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GUIDE TO
COORDINATING SWAT AND MODFLOW
WITH INSTALLATION NOTES

by

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Preface

The SWAT-MODFLOW linkage is based on Swat v.99.2 and Modflow-96 v.3.3. The linkage is described by the three documents, listed below. The first of these, OFR 2000-67, is a detailed presentation of the methods and procedures. The second, OFR 2000-68, is a User's Manual, and provides specifications for input data requirements for the linkage. The third of these, the present document, presents an introduction in Chapters 1-3. Chapter 2 summarizes methods of the linkage, and Chapter 3 presents examples. Chapter 4 presents installation notes for the documentation, executable files, test cases, and source code.

Perkins, S.P. and M.A. Sophocleous, 2000a. Combining SWAT and MODFLOW Into an Integrated Watershed Model. Open-File Report No. 2000–67, Kansas Geol. Survey, Lawrence, KS, 70 p.

Perkins, S.P. and M.A. Sophocleous, 2000b. User's manual for a combined watershed and stream-aquifer modeling program based on Swat-99.2 and Modflow-96. Open-File Report No. 2000–68, Kansas Geol. Survey, Lawrence, KS, 140 p.

Perkins, S.P. and M.A. Sophocleous, 2000b. Introduction and Installation Notes for SWAT-MODFLOW. Open-File Report No. 2000–XX, Kansas Geol. Survey, Lawrence, KS, 36 p.

1. Introduction

A combined code based on SWAT and MODFLOW was originally developed to address water management questions concerning how ground water pumping for irrigation water use affects streamflows in the Lower Republican River basin in north-central Kansas (Perkins and Sophocleous [P&S], 1999a) and in the Rattlesnake Creek watershed in south-central Kansas (Sophocleous et al., 1999). The model codes for these studies combined SWAT v.94.2 and MODFLOW-88. The integrated model code has recently been updated to SWAT v.99.2 and MODFLOW-96, which is documented in a Final Report and User's Manual (Perkins and Sophocleous [P&S], 2000a-b).

This document is intended to provide a self-contained introduction to coordinating SWAT and MODFLOW. Included are a summary of the conceptual models implemented by the coordinated model code, data passed between SWAT and MODFLOW, and examples. An installation procedure from self-extracting files is described in the separate text document Install.txt. The coordinated SWAT-MODFLOW model code and its application are presented in greater detail in Final Report (Perkins and Sophocleous [P&S], 2000a) and a User's Manual (P&S, 2000b).

1.1. Recent SWAT-MODFLOW linkage developments

Since submitting our Final Report, we have revised the coordinated model code and User's Manual to incorporate the following features, which are intended to improve the model code's applicability:

The SWAT component of the combined SWAT-MODFLOW code has been updated to the final release of SWAT v. 99.2 (June 2000), which includes the latest version of the land use data base for crops (Crop.dat, April 2000). This version of SWAT 99.2 was tested through the ArcView extension AvSwat by comparison for the Lakefork test case described in the AvSwat manual (Neitsch and DiLuzio [N&D], 1999) against the downloaded executable file swat992.exe that accompanied AvSwat. This case was also used for testing as code changes were made to incorporate the SWAT-MODFLOW linkage. A "workaround" to adapt the example procedure presented by N&D (1999) to generate input data for MODFLOW based on SWAT's simulation is presented in Section 4.1.

The option for specifying recharge over the spatial extent of the ground water model has been expanded as described in the section "Spatial distribution of recharge." This option, Ioprch, is specified by input to the SWB package in MODFLOW. For Ioprch > 0, the spatial distribution of recharge is specified by input to Modflow's Recharge package in the first stress period; this option is illustrated in Example 3 of the Guide.

An option to calculate HRU weights for virtual subbasins has been incorporated into Swat. HRU weights are based on spatial variability factors for soils, land use, and subsurface features. Areal fractions of each subbasin are specified for these factors in an extended version of the Control Codes (*.cod) input file. This file also defines

combinations of these factors that can be used to calculate HRU weights. An additional numeric field is read from the configuration (*.fig) file to allow associating these combinations with HRUs. If the option Iopwts > 0 has been set in the Control Codes input file, and if the combination specified in the Configuration file has been defined in the Control Codes input file, then the initial HRU weight and the corresponding virtual subbasin area are calculated, thereby replacing the value specified in the Subbasin (*.sub) file. Similarly, HRU weights and the corresponding virtual subbasin areas can be updated for each groundwater model time step to reflect changing areas of shallow groundwater in response to storm-interstorm cycles. These code changes have allowed the Lower Republican River basin model to be run with only a single execution of SWAT under HRU schemes 1-3 (see Ch. 3 of the companion report).

Program Swbmerge was written to accommodate an additional mode of operation in which SWAT simulates each subbasin with a separate execution. The option Iophru = 2 is assumed to have been chosen so that SWAT calls subroutine Sumstep at the end of each aquifer time step to summarize results for the subbasin, combine hydrologic components to represent recharge and tributary flow for a stream-aquifer model, and converts simulation results from volumes per unit area (depths) to flow rates in MODFLOW's system of units. After SWAT has simulated all subbasins, Swbmerge can combine them into a basin summary file for input to MODFLOW.

The input variables Itmuni and Lenuni are read from the extended Control Codes input file to indicate time and length unit conversions, respectively, between SWAT and MODFLOW. The definition of Itmuni is the same as that for input to MODFLOW's Basic package. The definition of Lenuni is the same as that for input to MODFLOW-2000 from the Discretization input file. Lenuni replaces input variables Cnvlen and Cnvlbl, which are now specified in terms of Lenuni internally (subr. Readcod). Introducing the inputs Itmuni and Lenuni provides a means of generalizing time and length unit conversions between SWAT and MODFLOW that is consistent with MODFLOW's definitions, and anticipates eventual conversion to coordinating with MODFLOW-2000 (Harbaugh et al., 2000; Hill et al., 2000), which was released in July 2000.

See Section 1.2 of the User's Manual for a summary of known problems and issues of program version compatibility.

2. Method

2.1. Spatial variability within subbasins

The updated SWAT-MODFLOW linkage is based on a set of conceptual models for spatial heterogeneity 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 landuse to be the soil or landuse of the subbasin, each subbasin is discretized into virtual areas (referred to as virtual basins), each having a unique soil and landuse 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 (Fig. 2.1). 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 or HRUAVG) 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. This alternative HRU approach is indicated by setting the added input Iopmod = 1, which is read from the extended Control Codes (*.cod) input file by both SWAT and SWBAVG.

The approach summarized above for representing spatial heterogeneity was implemented for the following reasons. First, it allowed HRU weights to vary over time to represent temporal variation in land use. Secondly, refined HRU schemes, presented in the Final Report, include as HRU factors not only land use and soil type but also features underlying the soil profile, classified as bedrock, deep groundwater, or shallow groundwater. Using the intermediate program SWBAVG or HRUAVG, HRU weights reflected temporal variations in land uses and shallow ground water areas. Additionally, two of three HRU schemes that were simulated accounted for spatial dependencies based on basin geomorphology, in contrast to assuming spatial independence of soil, land use, and subsurface types.

> 1. Soil water-atmosphere simulation: SWAT (v.99.2)
>   For each day of the simulation period:
>   At beginning of aquifer solution time step: If **Iopshl** > 0 (HRU scheme 3),
>   read evap. from shallow gw summary written by MODFLOW;
>   For each subbasin:
>   Run lumped watershed model code;
>   Accumulate results over aquifer solution time step;
>
> 2. Summarize SWAT results for input to MODFLOW.
> At the end of each aquifer solution time step, summarize results for Modflow.
> If Iopmod=2, steps 2a-2e are performed by SWAT as follows. (If Iopmod=1, these
> steps are performed externally by program Swbavg or Hruavg; see Ch. 6 of User's
> manual for details).
>   2a. Evaluate spatial weights corresponding to HRUs simulated by SWAT.
>   If Iopwts > 0, HRU weights may be calculated and updated during simulation.
>   2b. Take a spatially weighted average over the HRUs simulated by SWAT for
>   each hydrologic term in each subbasin (subr. Sumhrus).
>   2c. Specify tributary inflow and ground water recharge in terms of SWAT's
>   simulation results (subr. Sumstep).
>   2d. Convert SWAT simulation results from units of volume per unit subbasin area
>   (mm) to MODFLOW's units of flow rate (subr. Sumstep).
>   2e. Write tributary inflows, recharge, irrigation demand, and potential evaporation
>   rate from shallow ground water for input to MODFLOW (subr. Sumstep).
>
> 3. Stream-aquifer simulation: MODFLOW-96 (v.3.3)
> For each aquifer solution time step:
>   Distribute HRU-averaged flow rates for each subbasin over grid to specify
>   recharge, tributary flow, surface and ground water diversions, and max.
>   evaporation for shallow gw (**SWBX**, **STRX** and **WELX** packages).
>   Formulate and solve finite difference equations (FM_ and solver routines);
>   Write summary of evaporation from shallow ground water to be read by SWAT
>   on a subsequent run (subr. SWB2BD);

Fig. 2.1. Overview of procedure followed in applying the SWAT-MODFLOW code.

2.2. Applying SWAT's virtual subbasin capability

The SWAT-MODFLOW linkage has recently been modified for application to basin
models in which spatial heterogeneity is represented by virtual subbasins in SWAT
(Neitsch et al., 1999; N&D, 1999). To allow this, SWAT was modified to incorporate the
functions provided by the intermediate programs SWBAVG and HRUAVG. This option
allows specifying all HRUs to be simulated with a single execution f SWAT. This
requires defining more extensive watershed configuration (*.fig) and file control (*.cio)
files, and specifying the spatial weight of each HRU as the area of a virtual subbasin in
the subbasin (*.sub) input files. In addition, the option was added to calculate HRU
weights in terms of soil, land use, and subsurface features, using functions developed for

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the intermediate program HRUAVG. Fig. 2 summarizes the procedure followed for the revised linkage of SWAT and MODFLOW.

To take advantage of the capability to evaluate HRU weights within SWAT, the configuration specifies an added field that identifies each combination of HRU factors corresponding to the spatial weight that is to be computed. These combinations are defined by input to the extended version of the Control Code (*.cod) input file, which was previously used as input to SWBAVG and HRUAVG, to specify areal fractions of each soil type, land use, and subsurface features within each subbasin. At the end of each groundwater time step, SWAT first calls subr. Sumhrus to take a spatially weighted average over HRUs within each subbasin, and then calls subr. Sumstep to perform the remaining functions of SWBAVG or HRUAVG (steps 2d-2f in Fig. 1) are performed in SWAT by subroutine Sumstep, thereby producing a data file for input to MODFLOW.

The above options are illustrated by an example based on the data set provided with AvSwat (Lakefork), and by test runs of the Lower Republican River basin model. Examples are shown for specifying this version of HRU schemes 1-3, and results for these cases are presented in the section entitled "Using virtual subbasins to simulate HRU schemes 1-3."

2.3. Procedure to coordinate separate SWAT and MODFLOW data sets
The procedure outlined in N&D (1999) for the Lakefork example using AvSwat is adapted to produce a summary data file for input to MODFLOW. The following is assumed: (a) The SWAT data set runs under SWAT v.99.2, which may be executed through the AvSwat extension for ArcView; and (b) the MODFLOW data set runs under MODFLOW-96. Specific procedures and key data file listings are provided with a set of examples in a section below.

2.3.1. Watershed simulation using modified SWAT v.99.2 within AvSwat
1. Replace the executable file for SWAT v.99.2 provided with the AvSwat extension, \Avswat\Avswatpr\swat992.exe, with the modified version, file swt99opt.exe; rename this file to the original file's name, swat992.exe.
2. Set up input for SWAT (v.99.2) through AvSwat (ArcView extension) as described in the AvSwat User's Guide (Neitsch and DiLuzio [N&D], 1999), Sections 5.1.1-5.1.5 of the Example Data Set.
3. Modify the Control Codes input file created by the above procedure to specify Iopmod = 2 and other options as described by Input Instructions for the modified Control Codes (*.cod) input file in P&S (2000b).
4. Proceed with running SWAT and working with SWAT input and output data through the AvSwat extension described in Sections 5.1.6 and 5.1.7 of N&D (1999) for the Example Data Set. Execution of SWAT with Iopmod = 2 will produce a file for input to MODFLOW with a name based on the standard output file and extension ".bal". For a standard output file name basi.std, the file written for input to MODFLOW will be named basi.bal, as in the above AvSwat example. This file will contain the results of steps 1 and 2 shown in Fig. 2.1.

2.3.2. Stream-aquifer simulation using MODFLOW-96 (v.3.3)

1. In addition to the standard MODFLOW-96 packages and corresponding data files required to simulate a case, the Name file must specify the SWB package and two input files. One of these is the file written by SWAT (extension ".bal"), above. The other is the*.swb input file, which defines the following two associations:

1a. An integer array, Ibshed, associates the geographical extent of each subbasin with the corresponding model grid cells of the underlying ground water simulated by MODFLOW. For grid cells underlying each subbasin, i, for i from 1 to n, the array Ibshed specifies the integer, i. The array Ibshed is similar in form to the Ibound array given for Modflow's Basic package, except that only one layer is defined for Ibshed.

1b. the outflow for each subbasin is associated with a stream reach as defined for MODFLOW's STREAM package (Prudic, 1989).

2. Use of the SWB package requires that both the WEL and STR packages also be invoked, since the SWB package is coordinated with modified versions of the WEL and STR packages. On the other hand, if the SWB package is not invoked, the standard versions of the WEL and STR packages will be called if invoked unless the modified versions are specified by input data (P&S, 2000b).

2.4. SWAT-specified flow conditions for MODFLOW's solution

[This section is adapted from the Final Report (P&S, 2000a), and retains the equation numbers used in that report for reference.]

SWAT simulates watershed hydrology in a continuous mode with daily time steps. It is quasi-distributed: a basin model 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

$$d_{sw}(t) - d_{sw}(0) = \sum_{i=1}^{t} \left(d_{pcp} + d_{irr} - d_{ro} - d_{lat} - d_{perc} - d_{et} \right) \qquad (2.1)$$

Terms of eqn. (2.1) are in units of length (mm) representing water volume per unit area, where water volume is given by integrating flow rate over time; that is, $d = Q\Delta t / A$. 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 ground water and not to soil water.

The hydrologic terms simulated by SWAT are transformed from cumulative volumes per unit area [L] to flow rates [L^3/T] in the system of units specified for MODFLOW's simulation. These operations are performed either by SWBAVG for the option Iopmod = 1, or by the added subroutine Sumstep called by SWAT for the option Iopmod = 2, as indicated in Fig. 1. The terms in (2.1) have the units of depth corresponding to a volume given by $V = dfA$, where f is the areal fraction of watershed area, A, to which the hydrologic term applies. This volume is given by integrating flow

rate over time. For average flow rate, Q, and time step, Δt, $V = Q\Delta t$. Combining these relates the flow rates, Q, to depths, d, by

$$cQ\Delta t = dfA, \qquad (2.8)$$

where c is a constant that depends on both the time unit indicator, Itmuni, and length conversion factor, Cnvrsn, both of which are specified in the modified Control Codes (*.cod) input file for SWAT and SWBAVG. The input Itmuni specifies the time units used in MODFLOW as defined in Harbaugh and McDonald (1996). The input Cnvlen specifies the length conversion factor between MODFLOW and SWAT. See the User's Manual (P&S, 2000b) for further details on these.

Hydrologic terms simulated by SWAT for each subbasin are combined to specify fluxes for MODFLOW's solution in each time step. These fluxes include irrigation demand, ground water recharge, tributary inflow, and a maximum rate for evaporation from shallow ground water. Conceptual models for these are described by equations (2.11–2.16) as follows.

Irrigation demand is simulated by SWAT and converted to a flow rate according to equation (2.8) by

$$Q_{irr} = d_{irr}f_{irr}A/c\Delta t, \qquad (2.11)$$

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

Recharge to ground water 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 presumed presence of an underlying aquifer. Consistent with this assumption, the ground water recharge flow rate for a subbasin is given by

$$Q_{rech} = (d_{perc} + d_{xm} + d_{psep})A/c\Delta t. \qquad (2.12)$$

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 Republican River 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

$$Q_{trib} = (d_{sro} + d_{lat})f_{con}A/c\Delta t \qquad (2.13)$$

An additional component of tributary flow, Q_{po}, may be due to overflow from ponds created by artificially damming streams.

Finally, potential evaporation simulated by SWAT is used to represent the maximum evaporation rate from shallow ground water.

2.4.1. HRU scheme 1: adjusting for SWAT's "deep aquifer" assumption

Simulations by SWAT presume an underlying aquifer, to which percolation out of the soil profile and transmission losses flow. This corresponds to the default value

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Ipurk(j) = 0 in the SWAT ground water input file (*.gw) for each virtual subbasin, j. Whether HRUs are averaged in SWAT or SWBAVG to represent spatial heterogeneity, the same conceptual model is applied under HRU scheme 1 for subbasins partially underlain by an aquifer as presented in the Final Report (P&S, 2000a). For the areal fraction of a subbasin underlain by bedrock, percolation out of the soil profile and transmission losses are routed to the stream network as tributary inflow. This is simulated as part of step 2b (Fig. 1) using an ad hoc correction as follows.

The areal fraction of each subbasin j underlain by an aquifer is given by **aqf_fr**(j), which is specified by the extended form of the Control Codes input file *.cod. If the SWAT-MODFLOW linkage option Iopmod = 1, **aqf_fr**(j) is read by either SWBAVG or HRUAVG, which apply steps 2a-2d (Fig. 1). If Iopmod = 2, **aqf_fr**(j) is read by SWAT's modified subroutine Readcod and used in subroutine Sumstep, which applies steps 2b-2d.

SWAT simulates percolation, transmission losses, and pond seepage, the terms included for recharge in equation (2.12), based on the assumption that the full areal extent of a subbasin's soil profile is underlain by an alluvial aquifer. To represent a subbasin only partially underlain by an aquifer, several alternatives are available. First, an ad hoc variation on HRU scheme 1 might be used. A somewhat simplistic method is to partition recharge according to equation (2.12) into two components,

$$Q_{rech} = Q_{raqf} + Q_{rbed} \qquad (2.14)$$

Ground water recharge is restricted to the first term, Q_{raqf}, which is associated with the areal fraction of a given subbasin underlain by an alluvial aquifer, f_{aqf}:

$$Q_{raqf} = Q_{rech} f_{aqf} \qquad (2.15a)$$

The second term, Q_{rbed}, is associated with the complementary fraction outside the alluvial valley, $(1 - f_{aqf})$, where the soil profile is underlain by bedrock:

$$Q_{rbed} = Q_{rech}(1 - f_{aqf}) \qquad (2.15b)$$

This term is added into tributary flow as a variation on equation (2.13).

$$Q_{trib} = (d_{sro} + d_{lat}) f_{con} A/c\Delta t + Q_{po} + Q_{rbed} \qquad (2.16)$$

This ad hoc scheme is based on the partitioning given by equation (2.14) to satisfy continuity, but this is inconsistent with the hydrologic model simulated by Swat, in which the full extent of the subbasin is assumed to be underlain by an aquifer. More hydrologically consistent alternatives are provided by refined conceptual models of spatial heterogeneity; see "HRU schemes 2 and 3" in the Final Report (P&S, 2000a).

2.5. Distributing fluxes specified by SWAT over MODFLOW's model grid

This section summarizes how flow rates specified by SWAT's simulations are distributed over the stream-aquifer grid for MODFLOW's solution. The SWBX package was written to provide a means of specifying conditions for MODFLOW's stream-aquifer solution in terms of results from a watershed simulator. SWAT and SWBAVG provide HRU-averaged, lumped quantities as flow rates from each subbasin to simulate these conditions for each solution time step. Simulated recharge and potential evaporation for

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 ground water points of diversion. The associations of tributary inflows and diversions involve nonstandard versions of MODFLOW's STREAM and WELL packages, referred to as STRX and WELX, respectively, which provide features necessary for the SWAT-MODFLOW linkage.

2.5.1. Associating watershed subbasins with stream-aquifer grid with SWBX

To initialize an association between MODFLOW's stream-aquifer grid with the subbasins simulated by SWAT, SWBX reads an input file that provides the following two items:

1. The point of exit for runoff, or pour point, from each subbasin is associated with a reach of the stream network based on its grid cell coordinates and an association matrix in the STRX package, IDXSTR (described below).

2. Associate the geographical extent of each subbasin with the grid cells of the aquifer and stream. A two-dimensional integer-valued array, IBSHED, associates each grid cell with the subbasin enclosing the cell's center, and follows MODFLOW's convention for reading arrays. The approximate areal fraction of each subbasin underlain by an aquifer is based on the area of active grid cells corresponding to positive-valued elements of MODFLOW's IBOUND array.

Two additional arrays are declared by the SWBX package to represent depth to water and evapotranspiration from shallow ground water. The corresponding values are calculated in the Evapotranspiration package but not retained as arrays. These arrays are summarized for each subbasin in subroutine SWB2BD of the SWBX package and written to a file for input to subsequent runs of SWAT and SWBAVG under HRU scheme 3; see "HRU schemes to account for aquifer heterogeneity and spatial dependence," below.

2.5.2. Distributing HRU-averaged flow rates over a stream-aquifer grid

In each time step, SWBX reads tributary inflows, ground water recharge, irrigation demand, and potential evaporation for each subbasin as HRU-averaged flow rates from a data file written by SWBAVG. In addition, simulated actual evaporation and rates of change in storage for soil water and ponds are passed, allowing evaluation of an overall water balance according to equation (2.7) based on these and MODFLOW's results. Pumping rates from surface and ground water 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. The nonstandard MODFLOW packages STRX and WELX are both involved in satisfying these constraints.

STRX, the modified version of the STREAM package, uses a modified routing procedure to account for net lateral surface inflows in each reach, which represents the sum of any tributary inflows, surface water diversions (outflows), and optional

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evaporation from the stream surface that might be specified for the reach. In addition, an indexing array, Idxstr, is a feature added to look up a stream reach that is to be associated with grid coordinates specified for subbasin outflows (item 1, above) and surface water diversions.

2.5.3. Spatial distribution of recharge

This section has been added since submission of the Final Report (P&S, 2000a) to reflect an update of the SWBX package for distributing recharge. Equations used in this description are identified as (2.16b-2.16e) for this document version to avoid renumbering the equations that follow this section. The following terms are defined:

$R_{in}(ic,ir,t)$ [L/T] = array for recharge as a flux, the form of the input read by the Recharge package, for each column, ic and row, ir, at the beginning of each stress period.

$R(ic,ir,t)$ [L^3/T] = array for recharge as a flow rate for each column, ic and row, ir, at time, t.

$Q_r(isub,t_0)$ [L^3/T] = sum of recharge taken over $R(ic,ir)$, as specified for the Recharge package in the first stress period, for grid cells corresponding to subbasin, isub.

$Q_r(isub,t)$ [L^3/T], the recharge for each subbasin, isub, at time, t, given by SWAT's simulation.

$f_r(ic,ir)$ = recharge distribution function.

At the beginning of each stress period, the Recharge package subroutine Rch5rp 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. Rch5rp converts this flux to a flow rate, R [L^3/T] by multiplying the flux specified for each grid cell by the grid cell's area,

$$R(ic,ir,t) = R_{in}(ic,ir)A(ic,ir), \qquad (2.16b)$$

where $A(ic,ir)$ denotes grid cell area, and is given by $A(ic,ir) = delc(ir) \cdot delr(ic)$, the product of row width delc in row ir and column width delr in column ic; see the MODFLOW manual (McDonald and Harbaugh, 1988, or Harbaugh and McDonald, 1996). If the SWB package is invoked, the use of the recharge array depends on the option Ioprch, which is read by the SWB package (see Input Instructions in the User's Manual).

For the default option Ioprch = 0, recharge specified by (2.16b) is applied for each time step of the stress period by the Recharge package subroutine Rch5fm. If Ioprch > 0, 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

$$f_r(ic,ir) = R(ic,ir,t_0)/Q_r(isub,t_0), \qquad (2.16c)$$

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

$$Q_r(\text{isub},t_0) = \sum_{j,k} R(j,k,t_0). \tag{2.16d}$$

The array $f_r(\text{ic,ir})$ 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, $f_r(\text{ic,ir})$ is used to distribute the recharge flow rate simulated by SWAT, $Q_r(\text{isub},t)$, over the grid cells of the subbasin according to

$$R(\text{ic,ir},t) = f_r(\text{ic,ir})Q_r(\text{isub},t). \tag{2.16e}$$

This operation is applied by subroutine Swb2fm to specify the recharge array RECH prior to the iterative solution in each time step. Then the Recharge package Rch5fm specifies recharge as a boundary condition according to the array RECH as it does for the default case (Ioprch = 0).

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 (2.16e) 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.

Subroutine Swb2rch, which specifies the initial recharge distribution array, $f_r(\text{ic,ir})$, was derived from subroutine Rch5fm of the Recharge package to ensure that the correct grid cells are included in the sums given by (2.16d) for all recharge options specified by the code NRCHOP (see MODFLOW manual Input Instructions).

The initial distribution of recharge over the grid cells according to (2.16e) does not take into account the possible occurrence of "dry cells," in which case initially active grid cells become inactive, or "no-flow" cells, as indicated by the Ibound array (defined in MODFLOW's Basic package). If necessary, this problem might be remedied by additional calls to subroutine Swb2rch to update the recharge distribution array for each time step in which dry cells occur.

2.5.4. Meeting irrigation demand with surface and ground water diversions

WELX, the modified version of the WELL package, 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 MODSTR, is used to look up corresponding reaches of a stream network that is specified by input to MODSTR. Diversions are further distinguished by type of use, (irrigation, domestic, municipal, etc., including fictitious wells to represent boundary

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conditions. Irrigation demand simulated by SWAT is distributed only over points of diversion associated with irrigation water use. The method of this distribution is described as follows.

Annual appropriations are specified as flow rates for both ground water diversions, q_{gk}, and surface water diversion, q_{sk}, by MODFLOW's WELL package; modified as described above to represent diversions from both ground water and streamflow. Total annual appropriations for irrigation are denoted by the sum over both appropriation sources,

$$Q_{app} = \Sigma q_{gk} + \Sigma q_{sk} \tag{2.17}$$

The first summation on the right is taken over the appropriations for n_g individual ground water rights, and the second for n_s individual surface water rights. For a given time period of interest, if water use is known for the individual water rights, total water use can be similarly expressed. Otherwise, the irrigation demand simulated by SWAT and given as a flow rate, Q_{irr}, by equation (2.11) can be distributed over water rights appropriated for irrigation. This is done by defining the factor, $s = Q_{irr}/Q_{app}$, which is used to scale the annual appropriations of the individual diversions, expressed as pumping rates. Multiplying equation (2.17) by s gives

$$Q_{irr} = sQ_{app} = s(\Sigma q_{gk} + \Sigma q_{sk}) = \Sigma s q_{gk} + \Sigma s q_{sk} \tag{2.18}$$

Here, the normalized spatial distribution of appropriations is given by dividing equation (2.17) by Q_{app}, and is used in place of one for water use in the absence of sufficient information regarding water use by individual water rights.

In the case of the Lower Republican River basin model, irrigation demand was simulated in SWAT on a daily basis, summarized for monthly time steps Δt, and averaged over the eighteen HRUs for each subbasin by equation (2.9) to give the average depth $d_{irr}f_{irr}$. The flow rate corresponding to this monthly demand is given by equation (2.11). The total annual appropriations for ground and surface water rights meet this demand by distributing the scaling factor, s, which is zero except during the growing season, over the individual water rights according to equation (2.18).

2.5.5. Operational and supply limits on surface and ground water diversions

Pumping limits may be specified for WELX in terms of both operating and supply limits. Operating limits with respect to pumping capacity are specified as maximum scaling factors for ground and surface water diversions, s_g and s_s, as a variation on equation (2.18) given by

$$Q'_{irr} = \sum_{k=1,n_s} q'_{sk} + \sum_{k=1,n_g} q'_{gk},$$

$$q'_{gk} = \min(s, s_g)\, q_{gk}, \tag{2.19}$$

$$q'_{sk} = \min(s, s_s)\, q_{sk}.$$

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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 ground water diversions is limited by the aquifer's saturated thickness, $d_s(h) = h - z_b$, where $h =$ hydraulic head and $z_b =$ bedrock elevation. Above an upper limit, d_u, and corresponding elevation, z_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 is expressed by

$$q''_{gk}(h) = \begin{cases} q'_{gk} & h > z_u, \\ q'_{gk}\left(\dfrac{h - z_l}{z_u - z_l}\right) & z_u > h > z_l, \\ 0 & h < z_l \end{cases} \tag{2.20}$$

The above method to limit pumping provides a realistic means of preventing grid cells from going "dry" as a result of excessive pumping from wells. But through equation (2.20), the head-dependent pumping rates are coupled to the solution of the groundwater flow equation, which can adversely affect solution convergence if not handled properly. These head-dependent fluxes are incorporated into the solution in the same way that other head-dependent fluxes are represented, including evaporation from shallow ground water and streambed leakage. The technique for doing this is presented in the Final Report in Ch. 2 under the section "Incorporating head-dependent fluxes."

2.6. Data to be passed between Swat and Modflow

This section is adapted from Chapter 3 of the Final Report (P&S 2000a) to summarize the correspondence between array locations for hydrologic simulation results that are passed from SWAT to MODFLOW. Table 2.1 summarizes the data written to the balance file in SWAT and identifies equations in which the data are used, including hydrologic balances and conceptual models for the linkage.

Table 2.1. Data passed from SWAT to MODFLOW

i	term	usage (eqns. from report)	Swat sub-basin ssub[1] index	Mod-flow array Shed[2] index	flow rates passed to Modflow[3]
1	precip	2.1, 2.7	1	10	pcp
2	irrigation	2.1, 2.11	22	11	irr
3	evap (act.)	2.1, 2.7	12	12	et + pnd_evap[4]
4	runoff, surq	2.1, 2.13	4	13	surq
5	transm. loss	2.12,2.13	13	14	tloss
6	subsurf. latq	2.13	5	15	latq
7	percolation	2.12	11	16	perc
8	da_rech,gwre		9	17	qrech (2.12, 2.14)
9	revap,rev		7	18	qtrib (2.13, 2.16)
10	gw_q		6	19	baseflow[5]
11	pond seep.	2.12	16	20	
12	etpot	2.23	25	21	
13	pnd_out		20	22	
14	pnd_evap		15		
15	dSol_mm	2.1, 2.7		6	dSol
16	dPnd_mm	2.7		5	dPnd
17	et_gw(mm)				
18	egwuna				
19	Sol_sw,mm				
20	qtrib	2.13, 2.16			
21	qrech	2.12, 2.14			

[1]Swat subbasin array ssub index is given by (idxsub(i), i=1 to 14) in Swtmod99.h.

[2]Modflow (SWBX package) array shed index is given by idx = i + 9.

[3]Converted to flow rates $Q = d*cA/\Delta t$., where d represents volumes per unit area simulated by Swat (eqn. 2.8 in Final Report).

[4]Based on the sum of actual evaporation, ssub(12,j), and pond evaporation, ssub(15,j).

[5]Baseflow is evaluated as coupled stream-aquifer solution in MODFLOW's STREAM package based on Darcy's law applied to the hydraulic gradient across the streambed.

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Swat accumulates its hydrologic results for each time step in array ssub, from which data are written to the balance file. HRU-averaged simulation results from SWAT are read by the MODFLOW package SWBX into the Shed array. The correspondence between vectors in Swat's array Ssub and Modflow's array Shed for hydrologic components of interest for the linkage are shown in Table 2.1. The components listed in Table 2.1 can be classified into the following three groups:

1. Data to check soil water balance (eq. 2.1): precipitation, irrigation, evaporation, runoff, subsurface lateral flow, percolation. Note that the term for runoff accumulated by SWAT as ssub(4,j) for subbasin j, includes transmission losses.

2. Data to be passed to Modflow to specify time step, irrigation, recharge, tributary inflow, potential evaporation (conceptual models given by eqns. 2.11-2.16 and 2.23). As noted above, transmission loss is included in the term for runoff, ssub(4,j); this is reflected in the conceptual models for tributary flow and recharge (eqns. 2.12-2.16). Potential evaporation is used in MODFLOW to represent maximum evaporation rate from shallow ground water, eq. (2.23).

3. Data used to calculate an overall hydrologic balance (eq. 2.7): precipitation, evaporation, time rate of change in pond storage, time rate of change in soil water storage.

3. Examples incorporating SWAT's virtual subbasin capability

The following examples illustrates a sequence of operations to run SWAT and MODFLOW in which SWAT applies the HRU approach internally using virtual subbasins.

3.1. Ex. 1, based on the AvSwat Lakefork example

A procedure for using the SWAT-MODFLOW linkage in conjunction with the AVSwat extension for ArcView was outlined in Section 2.3. This example shows how the modified version of SWAT can be applied to the Lakefork example through the AvSwat interface. The Control Codes input file basi, which was generated by AvSwat, was modified so that execution of Swat produces a summary of results that could be used to specify conditions for a groundwater model simulated by MODFLOW. Notes on installing the modified version of SWAT for use through the AvSwat interface are provided in Ch. 4 and in the separate text document, Install.txt.

The first example is a variation on the "Example Data Set" in Chapter 5 of the AvSwat User's Guide (Neitsch and DiLuzio [N&D], 1999), which was followed as described in Sections 5.1.1-5.1.7 (see also Fig. 2, above). After following the steps described in Sections 5.1.1-5.1.5, the Control Codes input file basi.cod was edited to specify Iopmod = 1 in column 92 of record 2, and to add data records 6 and 7 as shown below (line 6 is read if Iopmod > 0; line 7 is read if Iopwts > 0).

Modified input file basi.cod:
```
20000815 Simulation in Basin Watershed:  .COD control file ArcView-SWAT interface     MDL
   21977   0   0   1   1   0   0   0   0   0   0   0   0   1 365   0   1   0   2   0   1   2
                                                                                        3
                                                                                        4
                                                                                        5
     0   1   1  ' ',  ' '                 ! (3i4,2a) iopshl itmuni Lenuni nambal namshl  6
     1   0   0                            ! (3i4)    iophru iopwts iprwts                7
```

The options added to file basi.cod indicate the following:

(Line 2)
Iopmod = 2: SWAT is to apply steps 2a-2e as summarized in Fig. 2.1 for input to Modflow.

(Line 6: read if Iopmod > 0, from line 2)
Iopshl = 0: option declined to read a summary of evaporation from shallow ground water (see Namshl def., below). This option applies to refined HRU scheme 3, described in Final Report (P&S, 2000a), and provides a 2-way coupling between SWAT and MODFLOW in which HRUs with shallow groundwater are simulated by SWAT, and evaporation from shallow groundwater is simulated by MODFLOW.
Itmuni = 1: MODFLOW's time units are specified as seconds.
Lenuni = 1: MODFLOW's length units are specified as feet. Itmuni and Lenuni are used for unit conversion between SWAT and MODFLOW.
Nambal = ' ': if not blank, use this for the name of the output file that is to be read by MODFLOW (or by SWBAVG or HRUAVG for the case that Iopmod = 1).

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Namshl = ' ': if not blank, this is the name of the file summarizing evaporation from shallow ground water, written by subr. SWB2BD in the SWB package for a previous execution of MODFLOW.

(Line 7: read if Iopmod = 2, from line 2)
Iophru = 1: default option for subsurface model; soil profile is assumed to be underlain by a deep aquifer.
Iopwts = 0: HRU weights are read from subbasin (*.sub) input files for each HRU.
Iopwts = 0: option to write table of calculated HRU weights (for Iopwts > 0).

After adding the above data to the file basi.cod, the procedure described in Sections 5.1.6-5.1.7 of the AvSwat manual (N&D, 1999) was then followed. In addition to SWAT's standard output, execution of the modified version of SWAT from the AvSwat interface produced the file basi.bal, which could be used for input to MODFLOW if a suitable input data set were available for the Longfork model. The following files were written by SWAT for this case:

basi.std	standard output file for SWAT
basi.bal	HRU-averaged summary of results for each subbasin and time step.
basi.dep	summary of results in SWAT's units (mm) averaged over subbasins.
basi.sum	summary of results in MODFLOW's units (cfs) summed over subbasins.

The options specified in the Control Codes input file were summarized in the standard output by the added subroutine Init_bal as follows:

```
Init_bal: Iopmod=2
  Iopmod=1: avg HRUs externally (Swbavg);
  Iopmod=2: Swat virtual subbasins represent spatial heterogeneity.
Initialize the following files:
Write nambal=basi.bal    , to be read by Modflow;
Write namdep=basi.dep    , summary of file namdep (SWAT units);
Write namsum=basi.sum    , summary of file namsum (MODFLOW units);
Modflow time units: Itmuni=1 (1:sec, 2:min, 3:hr, 4:day, 5:year)
Modflow length units: Lenuni=1 (1:feet, 2:meters, 3:centimeters)
```

3.2. Ex. 2. L. Republican R. test case based on HRU scheme 1

For this case, each subbasin is represented by up to 15 HRUs. Example 2 illustrates the procedure for the test case hru1virt, assuming that the executable files Swt99opt.exe and Modflx96.exe are in the directory \gh\. First, copy file hru1virt.cio to file.cio, the name assumed by SWAT99.2:

```
copy /y   hru1virt.cio file.cio
```

This file identifies the Control Codes input file hru1virt.cod, which specifies the option to summarize results for input to MODFLOW. File hru1virt.fig specifies the routing sequence for all HRUs, and also identifies the HRUs as combinations of factors that are defined by input to the extended Control Codes input file (Hru1virt.cod).

From the directory \gh\rep992\ with the Swat executable file swt99opt.exe in the parent directory \gh\, run SWAT as follows:

```
..\swt99opt
```

Execution time for this case is approximately 45 min on a 90-MHz Pentium-1 PC. SWAT writes a summary of its simulation results to file hru1virt.bal for input to MODFLOW, which is run from \gh\rep992\hruvirt\ as follows, assuming that modflx96.exe is in the directory \gh\:

```
\gh\modflx96
```

Modflow-96 prompts for a Name file, which is given by Hru1virt.nam. For the SWAT-MODFLOW connection, the Name file invokes the added SWB package. The associated file rptest96.swb associates subbasins with the stream-aquifer grid, and the file Hru1virt.bal, written by SWAT, is specified for input to the SWB package. Files Hru1virt.cio, Hru1virt.cod, Hru1virt.nam, and Rptest96.swb are listed in Ch. 7 of the User's Manual, and can also be found with the test data set files.

The corresponding execution time of MODFLOW for this case is on the order of 15 s. That is, over 99 percent of execution time is spent running SWAT.

Beyond the standard package and associated files, the key additions in file hru1virt.Nam are for the SWBX package and the associated files, including the following:

*.swb (In): specify the relationships between the subbasins simulated by SWAT and the stream-aquifer grid simulated by MODFLOW.
*.bal (In): simulation results written by SWAT
*.shl (Out): shallow ground water area and evaporation summary for each subbasin; can be used as input to a subsequent run by SWAT and SWBAVG.

Because the SWBX package is invoked, the modified WELX and STRX packages are also invoked instead of the standard WEL5 and STR1 packages. Some additional output files are associated with the nonstandard WELX and STRX packages:
*.stm: stream routing details for initial and final conditions in each time step
*.reg: record of pumping rates that have been reduced due to low saturated thickness or streamflow.

The SWBX package subroutine Swb2bd writes a summary of shallow groundwater conditions in each subbasin. This summary is illustrated below for the first two time steps of the simulation for case Hru1virt:

```
year  per  stp  sub frc shall frc activ  shal dtw  avg dtw   frcpot
1977   1    1    1 0.0137352 0.0732544   3.73     19.03  0.340095
1977   1    1    2 0.0410648 0.2053238   3.44     16.37  0.426082
1977   1    1    3 0.0147972 0.2367549   5.32     25.65  0.113243
1977   1    1    4 0.0000000 0.0923757   0.00     28.58  0.000000
```

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```
1977   1   1   5 0.0190824 0.2099068      3.02    22.07 0.497327
1977   1   1   6 0.0000000 0.0122218      0.00    36.51 0.000000
1977   1   1   7 0.0000000 0.0828818      0.00    17.87 0.000000
1977   1   1   8 0.0000000 0.0256515      0.00    38.11 0.000000
1977   1   1   9 0.0000000 0.2503694      0.00    20.64 0.000000
1977   1   2   1 0.0045784 0.0732544      0.23    19.58 0.961604
1977   1   2   2 0.0410648 0.2053238      4.07    16.90 0.322466
1977   1   2   3 0.0098648 0.2367549      5.66    26.09 0.057367
1977   1   2   4 0.0000000 0.0923757      0.00    29.11 0.000000
1977   1   2   5 0.0190824 0.2099068      3.74    22.53 0.376874
1977   1   2   6 0.0000000 0.0122218      0.00    37.34 0.000000
1977   1   2   7 0.0000000 0.0828818      0.00    18.43 0.000000
1977   1   2   8 0.0000000 0.0256515      0.00    39.30 0.000000
1977   1   2   9 0.0000000 0.2503694      0.00    21.10 0.000000
```

Column descriptors:

frc_shall: shallow groundwater areal fraction of subbasin (depth less than extinction depth as specified for Modflow's EVT package);

frc_activ: total groundwater areal fraction of subbasin;

shal_dtw: mean depth to water for area of shallow groundwater;

avg_dtw: mean depth to water taken over total area of groundwater in subbasin;

frcpot: evaporation from shallow groundwater as a fraction of potential evaporation.

File rptest96.swb: input to SWBX; associates subbasins with stream-aquifer grid.

```
    9,    nwshed (no. subbasins); file c:\gh\test\inbase\rptest.swb
    1    3    1    1 0.00    1    0 0.0 irropt,ievopt,ioprch,rchmpy,evapir,welmpy
  sub   act  row col sbnxt      tributary
    1    1    4   16    1      Salt Cr
    2    1    6   14    2      Oak Cr
    3    1    6   21    3      Elm Cr
    4    1    5   24    4      Elk Cr
    5    1    7   30    5      Scribner Cr
    6    1    7   30    6      Parsons Cr
    7    1   11   32    7      Peats Cr
    8    1   21   36    8      Five Cr
    9    1   21   37    9      Huntress Cr (Spring & Dry Cr's)
       66          1 (39i2)                 2      iwshed.mod
 0 1 1 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 4 5 5 5 6 6 6 6 6 6 7 7 7 7 7 7
 0 1 1 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 4 5 5 5 6 6 6 6 6 6 7 7 7 7 7 7
 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 5 5 5 5 6 6 6 6 7 7 7 7 7 7 7
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4 4 4 4 5 5 5 5 6 6 6 6 7 7 7 7 7 7 7
 1 1 1 1 1 2 1 1 1 2 2 2 2 1 1 3 3 3 3 3 4 4 4 4 5 5 5 5 6 6 6 7 7 7 7 7 7 7 7
 0 0 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 5 5 5 5 5 6 6 7 7 7 7 7 7 7 7
 0 0 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 5 5 5 5 6 6 7 7 7 7 7 9 9 0
 0 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 5 5 5 3 7 7 7 7 7 7 7 9 9 9
 2 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 7 7 7 7 7 9 9 9 9
 2 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 7 7 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 2 2 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 7 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 3 3 3 3 3 3 3 3 8 8 3 3 3 3 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 3 3 3 8 8 8 8 8 8 3 3 3 7 9 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 3 8 8 8 8 8 8 8 8 3 3 9 9 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 3 8 8 8 8 8 8 8 8 8 3 3 9 9 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 8 3 3 9 9 9 9 9 9
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 8 8 3 3 9 9 9 9 9 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 8 8 8 3 3 3 9 9 9 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 8 8 8 8 3 9 9 9 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 9 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 8 8 8 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 8 8 8 8 8 8 8 8 8 0 0 0 0
```

Excerpt from file rptest96.bas: input to Modflow's Basic package (BAS5) for the Ibound array, to identify active (ibound=1), inactive (ibound=0), and constant-head (ibound=-1) grid cells. Active grid cells are associated with the geographical extent of the alluvial aquifer with a minimum initial saturated thickness on the order of 5 meters along the alluvial valley.

```
1           1 (39i2)                        2   \sp\basin27\ibrepub.3/21/96
 0-1-1-1-1 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
 0-1-1-1-1 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
 0-1-1-1-1-1-1-1 1 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
-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 0 0 0 0 0 0 0 0 0 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 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0-1-1-1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 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 1 1 1 1 1 1 1 1 1 1 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 1 1 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 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 1 1 1 1 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 1 1 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 1 1 1-1 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
```

3.3. Ex. 3. Specify a spatial distribution of recharge for MODFLOW

In the case of Ex. 2 (above), input to the MODFLOW Recharge package specified a uniform spatial distribution for the initial recharge array RECH (see MODFLOW manual for input instructions). For the initial stress period corresponding to the first year of the simulation, a uniform distribution could be specified by the following input to the Recharge package from file Onezone.rch:

```
1          0      nrchop irchcb                    onezone.rch
1          0      inrech inirch
0        1.0 (40f5.1)                    12
```

As a variation on a uniform distribution of recharge, the following test case was assumed. With respect to grid columns 28-39, recharge was assumed to be twice as great in columns 7-28 and three times as great in columns 1-6. For the first stress period, this is specified by the following input to Recharge package file 3zones.rch:

```
1          0      nrchop irchcb                    3zones.rch
1          0      inrech inirch
67        1. (40f2.1)                    12
3.3.3.3.3.3.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.
3.3.3.3.3.3.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.
```

```
3.3.3.3.3.3.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
3.3.3.3.3.3.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
3.3.3.3.3.3.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
3.3.3.3.3.3.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
1.1.1.1.1.1.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.2.1.1.1.1.1.1.1.1.1.1.1.1.
```

With the SWB package input file Rptest96.swb (above) specifying Ioprch > 0, this input to the Recharge package is used to specify a spatial distribution of recharge with respect to each subbasin. The spatial distribution with respect to the entire basin will not be preserved unless either Ioprch = 0, so that input from SWAT is ignored; or for Ioprch > 0, the recharge flux specified by SWAT is the same for all subbasins, which would generally not be the case.

This test case for Modflow-96 is run from the subdirectory \gh\rep992\rchzon\ using the Name file Hru1zon3.nam as follows, assuming that the executable file modflx96.exe is in the directory \gh\:

```
\gh\modflx96
```

The Name file specified by Modflow, Hru1zon3.nam, is the following:

```
LIST  6    hru1zon3.lst              case name (~.log, ~.prn, ~.rsp)
BAS   1    ..\inbase\bcase_t4.bas       .bas unit   1 Monthly Basic package
OC   69    ..\inbase\rpbase.oc          .oc  unit  69 Output control
BCF  61    ..\inbase\kbase20b.bcf       .bcf unit  61 Block-centered flow
RCH  67    ..\inbase\3zones.rch         .rch unit  67 Recharge
PCG  68    ..\inbase\model1bs.pcg       .pcg unit  68 precond. conjugate grad.
#
# Non-standard Modflow-88 modules substituted for standard Modflow-96 modules:
# These modules were modified for coordination with the added SWB module.
EVT  65    ..\inbase\repsurf.evt        .evt unit  65
WEL  62    ..\inbase\wrrepub.wel        .wel unit  62 Well: groundwater use
STR  70    ..\inbase\rptest.str         .str unit  70 monthly Streamflow, Ks=0.54
ft/day
#
#             Modules added to Modflow-96:
#               SWB: 2 input files are specified, *.swb and *.bal:
SWB  66    ..\inbase\rptest96.swb              .swb unit  66 Soil water balance
#   1, iobal: Soil Water Balance simulation results
DATA 116 ..\hru1virt.bal
#
# The following files were formerly opened in the modified Modflow-88 mainline.
#
# additional output data files:
```

```
#    2, iostrm: Str2fm (stream routing details for istrbd = 0 or 2)
DATA 117    hru1zon3.stm
#
# If invoking WELX, STRX, and SWBX, open:
#    3, ioreg: Str2fm, Wel2stp: record of pumping rates that have been
#       reduced due to low saturated thickness or streamflow.
DATA 218    hru1zon3.reg
#    4, ioswm: Swb2bd, combined surface & gw budget terms
DATA 219    hru1zon3.swm
#    5, ioshl: Swb2bd, summary of evaporation from shallow gw for each subbasin
DATA 220    hru1zon3.shl
```

The Name file Hru1zon3.nam refers to the recharge input file 3zones.rch, shown above, to the SWB package Rptest96.swb to associate grid cells with subbasins, and the hydrologic simulation summary file Hru1gen.bal, which is produced as shown in Ex. 5.

The resulting spatial distribution of recharge normalized with respect to individual subbasins (below) shows almost no difference from previous case in which a uniform spatial distribution was specified for the initial recharge array. Only subbasins 3 and 5 show any effect, since these subbasins include grid cells from two recharge zones that are divided between columns 27 and 28. If the basin-wide spatial distribution indicated by the above array is to be preserved, then it must be applied to a basin-wide recharge flux simulated by SWAT.

```
Sum recharge distribution for each subbasin
 sub cell  check: Rchsum  input: Rchshd (Swb2rch)
   1   16      1.0000000    0.8921088E+09
   2   10      1.0000001    0.5575680E+09
   3   48      1.0000004    0.1979366E+10
   4    8      1.0000000    0.4460544E+09
   5   11      1.0000001    0.5018112E+09
   6    1      1.0000000    0.2787840E+08
   7    9      1.0000000    0.2509056E+09
   8    3      1.0000000    0.8363520E+08
   9   19      0.9999998    0.5296896E+09

 row  col  sub rchdst(ic,ir): distribution normalized with respect to subbasin

   9    3    1   0.6250000E-01      subbasin 1 (16 active grid cells)
  10    3    1   0.6250000E-01
   9    4    1   0.6250000E-01
  10    4    1   0.6250000E-01
  11    4    1   0.6250000E-01
  12    4    1   0.6250000E-01
  13    4    1   0.6250000E-01
  14    4    1   0.6250000E-01
  15    4    1   0.6250000E-01
  16    4    1   0.6250000E-01
  17    4    1   0.6250000E-01
  18    4    1   0.6250000E-01
  19    4    1   0.6250000E-01
   9    5    1   0.6250000E-01
  14    5    1   0.6250000E-01
  15    5    1   0.6250000E-01

  10    5    2   0.1000000E+00      subbasin 2 (10 active grid cells)
  11    5    2   0.1000000E+00
  12    5    2   0.1000000E+00
  13    5    2   0.1000000E+00
   9    6    2   0.1000000E+00
  10    6    2   0.1000000E+00
  11    6    2   0.1000000E+00
  12    6    2   0.1000000E+00
  13    6    2   0.1000000E+00
```

```
14      6     2    0.1000000E+00

16      5     3    0.2816901E-01    subbasin 3 (48 active grid cells)
17      5     3    0.2816901E-01
18      5     3    0.2816901E-01
19      5     3    0.2816901E-01
20      5     3    0.2816901E-01
15      6     3    0.2816901E-01
16      6     3    0.2816901E-01
17      6     3    0.2816901E-01
18      6     3    0.2816901E-01
19      6     3    0.2816901E-01
20      6     3    0.2816901E-01
21      6     3    0.2816901E-01
22      6     3    0.2816901E-01
23      6     3    0.2816901E-01
24      6     3    0.2816901E-01
20      7     3    0.2816901E-01
21      7     3    0.2816901E-01
22      7     3    0.2816901E-01
23      7     3    0.2816901E-01
24      7     3    0.2816901E-01
25      7     3    0.2816901E-01
25      8     3    0.2816901E-01
26      8     3    0.2816901E-01
30      8     3    0.1408451E-01
28      9     3    0.1408451E-01
29      9     3    0.1408451E-01
30      9     3    0.1408451E-01
28     10     3    0.1408451E-01
29     10     3    0.1408451E-01
30     10     3    0.1408451E-01
29     11     3    0.1408451E-01
30     11     3    0.1408451E-01
31     11     3    0.1408451E-01
29     12     3    0.1408451E-01
30     12     3    0.1408451E-01
31     12     3    0.1408451E-01
32     12     3    0.1408451E-01
31     13     3    0.1408451E-01
32     13     3    0.1408451E-01
31     14     3    0.1408451E-01
32     14     3    0.1408451E-01
31     15     3    0.1408451E-01
32     15     3    0.1408451E-01
33     18     3    0.1408451E-01
33     19     3    0.1408451E-01
34     19     3    0.1408451E-01
35     19     3    0.1408451E-01
35     20     3    0.1408451E-01

20      4     4    0.1250000E+00    subbasin 4 (8 active grid cells)
21      4     4    0.1250000E+00
22      4     4    0.1250000E+00
23      4     4    0.1250000E+00
21      5     4    0.1250000E+00
22      5     4    0.1250000E+00
23      5     4    0.1250000E+00
24      5     4    0.1250000E+00

25      5     5    0.1111111E+00    subbasin 5 (11 active grid cells)
25      6     5    0.1111111E+00
26      6     5    0.1111111E+00
27      6     5    0.1111111E+00
26      7     5    0.1111111E+00
27      7     5    0.1111111E+00
28      7     5    0.5555556E-01
29      7     5    0.5555556E-01
27      8     5    0.1111111E+00
28      8     5    0.5555556E-01
29      8     5    0.5555556E-01
```

```
30      7      6    0.1000000E+01      subbasin 6 (1 active grid cell)

31      9      7    0.1111111E+00      subbasin 7 (9 active grid cells)
31     10      7    0.1111111E+00
32     10      7    0.1111111E+00
32     11      7    0.1111111E+00
33     11      7    0.1111111E+00
33     12      7    0.1111111E+00
33     13      7    0.1111111E+00
34     13      7    0.1111111E+00
33     14      7    0.1111111E+00

35     21      8    0.3333333E+00      subbasin 8 (3 active grid cells)
36     21      8    0.3333333E+00
37     21      8    0.3333333E+00

34     14      9    0.5263158E-01      subbasin 9 (19 active grid cells)
33     15      9    0.5263158E-01
34     15      9    0.5263158E-01
35     15      9    0.5263158E-01
32     16      9    0.5263158E-01
33     16      9    0.5263158E-01
34     16      9    0.5263158E-01
35     16      9    0.5263158E-01
33     17      9    0.5263158E-01
34     17      9    0.5263158E-01
35     17      9    0.5263158E-01
36     17      9    0.5263158E-01
34     18      9    0.5263158E-01
35     18      9    0.5263158E-01
36     18      9    0.5263158E-01
36     19      9    0.5263158E-01
37     19      9    0.5263158E-01
36     20      9    0.5263158E-01
37     20      9    0.5263158E-01
```

3.4. Ex. 4. Test case using Swbmerge

Program Swbmerge accommodates cases in which SWAT is applied separately to each subbasin using the added option Iopmod = 2. Under this option, the summary file written by subroutine Sumstep in SWAT specifies the data to be read by MODFLOW for one subbasin. Swbmerge was written to merge the results for all subbasins into a single basin summary file for input to MODFLOW. Swbmerge reads a modified version of the Control Codes (*.cod) input file. Input formats for records 1-6 are the same as those given for SWAT. For line 7 as read by Swbmerge, the inputs Nsubs and Casnam are added onto the input read in SWAT by subr. Readwts.

7. No. subbasins; HRU scheme and options to calculate and write HRU weights
```
Data (FREE)  iophru iopwts iprwts nsubs casnam                    (7
```

8. File names of summary results for separate simulations of subbasins by SWAT
For each subbasin i from 1 to Nsubs:
```
    Data (FREE): Idx, Hrufil(i)                                   (8
```

An example of the input format for Swbmerge is given by file Hru1x.cod as follows, from the test case Hru1x (see also Example 5 in the "Guide"):

26

```
hrulx.cod (1 HRU/1 subbasin, cn2=75) iophru=1; swminf=0.65,ipet=0(Priestley-Taylor) iaqufr=1
   181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   2
                                                                              Ipdvar   3
                                                                              Ipdvab   4
                                                                              Ipdvas   5
     0   1   1 ' '   ' '   !  '(3i4,2a)': iopshl itmuni Itmuni nambal namshl             6
     1   1   1   9 'hrulx' ! '(4i4,a)': iophru iopwts iprwts nsubs hrunam (prog. SWBMERGE) 7
     1 'carrwst1.bal'                                                                    8
     2 'carrwst2.bal'
     3 'carrwst3.bal'
     4 'carrwst4.bal'
     5 'carrwst5.bal'
     6 'carrwst6.bal'
     7 'carrwst7.bal'
     8 'carrwst8.bal'
     9 'carrwst9.bal'
```

The input Nsubs is read by the program Swbmerge from record 7 as documented for programs SWBAVG and HRUAVG. An example of the input format for Swbmerge is given by file Hru1x.cod (below)

3.4.1. Procedure for test case Hru1x

1 SWAT and Swbmerge are executed under control of the batch file Hru1x.bat from the directory \gh\rep992\. SWAT is executed separately for each subbasin and writes the nine summary files listed in file Hru1x.cod (below). Swbmerge reads these summary files and merges them into a single basin summary file, Hru1x.bal for input to Modflow.

2. MODFLOW is executed from the subdirectory \gh\rep992\Hru1x\, where the Name file Hru1x.nam resides. Input files are in the directory \gh\rep992\inbase\ except for the summary file Hru1x.bal, which is in \gh\rep992\. The executable file Modflx96.exe is invoked to run Modflow.

Key file listings

Batch file Hru1x.bat (to run SWAT and Swbmerge):
```
rem simulate hrus with deep aquifer: set ipurk(j) = 0 for each subbasin
copy /y hru_deep.gw h2.gw

copy /y   carrwst1.cod hru.cod

copy /y   carrwst1.cod hru.cod
copy /y   carrwst1.cio file.cio
..\swt99opt >hrulx.jnl
copy /y   carrwst2.cod hru.cod
copy /y   carrwst2.cio file.cio
..\swt99opt >hrulx.jnl
copy /y   carrwst3.cod hru.cod
copy /y   carrwst3.cio file.cio
..\swt99opt >hrulx.jnl
copy /y   carrwst4.cod hru.cod
copy /y   carrwst4.cio file.cio
..\swt99opt >hrulx.jnl
copy /y   carrwst5.cod hru.cod
copy /y   carrwst5.cio file.cio
```

```
..\swt99opt >hru1x.jnl
copy /y   carrwst6.cod hru.cod
copy /y   carrwst6.cio file.cio
..\swt99opt >hru1x.jnl
copy /y   carrwst7.cod hru.cod
copy /y   carrwst7.cio file.cio
..\swt99opt >hru1x.jnl
copy /y   carrwst8.cod hru.cod
copy /y   carrwst8.cio file.cio
..\swt99opt >hru1x.jnl
copy /y   carrwst9.cod hru.cod
copy /y   carrwst9.cio file.cio
..\swt99opt >hru1x.jnl


..\swbmerge <hru1x.cod >>hru1x.jnl
```

File Carrwst1.cio (example File control input file for Swat simulation of subbasin 1)

```
Republican River Project, KS case carr-wst irrig99.mco(wsf=.99), h2.gw(gwht=2m)
hrutst.cod; ponds; simulate subbasin #1 only.

carrwst1.std   out10.sbs   out10.rch   out10.rsv   out10.lqo   out10.pso
  out10.eve    crop.dat    till.dat    pest.dat    hru.cod     in10.bsn
   lwqfile     in101.fig   in10.sta    in10.bsb    Watqual       WQOUT
  1   1   9   4   9   4    (nrgage, ntgage, nrtot, nttot, nrgfil, ntgfil)
   repub.pcp


   repub.tmp


   resrvr
  1   0     0   slp101.sub   in101.rte    in1.pnd    in101.chm   carr.sol
       3-wsf.mgt optional.wus  h2.gw      in10.wgn    WQLDAT      1   1
```

File In101.fig (configuration input file for simulating one subbasin)

```
*              command hyd  hru          sub last hru   gis code
*              code    no.  no.          no. (1=last)   (not used)
* subbasin: command, hyd_store, hru_num, sub_num, final_flag, gis_code
* columns:     11-16,         17-22,   23-28,   35-40,      41-46,   47-55
* fields: 10x, 3i6,6x,i6,f6.3,i9
*
subbasin       1       1    1          1     1           1
finish         0
```

File Carrwst1.cod (example Control Codes input file for Swat simulation of subbasin 1)

```
carrwst1.cod (15 HRUs, cn2=75) ipet=0(Priestley-Taylor)
  181977  0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
2
                                                                    Ipdvar
                                                                    Ipdvab
                                                                    Ipdvas

   0   1   1 ' '   ' '   ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl
   1,naqfrc=no. subbasins for which aquifer areal fraction is to be read
   1 0.0733  !for selected subbasins idx=1 to naqfrc, read (in,*) j, aqf_fr(j)
```

File Hru1x.cod (example Control Codes input to Swbmerge)

```
hru1x.cod (1 HRU/1 subbasin, cn2=75) iophru=1; swminf=0.65,ipet=0(Priestley-Taylor) iaqufr=1
  181977  0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   2
                                                                    Ipdvar
                                                                    Ipdvab
                                                                    Ipdvas
```

```
   0    1    1 ' '  ' '   ! '(3i4,2a)': iopshl itmuni Itmuni nambal namshl          6
   1    0    0 'hru1x' ! '(3i4,a)': iophru iopwts iprwts nsubs hrunam (for SWBMERGE) 7
   1 'carrwst1.bal'                                                                  8
   2 'carrwst2.bal'
   3 'carrwst3.bal'
   4 'carrwst4.bal'
   5 'carrwst5.bal'
   6 'carrwst6.bal'
   7 'carrwst7.bal'
   8 'carrwst8.bal'
   9 'carrwst9.bal'
```

File Hru1x.nam (Names input file for Modflow)

```
LIST 6    hru1x.1st                   case name (~.log, ~.prn, ~.rsp)
BAS  1    ..\inbase\bcase_t4.bas          .bas unit   1 Monthly Basic package
OC   69   ..\inbase\rpbase.oc             .oc  unit  69 Output control
BCF  61   ..\inbase\kbase20b.bcf          .bcf unit  61 Block-centered flow
RCH  67   ..\inbase\matrix1.rch           .rch unit  67 Recharge
PCG  68   ..\inbase\model1bs.pcg          .pcg unit  68 precond. conjugate gradient
#
# Non-standard Modflow-88 modules substituted for standard Modflow-96 modules:
# These modules were modified for coordination with the added SWB module.
EVT  65   ..\inbase\repsurf.evt           .evt unit  65
WEL  62   ..\inbase\wrrepub.wel           .wel unit  62 Well: groundwater use
STR  70   ..\inbase\rptest.str            .str unit  70 monthly Strflo, Ks=0.54 ft/day
#
#               Modules added to Modflow-96:
#               SWB: 2 input files are specified, *.swb and *.bal:
SWB  66   ..\inbase\rptest96.swb          .swb unit  66 Soil water balance
#   1, iobal: Swb2rp and Swb2fm, In: Soil Water Balance simulation results
DATA 116  ..\hru1x.bal
#   5, ioshl: Swb2bd, Out: summary of evaporation from shallow gw for each subbasin
DATA 220  hru1x.shl
#   4, ioswm: Swb2bd, Out: combined surface & gw budget terms
DATA 219  hru1x.swm
#
# add'l output data files (WELX and STRX are invoked because SWBX is invoked):
#
# If invoking WELX, STRX, and SWBX, open:
#   2, iostrm: Str2fm (stream routing details for istrbd = 0 or 2)
DATA 117  hru1x.stm
#   3, ioreg: Str2fm, Wel2stp: record of pumping rates that have been
#        reduced due to low saturated thickness or streamflow.
DATA 218  hru1x.reg
```

4. Installation notes for a combined Swat-Modflow model code

These notes accompany documentation of the SWAT-MODFLOW linkage (Perkins and Sophocleous, 2000), published as Kansas Geological Survey Open-File Reports 2000-67 and 2000-68. This is also included as Ch. 4 of "A Guide to Coordinating SWAT and MODFLOW" (file name swtmdv1.doc), where it provides a reference to files associated with the examples given in the Guide.

4.1. Installing combined Swat-Modflow programs, test cases and documentation

The following self-extracting files are available (those with source code are available for non-commercial uses):

swtmddoc.exe   documentation as Microsoft Office 97 Word documents: this document (swtmdv1.doc), and User's Manual (swtmod99.doc).

swtmdexe.exe   executable files for modified SWAT 99.2 and MODFLOW-96 (swt99opt.exe and modflx96.exe);

swtmd992.exe   test cases in subdirectories Y7, Lakefork, and Rep992; see swtmddoc.txt for directory listing.

swtmdsrc.exe   source code for modified versions of SWAT 99.2 and MODFLOW-96, and intermediate programs Swbavg and Hruavg; see Swtmdsrc.txt for directory listing.

swbavexe.exe   executable files for intermediate programs Swbmerge, Swbavg, and Hruavg.

Text files listing contents of these self-extracting files are included, and have the same prefixes as the files above with the extension ".txt".

The required files for running coordinated versions of SWAT and MODFLOW are included in the self-extracting file swtmdexe.exe. The file swtmddoc.exe includes supporting documentation, intermediate executable files, and test data. This document describes test cases for which spatial heterogeneity within subbasins is assumed to be simulated by virtual subbasins in SWAT. Test cases are also included for refined hydrologic response unit (HRU) schemes that can represent temporally varying HRU weights in response to changing land uses and variable areas of shallow ground water. These schemes are described in the report, "Combining Swat and Modflow into an Integrated Watershed Model (P&S, 2000a) and the User's Manual (P&S, 2000b).

Documentation, executable files, and test cases
    Create the directory \gh\. Put the self-extracting files swtmdexe.exe and swtmddoc.exe in directory \gh\. From that directory, extract the files as follows:

swtmdexe
swtmddoc -d -o

The first self-extracting file, Swtmdexe.exe, contains the executable files Swt99opt.exe and Modflx96.exe, which correspond to coordinated versions of Swat-99.2 and Modflow-96 (v.3.3), respectively. The files are presented as two self-extracting files so that they will each fit on a 1.4 Mbyte floppy disk. Using the options -d and -o in the above command, the following directory structure should result:

\gh\   executable files Swt99opt, Modflx96, Swbavg, and Hruavg (*.exe);

\gh\docs\   documentation files (Microsoft Office 97 documents (*.doc)

\gh\y7\   Y7 test case: input to SWAT v.99.2
\gh\lakefork\   modified input file basi.cod and associated output files for Ex. 1, the adapted version of an example data set in AvSwat and described in the AvSwat User's Guide (Neitsch and DiLuzio, 1999).

Subdirectories for Lower Republican River basin test cases

The subdirectories \gh\rep992\ciofiles\ and \gh\rep992\hru1-3\ are provided as examples and for testing of HRU schemes 1-3 according to a procedure described in Chapters 6 and 7 of the User's Manual (P&S, 2000). This procedure applies SWBAVG or HRUAVG to perform intermediate steps of HRU averaging and conversion of SWAT's hydrologic terms to specify fluxes for input to MODFLOW. Recent changes to SWAT incorporate the functionality of HRUAVG to represent spatial variabilitywithin subbasins. Examples of the new, simplified approach to simulating HRU schemes 1-3 may be run from the subdirectory \gh\rep992\hruvirt\; see Example 2 of this document for HRU scheme 1.

\gh\rep992\   test case: Lower Republican River basin input to Swat99_2 (see Ex. 2). Programs Swbavg and Hruavg may also be run from this directory for cases described in the User's Manual (Ch. 6-7).

\gh\rep992\inbase\   input to Modflx96 for L. Repub. R., Examples 2-4;

\gh\rep992\hruvirt\   area for running Modflx96 for HRU schemes 1-3 based on SWAT's virtual subbasin capability (see Ex. 2);

\gh\ rep992\rchzon\   area for running Modflx96 for Ex. 3;

\gh\ rep992\ciofiles\   *.cio files corresponding to separate HRUs for HRU schemes 1-3. These can be copied into the parent directory ..\rep992\, where batch files Hru1.bat, Hru2.bat, and Hru3.bat are located that can be used to run SWAT and an intermediate program (SWBAVG or HRUAVG) for HRU schemes 1-3.

\gh\ rep992\hru1-3\ area for running Modflx96 for Lower Repub. R. test cases based on HRU schemes 1-3 according to procedures using programs SWBAVG or HRUAVG as described in the User's Manual, Ch. 6-7. This directory contains the Name files Hru1.nam, Hru2.nam, and Hru3.nam to run Modflow, given the results Hru1.bal, Hru2.bal, or Hru3.bal, respectively, which are generated under control of corresponding batch files (see ..\ciofiles\, above). These illustrate the original procedures developed for linking SWAT and MODFLOW and have been recently replaced by the simpler procedure applied to the corresponding cases in subdirectory \gh\rep992\hruvirt\.

Source code

Put the self-extracting file swtmdsrc.exe into a directory designated for the source code such as \ghsrc\. From this directory execute this file as follows:

swtmdsrc -d -o

The following directory structure for source code results:

\ghsrc\swat992\   Swat 99.2 (released June 2000 and subsequently modified for coordination with Modflow);
\ghsrc\modfl96\   Modflow-96 (v.3.3) with modified mainline (modflx96) and added packages (Swbx, Welx, Strx, Rsdx, and Postx);
\ghsrc\swbmerge\   program Swbmerge, to merge results from SWAT if subbasins are simulated by separate executions of SWAT.
\ghsrc\swbavg\   intermediate program Swbavg to calculate HRU weights and take spatially weighted average of SWAT simulation results over HRUs; used for refined HRU schemes described in User's Manual (Ch. 6-7);
\ghsrc\hruavg\   more general version of Swbavg (see User's Manual, Ch. 6-7).

Generating self-extracting files
        The self-extracting files were produced in two steps, as illustrated here for the file swtmddoc.exe. First, from the root directory \gh\, program Pkzip was used to compress the contents of \gh\ and all subdirectories into file Swtmddoc.zip while preserving the directory structure. Program Zip2exe was then used to convert the compressed file into a self-extracting file:

1.   pkzip -P -r swtmddoc *.*
2.   zip2exe swtmddoc

Documentation (*.doc, Office 97 Word files)
rptrev00.doc: Perkins and Sophocleous, 2000. Combining SWAT and MODFLOW into an Integrated Watershed Model. KGS OFR 2000-67, December.
swtmod99.doc: Perkins and Sophocleous, 2000. User's Manual for the SWAT-MODFLOW linkage. KGS OFR 2000-68, December.

swtmdv1.doc: this file, "A Guide to coordinating SWAT and MODFLOW," (KGS OFR 2000-38).

Executable files

swt99opt.exe: executable version of SWAT 99.2 modified for use with MODFLOW. If the most recent version of the AvSwat extension is being used, then this file may be renamed to be used in place of the standard version, swat992.exe, in the directory \AvSwat\AvSwatpr\.

modflx96.exe: executable version of MODFLOW-96 (v.3.3, May 2000), modified for use with data generated by SWAT and intermediate programs SWBAVG or HRUAVG.

swbmerge.exe: executable file to merge results of SWAT simulations if subbasins are simulated by separate executions of SWAT.

swbavg.exe: executable file for SWBAVG, available for applying alternative HRU approaches described in the User's Manual.

hruavg.exe: executable file for HRUAVG (a generalized version of SWBAVG), available for applying alternative HRU approaches described in the User's Manual.

If the ArcView extension AvSwat is being used, the executable file Swt99opt.exe can be substituted for the original version named Swat992.exe in directory AvSwat\Avswatpr. Retain the original as swatorig.exe, for example, and copy Swt99opt.exe into this directory with the name Swat992.exe. Example 1 describes applying the modified version of SWAT to the Lakefork example. Nonstandard input and output files associated with this case are in the following directory:

\y7\: Swat v.99.2 test case Y7 input files
    y7anntst.cio (copy to file.cio before running SWAT
    (crop pest fert till).dat: general input data files
    Case-specific input data files:
        y7.(bsn fig sta wgn gw wql wqo lwq)
        (y70-y76).(sub rte mgt wus ins)   (distinct files for subbasins 1-7)
        reisel.pcp   daily precipitation
        (heiden houston).sol
        pond.pnd, chemical.chm

Ex. 1. Swat v.99.2 test case Lakefork (based on the AvSwat example)

basi.cod: a modified version of the Control Codes input file generated by AvSwat for the Lakefork example described in the AvSwat manual (see "Example Data Set").

basi.bal: an output file written by SWAT for input to MODFLOW.

basi.dep: a summary of SWAT's simulation for the example (basin-wide average, SWAT units);

basi.sum: summary of SWAT's simulation for the example (basin-wide average, MODFLOW units).

Each of the three HRU schemes 1-3 is specified by Name file: hruNvirt.nam, for N = 1 to 3. The Name file refers to most input files for these cases in the directory \rep992\inbase\. Additional distinguishing input data for each of these cases are given by file hruNvirt.bal, for N = 1 to 3. The case Hru1virt is taken as an example.

Before running SWAT for case Hru1virt, copy file hru1virt.cio to File.cio. After running SWAT, the resulting balance file, hru1virt.bal, is available for input to MODFLOW. MODFLOW is run from the directory \rep992\hruvirt\ with reference to the Name file, hru1virt.nam, which specifies the balance file.

Key input data files include the following:

hru1virt.nam: invokes packages and data files for running this case with MODFLOW-96.
rptest96.swb: specifies connections between subbasins simulated by SWAT and
   MODFLOW's stream-aquifer grid. Connections include (a) subbasin outflow
   locations with stream reaches, and (b) subbasin geographical domain with grid cells
   of MODFLOW's ground water model.
hru1virt.bal: written by the added SWAT subroutine Sumstep; specifies fluxes for
   tributary inflows, gw recharge, irrigation, and potential evaporation (as a maximum
   for evaporation from shallow ground water, simulated by MODFLOW's EVT
   package).
wrrepub.wel: data set for the modified Well package to specify both surface and ground
   water rights as points of diversion for irrigation pumping.
rptest.str: data set for the modified Stream package

\rep992\hru1-3\: MODFLOW-96 test cases, Lower Republican R. basin model

HRU schemes 1-3 are the same as above, with the exception that the specified fluxes are given by files hruN.bal, for N = 1 to 3. These files are produced by a more complex but essentially equivalent procedure in which SWAT simulates each HRU individually, and then either of the programs SWBAVG or HRUAVG produces an average over the HRUs in the form of flow rates for input to MODFLOW.

SWAT Input files
hru1virt.cio (copy to file.cio before running SWAT. This file refers to files
   hru1virt.cod, hru1virt.fig, and hru-specifying input files for soils (*.sol), land use
   management (*.mgt), and subsurface (*.gw); the subbasin (*.sub) files could be
   included in this list if the curve number were varied over the HRUs.
(crop pest fert till).dat: general input data files

HRU-specific input data files:
   (hru_deep hru_shl hru_bedr).gw
   in10.(bsn fig sta wgn)
   repub.(pcp tmp): daily precipitation and temperature
   (3-wsf, corn, pasture).mgt: land use management data

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(carr, crete, hastings, hedville, kipson, and muir).sol: soil type data

For subbasin N from 1 to 9:

    slp10N.sub   subbasin data

    in10N.rte   subbasin routing data

    inN.pnd   subbasin pond data

SWAT output files:

    hru1virt.std: standard SWAT output

    output files written if Iopmod > 0 (specified in Control Codes input file *.cod):

        hru1virt.bal: SWAT simulation results for each time step. If Iopmod=1, results are written in Swat's units' if Iopmod=2, results are written in Modflow's units. The first option is used for the case that an intermediate program, SWBAVG or HRUAVG, is run to average HRUs simulated separately by SWAT.

        hru1virt.dep: basin-wide summary of hru1virt.bal, Swat's units;

        hru1virt.sum: basin-wide summary of hru1virt.bal, Modflow's units.

<u>MODFLOW data set for case hru1virt</u>

Input files for standard packages (as specified on the Name file hru1virt.nam):

```
BAS   1   ..\inbase\bcase_t4.bas          .bas  unit   1 Monthly Basic package
OC   69   ..\inbase\rpbase.oc             .oc   unit  69 Output control
BCF  61   ..\inbase\kbase20b.bcf          .bcf  unit  61 Block-centered flow
RCH  67   ..\inbase\matrix1.rch           .rch  unit  67 Recharge
PCG  68   ..\inbase\model1bs.pcg          .pcg  unit  68 preconditioned conjugate grad.
EVT  65   ..\inbase\repsurf.evt           .evt  unit  65
WEL  62   ..\inbase\wrrepub.wel           .wel  unit  62 Well: groundwater use
STR  70   ..\inbase\rptest.str            .str  unit  70 monthly Strmfl, Ks=0.54 ft/da
```

Input files for the non-standard SWB package (also given by the Name file):

```
SWB  66   ..\inbase\rptest96.swb          .swb  unit  66 Soil water balance
#    1, iobal: Swb2rp and Swb2fm, In: Soil Water Balance simulation results
DATA 116  ..\hru1virt.bal
```

Other files are specified for output by the Name file; see the User's Manual for further details. Modflow prompts for the Name file. The key files specified by the Name file to coordinate SWAT and MODFLOW are:

    rptest96.swb: input to the SWB package; associates geographical subbasins defined for SWAT with stream-aquifer grid defined for MODFLOW.

    hru1virt.bal: HRU-averaged balance file written by SWBAVG, read by SWB package.

    hru1virt.shl: summary of shallow ground water, written by SWB package.

Nonstandard WEL and STR packages are invoked if the SWB package is invoked to coordinate (a) subbasin outflows with tributary inflows, and (b) surface and ground water supplies for irrigation. Other nonstandard packages (RSD and POS) are not required but may be invoked for in-line residual calculations and postprocessing.

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