equation 3.

The accuracy of the diffusive-wave form of the flow equation, therefore of DAFLOW, depends on the relative size of the advection and diffusion terms. The model accuracy degrades as the wave diffusion increases relative to advection. As can be seen from equation 8, the wave-diffusion coefficient is inversely proportional to the stream slope, so the model accuracy decreases as the slope decreases. One measure of the importance of the advection and diffusion terms is the ratio of the distance traveled by a wave during a time step (L_a) to the diffusive length scale (D_L). It has been found empirically that DAFLOW gives good results as long as:

$$\frac{L_a}{D_L} \geq 0.87 \quad .$$

Much geomorphic information indicates that, in an average sense, the cross-sectional area of natural channels can be approximated by an equation of the form:

$$A = A0 + A1 \bullet Q_S^{A2}, \tag{11}$$

in which A1 and A2 are constants called the hydraulic-geometry coefficient and exponent for area, respectively, and A0 is the average cross-sectional area at zero flow. Theoretically the value of A2 can range from 0 to 1, but its value is usually found to be between 0.5 and 0.8 with an average of 0.66 (Leopold and Maddock, 1953; Stall and Yang, 1970; Boning, 1974; Boyle and Spahr, 1985; Jobson 1989). Likewise, the width can be approximated by an equation of the form:

$$W = W1 \bullet Q_S^{W2}, \tag{12}$$

in which W1 and W2 are constants called the hydraulic-geometry coefficient and exponent for width, respectively. The value of W2 is generally found to range from 0.1 to 0.4 with a typical value of 0.26 (Leopold and Miller, 1956; Stall and Yang, 1970; Jobson, 1989). Hydraulic-geometry exponents have been found to maintain relatively consistent values both at a site on a stream and between streams, (Jobson 1989, Beven & Kirkby 1993, page 91).

Differentiating equation 11 and inverting, it is easily seen that the wave speed is determined as:

$$C = \frac{Q_S^{(1-A2)}}{A1 \bullet A2}. \tag{13}$$

Likewise the diffusive length scale can be determined by combining equations 8, 10 and 12 as:

$$D_L = \frac{Q_S^{(1-W2)/2} \bullet \sqrt{\Delta t}}{\sqrt{S_O \bullet W1}}. \tag{14}$$

So the ratio L_a/D_L can be determined as:

$$\frac{L_a}{D_L} = \frac{\sqrt{S_O \bullet W1} \bullet Q_S^{(0.5-A2+W2/2)} \bullet \sqrt{\Delta t}}{A1 \bullet A2}. \tag{15}$$

The accuracy of DAFLOW depends on the time-step size and streambed slope. Streams with smaller slopes can be reasonably simulated using a larger time step. In other words, DAFLOW may provide reasonable estimates of daily flows for a low gradient stream, such as the lower reaches of the Mississippi, even though it can not resolve the small scale variations, such as might occur on a 5-minute time scale. Recall that typical values of A2 and W2 are 0.66 and 0.26, respectively, so the exponent on Q_s is typically small and discharge generally has little influence on the accuracy of the model. As a rule of thumb, the following table gives the approximate minimum slope that should be simulated by DAFLOW for various time steps.

Time step	Minimum Slope
5 minute	10 ft/mile; 0.002
1 hour	1.5 ft/mile; 0.0003
6 hour	0.25 ft/mile; 0.00005
12 hour	0.1 ft/mile; 0.00002

STRUCTURE OF THE MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL AND THE DIFFUSION ANALOGY SURFACE-WATER FLOW MODEL

MODFLOW solves the three-dimensional ground-water flow equation using finite-difference approximations (McDonald and Harbaugh, 1988, p 2-35). The finite difference procedure requires that the aquifer be divided into blocks called cells, which have dimensions x, y, and z. The aquifer properties in each cell are assumed uniform. The head in each cell is calculated at a point, or node, at the center of the cell. The head is calculated by iterating through the finite-difference equations for all nodes until the maximum head change in any cell between the previous and current iteration is less than a value specified by the user. Once this criterion is met, the program advances to a new time step and the process is repeated. Because the response time of surface-water systems are generally much smaller than those of ground-water systems, the appropriate time step of a SW model is likely smaller than the appropriate time step of the GW model.

DAFLOW was, therefore, structured so that multiple DAFLOW time steps can occur within a MODFLOW time step. During each iteration of a MODFLOW time step, a subroutine is called to calculate seepage to or from the stream. DAFLOW must also be run to route the SW flow for the MODFLOW time step. For the seepage calculations, ground-water head can either be assumed to remain constant during the GW time step, or be approximated by straight-line interpolation between the head at the beginning and end of the GW time step. The heads are assumed to remain constant during a single SW time step. The SW flow conditions at the beginning of the GW time step are stored so that the iterative process can be repeated.

NUMBERING AND ORDERING OF STREAMS

Streams superimposed on the aquifer are divided into branches and subreaches as defined in the DAFLOW documentation (Jobson, 1989) and shown on figure 2. Each branch begins and ends at a junction and junctions are numbered, starting with the interior junctions (those connecting two or more branches). Any number of branches can start or end at a junction. Each branch is divided into subreaches by node points or cross sections. Subreach 1 of branch 1, for example, is the stream reach extending from node 1 to node 2 (figure 2). Each branch must have at least one subreach defined by two nodes, one at each end. The example shown in figure 2 contains three branches with one internal junction, number 1. Branch 1 delivers water from junction 2 to junction 1 and is divided into 8 subreaches by 9 nodes. The nodes must be numbered sequentially, starting at the upstream end of the channel. The locations of the nodes are input as the distance downstream from a reference point, in miles or kilometers. The location of node 1 does not have to be zero, but negative river miles are not allowed. The locations of nodes must increase with increasing node number and should be separated by at least 0.0002 units (mile or kilometer). Multiple node points at the same location are not allowed.

Flow additions, or extractions, are allowed at any interior node (for example, if a branch contains 9 nodes, flow can be exchanged at nodes 2 through 8). The flow exchange is assumed to occur just upstream of the node.

When MODFLOW is coupled to DAFLOW, the user specifies the MODFLOW cell to which the ground-water seepage is connected for each interior SW subreach. This means that as a minimum, a node should be placed at every point where the stream intersects a cell boundary. This will divide the stream into subreaches that are each contained within a single cell. Ground-water seepage for the downstream node of the subreach should be assigned to the cell that contains the subreach. As shown in figure 2, most of the nodes were selected using this approach. For example, nodes 2 and 3 of branch 1 define a subreach within the cell at row 1, column 2. The seepage for node 3, subreach 2, would accordingly be assigned to the cell at row 1, column 2. Technically the water enters the aquifer at the center of the cell, the GW node, but it leaves the stream at the downstream edge of the cell. Additional nodes can be used if needed to define changes in hydraulic conditions or inflow points, for example, see node 4, branch 3. In this example, the seepage for both nodes 4 and 5 would be assigned to the same MODFLOW cell: row 4, column 4.

As shown in figure 2, node 4 in branch 3 is needed because there is an additional inflow at this point. It might also define a point of significant change in the hydraulic characteristics of the stream, such as slope, width or depth. DAFLOW allows flow additions or extractions, in addition to ground-water seepage, at each interior node. An example diversion is shown for branch 2, node 4. The flow additions and subtractions are assumed not to interact with the ground water until they enter the stream. If ground-water interaction is desired, an additional branch representing the diversion or inflow would be needed.

Notice that the surface-water system can extend beyond the aquifer, e.g. branch 2, subreach 1 or branch 3, subreach 7. Subreaches that are outside of the aquifer have no interaction with the ground-water system.

Because DAFLOW does not allow flow exchanges at the last node in a branch, ground-water seepage is not allowed for the last subreach in any branch. This limitation can be minimized, for example at the ends of branches 1 and 2 in figure 2, by placing the next to the last node a very short distance upstream from the last node (however nodes must be separated by at least 0.0002 miles). In branch 3 the limitation was removed by adding a node downstream of the boundary of the GW model.

There is never any ground-water seepage represented at the first node of a branch because the ground-water seepage for a subreach is associated with the downstream node for that subreach. Thus, the seepage for subreach 1 occurs at the cell that is connected to node 2.

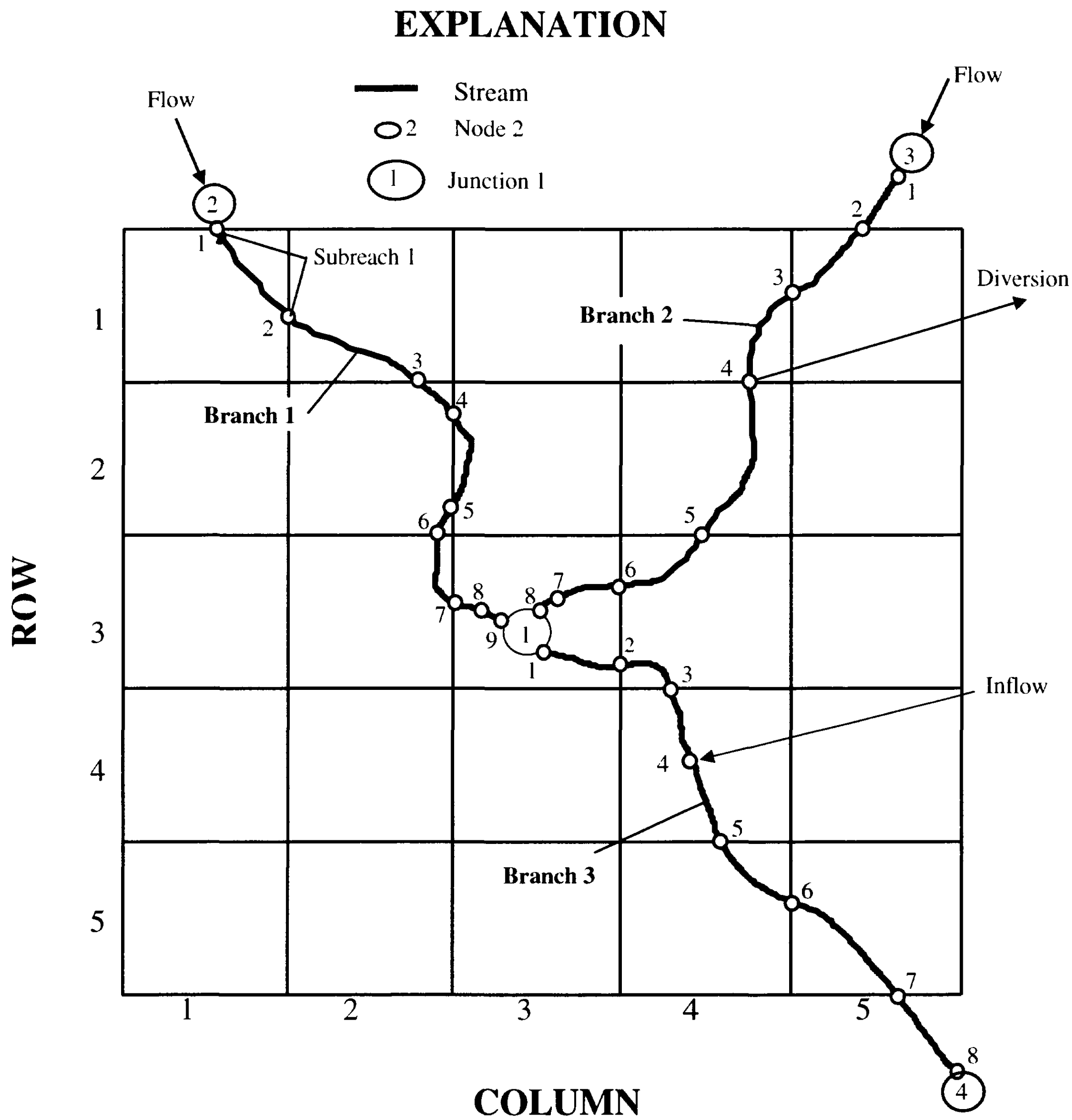

Figure 2. Example schematic showing the numbering system of the linked surface-water and ground-water model.

COMPUTING FLOW BETWEEN THE STREAM AND AQUIFER

Leakage to or from a stream subreach is computed using Darcy's law as follows:

$$S_{ep} = K_c\, L\, W\, (H_d\text{-}Y\text{-}B_e)/B_t, \tag{16}$$

in which S_{ep} = flow from the aquifer to the stream through the streambed, (L^3/T); K_c = hydraulic conductivity of the streambed, (L/T); L = length of stream reach in hydraulic connection with the aquifer cell, (L); W = average width of stream along the aquifer cell, (L); H_d = head of aquifer in the cell, (L); Y = average depth of stream in subreach crossing the aquifer cell, (L); B_e = average elevation of streambed as it crosses the aquifer cell,(L); and B_t = thickness of the streambed. A sketch of the properties used in the calculation of stream leakage to or from the aquifer is shown in figure 3.

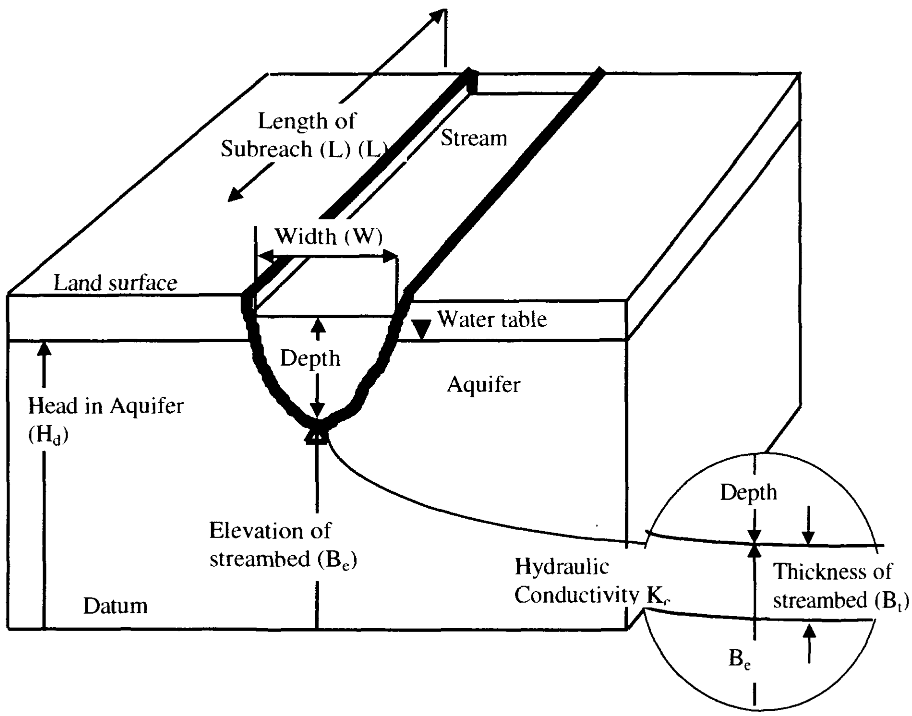

Figure 3. Diagram showing one ground-water cell with stream depicting properties used in calculation of the streambed leakage for a subreach.

The rate of flow between the aquifer and stream is computed for each SW time step. The first step is to compute the cross-sectional area, top width, and depth in the channel. The average cross-sectional area is computed as the volume of water divided by the subreach length. A characteristic discharge is then computed from equation 11. Finally, the stream depth is computed as the cross-sectional area divided by the top width computed from equation 12.

The seepage flow (S_{ep}) is then computed by use of equation 16. The bed elevation, B_e, is input for each internal node but is not used by DAFLOW for any purpose except in solving equation 16. It is not necessary, therefore, for the bed elevations to be consistent with the bed slope, which is also input to the model. The bed elevation input for a node should represent the average bed elevation of the subreach upstream of the node, or the bed elevation near the center of the GW cell associated with the node.

Either backward or central differencing can be used in the MODFLOW model. If backward differencing is selected, the ground-water head (H_d) is constant for all SW time steps within a single GW time step and is equal to the value computed at the end of the GW time step. If central differencing is selected, the GW head is computed for each SW time step by linear interpolation with time between the values of H_d at the beginning and end of the GW time step. The seepage volume during each SW time step is summed during the GW time step to compute the total exchange with the aquifer.

If seepage is from the channel to the aquifer (S_{ep} is negative) the magnitude of the seepage during any SW time step is limited to the total flow in the channel subreach plus any positive tributary inflow. If both surface-water extraction and negative seepage (flow from the stream to the aquifer) are occurring at a node and if there is not enough flow in the stream to satisfy both demands, the SW extraction is reduced first. If the seepage demands exceed the streamflow, the flow in the stream is set to zero and the seepage term is set equal to the available water in the stream.

ASSUMPTIONS AND LIMITATIONS

The DAFLOW model can simulate the flow in a network of interconnected one-dimensional channels with unsteady, unidirectional flow. The model should be applied only to channels that are characterized by one-dimensional, un-stratified flow, with fixed-channel geometry, and little backwater. The discharge at all upstream boundary points (upstream ends of external branches and tributary inflows) must be specified as a function of time. When more than one branch originates at a junction, a constant percentage of the flow at the junction must enter each branch and the percentage must be specified. Because backwater conditions are not simulated, no downstream boundary conditions are required.

DAFLOW uses a simplification of the dynamic wave equations, and therefore, it should be used with caution. Model accuracy increases with increasing slope. The accuracy is excellent for upland streams where generally there is a unique relation between stage and discharge.

The model allows no diffusion (backwater) through junctions so the peak-flow attenuation is somewhat limited if numerous junctions occur. Tributaries allow flow exchange without affecting backwater or peak-flow attenuation and add little complexity to the system, so they should be used wherever possible in place of a branch. However, it is desirable to treat the tributary as a branch rather than just a point addition if a significant time lag and (or) flow attenuation is expected to occur in the tributary.

The restriction that each stream subreach can interact with a single cell in the ground-water flow model results in some limitations on cell size compared to the dimensions of the stream. First, the maximum width of a subreach should be no wider than a finite-difference cell. The model will still operate if this assumption is violated, but some accuracy will be lost because the ground-water seepage will occur in a single cell when it should be divided among all the cells covered by the width of the subreach. Similarly for the vertical direction, the channel depth for a subreach should not cross through more than one model layer. Again, the model will operate if this assumption is violated, but the ground-water seepage will be represented in only a single layer.

When the MODFLOW cell is much wider than the width of a stream, the ground-water model may not represent the ground-water head near the stream very accurately. This is because the head distribution near a stream that has significant ground-water interaction can be complex. The more complex the head distribution is in an area, the more cells are required to represent that distribution accurately. If there is an inadequate number of cells to represent the stream-affected head distribution, then the seepage will not be accurately simulated.

MODIFICATIONS TO THE DIFFUSION ANALOGY FLOW MODEL

A number of modifications have been made to DAFLOW since it was first published in 1989. These modifications will be discussed first and then the modifications that were made so that it can be linked with MODFLOW will be outlined.

When DAFLOW was first published, the user input a constant wave-diffusion coefficient (D_f) for each subreach even though, as can be seen from equation 8, the wave-diffusion coefficient should vary with discharge, width, and slope. The code was later modified such that the user supplies the slope for each subreach and the model computes a wave-diffusion coefficient from equation 8. The slope replaced the wave-diffusion coefficient in the input stream of the file, flow.in. This modification allows the model to better simulate the wave attenuation under conditions of highly variable flow and has the added advantage of using input variables that are more readily available.

The diffusion step, in subroutine ROUTE, was modified to allow reaches of zero flow, interspersed with reaches with non-zero flow. In the previous version of DAFLOW, the channel could start as a dry channel, but once flow was established, the code would not allow the flow to return completely to zero. This limitation has been removed.

In order to make the DAFLOW model easily implemented in the MODFLOW program the coding was re-organized into subroutines that perform functions consistent with the major components of MODFLOW. The DAFLOW code was grouped into a shell program and eight subroutines called by the shell program, (see figure 4).

The input file, flow.in, used by DAFLOW contains three types of information: general, branch, and boundary. The general and branch information is read by subroutine STARTDAF that also writes these data to the output file so that the user can verify that the information is correctly read by the program. STARTDAF also makes preliminary calculations, such as computing the unit conversion factors, setting the initial number of waves in the system, and initializing the arrays containing the wave information, wave flow, and the location of each shock. The initial volume of water in each subreach is also computed, and the tributary inflows are stored in the appropriate arrays.

The subroutine PRERTE transfers the data in the initial value arrays to the current flow arrays to prepare to route any number of time steps, such as will occur with MODFLOW.

The subroutine GETBC reads boundary conditions from the file, flow.in, for a single time step.

The subroutine SETJNVL sets mixing codes for all branches and nodes to values, which indicate no routing has yet taken place.

Branches can be numbered in any order, and they are not routed in numerical order. Flows in branches that originate on the exterior boundaries must be routed first, and all branches terminating at an interior junction must be routed before any branch originating there can be routed. The subroutine RTBR determines the order in which the branches will be routed, routes the flow in each individual branch, and updates the global arrays and mixing codes for both the junctions and branches. Routing in each individual branch is carried out in a subroutine called ROUTE.

The volume of water in a subreach at the beginning of the time step is passed to the subroutine FGQ. The subroutine FGQ then computes the volume of water in the subreach at the end of the time step, based on the position of the shocks and the magnitude of flow in the waves between shocks. Finally, FCQ computes the average flow out of the subreach during the time step by use of equation 1, knowing the volumes at the beginning and end of the time step, as well as the tributary (seepage and real tributaries) and upstream flows during the time step. The flow at node one is known either from boundary conditions, for branches that originate at an exterior junction, or from the flow at the upstream junction, and the percent of flow that enters the branch that originate at an interior junction.

The subroutine SETJV2 updates the mixing codes for the branches and junctions that are affected by the computations in the branch and distributes the flow at interior junctions between the various branches that originate there.

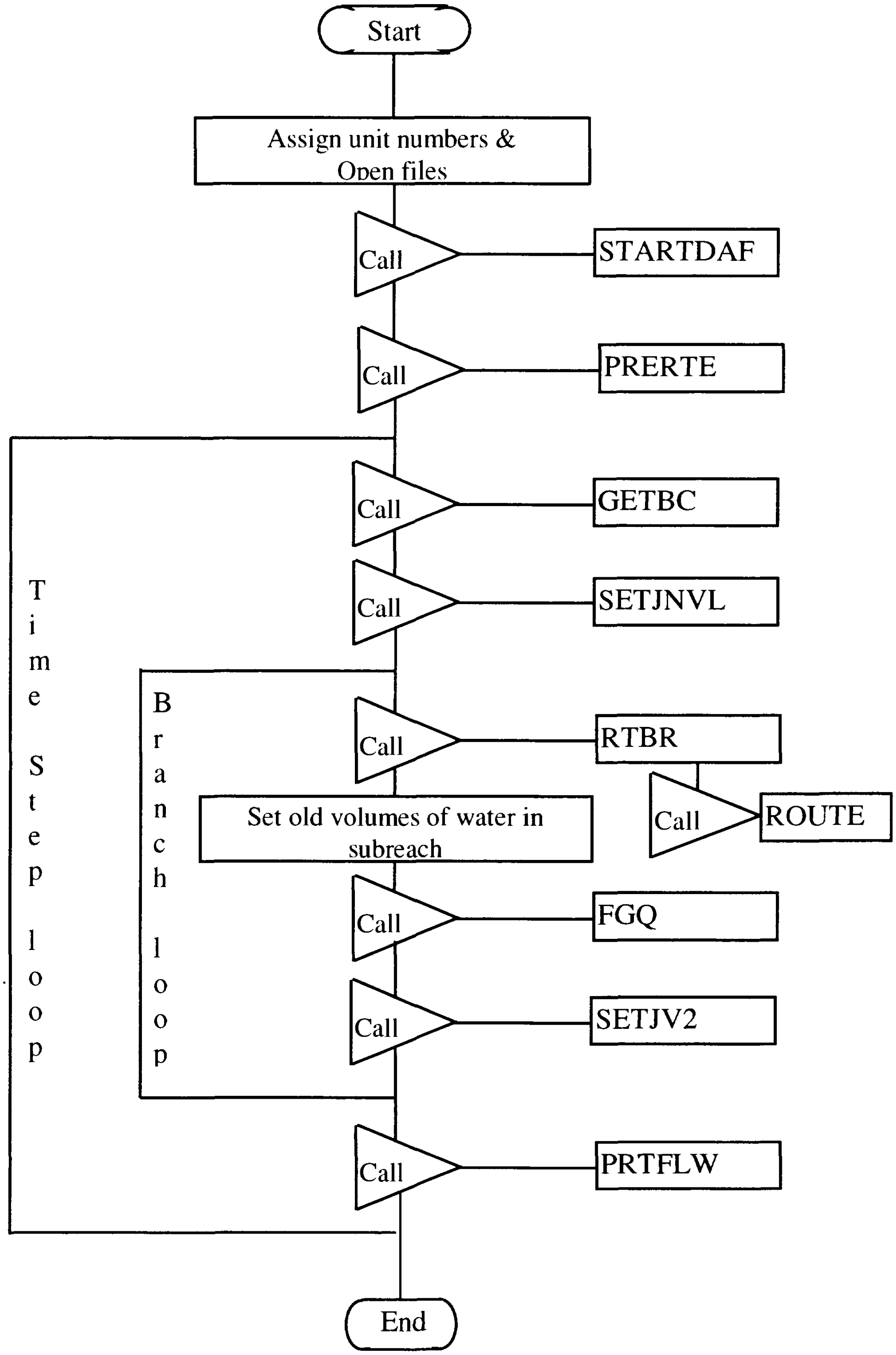

Figure 4. Overall program structure of the Diffusion Analogy Flow model.

The subroutine PRTFLW computes the clock time, the average cross-sectional area, and top width for the subreach. It then prints the results in the output file, as well as in the file bltm.flw.

A file called params.inc sets parameters to define the size of arrays in DAFLOW. This file is included, by use of the INCLUDE statement, in all subroutines so that array sizes will be consistent among subroutines. It also allows array sizes to be easily adjusted to fit a particular problem. The model must be re-compiled if the array sizes are modified.

The variables that are used by the several subroutines are declared, defined, and placed in common, in files called startdaf.com and ground.com. Identical statements are placed in each subroutine by including these files as an INCLUDE statement. The three files params.inc, startdaf.com, and ground.com are listed in Appendix A along with all DAFLOW code.

The overall program structure of the combined DAFLOW/MODFLOW program is shown in figure 5. The left part of the figure represents the MODFLOW program. As shown in figure 5, calls to four subroutines were added to combine DAFLOW with MODFLOW.

A call to the DAF1AL subroutine is placed in the Allocate Procedure of MODFLOW. This subroutine first calls the subroutine STARTDAF to read the flow.in input file for DAFLOW. DAF1AL then reads the information in a second input file to determine the bed elevation, bed thickness and hydraulic conductivity of each subreach of the SW model. It also reads the layer, row, and column of the MODFLOW cell that is hydraulically connected to the subreach. If a subreach in the SW model does not interact with the GW system, zero's are entered as the layer, column, and row of the GW model. This second input file also contains the flags that control the printout for MODFLOW, debug output for the DAFLOW model, and differencing scheme used by MODFLOW. The values of these flags are also read by the subroutine. Variables that are needed for use with MODFLOW but not with the SW version of DAFLOW are declared, defined, and placed in common in a file called ground.com, which is included as needed by use of the INCLUDE statement.

A call to the DAF1AD subroutine is placed within the GW time-step loop (the Advance Procedure of MODFLOW, figure 5). This subroutine initializes arrays that will be used for numerous iterations of the SW model, determines the number of SW time steps per GW time step (NHRR), and reads, by use of GETBC, and stores the SW boundary conditions for NHRR SW time steps.

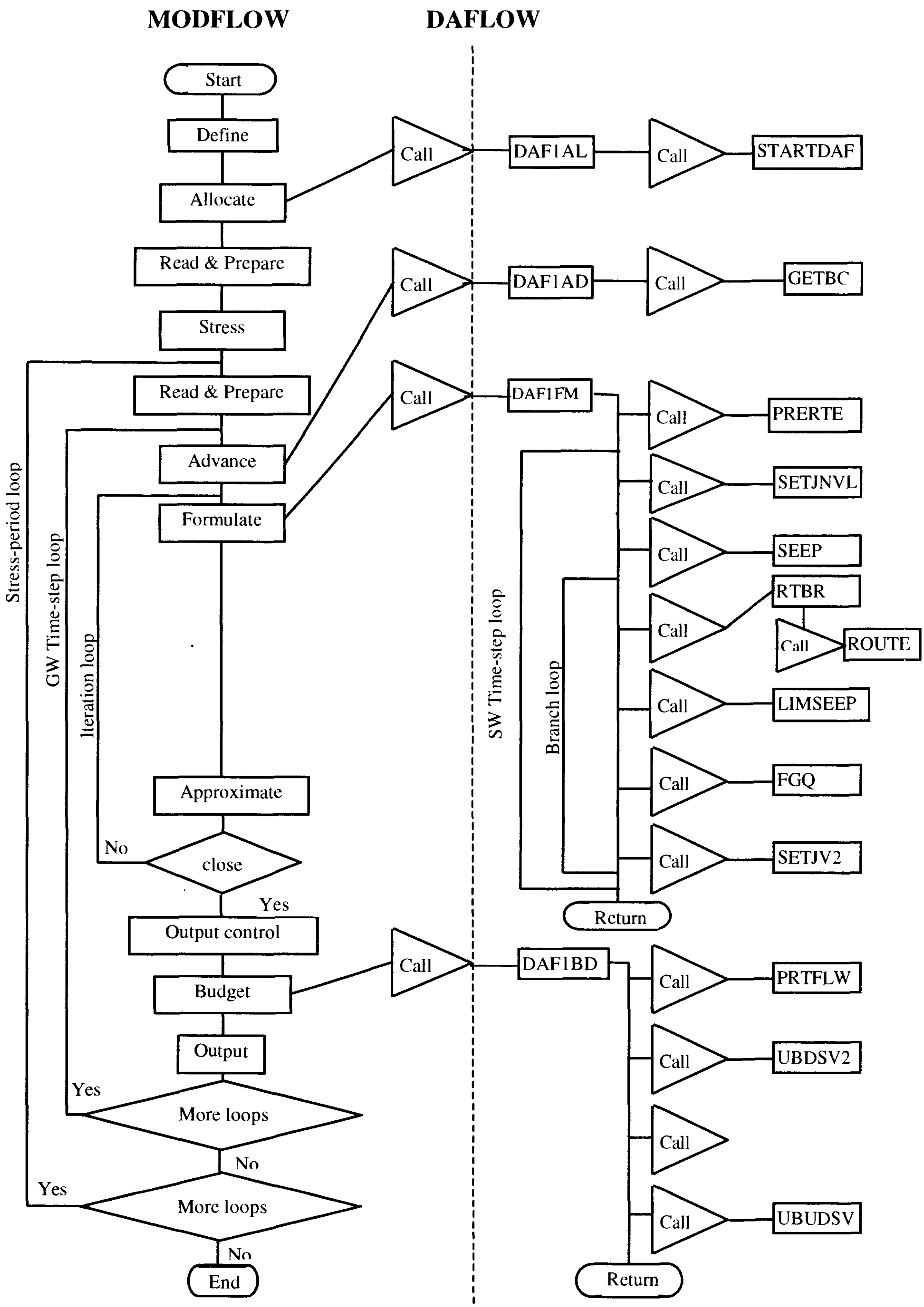

Figure 5. Overall program structure of the Diffusion Analogy Flow model linked to the Modular Finite-Difference Ground-Water Flow model.

The actual surface-water routing is accomplished in the subroutine DAF1FM that is called from within the GW iteration loop (the Formulate Procedure of MODFLOW, figure 5). This subroutine computes the exchange of water between the SW subreaches and the MODFLOW cells and routes the SW flow for NHRR time steps. It accomplishes this by calling subroutines of the DAFLOW model as well as two additional subroutines, SEEP and LIMSEEP.

The subroutine SEEP computes the potential exchange of water (assuming a sufficient supply of water exists in the channel) between each subreach of the DAFLOW and the corresponding aquifer cell. The hydraulic depth is computed as the cross-sectional area divided by the top width. The head in the aquifer at a time centered on the SW time step is then determined if central differencing is being used. If the aquifer head is above the elevation of the streambed layer, then the aquifer is assumed to be in hydraulic connection with the stream and the leakage is computed by use of equation 16. If the aquifer head is below this point, it is assumed that the aquifer does not have hydraulic connection with the stream and the driving head on equation 16 is changed to the negative of the sum of the depth and the bed thickness. Leakage is assumed to be negative, in DAFLOW, when the flow is from the stream to the aquifer. Negative leakage rates are considered to be potential values because the actual leakage may be limited by the amount of water available in the stream.

Leakage computed in subroutine SEEP are combined with any tributary flow occurring at the node and treated as a single tributary exchange in DAFLOW.

If flow extractions exceed the quantity of water available in the stream, the subroutine ROUTE reduces the flow extraction to what is available.

The subroutine LIMSEEP detects any change in flow extraction and apportions the limitation between surface-water extractions and leakage to the aquifer. The available water is first given to leakage to the aquifer and any excess is provided for SW extraction. The subroutine LIMSEEP also accumulates the total exchange between the stream and aquifer for all SW time steps within a GW time step.

At the end of the SW time loop, the subroutine DAF1FM fills the leakage arrays for use in MODFLOW, based on the accumulated exchange during all SW time steps.

Finally, a call to the DAF1BD subroutine is placed within the GW Budget Procedure of MODFLOW. This subroutine writes selected results for the SW flow computations for each time step by calling PRTFLW. It also calculates various budget terms for MODFLOW by calling the subroutines UBDSV2, UBDSVA, and UBUDSV. The Fortran code for all subroutines shown in figure 5 is listed in Appendix A.

IMPLEMENTATION IN THE MODULAR FINITE-DIFFERENCE GROUND-WATER FLOW MODEL

Input files

Two input files are necessary to run DAFLOW with MODFLOW. One file is identical to the input file needed to run DAFLOW alone. It defines the physical system to be modeled, specifies model options used for the simulation, and contains the boundary conditions as a function of time. In DAFLOW without MODFLOW, this file must be named flow.in, and throughout this report, it will be referred to as the flow.in file. But in the coupled version of DAFLOW and

MODFLOW, this file can have any name. The name of the flow.in file is specified in the MODFLOW name file. The MODFLOW name file specifies all of the files used in a MODFLOW simulation. One line is used for each file, and this line consists of the file type, file unit, and file name. The file type for the flow.in file must be DAF. For example, the following line indicates that the flow.in file will be named test.inf:

DAF 42 test.inf .

The information contained in flow.in is divided into three data groups: (1) general information, (2) branch information, and (3) boundary conditions.

Table 1 is a summary description of the input data records as required in the file flow.in.

Table 1.--Input format for the Diffusion Analogy Flow Model

Data Group 1 - General information				
Record	Field	Variable	Format	Description
	1	TITLE	A80	Title of simulation
2	1	NBRCH	20X,I10	Number of branches
3	1	NJNCT	20X,I10	Number of interior junctions
4	1	NHR	20X,I10	Number of time steps to be modeled
5	1	JTS	20X,I10	Number of time steps between midnight and the start of the simulation
6	1	JGO	20X,I10	Number of time steps between printouts in FLOW.OUT
7	1	IENG	20X,I10	Input units [0 = metric (length unit is meters except for river miles), 1 = English (length unit is feet except river miles)]
8	1	DT	20X,F10.3	Time-step size in hours
9	1	QP	20X,F10.0	Maximum discharge of interest ("peak discharge"), discharge below QP/100000.0 will be considered to be zero

Table 1.--Input format for the Diffusion Analogy Flow Model--continued

Data Group 2 - Branch information
(one set required for each branch)
(Record 3 is repeated for each node in the branch)

Record	Field	Variable	Format	Description
1	1	NXSEC(N)	13X,I3	Number of nodes (cross sections) in branch N
1	2	PF (N)	16X,F5.2	Fraction of flow at upstream junction to enter branch N
1	3	JNCU (N)	16X,I3	Junction number at upstream end of branch N
1	4	JNCD (N)	8X,I3	Junction number at downstream end of branch N
2	1	---	A	Header card for information only
3	1	I	I3	Node of data in record
3	2	X (N,I)	G11.4	Distance of node I of branch N from reference point in miles
3	3	IOUT (N,I)	I2	Output flag (equal 1 if output in BLTM.OUT is desired for this node, 0 otherwise)
3	4	F (N,I)	G11.4	Initial flow in subreach I (between node I and I+1)
3	5	A1 (N,I)	G10.3	Constant A1 in equation 3 for subreach I
3	6	A2 (N,I)	G10.3	Constant A2 in equation 3 for subreach I
3	7	A0 (N,I)	G10.3	Constant A0 in equation 3 for subreach I
3	8	SL (N,I)	G10.3	Bed slope of subreach, in ft/ft or m/m
3	9	W1 (N,I)	F7.1	Constant W1 in equation 4 for subreach I
3	10	W2 (N,I)	F7.6	Constant W2 in equation 4 for subreach I

Data Group 3 – Boundary condition
(one set for each time step)

Record	Field	Variable	Format	Description
1	1	NBC	18X,I3	Number of new boundary conditions to be input for this time step
2	1	N	10X,I3	Branch number for new boundary condition
2	2	I	5X,I3	Node number for new boundary condition
2	3	TRB(I,N)	3X,G14.5	New boundary flow for branch N, node I

The first data group consists of nine records that define parameters to control the simulation. The title is specified as any combination of letters, symbols, or numbers of up to 80 characters in length. It will be printed in the output file for identification purposes but otherwise is not used. The remaining lines of the general information are read as formatted input so it is important that the numbers be placed in columns 21 to 30. The number of branches is self evident and only the number of interior junctions, not total junctions, is input as the third record. An interior junction is one that connects two or more branches. The number of time steps in the simulation is calculated as the duration of the simulation divided by the SW time-step size, expressed in hours. The time reference for the simulation is midnight of the first day of the simulation. This is specified to the model as the number of time steps from midnight to the start of the simulation. For example, if the simulation is to begin at 06:00 hours and the time-step size is 0.5 hours, the value specified for JTS is 6 divided by 0.5, which equals 12 time steps. The printout frequency is specified in terms of the number of time steps between printouts. For example, if tabular flow information is desired every 3 hours and the time-step size is 0.5 hours, the value of JGO is specified as 3 divided by 0.5, which equals 6 time steps. The length units are specified as either 1 = English (ft) or 0 = metric (meter), except that the distance to node points (specified in data group 2) is input as either miles or kilometers. The time-step size is input in hours. DAFLOW uses an iterative solution scheme, such that its solutions must converge to a given tolerance. DAFLOW assumes that discharges (cubic feet or meter per second), differences in discharges, and water volumes divided by the time-step size, which are less than a tolerance, to be insignificant (nearly zero). The model calculates the tolerance from a given "peak" discharge divided by 100,000. This peak discharge should be larger than the maximum discharge expected during the simulation. It follows that the accuracy of the model results can be no better than this tolerance value. If the tolerance value is set too small, the program may not converge because the tolerance is smaller than the round-off error of flows carried in computer memory.

Data group two consists of two types of records: (1) branch record, (2) node/subreach records. The branch record specifies the number of nodes (cross sections) in the branch, the fraction of flow at the upstream junction that enters the branch, and the upstream and downstream junction numbers. When more than one branch originates at a junction, the water that enters the junction is split between these outgoing branches. This is specified to the model as the fraction of flow to enter the branch. For example, if two branches receive equal amounts of flow from the junction, this value should be specified as 0.5 for each branch. If only one branch receives flow from a junction (the most common case), this value is specified as 1.0.

A header line follows the branch information to define the columns of data for the nodes or subreaches. The model ignores this line so it could be simply a blank line. The node records define the node number, location of the node in miles or kilometers, an output flag, for each node and the initial flow, hydraulic-geometry parameters and slope for each subreach. The hydraulic-geometry exponents are independent of the system of units, but the hydraulic-geometry coefficients are dependent upon the units used. The number of node-records input must equal the number specified on the branch record. Node records are input in sequence starting with the node 1, at the upstream end of the branch. The node location is specified as the distance to the cross section from a reference point at or above the upstream end of the branch. The initial discharge, slope, and all coefficients apply to the subreach extending from the node for which it is specified to the next node downstream. For example, the value of A1 input for node 1 applies to the subreach extending from node 1 to node 2. Because there is no subreach downstream of the last node, only the river mile and output flag needs to be specified for the last node. The model is based on the assumption that tributaries enter the stream just upstream of the node. The initial discharge for subreach I, therefore, should include the effect of the tributary flow at node I. The output flag (IOUT) specifies whether or not the flow information for the node is to be printed in the output file. The data at each node is read as a free-field format, so it is not necessary to keep the numbers in any particular column or even to line them up. It is necessary that at least one blank space separate each number and that a number be available for each variable. Exponential formats (see slope) are acceptable. The formats shown in Table 1 are used if the file is created interactively using the program BDAFLOW (Jobson, 1989).

Boundary conditions must represent the average flow during the time step. For example, the first boundary condition should represent the average flow between time 0 and the end of the first time step. For the first time step, all boundary conditions should be entered because DAFLOW assumes all unspecified boundary conditions to be zero. After the first time step, however, DAFLOW assumes all boundary conditions remain constant unless specifically changed. The third data group is used to input boundary conditions and consists of two types of records. The first record for each time step specifies the number of boundary conditions that have changed for this time step (NBC). A line for each boundary condition that has changed must follow. For example, if NBC=0, no records are required but if NBC = 5, five records must follow. The second type of record specifies the branch number, node number, and flow for the changed boundary condition. Data group 3 must be input for each time step of the simulation. The first record is always required, whereas the second record is only required if one or more boundary conditions are changed.

An example input file is shown in figure 6 for the network shown in figure 2.

The input file shown in figure 6 has a header line identifying the data that is to follow. As indicated in the next eight lines; the model has three branches and one internal junction, it will run 5 time steps, the model starts at midnight (starts 0 time steps after midnight), output will be printed every time step, English units will be used (IENG = 1), the time-step size is 1.0 hour, and flows less than 1.0 ft^3/s (100,000/100,000) will be considered to be insignificant. Numbers for these variables must be placed within the columns 21 through 30 and the last two should contain decimal points.

```
   Example input "flow.in" for example shown in figure 2
 2 No. of Branches            3 *
 3 No. of Internal            1 * Junctions
 4 No. Time Steps             5 * Modeled
 5 Model Starts               0 time steps after midnight.
 6 Output Given Every         1 Time Steps in "flow.out"
 7 0=Metric,1=Englis          1 *
 8 Time Step Size         1.000 Hours.
 9 Peak Discharge       100000. *
Branch   1 has  9 xsects & routes 1.00 of flow at JNCT  2 To JNCT  1
Grd  Mi/Km  IOUT  Disch       A1         A2        AO       Slope       W1     W2
 1 0.0000     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 2 0.7000     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 3  1.500     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 4  1.600     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 5  2.400     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 6  2.500     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 7  3.000     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 8  3.150     0  5000.      7.00      0.660     0.000    0.800E-03   50.0 0.260
 9  3.160     0
Branch   2 has  8 xsects & routes 1.00 of flow at JNCT  3 To JNCT  1
Grd R Mile  IOUT  Disch       A1         A2        AO       Slope       W1     W2
 1  3.000     0  50.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 2  3.400     0  50.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 3  4.000     0  50.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 4  4.600     1  25.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 5  5.500     0  25.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 6  6.000     0  25.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 7  6.490     0  25.00      7.00      0.660     0.000    0.150E-02   50.0 0.260
 8  6.500     0
Branch   3 has  8 xsects & routes 1.00 of flow at JNCT  1 To JNCT  4
Grd R Mile  IOUT  Disch       A1         A2        AO       Slope       W1     W2
 1  6.500     0  5025.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 2  7.000     0  5025.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 3  7.800     0  5025.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 4  8.300     0  5050.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 5  8.900     0  5050.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 6  9.500     0  5050.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 7  10.40     1  5050.      7.00      0.660     0.000    0.700E-03   50.0 0.260
 8  11.00     0
for Time    1 NBC=   4 *
 Branch     1 Node   1 Q=    5000.0      *
 Branch     2 Node   1 Q=    50.000      *
 Branch     2 Node   4 Q=   -25.000      *
 Branch     3 Node   4 Q=    25.000      *
for Time    2 NBC=   1 *
 Branch     1 Node   1 Q=    50000.      *
for Time    3 NBC=   0 *
for Time    4 NBC=   2 *
 Branch     1 Node   1 Q=    5000.0      *
 Branch     2 Node   4 Q=   0.00000      *
for Time    5 NBC=   0 *
```

Figure 6. Input file, flow.in, to run the example shown in figure 2.

The next group contains the branch and node information. The first line of this group indicates that branch 1 contains 9 nodes and routes 100 percent of the flow at junction 2 to junction 1. The numbers on this line need to be in the columns indicated in Table 1. The next line is ignored, but it is recommended to place column headings here. Following the column header is one line of data for each of the 9 nodes in branch 1. The first line indicates that node 1 is located at mile 0.0, that output is not to be printed (IOUT=0), the initial discharge in the subreach (from node 1 to node 2) is 5,000 ft^3/s, and the slope and hydraulic-geometry parameters for the subreach extending from node 1 to 2 are as indicated. There is no initial discharge or hydraulic-geometry information for node 9, because these values represent subreach average values, and the branch has only 8 subreaches.

Notice that node 9 is only 0.01 mile below node 8, thereby minimizing the reach length for which seepage is not allowed. Branch 1 begins at the aquifer boundary, whereas branch 2 begins upstream of the aquifer boundary and branch 3 extends below the aquifer boundary. Steady-state conditions, with no leakage to the aquifer, are assumed to have occurred for some time before the start of the model so the initial discharge at node 4 of branches 2 and 3 reflects only the tributary exchanges. The flow at node 1 in branch 3 also represents the sum of the flows at the downstream ends of branches 1 and 2. Although assumed to be constant here, the slopes, initial discharges, and hydraulic-geometry parameters generally will be different for each subreach and branch. Notice a header line is placed above the node information for each branch.

The boundary conditions follow the branch information. In this example, only 5 time steps were assumed. All external boundary conditions (flows at exterior upstream junctions, and all interior nodes) are assumed to be zero until given a value in the boundary conditions section. So four boundary conditions are needed for the first time step to define the flow at node 1 of branches 1 and 2, and at node 4 of branches 2 and 3. All boundary conditions are read as formatted data so it is important for the numbers to be in the correct columns. All boundary conditions are assumed to remain constant until changed by new input. In this case the flow at node 1, branch 1 is assumed to change from 5,000 to 50,000 at the beginning of the second time step and to change back to 5,000 at the beginning of the fourth time step. The flows at branch 2, node 1 and branch 3, node 4 are assumed to remain constant for the entire run so only the entry at the first time step is needed. The flow at node 4, branch 2 changes from -25 to 0 at time step 4.

When DAFLOW is linked to MODFLOW, input information is required in addition to what is contained in the flow.in file. This information is contained in a file that has file type DAFG in the MODFLOW name file. The first 80 characters of the first three lines of the DAFG file are simply read in as text and printed in the MODFLOW output file for information purposes. It is recommended that the first line contain identifying information, and the second two lines contain column headings to identify the eight data fields that will follow. Examples of the column headings are shown in figure 7, which contains input data for the example shown in figure 2. Following the three header lines, eight fields of bed property and linkage information are needed for each interior node of each SW branch. The data fields include; (1) branch number, (2) node number, (3) bed elevation of subreach upstream of the node, (4) average bed thickness of the subreach, (5) bed hydraulic conductivity of subreach, and (6), (7), (8) layer, row, and column number respectively, of the cell in MODFLOW that is in hydraulic connection with the subreach. These columns of information are read using free format so it is not important that the numbers be in any particular column or that the numbers line up. It is necessary, however that there be at least one blank space between each data field and that a number be available for each field. There must be one row of data for each interior node of each branch. For example, branch 1 contains nine nodes so seven entries are needed, for nodes 2 through 8. Node 2 defines the ground-water interaction for subreach 1 and GW interaction is not allowed for the last subreach. If a SW subreach is not connected to a GW cell enter zero for the layer, row, and column numbers.

Following the bed properties and linkage information is another line of text information that can be used to identify the three parameters that are input as the last line of the file. If the first parameter (IDAFCB) is an integer less than zero, the cell-by-cell flows will be printed to the output file, if it is an integer greater than zero they will be saved to a file. If the second parameter (IDBG) is set to 1, extra debugging information will be written to the output file, otherwise it will not. This parameter should normally be set to zero (not 1) because the debug information generates a large volume of output. The third parameter (IDAFBK) specifies whether central or backwards differencing will be used for ground-water heads in MODFLOW. Enter a zero if central differencing is to be used. Any integer, other than zero, causes backwards differencing to occur. These integers can be placed in any column as long as they are separated by at least one blank space.

Figure 7 contains an example DAFG file that could be used to run the example problem shown in figure 2. The streambed elevations for this example are computed on the basis of the assumption that the elevation of node 1, in branch 1 is 100 ft, and the bed slopes are as shown in figure 6. For example, figure 2 shows that the subreach upstream of node 2 in branch 1 should be in communication with row 1, column 1 of the aquifer, and it is assumed that only one layer is involved. The elevation of the bed for this subreach is estimated as the elevation of the midpoint of the subreach. So it should be the elevation of node 1 (100) minus the slope (0.0008 = 4.224 ft/mile) times one-half the subreach length (0.7 - 0.0 mile), or 98.522 ft.

Also, notice that there is no connection for node 2, branch 2 (subreach 1) with the aquifer so zeros are entered for the layer, row, and column of the interaction. Leakage from all three branches interact with cell 3,3. The thickness of the streambed layer is assumed to be 1.0 ft, and the hydraulic conductivity of the bed layer is assumed to be 0.00120 ft/s for all subreaches.

Because IDAFCB is greater than zero, the cell-by-cell flows will be saved to a separate file rather than printed to the output file. The code IDBG is not equal to 1 so the extensive debug printout will not be listed. Because IDAFBK is not equal to zero, backwards differencing will be used in MODFLOW.

```
 Example "DAFG" input for example shown in figure 2
                    Bed         Bed          Bed       GW node of exchange
  Brch   Node      Elev      Thickness   Conductivity Layer    Row Column
   1      2       98.522       1.0         1.20E-01      1       1      1
   1      3       95.354       1.0         1.20E-01      1       1      2
   1      4       93.453       1.0         1.20E-01      1       2      2
   1      5       91.522       1.0         1.20E-01      1       2      3
   1      6       89.651       1.0         1.20E-01      1       2      2
   1      7       88.384       1.0         1.20E-01      1       3      2
   1      8       86.652       1.0         1.20E-01      1       3      3
   2      2      112.788       1.0         1.20E-01      0       0      0
   2      3      108.828       1.0         1.20E-01      1       1      5
   2      4      104.076       1.0         1.20E-01      1       1      4
   2      5       98.136       1.0         1.20E-01      1       2      4
   2      6       92.592       1.0         1.20E-01      1       3      4
   2      7       88.672       1.0         1.20E-01      1       3      3
   3      2       85.728       1.0         1.20E-01      1       3      3
   3      3       83.326       1.0         1.20E-01      1       3      4
   3      4       80.923       1.0         1.20E-01      1       4      4
   3      5       78.891       1.0         1.20E-01      1       4      4
   3      6       76.673       1.0         1.20E-01      1       5      4
   3      7       73.901       1.0         1.20E-01      1       5      5
IDAFCB IDBG IDAFBK
   1      0     1
```

Figure 7. Input file, DAFG, to run the example shown in figure 2.

Output files

The output of the DAFLOW model is written to two files: a bltm.flw, file and the standard output file of MODFLOW. The information in the MODFLOW output file is designed to provide tabular information summarizing the simulation and, the bltm.flw file provides flow field information for plotting or other post-processing programs. The bltm.flw file is specified in the MODFLOW name file using file type DAFF.

The DAFLOW model echoes the input information from the flow.in and DAFG files into the MODFLOW output file as well as presenting a summary of the simulation results at the selected nodes and time frequency. This summary consists of the time, branch number, node number, and the average flow during the time step at the node. If the debug option is selected (IDBG=1), a detailed summary of the results is written to the MODFLOW output file. The debug option is useful if a problem is encountered with the model, and it is desired to investigate further where and (or) why the problem is occurring. Because it generates a large volume of output, the debug option should not be used unless specific problems are suspected.

The second output file, the bltm.flw file, contains flow information at every node for each time step of the simulation. This information includes the channel flow rate, cross-sectional area, top width, and tributary flow. The node and tributary flow represent the average flow during the SW time step, and the area and top width represent the instantaneous values at the end of the time step, but averaged over the subreach. The cross-sectional area for the subreach is computed as the volume of water in the subreach divided by the length of the subreach. The width is computed on the basis of the area and the hydraulic-geometry relations used by DAFLOW. The information in the bltm.flw file is designed to be used to provide hydraulic information to a transport model, like the BLTM model (Jobson and Schoellhamer, 1987), or to be used with post-processor programs.

EXAMPLE APPLICATIONS

Example 1, Streamflow resulting from variable recharge, comparison with an analytical solution

The first example will compare simulated results with an analytical solution developed by Oakes and Wilkinson (1972) using the grid and aquifer properties assumed by Prudic (1989). The example consists of an idealized unconfined aquifer with a stream flowing north to south as shown in figure 8. The width of the aquifer perpendicular to the stream is 4,000 ft on each side, while the length parallel to the stream is 13,000 ft. The transmissivity, and storage coefficient of the aquifer are 0.037 ft^2/s and 0.20 respectively. The streambed thickness is assumed to be 1 foot. The product of the streambed hydraulic conductivity and the stream width is assumed to be equal to 0.037 ft^2/s. Other assumptions used in both the analytical solution and the model simulation include:

1. The lateral boundaries of the aquifer are impermeable (no flow is allowed).
2. The layer beneath the aquifer are impermeable.
3. The stream penetrates the entire depth of the aquifer and has vertical banks.
4. The transmissivity and storage coefficient are constant throughout the aquifer and remain constant in time.
5. The aquifer is unconfined and Darcy's Law is valid.
6. The flow of ground water is horizontal.
7. The water level in the stream is constant along its length and with time.
8. The infiltration of recharge to the aquifer is instantaneous (no delay between the time precipitation infiltrates the surface until it reaches the water table).
9. The discharge from the aquifer is only to the stream.

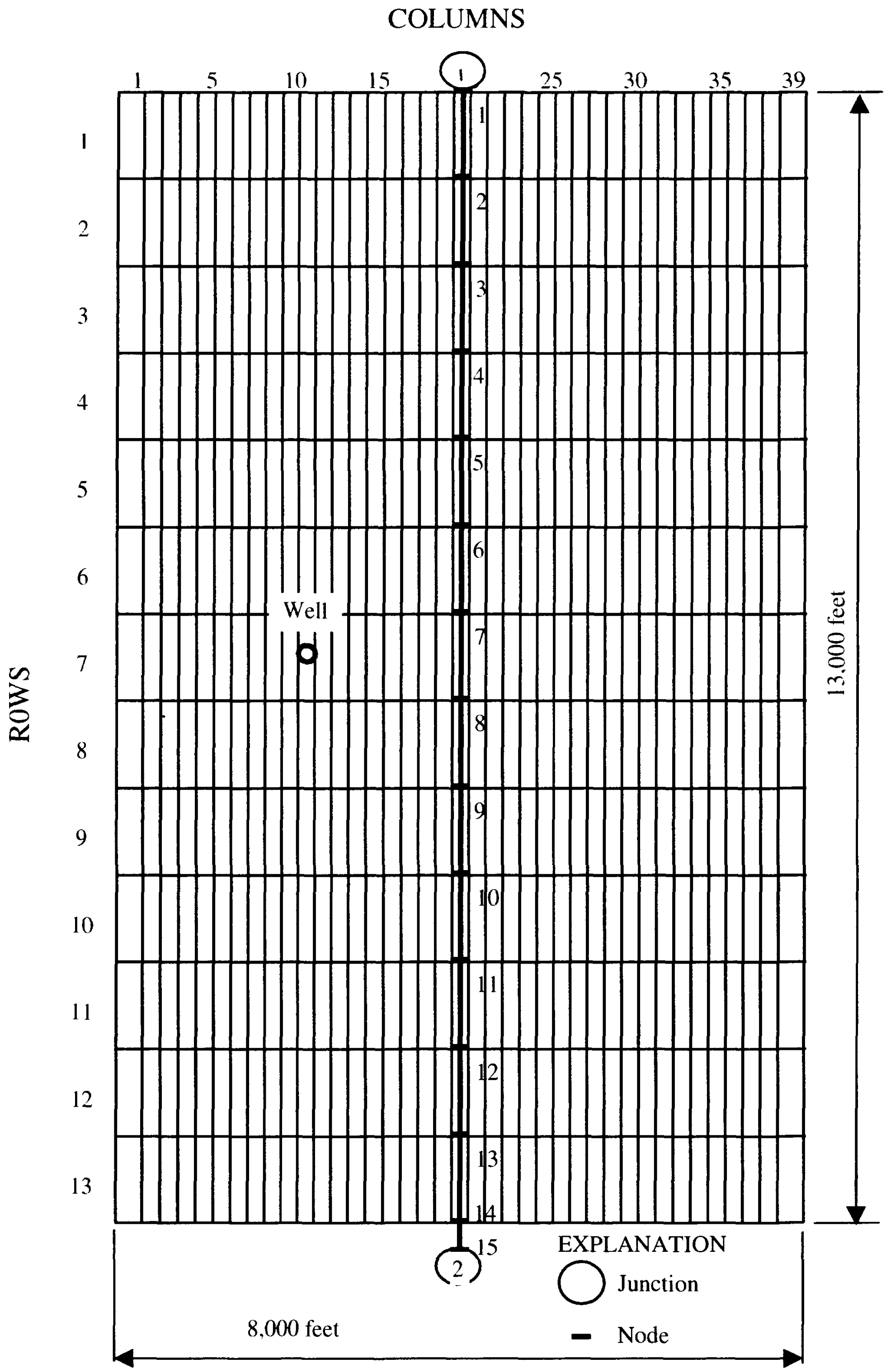

Figure 8. Aquifer grid of example 1 with surface-water model grid superimposed.

The analytical solution provides the stream discharge and the ground-water elevations as a function of time for a system in equilibrium with the periodic recharge function shown on figure 9. The total "annual" (360 days) recharge is 1.5 ft and is applied evenly over the aquifer. The daily recharge rate has a sinusoidal distribution for the first 180 days and is zero for the next 180 days.

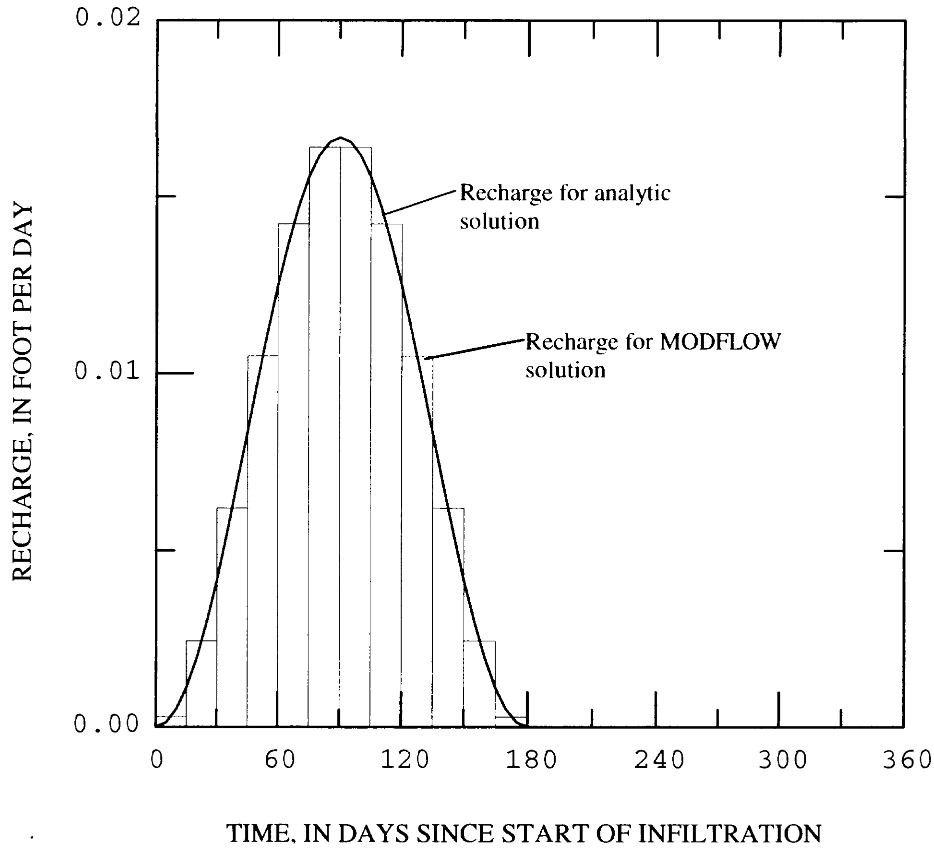

Figure 9. Distribution of recharge used for the analytical and numerical simulation of example 1.

As illustrated on figure 8, the aquifer was represented in the MODFLOW model by a grid with 39 columns and 13 rows. Each cell was 1,000 ft long and 200 ft wide, except for cells in columns 1 and 39, which were 300 ft wide. The stream ran vertically through the center of column 20. The initial heads in the aquifer were assumed to be the heads from the analytical solution for time zero at the center of each cell. The annual cycle was represented in MODFLOW by 24 stress periods, each 15-days long. Each stress period was divided into two, 7.5 day time steps. Equilibrium conditions were assumed to have been reached after 5 annual cycles.

Assumption 7 implies that the stream has a slope of zero and a constant depth under varying flow conditions. Such assumptions are physically impossible and can not be duplicated exactly by DAFLOW. The DAFLOW solution is based on the assumption that the stream had a small slope, a constant depth, and nearly constant width and area. This was accomplished by assuming the area and width of the stream are described by the hydraulic-geometry parameters shown in figure 10. For these assumed hydraulic-geometry parameters, the cross-sectional area and width, respectively, vary from 398.4 ft^2 and 99.60 ft at a discharge of 10 ft^3/s to 401.2 ft^2 and 100.3 ft at a discharge of 20 ft^3/s. Dividing each area by the top width, yields a constant hydraulic depth of 4.00 ft. The slope, which is only used by DAFLOW to compute the diffusion of the flow waves along the channel, was set at a small value of 0.0001. The bed elevation of each subreach in the flow model, which is not used by the hydraulic calculations in DAFLOW, was set at a constant value of 46.00 ft. So as far as MODFLOW is concerned, the water surface elevation is constant at 50.000 ft for all times and locations. The contact area between the stream and the aquifer (width) varies by about 1 percent as the discharge doubles from 10 to 20 ft^3/s. For the high hydraulic conductance chosen for this example, the results are insensitive to variations in channel width.

The DAFLOW input file, flow.in, for the example is shown in figure 10. As shown in figure 8, branch 1 begins at junction 1, which is located at the upstream boundary of the aquifer in the middle of column 20. Branch 1 contains 15 nodes, with 14 located at the points where the stream crosses the boundary between each row plus a node at junction 2, which is downstream of the aquifer. DAFLOW is set to run for 288 time steps, each 180 hours (7.5 days) long for a total time of six, 360-day years. The peak discharge is set at 100 ft^3/s, which indicates that DAFLOW ignores discharges of less than 0.001 ft^3/s. The first 14 nodes are spaced 0.189 miles (1,000 ft), and output is to be listed for nodes 7 and 15. The initial base-flow discharge is 10 ft^3/s. The only boundary condition is for the upstream boundary at time step 1, which sets the inflow at 10 ft^3/s. The inflow remains constant at 10 ft^3/s for the duration of the simulation. The actual file would have 288 entries for boundary conditions, all except the first, indicating that zero boundary conditions are changed (NBC = 0).

```
  Prudic example 1, page 12
No. of Branches                1 *
Internal Junctions             0 *
Time Steps Modeled           288 *
Model Starts                   0 time steps after midnight.
Output Given Every             1 Time Steps in "flow.out"
0=Metric,1=English             1 *
Time Step Size             180.0 Hours.
Peak Discharge              100. *
Branch   1 has 15 xsects & routes 1.00 of flow at JNCT  1 To JNCT  2
Grd   Mi/Km   IOUT Disch       A1       A2      AO      Slope          W1     W2
  1 0.0000    0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  2 0.1890    0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  3 0.3790    0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  4 0.5680    0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  5 0.7580    0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  6 0.9470    0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  7   1.136   1   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  8   1.326   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
  9   1.515   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
 10   1.705   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
 11   1.894   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
 12   2.083   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
 13   2.273   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
 14   2.462   0   10.00  389.32  0.010  0.00   0.100E-03  97.33 0.010
 15   2.5     1
for Time     1 NBC=  1 *
 Branch      1 Node  1 Q=     10.000      *
for Time     2 NBC=  0 *
         .
         .
         .
for Time   288 NBC=  0 *
```

Figure 10. Input file, flow.in, for example 1.

Information not needed by DAFLOW for a purely surface-water model is contained in the DAFG file. A listing of this file is shown in figure 11. Notice that data are required for nodes 2 through 14, but not for nodes 1 or 15. The columns are not necessarily aligned. The actual format of these data is not important as long as values are included in each data field and that the data are separated by at least one space. The hydraulic conductivity times the stream width was assumed to be 0.037 ft^2/s in the analytical model. The stream width is 100.0 ft so the hydraulic conductivity is input as 0.00037 ft/s. Only one layer is used in the ground-water model, and all stream nodes are in column 20. Node 2 is associated with row 1, and each succeeding node is associated with the next row. IDAFCB is zero, which means that cell-by-cell flows for each stream node will not be saved to a file or written to the listing file. If IDAFCB is less than then zero, the flows will be printed to the output file. If IDAFCB is an integer greater than zero, the flows will be saved to a file. Because IDBG is equal to zero, the DAFLOW debug printouts will not be written. Backwards differencing will be used in MODFLOW because IDAFBK is not equal to zero.

```
This is input for DAFLOW/MODFLOW
                      Bed        Bed                            GW node of exchange
  Brch   Node        Elev       Thickness   Conductivity Layer     Row Column
   1      2          46.00      1.00        3.70E-04       1        1      20
   1      3          46.00      1.0         3.70E-04       1        2      20
   1      4          46.00      1.0         3.70E-04       1        3      20
   1      5          46.00      1.0         3.70E-04       1        4      20
   1      6          46.00      1.0         3.70E-04       1        5      20
   1      7          46.00      1.0         3.70E-04       1        6      20
   1      8          46.00      1.0         3.70E-04       1        7      20
   1      9          46.00      1.0         3.70E-04       1        8      20
   1     10          46.00      1.0         3.70E-04       1        9      20
   1     11          46.00      1.0         3.70E-04       1       10      20
   1     12          46.00      1.0         3.70E-04       1       11      20
   1     13          46.00      1.0         3.70E-04       1       12      20
   1     14          46.00      1.0         3.70E-04       1       13      20
  IDAFCB IDBG IDAFBK
     0     0     1
```

Figure 11. Input file, DAFG, for example 1.

All additional input files for MODFLOW are shown in Appendix B.

Selected output of the MODFLOW/DAFLOW model is given in figure 12 for stress period 134 that is near the end of the recharge period of the final year of simulation. The elevations are given for only one row because all rows have equal heads (the water surface has zero slope parallel to the stream). This confirmed the one-dimensional nature of the MODFLOW solution. For a given node and day of the year, the streamflows were the same for any year (within 0.01 ft^3/s) after the first year of simulation. Variability in flows between the first and the last year were generally within 0.04 ft^3/s. One note of caution may be in order. The surface-water flow results represent the average during the SW time step and are, therefore, shown to occur at the midpoint of the time step (Day 2007, Hour 6.0). The heads in the aquifer, on the other hand, are those occurring at the end of the time step. For the example shown, this is for stress period 134, which is at the end of day 2010 (day 210 of year 6). The difference in these times is 3.75 days, one half of the 7.5 day time step of the SW model.

```
STRESS PERIOD NO. 134, LENGTH =   1296000.
                          ---------------------------------------------
                                NUMBER OF TIME STEPS =       2
                                MULTIPLIER FOR DELT =      1.000
                                INITIAL TIME STEP SIZE =   648000.0
                                RECHARGE =  0.0000000
No of DAFLOW steps per MODFLOW step = 1
    4 ITERATIONS FOR TIME STEP  1 IN STRESS PERIOD 134

MAXIMUM HEAD CHANGE FOR EACH ITERATION:
   HEAD CHANGE   HEAD CHANGE   HEAD CHANGE   HEAD CHANGE   HEAD CHANGE
 LAYER,ROW,COL LAYER,ROW,COL LAYER,ROW,COL LAYER,ROW,COL LAYER,ROW,COL
 ----------------------------------------------------------------------
    -0.1856       -0.2088E-01   -0.8517E-03   -0.1040E-04
  (  1, 13, 10) (  1,  2,  9) (  1,  7,  8) (  1, 13,  1)

NO OUTPUT CONTROL FOR STRESS PERIOD 134   TIME STEP  1
 Day 1999  Hour 18.00 Branch  Node  Discharge
                           1     7     12.36
                           1    15     15.11
 No of DAFLOW steps per MODFLOW step = 1
     4 ITERATIONS FOR TIME STEP   2 IN STRESS PERIOD 134

MAXIMUM HEAD CHANGE FOR EACH ITERATION:
   HEAD CHANGE   HEAD CHANGE   HEAD CHANGE   HEAD CHANGE   HEAD CHANGE
 LAYER,ROW,COL LAYER,ROW,COL LAYER,ROW,COL LAYER,ROW,COL LAYER,ROW,COL
 ----------------------------------------------------------------------
   -0.1803       -0.2042E-01   -0.8369E-03   -0.1040E-04
 (  1, 13,  9) (  1,  2,  8) (  1,  7,  7) (  1, 13,  1)

OUTPUT CONTROL FOR STRESS PERIOD 134   TIME STEP  2
    PRINT HEAD FOR ALL LAYERS
Day 2007  Hour  6.00 Branch  Node  Discharge
                          1     7     12.28
                          1    15     14.95

     HEAD IN LAYER  1 AT END OF TIME STEP  2 IN STRESS PERIOD 134
 -----------------------------------------------------------------------
   1      2      3      4      5      6      7      8      9     10
  11     12     13     14     15     16     17     18     19     20
  21     22     23     24     25     26     27     28     29     30
  31     32     33     34     35     36     37     38     39
 .......................................................................
61.805 61.694 61.546 61.338 61.069 60.739 60.346 59.889 59.368 58.784
58.136 57.425 56.655 55.827 54.947 54.021 53.055 52.058 51.039 50.010
51.039 52.058 53.055 54.021 54.947 55.827 56.655 57.425 58.136 58.784
59.368 59.889 60.346 60.739 61.069 61.338 61.546 61.694 61.805
```

Figure 12. Selected output of the Modular Finite-Difference Ground-Water Flow model results at stress period 134, for example 1.

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 2 IN STRESS PERIOD 134
-----------------------------------------------------------------------------

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

           IN:                                      IN:
           ---                                      ---
            STORAGE =   437817024.0000             STORAGE =          4.9503
      CONSTANT HEAD =          0.0000        CONSTANT HEAD =          0.0000
           RECHARGE =   935983168.0000            RECHARGE =          0.0000
             DAFLOW =          0.0000               DAFLOW =          0.0000
           TOTAL IN =  1373800190.0000            TOTAL IN =          4.9503

          OUT:                                     OUT:
          ----                                     ----
            STORAGE =   488860480.0000             STORAGE =          0.0000
      CONSTANT HEAD =          0.0000        CONSTANT HEAD =          0.0000
           RECHARGE =          0.0000             RECHARGE =          0.0000
             DAFLOW =   884837632.0000              DAFLOW =          4.9488
          TOTAL OUT =  1373698050.0000           TOTAL OUT =          4.9488

           IN - OUT =      102144.0000            IN - OUT =      1.4739E-03
PERCENT DISCREPANCY =            0.01    PERCENT DISCREPANCY =          0.03

         TIME SUMMARY AT END OF TIME STEP 2 IN STRESS PERIOD 134
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
   TIME STEP LENGTH 6.48000E+05  10800.     180.00      7.5000     2.05339E-02
 STRESS PERIOD TIME 1.29600E+06  21600.     360.00      15.000     4.10678E-02
         TOTAL TIME 1.73664E+08 2.89440E+06 48240.      2010.0      5.5031
```

Figure 12 (Continued). Selected output of the Modular Finite-Difference Ground-Water Flow model results at stress period 134, for example 1.

The simulated streamflow at node 14 as a function of time in comparison to the analytic values is shown in figure 13. The simulated flows average 0.007 ft^3/s higher than the analytic values, with an RMS error of 0.074 ft^3/s. The maximum positive error in the simulated flow of +0.169 ft^3/s occurred at day 60 and was 1.1 percent of the instantaneous flow. The maximum negative error of -0.090 ft^3/s occurred at day 150 and represented 0.5 percent of the instantaneous flow. Note that the computed flows have a scalloped appearance. Recharge was assumed constant during each 15 day stress period. The flow changes rapidly at the beginning of the stress period, but changes much more slowly near the end of the stress period.

An assumption in the analytical solution is that a change in seepage anywhere along the stream results in an instantaneous change in streamflow at all downstream points. DAFLOW, however, will simulate the lag time between when water enters at one point and travels downstream to another point. The time lag is equal to the distance between the nodes divided by the wave celerity. The wave celerity can be computed from equation 11 and varies from 2.5 ft/s at 10 ft^3/s to 5.0 ft/s at 20 ft^3/s. So the lag time for a change in inflow at node 2 to affect the flow at node 14 varies from about 0.7 to 1.4 hours. This lag is not significant in comparison to the time step of 180 hours used in DAFLOW. So it can be concluded that the two-dimensional system simulated by MODFLOW/DAFLOW behaves the same as the one-dimensional analytical counterpart at this time scale.

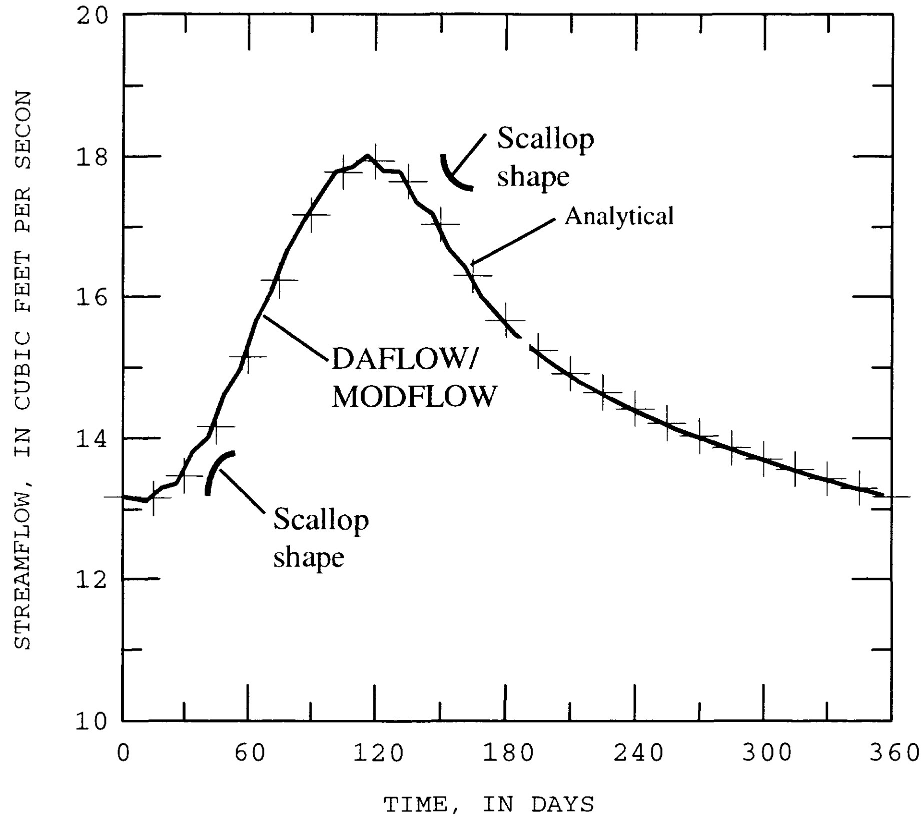

Figure 13. Simulated streamflow at node 14 and the analytical solution.

The simulated time variation of the head in a well that is assumed to be in row 7, column 10, with the variation computed by the analytical solution is shown in figure 14. The mean difference between the analytical and simulated results is 0.006 ft with a standard deviation of 0.026 ft. The maximum errors are +0.081 ft (analytical larger than simulated) on day 45, and –0.029 ft on day 360.

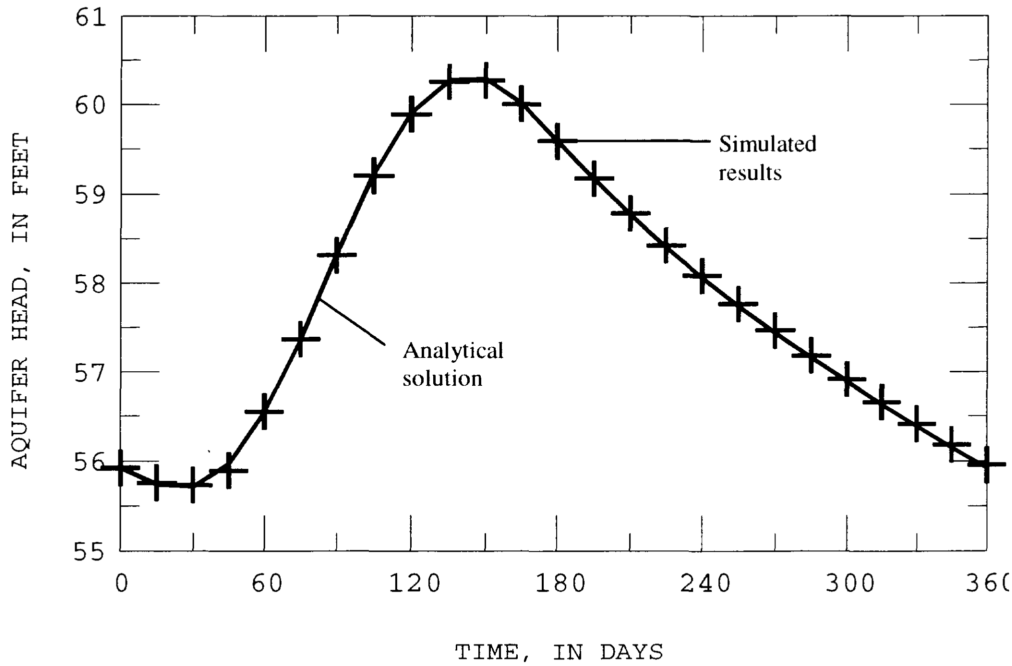

Figure 14. The simulated and analytical variation of water level in a well located in row 7, column 10 of figure 8.

Profiles of the aquifer head in row 7 on the right side of the stream on day 177, near the end of the recharge period are shown in figure 15. The initial profile, on day zero is also shown to give an indication of the approximate maximum variation of head in the aquifer. Profiles in all rows of the aquifer are identical because of the assumptions of the stream level being constant, uniform recharge, and no transport across the boundaries. All rows in the simulated results were identical to within at least 0.01 ft. This further confirms that the system is behaving as the one-dimensional analytical model. The mean error of the simulated points is 0.007 ft and the RMS error is 0.026 ft.

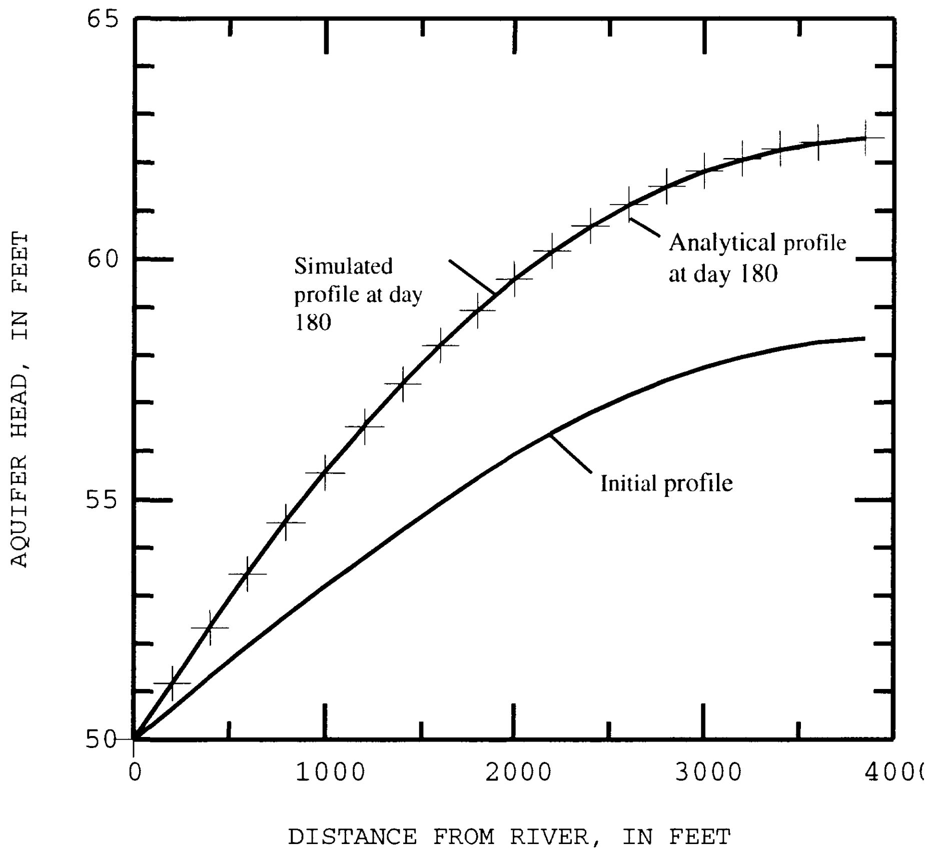

Figure 15. Aquifer-head profiles simulated by the Diffusion Analogy Flow model linked to the Modular Finite-Difference Ground-Water Flow model and the analytical solution.

The small differences in the assumed discharge distribution between the analytical solution and the simulation results, support the conclusion that the linked MODFLOW/DAFLOW simulation model duplicated the analytical solution.

Example 2, Bank storage due to flood stages, comparison with an analytical solution

The second example compares simulated leakage to an aquifer resulting from a flood wave with the analytical solution developed by Cooper and Rorabaugh (1963). The example uses the same model grid, stream, as well as streambed and aquifer characteristics as used in the first example (see figure 8). Assumptions used in both the analytical solution and the model simulation are also the same as those listed for example 1 except for assumptions 9 and 10. These are replaced with the following:

1. The recharge to the aquifer is only from the stream as the stream stage increases with time.
2. The discharge from the aquifer is also only to the stream as the stream stage decreases with time.

The analytical solution does not specify a discharge but assumes the stream stage varies during the first 30 days according to the equation:

$$\text{stage} = H_0 + H_1 \sin((\text{day}-7.5)2\pi/30),$$

in which H_0 and H_1 are constants. It assumes the stage is constant at H_0 - H_1 after that. The stream stage is the driving force for the leakage. Following Prudic (1989), it is assumed that the stage and stream depth are the same and that $H_0 = 10$ ft and $H_1 = 2$ ft. It is also assumed that the stream inflow varies from a minimum of 2,000 ft^3/s to a maximum of 4,000 ft^3/s. The DAFLOW model does not allow the width to remain precisely constant (W2 = 0) so the width is assumed to be 100.00 ft at 3,000 ft^3/s and to vary slightly (W2 = 0.01) from 99.59 ft at 2,000 ft^3/s to 100.28 ft at 4,000 ft^3/s. To match the assumed stages, the area must vary from 8 x 99.59 = 796.71 ft^2 to 12 x 100.28 = 1203.37 ft^2 as the flow varies from 2,000 to 4,000 ft^3/s. The hydraulic-geometry parameters that provide these areas can be computed from equation 11 as A1 = 8.655 and A2 = 0.595. Knowing the hydraulic-geometry parameters, the discharge for any depth can be computed as:

$$Q = \left(D \cdot W1 / A1\right)^{\frac{1}{A2 - A1}},$$

where Q = discharge, D = depth. The assumed inflow at node 1 for the numerical model is as shown in figure 16. DAFLOW was run using a one-day time step, so the inflows for any day are based on the depth occurring at the midpoint of the day. Because discharge is not linearly related to depth, the inflows are not distributed in a sinusoidal pattern. The inflow to the numerical model is represented by a series of histograms of width equal to one day, whereas the flow in the analytical model is a smooth curve.

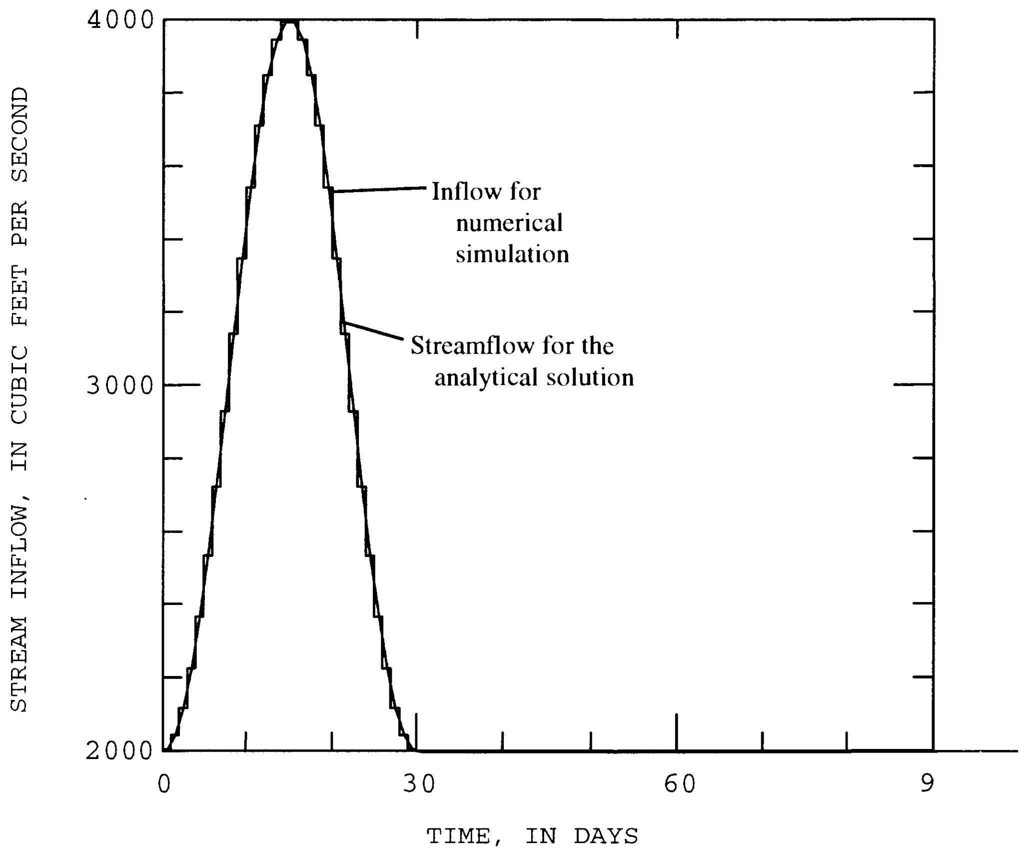

Figure 16. Distribution of streamflow for a 30-day flood event used in example 2.

The analytical model is one-dimensional so it solves only one row in the numerical model. For the results of the two models to be comparable the stream depth in all rows of the numerical model must be the same. To achieve this, the model was first run with constant hydraulic-geometry coefficients as shown for subreach 1 in figure 17, which is a listing of the input file, flow.in. The streamflow in the numerical model varies from node to node as leakage is withdrawn or added to the flow. After the model was run with constant hydraulic-geometry parameters, the peak flow in each subreach was determined, and the parameters were adjusted such that the water depth varied between 8 and 12 ft as the flow varied from 2,000 ft^3/s to the peak flow in the subreach. The final coefficients are shown in figure 17.

```
Prudic example 2, page 12
No. of Branches              1 *
Internal Junctions           0 *
Time Steps Modeled          90 *
Model Starts                 0 time steps after midnight.
Output Given Every           1 Time Steps in "flow.out"
0=Metric,1=English           1 *
Time Step Size           24.00 Hours.
Peak Discharge           4000. *
Branch  1 has 15 xsects & routes 1.00 of flow at JNCT  1 To JNCT  2
Grd  Mi/Km IOUT  Disch      A1        A2    AO     Slope          W1    W2
  1 0.0000    0 2000.0   8.655     0.595  0.00    0.100E-03   92.306 0.010
  2 0.1890    0 2000.0   8.655     0.595  0.00    0.100E-03   92.306 0.010
  3 0.3790    0 2000.0   8.656     0.595  0.00    0.100E-03   92.306 0.010
  4 0.5680    0 2000.0   8.656     0.595  0.00    0.100E-03   92.306 0.010
  5 0.7580    0 2000.0   8.656     0.595  0.00    0.100E-03   92.306 0.010
  6 0.9470    0 2000.0   8.586     0.596  0.00    0.100E-03   92.306 0.010
  7   1.136   1 2000.0   8.587     0.596  0.00    0.100E-03   92.306 0.010
  8   1.326   0 2000.0   8.587     0.596  0.00    0.100E-03   92.306 0.010
  9   1.515   0 2000.0   8.589     0.596  0.00    0.100E-03   92.306 0.010
 10   1.705   0 2000.0   8.589     0.596  0.00    0.100E-03   92.306 0.010
 11   1.894   0 2000.0   8.589     0.596  0.00    0.100E-03   92.306 0.010
 12   2.083   0 2000.0   8.590     0.596  0.00    0.100E-03   92.306 0.010
 13   2.273   0 2000.0   8.590     0.596  0.00    0.100E-03   92.306 0.010
 14   2.462   0 2000.0   8.590     0.596  0.00    0.100E-03   92.306 0.010
 15   2.5     1
for Time     1 NBC=   1 *
 Branch      1 Node   1 Q=    2004.70      *
for Time     2 NBC=   1 *
 Branch      1 Node   1 Q=    2042.03      *
for Time     3 NBC=   1 *
 Branch      1 Node   1 Q=    2115.88      *
for Time     4 NBC=   1 *
 Branch      1 Node   1 Q=    2224.52      *
for Time     5 NBC=   1 *
 Branch      1 Node   1 Q=    2365.09      *
for Time     6 NBC=   1 *
 Branch      1 Node   1 Q=    2533.39      *
for Time     7 NBC=   1 *
 Branch      1 Node   1 Q=    2723.71      *
for Time     8 NBC=   1 *
 Branch      1 Node   1 Q=    2928.81      *
for Time     9 NBC=   1 *
 Branch      1 Node   1 Q=    3140.05      *
for Time    10 NBC=   1 *
 Branch      1 Node   1 Q=    3347.74      *
for Time    11 NBC=   1 *
 Branch      1 Node   1 Q=    3541.63      *
for Time    12 NBC=   1 *
 Branch      1 Node   1 Q=    3711.61      *
for Time    13 NBC=   1 *
 Branch      1 Node   1 Q=    3848.39      *
for Time    14 NBC=   1 *
 Branch      1 Node   1 Q=    3944.24      *
```

Figure 17. Input file, flow.in, for example 2.

```
for Time    15 NBC=  1 *
 Branch      1 Node  1 Q=    3993.61       *
for Time    16 NBC=  1 *
 Branch      1 Node  1 Q=    3993.61       *
for Time    17 NBC=  1 *
 Branch      1 Node  1 Q=    3944.24       *
for Time    18 NBC=  1 *
 Branch      1 Node  1 Q=    3848.39       *
for Time    19 NBC=  1 *
 Branch      1 Node  1 Q=    3711.61       *
for Time    20 NBC=  1 *
 Branch      1 Node  1 Q=    3541.63       *
for Time    21 NBC=  1 *
 Branch      1 Node  1 Q=    3347.74       *
for Time    22 NBC=  1 *
 Branch      1 Node  1 Q=    3140.05       *
for Time    23 NBC=  1 *
 Branch      1 Node  1 Q=    2928.81       *
for Time    24 NBC=  1 *
 Branch      1 Node  1 Q=    2723.71       *
for Time    25 NBC=  1 *
 Branch      1 Node  1 Q=    2533.39       *
for Time    26 NBC=  1 *
 Branch      1 Node  1 Q=    2365.09       *
for Time    27 NBC=  1 *
 Branch      1 Node  1 Q=    2224.52       *
for Time    28 NBC=  1 *
 Branch      1 Node  1 Q=    2115.88       *
for Time    29 NBC=  1 *
 Branch      1 Node  1 Q=    2042.03       *
for Time    30 NBC=  1 *
 Branch      1 Node  1 Q=    2004.70       *
for Time    31 NBC=  1 *
 Branch      1 Node  1 Q=    2000.00       *
for Time    32 NBC=  0
          .
          .
          .
for Time    90 NBC=  0
```

Figure 17 (continued). Input file, flow.in, for example 2.

The other input file for DAFLOW, the DAFG file, used for example 2 is the same as the one shown in figure 11, except that the arbitrary bed elevation is changed from 46.00 to 40.00. All additional input files for MODFLOW are shown in Appendix C for example 2.

Selected output of MODFLOW/DAFLOW is shown in figure 18 for stress period 15, the peak inflow period. Heads in only one row are shown, but the heads in all other rows were within 0.002 ft, indicating that the system is essentially one-dimensional. As seen from the volumetric budget for the entire model, the leakage from the stream to the aquifer averages 7.5539 ft^3/s for this stress period.

```
STRESS PERIOD NO. 15, LENGTH = 86400.00
                       ---------------------------------------------
                              NUMBER OF TIME STEPS = 1
                               MULTIPLIER FOR DELT = 1.000
                            INITIAL TIME STEP SIZE = 86400.00
No of DAFLOW steps per MODFLOW step = 1
    15 ITERATIONS FOR TIME STEP 1 IN STRESS PERIOD 15

MAXIMUM HEAD CHANGE FOR EACH ITERATION:
   HEAD CHANGE    HEAD CHANGE    HEAD CHANGE    HEAD CHANGE    HEAD CHANGE
 LAYER,ROW,COL  LAYER,ROW,COL  LAYER,ROW,COL  LAYER,ROW,COL  LAYER,ROW,COL
---------------------------------------------------------------------------
    0.1466        0.8551E-01    -0.6441E-01     0.8890E-01    -0.5130E-01
 (  1, 13, 22) (  1, 12, 20) (  1, 13, 20) (  1, 13, 20) (  1, 13, 20)
    0.3890E-01   -0.1791E-01     0.9673E-02    -0.3659E-02     0.1549E-02
 (  1, 13, 20) (  1, 13, 20) (  1, 13, 20) (  1, 13, 20) (  1, 13, 20)
   -0.4899E-03    0.1684E-03    -0.4645E-04     0.1292E-04    -0.3231E-05
 (  1, 13, 20) (  1, 13, 20) (  1, 13, 20) (  1, 13, 20) (  1, 13, 20)

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

 OUTPUT FLAGS FOR EACH LAYER:
          HEAD     DRAWDOWN  HEAD  DRAWDOWN
 LAYER  PRINTOUT  PRINTOUT  SAVE    SAVE
 ----------------------------------------
    1       1         0       0       0

Day  15  Hour 12.00 Branch  Node  Discharge
                       1     7     3990.
                       1    15     3985.

      HEAD IN LAYER 1 AT END OF TIME STEP 1 IN STRESS PERIOD 15
 ------------------------------------------------------------------------
   1      2      3      4      5      6      7      8      9     10
  11     12     13     14     15     16     17     18     19     20
  21     22     23     24     25     26     27     28     29     30
  31     32     33     34     35     36     37     38     39
.......................................................................
48.000 48.000 48.000 48.000 48.000 48.000 48.000 48.001 48.002 48.004
48.009 48.021 48.047 48.101 48.211 48.424 48.811 49.473 50.515 51.972
50.515 49.473 48.811 48.424 48.211 48.101 48.047 48.021 48.009 48.004
48.002 48.001 48.000 48.000 48.000 48.000 48.000 48.000 48.000
```

Figure 18. Selected output of the Modular Finite-Difference Ground-Water Flow model at stress period 15, for example 2.

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1 IN STRESS PERIOD 15
------------------------------------------------------------------------------
   CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
   ------------------                 ------------------------

        IN:                                  IN:
        ---                                  ---
      STORAGE =          0.0000            STORAGE =          0.0000
CONSTANT HEAD =          0.0000      CONSTANT HEAD =          0.0000
       DAFLOW =    7908670.0000             DAFLOW =          7.5539
     TOTAL IN =    7908670.0000           TOTAL IN =          7.5539

       OUT:                                 OUT:
       ----                                 ----
      STORAGE =    7908625.5000            STORAGE =          7.5542
CONSTANT HEAD =          0.0000      CONSTANT HEAD =          0.0000
       DAFLOW =          0.0000             DAFLOW =          0.0000
    TOTAL OUT =    7908625.5000          TOTAL OUT =          7.5542
     IN - OUT =         44.5000           IN - OUT =     -3.2043E-04

PERCENT DISCREPANCY =          0.00     PERCENT DISCREPANCY =          0.00

          TIME SUMMARY AT END OF TIME STEP   1 IN STRESS PERIOD 15
                  SECONDS      MINUTES       HOURS        DAYS         YEARS
                  -----------------------------------------------------------
 TIME STEP LENGTH  86400.       1440.0       24.000       1.0000   2.73785E-03
STRESS PERIOD TIME 86400.       1440.0       24.000       1.0000   2.73785E-03
      TOTAL TIME 1.29600E+06  21600.       360.00       15.000     4.10678E-02
```

Figure 18 (continued). Selected output of the Modular Finite-Difference Ground-Water Flow model at stress period 15, for example 2.

The simulated ground-water exchange between the stream and the aquifer and the analytical value are shown in figure 19. The mean and RMS differences on figure 19 are –0.0044 and 0.0102 ft^3/s respectively. The close agreement in the computed leakage values again supports the accuracy of the linked MODFLOW and DAFLOW models.

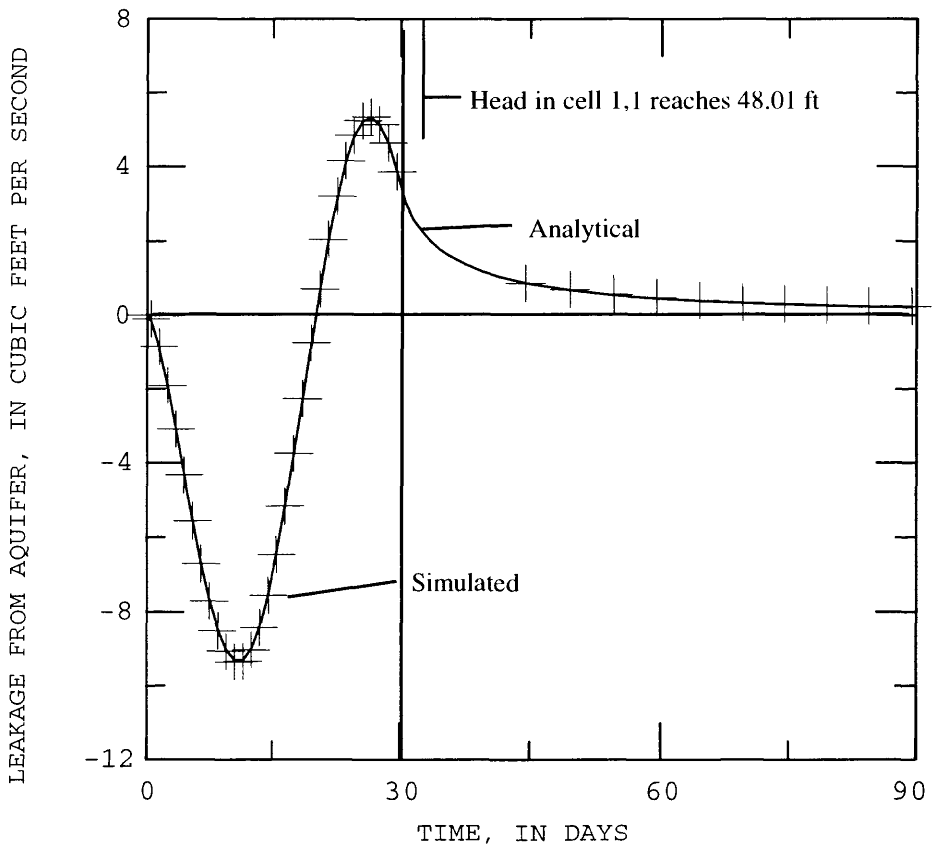

Figure 19. Simulated and analytical flow between the aquifer and the stream for example 2.

For the hydraulic-geometry parameters assumed in this example, the wave celerity varies from 4.1 to 5.4 ft/s as the discharge varies from 2,000 to 4,000 ft^3/s. Thus, the lag time for a response at node 2 to influence the flow at node 14 varies from about 0.6 to 0.8 hours. In comparison to the 24-hour time step, this lag is expected to have minimal effect on the results. The analytical solution is for an aquifer of infinite width, whereas the numerical solution assumes a finite width. It is sometime after day 30 that the head in columns 1 and 39 change from the initial values by as much as 0.01 ft. The maximum head in these cells of 48.058 occurs at the end of the simulation. The effect of the walls on the leakage probably would be minimal for times less than 90 days.

Example 3, Bank storage under unsteady flow

The third example illustrates the effect of bank storage resulting from unsteady flow. The example uses the grid and surface-water network of the third example of Swain & Wexler (1993). This example also illustrates the use of the model with a branched surface-water flow system.

The hypothetical aquifer stretches 20,500 ft from north to south and 10,500 ft from east to west. A schematic of the aquifer and surface-water grid is shown on figure 20. The aquifer has impermeable boundaries on the east and west, a specified-flow northern boundary, and a constant head southern boundary. The aquifer has a transmisivity of 0.116 ft^2/s, a storage coefficient of 0.20, and a constant flow across the northern boundary of 126,000 ft^3/day (1.46 ft^3/s). By using 21 columns and 41 rows, the MODFLOW cells are 500 ft square. The initial aquifer head is assumed to vary uniformly from 25.6 ft at the northern boundary to 1.00 ft at the southern boundary giving, a slope of 0.0012 (6.34 ft/mi). The ground-water model is run for 32, 30-minute time steps.

The surface-water system consists of minor channels entering the aquifer at the northeast and northwest corners and joining to form a single channel at a distance of 5,250 feet south of the northern boundary, in the center of cell 11,11. This single channel flows straight south down the center of the aquifer to the southern boundary. The channel flows are initially zero, and a runoff hydrograph enters each minor channel starting 30 minutes into the run.

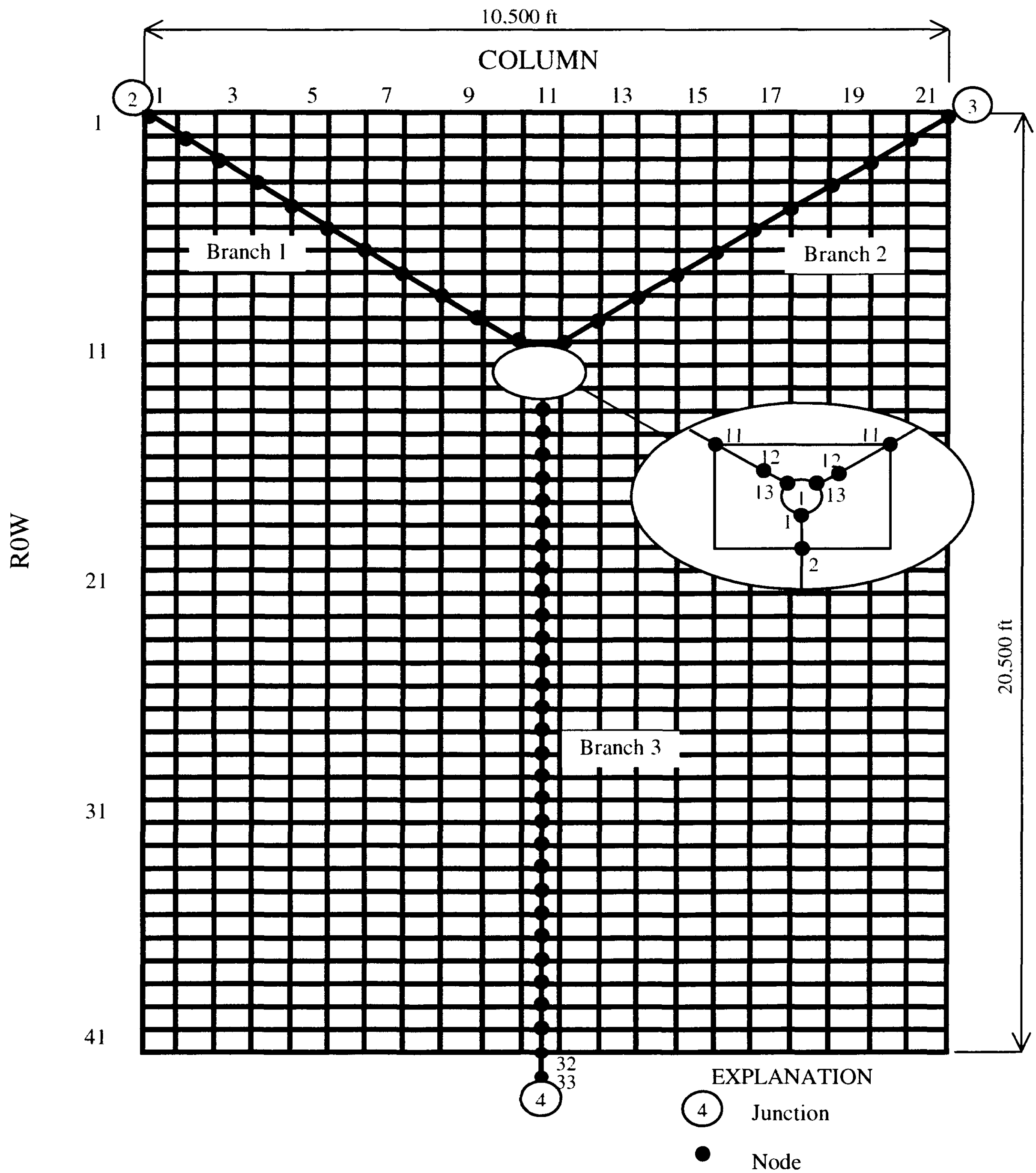

Figure 20. Ground-water model grid of example 3 with surface-water model grid superimposed.

It is assumed that the minor and main channels are typical of streams in Missouri with drainage areas of 10 and 30 sq mi, respectively. It is also assumed that the bed elevation of all channels are the same as initial surface elevation of the aquifer, so the slope of the upstream channels is 0.000848 and the slope of the downstream channel is 0.0012. According to Jennings and others (1994, p.99), a runoff event with an expected return period of 2 years should have a peak flow of about 463 ft^3/s for streams with the drainage area and slope of the upstream channels. Likewise, the time of concentration can be expected to be about 2.7 hours (Jennings and others, 1994, p.196). Based on the peak flow and lag time, the inflow hydrograph was determined for the upstream channels by using the dimensionless hydrograph presented by Inman (1987, p. 7).

The next task was to select hydraulic characteristics for the channels. Hydraulic-geometry exponents of area and width were selected as 0.66 and 0.26, respectively, which are typical of values observed for a wide range of streams (Jobson, 1989, p. 7). Many studies have shown that channel widths are correlated with the channel-forming discharge, which in turn, is often approximated as the peak flow with a return period of 2 years. Combining the work of Osterkamp (1980), Kilpatrick and Barnes (1964) and Wolman and Leopold (1957), an empirical expression for the hydraulic-geometry coefficient for width can be developed as:

$$W1 = 3.34 Q_c^{0.56 - W2},$$

in which W1 = hydraulic-geometry coefficient for width using the English system of units (ft, ft^3/s), Q_c = channel forming discharge, in ft^3/s, and W2 = the hydraulic-geometry exponent for width (see equation 12). Assuming channel forming discharges of 463 and 1,000 ft^3/s, the values of W1 are 21.1 and 26.6, respectively, for the upper and lower channels.

It was assumed that the upper and lower channels have a Mannings n of 0.035 at a flow of 250 ft^3/s and 500 ft^3/s respectively. Assuming A0 to be zero (not a pool and riffle stream), equation 11 yields values of A1 to be 3.79 and 3.87, respectively, for the upstream and downstream channels. As the discharge increases from 50 to 450 ft^3/s in the upstream channels, the velocity, width, and depth increase from 1.0 to 2.1 ft/s, 58 to 103 ft, 0.86 to 2.1 ft, respectively. The width depth ratio decreases from 67 to 50. Likewise, as the discharge in the lower channel increases from 100 to 1,000 ft^3/s, the velocity, width, and depth increase from 1.2 to 2.3 ft/s, 88 to 160 ft, and 0.9 to 2.3 ft, respectively. The width depth ratio decreases from 96 to 69.

The input file flow.in (example3.inf) used for example 3 is shown in figure 21. Notice the model has 3 branches, and 1 internal junction (that must be numbered 1). The flow model is run for 64 time steps, each 0.25 hours long, (2 for each MODFLOW time step). The output is written every time step. Because the MODFLOW model is run for 32 time steps, the surface-water output is written twice for each MODFLOW time step. The peak discharge is set at 1,000 ft^3/s, so any flow of less than 0.01 ft^3/s will be ignored. Branch 1 has 13 nodes (xsects) with the first being at the northern boundary of the aquifer and node 12 being at mile 1.406 (7,423.7 ft from the northern boundary and 0.9 ft from the center of cell 11,11). Subreach 11, which is upstream of node 12, is the last subreach for branch 1 that interacts with the aquifer, so node 13 is located only a short distance downstream. The slopes of branch 1 (0.000848) and branch 3 (0.0012) yield the same north-south fall as the initial aquifer head.

```
Example 3
 2 No. of Branches              3 *
 3 No. of Internal              1 * Junctions
 4 No. Time Steps              64 * Modeled
 5 Model Starts                 0 time steps after midnight.
 6 Output Given Every           1 Time Steps in "flow.out"
 7 0=Metric,1=English           1 *
 8 Time Step Size           0.250 Hours.
 9 Peak Discharge           1000. *
Branch  1 has 13 xsects & routes 1.00 of flow at JNCT  2 To JNCT  1
Grd  Mi/Km IOUT Disch    A1      A2      AO     Slope        W1    W2
  1 0.0000   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  2 0.1340   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  3 0.2680   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  4 0.4020   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  5 0.5360   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  6 0.6700   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  7 0.8040   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  8 0.9370   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  9   1.071  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 10   1.205  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 11   1.339  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 12   1.406  1  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 13   1.410  0
Branch  2 has 13 xsects & routes 1.00 of flow at JNCT  3 To JNCT  1
Grd  Mi/Km IOUT Disch    A1      A2      AO     Slope        W1    W2
  1 0.0000   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  2 0.1340   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  3 0.2680   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  4 0.4020   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  5 0.5360   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  6 0.6700   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  7 0.8040   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  8 0.9370   0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
  9   1.071  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 10   1.205  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 11   1.339  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 12   1.406  0  0.000 3.79    0.66   0.000   0.848E-03   21.1  0.26
 13   1.410  0
Branch  3 has 33 xsects & routes 1.00 of flow at JNCT  1 To JNCT  4
Grd  Mi/Km IOUT Disch    A1      A2      AO     Slope        W1    W2
  1 0.0000   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  2 0.0470   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  3 0.1420   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  4 0.2370   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  5 0.3310   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  6 0.4260   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  7 0.5210   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  8 0.6160   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
  9 0.7100   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 10 0.8050   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 11 0.9000   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 12 0.9940   0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 13   1.089  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 14   1.184  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 15   1.278  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 16   1.373  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 17   1.468  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 18   1.563  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 19   1.657  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
 20   1.752  0  0.000 3.87    0.66   0.000   1.200E-03   26.6  0.26
```

Figure 21. Input file, flow.in, for example 3.

```
  21  1.847   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  22  1.941   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  23  2.036   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  24  2.131   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  25  2.225   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  26  2.320   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  27  2.415   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  28  2.509   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  29  2.604   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  30  2.699   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  31  2.794   0  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  32  2.888   1  0.000  3.87     0.66    0.000    1.200E-03    26.6  0.26
  33  3.000   0
for Time     1 NBC=   0  *
for Time     2 NBC=   0  *
for Time     3 NBC=   2  *
 Branch      1 Node   1 Q=     10.300      *
 Branch      2 Node   1 Q=     10.300      *
for Time     4 NBC=   2  *
 Branch      1 Node   1 Q=     30.890      *
 Branch      2 Node   1 Q=     30.890      *
for Time     5 NBC=   2  *
 Branch      1 Node   1 Q=     51.480      *
 Branch      2 Node   1 Q=     51.480      *
for Time     6 NBC=   2  *
 Branch      1 Node   1 Q=     85.220      *
 Branch      2 Node   1 Q=     85.220      *
for Time     7 NBC=   2  *
 Branch      1 Node   1 Q=     131.20      *
 Branch      2 Node   1 Q=     131.20      *
for Time     8 NBC=   2  *
 Branch      1 Node   1 Q=     192.90      *
 Branch      2 Node   1 Q=     192.90      *
for Time     9 NBC=   2  *
 Branch      1 Node   1 Q=     270.00      *
 Branch      2 Node   1 Q=     270.00      *
for Time    10 NBC=   2  *
 Branch      1 Node   1 Q=     347.30      *
 Branch      2 Node   1 Q=     347.30      *
for Time    11 NBC=   2  *
 Branch      1 Node   1 Q=     409.50      *
 Branch      2 Node   1 Q=     409.50      *
for Time    12 NBC=   2  *
 Branch      1 Node   1 Q=     448.10      *
 Branch      2 Node   1 Q=     448.10      *
for Time    13 NBC=   2  *
 Branch      1 Node   1 Q=     461.00      *
 Branch      2 Node   1 Q=     461.00      *
for Time    14 NBC=   2  *
 Branch      1 Node   1 Q=     439.00      *
 Branch      2 Node   1 Q=     439.00      *
for Time    15 NBC=   2  *
 Branch      1 Node   1 Q=     394.10      *
 Branch      2 Node   1 Q=     394.10      *
for Time    16 NBC=   2  *
 Branch      1 Node   1 Q=     342.60      *
 Branch      2 Node   1 Q=     342.60      *
for Time    17 NBC=   2  *
 Branch      1 Node   1 Q=     291.20      *
 Branch      2 Node   1 Q=     291.20      *
for Time    18 NBC=   2  *
 Branch      1 Node   1 Q=     243.00      *
 Branch      2 Node   1 Q=     243.00      *
```

Figure 21 (continued). Input file, flow.in, for example 3.

```
for Time   19 NBC=  2 *
 Branch     1 Node  1 Q=     207.30       *
 Branch     2 Node  1 Q=     207.30       *
for Time   20 NBC=  2 *
 Branch     1 Node  1 Q=     174.90       *
 Branch     2 Node  1 Q=     174.90       *
for Time   21 NBC=  2 *
 Branch     1 Node  1 Q=     149.20       *
 Branch     2 Node  1 Q=     149.20       *
for Time   22 NBC=  2 *
 Branch     1 Node  1 Q=     128.60       *
 Branch     2 Node  1 Q=     128.60       *
for Time   23 NBC=  2 *
 Branch     1 Node  1 Q=     111.40       *
 Branch     2 Node  1 Q=     111.40       *
for Time   24 NBC=  2 *
 Branch     1 Node  1 Q=     94.320       *
 Branch     2 Node  1 Q=     94.320       *
for Time   25 NBC=  2 *
 Branch     1 Node  1 Q=     81.800       *
 Branch     2 Node  1 Q=     81.800       *
for Time   26 NBC=  2 *
 Branch     1 Node  1 Q=     71.710       *
 Branch     2 Node  1 Q=     71.710       *
for Time   27 NBC=  2 *
 Branch     1 Node  1 Q=     63.100       *
 Branch     2 Node  1 Q=     63.100       *
for Time   28 NBC=  2 *
 Branch     1 Node  1 Q=     54.560       *
 Branch     2 Node  1 Q=     54.560       *
for Time   29 NBC=  2 *
 Branch     1 Node  1 Q=     46.350       *
 Branch     2 Node  1 Q=     46.350       *
for Time   30 NBC=  2 *
 Branch     1 Node  1 Q=     38.490       *
 Branch     2 Node  1 Q=     38.490       *
for Time   31 NBC=  2 *
 Branch     1 Node  1 Q=     30.640       *
 Branch     2 Node  1 Q=     30.640       *
for Time   32 NBC=  2 *
 Branch     1 Node  1 Q=     22.790       *
 Branch     2 Node  1 Q=     22.790       *
for Time   33 NBC=  2 *
 Branch     1 Node  1 Q=     14.940       *
 Branch     2 Node  1 Q=     14.940       *
for Time   34 NBC=  2 *
 Branch     1 Node  1 Q=     7.0870       *
 Branch     2 Node  1 Q=     7.0870       *
for Time   35 NBC=  2 *
 Branch     1 Node  1 Q=      0.000       *
 Branch     2 Node  1 Q=      0.000       *
for Time   36 NBC=  0 *
         .
         .
         .
for Time   64 NBC=  0 *
```

Figure 21 (continued). Input file, flow.in, for example 3.

The other input file for DAFLOW, the DAFG file, used for example 3 is the shown in figure 22. As before, notice that there are three lines of text at the beginning and that the bed elevation, bed thickness and hydraulic conductivity are defined for each interior node (2 through 12, or 2 through 32). The bed elevation represents the elevation of the subreach, upstream of the node, at the midpoint of the ground-water cell. The ground-water cell that interacts with this subreach is identified in the last three columns. The format of the data is not important, but each column must be separated by at least 1 blank space. Following the bed interaction data is one line of text identifying the three flags input on the last line of the file. In this case, the print code for MODFLOW (IDAFCB) is 44, which means that the MODFLOW budget information is stored in file 44. The debug output option (IDBG) is set to zero, so the debugging information is not printed, and central differencing is used for ground-water head, (IDAFBK=0).

```
This is input for DAFLOW/MODFLOW
                Bed        Bed                      GW node of exchange
 Brch   Node    Elev       Thickness  Conductivity Layer   Row Column
  1      2     25.300      1.00       1.00E-04       1       1      1
  1      3     24.700      1.0        1.00E-04       1       2      2
  1      4     24.100      1.0        1.00E-04       1       3      3
  1      5     23.500      1.0        1.00E-04       1       4      4
  1      6     22.900      1.0        1.00E-04       1       5      5
  1      7     22.300      1.0        1.00E-04       1       6      6
  1      8     21.700      1.0        1.00E-04       1       7      7
  1      9     21.100      1.0        1.00E-04       1       8      8
  1     10     20.500      1.0        1.00E-04       1       9      9
  1     11     19.900      1.0        1.00E-04       1      10     10
  1     12     19.300      1.0        1.00E-04       1      11     11
  2      2     25.300      1.00       1.00E-04       1       1     21
  2      3     24.700      1.0        1.00E-04       1       2     20
  2      4     24.100      1.0        1.00E-04       1       3     19
  2      5     23.500      1.0        1.00E-04       1       4     18
  2      6     22.900      1.0        1.00E-04       1       5     17
  2      7     22.300      1.0        1.00E-04       1       6     16
  2      8     21.700      1.0        1.00E-04       1       7     15
  2      9     21.100      1.0        1.00E-04       1       8     14
  2     10     20.500      1.0        1.00E-04       1       9     13
  2     11     19.900      1.0        1.00E-04       1      10     12
  2     12     19.300      1.0        1.00E-04       1      11     11
  3      2     19.300      1.00       1.00E-04       1      11     11
  3      3     18.700      1.0        1.00E-04       1      12     11
  3      4     18.100      1.0        1.00E-04       1      13     11
  3      5     17.500      1.0        1.00E-04       1      14     11
  3      6     16.900      1.0        1.00E-04       1      15     11
  3      7     16.300      1.0        1.00E-04       1      16     11
  3      8     15.700      1.0        1.00E-04       1      17     11
  3      9     15.100      1.0        1.00E-04       1      18     11
  3     10     14.500      1.0        1.00E-04       1      19     11
  3     11     13.900      1.0        1.00E-04       1      20     11
  3     12     13.300      1.0        1.00E-04       1      21     11
  3     13     12.700      1.0        1.00E-04       1      22     11
  3     14     12.100      1.0        1.00E-04       1      23     11
  3     15     11.500      1.0        1.00E-04       1      24     11
  3     16     10.900      1.0        1.00E-04       1      25     11
  3     17     10.300      1.0        1.00E-04       1      26     11
  3     18      9.700      1.0        1.00E-04       1      27     11
  3     19      9.100      1.0        1.00E-04       1      28     11
  3     20      8.500      1.0        1.00E-04       1      29     11
  3     21      7.900      1.0        1.00E-04       1      30     11
  3     22      7.300      1.0        1.00E-04       1      31     11
  3     23      6.700      1.0        1.00E-04       1      32     11
  3     24      6.100      1.0        1.00E-04       1      33     11
  3     25      5.500      1.0        1.00E-04       1      34     11
  3     26      4.900      1.0        1.00E-04       1      35     11
  3     27      4.300      1.0        1.00E-04       1      36     11
  3     28      3.700      1.0        1.00E-04       1      37     11
  3     29      3.100      1.0        1.00E-04       1      38     11
  3     30      2.500      1.0        1.00E-04       1      39     11
  3     31      1.900      1.0        1.00E-04       1      40     11
  3     32      1.300      1.0        1.00E-08       1      41     11
 IDAFCB IDBG IDAFBK
 44       0     0
```

Figure 22. Input file, DAFG, for example 3.

All additional input files for MODFLOW are shown in Appendix D for example 3.

Selected output of MODFLOW/DAFLOW is shown in figure 23 for the MODFLOW time steps 6 and 11. At time step 6 (hour 2.5-3.0), the inflow at the upstream boundary is near the peak (figure 24), and there is no flow in the lower part of the downstream branch. Nine iterations are required (figure 23) for convergence during this time of rapidly changing conditions. The leading edge of the hydrograph is near node 4 in branch 3 for the first half of the MODFLOW time step. It is normal for very small negative streamflow to be computed as the hydrograph advances over a dry bed. The negative values are caused by truncation errors in the approximate solution. The warning messages may occur for each iteration, but only the values for one iteration are shown in figure 23. The negative values should remain less than the flow tolerance selected for DAFLOW, which in this case 0.01 ft^3/s. The step number shown in the negative flow warning represents the DAFLOW time step within the MODFLOW time step. The output indicates that the streamflow at branch 1, node 12 is only 27.5 ft^3/s during the first half of the MODFLOW time step, but increases to 153.9 ft^3/s during the second half of the time step. The streamflow is zero at the downstream end of branch 3 for the entire time step. As can be seen from the volumetric budget, between hours 2.5 and 3.0, the average seepage from the stream to the aquifer is 16,130,487 ft^3/day, or 187 ft^3/s. The seepage from the aquifer to the stream is virtually zero (0.0049338 ft^3/day).

During time-step 11 (hours 5.0-5.5), most of the flow has entered the system, and the leading edge of the hydrograph has passed the downstream boundary. The entire channel has some flow, and there are no negative flow warnings. Conditions are still changing rapidly, so 7 iterations are required for convergence. Seepage from the stream to the aquifer (15,748,558 ft^3/day = 182 ft^3/s) is less than the maximum value of 278 ft^3/s which occurred between hours 3.5 and 4.0. This is the first time step for which significant return flow (1.26 ft^3/s) occurs from the aquifer to the stream.

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

 DAF test problem
 1 LAYERS   41 ROWS  21 COLUMNS
 MODEL TIME UNIT IS DAYS
 MAXIMUM OF   21 WELLS
 No of DAFLOW steps per MODFLOW step = 2

Computed negative flow of -0.359E-05 at step 1 branch 3 node 4
Computed negative flow of -0.207E-02 at step 2 branch 3 node 7
9 TOTAL ITERATIONS

OUTPUT CONTROL FOR STRESS PERIOD 1 TIME STEP 6
 Day   1  Hour  2.63 Branch  Node  Discharge
                        1     12      27.50
                        3     32     0.0000
 Day   1  Hour  2.88 Branch  Node  Discharge
                        1     12      153.9
                        3     32     0.0000

VOLUMETRIC BUDGET OF ENTIRE MODEL, END OF TIME STEP 6, STRESS PERIOD 1
------------------------------------------------------------------------
 CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
 ------------------                 ------------------------

           IN:                                   IN:
           ---                                   ---
      STORAGE =       0.0000               STORAGE =          0.0000
CONSTANT HEAD =       0.0000         CONSTANT HEAD =          0.0000
        WELLS =   15750.0000                 WELLS =     126000.0000
       DAFLOW = 666534.6250                 DAFLOW =   16130487.0000
     TOTAL IN = 682284.6250               TOTAL IN =   16256487.0000

          OUT:                                  OUT:
          ----                                  ----
      STORAGE = 666548.9380                STORAGE =   16130926.0000
CONSTANT HEAD =   15750.0010         CONSTANT HEAD =     126000.0080
        WELLS =       0.0000                 WELLS =          0.0000
       DAFLOW =   1.0349E-04                DAFLOW =      4.9338E-03
    TOTAL OUT = 682298.9380              TOTAL OUT =   16256926.0000

     IN - OUT =     -14.3125              IN - OUT =       -439.0000
PERCENT DISCREPANCY =   0.00       PERCENT DISCREPANCY =        0.00


7 TOTAL ITERATIONS
OUTPUT CONTROL FOR STRESS PERIOD 1 TIME STEP 11

Day   1  Hour  5.13 Branch  Node  Discharge
                        1     12      232.7
                        3     32      320.1
 Day   1  Hour  5.38 Branch  Node  Discharge
                        1     12      205.8
                        3     32      421.1
```

Figure 23. Selected output of the Modular Finite-Difference Ground-Water Flow model at end of time steps 6 and 11, for example 3.

```
VOLUMETRIC BUDGET OF ENTIRE MODEL, END OF TIME STEP 11, STRESS PERIOD 1
-----------------------------------------------------------------------
CUMULATIVE VOLUMES      L**3        RATES FOR THIS TIME STEP      L**3/T
 ------------------                  ------------------------

          IN:                                  IN:
          ---                                  ---
      STORAGE =      9933.2813             STORAGE =    473831.1880
CONSTANT HEAD =         0.0000       CONSTANT HEAD =         0.0000
        WELLS =     28875.0000               WELLS =    126000.0000
       DAFLOW =   2892877.0000              DAFLOW =  15748558.0000
     TOTAL IN =   2931685.2500            TOTAL IN =  16348389.0000

         OUT:                                 OUT:
         ----                                 ----
      STORAGE =   2900506.5000             STORAGE =  16113922.0000
CONSTANT HEAD =     28990.2402       CONSTANT HEAD =    130356.0080
        WELLS =         0.0000               WELLS =         0.0000
       DAFLOW =      2264.2395              DAFLOW =    108683.4840
    TOTAL OUT =   2931761.0000           TOTAL OUT =  16352961.0000

     IN - OUT =       -75.7500            IN - OUT =     -4572.0000
PERCENT DISCREPANCY =     0.00       PERCENT DISCREPANCY =     -0.03
```

Figure 23 (continued). Selected output of the Modular Finite-Difference Ground-Water Flow model at end of time steps 6 and 11, for example 3.

The channel flow at the upstream and downstream boundaries of the system as well as at the upstream end of Branch 3 are shown in figure 24. The flow distribution that would have occurred if the stream/aquifer interaction had not occurred is also shown as dashed lines to illustrate the effect of bank storage on the flow hydrograph.

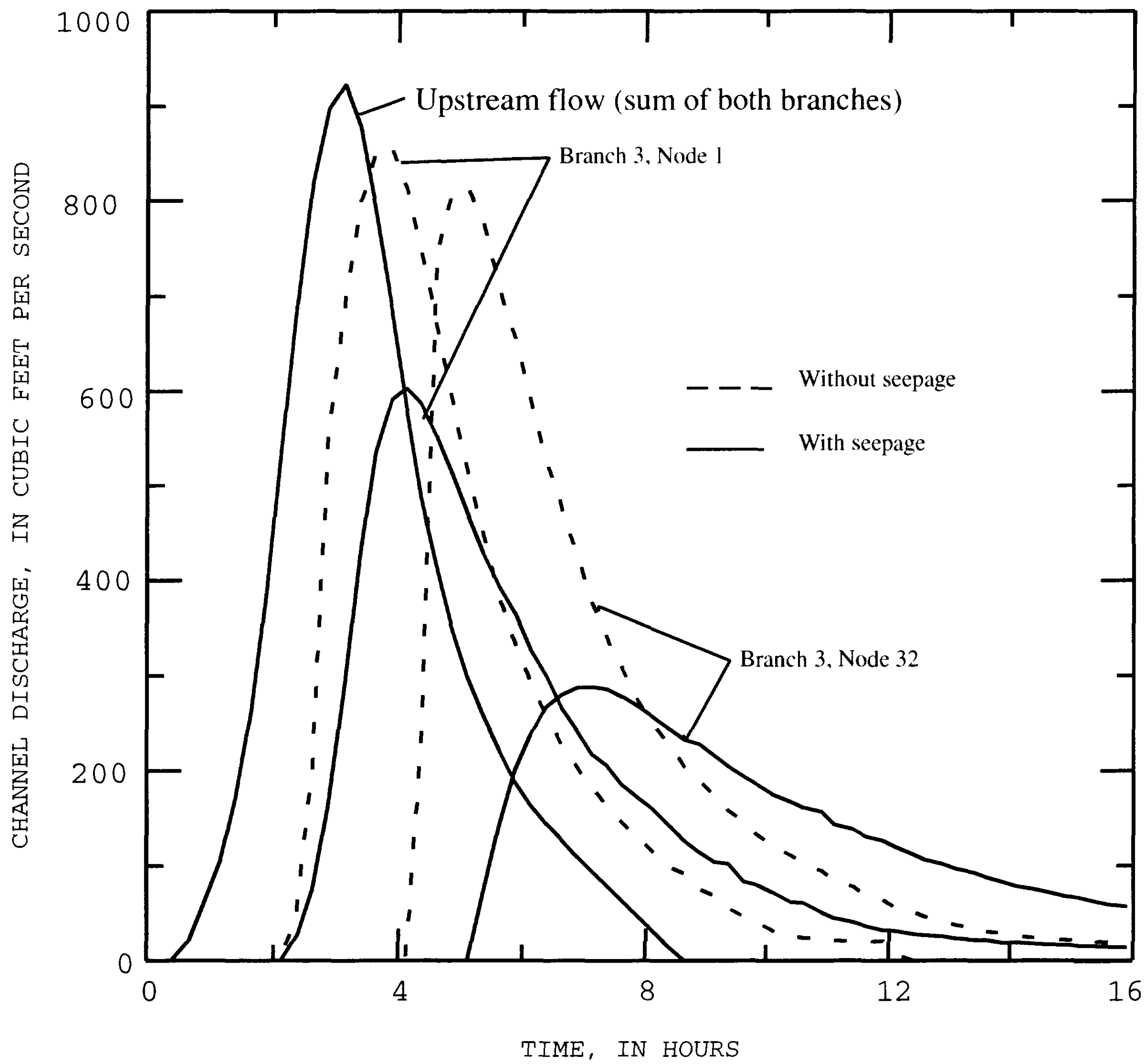

Figure 24. Flow distribution at selected points of the channel in example 3, illustrating the bank-storage effect on the flow hydrograph.

The effective flow into and out of the aquifer as a function of time is shown in figure 25. These values were obtained from the volumetric budget of the entire model shown in the MODFLOW output (figure 23). The peak flow into the aquifer of nearly 300 ft^3/s occurs at about hour 4, which corresponds to the time that the peak channel flow is near the junction. The flow into the aquifer accounts for most of the attenuation in peak channel flow between the upstream boundary and the junction. Return flow from the aquifer begins in the upstream reaches a little after hour 4, after the flow at the upstream boundary has been reduced to about half of its peak value. The flow out of the aquifer peaks between hour 9 and 10 after the channel flow at the downstream boundary is well past its peak.

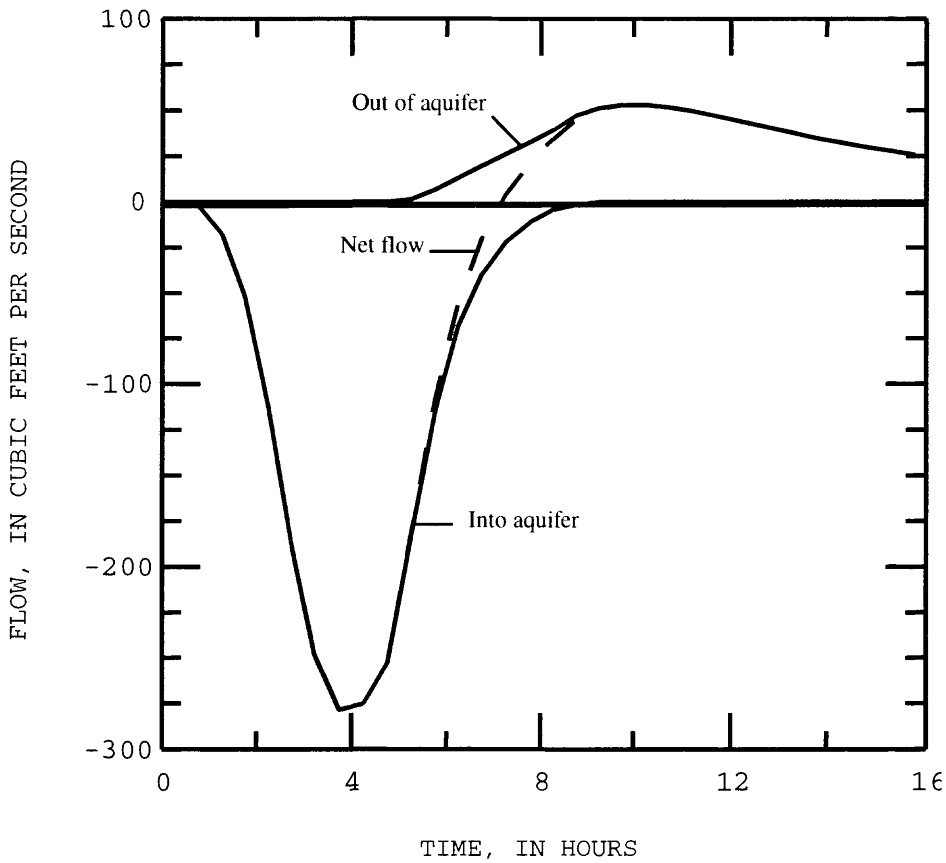

Figure 25. Flow into and out of the aquifer of example 3 as a function of time.

SUMMARY

Computer models are widely used to simulate ground-water flow, as well as flow in rivers and streams, for evaluating and managing water resources. To facilitate the simulation of the interaction of surface water and ground water, the surface-water flow model (DAFLOW) was linked to the modular, finite-difference, ground-water flow model (MODFLOW). The linkage was accomplished by separating the code of the DAFLOW model into a group of subroutines that can be called by MODFLOW. The subroutines were structured such that multiple DAFLOW time steps can be run iteratively for a single MODFLOW time step, and the leakage to each ground-water cell is averaged over the MODFLOW time step.

The DAFLOW model, which solves the diffusive-wave form of the surface-water flow equations, is designed to simulate flow in upland stream systems where flow reversals do not occur, and backwater conditions are not severe. If these two conditions are satisfied, the DAFLOW model can be applied with good accuracy using minimal field data.

This report documents the modifications to the DAFLOW model needed for it to be linked to the MODFLOW package, describes the calls necessary to implement DAFLOW with MODFLOW, and describes the input files necessary to run DAFLOW with MODFLOW. Three example applications illustrate the information contained in the output files and allow the user to assess the accuracy of the solutions of the combined models.

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APPENDIXES

APPENDIX A. SOURCE CODE FOR DAFLOW SUBROUTINES

The stand-alone version of DAFLOW consists of a main program and a series of subroutines. This code is normally stored in three primary files, called daflow.for, gutsdaf.for, and rtedaf.for. Two additional files, which are included in the code by use of INCLUDE statements, must also be available. These files are params.inc and startdaf.com. When used with MODFLOW, the main program is replaced by additional subroutines that perform the ground-water specific functions. This file is called daf1.for. An additional include file called ground.com is also needed.

All USGS hydrologic analysis software is available for electronic retrieval by means of either the World-Wide Web (WWW) at http://water.usgs.gov/software or by anonymous File Transfer Protocol (FTP) from water.usgs.gov in the /pub/software/surface_water directory.

In addition to the electronically available information, all code is listed below, in the following order: daflow.for, gutsdaf.for, rtedaf.for, daf1.for, params.inc, startdaf.com, and ground.com.

Code in the file daflow.for

```
C
C     ************ Modular MULTIPLE BRANCH UPLAND FLOW MODEL ***********
C
      PROGRAM   DAFLOW
C
C     + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     ****** This program uses a variable DF=Q^(1-W2)/(2 W1 S) *********
C     This program assumes A=AO+A1(Q**A2), computes celerity from dQ/dA,
C     and conserves mass to compute the average flow at the nodes.
C     All boundry conditions represent the average during the time step.
C     The first BC represents the flow from time 0 to Dt, for example.
C     Dispersion is modeled by mixing at shocks over a dispersion distance.
C     The Q is at the node point with QT occuring just upstream of node.
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR    - Maximum number of branches allowed in model
C     NOSC    - Maximum number of cross sections (nodes) allowed in branch
C     NOSH    - Maximum number of shocks allowed in branch
C               (NOSH should be at least 4 times NOSC)
C
C     + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C
C     + + + + + + + + + + + COMMON DEFINTIONS (startdaf.com) + + + + + +
C     F(I,N) FI(I,N) IDBG NBRCH NHR NS NSI NXSEC(N) PX(I,N)
C     PXI(I,N) TF(I,N) TFI(I,N) V(I,N)
C
C     + + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + +
C
      INTEGER I,IERR,INX,J,JCD(NOBR),JN,K,LUIN,LUOT,LUFLW,N,NN,NCD(NOBR)
C     REAL VO
C     CHARACTER*64 VERSN
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + + +
C     IERR     Error code IERR<20 for warning, IERR>20 fatal
C              (1=DL too large, 21=too many shocks)
C     JCD(M)   Code for junction mixing (0=mixed, 2=not mixed,
C                  1=not all inflows known)
C     JN       Junction being updated
C     N        Branch being routed
C     NCD(N)   Branch code (0=routed, 1=not routed)
C     VO       Volume in subreach at beginning of time step
C
C     + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
C
C     + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + + +
C     EXTERNAL STARTDAF,GETBC,PRERTE,SETJNVL,RTBR,FGQ,SETJV2,PRTFLW
C
C    + + + + + + + + + + + + + INPUT FORMATS + + + + + + + + + + + + + + +
C
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
 2000 FORMAT(' Something wrong in subroutine STARTDAF')
 2010 FORMAT(' Warning DL>C DT in branch',I3,'. Increase DT to smooth.')
 2020 FORMAT(' Something wrong in subroutine ROUTE for time',I5)
 2030 FORMAT ('Too many shocks in branch',I3,' at J=',I5)
C
C      + + + + + + + + + + + END SPECIFICATIONS  + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - last modified June 24, 1998, hej'
C     correction in computing range of possible mixed Qs - hej
C
C     notice to user
      WRITE(*,*)' DAFLOW is dimensioned for:'
      WRITE(*,*)'       ',NOBR, ' Branches'
      WRITE(*,*)'       ',NOSC, ' Cross sections per branch'
      WRITE(*,*)'       ',NOSH, ' Shocks per branch'
C
```

```
C     *********** Set unit numbers and open required data files ********
      LUIN=15
      LUOT=LUIN+1
      LUFLW=LUIN+2
      OPEN (LUIN,FILE='flow.in')
      OPEN (LUOT,FILE='flow.out')
      OPEN (LUFLW,FILE='bltm.flw')
C
C     notice to user
      WRITE(*,*)' This program reads "flow.in" '
      WRITE(*,*)' It writes the files "flow.out" and "bltm.flw"'
C
C     *************** Zero arrays and preliminaries ********************
      IERR=0
      CALL STARTDAF (IERR,LUFLW,LUIN,LUOT)
      IF(IERR.GT.20)THEN
        WRITE(LUOT,2000)
        GO TO 900
      END IF
C
      IDBG=0
C      WRITE(*,*)' Do you want the debug statements, ',
C     $          '0 or N = no, 1 = yes'
C      READ(*,'(I10)',ERR=10)I
C        IDBG=I
   10 CONTINUE
C     ************************* Start time loop ***********************
      CALL PRERTE
      DO 100 J=1,NHR
        WRITE(*,*)' Starting time step',J
C       *********** Read boundary conditions **************************
        CALL GETBC (IERR,J,LUIN,LUOT)
        IF(IERR.GT.20)GO TO 900
C       ****************** Route **************************************
        CALL SETJNVL (JCD,NCD)
        DO 50 NN=1,NBRCH
          CALL RTBR (IERR,LUOT,J,JCD,JN,N,NCD)
          IF(IERR.EQ.1)THEN
            WRITE(*,2010)N
            WRITE(LUOT,2010)N
          END IF
          IF(IERR.GT.20)THEN
            WRITE(LUOT,2020)J
            IF(IERR.EQ.21)WRITE(LUOT,2030)N,J
            GO TO 900
          END IF
          INX=NXSEC(N)-1
          DO 40 I=1,INX
            IF(J.EQ.1)THEN
              VO=VIN(I,N)
            ELSE
              VO=V(I,N)
            END IF
            CALL FGQ (I,J,LUOT,N,VO)
   40     CONTINUE
          CALL SETJV2 (JCD,JN,NCD)
   50   CONTINUE
C       ****************** Write results
 ******************************
        CALL PRTFLW (LUFLW,LUOT)
  100 CONTINUE
C     ************************ Close files **************************
  900 CLOSE(LUIN)
      ENDFILE(LUOT)
      CLOSE(LUOT)
      ENDFILE(LUFLW)
      CLOSE(LUFLW)
      STOP
      END
C
```

Code in the file gutsdaf.for

```
C
      SUBROUTINE STARTDAF (IERR,LUFLW,LUIN,LUOT)
C
C       + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C       ************  This subroutine starts DAFLOW *********************
C       DAFLOW uses a variable DF=Q^(1-W2)/(2 W1 S) and assumes
C       A=AO+A1(Q**A2), computes celerity from dQ/dA, conserves mass to
C       compute the average flow at the nodes. All boundry conditions
C       represent the average during the time step. The first BC represents
C       the flow from time 0 to Dt, for example. Dispersion is modeled by
C       mixing at shocks over a dispersion distance.
C       The Q is at the node point with QT occuring just upstream of node.
C
C       + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR    - Maximum number of branches allowed in model
C     NOSC    - Maximum number of cross sections (nodes) allowed in branch
C     NOSH    - Maximum number of shocks allowed in branch
C                (NOSH should be at least 4 times NOSC)
C
C       + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C
C       + + + + + + + + + +  COMMON VARIBLES (startdaf.com)  + + + + + + +
C     AO(I,N) A1(I,N) A2(I,N) F(K,N) FI(K,N) DT IENG IOUT(I,N)
C     JNCD(N) JNCU(N) JGO JTS NBRCH NHR NHRR NJNCT NS(N) NSI(N) NXSEC(N)
C     PF(N) PX(K,N) PXI(K,N) QI SL(I,N) TF(I,N) TFI(I,N) TIME VIN(I,N)
C     VI W1(I,N) W2(I,N) X(I,N) XFACT
C
C       + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + +
      INTEGER      I,IERR,J,K,LUFLW,LUIN,LUOT,N
      REAL         A,AA
C     CHARACTER*64 VERSN
      CHARACTER*80 TITLE
C
C       + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     IERR     Error code (0=ok, 20<stop as gracefully as you can)
C     TITLE    Title of program (80 characters max)
C
C       + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
      INTRINSIC  FLOAT
C       + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + +
C
C      + + + + + + + + + + + + + INPUT FORMATS + + + + + + + + + + + + + + +
 1000 FORMAT (A)
 1010 FORMAT (20X,I10)
 1020 FORMAT (20X,F10.3)
 1030 FORMAT (13X,I3,16X,F5.2,16X,I3,8X,I3)
C
C       + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + +
 2000 FORMAT (1X,A,/)
 2010 FORMAT (' The',I3,' Branch Model with',I3,' Internal Junctions',
     #        ' is run',I5,' Time Steps each',F5.2,' hours long.')
 2020 FORMAT ('The Model starts at',F6.2,' hours past midnight.')
 2030 FORMAT ('The node output is given in "bltm.out" every',I4,
     #        ' time steps.')
 2040 FORMAT ('Input units are Metric (Meters & river kilometers')
 2050 FORMAT ('Input units are English (feet and river miles)')
 2060 FORMAT (' Width=W1(Q)**W2')
 2070 FORMAT (' Cross sectional area = AO+A1(Q**A2)')
 2080 FORMAT (' AO = Cross sectional area at zero flow.')
 2090 FORMAT (/,28X,'* * *  INITIAL CONDITIONS  * * *')
 2100 FORMAT (/,' node   Mi/km  Disch        Area      Width   ',
     $         ' Slope          A1          A2          W1         ',
     $         ' W2          AO')
 2110 FORMAT (/,'Branch',I4,' Extends from JNCT',I3,' to JNCT',I3,
     $        ' and receives',F5.2,' of flow at JNCT',I3,/)
 2120 FORMAT (I5,F8.2,9G11.4)
 2130 FORMAT (/,25X,'* * *  OUTPUT  * * *',/)
```

```
 3000 FORMAT (3I5,4E18.5)
C
C      + + + + + + + + + + + END SPECIFICATIONS  + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - last modified June 27, 1997 hej '
C     VERSN = Written by HEJ on March 11, 1998
C
C     **************** Zero arrays and preliminaries *******************
      NHRR=1
      DO 40 N=1,NOBR
        JNCU(N)=0
        JNCD(N)=0
        NS(N)=0
        NSI(N)=0
        NXSEC(N)=0
        PF(N)=0.0
        DO 20 I=1,NOSC
          AO(I,N)=0.0
          A1(I,N)=0.0
          A2(I,N)=0.0
          SL(I,N)=0.0
          IOUT(I,N)=0
          X(I,N)=0.0
          TF(I,N)=0.0
          TFI(I,N)=0.0
          W1(I,N)=0.0
          W2(I,N)=0.0
          VIN(I,N)=0.0
   20   CONTINUE
        DO 30 K=1,NOSH
          F(K,N)=0.0
          FI(K,N)=0.0
          PX(K,N)=0.0
          PXI(K,N)=0.0
   30   CONTINUE
   40 CONTINUE
C
C     *********************** Read common input ***********************
      READ(LUIN,1000)TITLE
      WRITE(LUOT,2000)TITLE
      READ(LUIN,1010,ERR=900)NBRCH
      READ(LUIN,1010,ERR=900)NJNCT
      READ(LUIN,1010,ERR=900)NHR
      READ(LUIN,1010,ERR=900)JTS
      READ(LUIN,1010,ERR=900)JGO
      READ(LUIN,1010,ERR=900)IENG
      READ(LUIN,1020,ERR=900)DT
      READ(LUIN,1020,ERR=900)AA
      QI=AA/100000.0
      VI=QI*DT*3600.0
      TIME=(FLOAT(JTS)-0.5)*DT
      WRITE(LUOT,2010)NBRCH,NJNCT,NHR,DT
      AA=DT*FLOAT(JTS)
      WRITE(LUOT,2020)AA
      WRITE(LUOT,2030)JGO
C
C     ************************* Read data for each branch **************
      DO 60 N=1,NBRCH
        READ(LUIN,1030,ERR=900)NXSEC(N),PF(N),JNCU(N),JNCD(N)
        READ(LUIN,1000)TITLE
        DO 50 I=1,NXSEC(N)
          IF(I.LT.NXSEC(N))THEN
            READ(LUIN,*,END=900,ERR=900)K,X(K,N),IOUT(K,N),F(K,N),
     #             A1(K,N),A2(K,N),AO(K,N),SL(K,N),W1(K,N),W2(K,N)
          ELSE
            READ(LUIN,*,END=900,ERR=900)K,X(K,N),IOUT(K,N)
          END IF
   50   CONTINUE
   60 CONTINUE
C
```

```
C     ***** Make preliminary computation and write initial conditions **
      IF(IENG.EQ.0)THEN
C       Metric units
        WRITE(LUOT,2040)
C       XFACT=1609.34
        XFACT=1000.0
      ELSE
C       English units
        WRITE(LUOT,2050)
        XFACT=5280.00
      END IF
      WRITE(LUOT,2070)
      WRITE(LUOT,2080)
      WRITE(LUOT,2060)
C
      WRITE(LUOT,2090)
      WRITE(LUOT,2100)
      J=0
      DO 80 N=1,NBRCH
        NS(N)=NXSEC(N)-1
        NSI(N)=NS(N)
        WRITE(LUOT,2110)N,JNCU(N),JNCD(N),PF(N),JNCU(N)
        DO 70 I=1,NXSEC(N)
          IF(I.LT.NXSEC(N))THEN
            PX(I,N)=X(I,N)*XFACT
            PXI(I,N)=PX(I,N)
            FI(I,N)=F(I,N)
            IF(F(I,N).GT.0.0)THEN
              A=AO(I,N)+A1(I,N)*(F(I,N)**A2(I,N))
              AA=W1(I,N)*(F(I,N)**W2(I,N))
            ELSE
              A=AO(I,N)
              AA=0.0
            END IF
            VIN(I,N)=A*XFACT*(X(I+1,N)-X(I,N))
            IF(I.GT.1)THEN
              TF(I,N)=F(I,N)-F(I-1,N)
              TFI(I,N)=TF(I,N)
            END IF
            WRITE(LUOT,2120)I,X(I,N),F(I,N),A,AA,SL(I,N),
     $                      A1(I,N),A2(I,N),W1(I,N),W2(I,N),AO(I,N)
            WRITE(LUFLW,3000)J,N,I,F(I,N),A,AA,TF(I,N)
          ELSE
            WRITE(LUOT,2120)I,X(I,N),F(I-1,N)
            WRITE(LUFLW,3000)J,N,NXSEC(N),F(I-1,N)
          END IF
          X(I,N)=X(I,N)*XFACT
   70   CONTINUE
   80 CONTINUE
C
      WRITE(LUOT,2130)
      GO TO 999
  900   IERR=22
  999 RETURN
      END
C
      SUBROUTINE GETBC (IERR,J,LUIN,LUOT)
C
C     + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     ******This subroutine reads the boundary conditions for DAFLOW ***
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C
C     + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C
C     + + + + + + + + + + + COMMON VARIABLES (startdaf.com) + + + + + +
C     DT IDBG JTS TIME TRB(I,N)
C
C     + + + + + + + +  + + + LOCAL VARIABLES  + + + + + + + + + + + + +
      INTEGER I,IERR,J,JJ,K,LUIN,LUOT,N,NBC
```

```
C     CHARACTER*64 VERSN
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     IERR     Error code (0=ok, 20<stop as gracefully as you can)
C     NBC      Number of boundary conditions to be read
C
C     + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + + +
C
 1000 FORMAT (18X,I3)
 1010 FORMAT (10X,I3,5X,I3,3X,G14.5)
C
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + +
 2000 FORMAT('Format error on number of boundary condition for time',I5)
 2010 FORMAT('Format error on boundary condition',I5,' Time step',I5)
C      + + + + + + + + + + + END SPECIFICATIONS  + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - written by HEJ March 16, 1998'
C
C     *********************** read boundary conditions ***************
      READ(LUIN,1000,ERR=900)NBC
      IF(NBC.GT.0)THEN
C       ***********  boundary conditons for this time are to be read ***
        DO 40 K=1,NBC
          READ(LUIN,1010,ERR=910)N,I,TRB(I,N)
          JJ=IFIX(TIME/DT+0.501)-JTS+1
          IF(IDBG.EQ.1) WRITE(LUOT,*)'J,N,I,TRB',JJ,N,I,TRB(I,N)
   40   CONTINUE
      END IF
C
      GO TO 999
  900   IERR=22
        WRITE(LUOT,2000)J
        GO TO 999
  910   IERR=22
        WRITE(LUOT,2010)K,J
  999 RETURN
      END
C
      SUBROUTINE PRERTE
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     Prepare for routing NHRR time steps by setting current flow arrays
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C
C     + + + + + + + + + +  COMMON VARIBLES (startdaf.com)  + + + + + + +
C     F(K,N) FI(K,N) NBRCH NS(N) NSI(N) NXSEC(N) PX(K,N) PXI(K,N)
C     TF(I,N) TFI(I,N)
C     + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + +
      INTEGER  I,N
C     CHARACTER*64 VERSN
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + +
C     + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = 'Written by HEJ on March 17, 1998'
C     *************** Zero arrays and preliminaries ******************
      DO 20 N=1,NBRCH
        NS(N)=NSI(N)
```

```
      DO 10 I=1,NXSEC(N)
        TF(I,N)=TFI(I,N)
 10   CONTINUE
      DO 20 I=1,NS(N)
        F(I,N)=FI(I,N)
        PX(I,N)=PXI(I,N)
 20 CONTINUE
999 RETURN
    END
C
      SUBROUTINE SETJNVL (JCD,NCD)
C
C     + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + + +
C     Set junction values and mixing codes
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR    - Maximum number of branches allowed in model
C
C     + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C     + + + + + + + + + +  COMMON VARIBLES (startdaf.com)  + + + + + + +
C     NBRCH NJNCT
C     + + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + +
      INTEGER JCD(NOBR),N,NCD(NOBR)
C
C     + + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + + +
C     JCD(M)   Code for junction mixing (0=mixed, 2=not mixed,
C                    1=not all inflows known)
C     NCD(N)   Branch code (0=routed, 1=not routed)
C     + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
C     + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + + + +
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = 'Written by HEJ on March 17, 1998'
C       ** set branch code to not routed and junction code to not mixed*
        DO 10 N=1,NBRCH
          NCD(N)=1
 10     CONTINUE
        DO 20 N=1,NJNCT
          JCD(N)=2
 20     CONTINUE
999 RETURN
    END
C
C
      SUBROUTINE RTBR (IERR,LUOT,J,JCD,JN,N,NCD)
C
C     + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + + +
C     Find branch to route and route it
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR    - Maximum number of branches allowed in model
C     NOSC    - Maximum number of cross sections (nodes) allowed in branch
C     NOSH    - Maximum number of shocks allowed in branch
C               (NOSH should be at least 4 times NOSC)
C
C     + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C
C     + + + + + + + + + +  COMMON VARIBLES (startdaf.com)  + + + + + + +
C     AO(I,N) AQ(I,N) A1(I,N) A2(I,N) DT F(K,N) IDBG JNCD(N) JNCU(N)
C     NS(N) NXSEC(N) PX(K,N) QI SL(I,N) TF(I,N) TRB(I,N) VI W1(I,N)
C     W2(I,N) X(I,N)
C
C     + + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + +
      INTEGER  IERR,JCD(NOBR),J,JN,K,LUOT,N,NCD(NOBR),NSS
      REAL     DTS,FS(NOSH),PXS(NOSH)
```

```
C
C     + + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + + +
C     DTS       Time step in seconds
C     FS(K)     Flow in shock k of local branch
C     J         Time step
C     JCD(M)    Code for junction mixing (0=mixed, 2=not mixed,
C                   1=not all inflows known)
C     JN        Junction being updated
C     N         Branch being routed
C     NCD(N)    Branch code (0=routed, 1=not routed)
C     PXS(K)    Location of shock K for local branch
C
C     + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
C     + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + + +
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = Written by HEJ on March 17, 1998
C     *************** Zero arrays and preliminaries ******************
      DTS=DT*3600.0
      N=0
      IERR=0
   10 CONTINUE
C       **************** Looking for something to route? *************
        N=N+1
        IF(JCD(JNCU(N)).EQ.1)GO TO 10
        IF(NCD(N).EQ.0)GO TO 10
      NSS=NS(N)
      DO 20 K=1,NSS
        FS(K)=F(K,N)
        PXS(K)=PX(K,N)
   20 CONTINUE
      CALL ROUTE
     I      (AO(1,N),A1(1,N),A2(1,N),SL(1,N),DTS,IDBG,IERR,J,LUOT,
     M      N,NXSEC(N),NSS,FS,PXS,QI,TRB(1,N),TF(1,N),VI,W1(1,N),
     N      W2(1,N),X(1,N))
C     ********** An error here causes a quick and nasty exit *********
      IF(IERR.GT.20)GO TO 999
        NS(N)=NSS
        DO 30 K=1,NSS
          F(K,N)=FS(K)
          PX(K,N)=PXS(K)
   30   CONTINUE
C       ***************** update junction flows and codes ************
        NCD(N)=0
        JN=JNCD(N)
        JCD(JN)=0
        AQ(1,N)=TRB(1,N)
  999 RETURN
      END
C
C
      SUBROUTINE FGQ (I,J,LUOT,N,VO)
C
C     + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     Find volumes in subreaches and compute node flows
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR   - Maximum number of branches allowed in model
C     NOSC   - Maximum number of cross sections (nodes) allowed in branch
C     + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C     + + + + + + + + + + + + COMMON VARIBLES (startdaf.com) + + + + + +
C     AO(I,N) AQ(I,N) A1(I,N) A2(I,N) DT F(I,N) IDBG NS(N) NXSEC(N)
C     PX(I,N) QI TF(I,N) TRB(I,N) V(I,N) X(I,N)
C
C     + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + +
      INTEGER  I,J,K,LUOT,N
      REAL     BB,VO,XL,XR
```

```
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     I      - node of flow or subreach of volume
C     J      - Time step number
C     N      - Branch number
C     + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
      INTRINSIC  ABS
C     + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + +
 2000 FORMAT ('Computed negative flow of',G14.3,' at',
     $         I4,' branch',I3, ' node',I3)
C     + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + + +
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = 'Written by HEJ on March 18, 1998'
C
            XL=X(I,N)
            XR=X(I+1,N)
            CALL FKAI(K,NS(N),PX(1,N),X(I,N))
            CALL FVOL(AO(1,N),A1(1,N),A2(1,N),K,NS(N),NXSEC(N),F(1,N),
     #                PX(1,N),TF(1,N),V(I,N),X(1,N),XL,XR,AA,BB)
            AQ(I+1,N)=AQ(I,N)+TRB(I+1,N)+(VO-V(I,N))/(DT*3600.0)
            IF (AQ(I+1,N).LT.0.0) THEN
C             ************* Can't have negative flow ******************
              K=I+1
              WRITE(LUOT,2000) AQ(K,N),J,N,K
            END IF
            IF(AQ(I+1,N).LT.QI)AQ(I+1,N)=0.0
            IF(IDBG.EQ.1)THEN
C             ************ Debug output *******************************
              WRITE(LUOT,*)'VO,V(I,N,J),AQ',VO,V(I,N),AQ(I+1,N)
            END IF
  999 RETURN
      END
C
      SUBROUTINE SETJV2 (JCD,JN,NCD)
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     Set junction values after route
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR   - Maximum number of branches allowed in model
C     NOSC   - Maximum number of cross sections (nodes) allowed in branch
C     + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C     + + + + + + + + + +  COMMON VARIBLES (startdaf.com)  + + + + + + +
C     AQ(I,N) JNCD(N) JNCU(N) NBRCH NXSEC(N) PF(N) TRB(I,N)
C
C     + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + +
      INTEGER  JCD(NOBR),JN,N,NCD(NOBR)
      REAL     QJ
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     JCD(M)   Code for junction mixing (0=mixed, 2=not mixed,
C                  1=not all inflows known)
C     JN       Junction in question
C     NCD(N)   Branch code (0=routed, 1=not routed)
C     QJ       Flow at junction
C
C     + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + +
C     + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = 'Written by HEJ on March 11, 1998'
C     **************** Set junction codes and flows *******************
      QJ=0.0
      DO 10 N=1,NBRCH
```

```
        IF(JNCD(N).EQ.JN)THEN
          IF(NCD(N).NE.0)JCD(JN)=1
          QJ=QJ+AQ(NXSEC(N),N)
        END IF
   10 CONTINUE
      IF(JCD(JN).NE.1) THEN
        DO 20 N=1,NBRCH
          IF(JNCU(N).EQ.JN) THEN
            TRB(1,N)=QJ*PF(N)
          END IF
   20   CONTINUE
      END IF
  999 RETURN
      END
C
      SUBROUTINE PRTFLW (LUFLW,LUOT)
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     *** This subroutine prints the results *************************
C     + + + + + + + + + + + + PARAMETERS + + + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR   - Maximum number of branches allowed in model
C     NOSC   - Maximum number of cross sections (nodes) allowed in branch
C
C     + + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
C
C     + + + + + +  COMMON DEFINTIONS  (startdaf.com) + + + + + + + + + +
C     AO(I,N) AQ(I,N) A1(I,N) A2(I,N) DT IOUT(I,N) JGO JTS NBRCH
C     NXSEC(N) TIME TRB(I,N) V(I,N) W1(I,N) W2(I,N) X(I,N)
C
C     + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + + +
      INTEGER I,LUFLW,LUOT,N,NTS
      REAL    A,AA,Q,W
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     A         Area of flow
C     NTS       Number of time steps since start of model
C     Q         Discharge
C     W         Top width of channel in subreach
C
C     + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + +
      INTRINSIC  FLOAT,IFIX,MOD
C     + + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + +
C     + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
 2000 FORMAT (' Day',I4,'  Hour',F6.2,' Branch  node  Discharge')
 2010 FORMAT (20X,I7,I6,G14.4)
 3000 FORMAT (3I5,4E18.5)
C     + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + +
C
C     *********************** Write results  *************************
        TIME=TIME+DT
        I=IFIX(TIME/24.0)+1
        AA=TIME-FLOAT(I-1)*24.0
        NTS=IFIX((TIME+DT/2.0+0.0001)/DT)-JTS
        IF(MOD(NTS,JGO).EQ.0) THEN
          WRITE(LUOT,2000)I,AA
        END IF
        DO 20 N=1,NBRCH
          DO 10 I=1,NXSEC(N)
            IF(MOD(NTS,JGO).EQ.0.AND.IOUT(I,N).EQ.1)THEN
              WRITE(LUOT,2010)N,I,AQ(I,N)
            END IF
            IF(I.LT.NXSEC(N))THEN
              AA=0.0
              IF(I.GT.1)AA=TRB(I,N)
              A=V(I,N)/(X(I+1,N)-X(I,N))
              IF(A.GT.AO(I,N))THEN
                Q=((A-AO(I,N))/A1(I,N))**(1.0/A2(I,N))
              ELSE
                Q=0.0
```

```
              END IF
              IF(Q.GT.0.0)THEN
                W=W1(I,N)*(Q**W2(I,N))
              ELSE
                W=0.0
              END IF
              WRITE(LUFLW,3000)NTS,N,I,AQ(I,N),A,W,AA
            END IF
   10     CONTINUE
          WRITE(LUFLW,3000)NTS,N,NXSEC(N),AQ(NXSEC(N),N)
   20   CONTINUE
  999 RETURN
      END
C
```

Code in the file rtedaf.for

```
C
C      ***********************  ROUTE  ********************************
C
       SUBROUTINE ROUTE
      I                (AO,A1,A2,SL,DT,IDBG,IERR,J,LUOT,NN,NXSEC,
      M                 NS,F,PX,QI,TRB,TF,VI,W1,W2,X)
C
C      + + + PURPOSE + + +
C      Route through each branch.

C      + + + PARAMETERS + + +
       INCLUDE 'params.inc'
C      NOSC   - Maximum number of cross sections (nodes) allowed in branch
C      NOSH   - Maximum number of shocks allowed in brach
C               (NOSH should be at least 4 times NOSC)
C
C      + + + DUMMY ARGUMENTS + + +
       INTEGER     IDBG,IERR,J,LUOT,NN,NS,NXSEC
       REAL        AA,AO(NOSC),A1(NOSC),A2(NOSC),BB,SL(NOSC),DT,F(NOSH),
      $            QI,TRB(NOSC),TF(NOSC),PX(NOSH),VI,W1(NOSC),W2(NOSC),
      $            X(NOSC)
C
C       + + + ARGUMENT DEFINITIONS + + +
C      AO(I)    - cross sectional area at zero flow
C      A1(I)    - coefficient in area equation A=AO+A1(Q**A2).
C      A2(I)    - coefficient in area equation A=AO+A1(Q**A2).
C      SL(I)    - Slope, wave dispersion coefficient = Q/(2*S*W)
C      DT       - time step size in seconds
C      F(K)     - flow in shock K
C      IDBG     - debugger code(0=no, 1=write debug code)
C      J        - time step
C      NN       - branch number
C      NS       - number of shocks
C      NXSEC    - number of Eulerian nodes (subreaches in a branch)
C      PX(K)    - location of u/s boundary of shock K
C      QI       - Insignificant discharge (QP/100000)
C      TRB(I)   - new flow in trib at node I
C      TF(I)    - flow in trib at start of time step at node I
C      VI       - Insignificant volume (QI*DTS)
C      X(I)     - dist of node I from u/s boundry
C
C      + + + LOCAL VARIABLES + + +
       INTEGER  I,IDT,IC(NOSH),INX,JJ,K,KC,KK,KL,KM,KR,K1,L,LT(NOSH),
      #         LTTF(NOSC),MX,N,NSN,NT(NOSH),NTC,NTG,NTW,KAI           ********
       REAL     A,ATF(NOSC),C(NOSH),COF,DL,DLM,PDX,QL,QS,QT,TPT,VM,VS,
      #         VL,VT,XI,XL,XR1,XR,ERV,DLR                             ********
C
C      + + + LOCAL VARIABLE DEFINITIONS + + +
C      A      - cross sectional area A=AO+A1*Q**A2
C      ATF(I) - actual tributary flow at node as liminted by supply
C      COF    - local coefficient
C      TPT    - local coefficient
C      XR1    - local coefficient
C      XI     - local coefficient
C      C(K)   - celerity of shock K
C      DL     - dispersion length DL=(SQRT(2*D*DT)) where D=dispersion coef
C      DLM    - minimum value of DL to keep NS<NOSH
C      IC(K)  - code for shock status (0=move complete, 1=no limits,
C               2=will pass node next, 3=will pass shock next)
C      INX    - number of subreaches
C      K      - shock number
C      KC     - critical shock
C      KL     - last shock in series
C      KM     - number of shock to be mixed
C      KR     - reference shock or wave on upstream side
C      LT(K)  - last time shock K was updated (in seconds*100)
C      LTTF(I)- last time actual trib flow was updated (in sec*100)
C      MX     - subreach where shock is located
C      NSN    - new number of shocks
```

```
C     NT(K)   - next time shock K needs updated (in seconds*100).
C     NTC     - time to next critical point, in 0.01 seconds
C     NTG     - time to pass next node in 0.01 seconds
C     NTW     - time to pass next wave in 0.01 seconds
C     PDX     - part of subreach or shock in question
C     QL      - largest discharge of mixed wave
C     QS      - smallest discharge of mixed wave
C     QT      - trial value of discharge
C     VL      - volume of large wave
C     VM      - volume of mixed shock
C     VS      - volume of small wave
C     VT      - trial volume
C     XL      - left coordinate of mixed shock
C     XR      - right coordinate of mixed shock
C
C     + + + INTRINSICS + + +
      INTRINSIC ABS,FLOAT,SQRT,MAX,MIN,IFIX
C
C     + + + EXTERNALS + + +
      EXTERNAL FMX,FKAI,FTPT,FVOL,FC
C
C     + + + END SPECIFICATIONS + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - last modified October 4, 1998, hej'
C     Compution of volumes made more robust to allow dry sections
C
      INX=NXSEC-1
C
C     **** Add shock and set inflow boundary values statements *********
      TF(1)=TRB(1)
        IF((ABS(TF(1)-F(1))).LT.QI)GO TO 20
        NS=NS+1
        DO 10 K=NS,2,-1
          F(K)=F(K-1)
          PX(K)=PX(K-1)
   10   CONTINUE
   20 CONTINUE
      F(1)=TF(1)
      IF(F(1).GT.0.0)THEN
        A=AO(1)+A1(1)*(F(1)**A2(1))
      ELSE
        A=AO(1)
      END IF
      PX(1)=0.0
      IF(A.GT.AO(1))PX(1)=X(1)-DT*F(1)/A
C
C     ************ Disperse constituents statements ********************
      DLM=0.5*(X(NXSEC)-X(1))/FLOAT(NOSH-NXSEC)
      KR=1
      XR=PX(1)
   30 KL=KR
          IF(KL.GE.NS)GO TO 130
            XL=XR
            CALL FMX(MX,NXSEC,PX(KL+1),X)
            DL=(DT*F(KL)**(1.0-W2(MX))/(W1(MX)*SL(MX)))**0.5
            DLR=A1(MX)*A2(MX)*(F(KL)**(A2(MX)-0.5-W2(MX)*0.5))
            DLR=DLR/((W1(MX)*SL(MX)*DT)**0.5)
            IF(DLR.GT.1.15)IERR=1
            IF(DL.LT.1.0)THEN
              KR=KR+1
              XR=PX(KR)
              GO TO 30
            END IF
          IF(DL.GE.DLM)GO TO 40
            DL=DLM
            WRITE(LUOT,*)' Dispersion length increased to keep',
     $                   ' NS < NOSH'
   40     CONTINUE
          AA=ABS(100.0*(PX(KL+1)-DL-XL))
          IF(AA.GT.DL)THEN
```

```
            XL=MAX(XL,(PX(KL+1)-DL))
          END IF
          XR=XL+2.0*DL
          XR=MIN(XR,X(NXSEC))
          CALL FKAI(KR,NS,PX,XR)
          XR1=XR
          IF(KR.GT.1.AND.KR.LT.NS)XR1=0.5*(PX(KR)+PX(KR+1))
          XR=MIN(XR,XR1)
          IF((KL+1).NE.KR)GO TO 50
            CALL FMX(MX,NXSEC,PX(KL),X)
            TPT=F(KL)
            CALL FTPT(MX,NXSEC,TPT,TF,X,PX(KR))
            IF((ABS(F(KR)-TPT)).LT.QI)GO TO 30
C
C         ****** Compute volume in mixed shock and find range of Q's ***
   50     CALL FVOL(AO,A1,A2,KL,NS,NXSEC,F,PX,TF,VM,X,XL,XR,QS,QL)
          IF(IDBG.EQ.1.AND.NN.EQ.1)WRITE(LUOT,*)'COMPUTE VOLUMES WITH ',
     $                            'KL,KR,XL,XR,DL', KL,KR,XL,XR,DL
C
C       ********** Correct flow in shock KR for tributaries ************
        CALL FMX(MX,NXSEC,PX(KR),X)
        CALL FTPT(MX,NXSEC,F(KR),TF,X,XR)
C
C       *************** Renumber shocks ********************************
        IF(XL.GT.PX(KL).OR.KL.EQ.1)THEN
          NSN=KL+2+NS-KR
          KM=KL+1
        ELSE
          NSN=KL+1+NS-KR
          KM=KL
        END IF
        IF(NSN.GT.NOSH)THEN
          WRITE(*,*)' Too many shocks in branch',NN
          IERR=21
          GO TO 290
        END IF
        IF(NSN.LE.NS)GO TO 80
C         ****************** Add shock *********************************
          DO 70 K=NS,KR,-1
            PX(K+1)=PX(K)
            F(K+1)=F(K)
   70     CONTINUE
   80   PX(KM+1)=XR
        F(KM+1)=F(KR)
        PX(KM)=XL
        IF(XR.GE.X(NXSEC))NSN=NSN-1
        K1=KM+2
        IF(K1.GT.NSN)GO TO 100
          KK=NS-NSN
          IF(KK.LE.0)GO TO 100
            DO 90 K=K1,NSN
              PX(K)=PX(K+KK)
              F(K)=F(K+KK)
   90       CONTINUE
  100   NS=NSN
C
C       *********** Compute mixed discharge ***************************
        F(KM)=1.01*QI
        CALL FVOL(AO,A1,A2,KM,NS,NXSEC,F,PX,TF,VS,X,XL,XR,AA,BB)
        IF(VS.LT.VM)THEN
          AA=1.01*QI
          QS=MAX(QS,AA)
        ELSE
          QS=0.0
        END IF
        F(KM)=QS
        CALL FVOL(AO,A1,A2,KM,NS,NXSEC,F,PX,TF,VS,X,XL,XR,AA,BB)
        F(KM)=QL
        CALL FVOL(AO,A1,A2,KM,NS,NXSEC,F,PX,TF,VL,X,XL,XR,AA,BB)
        ERV=VL-VS
        IF(IDBG.EQ.1.AND.NN.EQ.1)WRITE(LUOT,*)'Start,VM',VM
  110   IF(ABS(ERV).GT.VI)THEN
```

```
C           ************** Need another itteration **********************
            IF(QS.GT.0.0)THEN
              AA=(ALOG(QL)-ALOG(QS))/(ALOG(VL)-ALOG(VS))
              QT=QL*((VM/VL)**AA)
            ELSE
              QT=QS+(QL-QS)*(VM-VS)/(VL-VS)
            END IF
            F(KM)=QT
            CALL FVOL(AO,A1,A2,KM,NS,NXSEC,F,PX,TF,VT,X,XL,XR,AA,BB)
            ERV=VM-VT
            IF(IDBG.EQ.1.AND.NN.EQ.1)WRITE(LUOT,*)'QS,VS,QL,VL,QT,VT',
     #                                 QS,VS,QL,VL,QT,VT
            IF(ERV.GT.0.0)THEN
C             ***************** Concave up *******************************
              QS=QT
              VS=VT
            ELSE
C             ****************** Concave down ****************************
              QL=QT
              VL=VT
            END IF
            GO TO 110
          END IF
C         ****************** Done ****************************************
          KR=KM+1
        GO TO 30
  130   CONTINUE
        IF(PX(NS).GE.X(NXSEC))NS=NS-1
        PX(1)=X(1)
        JJ=IFIX(TIME/DT+0.501)-JTS+1
        IF(IDBG.EQ.1)WRITE(LUOT,*)' AFTER MIX J,N',JJ,NN
        IF(IDBG.EQ.1)WRITE(LUOT,*)' PX=',(PX(K),K=1,NS)
        IF(IDBG.EQ.1)WRITE(LUOT,*)' F=',(F(K),K=1,NS)
C
C       ****************** Add shocks at tributaries ******************
        DO 160 I=2,INX
          LTTF(I)=0
          ATF(I)=0.0
          IF((ABS(TF(I)-TRB(I))).LT.QI)GO TO 160
            CALL FKAI(K,NS,PX,X(I))
            A=AO(I)+A1(I)*(F(K)**A2(I))
            XI=0.01
            IF(A.GT.0.0)XI=QI*DT/A
            IF(ABS(X(I)-PX(K)).LT.XI)GO TO 160
C             *************************** Add shock ********************
              CALL FKAI(KK,NS,PX,X(I))
              NS=NS+1
              K1=KK+2
              DO 150 K=NS,K1,-1
                PX(K)=PX(K-1)
                F(K)=F(K-1)
  150         CONTINUE
              PX(KK+1)=X(I)
              CALL FMX (MX,NXSEC,PX(KK),X)
              TPT=F(KK)
              CALL FTPT(MX,NXSEC,TPT,TF,X,X(I))
              IF(TPT.LE.0.0)THEN
                F(KK+1)=0.0
              ELSE
                F(KK+1)=TPT
              END IF
  160   CONTINUE
        IF(IDBG.EQ.1)WRITE(LUOT,*)'AFTER TF SHOCKS'
        IF(IDBG.EQ.1)WRITE(LUOT,*)'PX=',(PX(K),K=1,NS)
        IF(IDBG.EQ.1)WRITE(LUOT,*)'F=',(F(K),K=1,NS)
C
C       ************************* Move shocks *************************
        DO 180 K=2,NS
          CALL FC(AO,C(K),A1,A2,K,NS,NXSEC,F,PX,TRB,X,QI)
          LT(K)=0
  180   CONTINUE
C       ********************** Compute break points ********************
```

```
      IDT=IFIX(DT*100.0+0.5)
      KC=0
      K=1
  190 K=K+1
        IF(K.GT.NS)GO TO 220
          IF(KC.NE.0)GO TO 220
  200       IC(K)=1
              NT(K)=IDT
              CALL FMX(MX,NXSEC,PX(K),X)
              IF(C(K).LE.0.0)THEN
                NTG=2*IDT
              ELSE
                NTG=LT(K)+IFIX(0.5+100.0*(X(MX+1)-PX(K))/C(K))
              END IF
              IF(NTG.GT.NT(K))GO TO 210
                IC(K)=2
                NT(K)=NTG
  210         IF(K.GE.NS)GO TO 220
                PDX=PX(K+1)-PX(K)
                PDX=PDX+0.01*(C(K)*FLOAT(LT(K))-C(K+1)*FLOAT(LT(K+1)))
                COF=PDX/DT
                TPT=C(K)-C(K+1)
        IF(TPT.LE.COF)GO TO 190
                NTW=IFIX(0.5+100.0*PDX/(C(K)-C(K+1)))
        IF(NTW.GT.NT(K))GO TO 190
                IC(K)=3
                NT(K)=NTW
        IF(KC.EQ.0.AND.K.LT.NS)GO TO 190
C       ********************** Find critical shock ********************
  220   KC=1
        NTC=IDT
        DO 230 K=2,NS
          IF(IC(K).EQ.0)GO TO 230
            IF(NT(K).GT.NTC)GO TO 230
              NTC=NT(K)
              KC=K
  230   CONTINUE
        IF(KC.EQ.1)GO TO 290
C         *********************** Move critical shock *****************
          K=KC
          CALL FMX(MX,NXSEC,PX(K),X)
          PX(K)=PX(K)+0.01*C(K)*FLOAT(NT(K)-LT(K))
          IF(IC(K).EQ.2)PX(K)=X(MX+1)
          IF(IC(K).EQ.3.AND.C(K+1).LE.0.0)PX(K)=PX(K+1)
          LT(K)=NT(K)
          IF(IC(K).NE.1)GO TO 240
C           **************************** Move complete ****************
            IC(K)=0
            GO TO 220
  240     IF(IC(K).NE.3)GO TO 270
C           *********************** Passed shock **********************
            AA=ABS(PX(K)-X(MX+1))
            IF(AA.LT.1.0)THEN
C             **************** Passed node to *************************
              MX=MX+1
              AA=F(K)+TRB(MX)
              IF(AA.LT.0.0)THEN
C               **************** Channel is dry **********************
                ATF(MX)=ATF(MX)-F(K)*FLOAT(NT(K)-LTTF(MX))*0.01
              ELSE
C               ************ No limit on withdrawal *******************
                ATF(MX)=ATF(MX)+TRB(MX)*FLOAT(NT(K)-LTTF(MX))*0.01
            END IF
            LTTF(MX)=NT(K)
            END IF
            DO 260 KK=K,NS
              IF(KK.LE.K)GO TO 250
                PX(KK)=PX(KK+1)
                LT(KK)=LT(KK+1)
                IC(KK)=IC(KK+1)
  250         C(KK)=C(KK+1)
              F(KK)=F(KK+1)
```

```
260       NT(KK)=NT(KK+1)
          NS=NS-1
270     IF(IC(K).NE.2)GO TO 280
C         *********************** Passed node **********************
          MX=MX+1
          IF(MX.LT.NXSEC)GO TO 280
            IC(K)=0
            NS=NS-1
            GO TO 220
280     IF(IC(K).EQ.2)THEN
          AA=F(K)+TRB(MX)
          IF(AA.LT.0.0)THEN
C           **************** Channel is dry ***********************
            ATF(MX)=ATF(MX)-F(K)*FLOAT(NT(K)-LTTF(MX))*0.01
            F(K)=0.0
          ELSE
C           *********** No limit on withdrawal ********************
            ATF(MX)=ATF(MX)+TRB(MX)*FLOAT(NT(K)-LTTF(MX))*0.01
            F(K)=AA
          END IF
          LTTF(MX)=NT(K)
        END IF
        CALL FC(AO,C(K),A1,A2,K,NS,NXSEC,F,PX,TRB,X,QI)
C       ******************** Update NTW for upstream wave ***********
        PDX=PX(K)-PX(K-1)
        PDX=PDX+0.01*(C(K-1)*FLOAT(LT(K-1))-C(K)*FLOAT(LT(K)))
        COF=PDX/DT
        TPT=C(K-1)-C(K)
        IF(TPT.LT.COF)GO TO 200
          NTW=IFIX(0.5+100.0*PDX/TPT)
        IF(NTW.GT.NT(K-1))GO TO 200
          IC(K-1)=3
          NT(K-1)=NTW
        GO TO 200
290   CONTINUE
C     ************  Complete trib withdrawls **********************
      DO 300 I=2,INX
        XR=X(I)-0.1
        CALL FKAI (KAI,NS,PX,XR)
        CALL FMX(MX,NXSEC,PX(KAI),X)
        TPT=F(KAI)
        CALL FTPT (MX,NXSEC,TPT,TRB,X,XR)
        AA=TPT+TRB(I)
        IF(AA.LT.0.0)THEN
C         ************** Channel is dry ****************************
          ATF(I)=ATF(I)-TPT*FLOAT(IDT-LTTF(I))*0.01
          TF(I)=-TPT
        ELSE
C           *********** No limit on withdrawal ********************
          ATF(I)=ATF(I)+TRB(I)*FLOAT(IDT-LTTF(I))*0.01
          TF(I)=TRB(I)
        END IF
        TRB(I)=ATF(I)/DT
300   CONTINUE
      IF(IDBG.EQ.1)WRITE(LUOT,*)'AFTER MOVE J,N, PX=',JJ,NN,
     #                         (PX(K),K=1,NS)
      IF(IDBG.EQ.1)WRITE(LUOT,*)'F',(F(K),K=1,NS)
C
999 RETURN
    END
C
    SUBROUTINE FKAI (KAI,NS,PX,X)
C
C   + + + PURPOSE + + +
C   Find the value of KAI which is the shock located at node I
C
C   + + + PARAMETERS + + +
    INCLUDE 'params.inc'
C   NOSH   - Maximum number of shocks allowed in branch
C
C   + + + DUMMY ARGUMENTS + + +
    INTEGER KAI,NS
```

```
      REAL    PX(NOSH),X
C
C     + + + LOCAL VARIABLES + + +
      INTEGER   ID, K
C
C     + + + INTRINSICS + + +
      INTRINSIC  IFIX
C
C     + + + END SPECIFICATIONS + + +
C
      K=0
    1 K=K+1
        IF(K.GT.NS) GO TO 2
          ID=IFIX(10.0*(X-PX(K)))
      IF(ID.GE.0)GO TO 1
    2 KAI=K-1
C
      RETURN
      END
C
      SUBROUTINE FMX (MX,NXSEC,PX,X)
C
C     + + + PURPOSE + + +
C     Find the subreach occupied by PX
C
C     + + + PARAMETERS + + +
      INCLUDE 'params.inc'
C     NOSC   - Maximum number of cross sections (nodes) allowed in branch
C
C     + + + DUMMY ARGUMENTS + + +
      INTEGER MX,NXSEC
      REAL PX,X(NOSC)
C
C     + + + LOCAL VARIABLES + + +
      INTEGER I,ID
C
C     + + + INTRINSICS + + +
C     INTRINSIC IFIX
C
C     + + + END SPECIFICATIONS + + +
C
      IF(PX.GT.X(1))THEN
        I=0
    1   I=I+1
          IF(I.GT.NXSEC) GO TO 2
     .      ID=IFIX(10.0*(X(I)-PX))
        IF(ID.LE.0)GO TO 1
    2   MX=I-1
      ELSE
        MX=1
      END IF
      IF(MX.GE.NXSEC)MX=NXSEC-1
C
      RETURN
      END
C
      SUBROUTINE FVOL(AO,A1,A2,KL,NS,NXSEC,F,PX,TF,V,X,XL,XR,QS,QL)
C
C     + + + PURPOSE + + +
C     This subroutine finds the volume of water in a subreach
C     bounded by XL and XR as well as find the range of Q's
C
C     + + + PARAMETERS + + +
      INCLUDE 'params.inc'
C
C     + + + PARAMETER DEFINITIONS + + +
C     NOSC   - Maximum number of cross sections (nodes) allowed in brach
C     NOSH   - Maximum number of shocks allowed in branch
C              (NOSH should be at least 4 times NOSC)
C
C     + + + DUMMY ARGUMENTS + + +
      INTEGER KL,NS,NXSEC
```

```
      REAL AO(NOSC),A1(NOSC),A2(NOSC),F(NOSH),PX(NOSH),QL,QS,TF(NOSC),
     #     V,X(NOSC),XL,XR
C
C     + + + LOCAL VARIABLES + + +
      INTEGER    K, MX
      REAL       A, TPT, TXL, TXR
C
C     + + + EXTERNALS + + +
      EXTERNAL   FMX, FTPT
C
C     + + + END SPECIFICATIONS + + +
C
      TXL=XL
      V=0.0
      K=KL
      TPT=F(K)
      CALL FMX(MX,NXSEC,PX(K),X)
      CALL FTPT(MX,NXSEC,TPT,TF,X,XL)
      CALL FMX(MX,NXSEC,XL,X)
      QS=TPT
      QL=TPT
   10   IF(TPT.GT.0.0)THEN
          A=AO(MX)+A1(MX)*(TPT**A2(MX))
        ELSE
          A=AO(MX)
        END IF
        IF(TPT.LT.QS)QS=TPT
        IF(TPT.GT.QL)QL=TPT
        TXR=XR+X(NXSEC)
        IF(K.LT.NS)TXR=PX(K+1)
        IF(TXR.GE.X(MX+1))THEN
          TXR=X(MX+1)
          TPT=TPT+TF(MX+1)
          MX=MX+1
          IF(MX.GE.NXSEC)TXR=XR
        ELSE
          K=K+1
          TPT=F(K)
          TXR=PX(K)
        END IF
        IF(TXR.GE.XR)TXR=XR
        V=V+A*(TXR-TXL)
        TXL=TXR
      IF(TXR.LT.XR)GO TO 10
C
      RETURN
      END
C
      SUBROUTINE FC(AO,C,A1,A2,K,NS,NXSEC,F,PX,TF,X,QI)
C
C     + + + PURPOSE + + +
C     Compute the wave celerity for shock K.
C
C     + + + PARAMETERS + + +
      INCLUDE 'params.inc'
C     NOSC   - Maximum number of cross sections (nodes) allowed in branch
C     NOSH   - Maximum number of shocks allowed in branch
C              (NOSH should be at least 4 times NOSC)
C
C     + + + DUMMY ARGUMENTS + + +
      INTEGER    K,NS,NXSEC
      REAL       AO(NOSC),A1(NOSC),A2(NOSC),C,F(NOSH),PX(NOSH),
     #           TF(NOSC),X(NOSC)
C
C     + + + LOCAL VARIABLES + + +
      INTEGER    MX,MXU
      REAL       AD,AU,COF,QM,TPT,XR
C
C     + + + INTRINSICS + + +
      INTRINSIC  ABS
C
C     + + + EXTERNALS + + +
```

```
      EXTERNAL   FMX, FTPT
C
C     + + + END SPECIFICATIONS + + +
C
      C=0.0
      CALL FMX (MX,NXSEC,PX(K),X)
      AU=AO(MX)
      CALL FMX (MXU,NXSEC,PX(K-1),X)
      AD=AO(MX)
      TPT=F(K-1)
      XR=PX(K)
      COF=ABS(PX(K)-X(MX))
      IF(COF.LT.0.1)XR=X(MX)+0.1
      CALL FTPT(MXU,NXSEC,TPT,TF,X,XR)
      IF(TPT.LE.0.0)TPT=0.0
      QM=(TPT+F(K))/2.0
      IF(QM.GT.QI)C=(QM**(1.0-A2(MX)))/(A2(MX)*A1(MX))
      IF(TPT.GT.QI)AU=AO(MX)+A1(MX)*(TPT**A2(MX))
      IF(F(K).GT.QI)AD=AO(MX)+A1(MX)*(F(K)**A2(MX))
      COF=ABS(AU-AD)
      IF(COF.GT.0.1)COF=ABS((AU-AD)/QM)
      IF(COF.GT.0.01)C=(TPT-F(K))/(AU-AD)
C
      RETURN
      END
C
      SUBROUTINE FTPT (MX,NXSEC,TPT,TF,X,XL)
C
C     + + + PURPOSE + + +
C     Find the flow (TPT) at XL in shock affected
C     by tributary inflow between X(MX) and XL.
C
C     + + + PARAMETERS + + +
      INCLUDE 'params.inc'
C     NOSC   - Maximum number of cross sections (nodes) allowed in branch
C
C     + + + DUMMY ARGUMENTS + + +
      INTEGER   MX,NXSEC
      REAL      TPT,TF(NOSC),X(NOSC),XL
C
C     + + + LOCAL VARIABLES + + +
      INTEGER   I, I1, I2
C
C     + + + END SPECIFICATIONS + + +
C
      I1=MX+1
      I2=0
    1 I2=I2+1
        IF(I2.GE.NXSEC)GO TO 2
      IF(XL.GE.X(I2))GO TO 1
    2 I2=I2-1
      IF(I2.LT.I1)GO TO 4
        DO 3 I=I1,I2
          IF(TPT.LE.0.0)TPT=0.0
          TPT=TPT+TF(I)
    3   CONTINUE
    4 CONTINUE
C
      RETURN
      END
```

Code in the file daf1.for

```
C
C
      SUBROUTINE DAF1AL(IERR,LUFLW,LUGW,LUIN,LUOT,IDAFCB,IDAFBK)
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     Read input and do preliminary computations
C
C     + + +  + + + + + + + + + + + PARAMETERS  + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR    - Maximum number of branches allowed in model
C     NOSC    - Maximum number of cross sections (nodes) allowed in branch
C     NOTS    - Maximum of time steps per ground water step
C
C     + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
      INCLUDE 'ground.com'
C
C     + + + + + + + + + + + COMMON DEFINTIONS (startdaf.com) + + + + + +
C     IDBG,NBRCH NXSEC(N) VIN(I,N)
C
C     +  + + + + + + + + + + COMMON DEFINTIONS  (ground.com) + + + + + +
C     AQGW(I,N,J) BC(I,N,J) BEL(I,N) BTH(I,N) CND(I,N) NCL(I,N) NLY(I,N)
C     NRW(I,N) VGW(I,N,J)
C
C     + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + +
      INTEGER     I,IDAFBK,IDAFCB,IERR,II,INX,J,LUFLW,LUIN,LUGW,LUOT,N,NN
C     CHARACTER*64 VERSN
      CHARACTER*80 TITLE
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     IDAFBK   Central vs backward differencing flag for MODFLOW
C     IDAFCB   Print code for MODFLOW
C     IERR     Error code (0=ok, 20<stop as gracefully as you can)
C     TITLE    Title of program (80 characters max)
C
C     + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
C     + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + +
      EXTERNAL STARTDAF
C     + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + + +
 1000 FORMAT (A)
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + +
 2000 FORMAT(1X,A)
 2010 FORMAT(2I6,2F10.2,G15.3,3I6)
 2020 FORMAT(' Something wrong in subroutine DAF1AL')
 2030 FORMAT(1X,'The DAFLOW ground-water file (file type DAFG) was',/
     1       1X,'not included in the name file')
 2040 FORMAT(1X,' The DAFLOW output flow file (file type DAFF) was',/
     1       1X,'not included in the name file')
C
C     + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - last modified June 24, 1998 hej '
C
C     ***************** zero arrays and preliminaries ******************
      IF(LUFLW.LE.0) THEN
        WRITE(LUOT,2040)
        STOP
      END IF
      IERR=0
      DO 40 N=1,NOBR
        DO 40 I=1,NOSC
          BEL(I,N)=0.0
          BTH(I,N)=0.0
          CND(I,N)=0.0
          NCL(I,N)=0
          NLY(I,N)=0
          NRW(I,N)=0
```

```
          DO 40 J=1,NOTS
            BC(I,N,J)=0.0
            AQGW(I,N,J)=0.0
            VGW(I,N,J)=0.0
   40 CONTINUE
C
C     ********************** Initialize DAFLOW ************************
      CALL STARTDAF (IERR,LUFLW,LUIN,LUOT)
      IF(IERR.GT.20)GO TO 999
C
C     ******************** read ground water input ********************
      IF(LUGW.LE.0) THEN
         WRITE(LUOT,2030)
         STOP
      END IF
      READ(LUGW,1000) TITLE
      WRITE(LUOT,2000) TITLE
      READ(LUGW,1000) TITLE
      WRITE(LUOT,2000) TITLE
      READ(LUGW,1000) TITLE
      WRITE(LUOT,2000) TITLE
C
C     ************* read data for each branch and subreach *************
      DO 60 NN=1,NBRCH
        INX=NXSEC(NN)-1
        VGW(1,NN,1)=VIN(1,NN)
        DO 50 II=2,INX
           VGW(II,NN,1)=VIN(II,NN)
           READ(LUGW,*)N,I,BEL(I,N),BTH(I,N),CND(I,N),NLY(I,N),
     #                NRW(I,N),NCL(I,N)
          WRITE(LUOT,2010)N,I,BEL(I,N),BTH(I,N),CND(I,N),NLY(I,N),
     #                    NRW(I,N),NCL(I,N)
   50   CONTINUE
   60 CONTINUE
      IDAFCB=0
      IDBG=0
      IDAFBK=0
      READ(LUGW,1000) TITLE
      READ(LUGW,*,END=70) IDAFCB,IDBG,IDAFBK
   70 IF(IDAFCB.LT.0) WRITE(LUOT,*)
     1    ' CELL-BY-CELL FLOWS WILL BE PRINTED WHEN ICBCFL NOT 0'
      IF(IDAFCB.GT.0) WRITE(LUOT,*)
     1    ' CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT',IDAFCB
      IF(IDBG.NE.1) WRITE(LUOT,*) ' DAF debugging is turned off'
      IF(IDBG.EQ.1) WRITE(LUOT,*) ' DAF debugging is turned on'
      IF(IDAFBK.EQ.0) WRITE(LUOT,*)
     1    ' DAFLOW is using central differencing for ground-water head'
      IF(IDAFBK.NE.0) WRITE(LUOT,*)
     1    ' DAFLOW is using backward differencing for ground-water head'
  999 CLOSE(LUGW)
      IF(IERR.GT.20)THEN
        WRITE(LUOT,2020)
        STOP
      END IF
      RETURN
      END
C
      SUBROUTINE DAF1AD(DELT,IERR,ITMUNI,LUIN,LUOT)
C
C     + + + + + + + + + + + + + PURPOSE + + + + + + + + + + + + + + +
C     Compute NHRR, set VIN for repeated cycles, and
C     read boundary conditions for NHRR time steps
C
C     + + +  + + + + + + + + + + PARAMETERS + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C
C     + + + + + + + + + + + + COMMONS + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
      INCLUDE 'ground.com'
C
C     + + + + + + + + + + + ++ COMMON VARIABLES (startdaf.com) + + + + + +
C     DT F(K,N) FI(K,N) JTS NBRCH NHRR NS(N) NSI(N) NXSEC(N)
```

```
C      PX(K,N) PXI(K,N) TF(I,N) TFI(I,N) TIME TRB(I,N) VIN(I,N)
C
C      + + + + + + + + + + + + + + COMMON VARIABLES (ground.com)+ + + + + +
C      BC(I,N,J) VGW(I,N)
C
C      + + + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + +
       INTEGER I,IERR,INX,ITMUNI,J,K,LUIN,LUOT,N
       REAL    AA,DELT
C
C      + + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C      DELT     Unitless time step size in MODFLOW
C      IERR     Error code (0=ok, 20<stop as gracefully as you can)
C      ITMUNI   Code for units of DELT (1=sec,2=min,3=hr,4=day,5=year)
C
C      + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + + +
       INTRINSIC  ABS, FLOAT, IFIX
C
C      + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + + + +
C      EXTERNAL GETBC
C
C      + + + + + + + + + + + + +  INPUT FORMATS + + + + + + + + + + + + + + +
C      + + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
 2000   FORMAT(' Something wrong in subroutine DAF1AD for time',I5)
C       + + + + + + + + + + + + END SPECIFICATIONS  + + + + + + + + + + + + +
C
C      ***************** Unix what information ************************
C      INCLUDE 'versn.inc'
C      VERSN = '@(#)DAFLOW - written by HEJ June 24, 1998'
C
C      *********************  Set initial conditions  ******************
        DO 20 N=1,NBRCH
         NSI(N)=NS(N)
         INX=NXSEC(N)-1
         DO 10 I=1,INX
           TFI(I,N)=TF(I,N)
           VIN(I,N)=VGW(I,N,NHRR)
           BC(I,N,1)=BC(I,N,NHRR)
   10    CONTINUE
         DO 20 K=1,NS(N)
           FI(K,N)=F(K,N)
           PXI(K,N)=PX(K,N)
   20   CONTINUE
C     ***  Compute number of daflow time steps per MODFLOW time step ****
       AA=0.0
       IF(ITMUNI.EQ.1)AA=DELT/(3600.0*DT)
       IF(ITMUNI.EQ.2)AA=DELT/(60.0*DT)
       IF(ITMUNI.EQ.3)AA=DELT/DT
       IF(ITMUNI.EQ.4)AA=DELT*24.0/DT
       IF(ITMUNI.EQ.5)AA=DELT*365.0/DT
       NHRR=IFIX(AA)
       AA=ABS(AA-FLOAT(NHRR))
       IF(AA.GT.0.01)THEN
         WRITE(LUOT,*)' MODFLOW time step is not an even multiple of',
      #              ' the daflow time step.'
         IERR=22
       END IF
       WRITE(LUOT,*)' No of DAFLOW steps per MODFLOW step = ',NHRR
       DO 50 J=1,NHRR
         DO 30 N=1,NBRCH
           DO 30 I=1,NXSEC(N)
             IF(J.GT.1) BC(I,N,J)=BC(I,N,J-1)
             TRB(I,N)=BC(I,N,J)
   30    CONTINUE
         CALL GETBC (IERR,J,LUIN,LUOT)
         DO 50 N=1,NBRCH
           INX=NXSEC(N)-1
           DO 50 I=1,INX
             BC(I,N,J)=TRB(I,N)
   50  CONTINUE
       IF(IERR.GT.20)THEN
         I=IFIX(TIME/DT+0.501)-JTS+1
         WRITE(LUOT,2000)I
```

```
        STOP
      END IF
      RETURN
      END
C
      SUBROUTINE DAF1FM (IERR,ITMUNI,HNEW,HOLD,LUOT,
     1        IBOUND,HCOF,RHS,NCOL,NROW,NLAY,KITER,IDAFBK)
C
C     + + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + + + +
C     *****This subroutine solves daflow for NHRR time steps and computes
C     the ground water exchange.
C     + + + + + + + + + + + + + + PARAMETERS + + + + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     NOBR   - Maximum number of branches allowed in model
C
C     + + + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
      INCLUDE 'ground.com'
C
C     + + + + + + + + + COMMON DEFINTIONS  (startdaf.com)  + + + + + + + +
C     AQ(I,N) NBRCH NHRR NXSEC(N) TIME TRB(I,N) V(I,N) VIN(I,N)
C
C     + + + + + + + + + COMMON DEFINTIONS  (ground.com)  + + + + + + + + +
C     AQGW(I,N,J) BC(I,N,J) CCSTR(I,N) NCL(I,N) NLY(I,N) NRW(I,N)
C     RHSSTR(I,N) SEP(I,N) SSEP(I,N) VGW(I,N)
C
C     + + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + + + +
      INTEGER      I,IERR,INX,ITMUNI,J,JCD(NOBR),JN,K,L,LUOT,N,
     #             NCD(NOBR),NN
      INTEGER IDAFBK,NCOL,NROW,NLAY,IBOUND(NCOL,NROW,NLAY),KITER
      DOUBLE PRECISION HNEW(NCOL,NROW,NLAY)
      REAL HCOF(NCOL,NROW,NLAY),RHS(NCOL,NROW,NLAY)
      REAL AA,HOLD(NCOL,NROW,NLAY),VO
C     CHARACTER*64 VERSN
C
C     + + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     HNEW(M,N,L) Ground water head at end of time step in cell M,N,L
C     HOLD(M,N,L) Ground water head at start of time step in cell M,N,L
C     IDAFBK   Central vs backward differencing flag for MODFLOW
C     IERR     Error code IERR<20 for warning, IERR>20 fatal
C              (1=DL too large, 21=too many shocks)
C     ITMUNI   Code for units of DELT (1=sec,2=min,3=hr,4=day,5=year)
C     JCD(M)   Code for junction mixing (0=mixed, 2=not mixed,
C                  1=not all inflows known)
C     NCD(N)   Branch code (0=routed, 1=not routed)
C     NCOL     Number of columns in ground-water model
C     NLAY     Number of layers in ground-water model
C     NROW     Number of rows in ground-water model
C     VO     . Volume in subreach at beginning of time step
C
C     + + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + + +
      INTRINSIC FLOAT,IFIX
C     + + + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + + +
      EXTERNAL PRERTE, SETJNVL, SEEP, RTBR, LIMSEEP, FGQ, SETJV2
C
C     + + + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + + +
C
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + + +
 2000 FORMAT(' Warning DL>C DT, Increase DT to smooth.')
 2010 FORMAT(' Something wrong in subroutine DAF1FM for time',I5)
 2020 FORMAT(' Too many waves in branch',I3,' at J=',I5)
C
C     + + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - last modified June 24, 1998 by hej '
C     Broken into subroutines for use with MODFLOW
C
C     ******************** Preliminaries ****************************
      CALL PRERTE
      DO 10 N=1,NBRCH
```

```
         DO 10 I=1,NXSEC(N)
           SEP(I,N)=0.0
           SSEP(I,N)=0.0
           CCSTR(I,N)=0.0
           RHSSTR(I,N)=0.0
   10    CONTINUE
C     ************************ Start time loop ************************
      IERRR=0
      DO 300 J=1,NHRR
        CALL SETJNVL (JCD,NCD)
        CALL SEEP (HNEW,HOLD,J,LUOT,IBOUND,NCOL,NROW,NLAY,KITER,
     1            IDAFBK)
        IF(IERR.GT.20)GO TO 900
C       ************* Add seepage to trib flow ************************
        DO 20 N=1,NBRCH
          DO 20 I=1,NXSEC(N)
            TRB(I,N)=BC(I,N,J)+SEP(I,N)
   20   CONTINUE
C
C       ************************* Route branches *********************
        DO 200 NN=1,NBRCH
          CALL RTBR (IERR,LUOT,J,JCD,JN,N,NCD)
          IF(IERR.EQ.1)IERRR=1
          IF(IERR.GT.20)GO TO 900
          AQGW(1,N,J)=AQ(1,N)
          DO 100 I=1,NXSEC(N)
            IF(I.LT.NXSEC(N))THEN
              IF(I.GT.1. AND. NLY(I,N).GT.0 )CALL LIMSEEP (HOLD,I,
     1                    J,LUOT,N,NCOL,NROW,NLAY,IDAFBK)
              IF(J.EQ.1)THEN
                VO=VIN(I,N)
              ELSE
                VO=VGW(I,N,J-1)
              END IF
              CALL FGQ (I,J,LUOT,N,VO)
            END IF
            AQGW(I,N,J)=AQ(I,N)
            VGW(I,N,J)=V(I,N)
  100     CONTINUE
          CALL SETJV2 (JCD,JN,NCD)
  200   CONTINUE
  300 CONTINUE
C     ************************ End of time loop ***********************
C
      IF(IERRR.EQ.1)WRITE(LUOT,2000)
      AA=1.0
      IF(ITMUNI.EQ.2)AA=60.0
      IF(ITMUNI.EQ.3)AA=3600.0
      IF(ITMUNI.EQ.4)AA=86400.0
      IF(ITMUNI.EQ.5)AA=31536000.0
      DO 400 N=1,NBRCH
        INX=NXSEC(N)-1
        DO 400 I=2,INX
          L=NLY(I,N)
          IF(L.GT.0) THEN
            K=NRW(I,N)
            NN=NCL(I,N)
            IF(IBOUND(NN,K,L).GT.0) THEN
              RHS(NN,K,L)=RHS(NN,K,L)+AA*RHSSTR(I,N)/FLOAT(NHRR)
              HCOF(NN,K,L)=HCOF(NN,K,L)-AA*CCSTR(I,N)/FLOAT(NHRR)
            END IF
          END IF
  400 CONTINUE
  900 CONTINUE
C       ************* Nasty error comes to here ***********************
        IF(IERR.GT.20)THEN
          I=IFIX(TIME/DT+0.501)-JTS+1
          WRITE(LUOT,2010)I
          IF(IERR.EQ.21)WRITE(LUOT,2020)N,I
          STOP
        END IF
      RETURN
```

```
      END
C
      SUBROUTINE SEEP (HNEW,HOLD,J,LUOT,IBOUND,NCOL,NROW,NLAY,
     1           KITER,IDAFBK)
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     *****This subroutine computes the seepage to the channel
C     + + + + + + + + + + + + PARAMETERS + + + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     + + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
      INCLUDE 'ground.com'
C
C     + + + + + + + + COMMON DEFINTIONS  (startdaf.com)  + + + + + + + +
C     AO(I,N) A1(I,N) A2(I,N) IDBG NBRCH NHRR NXSEC(N) VIN(I,N)
C     W1(I,N) W2(I,N) X(I,N)
C
C     + + + + + + + + COMMON DEFINTIONS  (ground.com)  + + + + + + + + +
C     BEL(I,N) BTH(I,N) CND(I,N) CSTR(I,N) NCL(I,N) NLY(I,N)
C     NRW(I,N) QSTR(I,N) SEP(I,N) STAGE(I,N) VGW(I,N)
C
C     + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + + +
      INTEGER I,IDAFBK,INX,J,KITER,LUOT,N
      INTEGER NCOL,NROW,NLAY,IBOUND(NCOL,NROW,NLAY)
      DOUBLE PRECISION HNEW(NCOL,NROW,NLAY)
      REAL A,AA,AR,DPT,HD,HOLD(NCOL,NROW,NLAY),Q,W
C     CHARACTER*64 VERSN
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     A         Cross sectional area of flow in subreach
C     AR        Surface area of water in subreach
C     DPT       Depth of flow (A/W)
C     HNEW(M,N,L) Ground water head at end of time ste in cell M,N,L
C     HD        Head, either water surface elev or seepage head
C     HOLD(M,N,L) Ground water head at start of time step in cell M,N,L
C     IDAFBK    Central vs backward differencing flag for MODFLOW
C     J         Time step
C     W         Top with of water surface in subreach
C
C     + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + +
C     INTRINSIC  FLOAT
C
C     + + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + +
C
C     + + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + +
C
C     + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
 2000 FORMAT(' For time step ',I5,', branch ',I3,
     #       ' The requested Seepage =')
 2010 FORMAT(10G11.4)
C
C     + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + +
C
C     unix what information
C     INCLUDE 'versn.inc'
C     VERSN = '@(#)DAFLOW - coded by hej June 2,1997'
C
C     ****************** Compute seepage terms *********************
      DO 20 N=1,NBRCH
        INX=NXSEC(N)-2
        DO 10 I=1,INX
          SEP(I+1,N)=0.
          QSTR(I+1,N)=0.
          STAGE(I+1,N)=0.
          CSTR(I+1,N)=0.
          IF(NLY(I+1,N).GT.0) THEN
            IF(IBOUND(NCL(I+1,N),NRW(I+1,N),NLY(I+1,N)).NE.0) THEN
C             ******** MODFLOW cell is active ************************
              IF(KITER.EQ.1)THEN
                IF(J.EQ.1) THEN
                  A=VIN(I,N)/(X(I+1,N)-X(I,N))
                ELSE
```

```
              A=VGW(I,N,J-1)/(X(I+1,N)-X(I,N))
            END IF
          ELSE
            A=VGW(I,N,J)/(X(I+1,N)-X(I,N))
          END IF
          IF(A.GT.AO(I,N)) THEN
            Q=((A-AO(I,N))/A1(I,N))**(1.0/A2(I,N))
          ELSE
            Q=0.0
          END IF
          IF(Q.GT.0.0) THEN
            W=W1(I,N)*(Q**W2(I,N))
            DPT=A/W
          ELSE
            W=0.0
            DPT=0.0
          END IF
          AR=W*(X(I+1,N)-X(I,N))
          IF(IDAFBK.EQ.0) THEN
            HD=HOLD(NCL(I+1,N),NRW(I+1,N),NLY(I+1,N))
          ELSE
            HD=HNEW(NCL(I+1,N),NRW(I+1,N),NLY(I+1,N))
          END IF
          AA=HNEW(NCL(I+1,N),NRW(I+1,N),NLY(I+1,N))
          HD=HD+(FLOAT(J)-0.5)*(AA-HD)/FLOAT(NHRR)
          HD=HD-BEL(I+1,N)-DPT
          AA=DPT+BTH(I+1,N)+HD
C          IF(IDBG.EQ.1) WRITE(LUOT,*) ' I,DPT,DPT+BTH+HD',
C     1                                  I+1,DPT,AA
          IF(AA.LT.0.0) THEN
C           * GW head does not have hydraulic connection to stream *
            IF(DPT.GT.0) THEN
              HD=-BTH(I+1,N)-DPT
              SEP(I+1,N)=CND(I+1,N)*HD*AR/BTH(I+1,N)
            ELSE
              SEP(I+1,N)=0.0
            END IF
            QSTR(I+1,N)=SEP(I+1,N)
            STAGE(I+1,N)=0.
            CSTR(I+1,N)=0.
          ELSE
C           ** GW head  has hydraulic connection too stream ********
            IF(DPT.LE.0.0 .AND. HD.LE.0.0) THEN
              SEP(I+1,N)=0.0
              STAGE(I+1,N)=0.0
              CSTR(I+1,N)=0.0
            ELSE
              IF(HD.GT.0.0) THEN
                AA=2.0*W2(I,N)
                IF(A2(I,N).GT.AA)THEN
C               ********* Width depth ratio decreases with Q *******
                  AA=A2(I,N)-W2(I,N)
                  AA=((HD+DPT)*W1(I,N)/A1(I,N))**(1.0/AA)
                  AR=(W1(I,N)*AA**W2(I,N))*(X(I+1,N)-X(I,N))
                  IF(IDBG.EQ.1) WRITE(LUOT,*)
     1      'Width, Area based on gw head',W1(I,N)*AA**W2(I,N),AR
                ELSE
C               ******** Width depth ratio increases with Q ********
                  AR=(W+2.0*HD)*(X(I+1,N)-X(I,N))
                  IF(IDBG.EQ.1) WRITE(LUOT,*)
     1     'Width, Area based on GW head',W+2.0*HD,AR
                END IF
              END IF
              CSTR(I+1,N)=CND(I+1,N)*AR/BTH(I+1,N)
              SEP(I+1,N)=CSTR(I+1,N)*HD
              STAGE(I+1,N)=BEL(I+1,N)+DPT
            END IF
            QSTR(I+1,N)=0.0
          END IF
        END IF
      END IF
C      IF(IDBG.EQ.1) WRITE(LUOT,*) ' I,CSTR,STAGE,QSTR,SEP',
```

```
C     1              I+1,CSTR(I+1,N),STAGE(I+1,N),QSTR(I+1,N),SEP(I+1,N)
   10   CONTINUE
        IF(IDBG.EQ.1)WRITE(LUOT,2000)J,N
        INX=NXSEC(N)-1
        IF(IDBG.EQ.1)WRITE(LUOT,2010)(SEP(I,N),I=2,INX)
   20 CONTINUE
C
      RETURN
      END
C
      SUBROUTINE LIMSEEP (HOLD,I,J,LUOT,N,NCOL,NROW,NLAY,IDAFBK)
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + + +
C     *** This subroutine apportions any increase in TRB (reduction in
C     *** outflow from the stream) that is calculated by ROUTE between
C     *** BC and SEP.  Negative BC values are increased to 0 prior to
C     *** increasing negative SEP values.  Coefficients SSEP, RHSSTR,
C     *** & CCSTR  are also set.
C     + + + + + + + + + + + PARAMETERS + + + + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
      INCLUDE 'ground.com'
C
C     + + + + + + + + COMMON DEFINTIONS  (startdaf.com)  + + + + + + + +
C     DT JTS QI IDBG NHRR TIME TRB(I,N)
C
C     + + + + + + + + COMMON DEFINTIONS  (ground.com)  + + + + + + + + +
C     BC(I,N,J) CCSTR(I,N)  CSTR(I,N) NCL(I,N) NLY(I,N) NRW(I,N)
C     QSTR(I,N) RHSSTR(I,N) SEP(I,N) SSEP(I,N) STAGE(I,N)
C
C     + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + + +
      INTEGER I,IDAFBK,J,JJ,LUOT,N,NCOL,NROW,NLAY
      REAL    AA,BCNEW,HOLD(NCOL,NROW,NLAY),TRBOLD,TRBCHG
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     BCNEW     - Adjusted value of withdrawal caused by lack of water
C     HOLD(M,N,L) Ground water head at start of time step in cell M,N,L
C     IDAFBK    - Central vs backward differencing flag for MODFLOW
C     N         - Branch number
C     NCOL      - Number of columns in ground-water model
C     NLAY      - Number of layers in ground-water model
C     NROW      - Number of rows in ground-water model
C     J         - Time step number
C     TRBOLD    - Value of TRB that was sent to ROUTE (BC+SEP).
C     TRBCHG    - Reduction necessary in the extraction
C
C     + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + +
      INTRINSIC FLOAT,IFIX
C     + + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + INPUT FORMATS  + + + + + + + + + + + + +
C     + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
 4030 FORMAT(' Channel dry, reduced BC withdrawal to',G12.3,
     $        ' at time step',I6,' Branch',I4,' Node',I4)
 4040 FORMAT(' Channel dry, limited GW seepage to',G12.3,
     $        ' at time step',I6,' Branch',I4,' Node',I4)
C     + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + +
C
      JJ=IFIX(TIME/DT+0.501) -JTS +1
      TRBOLD=SEP(I,N)+BC(I,N,J)
C     *** ROUTE will have modified TRB only when TRBOLD is negative. ***
      IF(TRBOLD.LT.0.0) THEN
        TRBCHG=TRB(I,N)-TRBOLD
C       * Apportion change in TRB only if there was a significant change
        IF(TRBCHG.GT. -1.E-6*TRBOLD) THEN
          IF(BC(I,N,J).LT.0) THEN
            IF(-BC(I,N,J).GE.TRBCHG) THEN
C             ********* The entire TRB change is taken from BC *********
              BCNEW=BC(I,N,J)+TRBCHG
              IF(IDBG.EQ.1) WRITE(LUOT,4030) BCNEW,J,N,I
            ELSE
C             ** Part of TRB change is taken from SEP and part from BC *
```

```
            IF(IDBG.EQ.1) WRITE(LUOT,4030) 0.,J,N,I
            SEP(I,N)=SEP(I,N)+BC(I,N,J)+TRBCHG
            QSTR(I,N)=SEP(I,N)
            CSTR(I,N)=0.0
            STAGE(I,N)=0.0
            IF(IDBG.EQ.1) WRITE(LUOT,4040) SEP(I,N),JJ,N,I
          END IF
        ELSE
C         ********* The entire TRB change is taken from SEP *********
          SEP(I,N)=SEP(I,N)+TRBCHG
          QSTR(I,N)=SEP(I,N)
          CSTR(I,N)=0.0
          STAGE(I,N)=0.0
           JJ=IFIX(TIME/DT+0.501)-JTS+1
          IF(IDBG.EQ.1) WRITE(LUOT,4040) SEP(I,N),JJ,N,I
        END IF
      END IF
    END IF
C
C     ************** Accumulate SSEP, RHSSTR, and CCSTR ***************
      IF(IDAFBK.EQ.0) THEN
        AA=(FLOAT(J)-.5)/FLOAT(NHRR)
      ELSE
        AA=1.0
      END IF
      SSEP(I,N)=SSEP(I,N)+SEP(I,N)
      RHSSTR(I,N)=RHSSTR(I,N)
     1             +CSTR(I,N)*HOLD(NCL(I,N),NRW(I,N),NLY(I,N))*(1.-AA)
     2             -STAGE(I,N)*CSTR(I,N)+QSTR(I,N)
      CCSTR(I,N)=CCSTR(I,N)+CSTR(I,N)*AA
      IF(IDBG.EQ.1)THEN
        IF(N.EQ.1) WRITE(LUOT,*)'Final I, SEP ',I,SEP(I,N)
C       WRITE(LUOT,*)'I,SSEP,CCSTR,RHSSTR ',
C    1                                  I,SSEP(I,N),CCSTR(I,N),RHSSTR(I,N)
      END IF
      RETURN
      END
C
      SUBROUTINE DAF1BD (LUFLW,LUOT,ITMUNI,DELT,VBVL,VBNM,MSUM,
     #           KSTP,KPER,IDAFCB,ICBCFL,BUFF,PERTIM,TOTIM,NCOL,NROW,
     #           NLAY,IBOUND)
C
C     + + + + + + + + + + + + + PURPOSE  + + + + + + + + + + + + + + + +
C     *** This subroutine prints the results *************************
C     + + + + + + + + + + + + PARAMETERS + + + + + + + + + + + + + + + +
      INCLUDE 'params.inc'
C     + + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + +
      INCLUDE 'startdaf.com'
      INCLUDE 'ground.com'
C
C     + + + + + +  COMMON DEFINTIONS  (startdaf.com) + + + + + + + + + +
C     AQ(I,N) NBRCH NHRR NXSEC(N) TRB(I,N) V(I,N)
C
C     + + + + + + + + COMMON DEFINTIONS  (ground.com)  + + + + + + + + +
C     AQGW(I,N,J) BC(I,N,J) NCL(I,N) NRW(I,N) NLY(I,N) SSEP(I,N)
C     VGW(I,N,J)
C
C     + + + + + + + + + + LOCAL VARIABLES  + + + + + + + + + + + + + + +
      INTEGER NCOL,NROW,NLAY,IBOUND(NCOL,NROW,NLAY)
      INTEGER I,IBD,ICBCFL,IDAFCB,INX,ITMUNI,J,KPER,KSTP,LUFLW,LUOT,N
      INTEGER IBDLBL,IC,IL,IR
      REAL AA,DELT,BUFF(NCOL,NROW,NLAY),TOTIM,VBVL(4,MSUM)
      REAL RATE,RIN,ROUT,ZERO
      CHARACTER*16 VBNM(MSUM),TEXT
      DATA TEXT/'          DAFLOW'/
C
C     + + + + + + + + + + + LOCAL DEFINITIONS  + + + + + + + + + + + + +
C     DELT     Unitless time step size in MODFLOW
C     IDAFCB   Print code for MODFLOW
C     ITMUNI   Code for units of DELT (1=sec,2=min,3=hr,4=day,5=year)
C
      DOUBLE PRECISION RATIN,RATOUT,RRATE
```

```
C     + + + + + + + + + + + + + INTRINSICS + + + + + + + + + + + + + + +
C     INTRINSIC  FLOAT
C     + + + + + + + + + + + + + EXTERNALS  + + + + + + + + + + + + + + +
C     EXTERNAL PRTFLW, UBDSV2, UBDSVA, UBUDSV
C
C    + + + + + + + + + + + + + INPUT FORMATS + + + + + + + + + + + + + + +
C     + + + + + + + + + + + + + + OUTPUT FORMATS + + + + + + + + + + + + +
 2000 FORMAT(1X,/1X,A,'   PERIOD',I3,'   STEP',I3)
 2010 FORMAT(1X,'REACH',I4,'   LAYER',I3,'   ROW',I4,'   COL',I4,
     1       '   RATE',1PG15.6)
C     + + + + + + + + + + + + END SPECIFICATIONS + + + + + + + + + + + +
C
C     *********************** Write results  ************************
      DO 50 J=1,NHRR
        DO 20 N=1,NBRCH
          DO 20 I=1,NXSEC(N)
            AQ(I,N)=AQGW(I,N,J)
            V(I,N)=VGW(I,N,J)
            TRB(I,N)=BC(I,N,J)
   20   CONTINUE
        CALL PRTFLW (LUFLW,LUOT)
   50 CONTINUE
C
C  COMPUTE MODFLOW'S BUDGET TERMS
        AA=1.0
        IF(ITMUNI.EQ.2)AA=60.0
        IF(ITMUNI.EQ.3)AA=3600.0
        IF(ITMUNI.EQ.4)AA=86400.0
        IF(ITMUNI.EQ.5)AA=31536000.0
C
C1------INITIALIZE CELL-BY-CELL FLOW TERM FLAG (IBD) AND
C1------ACCUMULATORS (RATIN AND RATOUT).
      ZERO=0.
      RATIN=ZERO
      RATOUT=ZERO
      IBD=0
      IF(IDAFCB.LT.0 .AND. ICBCFL.NE.0) IBD=-1
      IF(IDAFCB.GT.0) IBD=ICBCFL
      IBDLBL=0
C
C2------IF CELL-BY-CELL FLOWS WILL BE SAVED AS A LIST, WRITE HEADER.
      IF(IBD.EQ.2) CALL UBDSV2(KSTP,KPER,TEXT,IDAFCB,NCOL,NROW,NLAY,
     1          NBRCH,LUOT,DELT,PERTIM,TOTIM,IBOUND)
C
C3------CLEAR THE BUFFER.
      DO 60 IL=1,NLAY
        DO 60 IR=1,NROW
          DO 60 IC=1,NCOL
            BUFF(IC,IR,IL)=ZERO
   60 CONTINUE
C
C4------IF NO REACHES, SKIP FLOW CALCULATIONS.
      IF(NBRCH.EQ.0)GO TO 200
C
C5------LOOP THROUGH EACH RIVER REACH CALCULATING FLOW.
        DO 150 N=1,NBRCH
          INX=NXSEC(N)-1
          DO 150 I=2,INX
            IC=NCL(I,N)
            IR=NRW(I,N)
            IL=NLY(I,N)
            RATE=ZERO
            IF(IBOUND(IC,IR,IL).LE.0.OR.IL.LE.0)GO TO 99
            RATE=-AA*SSEP(I,N)/FLOAT(NHRR)
            RRATE=RATE
C
C5G-----PRINT THE INDIVIDUAL RATES IF REQUESTED(IDAFCB<0).
        IF(IBD.LT.0) THEN
          IF(IBDLBL.EQ.0) WRITE(LUOT,2000) TEXT,KPER,KSTP
          WRITE(LUOT,2010) N,IL,IR,IC,RATE
          IBDLBL=1
        END IF
```

```
C
C5H------ADD RATE TO BUFFER.
        BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+RATE
C
C5I-----SEE IF FLOW IS INTO AQUIFER OR INTO RIVER.
        IF(RATE)94,99,96
C
C5J-----AQUIFER IS DISCHARGING TO RIVER SUBTRACT RATE FROM RATOUT.
   94 RATOUT=RATOUT-RRATE
      GO TO 99
C
C5K-----AQUIFER IS RECHARGED FROM RIVER; ADD RATE TO RATIN.
   96 RATIN=RATIN+RRATE
C
C5L-----IF SAVING CELL-BY-CELL FLOWS IN LIST, WRITE FLOW.
   99 IF(IBD.EQ.2) CALL UBDSVA(IDAFCB,NCOL,NROW,IC,IR,IL,RATE,IBOUND,
     1                         NLAY)
  150   CONTINUE
C
C6------IF CELL-BY-CELL FLOW WILL BE SAVED AS A 3-D ARRAY,
C6------CALL UBUDSV TO SAVE THEM.
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IDAFCB,BUFF,NCOL,NROW,
     1                           NLAY,LUOT)
C
C7------MOVE RATES,VOLUMES & LABELS INTO ARRAYS FOR PRINTING.
  200 RIN=RATIN
      ROUT=RATOUT
      VBVL(3,MSUM)=RIN
      VBVL(4,MSUM)=ROUT
      VBVL(1,MSUM)=VBVL(1,MSUM)+RIN*DELT
      VBVL(2,MSUM)=VBVL(2,MSUM)+ROUT*DELT
      VBNM(MSUM)=TEXT
C
C8------INCREMENT BUDGET TERM COUNTER.
      MSUM=MSUM+1
      RETURN
      END
```

Parameter definition file, params.inc

```
INTEGER NOBR,NOSC,NOSH,NOCO,NOPR,NOCP,NOTS
C
      PARAMETER (NOBR=5,  NOSC=35,   NOSH=200,  NOCO=10)
      PARAMETER (NOPR=150,NOCP=4000, NOTS=20)
C
C     + + + PARAMETER DEFINITIONS + + +
C     NOBR    - Maximum number of branches allowed in model
C     NOSC    - Maximum number of cross sections (nodes) allowed in branch
C     NOSH    - Maximum number of shocks allowed in branch
C               (NOSH should be at least 4 times NOSC)
C     NOCO    - Maximum number of constituents allowed
C     NOPR    - Maximum number of parcels allowed in branch
C               (NOPR should be at least 20 + 2 times NOSC)
C     NOCP    - Maximum number of computed or observed points
C     NOTS    - Maximum of time steps per ground water step
```

Common block include file, startdaf.com

```
C     + + + + + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + +
C     INCLUDE 'startdaf.com'
      INTEGER   IDBG,IENG,IOUT(NOSC,NOBR),JNCD(NOBR),JNCU(NOBR),JGO,JTS,
     #          NBRCH,NHR,NHRR,NJNCT,NS(NOBR),NSI(NOBR),NXSEC(NOBR)
      REAL      AO(NOSC,NOBR),AQ(NOSC,NOBR),A1(NOSC,NOBR),
     #          A2(NOSC,NOBR),DT,F(NOSH,NOBR),
     #          FI(NOSH,NOBR),PF(NOBR),PX(NOSH,NOBR),PXI(NOSH,NOBR),QI,
     #          SL(NOSC,NOBR),TF(NOSC,NOBR),TFI(NOSC,NOBR),TIME,
     #          TRB(NOSC,NOBR),V(NOSC,NOBR),VIN(NOSC,NOBR),VI,
     #          W1(NOSC,NOBR),W2(NOSC,NOBR),X(NOSC,NOBR),XFACT
C
      COMMON /STARTI/ IDBG,IENG,IOUT,JNCD,JNCU,JGO,JTS,NBRCH,NHR,NHRR,
     #                NJNCT,NS,NSI,NXSEC
      COMMON /STARTR/ AO,AQ,A1,A2,DT,F,FI,PF,PX,PXI,QI,SL,TF,TFI,
     #                TIME,TRB,V,VIN,VI,W1,W2,X,XFACT
      SAVE /STARTI/,/STARTR/
C
C     + + + + + + + + + + + COMMON DEFINTIONS (startdaf.com) + + + + + +
C     AO(I,N)  Cross sectional area at zero flow for subreach I, branch N
C     AQ(I,N)  Discharge at node I, branch N (time step averaged)
C     A1(I,N)  Cross sectional area at a flow of 1.0.
C     A2(I,N)  Exponent of area equation A=AO+A1(Q**A2).
C     F(K,N)   Steady flow in shock K of branch N
C     FI(K,N)  Initial steady flow in shock K of branch N
C     DT       Time step size (hours)
C     IDBG     Debugger code (0 or N = no, 1 = write debug code)
C     IENG     Input units: 0=metric , 1=English
C     IOUT(I,N) Flag (1 = output) for node I in branch N
C     JNCD(N)  d/s junction no. for branch N (number interior first)
C     JNCU(N)  u/s junction no. for branch N (number interior first)
C     JGO      Number of time steps between output in "flow.out"
C     JTS      Number of time steps from midnight to start of model
C     NBRCH    Number of branchs
C     NHR      Number of time steps to be modeled
C     NHRR     Number of time steps to be repeated
C     NJNCT    Number of interior junctions
C     NS(N)    Number of shocks in branch N
C     NSI(N)   Initial number of shocks in branch N
C     NXSEC(N) Number of nodes in branch N
C     PF(N)    Portion of flow at junction to enter branch N
C     PX(K,N)  Location of u/s boundary of shock K in branch N
C     PXI(K,N) Initial location of u/s boundary of shock K in branch N
C     QI       Insignificant discharge (QP/100000.0)
C     SL(I,N)  Slope, wave dispersion coefficient=Q/(2*S*W)
C     TF(I,N)  Flow  in tributary at node I of branch N
C     TFI(I,N) Initial flow  in tributary at node I of branch N
C     TIME     Time in hours since midnight on model start day
```

```
C      TRB(I,N) New flow in tributary at node I of branch N
C      V(I,N)   Volume of water in subreach I, of branch N
C      VIN(I,N) Initial volume of water in subreach I of branch N
C      VI       Insignificant volume (QI*DT, in seconds)
C      W1(I,N)  Coefficient in W=W1(Q)**W2 for subreach I branch N
C      W2(I,N)  Coefficient in W=W1(Q)**W2 for subreach I branch N
C      X(I,N)   Distance of node I in branch N downstream of reference point
C      XFACT    Conversion from miles to feet or meters, depending on IENG
```

Common block include file, ground.com

```
C      + + + + + + + + + + + COMMONS  + + + + + + + + + + + + + + + + + + +
C      INCLUDE 'ground.com'
C
       INTEGER
       REAL     AQGW(NOSC,NOBR,NOTS),BC(NOSC,NOBR,NOTS),BEL(NOSC,NOBR),
     #          BTH(NOSC,NOBR),CND(NOSC,NOBR),SEP(NOSC,NOBR),
     #          SSEP(NOSC,NOBR),VGW(NOSC,NOBR,NOTS)
       REAL CSTR(NOSC,NOBR),STAGE(NOSC,NOBR),QSTR(NOSC,NOBR)
       REAL CCSTR(NOSC,NOBR),RHSSTR(NOSC,NOBR)
C
       COMMON /GROUNDI/ NCL,NLY,NRW
       COMMON /GROUNDR/ AQGW,BC,BEL,BTH,CND,SEP,SSEP,
     1              CSTR,STAGE,QSTR,CCSTR,RHSSTR,VGW
       SAVE /GROUNDI/,/GROUNDR/
C
C      +  + + + + + + + + + + COMMON DEFINTIONS  (ground.com) + + + + + +
C      AQGW(I,N,J) Discharge at node I, brch N, averaged during time step J
C      BC(I,N,J) Boundary condition for node I, branch N, & time step J.
C      BEL(I,N)  Elevation of stream bed for subreach I, branch N
C      BTH(I,N)  Thickness of the stream bed for subreach I, branch N
C      CND(I,N)  Hydraulic conductivity of streambed for subreach I, branch N
C      CSTR(I,N) Zero if water table is below river bottom
C                  Seepage per unit head otherwise
C      NCL(I,N)  Column number of seepage connection to subreach I, branch N
C      NLY(I,N)  Layer number of seepage connection to subreach I, branch N
C      NRW(I,N)  Row number of seepage connection to subreach I, branch N
C      QSTR(I,N) Zero if water table is abov river bottom, seepage otherwise
C      SEP(I,N)  Seepage to river subreach I, branch N during daflow time step
C      SSEP(I,N) Seepage to river subreach I, branch N during MODFLOW time step
C      STAGE(I,N) Elev of river surface if water table above river bottom
C                  Zero if water table is below river bottom.
C      VGW(I,N)    Volume of water in subreach I of branch N, time J
```

APPENDIX B. MODFLOW DATA FILES FOR EXAMPLE 1 SIMULATION

MODFLOW name file for Example 1 simulation:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
LIST 8 example1.lst

BAS  9 example1.bas

BCF 11 example1.bcf

RCH 18 example1.rch

SIP 19 example1.sip

OC  22 example1.oc

DAF  31 example1.inf

DAFG 32 example1.ing

DAFF 90 bltm.flw
```

MODFLOW Basic Package file, example1.bas:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
TEST PROBLEM 1--CONSTANT STREAM STAGE AND VARIABLE RECHARGE TO AQUIFER
"

"
         1        13        39       144         1
Options
         0         1
CONSTANT 1
      999.
INTERNAL 1.0  (10F8.0)  16
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
```

```
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
  58.346  58.258  58.132  57.955  57.730  57.459  57.138  56.775  56.370  55.926
  55.445  54.930  54.384  53.810  53.213  52.595  51.961  51.314  50.659  50.000
  50.659  51.314  51.961  52.595  53.213  53.810  54.384  54.930  55.445  55.926
  56.370  56.775  57.138  57.459  57.730  57.955  58.132  58.258  58.346
   1296000.        2       1.0
[Repeat the previous line an additional 143 times.]
```

MODFLOW Block-Centered Flow Package file, example1.bcf:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
         0         0      1E30         0         0         0         0
 0
CONSTANT 1.
INTERNAL 100. (39F2.0) 0
 3 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 2 2 2 2 2 2 3
CONSTANT 1000.
CONSTANT 0.2
CONSTANT .037
```

MODFLOW Recharge Package file, example1.rch:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
         1         0

         1

CONSTANT 3.2865E-09

         1

CONSTANT 2.8250E-08

         1

CONSTANT 7.1487E-08
         1
CONSTANT 1.2141E-07
         1
CONSTANT 1.6465E-07
         1
CONSTANT 1.8961E-07
         1
CONSTANT 1.8961E-07
```

```
         1
CONSTANT 1.6465E-07
         1
CONSTANT 1.2141E-07
         1
CONSTANT 7.1487E-08
         1
CONSTANT 2.8250E-08
         1
CONSTANT 3.2865E-09
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
         1
CONSTANT 0.
```

[Repeat previous 48 lines five additional times – each set of 48 lines covers 24 stress periods.]

MODFLOW Strongly-Implicit Procedure Package file, example1.sip:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
       149         5
        1.     .0001         1         0         1
```

MODFLOW Output Control Option file, example1.oc:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
HEAD PRINT FORMAT 16

PERIOD 1 STEP 1

PRINT HEAD

PRINT BUDGET
PERIOD 121 STEP 2
PRINT HEAD
PERIOD 122 STEP 2
PRINT HEAD
PERIOD 123 STEP 2
PRINT HEAD
PERIOD 124 STEP 2
PRINT HEAD
PERIOD 125 STEP 2
```

```
PRINT HEAD
PERIOD 126 STEP 2
PRINT HEAD
PERIOD 127 STEP 2
PRINT HEAD
PERIOD 128 STEP 2
PRINT HEAD
PERIOD 129 STEP 2
PRINT HEAD
PERIOD 130 STEP 2
PRINT HEAD
PERIOD 131 STEP 2
PRINT HEAD
PERIOD 132 STEP 2
PRINT HEAD
PERIOD 133 STEP 2
PRINT HEAD
PERIOD 134 STEP 2
PRINT HEAD
PERIOD 135 STEP 2
PRINT HEAD
PERIOD 136 STEP 2
PRINT HEAD
PERIOD 137 STEP 2
PRINT HEAD
PERIOD 138 STEP 2
PRINT HEAD
PERIOD 139 STEP 2
PRINT HEAD
PERIOD 140 STEP 2
PRINT HEAD
```

APPENDIX C. MODFLOW DATA FILES FOR EXAMPLE 2 SIMULATION

MODFLOW name file for Example 2 simulation:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
LIST                      8 example2.lst

BAS                       7 example2.bas

BCF                      11 example2.bcf

OC                       22 example2.oc
SIP                      23 example2.sip
DAF   28 example2.inf
DAFG  29 example2.ing
DAFF  30 bltm.flw
```

MODFLOW Basic Package file, example2.bas:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
OFR 88-729 Test Problem 2


         1        13        39        32         1  NLAY,NROW,NCOL,NPER,ITMUNI
 11  0  0  0  0  0  0  0  0  0  0 22 23  0  0  0  0 28  0  0  0  0  0  0
         0         0  IAPART,ISTRT
         0         1                                IBOUND layer  1
    999.99  HNOFLO
         0 4.800E+01                                SHEAD layer  1
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 8.640E+04         1 1.000E+00  PERLEN,NSTP,TSMULT
 1.296E+06        15 1.000E+00  PERLEN,NSTP,TSMULT
 3.888E+06         9 1.000E+00  PERLEN,NSTP,TSMULT
```

MODFLOW Block-Centered Flow Package file, example2.bcf:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
         0         0  1.00E+30         0  5.00E-01         1         0
 0
         0 1.000E+00                                TRPY
        11 1.000E+00           (8F10.0)          0  DELR
 3.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02
 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02
 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02
 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02
 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 2.000E+02 3.000E+02
         0 1.000E+03                                DELC
         0 2.000E-01                                SF1 layer  1
         0 3.700E-02                                TRAN layer  1
```

MODFLOW Output Control Option file, example2.oc:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
        16         0         0         0  IHEDFM,IDDNFM,IHEDUN,IDDNUN

         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   1  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   2  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   3  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   4  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   5  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   6  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   7  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   8  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.   9  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  10  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  11  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  12  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  13  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  14  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  15  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  16  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  17  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  18  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  19  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  20  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  21  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  22  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  23  STEP   1
         1         0         0         0  Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1  1,1,IBUDFL,ICBCFL: PER.  24  STEP   1
```

```
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   25   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   26   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   27   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   28   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   29   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   30   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    2
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    3
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    4
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    5
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    6
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    7
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    8
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP    9
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP   10
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP   11
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP   12
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP   13
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         0         0 1,1,IBUDFL,ICBCFL: PER.   31   STEP   14
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   31   STEP   15
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    1
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    2
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    3
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    4
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    5
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    6
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    7
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         0 1,1,IBUDFL,ICBCFL: PER.   32   STEP    8
         0         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
         1         1         1         1 1,1,IBUDFL,ICBCFL: PER.   32   STEP    9
         1         0         0         0 Hdpr,Ddpr,Hdsv,Ddsv
```

MODFLOW Strongly-Implicit Procedure Package file, example2.sip:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
       149         5

        1.    .00001         1         0         1
```

APPENDIX D. MODFLOW DATA FILES FOR EXAMPLE 3 SIMULATION

MODFLOW name file for Example 3 simulation:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
LIST                      8 example3.lst

BAS                       7 example3.bas

BCF                      11 example3.bcf

WEL                      12 example3.wel
PCG                      23 example3.pcg
OC      22 example3.oc
DAF     30 example3.inf
DAFG    31 example3.ing
DAFF    90 bltm.flw
```

MODFLOW Basic Package file, example3.bas:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
DAF test problem

         1        41        21         1         4  NLAY,NROW,NCOL,NPER,ITMUNI

         0         1  IAPART,ISTRT

INTERNAL          1 '(5X,21I2)'     2    IBOUND layer  1
    1  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    2  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    3  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    4  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    5  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    6  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    7  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    8  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
    9  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   10  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   11  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   12  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   13  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   14  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   15  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   16  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   17  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   18  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   19  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   20  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   21  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   22  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   23  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   24  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   25  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   26  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   27  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   28  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   29  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   30  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   31  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   32  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   33  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   34  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
   35  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
```

```
 36  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 37  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 38  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 39  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 40  1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 41 -1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1
   999.99  HNOFLO
INTERNAL  1.  (11F7.0)                   9  shead
 25.30  25.30  25.30  25.30  25.30  25.30  25.30  25.30  25.30  25.30  25.30
 25.30  25.30  25.30  25.30  25.30  25.30  25.30  25.30  25.30

 24.70  24.70  24.70  24.70  24.70  24.70  24.70  24.70  24.70  24.70  24.70
 24.70  24.70  24.70  24.70  24.70  24.70  24.70  24.70  24.70

 24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10
 24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10  24.10
 23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50
 23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50  23.50

 22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90
 22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90  22.90
 22.30  22.30  22.30  22.30  22.30  22.30  22.30  22.30  22.30  22.30  22.30
 22.30  22.30  22.30  22.30  22.30  22.30  22.30  22.30  22.30

 21.70  21.70  21.70  21.70  21.70  21.70  21.70  21.70  21.70  21.70  21.70
 21.70  21.70  21.70  21.70  21.70  21.70  21.70  21.70  21.70

 21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10
 21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10  21.10

 20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50
 20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50  20.50

 19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90
 19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90  19.90
 19.30  19.30  19.30  19.30  19.30  19.30  19.30  19.30  19.30  19.30  19.30
 19.30  19.30  19.30  19.30  19.30  19.30  19.30  19.30  19.30

 18.70  18.70  18.70  18.70  18.70  18.70  18.70  18.70  18.70  18.70  18.70
 18.70  18.70  18.70  18.70  18.70  18.70  18.70  18.70  18.70

 18.10  18.10  18.10  18.10  18.10  18.10  18.10  18.10  18.10  18.10  18.10
 18.10  18.10  18.10  18.10  18.10  18.10  18.10  18.10  18.10

 17.50  17.50  17.50  17.50  17.50  17.50  17.50  17.50  17.50  17.50  17.50
 17.50  17.50  17.50  17.50  17.50  17.50  17.50  17.50  17.50

 16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90
 16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90  16.90
 16.30  16.30  16.30  16.30  16.30  16.30  16.30  16.30  16.30  16.30  16.30
 16.30  16.30  16.30  16.30  16.30  16.30  16.30  16.30  16.30

 15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70
 15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70  15.70
 15.10  15.10  15.10  15.10  15.10  15.10  15.10  15.10  15.10  15.10  15.10
 15.10  15.10  15.10  15.10  15.10  15.10  15.10  15.10  15.10

 14.50  14.50  14.50  14.50  14.50  14.50  14.50  14.50  14.50  14.50  14.50
 14.50  14.50  14.50  14.50  14.50  14.50  14.50  14.50  14.50

 13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90
 13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90  13.90
 13.30  13.30  13.30  13.30  13.30  13.30  13.30  13.30  13.30  13.30  13.30
 13.30  13.30  13.30  13.30  13.30  13.30  13.30  13.30  13.30

 12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70
 12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70  12.70
 12.10  12.10  12.10  12.10  12.10  12.10  12.10  12.10  12.10  12.10  12.10
 12.10  12.10  12.10  12.10  12.10  12.10  12.10  12.10  12.10

 11.50  11.50  11.50  11.50  11.50  11.50  11.50  11.50  11.50  11.50  11.50
```

```
   11.50   11.50   11.50   11.50   11.50   11.50   11.50   11.50   11.50

   10.90   10.90   10.90   10.90   10.90   10.90   10.90   10.90   10.90   10.90   10.90
   10.90   10.90   10.90   10.90   10.90   10.90   10.90   10.90   10.90

   10.30   10.30   10.30   10.30   10.30   10.30   10.30   10.30   10.30   10.30   10.30
   10.30   10.30   10.30   10.30   10.30   10.30   10.30   10.30   10.30

   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700
   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700   9.700
   9.100   9.100   9.100   9.100   9.100   9.100   9.100   9.100   9.100   9.100   9.100
   9.100   9.100   9.100   9.100   9.100   9.100   9.100   9.100   9.100

   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500
   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500   8.500
   7.900   7.900   7.900   7.900   7.900   7.900   7.900   7.900   7.900   7.900   7.900
   7.900   7.900   7.900   7.900   7.900   7.900   7.900   7.900   7.900

   7.300   7.300   7.300   7.300   7.300   7.300   7.300   7.300   7.300   7.300   7.300
   7.300   7.300   7.300   7.300   7.300   7.300   7.300   7.300   7.300

   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700
   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700   6.700
   6.100   6.100   6.100   6.100   6.100   6.100   6.100   6.100   6.100   6.100   6.100
   6.100   6.100   6.100   6.100   6.100   6.100   6.100   6.100   6.100

   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500
   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500   5.500
   4.900   4.900   4.900   4.900   4.900   4.900   4.900   4.900   4.900   4.900   4.900
   4.900   4.900   4.900   4.900   4.900   4.900   4.900   4.900   4.900

   4.300   4.300   4.300   4.300   4.300   4.300   4.300   4.300   4.300   4.300   4.300
   4.300   4.300   4.300   4.300   4.300   4.300   4.300   4.300   4.300

   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700
   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700   3.700

   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100
   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100   3.100

   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500
   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500   2.500
   1.900   1.900   1.900   1.900   1.900   1.900   1.900   1.900   1.900   1.900   1.900

   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300
   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300   1.300

.66666667         32 1.000E+00   PERLEN,NSTP,TSMULT
```

MODFLOW Block-Centered Flow Package file, example3.bcf:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
         0        44      1.E30         0         0         0         0

 0

CONSTANT 1.

CONSTANT 500.

CONSTANT 500.

CONSTANT .20        Storage coefficient

CONSTANT 10000.     Transmissivity
```

MODFLOW Well Package file, example3.wel:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
        21         0
        21
         1         1         1     6000.
         1         1         2     6000.
         1         1         3     6000.
         1         1         4     6000.
         1         1         5     6000.
         1         1         6     6000.
         1         1         7     6000.
         1         1         8     6000.
         1         1         9     6000.
         1         1        10     6000.
         1         1        11     6000.
         1         1        12     6000.
         1         1        13     6000.
         1         1        14     6000.
         1         1        15     6000.
         1         1        16     6000.
         1         1        17     6000.
         1         1        18     6000.
         1         1        19     6000.
         1         1        20     6000.
         1         1        21     6000.
```

MODFLOW Preconditioned Conjugant-Gradient Package file, example3.pcg:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
        50        20         1   MXITER  ITER1  NPCOND

  1.00E-03  1.00E+03  1.00E+00         2         1         0         0
```

MODFLOW Output Control Option file, example3.oc:

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
HEAD PRINT FORMAT 6

DRAWDOWN PRINT FORMAT 6

PERIOD 1 STEP 1

  PRINT HEAD
  PRINT BUDGET
PERIOD 1 STEP 6
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 8
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 11
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 16
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 20
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 24
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 28
  PRINT DRAWDOWN
  PRINT BUDGET
PERIOD 1 STEP 32
  PRINT HEAD
  PRINT DRAWDOWN
  PRINT BUDGET
```