

**KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 2000-77**

NUMERICAL APPROACHES TO MODELING GROUNDWATER
RECHARGE WITH EMPHASIS ON MODFLOW AND INTEGRATED
SWAT-MODFLOW MODELS

by

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Numerical approaches to modeling groundwater recharge with emphasis on MODFLOW and Integrated SWAT-MODFLOW models

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Open-File Report 2000-77
November 1st, 2000

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1. Introduction

Groundwater recharge can be considered in a general sense as the *net groundwater inflow*, which refers to the right-hand side of the groundwater balance equation solved by MODFLOW:

$$(dS/dt)_{gw} = Q_{gw} + Q_{rech} - Q_{gdiv} - Q_{et-gw} - Q_{base} \quad (1)$$

On the left-hand side of (1) is the rate of change in storage, $(dS/dt)_{gw}$. On the right, Q_{gw} = net lateral inflow, Q_{rech} = recharge, Q_{gdiv} = diversions (primarily irrigation pumping), Q_{et-gw} = evapotranspiration from shallow ground water; and Q_{base} = streambed leakage. The term shown for recharge in eq. (1), Q_{rech} , refers to a more restrictive sense of the term than used above, commonly consisting of a combination of percolation through a soil profile and transmission losses along ephemeral stream channels that also percolate to groundwater. Some of the methods used to represent the net groundwater inflow for a groundwater simulation model are summarized here. The components of net groundwater inflow can be specified through various packages within MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), such as the Recharge,

Drain, Well, Evapotranspiration, and Stream packages (River and Stream), as well as through boundary conditions such as general head boundary and specified head boundary conditions. These aspects are outlined in the next section. All of the components of the net groundwater inflow can be spatially distributed over the domain of the model simulated by MODFLOW.

2. Simulating recharge fluxes using MODFLOW packages and boundary conditions

{ The notes in this section are derived mainly from Anderson and Woessner (1992). }

Specified head values can be assigned to model grid nodes so that recharge can be calculated by the model. Specified head conditions are selected over specified flow because it is easier to measure head than to measure flow. In 2-D areal simulations, specified head boundary nodes represent fully penetrating surface water bodies or the vertically averaged head in the aquifer at hydraulic boundaries. It is important to recognize that a specified head boundary represents an inexhaustible supply of water. The groundwater system may pull water from the boundary or may discharge water into the boundary without changing the head at the specified head node. Of course, it is possible to change the head at the boundary as the simulation progresses provided a new value for the boundary head can be justified. A convenient way to change boundary head values during the simulation is through MODFLOW's General Head Boundary package (see further below).

Specified flow boundaries are simulated by using injection (or pumping) wells through the Well package to inject (or extract) water at the specified rate. The user specifies the injection (or pumping) rate and location of the well screen. Inflows are treated as volumes of water "placed" into the model grid cell. Conceptually, water may enter the top of the block as groundwater recharge or side of the block as underflow. The flux is assumed to be uniformly distributed over the face of the cell.

Head-dependent flow is dependent on the difference between a user-supplied head on one side of the boundary and the model-calculated head on the other side. Leakage to

or from a river, lake, or reservoir can be simulated using head-dependent conditions. The flux or leakage rate, Q is calculated as

$$Q = C (h_s - h), \quad (2)$$

where the conductance term, $C = (k_s A / b_s)$, k_s is the vertical hydraulic conductivity of the interface (e.g., riverbed sediments), A is the area of the cell through which leakage occurs, b_s is the thickness of the interface, h_s is the head in the source reservoir (e.g., a lake or river) and h is the head in the aquifer immediately below or adjacent to the source.

Evapotranspiration (ET) across the water table also can be represented as a head-dependent boundary, where the flux across the boundary is proportional to the depth of the water table below the land surface. Groundwater ET may occur when the water table is close to the land surface or when phreatophytes draw water from below the water table. The **ET package** requires the user to assign a maximum ET rate to each cell from which ET may occur. The maximum rate is used when the water table in a cell is at the land surface. No ET occurs when the water table declines below an assigned "extinction" depth, equal to the vegetation rooting depth. In between these two extremes, ET rate is assumed to be linear.

Another example of a head-dependent boundary is flow to a drain. Springs and seeps are normally simulated with the **Drain package**; the elevation of the spring or seep as it emerges at the land surface is the elevation of the drain. Diffuse flows, such as seepage to wetlands, can be simulated by specifying drain nodes in the general area where seepage is likely to occur. Leakage to the drain is simulated whenever h in eq. (2) is greater than h_s (the elevation of the drain). Leakage rate equals zero if h is less than h_s . The drain nodes will be activated only when the head in the aquifer equals or exceeds the land surface elevation. The River package, described below, also can simulate a spring or a drain by setting the bottom elevation of the streambed equal to the head in the source reservoir (i.e. the river stage)

The **River package** is used to simulate the flow of water between an aquifer and an overlying (or underlying) source reservoir, which is usually a river or lake. The River

package allows water to flow from the aquifer to the source reservoir, thereby removing water from the model by seepage to gaining stream reaches. Water can also flow out of the stream into the aquifer but the seepage out of the stream is independent of the stream discharge (which is not the case with the Stream package, to be described below.) Thus a losing reach of stream could recharge the aquifer with more water than is being carried in the stream. No adjustment is made in the stream stage. Even with these limitations, the River package adequately represents many surface-groundwater systems.

The **Stream package** also allows leakage to and from the stream, but also considers the volume of streamflow in each river segment; thus it will increase streamflow in areas of gaining reaches and reduce streamflow by water lost through riverbed seepage in losing reaches. The reach will go dry if leakage or surface water diversions for a given reach exceed streamflow. In this case, leakage is set to zero and downstream reaches are prevented from leaking until additional water is added by tributaries or groundwater seepage. Additional information on the Stream package is presented in the next section.

The **General Head Boundary package**, which is similar in concept to the Drain and River packages and governed by the same eq. (2), is more restrictive than the River and Drain packages in that it assumes continuous linear discharge or leakage, whereas the River and Drain packages allow for limits to discharge depending on the head in the aquifer relative to the bottom elevation of the streambed or the drain elevation.

The **Recharge package** simulates the water fluxes across the water table from an outside source. Recharge is specified as a rate (L/T) to the top layer of the model. The code computes the volume of water added to the model by multiplying nodal recharge rates by the area of the top of the cell per unit of time. Recharge can either be constant over the whole modeled area or it can be variable for each cell.

3. Head-dependent groundwater fluxes

The fluxes for the various components of net groundwater inflow can be distinguished by whether or not the components are head-dependent. As mentioned in the previous section, examples of head-dependent fluxes are evapotranspiration from shallow groundwater and streambed leakage when the stream stage and groundwater hydraulic head are coupled across the streambed.

Fluxes specified by the Recharge and Well packages are head-independent. However, we have developed a version of the Well package that has been modified to limit pumping to prevent depletion of groundwater beyond a specified limit (Perkins and Sophocleous, 2000b; Sophocleous and Perkins, 2000). This is implemented as a linear reduction of pumping rate over a range of saturated thickness from the pumping rate demanded to zero. (Additional details related to the modified Well package WELX are presented later in section 6.) This scheme serves to prevent grid cells from being pumped dry, but also makes the pumping rate head dependent over a range of saturated thickness. These fluxes are handled according to the technique used in MODFLOW for other head-dependent fluxes in order to preserve solution stability.

MODFLOW's linearly head-dependent flux options provide a physically based means of approximating these fluxes. Nonlinear relationships to hydraulic head may also be represented by linear approximation over an appropriate range of hydraulic head. For example, nonlinear variation of evaporation from shallow groundwater with hydraulic head might possibly be represented satisfactorily by such an approach. Another example of such nonlinear behavior can arise if MODFLOW's Stream package (Prudic, 1989) is modified to represent natural stream channels such that stream width, wetted perimeter, and, consequently, streambed conductance vary with streamflow conditions. Such a case is implemented in Ramireddygari et al. (2000) and outlined in the modified MODFLOW Stream package STRX in section 8 below.

Streambed leakage models are summarized below to illustrate both linear and non linear cases of head-dependent groundwater flux. The MODFLOW Stream package (Prudic, 1989) applies Darcy's law to represent streambed leakage for a given stream reach by

$$Q(\Delta h) = C \Delta h, \quad (3)$$

where streambed conductance $C = K_s LW/T$ for streambed hydraulic conductivity, K_s , length, L , width, W , and streambed thickness, T , within a given grid cell; and the hydraulic head difference $\Delta h = h_s - h$ across the streambed between stream stage, h_s , and groundwater head, h . The Stream package decomposes the groundwater flux given by (3) into head-dependent and head-independent components, that is,

$$Q(\Delta h) = C h_s - C h \quad (4)$$

MODFLOW solves a system of equations for the groundwater heads represented by

$$A h = b \quad (5)$$

The head-dependent term on the right-hand side of (4), Ch , is incorporated into the coefficient matrix, A , on the left-hand side of (5), while the head-independent term, Ch_s , is added to the vector, b , on the right-hand side of (5).

If streambed conductance is allowed to vary with streamflow conditions, streambed leakage is represented by

$$Q(\Delta h) = C(\Delta h) \Delta h \quad (6)$$

Here, streambed conductance varies with streamflow and, in turn, stream depth, stream stage, and hydraulic gradient across the streambed. This form of the streambed leakage is no longer linear as is (3), and shows that care must be taken to avoid introducing solution instability in the pursuit of a more realistic model. (A scheme to do this was applied to the Wet Walnut Creek model (Ramireddygarri et al., 2000) by allowing conductance to vary with streamflow conditions, but fixing the conductance against second-order variations in streamflow between solution iterations due to changes in streambed leakage.)

4. Predictive relations for recharge

Net inflows to groundwater may also be quantified in terms of hydrologic conditions using physically-based or experimentally determined relationships. For example, hydrologic predictors for groundwater recharge were developed by Sophocleous (1991, 1992) based on the soil water balance, field observations, multiple regression analysis and GIS. For Groundwater Management District No. 5 in south-

central Kansas, practical relationships were obtained for this purpose, and could be used to specify recharge for a groundwater model in terms of available hydrologic data including precipitation and groundwater depth measurements. GIS provided some of the key tools for that analysis. The summer floods of 1993 provided a significant recharge event with which to test some of these relationships and models (Sophocleous et al., 1996).

5. Recharge through inverse modeling

Inverse modeling provides another statistical approach to quantifying net inflows. In conventional groundwater models recharge is postulated known and hydraulic heads computed, whereas in inverse groundwater models it is recharge which is computed from field measurements of hydraulic head. MODINV (Doherty, 1990) and PEST (Doherty et al., 1994) were used to "optimize" groundwater parameters, including recharge, for the Rattlesnake Creek watershed (Sophocleous and Perkins, 1993; Sophocleous et al., 1999). Sophocleous (1984) also employed non-linear regression parameter estimation (inverse) modeling in the Equus Beds aquifer in central Kansas (an extension of the High Plains aquifer), and identified three different recharge zones in the model region.

6. Recharge through soil-water balance modeling

Soil-water balance models have proved to be valuable in estimating potential recharge from a soil profile. The change in soil-water storage at a site in any one day is expressed as $\Delta S = P - RO - ET$, where P is precipitation, RO is surface runoff, and ET is actual evapotranspiration, all expressed as water depths over the considered time interval. When applying this method to estimate recharge for a larger area such as a watershed, the water-balance calculation is repeated for areas with different climatic variables, soil type and crop type. Sophocleous and McAllister (1987, 1990) used this approach, in combination with a basinwide integrating methodology, to model recharge for an entire basin in south-central Kansas with reasonable results. The particular soil-water balance model they used was the Versatile Soil Moisture Budget (VSMB) model of Baier et al. (1979) because on its simplicity and detailed representation of root-zone processes.

7. Recharge through modeling of unsaturated zone flow processes (Richards equation)

Several studies have reported use of unsaturated zone hydraulic conductivity and water characteristic data to solve Richards equation in the unsaturated zone and to estimate soil water fluxes to the water table. Numerical simulation of Richards equation, which combines Darcy's law with the continuity equation, is fraught with problems of stability and convergence and thus is computationally intensive because the unsaturated hydraulic properties defining its coefficients are highly nonlinear. Consequently, only its one-dimensional form in the vertical direction is usually employed, and even then it is generally not applied in continuous simulations of soil-water flow processes on a watershed scale. Sophocleous (1985) used this type of modeling (employing the finite element model UNSAT2 –Neuman et al., 1974) to investigate the role of capillary fringe and variable specific yield in groundwater recharge estimation.

8. Using integrated watershed-groundwater models to estimate recharge

A physically-based hydrologic model of a watershed can be used to specify net groundwater inflows for MODFLOW, including tributary inflows, water use, evaporation from shallow groundwater, and recharge. The term "recharge" is used here in a narrower sense than used previously, and refers to a combination of percolation through the soil profile, transmission losses along ephemeral stream channels, and pond seepage. This approach was applied to three watersheds in Kansas (Sophocleous and Perkins, 2000). The model code, SWAT (Soil Water and Transport; Arnold et al., 1994) was applied to the Lower Republican River basin and Rattlesnake Creek watershed. The model code POTYLDR (Potential Yield; Zovne et al., 1977; Koelliker et al., 1981) was applied to Wet Walnut Creek. SWAT and POTYLDR simulate hydrologic processes in the watershed based on a soil water balance with a daily time step. The codes were modified to summarize results for each time step of a groundwater simulation. These summaries were read by a package, referred to here as SWBX, that was written for MODFLOW to provide an interface to such results (Perkins and Sophocleous, 2000a,b). This package

was coordinated with modified versions of MODFLOW's Stream and Well packages to simulate tributary inflows and both surface- and ground-water irrigation supplies, based on the watershed simulation results. The following summarizes the SWAT-MODFLOW linkage and conceptual models for groundwater fluxes specified for MODFLOW in terms of the hydrologic components simulated by SWAT.

The SWAT model component of the integrated model simulates watershed hydrology in a continuous mode with daily time steps (Arnold et al., 1993; 1994; Neitsch et al., 1999). It is quasi-distributed, i.e., a basin can be partitioned into an arbitrary number of subbasins, each of which is represented by a single set of characteristics without spatial variation. A lumped hydrologic model based on a soil water balance is applied separately to simulate each subbasin. The soil water balance has the form

$$d_{sw}(t) - d_{sw}(0) = \sum_{i=1}^t (d_{pcp} + d_{irr} - d_{ro} - d_{lat} - d_{perc} - d_{et}) \quad (7)$$

Terms of eq. (7) are in units of length (mm) representing water volume per unit area. On the left-hand side is the change in soil water content after t days; on the right are terms integrated over time for precipitation, d_{pcp} , including snowmelt; d_{irr} , applied irrigation; surface runoff, d_{ro} ; lateral subsurface flow, d_{lat} ; percolation from the soil profile, d_{perc} ; and evapotranspiration, d_{et} . Channel transmission losses, d_{xm} , are treated as a component of surface runoff that contribute to groundwater recharge.

The inputs required by the MODFLOW component of the integrated model are in flow-rate units (L^3/T). Flow rates, Q , are related to depths, d , by

$$c Q \Delta t = d f A, \quad (8)$$

where f is the areal fraction of watershed area, A , to which the hydrologic term applies, and c is a length conversion factor.

Spatial heterogeneity in the SWAT component of the integrated model is based on the hydrologic unit response (HRU) approach, which is summarized by Mamillapalli et al. (1996) as follows:

Instead of assuming the dominant soil and land use to be the soil or land use of the subbasin, each subbasin is discretized into virtual areas (referred to as virtual basins),

each having a unique soil and land use combination without reference to their spatial positioning within the subbasin...The hydrologic response is generated within each of these virtual areas and then the weighted average (by area) of the response from these virtual subbasins is taken to be the output of the subbasin.

As part of the original SWAT-MODFLOW linkage, we implemented a variation on SWAT's "virtual subbasin" approach to represent spatial heterogeneity as follows: Each HRU, based on a particular soil type-land use combination, is simulated by a separate execution of SWAT and summarized by a separate output data file. An intermediate program, SWBAVG (Perkins and Sophocleous, 1999; Sophocleous et al., 1999; Sophocleous and Perkins, 2000), evaluates spatial weights of HRUs based on soil type and land use areal fractions, and takes a spatially weighted average over the HRUs simulated separately by SWAT. The HRU-averaged simulation results are converted to flow rates that are used to specify flow conditions for MODFLOW's stream-aquifer solution.

Hydrologic terms simulated by the SWAT component for each subbasin are combined to specify fluxes for the MODFLOW component's solution in each time step. These fluxes include irrigation demand, groundwater recharge, tributary inflow, and a maximum rate for evaporation from shallow groundwater. All these fluxes impact upon groundwater recharge estimation. Conceptual models for these fluxes are described by equations (9–11) as follows.

Irrigation demand is simulated by SWAT and converted to a flow rate according to equation (8) by

$$Q_{irr} = d_{irr}f_{irr}A/c\Delta t, \quad (9)$$

where, f_{irr} = the areal fraction of the watershed appropriated for irrigation.

Recharge to groundwater includes contributions from percolation through the soil profile, d_{perc} , channel transmission losses, d_{xm} , and pond seepage, d_{psep} . SWAT's simulation of these components is based on the presence of an underlying aquifer. Consistent with this assumption, the groundwater recharge flow rate for a subbasin is given by

$$Q_{rech} = (d_{perc} + d_{xm} + d_{psep})A/c\Delta t. \quad (10)$$

This recharge rate is to be distributed over the active nodes of the aquifer grid within each subbasin.

Tributary flow, Q_{trib} , from a given subbasin is assigned as lateral inflow to a reach of the main stream associated with the tributary stream's grid location. It includes terms for surface runoff, d_{sro} , and lateral (subsurface) flow, d_{lat} , calculated by SWAT for each subbasin's contributing areal fraction, f_{con} . Tributary flow is expressed as

$$Q_{trib} = (d_{sro} + d_{lat})f_{con}A/c\Delta t + Q_{po} \quad (11)$$

The additional component of tributary flow, Q_{po} , represents the noncontributing component of the basin that drains to ponds from which water may overflow with a flow rate Q_{po} or seep to streams.

Simulated recharge and potential evaporation from each subbasin are distributed over the corresponding grid cells of arrays for MODFLOW's Recharge and Evapotranspiration packages. Simulated tributary inflows from each subbasin are associated with corresponding stream reaches, and irrigation demand is distributed over surface and groundwater points of diversion.

Evapotranspiration, d_{et} , shown in the water balance equation (6), is supplied in part by shallow groundwater. MODFLOW represents ET from shallow groundwater, Q_{et-gw} in eq. (1), as a linear function of depth to groundwater, with a maximum corresponding to groundwater at the land surface and a minimum of zero corresponding to a specified extinction depth. The maximum is represented by potential ET, simulated by SWAT, and is converted to a flow rate over the area of each active grid cell for MODFLOW's ET package.

A new MODFLOW package, known as SWBX package (Perkins and Sophocleous, 2000a,b), which is an upgraded version of the MODSWB package (Perkins and Sophocleous, 1999; Sophocleous et al., 1999; Sophocleous and Perkins, 2000), was written to provide a means of specifying conditions for MODFLOW's stream-aquifer solution in terms of results from the watershed simulator. In each time step, SWBX reads

tributary inflows, groundwater recharge, irrigation demand, and potential evaporation for each subbasin as HRU-averaged flow rates from a data file written by SWBAVG. Pumping rates from surface and groundwater diversions are specified to meet the irrigation demand simulated by SWAT, but are constrained to stay within operating limits imposed on individual water rights, and within supply limits imposed by available streamflow and aquifer saturated thickness. Modified versions of MODFLOW's STREAM and WELL packages, referred to as STRX and WELX, respectively, provide features necessary in satisfying these constraints for the SWAT-MODFLOW linkage. A short description of the modified STRX and WELX packages follows.

STRX, an upgraded version of MODSTR (Sophocleous and Perkins, 2000), uses a modified routing procedure to account for net lateral surface inflows in each reach that represent the sum of any tributary inflows, surface water diversions (outflows), and optional evaporation from the stream surface that might be specified for the reach. In addition, an indexing array, *Idxstr* (Perkins and Sophocleous, 1999b; 1999c), is a feature added to look up a stream reach that is to be associated with grid coordinates specified for subbasin outflows and surface water diversions. In STRX, channel-flow characteristics (depth, width, wetted perimeter, and others) can be represented not only for rectangular channels, but also for trapezoidal and natural channels. Streambed conductance may be calculated on the basis of streambed hydraulic conductivity and stream width. Hydraulic conductivity may be resolved into components corresponding to bottom and side walls; and streambed leakage due to flooding outside the main channel is characterized as recharge due to percolation instead of coupled stream-aquifer interaction.

WELX, an upgraded version of MODWEL (Sophocleous and Perkins, 2000), represents diversions from both ground and surface water, which are distinguished by a source indicator. Locations of both types of sources are given by grid coordinates. The indexing array, *Idxstr*, defined in STRX, is used to look up corresponding reaches of a stream network that is specified by input to STRX. Diversions are further distinguished by type of use, (irrigation, domestic, municipal, etc., including fictitious wells to represent flux boundary conditions). Irrigation demand simulated by SWAT is distributed only over points of diversion associated with irrigation water use.

The supply for surface-water diversions is limited by the sum of channel and lateral surface inflows to its associated stream reach. This limit is applied as part of the modified stream routing procedure in STRX. The supply for groundwater diversions is limited by the aquifer's saturated thickness. Above an upper limit, d_u , the specified pumping rate is unaffected; below this limit, the pumping rate decreases linearly with saturated thickness to zero at a lower limit, d_l . This technique, employed in the WELX package, provides a realistic means of preventing grid cells from going dry as a result of excessive pumping from wells. For additional details refer to Perkins and Sophocleous (2000a; 2000b; 2000c).

Spatial distribution of recharge using the integrated model

In the cases of the combined watershed and groundwater models for Lower Republican River and Wet Walnut Creek watershed, spatial distributions of groundwater recharge were assumed uniform within the areas of the subbasins simulated by the hydrologic models. For the Rattlesnake Creek combined model, a conceptual model for recharge as a decreasing function of depth was used to specify a spatial distribution of recharge within subbasins simulated by SWAT (Sophocleous et al., 1999). Groundwater recharge in areas of deep water table (exceeding 30 m) and clayey soils in semi-arid regions is likely to be negligible. Being a lumped-parameter model, SWAT calculates a uniform value of recharge in each subbasin, although variation in depth to the water table within a particular subbasin would imply variable net recharge within that subbasin also. The recharge specified to MODFLOW cells within a subbasin was, therefore, modified to account for such variations in the depth to the water table. This was achieved through a so-called "weight matrix," which determined the relative distribution of recharge within each subbasin (Sophocleous et al., 1999). The value at each location in this matrix, which corresponds to a MODFLOW grid cell, indicates the magnitude of recharge within a cell relative to other cells in the same subbasin. The recharge to each cell is therefore calculated by the following formula

$$\text{Recharge at cell} = [(\text{cell weight})/(\text{sum of weights of all cells in the corresponding sub-basin})] \times \text{the SWAT-calculated recharge for the corresponding subbasin.}$$

The recharge formula above preserves total quantity of water in the SWAT and MODFLOW models (i.e., the model-estimated total recharge for the subbasin is maintained); only the distribution of recharge within the cells in a subbasin is modified.

A capability to specify spatial distributions of recharge within subbasins has been incorporated into the latest version of the combined SWAT-MODFLOW code (based on SWAT v.99.2 and MODFLOW-96 (v.3.3); Perkins and Sophocleous, 2000a-c). The SWBX package, which distributes the fluxes simulated by a watershed model over the groundwater model grid cells, provides an option to specify how the recharge flux is distributed spatially over the grid cells within each subbasin. This is accomplished as follows.

At the beginning of each stress period, the MODFLOW Recharge module reads the recharge array RECH as a flux, $R_{in}(ic,ir)$ [L/T], for each column, ic , and row, ir , of the model grid. The initial recharge array $R(ic,ir,t_0)$ is used to specify the spatial distribution of recharge, $f_r(ic,ir)$. This is given by

$$f_r(ic,ir) = R(ic,ir,t_0)/Q_r(isub,t_0), \quad (12)$$

where the denominator represents the sum of recharge flow rate taken over grid cells within the corresponding subbasin, $isub$,

$$Q_r(isub,t_0) = \sum_{j,k} R(j,k,t_0). \quad (13)$$

The array $f_r(ic,ir)$ represents the spatial distributions with respect to each subbasin, $isub$, so that $\sum_{j,k} f_r(j,k) = 1$ for each sum taken over grid cells within a given subbasin. In each time step, $f_r(ic,ir)$ is used to distribute the recharge flow rate simulated by SWAT, $Q_r(isub,t)$, over the grid cells of the subbasin according to

$$R(ic,ir,t) = f_r(ic,ir)Q_r(isub,t). \quad (14)$$

If input to the Recharge package for the initial recharge array, RECH, is specified to be uniform (or uniform with respect to the grid cells within each subbasin), then recharge will be distributed uniformly over the grid cells within each subbasin. On the other hand, the spatial

distribution specified by the initial recharge array is preserved in the operation given by eq. (14) only with respect to the grid cells within each subbasin, and not with respect to the entire basin, unless the recharge flux specified in each time step, $Q_r(\text{isub},t)/A(\text{isub})$, is uniform over all subbasins. If the basin-wide spatial distribution indicated by the initial recharge array RECH is to be preserved in each time step, then it must be applied to a basin-wide recharge flux simulated by SWAT.

Advantages of the integrated model

Combining SWAT and MODFLOW into an integrated watershed model allows an overall water balance for the watershed to be determined that can serve as a check on continuity and a constraint on model parameters such as recharge. It also provides a forward model for hydrologic fluxes. Specifically, SWAT provides MODFLOW with a forward model for groundwater recharge, tributary inflows to the stream network, irrigation requirements, and evaporation from shallow groundwater, all of which must be specified as boundary conditions for MODFLOW's solution. As a result, the seasonal variation of water table levels and recharge can be more accurately predicted by the soil-moisture accounting system employed in the integrated model than by using only the groundwater model. A major benefit of the integrated model over either watershed or groundwater models alone, is the ability to "optimize" its parameters by calibrating against multiple targets, such as groundwater levels, streamflow data, irrigation water use, and other data, thus resulting in more reliable results than otherwise would be possible (Sophocleous and Perkins, 2000). Whereas traditional methods used to calibrate groundwater models may include adjustments to water-table elevations or recharge rates, in an integrated model, recharge is completely constrained by an overall water budget for the surface-water system. In addition, stream-aquifer interactions are constrained by the generated amount of surface runoff to streams that in turn, impacts the stream stage and thus the driving forces for stream-aquifer interaction.

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