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SURFACE/VADOSE-ZONE PACKAGE FOR MODFLOW

USER'S MANUAL

Surface/Vadose-Zone Package for MODFLOW User's Manual

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1 INTRODUCTION/BACKGROUND

Groundwater flow models can help assess the likely environmental impacts of future development, evaluate alternative groundwater management strategies, aid the development of minimum flows and levels (MFLs), and support consumptive-use permit decisions. The U.S. Geological Survey's MODFLOW simulator is a public domain, widely used, and widely accepted FORTRAN program used for many groundwater models.

While MODFLOW is familiar, easy to use, and well tested, it has limitations in its treatment of groundwater/surface-water interaction. This interaction is an important aspect of the hydrology of Florida, where the water table is generally near land surface, groundwater-fed wetlands are abundant, and evapotranspiration (ET) makes up a significant component of the water budget. In MODFLOW, the groundwater/surface-water interaction is typically treated very simply. Estimates of net groundwater recharge are applied as a specified-flux boundary condition in the Recharge Package and an estimated groundwater ET vs. water-table depth function is applied as a boundary condition in the ET Package.

In recent years, more complex groundwater/surface-water simulators such as MIKE-SHE (from DHI, Inc.), HMS-MODFLOW (from HydroGeologic, Inc.), ISGW (from SDI Environmental Services), and IHM (from Intera, Inc.) have been used for certain applications in Florida. These simulators explicitly model groundwater flow, overland runoff, ET, wetland flow, river flow, and lake flow. However, these simulators are significantly more complex than MODFLOW and much more difficult to use. Additionally, some of these simulators (e.g., MIKE-SHE, HMS-MODFLOW) are proprietary software packages, which cannot be updated or tailored to a specific application without the aid of the software developers and distributors.

GeoTrans has developed an open-source MODFLOW module that automatically calculates overland runoff, ET, and net groundwater recharge from given rainfall and anthropogenic inflows (e.g., irrigation, septic-tank discharge). The module is called the "Surface/Vadose Package for MODFLOW," or "SV Package," because it simulates the water-budget processes at the land surface and in the vadose zone. This Package can be used in lieu of the Recharge Package and ET Package.

This user's manual describes the overall design of the SV Package, the details of its calculations, the input file contents, and the model output. Each MODFLOW procedure is described. The developed Package consists of a set of FORTRAN routines added to the MODFLOW-2000 code (Harbaugh et al. 2000, available from the U.S. Geological Survey) to carry out the computations described here. The augmented MODFLOW simulator, the source code, and test problems are provided with this manual.

Unlike existing simulators such as MIKE-SHE and HMS-MODFLOW, the SV Package does not apply complex partial-differential equations to simulate the processes of overland runoff and unsaturated flow. Rather, the SV Package uses accepted empirical relationships to estimate the components of the surface/vadose water budget. For instance, overland runoff at a grid cell is based on the Soil Conservation Service (SCS) Curve Number method. ET varies linearly from a minimum value when the water table is very deep to a maximum value (potential ET, or PET) when the water table is at or above land surface. Net recharge is calculated by applying a water-balance equation – negative net recharge indicating groundwater discharge. Unlike the more

complex simulators, the SV Package does not simulate the overland (downhill) routing of surface water runoff from cell to cell.

Using empirical relationships for the surface and vadose zone has several advantages over more complex approaches:

- These relationships are already being used for many groundwater models.

- The relationships are simple to understand and apply.

- The focus of the modeling effort (including processing power) is on the groundwater flow field.

- The necessary data for these relationships are often readily available in GIS format (e.g., soil type, land use code), whereas complex models may require additional data that are unavailable and hard to obtain or estimate (e.g., relative permeability functions, land slope, land roughness).

The SV Package is ideally suited for many models in Florida and elsewhere. It is a relatively simple way to translate daily precipitation data into reasonable recharge, ET, and runoff rates. This alleviates the need for some of the time-consuming pre-processing that is often done to generate model input. While some applications may require very complex hydrologic simulators (such as MIKE-SHE, HMS-MODFLOW, or IHM), many only require a relatively simple, realistic method for determining how rainfall (with other inflows) is distributed among runoff, ET, and groundwater recharge. The SV Package is ideal for this – more capable than standard MODFLOW but not as complex (or computationally burdensome) as other simulators.

In addition, unlike some other simulators, the SV Package source code is completely open to SJRWMD and to the public. This allows open discussion on the procedures, critical review of the methods, future updating by SJRWMD or others, and free future use by the District or any contractor.

2   FUNCTIONALITY

2.1   Overall

The SV Package for MODFLOW provides efficient calculation of ET, overland runoff, and net recharge to groundwater given precipitation, irrigation, and other applied inflows (which can vary by time step and by grid cell). The package provides summaries of the surface/vadose water budget and provides the appropriate boundary condition (BC) to MODFLOW for calculation of saturated flow.

The main features of the Surface/Vadose Package are:

- Replaces Recharge (RCH) & ET Packages in function (those packages are not removed from the source code)

- Uses precipitation as the main input, calculates runoff, recharge & ET (unsaturated & saturated ET)

- Modifies MODFLOW variables *HCOF* (head coefficient vector) & *RHS* (right-hand-side vector) like existing BC packages

- Accounts for surface runoff using the SCS Curve Number method

- Allows for a user-specified ET-vs.-depth relationship, with maximum (potential) ET when the water table is at or above the land surface, and minimum ET when the water table is at or below a specified ET extinction (or root) depth

- Provides a simple method to store infiltration in the unsaturated zone when the water table is deep

- Acts like a drain (discharge rather than recharge) when the water table is above the land surface

- Updates flows and BCs each time step rather than each stress period (allowing daily rainfall with longer stress periods)

- Routes runoff to modeled lakes that are modeled with the GeoTrans Lake Package (Council 1999).

Figure 1 conceptually illustrates the processes of the SV Package. The SV Package manages inflows and outflows occurring above the water table and ET occurring below the water table.

2.2 Precipitation

Precipitation amounts (units of L/T) are input by the user in the SV Package input files. A specific value may be entered for each time step and each cell in the top model layer. The SV Package input structure (see Section 3) allows the user to enter data efficiently when the precipitation data are spatially zoned. The SV Package also allows for precipitation input to be read from a binary file (see Section 3).

The current time step precipitation rate is stored in the *PRECIP* array (dimensions *NCOL* by *NROW* where *NCOL* is the number of model columns and *NROW* is the number of model rows).

2.3 Irrigation (Surface Application)

The user may also enter surface application rates (L/T) for each cell and each time step (zones or binary files may be used to reduce input size). Surface application includes irrigation that is applied on the plants and/or land surface. This application, which can increase ET, does not run off unless the groundwater is near or above land surface (Section 2.5 describes the details of the runoff formulation and Section 2.6 describes the ET formulation).

The array *IRRIG* (*NCOL, NROW*) stores the current input irrigation rates.

2.4 Septic Tank and Rapid-Infiltration-Basin Discharge (Vadose-Zone Application)

Inflows (L/T) that occur in the vadose zone are also input by the user in a similar fashion. The vadose-zone inflows, stored in the array *SEPTIC* (*NCOL, NROW*), do not contribute to ET occurring above the water table (see Section 2.6) and are immediately routed to the groundwater (see Section 2.8). (Note: if subsurface discharges are expected to be delayed, they should be included as surface inflows (*IRRIG*)).

2.5 Precipitation Runoff

2.5.1 Application of SCS Runoff Method

In areas where the water table is not above land surface (or very near land surface) the SV Package calculates precipitation runoff by the Soil Conservation Service (SCS) runoff curve number (CN) method (USDA 1986). The user enters a CN value for each cell in the model. The CN scale ranges from 0 to 100, with higher numbers indicating conditions are more favorable for runoff. The SV Package calculates the watershed storage, S, using the empirical relationship:

$$S = \frac{1000\,\text{in}}{CN} - 10\,\text{in} \tag{1}$$

For a given amount of storm rainfall, the SCS runoff is calculated as:

$$SCSrunoff = \frac{(P - 0.2S)^2}{P + 0.8S} \;\text{ for } P > 0.2S$$
$$SCSrunoff = 0 \;\text{ for } P \le 0.2S \tag{2}$$

In equation 2, P is the total precipitation for a single storm event, in inches, and $SCSrunoff$ is the total amount of precipitation (in inches) that runs off from that storm event. The SV Package calculates P using the relationship:

$$P = PRECIP \times DELT \times INCONV \tag{3}$$

where $PRECIP$ refers to the input precipitation rate for the current time step at a certain cell (note that array indices are omitted for convenience), $DELT$ is the length of the current time step, and $INCONV$ is a user-supplied conversion factor for converting from input length units to inches (e.g., $INCONV = 12.0$ if the model length unit is ft). In equation (3), it is assumed that the precipitation in a given time step is due to a single storm event. Note that irrigation ($IRRIG$ array) does not contribute to SCS runoff.

The computed SCS runoff (equation 2) is converted into a rate (L/T) in model length and time units using the relationship:

$$SCSrate = \frac{SCSrunoff}{INCONV \times DELT} \tag{4}$$

2.5.2 Adjustments for Antecedent Moisture Conditions

Runoff is more likely to occur when prior rainfall has saturated the ground surface. Conversely, runoff is less likely to occur during periods when the soil is very dry. In some applications, the SCS curve number (CN) is modified to account for dry and/or wet antecedent moisture conditions. Dry conditions are called antecedent moisture condition I (AMC I), normal conditions are AMC II, and wet conditions are AMC III. An SCS publication (USDA 1986) tabulates the relationships between AMC I, II, and III runoff CNs.

In the SV Package, the user inputs normal-condition (AMC II) CNs for each cell. The SV Package calculates the corresponding AMC I and AMC III CNs. At each time step (or stress period), and for each cell, the user may specify which AMC is in effect.

2.5.3 Adjustment for Shallow Water Table

If the water table is at or above land surface, then all of the precipitation and irrigation falling on the cell will run off (the total ET demand is already being met in this case, see Section 2.6). If the water table is very shallow (e.g., within a few inches of land surface), then a storm event could quickly fill the available vadose-zone storage and cause remaining precipitation and irrigation to run off.

In the SV Package, a piecewise-linear function is used to define precipitation (and irrigation) runoff as a function of model head in a cell. The relationship is illustrated in Figure 2. For any head at or above land surface, the surface runoff rate is equal to *PRECIP + IRRIG*. When the depth to water (defined as cell top minus head, *DTW = TOP − HEAD*) is greater than a certain runoff depth (called *ROdepth*), then the runoff calculated by the SCS method (equations 1 through 4) applies. The value of *ROdepth* represents the soil depth that would be filled during the current time step. This value is calculated in the SV Package from the current values of *PRECIP* and *IRRIG* and the user-input value of vadose-zone specific yield (drainable porosity, called *VADPOR*):

$$ROdepth = \frac{DELT(PRECIP + IRRIG)}{VADPOR} \tag{5}$$

For proper MODFLOW formulation (see Section 3.4), it is necessary to mathematically define the precipitation runoff, *PRO* (*NCOL*, *NROW*) as a function of the simulated groundwater head. The following equations apply:

$$
\begin{aligned}
&PRO = PRECIP + IRRIG && \text{for } HEAD > TOP \\
&PRO = PRECIP + IRRIG - \frac{TOP - HEAD}{ROdepth}(PRECIP + IRRIG - SCSrate) && \text{for } TOP - ROdepth < HEAD < TOP \\
&PRO = SCSrate && \text{for } HEAD < TOP - ROdepth
\end{aligned}
\tag{6}
$$

2.5.4 Input for Precipitation Runoff Calculations

With this formulation, the following input values are required:

- SCS curve number at each cell for normal conditions, stored in the *CN* (*NCOL*, *NROW*) array,

- The conversion factor from model length units to inches, *INCONV* (constant, uniform),

- The antecedent moisture conditions in effect for each cell and each time step, stored in *AMC* (*NCOL*, *NROW*), (1 = dry, 2 or omitted = normal, 3 = wet), and

- Vadose zone specific yield in each cell, stored in *VADPOR* (*NCOL*, *NROW*).

2.6 Evapotranspiration

In the SV Package, ET is separated into two components, the ET that occurs in (or above) the vadose zone, and the ET that is extracted from the saturated zone. The user specifies the minimum total ET (*ETMIN*) and the potential ET (*PET*) for each cell and each model time step.

2.6.1 Vadose-Zone ET

The vadose zone ET is generally taken to be the minimum ET rate (*ETMIN* in L/T units) specified by the user, with certain exceptions. If the precipitation rate is low or zero and irrigation is not applied, then there may not be enough surface inflow to meet the minimum ET demand (in this case, stored infiltration may be used to meet the minimum ET demand as explained in Section 2.8.2). On the other hand, if significant irrigation is applied, then the amount of ET occurring in the vadose zone and above land surface is expected to be larger than *ETMIN* up to the maximum value of *PET* entered by the user. If the head is above land surface, then vadose-zone ET is assumed to be zero (full *PET* supplied by saturated zone).

The amount of vadose-zone ET (*ETVAD*) is calculated in the SV Package as follows (when *HEAD < TOP*):

$$
\begin{aligned}
ETVAD &= PRECIP + IRRIG - PRO &&\text{if } PRECIP + IRRIG - PRO < ETMIN \\
ETVAD &= ETMIN &&\text{if } ETMIN - PRECIP + PRO \le IRRIG \le ETMIN \\
ETVAD &= IRRIG &&\text{if } ETMIN < IRRIG < PET \\
ETVAD &= PET &&\text{if } PET \le IRRIG
\end{aligned}
\tag{7}
$$

Note that this quantity – *ETVAD* – is the amount of water taken from the current time step's precipitation and irrigation for vadose/surface ET. Additional ET may be taken from stored infiltration in the vadose zone is described in section 2.8.2.

2.6.2 Saturated Zone ET

As in standard MODFLOW, total ET is assumed to be a linear function of water table elevation. The maximum saturated-zone ET occurs when the water table is at or above land surface and no saturated-zone ET occurs when the depth to water is below a user-specified extinction depth (*ETDEPTH*). Figure 3 illustrates the ET vs. head relationship (assuming *PRECIP + IRRIG – PRO > ETMIN*).

The maximum saturated-zone ET (*ETSATMAX*) is simply the potential ET (*PET*) less the amount of ET that occurs in (and above) the vadose zone (*ETSATMAX = PET – ETVAD – ETSTOR*, where *ETSTOR* is the ET taken from stored infiltration as described in Section 2.8.2).

The following equations define saturated-zone ET (*ETSAT*) as a function of simulated head:

$$
\begin{aligned}
ETSAT &= 0 &&\text{for } HEAD \le TOP - ETDEPTH \\
ETSAT &= ETSATMAX - \frac{TOP - HEAD}{ETDEPTH} ETSATMAX &&\text{for } TOP - ETDEPTH < HEAD < TOP \\
ETSAT &= ETSATMAX &&\text{for } HEAD \ge TOP
\end{aligned}
\tag{8}
$$

Note in Figure 3 that the total ET (*ETVAD + ETSAT*) is a piecewise linear function of head.

2.6.3 Input for ET calculations

The three user inputs required for ET calculations are: 1) the minimum ET rate (*ETMIN* in L/T units), 2) the potential (maximum) ET rate (*PET* in L/T units), and 3) the ET extinction depth

(*ETDEPTH* in L units). Each of these values are input for each model cell (*NROW*, *NCOL*). *ETMIN* and *PET* may vary by time step.

2.7 Groundwater Drainage

When the water table rises above land surface, the SV Package calculates the amount of water that drains off. The formulation for this groundwater drainage is similar to that used in the MODFLOW Drain Package. Figure 4 shows the groundwater drainage (*GWDRAIN* in L/T units) as a function of model head.

The slope of the drainage vs. head line in Figure 4 is defined by the user input soil leakance (*SOILLEAK* in T^{-1} units). The soil leakance describes the hydraulic connection between the model cell center and the drain condition. For the case of a homogeneous aquifer material in layer 1 with no defined soil/sediment bed, the soil leakance is defined as:

$$SOILLEAK = \frac{K_z}{b/2} \tag{9}$$

where K_z is the vertical hydraulic conductivity of the aquifer/soil and b is the thickness of the cell in layer 1 (*TOP – BOT*). If there is a thin low-conductivity soil layer at the land surface, then the soil leakance can be calculated as the vertical conductivity of that thin soil layer divided by that layer's thickness. The user inputs the *SOILLEAK* array directly in the SV Package input file. The soil leakance array is assumed to be constant in time.

The definition of *GWDRAIN* is therefore:

$$\begin{aligned} GWDRAIN &= 0 & \text{for } HEAD \leq TOP \\ GWDRAIN &= SOILLEAK(HEAD - TOP) & \text{for } HEAD > TOP \end{aligned} \tag{10}$$

2.8 Stored Infiltration

A time delay can be specified so that the recharge from rain events is delayed by some period when the water table is deep. In the SV Package, this depth-dependent time delay is implemented by specifying a time delay vs. water table depth relationship. For ease of conceptualization and implementation, this is done by specifying the maximum number of time steps for a delay (*MAXDELAY*), and the minimum depths for each whole time step delay (*DELAYDEPTH* array, from *1* to *MAXDELAY*). Note that uniform time steps are required for proper use of stored infiltration and that delays occur only in multiples of the time step (0 time step delay, 1 time step delay, 2 time step delay, etc.). Also, be aware that implementation of this option means that the current time-step recharge will not be a continuous function of groundwater head (abrupt change at the depth where time delays begin). This could lead to numerical instability.

The three-dimensional array *STOREDINFIL* is used to keep track of stored infiltration amounts. The first array index goes from zero to *MAXDELAY*, and the other two indices identify model row and column. At the beginning of each time step, the contents of *STOREDINFIL* are shifted so that *STOREDINFIL*(0,*J*,*I*) represents the infiltration to be released in the current time step at row *I* and column *J*. *STOREDINFIL*(*N*,*J*,*I*) represents the infiltration at row *I* and column *J* that will be released *N* time steps in the future.

2.8.1 Delay Depth vs. Time Step Example

The concept of delayed infiltration is best illustrated by example. Suppose the model time step is 1 day and the model length unit is feet. The modeler wants to implement a time-delayed infiltration function such that there is no delay when the depth to water is less than three feet, there is a one week delay when the water table is 10 ft deep, and there is a two week delay when the water table is 15 ft deep or deeper. In this case, the user would specify the maximum delay (*MAXDELAY*) of 14 time steps. The user would then specify the depth that applies for each time-step delay from 1 through 14, as shown in Table 1. Note that the depth values for time step delays 2 through 6 and 8 through 13 are interpolated.

Table 1.   Example Specifications for Infiltration Time Delay

Time Delay (in time steps)	Minimum Depth to Water (ft)
1	3.0
2	4.167
3	5.333
4	6.5
5	7.667
6	8.833
7	10.0
8	10.714
9	11.429
10	12.143
11	12.857
12	13.571
13	14.286
14	15.0

The specified minimum depth values are stored in the vector *DELAYDEPTH* (*MAXDELAY*). *MAXDELAY* and *DELAYDEPTH* are assumed to be constant in time and space.

2.8.2 Use of Stored Infiltration to Meet Minimum ET Demand

Water stored in the vadose zone for later infiltration may be used to meet the minimum ET demand (*ETMIN*) when the current time step's precipitation and irrigation are insufficient (see equation 7, first condition). This is done by stepping through the stored infiltration amounts (if any) in *STOREDINIFIL* and subtracting from storage until *ETVAD + ETSTOR* is equal to *ETMIN* (where *ETSTOR* is the total subtracted amount) or there is no stored infiltration left. The stored water located farthest from the water table (*STOREDINFIL(MAXDELAY-1,J,I)*) is consumed first (and added to *ETSTOR*); if additional water is needed to meet *ETMIN*, then the next amount (*STOREDINFIL(MAXDELAY-2,J,I)*) is used, and so on (the stored infiltration being released in the current time step, *STOREDINFIL(0,J,I)*, is not used). This logic is not used if the stored infiltration option is not invoked in the model or where the water table depth results in a delay of one or zero time steps.

2.9 Net Recharge

The SV Package calculates net recharge to groundwater by applying a water-balance relationship. If the water table is near enough to land surface that there is no time delay, then:

$$RCH = STOREDINFIL(0) + PRECIP + IRRIG + SEPTIC - PRO - ETVAD - ETSAT - GWDRAIN \tag{11}$$

Note that the terms *PRO, ETSAT,* and *GWDRAIN* are functions of head, as illustrated in Figures 2 through 4.

If the water table is deeper, such that there is a time delay of N time steps, then the following equations are applied instead of equation 11:

$$RCH = STOREDINFIL(0) + SEPTIC - ETSAT \tag{12}$$

$$STOREDINFIL(N) = STOREDINFIL(N) + PRECIP + IRRIG - PRO - ETVAD \tag{13}$$

In equation 12, the groundwater recharge is made up of infiltration stored in one or more previous time steps for release in the current time step, plus current subsurface (*SEPTIC*) releases minus the computed saturated-zone ET (which is a function of head). The precipitation, irrigation, runoff, and vadose-zone ET rates are summed (equation 13) to compute stored infiltration for a future time step (which is added to any that is already stored for release in that time step). Note that groundwater drainage is zero since the water table is below land surface in this case. Also, it is assumed that the water table is deep enough (*DTW > ROdepth*) that the precipitation runoff is not a function of head (*PRO = SCSrate*). Therefore, the stored infiltration amount is not a function of head.

2.10 Water Budget Accounting

The SV Package provides special water-budget accounting capabilities to aid in model interpretation. First, the SV Package provides total net recharge rates to the MODFLOW groundwater budget for summary in the list file along with other BCs. The package also allows the user to have the model-wide surface/vadose-zone budget printed separately in the list file (or in a separate data file). The cell-by-cell flow rates for each component of the surface/vadose-zone water budget can be flagged for printing or saving in the usual MODFLOW formats. Alternatively, total cell-by-cell volumes (summed over time steps) can be saved instead of rates (useful for certain types of post-processing). The components of the surface/vadose-zone budget are precipitation inflow, irrigation inflow, septic inflow, runoff outflow, vadose-zone ET outflow, saturated-zone ET outflow, groundwater drainage outflow, vadose-zone storage, and net groundwater recharge/discharge. Section 5 describes some details of the water-budget output produced by the SV Package.

2.11 Specifying Active SV Package Cells and Linking Runoff to the Lake Package

An integer array called *SVUSE(NCOL,NROW)* flags the cells in the model that are handled by the SV Package. Where *SVUSE* is greater than zero, the SV Package will calculate runoff, ET, and groundwater drainage as described above. For cells that have *SVUSE* less than or equal to zero, no computations are made by the SV Package. It is generally a good idea to set *SVUSE* equal to zero in lakes and other water bodies – these features are typically modeled with other

MODFLOW packages. The SV Package also does not make computations at cells outside the MODFLOW domain (*IBOUND* of all layers equal to zero).

Runoff (including groundwater drainage) computed by the SV Package can be automatically routed to lakes that are modeled with the GeoTrans Lake Package for MODFLOW (Version 2.2, Council 1999). To implement this, a flag (*LINKLAKE*) is set to a positive integer and for each cell the user specifies the lake number which receives the runoff (i.e. the lake watershed) in the *SVUSE* array. The runoff volume computed by the SV Package is immediately added to the lake (no time delay). Runoff at cells that have *SVUSE* greater than the number of lakes in the Lake Package is not routed to any lake.

3 MODFLOW PROCEDURES

3.1 Memory Allocation

The SV package uses a FORTRAN module called "Sv_Module" to declare variables that are common to the SV Package subroutines. Each subroutine in the SV Package then invokes the "Use Sv_Module" command to have access to these variables. This removes the need to pass the numerous SV Package variables to and from the main MODFLOW routine. The arrays that are used in the SV Package are run-time allocatable arrays.

A subroutine called "SV_Allocate" is called at the beginning of a MODFLOW simulation when the SV Package is invoked. This routine reserves space in the allocatable arrays needed for the SV Package. The first two lines of the SV Package input file (see Section 4) are read to define the maximum number of time steps for delayed infiltration (*MAXDELAY*) and the cell-by-cell saving options. This routine also opens the secondary data files (see Section 4) that contain the time-variable input data, and reserves space for any zone arrays and multiplier arrays that are used.

3.2 Read and Prepare (Beginning of Simulation)

Once memory has been allocated, the Groundwater Flow Process calls subroutines to read and prepare data that remains constant for the entire simulation. A subroutine called "Sv_Read1" is called when the SV Package is invoked. This subroutine reads in the rest of the main SV Package input file (see Section 4), including the values for *SVUSE*, *CN*, *ETDEPTH*, *VADPOR*, *SOILLEAK*, and *DELAYDEPTH*. Also, for time-variable arrays, a portion of the secondary input files are read if the array is specified to be steady, if a zone array is used, or if a multiplier array is used. The array *STOREDINFIL* is initialized to zero.

3.3 Read, Prepare, and Advance (Each Time Step)

At the beginning of each groundwater flow time step, a second read-and-prepare subroutine, "Sv_Read2," is called to read in new values for *PRECIP*, *IRRIG*, *SEPTIC*, *ETMIN*, *PET*, and *AMC*. These values are read from secondary data files as described in Section 4. Also, this routine shifts the contents of the *STOREDINFIL* array so that *STOREDINFIL*(0) becomes the infiltration to release in the current (upcoming) time-step and *STOREDINFIL*(*MAXDELAY*) is initialized to zero.

3.4 Formulate

The purpose of the formulation routine, "Sv_Formulate," is to apply the head-dependent groundwater flow BC. This is accomplished by modifying the MODFLOW variables *RHS* and *HCOF* in a fashion similar to that of other BC Packages (River, Drain, Recharge, Well, etc.). The *RHS* array is augmented by the head-independent flow component (L^3/T units), with a positive increment used for groundwater outflows (by MODFLOW convention). The *HCOF* array contains the head-dependent flow component (L^2/T units), with a negative increment used when increasing head leads to increased groundwater outflow (or decreased inflow). In each flow-model iteration, MODFLOW clears the *RHS* and *HCOF* variables then calls the formulation routines to augment them.

Using the relationships described in Section 2, the logic for the formulation (at each active SV cell) flows as follows. The BC is applied to the top active layer in a particular row and column. The variables *HEAD*, *RHS*, and *HCOF* are taken from that cell. The *TOP* elevation always comes from layer 1.

3.4.1 Head Above Land Surface (all net recharge components)

First, it is determined whether or not the current estimate of head (in the top active layer of the current row/column) is above the model top elevation. If *HEAD* ≥ *TOP*, then the following relationships apply:

$$PRO = PRECIP + IRRIG$$

$$GWDRAIN = SOILLEAK (HEAD – TOP)$$

$$ETVAD = 0$$

$$ETSAT = PET$$

$$RCH = STOREDINFIL(0) + SEPTIC – PET – SOILLEAK(HEAD – TOP)$$

In this case there is no time delay and *RHS* and *HCOF* are modified as follows (with *A* representing the area of the cell):

$$RHS = RHS – A * [STOREDINFIL(0) + SEPTIC – PET + SOILLEAK * TOP]$$

$$HCOF = HCOF – A * SOILLEAK$$

If the cell is linked to a Lake Package lake, then the computed amounts of *PRO* and *GWDRAIN* are multiplied by the cell area (*A*) and added to the *RUNOFF* inflow for that lake.

3.4.2 DTW Less than ROdepth (all components except ETSAT)

If the current head is between *TOP* and *TOP – ROdepth*, and there is no time delay (*HEAD* ≥ *TOP – DELAYDEPTH(1)*) then, from equation 6,

$$PRO = PRECIP + IRRIG – W * (TOP – HEAD)$$

where *W = (PRECIP + IRRIG - SCSrate)/ROdepth*. In this case, *A * PRO* is added to Lake runoff (if linked to the Lake Package), *ETVAD* is computed by equation 7, and RHS and HCOF are modified as follows (saturated-zone ET is ignored for the moment):

$$RHS = RHS – A * [STOREDINFIL(0) + SEPTIC – ETVAD – W * TOP]$$

$$HCOF = HCOF - A * W$$

3.4.3   DTW Greater than ROdepth (all components except ETSAT)

If the current head is below *TOP – ROdepth* (or if there is a time delay) then

$$PRO = SCSrate$$

and *ETVAD* is computed using equation 7. (*A * PRO* is added to the Lake Package runoff if specified.) Again ignoring saturated ET temporarily, *HCOF* is not modified and, if there is no time delay

$$RHS = RHS - A *[STOREDINFIL(0) +PRECIP -IRRIG +SEPTIC -ETVAD -SCSrate]$$

If there is a time step delay, then *PRECIP*, *IRRIG*, *ETVAD*, and *PRO* are all delayed, and

$$RHS = RHS - A * [STOREDINFIL(0) + SEPTIC]$$

3.4.4   Saturated ET When Head below Top

Saturated-zone ET is addressed by comparing *HEAD* with the *ET* extinction elevation (*TOP – ETDEPTH*). If the current *HEAD* is above the extinction elevation (but below *TOP*), then

$$ETSAT = ETSATMAX - ETSATMAX/ETDEPTH * (TOP - HEAD)$$

RHS and HCOF are further modified as follows:

$$RHS = RHS + A * (ETSATMAX - ETSATMAX * TOP/ETDEPTH)$$

$$HCOF = HCOF - A * ETSATMAX/ETDEPTH$$

ETSAT is zero when the *HEAD* is below the ET extinction elevation, and no modifications to *RHS* or *HCOF* are required.

The value *ETSATMAX* is equal to *PET – ETVAD – ETSTOR*, where *ETSTOR* is the calculated amount of stored infiltration used to meet the minimum ET demand, as explained in Section 2.8.2.

3.5   Calculate Budget

At the end of each time step, when the final *HEAD* estimates are made, the routine "Sv_Budget" calculates the surface/vadose water budget. Each water-budget component is calculated at each SV cell as specified in equations 6, 7, 8, 10, 11, and 12 (volumetric rates are calculated by multiplying by cell area). The net recharge rate (calculated by equation 11 or 12) is saved in the MODFLOW *VBVL* array along with the total recharge applied in the time step (net recharge times *DELT*).

Additionally, the budget routine updates the *STOREDINFIL* array by subtracting any amounts used as *ETSTOR* and by applying equation 13 to add stored infiltration when the water table is deeper than *DELAYDEPTH*(1).

Finally, the budget subroutine produces surface/vadose budget output according to the user-defined options (see Section 4). The output specifications are provided in Section 5.

4 INPUT SPECIFICATIONS

The SV Package is invoked by specifying the name of the main SV Package input file in the MODFLOW name file. The file type (*FTYPE*) of this file should be set to **SV** to identify it as an SV Package input file.

4.1 Main SV Package Input File Format

The main SV Package input file is read during the memory-allocation subroutine and first read-and-prepare subroutine. The records in the SV Package input file are:

```
REC. CONTENTS

0.    [#TEXT]
      (Item 0 is optional – "#" must be in column 1. Item 0 can be repeated
      multiple times.)

1.    INCONV    READLEAK  SVBUDLIST SVBUDTAB   SVCBCFILE MAXDELAY   LINKLAKE

2.    CBCRCH    CBCPRECIP CBCIRRIG   CBCSEPTIC CBCRUNOFF CBCETVAD   CBCETSAT
      CBCGWDRN  CBCSTOR

3.    NFILE

4.    VARNAME   BINFLAG   FILEUNIT  CONVERT    FILENAME
      (Item 4 is repeated NFILE times)

5.    SVUSE(NCOL,NROW)      (U2DINT)

6.    CN(NCOL,NROW)         (U2DREL)

7.    ETDEPTH(NCOL,NROW)    (U2DREL)

8.    VADPOR(NCOL,NROW)     (U2DREL)

9.    SOILLEAK(NCOL,NROW)   (U2DREL)
      (Item 9 is included only if READLEAK > 0.)

10.   DELAYDEPTH(MAXDELAY)
      (Item 10 is included only if MAXDELAY > 0.)
```

Unless otherwise indicated, all records are read in free format by separate Fortran READ statements. Record 10 can be entered on one or more lines.

4.2 Explanation of Variables in the Main SV Package Input File

TEXT – is a character variable (199 characters) that starts in column 2. Any characters can be included in *TEXT*. The "#" character must be in column 1. *TEXT* is printed when the file is read.

INCONV (real) – is the conversion factor (multiplier) from model length units to inches (use 12.0 if model units are feet).

READLEAK (integer) – is a flag. If it is 1 or more, then *SOILLEAK* will be read from this file. If it is 0 or less, then the soil leakance will be computed according to equation 9 using information from the LPF and DIS Packages. **NOTE – LPF/DIS linkage is not yet implemented – set READLEAK > 0.**

SVBUDLIST (integer) – is a flag. If it is 1 or more, then the surface/vadose-zone budget will be printed whenever the groundwater budget is printed. If it is 0 or less, then the surface/vadose-zone budget will never be printed.

SVBUDTAB (integer) – is a flag and unit number. If it is positive, then the overall surface/vadose-zone budget will be output to the specified unit number (this file must be identified as type DATA in the MODFLOW Name File). A separate line will be printed for each time step. If SVBUDTAB is 0 or less, then the overall surface/vadose-zone budget will not be saved to a data file.

SVCBCFILE (integer) – is a flag and unit number. If it is positive, it indicates the file unit number for cell-by-cell saving (identified in the Name File as DATA(BINARY) type). If it is zero, no cell-by-cell terms will be saved. If it is negative, cell-by-cell terms will be printed in the list file.

MAXDELAY (integer) – is the maximum number of time steps for delaying infiltration. Use 0 for no delayed infiltration.

LINKLAKE (integer) – is a flag. If it is 1 or more, then computed runoff (including groundwater drainage) is linked to the Lake Package (version 2.2, Council 1999). Values in the *SVUSE* array specify which lake each cell is linked to (if any). If *LINKLAKE* is 0 or less, then the SV Package runoff is not linked to the Lake Package.

CBCRCH (integer) – is a flag for net recharge (*RCH*) cell-by-cell terms. The terms are saved whenever the "SAVE BUDGET" directive is used in the Output Control file (or *ICBCFL* is not zero). The terms are saved on the unit specified by *SVCBCFILE*. Table 2 describes what the flag values mean. In the cell-by-cell output file, positive values indicate recharge and negative values indicate discharge.

Table 2.   Flag Values for Cell-By-Cell Saving

Value	Meaning
1	Save cell-by-cell flow rates (L^3/T)
2	Save cell-by-cell cumulative volume (L^3) since beginning of simulation
3	Save cell-by-cell cumulative volume (L^3) since beginning of simulation or since last reset, and then reset
11	Save cell-by-cell flow rates per unit area (L/T)
12	Save cell-by-cell cumulative amounts per unit area (L)
13	Save cell-by-cell cumulative amounts per unit area (L) since beginning of simulation or since last reset, and then reset
Other	Do not save cell-by-cell rates

CBCPRECIP (integer) – is a flag for precipitation (*PRECIP*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate precipitation.

CBCIRRIG (integer) – is a flag for irrigation (*IRRIG*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate irrigation.

CBCSEPTIC (integer) – is a flag for septic inflow (*SEPTIC*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate septic inflow.

CBCRUNOFF (integer) – is a flag for precipitation runoff (*PRO*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate runoff.

CBCETVAD (integer) – is a flag for surface/vadose ET (*ETVAD* + *ETSTOR*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate ET loss.

CBCETSAT (integer) – is a flag for saturated-zone ET (*ETSAT*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate ET loss.

CBCGWDRN (integer) – is a flag for groundwater drainage (*GWDRAIN*) cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate drainage.

CBCSTOR (integer) – is a flag for storage change cell-by-cell terms. The definitions are the same as for *CBCRCH*. Positive values indicate net increase in (inflow to) storage; negative values indicate net decrease in (outflow from) storage.

NFILE (integer) – indicates the number of secondary files for time-variable input. Separate data files are required for specification of precipitation, irrigation, septic inflow, minimum ET, potential ET, and antecedent moisture condition.

VARNAME (6 character string) – indicates the type of input to be read. It can be one of the following: PRECIP, IRRIG, SEPTIC, ETMIN, PET, or AMC. Capitalization does not matter.

BINFLAG (integer) – indicates if the input is to be read from a binary (1 or greater) or text (0 or less) file

FILEUNIT (integer) – is the file unit for the specified secondary input file. This file unit should NOT be used in the MODFLOW name file.

CONVERT (real) – is a conversion factor (multiplier) to convert input into model L/T units (ignored if *VARNAME* = AMC)

FILENAME (200 character string) – is the name of the secondary file to be opened for reading the specified input.

SVUSE(*NCOL,NROW*) (integer) – is a flag. Where it is 0 or less, the SV Package is not used. Where it is 1 or more, the SV Package is used. If *LINKLAKE* is greater than zero, the values in *SVUSE* also determine which Lake Package lake each cell's runoff is linked to (use a number greater than the number of lakes if the runoff is not to be directed to a modeled lake). The array is read with the MODFLOW module U2DINT.

CN(*NCOL,NROW*) (real) – is the runoff curve number for normal conditions (AMC II). The array is read with the MODFLOW module U2DREL.

ETDEPTH(*NCOL*,NROW) (real) – is the ET extinction depth (L). The array is read with the MODFLOW module U2DREL.

SOILLEAK(*NCOL,NROW*) (real) – is the soil leakance (T^{-1}). The array is read with the MODFLOW module U2DREL, and is only read if *READLEAK* > 0.

VADPOR(*NCOL,NROW*) (real) – is the vadose-zone specific yield (drainable porosity). The array is read with the MODFLOW module U2DREL.

DELAYDEPTH(*MAXDELAY*) (real) – is the minimum depth for each time-step delay, up to *MAXDELAY*. If *MAXDELAY* = 0, this record is not read.

4.3   Example Main SV Package Input File

The following input might be used to define SV Package input for a model that has 8 rows and 15 columns.

```
#** EXAMPLE Run.sv **
       12.0          1          1       211       212        14          0
  1  0  0  0  3  0  1  3  2
    5
PRECIP               0        201  0.083333     Precip1.dat
IRRIG                1        202  0.083333     Irrig2.bin
ETMIN                0        205  0.083333     ETmin1.dat
PET                  0        203  0.083333     PotET1.dat
AMC                  0        204         1     MoistCond.dat
INTERNAL             1      (15I2)          2     *SVUSE*
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1
 1 1 0 0 0 0 1 1 1 1 1 1 1 1 1
 1 1 1 0 0 0 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
INTERNAL           1.0  (15F5.0)          8     *CN*
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 80. 80. 80. 80.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 80. 80. 80. 80.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 80. 80. 80. 80.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 80. 80. 80. 80.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 80. 80. 80. 80.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 98. 98. 98. 98.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 98. 98. 98. 98.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 98. 98. 98. 98.
  48. 48. 48. 48. 60. 60. 72. 72. 72. 72. 72. 98. 98. 98. 98.
CONSTANT           6.0                    *ETDEPTH*
CONSTANT           0.22                   *VADPOR*
CONSTANT           0.10                   *SOILLEAK*
3.0
4.167
5.333
6.5
7.667
8.833
10.0
10.714
11.429
12.143
12.857
13.571
14.286
15.0
```

In this example, the model length unit is feet (*INCONV* = 12.0) and the time unit is days. Time steps are uniform one-day steps. Leakance is read from this input file (*READLEAK* > 0). The overall SV budget is printed with the groundwater budget (*SVBUDLIST* = 1) and daily rates are printed on unit 211 (*SVBUDTAB*). The cell-by-cell unit number is 212 (*SVCBCFILE*). A

maximum of 14 time steps (days) are allowed for infiltration storage (*MAXDELAY*). There is no linkage to the Lake Package (*LINKLAKE* = 0).

The cell-by-cell flags in record 2 indicate that net recharge and saturated-zone ET flow rates are saved when indicated by Output Control (*CBCRCH* and *CBCETSAT* = 1). At the same times, cumulative runoff volumes are saved and reset (*CBCRUNOFF* = 3). This means that the total runoff volume from a cell is accumulated for each time step until the "SAVE BUDGET" directive is issued by Output Control, at that time, the cumulative volume is saved and then reset to zero so that the accumulation starts again until the next "SAVE BUDGET" directive. This also applies to groundwater drainage in the example (*CBCGWDRAIN* = 3). The accumulated volume of infiltrated storage at each cell is also saved – in this case the totals are not reset upon saving (*CBCSTOR* = 2). The other cell-by-cell flags are zero, so those terms are not saved.

The next section of the example input file identifies the 5 files used to read time-variable inputs. The file "Precip1.dat" is a text file (*BINFILE* = 0) opened on unit 201 and containing daily precipitation rates in inches (*CONVERT* = 0.083333 to convert to ft/d). "Irrig2.bin" is a binary file (*BINFILE* = 1) containing daily irrigation rates in inches. "ETmin1.dat" and "PotET1.dat" contain daily minimum ET and potential ET rates in inches. The antecedent moisture conditions are read from "MoistCond.dat". Specifications for these files are provided in Sections 4.4 and 4.5.

Since there is no file for subsurface inflows (*SEPTIC*) in the example, they are assumed to be zero (the default irrigation and precipitation rates are also zero). The default value for minimum ET is zero, and the default for potential ET is that $PET = ETMIN$. If no AMC file had been provided, then AMC II (normal conditions) would apply at all cells throughout the simulation.

The *SVUSE* array indicates that the SV Package will be used at all but 10 cells on the model top (these cells might be in a lake, for example). Five *CN* zones are used (values ranging from 48 to 98). The ET extinction depth is set to 6 ft throughout the model, the vadose-zone specific yield is set to 22%, and the soil leakance is set to 0.1 d^{-1}.

Finally, minimum depths of 3 ft to 15 ft are specified for delayed infiltration. These values are the same as those listed in Table 1.

4.4 Time-Variable Input Specifications (Text File)

Each non-binary time-variable input file specified in the main SV Package input file (for precipitation, irrigation, septic, minimum ET, potential ET, and antecedent moisture condition) must follow the following format:

```
REC. CONTENTS
0.    [#TEXT]
      (Item 0 is optional – "#" must be in column 1. Item 0 can be repeated
      multiple times.)

1.    NZONE     USEMULT   CONSTANT   ECHOFLAG

2.    ZONE(NCOL,NROW)  (U2DINT)
      (Read only if NZONE > 0.)

3.    MULT(NCOL,NROW)  (U2DREL)
      (Read only if USEMULT > 0.)
```

```
4.     VALUE(NZONE)
       (Repeat each time step if CONSTANT < 1. Use only if NZONE > 0.)
5.     VALUE(NCOL,NROW) (U2DREL or U2DINT)
       (Repeat each time step if CONSTANT < 1. Use only if NZONE < 1.)
```

These variables are explained below.

TEXT (character) – is similar to the *TEXT* variable explained in Section 4.2.

NZONE (integer) – identifies the number of zones used to define the input. If the data are not zoned, set *NZONE* = 0. If the data are spatially uniform, set *NZONE* = 1 and specify *ZONE* (below) to be 1 at every cell.

USEMULT (integer) – is a flag identifying whether to use a multiplier array (use if 1 or greater). If this file is for antecedent moisture conditions (an integer input) then *USEMULT* is ignored and a multiplier array cannot be used.

CONSTANT (integer) – is a flag. When positive, this flag indicates that the input does not change during the simulation (constant in time).

ECHOFLAG (integer) – is a flag. It tells MODFLOW how often to print the input array in the list file for checking. If it is 0, then the input will not be echoed. If it is a positive number, then the input will be echoed every *ECHOFLAG* time steps. If it is a negative number, then the input will be echoed only at the first and last time step of the simulation.

ZONE(*NCOL*, *NROW*) (integer) – is a zone array. It identifies the zone number for each cell. Where the value is less than 1 or greater than *NZONE*, the input takes on its default value (zero for *PRECIP, IRRIG, SEPTIC, ETMIN*, 2 for *AMC*, and equal to *ETMIN* for *PET*). If *NZONE* = 0 then *ZONE* is not read. This array is read with the MODFLOW module U2DINT.

MULT(*NCOL*, *NROW*) (real) – is a multiplier array. It is used to modify the input values for a particular cell. Generally, it should not be a constant value. If a constant multiplier is desired, use the *CONVERT* variable in the main SV Package input file. This array is read with the MODFLOW module U2DREL.

VALUE (by zone) (integer if AMC file, real otherwise) – is the input data when one or more zones are used (*NZONE* > 0). The zoned input values (from 1 to *NZONE*) are specified in this case. New values are supplied in each time step unless the data are constant in time (*CONSTANT* > 0). One or more free-format lines may be used for each time step, but data for different time steps should not appear on the same line.

VALUE (by cell) (integer if AMC file, real otherwise) – is the input data when data are not spatially zoned (*NZONE* = 0). In this case a value is specified for every cell (read by U2DREL or U2DINT) and a new array is required for each time step unless the data are constant in time (*CONSTANT* > 0). (Note that the MODFLOW U2DREL subroutine has been enhanced to allow the keyword "REUSE". When "REUSE" is entered as the first word on the line then the array from the prior time step is used.)

4.5   Time-Variable Input Specifications (Binary File)

If the time-variable input is read from a binary file (*BINFLAG* > 0 in the SV Package main input file), then a header record and data array record are read for each time step. The format is the same as the MODFLOW head-save file. The 44-byte header record contains the following data:

time step (integer), stress period (integer), time elapsed in period (real), total time elapsed (real), text label (16 characters), number of columns (integer), number of rows (integer), and layer (integer) (all real values and integers are 4 bytes). This header record information is not used by the SV Package, but may be useful for other programs.

The data record contains the *NCOL* x *NROW* real (or integer for AMC) input data values for a particular time step.

4.6   Time-Variable Input Files – Examples

Two examples of text time-variable input files are provided. The first one, below, uses four zones to define precipitation over 20 time steps.

```
#** Example Precip1.dat **
        4             0             0             5
INTERNAL             1      (15I2)           2     *ZONE*
 1 1 1 1 2 2 2 2 2 3 3 3 3 3 3
 1 1 1 1 2 2 2 2 2 3 3 3 3 3 3
 1 1 1 1 1 2 2 2 2 3 3 3 3 3 4
 1 1 1 1 1 1 2 2 2 3 3 3 3 3 4
 1 1 1 1 1 1 1 2 2 3 3 3 3 4 4
 1 1 1 1 1 1 1 1 2 3 3 3 3 4 4
 1 1 1 1 1 1 1 1 3 3 3 3 4 4 4
 1 1 1 1 1 1 1 1 3 3 3 3 4 4 4
        0.0           0.0           0.0           0.0  * step 1
        0.0           0.0           0.0           0.0
        0.5           0.3           0.6           0.5
        0.0           0.0           0.0           0.0
        0.0           0.0           0.0           0.0
        1.2           0.7           1.1           1.1
        0.3           0.6           0.0           0.2
        0.0           0.0           0.0           0.0
        0.3           0.2           0.3           0.3
        0.5           0.2           0.3           0.4  * step 10
        0.3           0.2           0.2           0.1
        0.0           0.0           0.0           0.0
        0.0           0.0           0.0           0.0
        0.0           0.0           0.0           0.0
        0.0           0.0           0.0           0.0
        0.0           0.0           0.0           0.0
        2.1           0.6           2.2           0.9
        0.5           0.2           0.1           0.1
        0.0           0.0           0.0           0.0
        0.0           0.0           0.0           0.0  * step 20
```

The second example, below, shows how to use zone and multiplier arrays for irrigation input. A multiplier array may be warranted, for example, when only a portion of a cell is irrigated. In this case, two small irrigation zones are used and the input rates are constant in time (*CONSTANT* = 1).

```
#** Example Irrig3.dat **
         2           1           1           -1
INTERNAL            1     (15I2)          2     *ZONE*
 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0
 0 1 1 1 0 0 0 0 0 0 2 2 2 0 0
 0 0 1 1 0 0 0 0 0 0 2 2 2 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
INTERNAL          1.0    (15F3.0)          8     *MULT*
  0.0  0.1  0.3  0.2  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  0.0  0.8  1.0  0.3  0.0  0.0  0.0  0.0  0.0  0.0  0.1  0.8  0.8  0.0  0.0
  0.0  0.0  0.5  0.5  0.0  0.0  0.0  0.0  0.0  0.0  0.1  1.0  1.0  0.0  0.0
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
      1.5          2.0        * all time steps
```

5   OUTPUT SPECIFICATIONS

The output from the SV Package includes an item called "Net Recharge/Discharge" in the printed overall groundwater budget (positive for groundwater inflow by MODFLOW convention). Additionally, the SV Package keeps track of all components in the surface/vadose-zone budget (rainfall, irrigation, septic inflow, precipitation runoff, vadose-zone ET, saturated-zone ET, groundwater drainage, and net recharge/discharge) for each cell and for the whole model. As explained in Section 4, The user can optionally print the overall surface/vadose budget at selected time steps and/or save any of the cell-by-cell budget components to a separate file for post-processing. Cumulative surface/vadose budgets can also be stored in cell-by-cell format and occasionally saved and reset. This facilitates certain post-processing computations – for instance, seasonal runoff to water bodies.

The surface/vadose volumetric budget printout, appearing in the list file, is formatted like this:

```
----------------------------------------------------------------------
              SURFACE/VADOSE-ZONE VOLUMETRIC BUDGET
        AT TIME STEP _____ OF STRESS PERIOD _____
----------------------------------------------------------------------
                        CURRENT RATE                CUMULATIVE
                   --------------------        --------------------
PRECIPITATION      +_____  L3/T     +_____  L3
IRRIGATION         +_____  L3/T     +_____  L3
SEPTIC INFLOW      +_____  L3/T     +_____  L3
PRECIP. RUNOFF     -_____  L3/T     -_____  L3
VADOSE ET          -_____  L3/T     -_____  L3
SATURATED ET       -_____  L3/T     -_____  L3
GW DRAINAGE        -_____  L3/T     -_____  L3
TO STORAGE         -_____  L3/T     -_____  L3
FROM STORAGE       +_____  L3/T     +_____  L3
GW RECHARGE(-)     -_____  L3/T     -_____  L3
GW DISCHARGE(+)    +_____  L3/T     +_____  L3

CURRENT VADOSE STORAGE                         +_____  L3
----------------------------------------------------------------------
```

(The blanks show where numbers would be printed.) In this table, positive flows indicate flow to the surface/vadose-zone control volume (Figure 1) and negative flows indicate flow out of this control volume. The listed "VADOSE ET" includes amounts taken from stored infiltration (*ETSTOR*).

If a budget table is saved on a separate file (*SVBUDTAB* > 0), then the current time step flow rates (precipitation, irrigation, septic inflow, runoff, vadose ET, saturated ET, flow to storage, flow from storage, and net recharge/discharge) are printed at the end of each time step. There is a one line header in this file, with the rates for each time step appearing on separate lines following the header.

Cell-by-cell amounts are stored with the UBDSV3 module in MODFLOW (single layer of values, *IMETH* = 4). This module saves each budget component in a binary file (identified by *SVCBCFILE*). The desired components are each saved at the desired time steps, depending on the flags set in the SV Package main input file and the Output Control file. Each saved array is preceded by two header records. The first is a 36-byte record identifying the time step (integer), stress period (integer), text label (16 characters), number of rows (integer), number of columns (integer), and a flag (integer = -1). The second is a 16-byte record identifying the saving method (integer = 4), the time step length (single), the elapsed time in the stress period (single) and the elapsed time in the simulation (single).

6 REFERENCES

Council, 1999. A Lake Package for MODFLOW (LAK2), Documentation and User's Manual, Version 2.2. HSI GeoTrans. June.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald 2000. *MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process.* U.S. Geological Survey Open-File Report 00-92, Reston, VA.

USDA (U.S. Department of Agriculture) 1986. *Urban Hydrology for Small Watersheds.* SCS Technical Publication #55, Washington, DC.
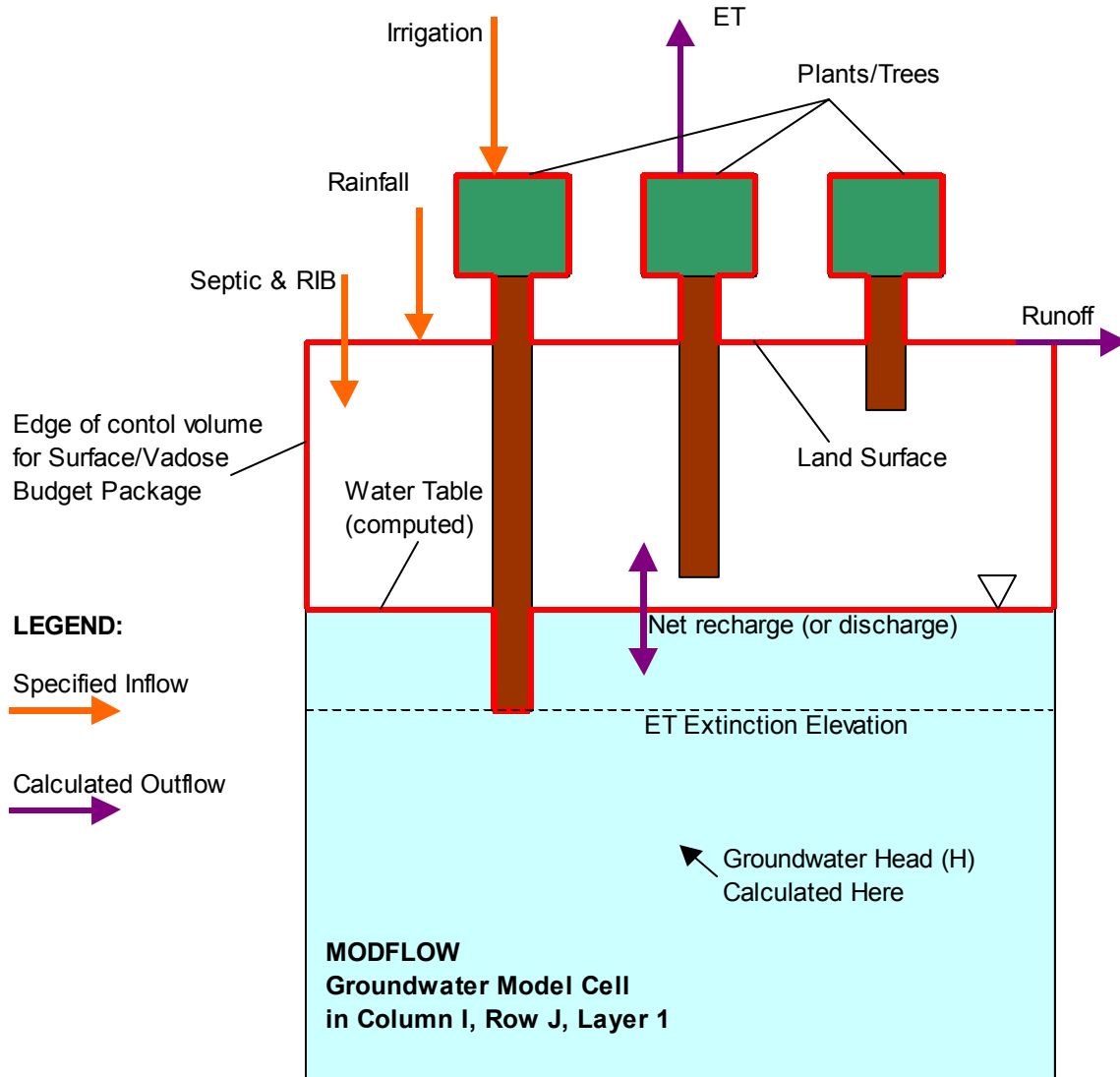
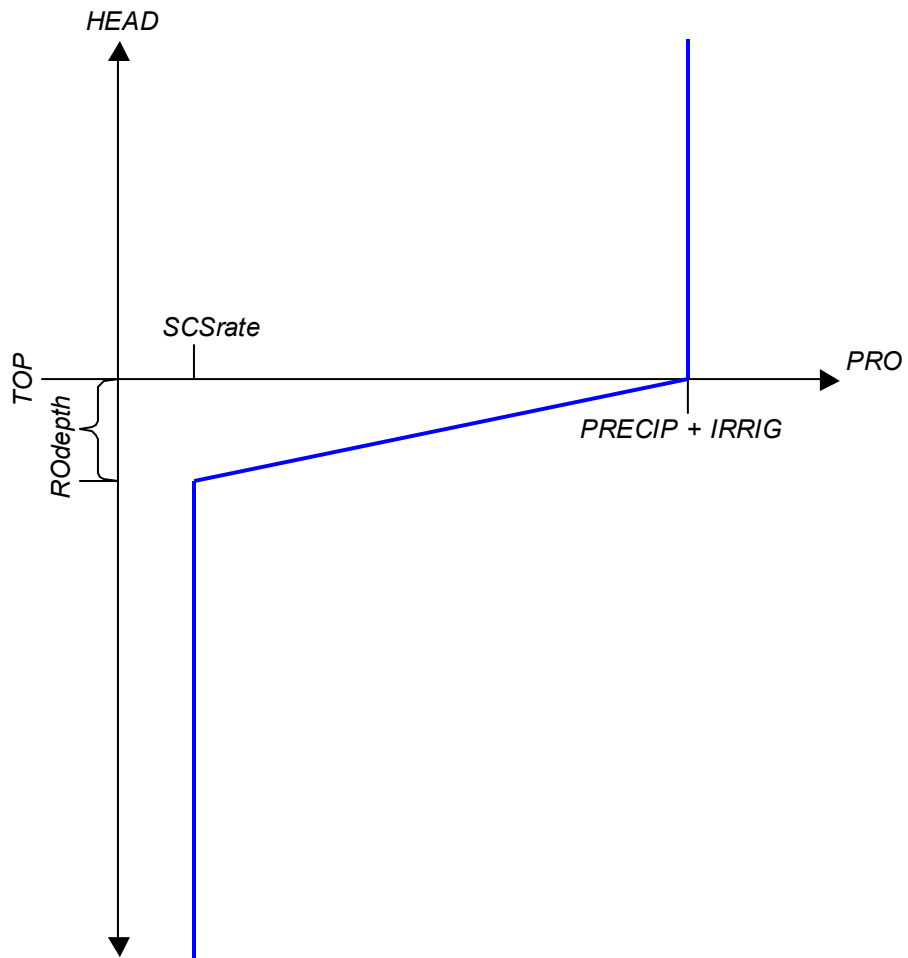**Figure 1   Conceptual Model for the Surface/Vadose Package for MODFLOW**

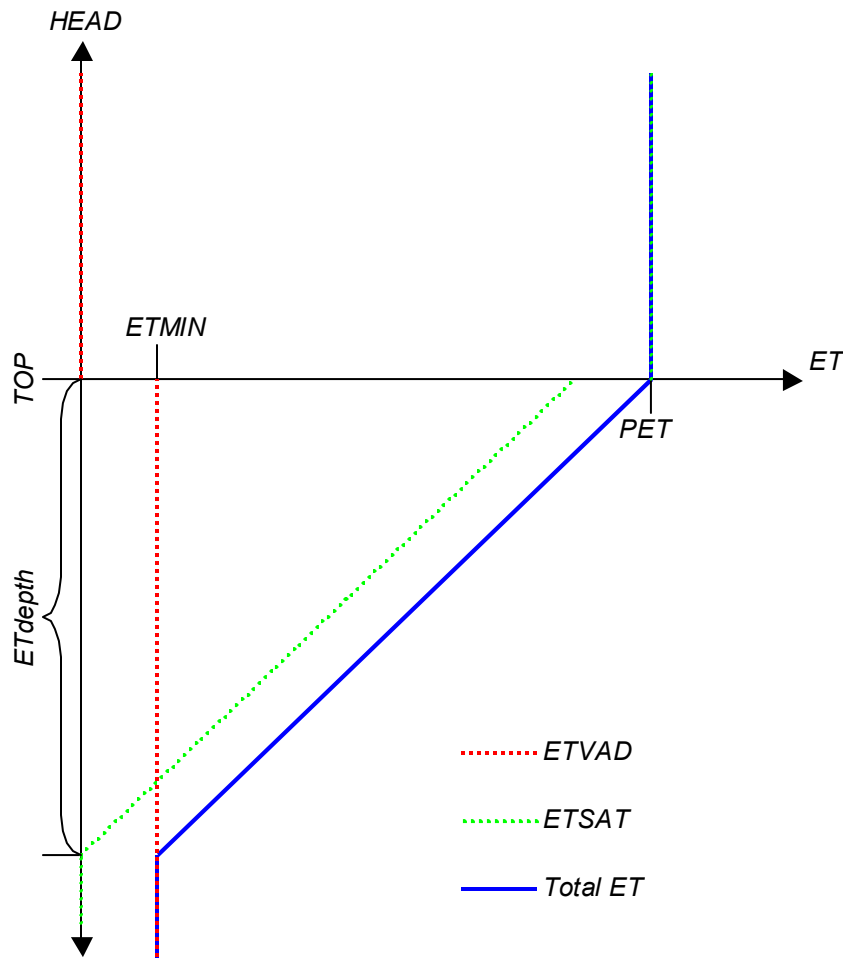**Figure 2   Generalized Relationship between Precipitation Runoff (*PRO*) and Simulated Head**

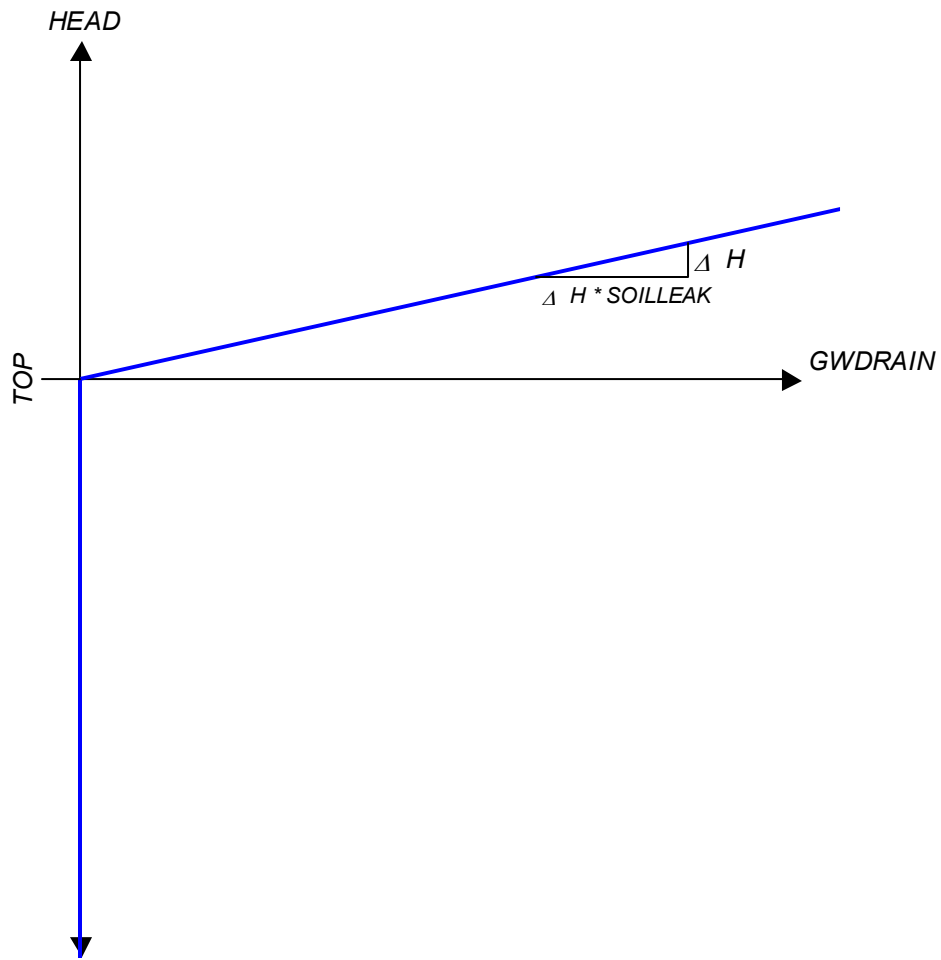**Figure 3   Generalized Relationship between Evapotranspiration and Simulated Head**

Figure 4 **Generalized Relationship between Groundwater Drainage (*GWDRAIN*) and Simulated Head**