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USER'S MANUAL FOR A COMBINED WATERSHED AND STREAM-AQUIFER MODELING PROGRAM BASED ON SWAT-99.2 AND MODFLOW-96

by

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User's manual for a combined watershed and stream-aquifer modeling program based on Swat-99.2 and Modflow-96

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1. Introduction

This report is intended to serve as a user's manual for the updated version of a watershed modeling program that combines the capabilities of SWAT v.99.2 (Arnold et al., 1994 and Neitsch et al., 1999), a model code based on a soil water balance, and MODFLOW-96 v.3.3 (Harbaugh and McDonald, 1996a-b), a ground water hydraulics simulation code.

The combined code documented by this report updates a version based on SWAT v.94.2 and MODFLOW-88 (McDonald and Harbaugh, 1988) that has been applied to the Lower Republican River Basin (P&S, 1999a; Perkins, 1999). This version, documented in P&S (1999b-c), served as a starting point for the updated version presented here. The User's Manual (Open-File Report 2000-68) is coordinated with the SWAT-MODFLOW Integration Report (Open-File Report 2000-67), which presents the methodology for the linkage and its implementation, both in terms of code additions and changes, and in setting up a basin model.

Chapter 2 of the User's Manual presents a summary of the SWAT-MODFLOW linkage. Chapter 3 presents an overview of the data files associated with the components of the SWAT-MODFLOW linkage, and of the procedure followed in applying the combined code to a watershed model. Chapters 4 and 5 provide input data instructions for SWAT v.99.2 and MODFLOW for a coordinated simulation such as the one introduced in Ch. 3. Chapter 6 provides a guide for applying SWBAVG and HRUAVG to represent effects of spatial variability on watershed hydrology. Chapter 7 presents test cases for HRU schemes 1-3 to simulate the Lower Republican River basin, first using SWBAVG, which is specific to this basin for schemes 2 and 3, and second using HRUAVG, which implements a more general method to specify equivalent HRU schemes.

Recent SWAT-MODFLOW linkage developments

The SWAT component of the combined SWAT-MODFLOW code has been updated to the final release of SWAT v. 99.2 (June 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.

1.2. Known problems and compatibility issues with SWAT-MODFLOW linkage

1.2.1. SWAT issues

The procedures implemented by HRUAVG have recently been incorporated into SWAT as part of the SWAT-MODFLOW linkage, thereby simplifying the procedure for running SWAT and MODFLOW. The SWAT-MODFLOW linkage report and this accompanying User's Manual have been revised to reflect this latest change. The superseded procedures using SWBAVG or HRUAVG to link SWAT and MODFLOW are presented in Chapters 6 and 7 of the this document.

The original SWAT program was neither coded nor compiled to rigorously exclude references to uninitialized variables and to undefined array locations. The Lahey compiler we used has the option to check for these and stop execution when they occur. Such compiler options are useful but should not be invoked to run SWAT unless one wishes to track down all such references and change the code accordingly. Occurrences of these references are infrequent and are hopefully harmless.

SWAT 2000, which is now available, has changed considerably from v.99.2, with respect to methods and input format, so the linkage would need to be modified to work with SWAT 2000. One of the changes that appears particularly desirable is that HRUs within a given subbasin are not specified as separate, virtual subbasins within the *.cio file, but are instead specified within the subbasin (*.sub) input file. Related changes have been made to the configuration (*.fig) input format. These changes should simplify the task of specifying input for subbasins with multiple HRUs, as in the case of Example 2 in this document.

1.2.2. MODFLOW issues

If binary results are to be written by MODFLOW such as for input to MODPATH, the binary file should be written in standard form, that is, without a header. Lahey's Fortran 77 and 90 compilers had the option to write binary files in standard form, but this option is apparently not available with the Lahey 95 compiler, which was used for our version of MODFLOW-96. If the writer is correct on this, and the user wishes to use binary results from MODFLOW as input to other programs, then a compiler should be applied to MODFLOW that will write standard binary files.

MODFLOW 2000 has also been released as an update to MODFLOW-96. To incorporate this version into the MODFLOW side of the linkage will require modifying the more complex mainline of MODFLOW 2000 to allow invoking the added SWBX, WELX, and STRX packages that were added to MODFLOW-96.

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.

2. Overview of SWAT-MODFLOW linkage

An integrated watershed simulation based on the coordination of SWAT and MODFLOW is illustrated by the block diagram of Fig. 2.1 (from Perkins and Sophocleous, referred to as P&S, 1999a), which shows the hydrologic connections that couple SWAT and MODFLOW's respective solutions. The procedure for simulating the hydrology of a watershed's hydrology is based on separate execution of SWAT and MODFLOW This coordination is implemented by three additional components of code, which are summarized here; the methodology of the linkage is presented in greater detail in the companion report.

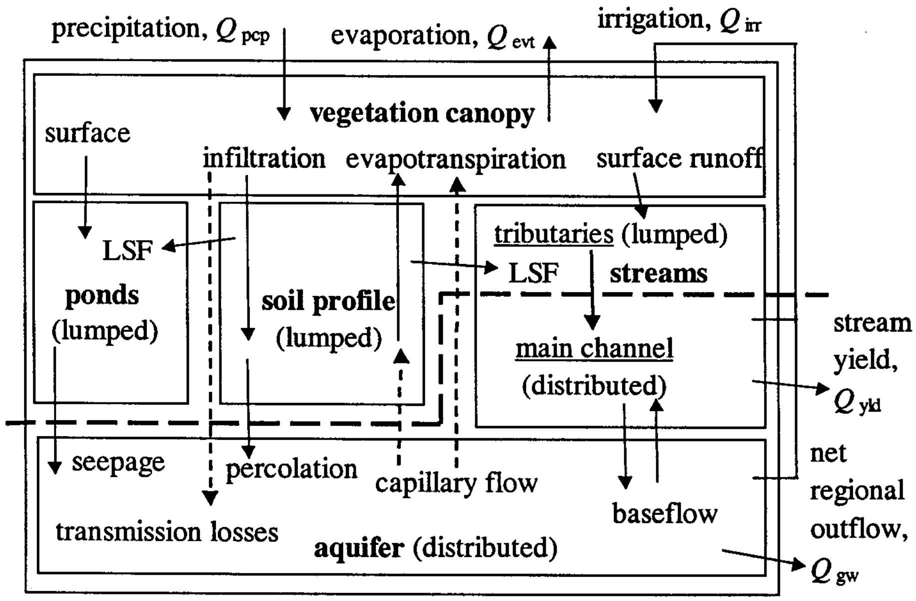

Fig. 2.1. SWAT simulates watershed control volume components above the dashed line (vegetation canopy, soils, and ponds), and MODFLOW those below (stream and aquifer); LSF = lateral subsurface flow. (from P&S, 1999a).

1. Hydrologic terms for SWAT's soil water balance are accumulated and written to a file to be used in specifying fluxes for MODFLOW's solution in each time step. This is implemented by subroutine SUMSTEP, which is called by modified versions of SWAT's subroutines Writed, Writem, and Writea, to summarize SWAT's results for daily, monthly, and annual time steps.

2. The second component of the linkage applies the HRU concept to represent the hydrologic effects of spatial heterogeneity within subbasins. HRUs, simulated individually by SWAT, may be averaged either within SWAT or externally by one of two programs written for this purpose, SWBAVG and HRUAVG. Through one of these options, three intermediate operations are applied to coordinate SWAT and MODFLOW.

a) Based on areal fractions for HRU factors (soils, land uses, and geomorphic features), calculate HRU weights and take a spatially weighted average over HRUs simulated by SWAT for each time step of the groundwater solution.

b) Transform the terms simulated by SWAT from cumulative volumes per unit area [L] to flow rates [L/T^3] in the system of units specified for MODFLOW's simulation as follows. The terms involved in SWAT's soil water balance simulation have the units of depth that corresponds to a volume given by $V = dfA$, where f is the areal fraction of watershed area, A. 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

$$cQ\Delta t = dfA, \tag{2.8}$$

where c is a length conversion factor. This operation is combined with item 3

c) Combine hydrologic terms simulated by SWAT for each subbasin 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.

3. The third component uses the spatially averaged results given by SWBAVG for each subbasin to specify boundary conditions over the grid of MODFLOW's spatially distributed stream-aquifer solution (Section 5). This component is provided by the package SWBX, which was written for this purpose, in conjunction with the packages WELX and STRX, which are modified versions of MODFLOW's WELL and STREAM packages, respectively.

As part of the changes made to implement the SWAT-MODFLOW linkage, SWAT's capability to represent HRUs has been extended recently by installing options to calculate virtual subbasin areas and to update these calculated areas during the simulation to reflect changing areas of virtual subbasins in terms of HRU factors, which include soil types, land use, and subsurface features. SWAT's Control Codes input file was extended to provide the data required for SWAT to evaluate spatial weights for the HRUs. This extension of SWAT's capability is provided by incorporating the functionality of the program HRUAVG. The third of the above-mentioned HRU factors is included to allow distinguishing conceptual models for a soil profile underlain by bedrock, a deep aquifer, or a shallow aquifer as part of SWAT's simulation. By incorporating the temporal variation of HRU weights corresponding to shallow groundwater into the virtual subbasin areas, the SWAT-MODFLOW linkage can be used to simulate a two-way coupling.

In each time step of MODFLOW's simulation, the added package SWBX reads the HRU-averaged results from SWBAVG as flow rates for each subbasin, and distributes the flow rates over the corresponding stream reaches and aquifer grid cells. WELX and STRX are coordinated with SWBX to supply the irrigation pumping demand simulated by SWAT with spatially distributed diversions from surface and ground water sources.

Table 2.1 summarizes the values required for the soil type and land use areal fractions. The irrigated areal fraction for the basin is derived from data obtained from the Kansas

Division of Water Resources (DWR) and varies weakly over time over an approximate range of 3-4 percent.

Table 2.1. Summary of land resources, land use, and soils for each subbasin

sub-basin	areal fract.[1]	non-contrib. fract.[2]	aquifer[3]	cropland[4]	Carr	Crete	Hasting	Hedville	Kipson	Muir
1	0.22015	0.0343	0.0733	0.5962	0.092	0.471	0.099	0	0.338	0
2	0.04909	0.0031	0.2053	0.5463	0.191	0.064	0.402	0	0.342	0
3	0.20435	0.0064	0.2368	0.6281	0.098	0.637	0.125	0.007	0.052	0.081
4	0.08729	0.0268	0.0924	0.5737	0.126	0.543	0.054	0	0.274	0.004
5	0.05282	0.0021	0.2106	0.7164	0.043	0.745	0	0	0.086	0.126
6	0.08247	0.0000	0.0122	0.6113	0	0.741	0	0.176	0.059	0.024
7	0.10945	0.0131	0.0829	0.6753	0	0.869	0	0.022	0	0.108
8	0.11788	0.0414	0.0257	0.5316	0	0.697	0	0.279	0	0.024
9	0.07649	0.0283	0.2504	0.4991	0	0.63	0	0.021	0	0.348
basin:	1.0000	0.0199	0.1261	0.5995	0.0629	0.6103	0.0718	0.0528	0.1352	0.0668

[1]Subbasin areal fraction of study area (2569.6 km^2). [2]Areal fraction of subbasin draining to ponds. [3]Areal fraction of subbasin underlain by alluvial aquifer. [4]From 1990 LANDSAT Thematic-Mapper (T-M) data analysis.

For the basic HRU scheme, areal fractions for soil type and land use are specified by input to the modified version of SWAT's *.COD input file. At the end of each aquifer solution time step, SWAT calls subroutine SUBWTS to calculate the weights, w_k, for each HRU and subbasin by equation (8b). After all HRUs have been simulated by independent executions of SWAT, program SWBAVG takes the weighted average according to equation (8a) over the HRUs. The areally weighted average hydrologic fluxes from SWAT and SWBAVG are used as input to MODFLOW's MODSWB package.

Converting fluxes simulated by SWAT to flow rates for input to MODFLOW

Most hydrologic components simulated by SWAT are expressed as cumulative volumes per unit area of subbasin [L]. An exception is in SWAT's simulation of ponds in which results are maintained as volumes. One of the functions of the program SWBAVG is to convert these hydrologic components into flow rates [L^3/T] for MODFLOW. The conversion is summarized as follows.

Length: convert hydrologic depths from mm in SWAT to ft: 304.8 mm/ft

Time: convert from days in SWAT to sec: (86400 sec/day)(no. days in month).

Basin area (SWAT); the Repub. R. basin area is 2569.6 km^2.

Conversion to flow rates (cfs) for MODFLOW: Apply

$$Q = k_q fdA / \Delta t ,$$

where Q (cfs) is in units required by MODFLOW's simulation; and d (mm), A (km^2), and t (days) are in SWAT's units.

k_q = conversion factor from SWAT's units to MODFLOW's for flow rate (below);
f = fraction of basin area corresponding to flux;
d = hydrologic depth (volume/unit area, mm);
A = basin area as specified in SWAT (above);
Δt = time step in days corresponding to aquifer solution time step simulated by MODFLOW.

<u>Example: convert volumes per unit area (mm) to flow rates (cfs):</u>

$$k_q = \frac{(10^{-3}\,\text{m/mm})(10^{6}\,\text{m}^2/\text{km}^2)}{(86400\,\text{sec/day})}\frac{1\,\text{ft}}{0.3048\,\text{m}} = \frac{35.3147\text{x}10^{3}}{86.4\text{x}10^{3}} = 0.4087346$$

The following basin areal fractions are used in the connections described below for tributary inflow, recharge, and irrigation:

f_p: Fraction of basin area contributing to ponds (as opposed to streams): 0.02
$f_{con} = 1 - f_p$ = contributing fraction of basin area
f_{aqf} = fraction of basin underlain by alluvial aquifer
f_{irr} = fraction of basin area appropriated for irrigation

Modifications to the MODFLOW code

Revisions to MODFLOW are contained within MODFLOW's mainline and the added packages SWBX, STRX, and WELX. SWBX is a new package, whereas STRX and WELX are modified versions of the standard STREAM and WELL packages. The user has the option of invoking either the standard or modified versions of these packages, so that simulations based on completely standard code may be executed. STRX and WELX may be invoked independently and without invoking the SWBX package to take advantage of some added capabilities—for example, to specify surface-water rights to be drawn from streamflow. These two packages may also be used in conjunction with the SWBX package, which can specify recharge, tributary inflows, diversions from surface and ground water for irrigation, and evaporation obtained from surface-water flow modeling of a watershed. SWBX has dependencies associated with both STRX and WELX, so that if SWBX is invoked, STRX and WELX must also be invoked.

<u>SWBX</u> provides a way to use results from a watershed simulation model to specify conditions for surface-and ground-water pumping based on (i) irrigation demand, (ii) lateral inflows due to storm runoff, and (iii) ground-water recharge based on soil-water percolation, channel transmission losses, and pond seepage.

<u>WELX</u> extends the modeling capabilities of MODFLOW's Well package by specifying diversions not only from ground water but also from surface water. If surface-water sources are specified, a stream network must also be specified using STRX, and each diversion's grid-cell location should correspond to a stream reach from which water is

diverted. Pumping limits may be specified with respect to both rated pumping capacity and availability of the source, which corresponds to available stream inflows for surface-water diversions and adequate saturated thickness for ground-water diversions.

STRX is a modified version of MODFLOW's Stream package. Its routing procedure has been modified so that lateral inflows are generalized to include not only streambed leakage but also tributary inflow, surface-water diversions, and evaporation. Streambed leakage is the only component of these that is treated as a head-dependent flux. Streamflow characteristics (depth, width, wetted perimeter, and others) for trapezoidal and natural channels can also be represented. Streambed conductance may vary with streambed hydraulic conductivity and stream width. Hydraulic conductivity may be resolved into components corresponding to bottom and side walls; and leakage due to flooding outside the main channel is characterized as recharge due to percolation instead of coupled stream-aquifer interaction.

STRX: representing natural streambed channels

STRX was modified for purposes of the Wet Walnut Creek basin model in Kansas to represent stream channel characteristics in terms of power functions of the form $f(Q) = aQ^b$, where $Q =$ streamflow and $f(Q)$ represents average stream depth, $y(Q)$; active channel width, $w(Q)$; active channel flow section, $A(Q)$, each given by corresponding coefficients a and b. In the case of the Wet Walnut Creek model (Ramireddygari et a., 2000), empirical relationships were developed for stream depth, $y(Q)$, and cross section, $A(Q)$. Stream width, $w(Q)$, was approximated in terms of these by $w = A/y$. STRX was also modified to represent the hydraulic gradient across the streambed for the special case of flood flows overtopping the side channels into the flood plains. In this case, the width of hydraulic contact wit groundwater is limited to the stream's maximum width within its banks. Between the stream's banks, streambed leakage is based on a composite hydraulic conductivity and a hydraulic head measured from the stream stage elevation to the water table. Outside its banks, a second, decoupled component of streambed leakage is calculated, based on a hydraulic head corresponding to the depth of water covering the flood plain plus an assumed saturation zone given by the streambed thickness.

WELX: Irrigation limits applied to ground and surface water sources

Annual irrigation water use for basin studies in Kansas was estimated on the basis of water-rights records and annual water-use reports from Kansas Division of Water Resources (DWR). Water-rights records included appropriated area of irrigation, A, annual volumetric limit, V, and maximum pumping rate, Q_r. Annual water-use reports included volume of water used, U. Annual irrigation depth was calculated from reported water use and corresponding appropriated irrigation area, i.e., $d = U/A$, for reporting water rights within each sub-basin for each year of available water use reports. The fraction of total appropriations reporting water-use was taken to be representative of the remaining non-reporting appropriations; that is the total appropriated area for irrigation was assumed to be irrigated at the depth calculated from the water-use reports.

The relative importance of irrigated cropland as a land use is expressed as a fraction of sub-basin area. Irrigation demand is simulated by SWAT for each subbasin and accumulated for each groundwater time step as a volume of water per unit of subbasin area. Irrigation demand simulated by SWAT has dimensions of depth, which is converted to a flow rate, $Q_i = d\,A/dt$, either within SWAT by the subroutine Sumstep or external to SWAT by SWBAVG or HRUAVG.

In the applications to basins in Kansas that we have developed, MODFLOW's stress periods corresponded to calendar years, and time steps corresponded to days, months, or years. This convention was convenient for the purpose of representing annual additions to water rights.

Because both ground and surface water were appropriated for irrigation, the WELX package was modified to represent both sources, using DWR's "G" and "S" designations to distinguish them. The WELX package also allows the type of use to be specified, which enables pumping from irrigation wells to be scaled to meet the demand simulated by SWAT, as discussed below. The location of a surface-water diversion is specified in the WELX package input file as a grid cell (layer, row, and column), as are the locations of ground- water diversions.

Monthly time steps were used for our applications of the modified MODFLOW program. Monthly irrigation demand was simulated for each subbasin by SWAT or, in the case of the Wet Walnut Creek model, POTYLDR; see Ramireddygari et al. (2000). The simulated demand was used to specify pumping rates in MODFLOW by applying a scaling factor, s, to the annual appropriation of each individual irrigation water right. The scaling factor is given by $s = Q_{irr}/Q_{app}$, where Q_{irr} = total simulated pumping rate for irrigation summed over all sub-basins, and Q_{app} = total appropriation of all irrigation water rights summed over all sub-basins. The scaling factor, s, is specified as nonzero only during months when irrigation was applied according to SWAT or POTYLDR simulations.

The saturated thickness limit for ground-water sources may be represented as follows. Two saturated thickness limits are specified; for example, an upper limit, $b_U = 3$ m, and a lower limit, $b_L = 4.6$ m. These are specified by input to the STRX package (see Input Instructions). Above the upper limit, the appropriated pumping rate scaled by the factor s (above) is unaffected; below the lower limit, the pumping rate is set to zero. For a saturated thickness between these limits, the pumping rate is scaled linearly between these two extremes. The implementation of this approach is presented in P&S (2000a).

3. Coordinating Swat and Modflow for an integrated watershed model

3.1. Data to be passed between Swat and Modflow

This section was written before the most recent update to the SWAT-MODFLOW linkage, which incorporated into SWAT the capabilities of the HRU-averaging program, HRUAVG. The following should be true, nevertheless, under the extended Control Codes input file option Iopmod = 1, which is intended for use with an intermediate program SWBAVG or HRUAVG to spatially average HRUs and produce input for Modflow. With the recent update to the code and with Iopmod = 2, SWAT can perform these functions. The equations referenced in this section appear in the SWAT-MODFLOW Integration Report, KGS OFR 2000-67 (P&S, December 2000).

SWAT simulation results summarized for input to MODFLOW

A summary of SWAT's simulation for each HRU is written to the balance file (*.bal). Under the option Iopmod = 2, this file specifies fluxes for recharge, tributary inflow, irrigation demand, and potential evaporation as flow rates for input to MODFLOW. Under the option Iopmod = 1, one of the external programs, SWBAVG or HRUAVG, performs intermediate functions of averaging HRUs and calculating inputs for MODFLOW as flow rates. In either case, the results are read in MODFLOW by the added package SWBX, which uses these data to specify flux conditions for MODFLOW's solution. SWBX applies these data to conceptual models for irrigation, eqs. (2.17-2.20), and evaporation from shallow ground water, eq. (2.23). SWBX also distributes recharge and tributary inflow over the grid cells of the ground water and stream network models, respectively.

Table 3.1 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. Swat accumulates its hydrologic results for each time step in array ssub, from which data are written to the balance file. HRU-averaged data written by SWBAVG 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 3.1. The separate correspondence to Swat's array ssb, which accumulates basin-wide averages of hydrologic fluxes, was referenced in the previous version of the SWAT-MODFLOW linkage but is not used in the updated version. The hydrologic components listed in Table 3.1 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.

Table 3.1. Data passed from SWAT to MODFLOW

i	term	usage (eqns. from report)	Swat sub-basin ssub[1] index	Swat basin ssb[2] index	Mod-flow array Shed[3] index	flow rates passed to Modflow[4]
1	precip	2.1, 2.7	1	1	10	pcp
2	irrigation	2.1, 2.11	22	tir	11	irr
3	evap (act.)	2.1, 2.7	12	7	12	et + pnd_evap[5]
4	runoff, surq	2.1, 2.13	4	3	13	surq
5	transm. loss	2.12,2.13	13	38	14	tloss
6	subsurf. latq	2.13	5	4	15	latq
7	percolation	2.12	11	5	16	perc
8	da_rech,gwre		9	107	17	qrech (2.12, 2.14)
9	revap,rev		7	105	18	qtrib (2.13, 2.16)
10	gw_q		6	104	19	baseflow[6]
11	pond seep.	2.12	16	20	20	
12	etpot	2.23	25	108	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]Swat basin array ssb index is given by (idxssb(i), i=1 to 14) in Swtmod99.h; not used.
[3]Modflow (SWBX package) array shed index is given by idx = i + 9.
[4]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).
[5]Based on the sum of actual evaporation, ssub(12,j), and pond evaporation, ssub(15,j).
[6]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.

MODFLOW simulation results summarized for input to SWAT

After MODFLOW has obtained a solution for hydraulic heads in each time step, the SWBX subroutine Swb2bd summarizes shallow ground water characteristics for each subbasin for output to a data file. Characteristics summarized on this file include areal fraction of subbasin with shallow groundwater, mean depth to water within the areal fraction of shallow groundwater, mean depth to water for active nodes in the subbasin, and mean evaporation from shallow groundwater as a fraction of the potential evaporation rate, which is specifiedd by SWAT. This data file that can be used as input to SWAT (and, under the option Iopmod = 1, to SWBAVG or HRUAVG) in a subsequent simulation by specifying the option Iopshl > 0 in the Control Codes input file (see User Manual). As part of HRU scheme 3 (refer to the SWAT-MODFLOW Integration Report), evaporation from shallow gw can be distributed over the soil profile, and is included in eq. (2.29), a variation on the soil water balance (2.1).

3.2. SWAT input data additions for the SWAT-MODFLOW linkage

Associated with our integration of SWAT and MODFLOW, additional data are read from SWAT's control codes (*.cod), management (*.mgt), and ground water (*.gw) input files, and changes to SWAT's management and ground water models, which are summarized below. Refer to the User's Manual for a description of input data formats and definitions.

Modified Control Codes (*.cod) input data

The modified *.cod input file format specifies the added control code, **Iopmod**, to coordinate SWAT with MODFLOW. Additional meanings were assigned to existing SWAT control codes, **Ipd** and **Iprn**, as follows. **Ipd** specifies how often SWAT's results are summarized (monthly[0], daily[1], or annually[2]). This was expanded to indicate the corresponding time steps for MODFLOW's solution and for reading and writing the simulation summaries that are used to pass data between SWAT and MODFLOW (see subroutines Init_bal and Init_shl, above. **Iprn** meaning was expanded to indicate whether to call EchoInpt from Main, to echo input data (**Iprn** < 0), and whether to halt execution after echoing the input data (**Iprn** < 0), which is useful when execution of SWAT is intended only to check input data for errors and the simulation is not of interest until the input data appear to be valid. A third control code, **Iopshl**, indicates whether a summary of evaporation from shallow ground water, written by a previous execution of MODFLOW (subr. Swb2bd in the SWBX package) is available to be read by SWAT and SWBAVG. If so, a two-way coupling between SWAT and MODFLOW can be simulated. If SWAT is simulating an HRU with shallow ground water, indicated by **Ipurk** > 0, an input that is read from the *.gw file (below), then subr. Subbasin calls the added subroutine Evap_gw to distribute evaporation from shallow ground water over the soil profile.

Modified Ground water (*.gw) input data file

Invoking the integration of SWAT with MODFLOW by the added control code **Iopmod** does not affect SWAT's simulation of ground water based on its lumped, analytical model, and input data are read from its *.gw input file as before. But in this case ground water is simulated in parallel by MODFLOW. The subsurface model option, **Ipurk**, specified in the *.gw input file, was added to provide two significant variations on SWAT's assumptions regarding flow paths between the watershed and ground water for coordination with MODFLOW. SWAT's conceptual model assumes the soil profile to be underlain by a deep aquifer, that is, by a saturated zone that is sufficiently deep to have negligible interaction with the root zone. The first variation allows representing a soil profile underlain by bedrock, so that percolation out of the root zone is blocked. The second variation allows representing evaporation from shallow ground water based on MODFLOW's simulation instead of SWAT's "Revap" model. Specifying the ground water as shallow for any subbasin requires data to be provided to both SWAT and SWBAVG that can be summarized by the SWBX package for a previous execution of MODFLOW. For SWAT, this summary specifies evaporation from shallow ground water for redistribution over the soil profile in each subbasin using the added subroutine Evapgw(see Summary of code changes and additions to SWAT 99.2 in Part 2).

For SWBAVG, the summary from MODFLOW specifies the areal extent of shallow ground water in each subbasin, which is used to compute spatial weights for HRUs in each time step. The two-way coupling between SWAT and MODFLOW is based on successive approximation, initiated by first applying SWAT and SWBAVG to a basin model in which all ground water is assumed to be deep, as specified by the option **Ipurk**. MODFLOW's simulation shows whether the areal extent of shallow ground water is significant enough to warrant a subsequent simulation of SWAT and MODFLOW that includes HRUs with shallow ground water. See the User Manual's chapter on methodology for a description of the successive approximation approach.

Modified Management (*.mgt) input data

Subroutine Readmgt reads the same set of data fields for every management operation; how the fields are interpreted depends on the management operation. For the automatic irrigation operation (**mgt_op** = 10), the data fields mgt3 and mgt4 are interpreted as plant stress factor threshold and irrigation efficiency, respectively, as described in the SWAT v.99.2 User's Manual (Neitsch et al., 1999). This management operation was modified by interpreting the two additional fields mgt5 and mgt7 as follows. If the fields mgt5 and mgt7 are positive, they are interpreted, respectively, as an irrigation threshold as a fraction of available field capacity, **auto_swf**, and a maximum daily irrigation limit, **auto_dmx**. The daily maximum is enforced whether the irrigation threshold is given by plant stress factor or by soil water content. Soil water content threshold may be specified in one of two ways (options a and b, below). In addition, the choice between plant stress factor and soil water content thresholds can be exclusive or inclusive (option c).

(a) A negative value in the field for plant stress factor, **auto_str**, is interpreted to be a soil water content deficit below available field capacity (mm), and is given by

$$\text{auto\_str} = \text{swcap}(\text{auto\_swf} - 1)\,.$$

This is a standard SWAT 99.2 option, but it is not documented in the Management Codes input file. To use this option, one must do the above calculation based on the desired soil water threshold, auto_wsf, which is not entered as input data for the standard version of SWAT 99.2 We augmented this option as follows.

(b) If the plant stress factor threshold is entered as negative but a positive value is entered for available field capacity fraction in the range 0 < **auto_swf** < 1, a corresponding deficit is calculated and substituted for **auto_str** that is given by the above equation. Under options (a) and (b), the choice between plant stress factor and soil water content threshold is exclusive. In addition, the following option was implemented:

(c) If both plant stress factor and soil water content thresholds are specified as positive, then irrigation is applied if either plant stress factor or soil water content falls below the respective threshold. This option was previously incorporated into SWAT 94.2 for application to the Lower Republican River basin in Kansas, and provides a better match of simulated annual irrigation use to estimates based on reported water use than simulations using either of the two optional thresholds exclusively. A comparison of simulated and "observed" irrigation for HRU scheme 1 under this option is shown in "Test Results." For further explanation of how the added options for daily irrigation limit and soil water threshold were implemented, see the User's Manual, "SWAT input data for SWAT-MODFLOW linkage: Instructions for modified Management Codes (*.mgt) input file.

3.3. Data files associated with the SWAT-MODFLOW linkage

SWAT

The Control Codes input file to SWAT (*.cod) was modified to read the added control code, **Iopmod**, from its second record. If **Iopmod** > 0, an additional record is read by subroutine **Readcod** to specify a conversion factor between units of length used in SWAT and MODFLOW, and file names for data to be transferred between SWAT and MODFLOW. In addition to the Control Codes input file, the Management codes (*.mgt) and Groundwater codes (*.gw) input files were modified to provide options used in the SWAT-MODFLOW linkage. The Final Report summarizes these changes, and the User's Manual shows how they are specified.

The names of additional files associated with a case executed by SWAT are based on the name of the standard output file as specified by the input file named File.cio. The following additional files are read or written if **Iopmod** > 0 in the modified Control Codes input file (*.cod).

*.shl (In, if **Iophru** = 3): summary of evaporation from shallow ground water for each subbasin, written by subr. SWB2BD of the SWBX package in a previous execution of MODFLOW.

*.bal (Out): subr. Sumstep writes simulated hydrologic components of soil water balance as volumes per unit area for each subbasin in each time step of MODFLOW's aquifer solution (day, month, or year)

*.dep (Out): basinwide averages of the hydrologic components of soil water balance (volumes per unit area) in each time step.

*.sum (Out): basinwide average of the HRU-averaged flow rates written to the *.bal file.

*.wts (Out): summary of spatial weights corresponding to each HRU in each time step; written if the extended Control Codes input option **Iprwts** > 0. If **Iprwts** = 1, write a basinwide average for each weight in each time step; if **Iprwts** = 2, write the HRU weights for each subbasin in each time step. These weights are written for comparisons and analysis, and are not used as input to the other programs.

MODFLOW

The standard Name file read by MODFLOW-96 is used to invoke the packages required to simulate a given case and the associated data files. The nonstandard packages used in the coordinated SWAT-MODFLOW simulations and their associated data files are also specified by the Name file. An example of the Name file for HRU scheme 1 is listed under "Coordination of SWAT, SWBAVG, and MODFLOW" (below). Each of the nonstandard packages is associated with at least one input file and some output files, identified by their name extensions and whether the files are for input or output. The data files written by the nonstandard packages are summarized below.

The SWBX package provides an interface to the simulation results produced by SWAT and SWBAVG. The nonstandard WELX and STRX packages are required and automatically invoked instead of the standard WEL5 and STR1 packages if the SWBX package is invoked. If the SWBX package is not invoked, the standard WEL5 and STR1 packages are invoked unless the nonstandard versions are specified by added options in the input files for these packages. See the User's Manual for further explanation and examples regarding the nonstandard WELX and STRX packages.

SWBX first reads a data file that associates the geographical extent of each HRU-averaged subbasin used for watershed simulation in SWAT with the underlying grid of cells defined by MODFLOW for simulating ground water movement. This data file also specifies a correspondence between the outflow from each subbasin and a reach of the stream network specified by STRX, a modified version of MODFLOW's STREAM package. In addition, WELX, a modified version of MODFLOW's WELL package, specifies both surface and ground water points of diversion over which irrigation demand, simulated by SWAT for each subbasin, is distributed.

In each time step, the HRU-averaged balance file written by SWAT (or by either SWBAVG or HRUAVG) is read by the SWBX package to specify tributary inflows, ground water recharge, irrigation demand, a potential evaporation rate for shallow ground water, and hydrologic components necessary to evaluate an overall watershed hydrologic balance. Following MODFLOW's solution, the SWBX package summarizes MODFLOW's results for shallow ground water, including evaporation flow rate, areal extent, and depth to ground water, for each subbasin. This summary of results for shallow ground water can be used in a subsequent SWAT-MODFLOW execution to simulate a two-way coupling between the soil water profile and ground water.

SWBX data files

*.swb (In): Associate grid cells with geographical extent of subbasins simulated by SWAT, and subbasin outflows ("pour points") with stream reaches specified by the STRX package. File rptest.swb, which is used in the above Name file and for HRU schemes 1-3, is listed below to show these associations.

*.bal (In): For each time step, specify flow rates for recharge, tributary inflow, irrigation demand, and potential evaporation for each subbasin, to be spatially distributed over corresponding grid domain to specify flux conditions for MODFLOW's solution.

*.shl (Out): For each time step of MODFLOW's solution, summarize evapotranspiration and the corresponding area of shallow ground water in each subbasin. This can be used as input to SWAT and SWBAVG in a subsequent simulation to provide a two-way hydrologic coupling of SWAT and MODFLOW using a successive approximation approach.

.swm (Out): For each time step of MODFLOW's solution, summarize both surface and ground water budget terms, esp. those that are based on SWAT/SWBAVG results that are read from the balance (.bal) file.

STRX data files

*.str (In): specify stream reach network (grid cell and channel characteristics). Standard input format (for standard package) is assumed unless SWBX is invoked or STRX is specified by added input option; modified to optionally specify stream inflow to top reaches of segments in each solution time step.

*.stm (Out): stream routing details before beginning or after convergence to a solution (diagnostic).

WELX data files

*.wel (In): specify water rights for pumping from both ground water and surface water sources; see User Manual.

*.reg (Out): subrs. Str2fm and Wel2stp record simulated pumping rates for ground water rights that have been reduced due to low saturated thickness (Wel2stp), or for surface water rights that have been reduced due to low streamflow.

3.4. Coordinating execution of SWAT and MODFLOW

Procedure for cases with HRU averaging executed by SWAT

The recent incorporation of the functionality of program HRUAVG into SWAT allows a greatly simplified, two-step procedure for coordinating SWAT and MODFLOW. For test cases of the Lower Republican River basin under HRU schemes 1-3, this procedure is outlined here. Assumptions about file locations are as follows:

1. Executable files swt99opt.exe (SWAT) and modflx96.exe (MODFLOW are in d:\gh\, where d: represents the disc drive.
2. SWAT is to be run from d:\gh\virtsubs\, the location of SWAT's input and data base files.
3. Modflow is to be run from d:\gh\virtsubs\hruNvirt\, where N = 1, 2, or 3, depending on which HRU scheme is to be run.

For the HRU scheme of interest, run SWAT and MODFLOW as follows:

1. Run SWAT: Rename (or copy) the File Control file for the case of interest to File.cio. For test cases of the Republican River basin model under HRU schemes 1-3, these files are named hruNvirt.cio, where N = 1, 2, or 3. Then with all SWAT input files in the local directory, and the executable file in the parent directory, execute as follows:

```
d:\gh\virtsubs>          ..\swt99opt
```

2. A successful execution of SWAT will write a summary of results to a file named, for the above cases, hruNvirt.bal (for N = 1, 2, or3). move this file to the working directory for running MODFLOW for the same case, and execute MODFLOW as follows:

```
d:\gh\virtsubs\hruNvirt>        \gh\modflx96
```

Modflow will prompt for the Name file; respond with the name hruNvirt.nam (where N = 1, 2, or 3). See Ch. 7 for examples of this procedure and listings of input files.

[Note: Before running HRU scheme 3, HRU scheme 1 or 2 must be run so that a shallow groundwater summary file is written by MODFLOW that can be specified as input to SWAT under HRU scheme 3.]

Equivalent versions of the above procedure may be run in which program SWBAVG or HRUAVG is used instead of SWAT to calculate HRU spatial weights, spatially weighted averages of HRUs, and specified fluxes for input to MODFLOW as flow rates. An outline of these equivalent procedures is given in Chapter 6.

MODFLOW-96 execution

Run MODFLOW as modified for the SWAT-MODFLOW linkage. From the subdirectory \gh\test99_2\modflw\, run \gh\modflx96 with the following command:

```
\gh\test99_2\modflw>  \gh\modflx96
```

MODFLOW prompts for the Name file, and the name HRU1.NAM is entered for this case. The Name file specifies all of the packages and the associated input and output data files required to run this case. The file Hru1.nam is listed below.

The first six packages (BAS, OC, BCF, RCH, EVT, and PCG) specified by the Name file are standard MODFLOW packages. The next commands, WEL and STR, invoke the modified packages WELX and STRX, respectively. As noted above, the nonstandard WELX and STRX packages are required and automatically invoked instead of the standard WEL5 and STR1 packages because the SWBX package is invoked. The added nonstandard package SWBX is invoked by the command SWB. Two in-line postprocessing packages, RSDX and POSTX, developed for internal use at Kansas Geological Survey for modeling studies, can also be invoked. These are described in a separate document (P&S, 2000d).

See the MODFLOW-96 User's Manual for further explanation of the Name file and of all standard MODFLOW packages, and notes below regarding nononstandard packages.

```
LIST 6   hru1.lst                        case name (~.log, ~.prn, ~.rsp)
BAS   1  ..\inbase\bcase_t4.bas                Monthly Basic package
OC   69  ..\inbase\rpbase.oc                   Output control
BCF  61  ..\inbase\kbase20b.bcf                Block-centered flow
RCH  67  ..\inbase\matrix1.rch                 67 Recharge
EVT  65  ..\inbase\repsurf.evt                 Evapotranspiration
PCG  68  ..\inbase\model1bs.pcg                preconditioned conjugate gradient
#
# Non-standard Modflow-88 modules substituted for standard Modflow-96 modules,
# modified for coordination with the added SWB module:
#
WEL  62  ..\inbase\wrrepub.wel                 Well: groundwater use
STR  70  ..\inbase\rptest.str                  monthly Streamflow, Ks=0.54 ft/day
#
# If invoking WELX and STRX to be used with SWB (below), open:
#   2, iostrm (OUT) Str2fm (stream routing details for istrbd = 0 or 2)
DATA 117   hru1.stm
#
#   3, ioreg (OUT) from Str2fm, Wel2stp: record of pumping rates that have been
#       reduced due to low saturated thickness or streamflow.
DATA 218   hru1.reg
#
#               Modules added to Modflow-96: SWB, RSD, POS
#
#               SWB: 2 input files are specified, *.swb and *.bal:
SWB  66  ..\inbase\rptest96.swb                 Soil water balance
#   1, iobal (IN) Soil Water Balance simulation produced by SWAT and SWBAVG:
DATA  116   hru1.bal
#
#   5, ioshl (OUT) Swb2bd, summary of evaporation from shallow gw for each subbasin.
#   This file can be used as input to a subsequent watershed simulation
#   (e.g. by SWAT) to implement a two-way coupling by successive approximation.
DATA 220   hru1.shl
#   4, ioswm (OUT) Swb2bd, combined surface & gw budget terms
DATA 219   hru1.swm
```

Execution of the modified version of MODFLOW-96 was tested by comparison with the previous version based on MODFLOW-88. This version was executed for the same case using redirected keyboard input from the following "response" file, which is shown here for comparison to the Name file (above):

```
hru1                                         case name (~.log, ~.prn, ~.rsp)
..\inbase\bcase_t4.bas                      .bas unit   1 Monthly Basic pkg
..\inbase\kbase20b.bcf                      .bcf unit  61 Block-centered flow
..\inbase\wrrepub.wel                       .wel unit  62 Well: gw, surf. use
..\inbase\repsurf.evt                       .evt unit  65 Evaporation from gw
..\inbase\rptest.swb                        .swb unit  66 Soil water balance
..\inbase\matrix1.rch                       .rch unit  67 Recharge
..\inbase\model1bs.pcg                      .pcg unit  68 precond. conj. grad.
..\inbase\rpbase.oc                         .oc  unit  69 Output control
..\inbase\rptest.str                        .str unit  70 Stream package
```

The SWAT-MODFLOW linkage based on SWAT-94.2 and MODFLOW-88 is documented in Perkins and Sophocleous (1999b-c).

Input file for the SWBX package

The following input file is read for the updated HRU schemes 1-3 by the SWBX package, which is documented in the User's Manual. It specifies execution options and initializes associations of subbasin outflows with stream reaches, and subbasin domains with grid cells.

```
9,   nwshed  (balance file: use case name); file c:\gh\test\inbase\rptest.swb
' ',     1    3    1    1 0.00    1    0 0.0   nambal,irropt,ievopt,ioprch,rchmpy,
                                               evapir,welmpy,iadcod,frseep
  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 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 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 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 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 3 5 5 5 3 7 7 7 7 7 7 9 9 9
 2 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 3 7 7 7 7 7 9 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 3 3 7 7 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 0 2 2 2 2 3 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 0 3 3 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 3 8 8 3 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 3 3 8 8 8 8 8 8 3 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 3 8 8 8 8 8 8 8 8 8 3 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 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 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 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 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 0 8 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 0 0 8 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 0 0 0 8 8 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 0 0 0 8 8 8 8 8 8 8 8 8 8 8 0 0 0 0
```

3.5. Compiling and linking SWAT, MODFLOW, and related programs

SWAT v.99.2 and MODFLOW-96 source code

SWAT v.99.2 and documentation was downloaded from the website http://www.brc.tamus.edu/swat/. Modflow-96 code and documentation was downloaded from the USGS Water Resources Applications Software website, ground water page, at http://water.usgs.gov/software/ground_water.html, as recently as May 2000, when v.3.3 became available. These versions of SWAT and MODFLOW were incorporated into the updated SWAT-MODFLOW linkage. The reader is referred to the User's Manual for details on compiling and linking the combined SWAT and MODFLOW codes.

The MODFLOW-96 v.3.3 installing file mdfw3_3.exe was downloaded and executed according to the Modflow Readme.txt file instructions, which are accessible from the Modflow96 web.page. The automatic installation produced the directory \modflw96.3_3\ and the following subdirectories:

```
DOC             documentation
DATA            Name files and associated input files for test cases
SRC             source code
TEST            batch files to run test cases
BIN             binary files: compiled and linked executable code.
```

The file subdirectories in \gh\modflw96\ on the Zip disk provided with KGS OFR 2000-38 reflect an expanded version of the the above scheme.

SWAT version 99.2

In the source code directory, one can simply type "automake" (or its abbreviation "am") to initiate automatic checking to see which source code files need compiling and subsequent linking into an executable file. An Automake window presents a simple choice between producing debugging and optimized versions of the executable file. With tdebugging version, compiler options are invoked so that references to undefined values and outside the bounds of arrays or strings are not allowed, and that subroutine line number and call tracebacks are provided for runtime encounters with fatal errors, due typically to divisions by zero and attempts to read input data that ar not in the expected format.

For SWAT 99.2, the choice between debugging and optimized versions drastically affects both executable file size and runtime. This effect is much less pronounced for SWBAVG and MODFLOW. For SWAT, the optimizing choice produces an executable file size that is comparable to that of the "Microsoft" compiler, about 1.2 Mb, whereas a debugging version of the executable file can be 18 Mb. For a year's execution of the Lower Republican test case on an ancient 90MHz pentium pc, the "Microsoft" version of the executable file takes about 15 sec. For the same case under Lahey 95, the debugging version takes 2:05 min, and the optimized version takes about 8 sec. With SWAT v.99.2, the approach taken was to use a debugging version until runtime errors were eliminated for both the Y7 and Lower Republican River basin test cases. Runtime errors uncovered with this approach were due primarily to references to undefined values of scalars or arrays and secondarily to references outside the bounds of arrays or character strings. These changes are detailed in the documentation file Swt99chg.doc. The same approach was taken in converting SWAT v.98.1 first to run under Lahey 95 and then to incorporate the changes and additions required for the SWAT-MODFLOW linkage. However, undownside of the optimized version is that it does not provide a trace to execution errors, so I'm working with a debugging version for testing.

Because the Lahey compiler interprets the source file extension ".for" to indicate fixed format, all source file extensions except for included files modparm.f and common.f were

renamed to the extension ".for". To compile under Lahey, the only problem encountered was the$debug statement, which was commented out of the following files:
Main, Operatn, Readbsn, Simulate, Subbasin, Virtual.

Initially, compiler and linking options were invoked for debugging. These included array bounds checking and line number identification with subroutine callback tracing for fatal runtime error occurrences. The following "debug" version of an automake configuration file, Automake.fig, was set up for compiling and linking SWAT v.99.2 under Lahey 95 (Lahey compiler for Fortran 90):

```
QUITONERROR

FILES=*.for
COMPILE=@lf95 -c -chk -trace -g -nco -f95 -lst -stchk -sav -w -xref %fi -O0

LINK=@lf95 @%rf -g -fullwarn -exe %ex
TARGET=Swt99trc.exe
```

This produces a very large executable file (~17 Mb) and is very slow, but is also very useful for identifying problems. Once the likelihood of runtime errors had been reduced, an "optimized" version of the executable file was produced that is about 1.2 Mb in size and very fast, but does not provide the checks and error tracing capability of the debugging version. The automake configuration file used to produce the optimized executable file is the following.

```
QUITONERROR

FILES=*.for
COMPILE=@lf95 -c -nchk -ntrace -nsav -nstchk -o1 -nw %fi

LINK=@lf95 @%rf -exe %ex
TARGET=swt99opt.exe
```

Not only do the executable file sizes differ drastically. Runtime for a year of the Lower Republican River test case is about 8 sec for the optimized version and about two minutes for the debugging version. However, the diagnostics provided by the debugging version have been very useful for identifying both coding and input data problems.

SWAT version 98.1

A similar approach to the one described for SWAT v.99.2 was taken to convert SWAT v. 98.1 to run under Lahey 95. Code changes for this conversion were largely the same ones made to SWAT v. 99.2. Swat 98.1 was set up to compare simulation results with v.99.2.

The following Swat 98.1 routines were modified: Main, Open, Readcod, Readmgt, Readgw, Simulate, Subbasin, Purk, Writem, Writea, Writed.

The following routines were added:

Swtmod99.h	defines added module, Swtmod99.h; include in Main.
Alloc_swtmod.for	allocate added arrays
Init_bal.for	initialize files that exchange data between SWAT and MODFLOW
Sumstep.for	read and write files passing data between SWAT and MODFLOW
Evap_gw.for	distribute evaporation from shallow gw over soil profile

The added files are the same versions of the files that were added to SWAT v.99.2 except for file Init_bal.for, which was modified only to make the following variable name changes:

Swat 98.1 name	Swat 99.2 name	description of SWAT variables referenced by subr. Init_bal
flu	hru_fr	HRU areal fraction of basin
sw	sol_sw	soil water content
v	pnd_vol	pond volume
fp	pnd_fr	pond areal fraction of subbasin
sumfc	sol_sumfc	field capacity of soil column
flu?	sub_fr	subbasin areal fraction of basin

The KGS Open-File Report 2000-38 entitled "A Guide to coordinating SWAT and MODFLOW" (Perkins and Sophocleous, 2000) compares simulations of the Y7 test case by SWAT versions 98.1 and 99.2, and discusses sources of differences in results. These include model differences, which are summarized in a document obtained from the SWAT website with the name Versdiff.txt (S.L. Neitsch, 2000).

MODFLOW-96 (v. 3.3)

Modflow-96 v. 3.3 is the most recent version of Modflow. It became available for download from a USGS website in early May 2000. We had previously downloaded Modflow-96 v.3.2, which we had incorporated into the updated SWAT-MODFLOW linkage. This work was further updated once the latest version of Modflow became available. The updated version has been tested by execution of three separate sets of tests. First, a standard set of examples provided by USGS with MODFLOW were run. Second, a more extensive set of examples available for download from EPA with an accompanying manual were run. Third, the data sets associated with the Lower Republican River basin for HRU schemes 1-3 were run. The first two sets of cases, from USGS and EPA, were run to demonstrate successfully that the code as modified for the SWAT-MODFLOW linkage could reproduce the results obtained from the unmodified code. In fact, none of the standard MODFLOW packages except for the mainline have been modified, but several packages listed below have been added. Execution of the third set of cases for the Lower Republican River basin were run to show that the same results were obtained for the modified version of Modflow-96 v.3.3 and the previously modified version of Modflow-88. More information regarding these tests is provided below.

Compiling and linking Modflow

Modflow-96 v. 3.3 is provided with a "Makefile" procedure for compiling and linking the code under the Lahey Fortran 90 compiler. We have worked with the more recent Lahey Fortran 95 compiler, and have set up associated Automake.* files that automate compiling and linking of Modflow-96 (v.3.3). These automake files, along with source code for the modified and added packages, are in the subdirectory \swbsrc\. All of the standard packages are included in the modified version, which is linked together into the executable file modflx96.exe. The following automake configuration file, Automake.fig, was used:

```
QUITONERROR

FILES=*.for
COMPILE=@lf95 -c -nchk -trace -nsav -nstchk -o1 -nw %fi

LINK=@lf95 @%rf -exe %ex
TARGET=modflx96.exe
```

SWBAVG

A debugging version of the executable code was produced for SWBAVG involving only two source files, Swbavg.for and Subwts.for, plus the included file swtmod99.h, referenced in the SWAT99.2 source code directory, and file swatmod1.h, referenced in the local SWBAVG source code directory. The following configuration file, Automake.fig, was used:

```
QUITONERROR

FILES=*.for
COMPILE=@lf95 -c -chk -trace -g -co -f95 -lst -sav -stchk -w -xref %fi

LINK=@lf95 @%rf -g -fullwarn -exe %ex
TARGET=swbavg.exe
```

A known problem that recurs when linking is the following. After making a change to a source file (or simply deleting an object file, which requires the source code to be recompiled), linkage fails and the following message is issued:

```
flist: Internal error pci not found (SWTMOD99xref)
```

The file SWTMOD99.mod is produced in the local SWBAVG source directory, which is apparently a duplicate of one in the SWAT source directory. The existence of both may be causing the linkage problem. The remedy taken has been simply to delete the file Swtmod99.mod in the local SWBAVG source code directory and reissue the "am" command, and the executable file is produced successfully, although the successful linkage also produces a list of warning messages of the following kind, where X refers to SWBAVG, SUBWTS, and a list of internal names:

```
Warning LINK 4310: Changing class of segment "CONST" of module X from
"DATA" to "CONST,"
```

These warnings have been ignored without apparent harm, and the resulting executable file Swbavg.exe executes successfully.

HRUAVG

In response to a need for a more general approach to representing spatial heterogeneity than that provided by the above program SWBAVG, an approach has been developed and implemented by writing the program HRUAVG. This approach is described in the document genhru.doc entitled "Generalizing a model of spatial heterogeneity for watershed hydrology" (Perkins and Sophocleous, 2000).

The program HRUAVG has been tested by comparing its calculated weights for the HRU schemes 1-3 of the Republican River basin model with the weights calculated by SWBAVG. This work is viewed as a starting point for possible application to other basins with different sets of assumptions associated with their own particular form of spatial heterogeneity.

HRUAVG compiles and links without the recurrence of the problem with the module noted above for program SWBAVG. This appears to be explained by the fact that HRUAVG does not refer to the module file swtmod99.h in the directory where the SWAT source code resides. Instead, the included file Swatmod1.h, which is in the same directory as the HRUAVG source code, was expanded to incorporate array declarations from swtmod99.h. The following automake.fig was used to compile and link HRUAVG:

```
QUITONERROR

FILES=*.for
COMPILE=@lf95 -c -chk -trace -g -co -f95 -lst -sav -stchk -w -xref %fi

LINK=@lf95 @%rf -g -fullwarn -exe %ex
TARGET=d:\gh\Hruavg.exe
```

4. SWAT: input data for SWAT-MODFLOW linkage

Chapter outline:
4.1. Quickstart: invoking the SWAT-MODFLOW linkage for a data set that is produced by the ArcView extension for SWAT, AvSwat.
4.2. Summary of added or modified SWAT input data for the Swat-Modflow linkage
4.3. Input instructions for each of the modified input files to SWAT.

4.1. Quickstart: Invoking the SWAT-MODFLOW linkage in AvSwat

The procedure shown in the AvManual for the Lakefork example is presented to show the variations on the procedure for obtaining a summary file that could be used for input to Modflow. Chapter 5 outlines Modflow's input data requirements for the linkage.

A second example presents a test case for the Lower Republican River basin in Kansas, beginning with an explanation of why the SWAT-MODFLOW linkage is a useful tool for this model. The HRUs and corresponding virtual subbasins are defined in terms of soils, land uses, and subsurface characteristics. Some of the essential features of the SWAT-MODFLOW linkage are shown. Model results are summarized in figures that compare simulated and measured values for stream yield, irrigation, and groundwater levels. Some of the key data files are listed for reference in Section 7.3.

Obtaining a Lakefork model summary for input to MODFLOW

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. The specific procedure is given below; see Chapter 7 for input data file listings.

<u>Watershed simulation using modified SWAT v.99.2 within AvSwat</u>

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). The resulting file basi.cod is shown below with changes on line 2 (col. 92) and the addition of lines 6 and 7.
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.

Lakefork 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
```

4.2. Summary of SWAT input data additions for the SWAT-MODFLOW linkage

Associated with our integration of SWAT and MODFLOW, additional data are read from SWAT's control codes (*.cod), management (*.mgt), and ground water (*.gw) input files, and changes to SWAT's management and ground water models. Fig. 2.3 in Ch. 2 of the Final Report illustrates how the procedure to simulate the soil water budget in Swat's subroutine Subbasin was adapted to implement these changes. See the Final Report for a summary of subroutines that were added to SWAT or modified to implement the SWAT-MODFLOW linkage.

Modified Control Codes (*.cod) input data

The modified Control Codes (*.cod) input file includes an additional item, Iopmod, on line 5. Depending on the value of this option, SWAT conditionally reads an additional line 6, which specifies the SWAT-MODFLOW connection. Additional input data lines (7-13) defined for this input file are read not by SWAT but by SWBAVG or HRUAVG for the purpose of specifying the overall scheme into which the HRU simulated by SWAT fits. Instructions are provided for this extended section of the Control Codes input file for SWBAVG and HRUAVG (below).

The modified *.cod input file format specifies the added control code, **Iopmod,** to coordinate SWAT with MODFLOW. Additional meanings were assigned to existing SWAT control codes, **Ipd** and **Iprn**, as follows. **Ipd** specifies how often SWAT's results are summarized (monthly[0], daily[1], or annually[2]). This was expanded to indicate the corresponding time steps for MODFLOW's solution and for reading and writing the simulation summaries that are used to pass data between SWAT and MODFLOW (see subroutines Init_bal and Init_shl, above. **Iprn** meaning was expanded to indicate whether to call EchoInpt from Main, to echo input data (Iprn < 0), and whether to halt execution after echoing the input data (Iprn < 0), which is useful when execution of SWAT is intended only to check input data for errors and the simulation is not of interest until the input data appear to be valid.

If **Iopmod** > 0, an additional record is read from the *.cod input file that includes the added control codes Iopshl and Itmuni, which are used as follows.

Iopshl indicates whether a data file is available for SWAT to read that summarizes evaporation from shallow ground water, and which was written by a previous simulation by

MODFLOW. This access allows a two-way coupling between SWAT and MODFLOW that is specified as part of the HRU scheme 3, which is specified for SWBAVG by iophru = 3 in item 7 of the *.COD input file. A related input, **ipurk(*j*)**, is a related input that is read from the modified *.gw file for each subbasin, *j*. If **Iopshl** > 0 and **Ipurk** > 0, then evaporation from shallow gw as summarized by MODFLOW is distributed over the subbasin's soil profile using a the added subroutine Evap_gw, which is called by subroutine Subbasin.

Itmuni indicates the time unit used in model data for MODFLOW, and is consistent with the definition given in MODFLOW's Basic package; see Control Codes (*.cod) Input Instructions for definition.

Only the first six lines of the modified Control Codes (*.cod) input data file are read by SWAT. The extended section of the file, line items 7-13, are read only by SWBAVG or HRUAVG. Instructions for the extended section are provided for these programs (below).

Modified Ground water (*.gw) input data

Invoking the integration of SWAT with MODFLOW by the added control code **Iopmod** does not affect SWAT's simulation of ground water based on its lumped, analytical model, and input data are read from its *.gw input file as before. But in this case ground water is simulated in parallel by MODFLOW. The subsurface model option, **Ipurk**, specified in the *.gw input file, was added to provide two significant variations on SWAT's assumptions regarding flow paths between the watershed and ground water for coordination with MODFLOW. SWAT's conceptual model assumes the soil profile to be underlain by a deep aquifer, that is, by a saturated zone that is sufficiently deep to have negligible interaction with the root zone. The first variation allows representing a soil profile underlain by bedrock, so that percolation out of the root zone is blocked. The second variation allows representing evaporation from shallow ground water based on MODFLOW's simulation instead of SWAT's "Revap" model. Specifying the ground water as shallow for any subbasin requires data to be provided to both SWAT and SWBAVG that can be summarized by the SWBX package for a previous execution of MODFLOW. For SWAT, this summary specifies evaporation from shallow ground water for redistribution over the soil profile in each subbasin using the added subroutine Evapgw(see Summary of code changes and additions to SWAT 99.2 in Part 2).

For SWBAVG, the summary from MODFLOW specifies the areal extent of shallow ground water in each subbasin, which is used to compute spatial weights for HRUs in each time step. The two-way coupling between SWAT and MODFLOW is based on successive approximation, initiated by first applying SWAT and SWBAVG to a basin model in which all ground water is assumed to be deep, as specified by the option **Ipurk**. MODFLOW's simulation shows whether the areal extent of shallow ground water is significant enough to warrant a subsequent simulation of SWAT and MODFLOW that includes HRUs with shallow ground water. See the Final Report's chapter on methodology for a description of the approach based on successive approximation.

Modified Management (*.mgt) input data

The management model changes, specified in the *.mgt input file, were made to allow specifying (a) a daily maximum limit for applied irrigation, and (b) an irrigation threshold given by soil water content as a fraction of available capacity. These options are applied by a modified version of SWAT's subroutine Subbasin. The second of these options is coordinated with SWAT's existing capability in versions 98.1 and 99.2 for specifying an irrigation threshold based on either plant water stress factor or soil water content. The model was extended to allow both thresholds to be observed by triggering irrigation during the growing season if either of the thresholds is not met by simulated conditions. While this is an ad hoc approach, it represents an update of our modified version of SWAT 94.2 for application to the Lower Republican River basin in Kansas, and provides a similarly satisfactory match of simulated annual irrigation use to estimates based on reported water use. These added options are disussed further in the Final Report, Ch. 3, under "SWAT input data additions for the SWAT-MODFLOW linkage: Modified Management (*.mgt) input data," and in this manual under "SWAT input data for SWAT-MODFLOW linkage: Instructions for modified Management Codes (*.mgt) input file."

4.3. Instructions for modified Configuration (*.fig) input data file

The option ID_COMB was added to the Subbasin command format for this input data file to associate each HRU with a combination of factors (soil, land use, and subsurface features) that allows the HRU's spatial weight to be calculated. The default value is ID_COMB = 0, which is assumed for a standard SWAT data set, and indicates that HRU weights are to be used as read from the subbasin (*.sub) input file for each HRU.

The option ID_COMB follows the standard input GIS_CODE in columns 56-61 of the Subbasin command. If positive, ID_COMB uniquely identifies a combination of factors on which the HRU weight is based. Factors include soil type, land use, and, if $Ipurk(j) \neq 0$, subsurface features (bedrock, deep groundwater, or shallow groundwater). Combinations of these factors are defined in the extended Control Codes input file. If ID_COMB in the Configuration input file specifies a combination of factors that is defined in the extended Control Codes input file, the weight of the associated HRU is calculated; otherwise, the HRU weight is specified as read from the *.Sub input file. See Section 7.3 for an example of this modified form of the configuration file for the Lower Republican River basin model under HRU scheme 1 (file Hru1virt.fig).

4.4. Instructions for modified Control Codes (*.cod) input data file

Control Codes input format: items 1 to 5 (to be read by SWAT subr. Readcod)

The following data records are read by SWAT subroutine READCOD from the Control Codes (*.cod) input file. The input variable Iopmod, which was added to line 2, specifies the option for a SWAT-MODFLOW linkage. This is the only additional input variable read by subr. Readcod. However, if Iopmod > 0, additional data (items 6-13) may be read from this file by the added SWAT subroutine Readwts and by the external HRU-averaging programs SWBAVG and HRUAVG, which are described in later chapters.

```
(text) title                                                        (1
```

title: input description line.

```
Data (23i4) nbyr,iyr,ideg,Ipd,nsim,msim,ign,iwst,isst,ires,igraf,
            irain,itemp,iresq,idaf,idaL,iprn,iprp,iopt,ipet,ilog,
            ipdwql,Iopmod                                            (2

fields 1-40:      1     2     3     4     5      6     7     8     9    10
data:          nbyr   iyr  ideg   Ipd pcpsim tmpsim   ign  iwst  isst nyskip
fields 41-80:    11    12    13    14    15     16    17    18    19    20
data:        ievent irtsub ihumus iresq idaf  idaL  iprn  iprp  iopt  ipet
fields 81-92:    21    22    23
data:          ilog ipdwql Iopmod


Data (20i4) (Ipdvar(i),i=1,20)                                      (3
Data (17i4) (Ipdvab(i),i=1,17)                                      (4
Data (20i4) (Ipdvas(i),i=1,20)                                      (5
```

Added items for SWAT-MODFLOW coordination (read by added subr. Readwts):

Extended Control Codes (*.cod) input (items 6 to 13)

In addition to records 1-5, SWAT, SWBAVG, or HRUAVG can read data records 6-13 (below) These data are used to calculate HRU weights, take spatially weighted averages over HRUs simulated by SWAT, and to specify flux conditions for MODFLOW's stream-aquifer solution as flow rates.

Record items 6-13 specify the HRU scheme, individual HRUs, and their properties as they pertain to the calculation of HRU weights, spatial averaging of HRUs simulated by SWAT for each hydrologic component, combination of hydrologic components to specify ground water recharge and tributary inflow; and conversion of HRU-averaged results simulated by SWAT from hydrologic depths (volumes per unit area) to flow rates for input to MODFLOW.

Items 6 and 7a are read if Iopmod > 0; the remaining items are read if Iopwts > 0.

If Iopwts > 0, all of the the following input data are read by the added SWAT subroutine Readwts from the extended Control Codes input file. If Iopwts = 0, these data may be read instead by program SWBAVG or HRUAVG. The first of these options is based on recent changes to incorporate the capability of HRUAVG into SWAT, allowing spatial weights to be calculated by SWAT in terms of soil, land use, and subsurface factors as the simulation proceeds.

Input instructions for Items 7-13 are the same for SWAT (subr. Readwts), and Hruavg, and Swbavg except where indicated by brackets [] and followed with an explanation. A separate, short outline of instructions is given for Swbmerge (4.7).

if (**Iopmod** > 0) call Readwts (from Main) to read items 6-13:

6. Shallow gw, unit conversions and file names (free; 2i4,f8.4,3a):

```
  Data (FREE) iopshl, itmuni, Lenuni, nambal, namshl                    (6
```

<u>7a. HRU scheme and options to calculate and write HRU weights</u>

```
Data (FREE) iophru iopwts iprwts [nsubs casnam]                        (7a
```

(Input variables **nsubs** and **casnam** are not read by Swat, but both are read by Hruavg, Swbavg, and Swbmerge.)

If (Iopmod > 0 and Iopwts > 0) Read the remaining items (7b-13):

<u>7b. No. soils, subsurface classes, land uses, physiographic regions, and HRU combinations</u>

```
Data (FREE) nsoils numaqf numuse numreg ncombs                         (7b
```

(numaqf is read for Swbavg but not used)

<u>8. Soil type areal fractions for each subbasin</u>

```
Data (FREE) (soilnm(i),i=1,nsoils)                                     (8a
```

Read for each subbasin j:

```
    Data (FREE) idx, (soilwt(j,i),i=1,nsoils)                          (8b
```

<u>9. Land area fractions for each subbasin</u>

```
Data (FREE) [(aqfnam*(i),i=1,numaqf)]                                  (9a*
Data (FREE) sublbl, pndlbl, aqflbl, shllbl                             (9b
```

Read for each subbasin, j:

```
Data (FREE) idx, subfrc(j), pndfrc(j), aqf_sub (j),shl_sub(j)          (9c)
```

(Line 9a, aqfnam, is not read by Swbavg)

<u>10. Land use fractions for each subbasin</u>

```
Data (FREE) (usenam(i),i=1,numuse)                                     (10a
Data (FREE) crplbl, irrlbl [,urblbl]*                                  (10b*
```

Read for each subbasin j:

```
Data (FREE) idx, crpfrc(j), dstirr(j) [,urbfrc*(j)]                    (10c)*
```

(urblbl, 10b, and urbfrc, 10c, are not read by Swbavg)

<u>11. Irrigated area (pct of basin) for each year</u>

```
Data (FREE) (pctirr(k), k=1,nyrs)                                      (11
```

12. Region areal fractions for each subbasin

If (numreg > 1):

```
    Data (FREE) (regnam(i),i=1,numreg)                                   (12a
    Read for each subbasin j:
        Data (FREE) idx,regfrc(i,j),i=1,numreg)                          (12b
    Read regional associations with soils (also gw and land use for Hruavg):
    Data (FREE)         (ireg_sol(i),i=1,nsoils)                         (12c
    Data (FREE)         [(ireg_aqf*(i),i=1,numaqf)]                      (12d*
    Data (FREE)         [(ireg_use*(i),i=1,numuse)]                      (12e*
```

(Lines 12d-12e, Ireg_aqf and Ireg_use, are read by Swat and Hruavg but not by Swbavg)

13. Table of properties associated with each HRU

```
Data (text) header                                                       (13a
Ror each combination i =1 to ncombs:
If (numreg == 1) then                                                    (13b
  Data (FREE) idx,idxsol(i),idxuse(i),idxaqf(i), namcmb(i)
Else (numreg > 1):                                                        (13c
  Data (FREE) idx,idxsol(i),idxuse(i),idxaqf(i), namcmb(i),idxreg(i)
End if
```

[close (incode)]

[end of input]

Examples of extended Control Codes (*.cod) input data files

Examples are given below for (a) input to SWAT with HRU averaging handled by SWBAVG or HRUAVG; and (b) input to SWAT with additional data required for calculating virtual subbasin areas in SWAT. The data file listed for Example (b) is nearly identical to the data read by SWBAVG or HRUAVG and used to calculate HRU weights and take spatially weighted averages over the HRUs within each subbasin for each hydrologic term.

Example Control codes input files (see Swbavg and Hruavg for extended *.cod input)

(a) hru_deep.cod: to be read by SWAT; HRUs are averaged by SWBAVG or HRUAVG.

```
Control File ! hru_deep.cod (aquifr=1, swminf=0.65)                           (1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
                                                                              (3
                                                                              (4
                                                                              (5
0,1,1, ' '  ' '                                  ! iopshl itmuni Lenuni nambal namshl (6
```

(b) hru1virt.cod: to be read by SWAT, which averages HRUs (iopmod = 2).

```
hru1virt.cod (15 HRUs, 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
                                                                             Ipdvab
                                                                             Ipdvas
   0   1   1  ' '  ' '  ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl         (6
   1   1   2            ! '(2i4)': iophru iopwts iprwts (read in Readwts)        (7
5,3,4,1,15,nsoils,numaqf,numuse,numreg,numcmb (no. specified HRU factor combinations)
   'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !nsoils, (soilnm(j),j=1,nsoils)
 1  0.092   0.471    0.099    0.338   0.
 2  0.191   0.064    0.402    0.342   0.
 3  0.098   0.637    0.132    0.052   0.081
 4  0.126   0.543    0.054    0.274   0.004
```

```
5  0.043    0.745    0.        0.086   0.126
6  0.       0.741    0.176     0.059   0.024
7  0.       0.869    0.022     0.      0.108
8  0.       0.697    0.279     0.      0.024
9  0.       0.630    0.021     0.      0.348
'bedrock','deep gw','shallow gw'          !numaqf,(aqfnam(j),j=1,numaqf)
     'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! land fractions
1     0.22015   0.0343    0.0733    0.1875
2     0.04909   0.0031    0.2053    0.2
3     0.20435   0.0064    0.2368    0.0625
4     0.08729   0.0268    0.0924    0.
5     0.05282   0.0021    0.2106    0.09091
6     0.08247   0.0000    0.0122    0..
7     0.10945   0.0131    0.0829    0.
8     0.11788   0.04139   0.0257    0.
9     0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd','urban'    !numuse, (usenam(j),j=1,numuse)
     'crpfrc'  'dstirr'   'urbfrc'
1     0.5962    0.139694   0.
2     0.5463    0.060835   0.
3     0.6281    0.315519   0.
4     0.5737    0.039543   0.
5     0.7164    0.100748   0.
6     0.6113    0.010547   0.
7     0.6753    0.094522   0.
8     0.5316    0.039287   0.
9     0.4991    0.182079   0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.2 4.2 4.3 4.5 4.4 4.8 4.7
  hru Soil  Use  Aqf     namhru (read region ID only if Numreg>1) HRU description
    1    1    1    2     'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.) (case, file name)
    2    1    2    2     'carr-irm'          (irrigated corn)
    3    1    3    2     'carr-pam'          (grass: range and pasture)
    4    2    1    2     'cret-wsm'   soil 2
    5    2    2    2     'cret-irm'
    6    2    3    2     'cret-pam'
    7    3    1    2     'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
    8    3    2    2     'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
    9    3    3    2     'hshd-pam'
   10    4    1    2     'kips-wsm'   soil 4
   11    4    2    2     'kips-irm'
   12    4    3    2     'kips-pam'
   13    5    1    2     'muir-wsm'   soil 5
   14    5    2    2     'muir-irm'
   15    5    3    2     'muir-pam'
```

Definitions for Control Codes input data: records 1 to 5 for SWAT

Record 2

Ipd (cols. 13-16): print code for standard output file (0: monthly, 1: daily, 2: annually). NOTE: if **Iopmod** > 0 (see below), **Ipd** also specifies ground water simulation time steps over which SWAT results are to be summarized for linkage to MODFLOW's stream-aquifer simulation. In addition, if **Iopshl** > 0 (specified on record 6; see below), then SWAT also reads a summary of results describing shallow ground water in the corresponding time steps; the name of this file is specified by the variable **namshl** (also on record 6); see the definition of **Iopshl** (below). If the added ground water option **Ipurk**(j) > 0, which is read from the *.gw file, then the evaporation from shallow ground water is read from this file and converted to a daily volume per unit area that is distributed over the soil profile by the added subr. **Evapgw**, called by subr. **Subbasin**.

iopmod (cols. 89-92): This input code is read from record 2 of the Control Codes input file (*.cod).

iopmod > 0: a summary file for the SWAT-MODFLOW linkage is to be written. An additional record of data is also read following the standard records; see also record item 6 (below).

Iopmod = 1: any of the HRU schemes may be applied; subr. Sumstep writes a balance file in units of volume per unit area. Program SWBAVG postprocesses SWAT results given by balance files, calculates spatial weights, and takes a spatially weighted average over the HRUs simulated by SWAT. SWBAVG also calculates recharge and tributary flow based on HRU schemes 1-3 and converts hydrologic terms to flow rates for input to MODFLOW.

iopmod = 2: indicates that HRU scheme 1 (iophru = 1) is assumed, and SWAT's HRU approach is applied to represent spatial heterogeneity within subbasins. For each groundwater solution time step (day, month, or year), subroutine Hrusum takes a spatially weighted average over the HRUs corresponding to each subbasin. Subroutine Sumstep then evaluates recharge and tributary inflow based on HRU scheme 1 (see also naqfrc, below), and converts hydrologic components from volumes per unit area to flow rates for input to MODFLOW. The summary written by Sumstep under this option is designed to be read by the added Modflow SWB package.

An additional program, Swbmerge, is designed for use with cases in which the hydrologic response of each subbasin is simulated by a separate execution of SWAT over the time period of interest, and the subroutine Sumstep writes a summary of the subbasin. After all subbasins have been simulated, the program SWBMerge reads the summaries and merges them into a summary file for the basin, which can then be used as input to MODFLOW. For an illustration of this mode, see Example 5 in the "Guide to the SWAT-MODFLOW linkage" (P&S, 2000: KGS Open-File Report 2000-38).

Usage of the input variable **iopmod** has been modified since the SWAT-MODFLOW linkage based on SWAT v.94.2, in which **iopmod** specified the time step for MODFLOW's stream-aquifer simulation (1:annual, 2:monthly, 3: daily) as documented in P&S (1999a,b). In the present version (99.2), SWAT's own code, **ipd**, which is read from the ~.cod input file, is used to specify the time steps over which SWAT's results are to be summarized. The previous meaning of **iopmod** is ignored in SWAT v. 99.2, but is retained for the linkage with MODFLOW in the form of the variable **iopstp**, which is defined in subr. Init_bal, called by subr. Simulate in SWAT. Init_bal sets iopstp as shown below and writes iopstp to the balance file (*.bal) and is passed to MODFLOW by way of SWBAVG. Values of **iopstp** are determined by **ipd** as follows:

Time step of summary	**iopstp** (balance file)	**ipd** (~.Cod input file)
simulation period	0	---
monthly	2	0
daily	3	1
annual	1	2

Rec. 3: Ipdvar(i); up to 20 output variables printed to the .rch file.
Rec. 4: Ipdvab(i); up to 17 output variables printed to the .bsb file.
Rec. 5: Ipdvas(i); up to 20 output variables printed to the .sbs file.

Definitions for extended Control Codes input (items 6 to 13)

If **iopmod** > 0, read the following data from records 6-13:
Record 6:
iopshl: option (yes:~>0, no:~=0) to read a summary of evapotranspiration from shallow ground water for each time step of an aquifer solution as summarized by MODFLOW. If iopshl > 0, evapotranspiration from shallow ground water for each subbasin is converted into a daily water volume per unit area, referred to as a depth. These data are read for the first time step by subr. **Init_shl** (called by subr. **Simulate**) and for succeeding time steps by subr. **Sumstep** (called by subrs. **Writed**, **Writem**, or **Writea**, depending on Control Code **Ipd**; see the modified *.COD input file description). The operations of reading and conversion of evaporation from shallow ground water to daily depths are performed effectively at the beginning of each aquifer solution time step to allow convergence to simultaneous solutions of SWAT and MODFLOW simulations. This is based on a successive approximation procedure that is initialized by taking evapotranspiration from shallow ground water to be zero. The first complete execution of SWAT, SWBAVG, and MODFLOW allows MODFLOW to summarize evapotranspiration from shallow ground water. This summary is then available for use in a succeeding execution of SWAT and MODFLOW. However, for each subbasin, *j*, SWAT does nothing with evapotranspiration from shallow ground water simulated by MODFLOW unless **Ipurk**(j) > 0, which is specified in the modified *.gw input file (below), which designates SWAT's simulation to represent an HRU with shallow ground water for each subbasin. That is, the results from MODFLOW must be available (**iopshl** > 0) and the HRU for the subbasin must be specified as having shallow ground water.

itmuni: indicates the time unit of model data for MODFLOW and printout of elapsed simulation time as follows:

Itmuni	Time unit	Time unit length (s)
0	undefined	1
1	seconds	1
2	minutes	60
3	hours	3600
4	days	86400
5	years	31536000

Definition and usage of **Itmuni** is consistent with MODFLOW as defined for input to the Basic package.

Lenuni: indicates the length unit of model data for MODFLOW, which must be consistent for all values involving length, including grid spacing, hydraulic head and conductivity, flow rates, water volumes, and concentrations (in the case of solute transport for MODFLOW-2000). Length units indicated by Lenuni are the following:

Lenuni	Time unit	Replaces Swat/Modflow conversion factor (previously input as **Cnvlen** and **Cnvlbl)**
0	undefined	1 (m/m)
1	feet	0.3048 (m/ft)
2	meters	1 (m/m)
3	centimeters	0.01 (m/cm)

The input **Lenuni** replaces the inputs **cnvlen** and **cnvlbl**, defined below, which are now specified in terms of **Lenuni** in the modified SWAT-99.2 subroutine Readcod. **Lenuni** was introduced as a step toward compatibility with MODFLOW-2000, which reads **Itmuni** (above) and **Lenuni** from the Discretization file. For more information see the documentation available from USGS (Harbaugh et al., 2000; Hill et al., 2000) for MODFLOW-2000 and the accompanying program mf96to2k, which can be used to convert a MODFLOW-96 data set for input to MODFLOW-2000.

The following two data items are now set internally on the basis of the input **Lenuni**:

cnvlen: conversion factor for standard units of length from Modflow to hydrologic model. Example: to convert units of length from Modflow (ft) to Swat (m): cnvlen = 0.3048 (m/ft).
cnvlbl: conversion factor label (8 characters max). ex. cnvlen=0.3048, cnvlbl='m/ft'

The following two conversion factors are also used in the conversions:
depmpy = conversion for model results from hydrologic depth to std unit of length. Ex. Swat: Hydrologic depths are in mm, std length units are m; so depmpy = 1.e-3 (m/mm)
widmpy = conversion for model results from units of length used for land surface areas to std unit of length. Ex. Swat: Land surface areas are given in km^2. The corresponding units of length are km, and std length units are m; so widmpy = 1.e+3 (m/km)
The factor **cnvlen** and the associated factors **depmpy** and **widmpy** are used in SWAT and Swbavg for conversions between SWAT and MODFLOW units. These include:
a) basin area, such as from km^2 in Swat to ft^2 for Modflow;
b) simulated hydrologic fluxes from volume per unit area [L] in Swat's SI-based units (mm) to flow rates [L^3/T] for Modflow in homogeneous units such as ft^3/s.

nambal, namshl: file names. nambal = name of "balance" file summarizing results at the end of each ground water time step. to be passed to SWBAVG for averaging according to the externally averaged scheme. namshl = name of file summarizing shallow ground water (area and rate of flow into soil profile), written by a previous execution of MODFLOW using a successive approximation scheme for coupling (iophru=3). The format of the balance file summarizing Swat's results is given by Input Instructions to the added Modflow package, SWBX.

nambal: output file name for hydrologic balance to be passed to Modflow. This file name is no longer read from this file but is now derived from Swat's standard output file name (extension ".std"), and will fail if the standard output file name does not at least include a period. Example: For a case with standard output file name carr-irm.std, the assumed balance file name is carr-irm.bal.

namshl: input file name for results from Modflow for a previous iteration of the combined Swat-Modflow solution. This file is expected for HRU option iophru=3, in which shallow aquifer HRUs are simulated. Results from Modflow on this file include areal fraction of shallow aquifer and evaporation from shallow ground water. If file name is given as blank (namshl=' '), it will be derived from Swat's standard output file name using the extension '.SHL'. File is opened and read for the first time step in Swat's Main by code on included file Swatmod3.h, and for succeeding time steps in subroutine Preswb.

naqfrc (read for **Iopmod** = 2): no. subbasins for which aquifer areal fractions are to be read.

aqf_fr(*j*) (read for **Iopmod** = 2): areal fraction of subbasin *j* that is underlain by an aquifer. The default value of 1 is assigned to all subbasins prior to reading aqf_fr for selected subbasins.

Record item 7a: **iophru iopwts iprwts**

iophru: option specifying one of HRU schemes 0-3 (conceptual models for spatial heterogeneity within subbasins). These schemes are presented in the Final Report, first as they are implemented with SWBAVG, which was designed primarily to satisfy requirements for studies of two watersheds in Kansas (Lower Republican River basin and Rattlesnake Creek watershed). The schemes are then presented as they were implemented with HRUAVG, which was developed in an effort to make the linkage of SWAT and MODFLOW under conditions of spatial heterogeneity available for application to other watersheds.

=1: original scheme for one region (**numreg** = 1) with spatially independent soils and land use types. HRUs are simulated by SWAT with the assumption that the entire basin is underlain by a deep aquifer. For a basin that is only partially underlain by an aquifer, however, ad hoc models for tributary inflows and ground water recharge are applied in SWBAVG; see the Final Report's chapter on Methodology for a review of these conceptual models. For the Lower Republican River basin, three land uses (dryland crop, irrigated crop, and grassland); and six soils were defined for a total of 18 HRUs. These were represented by 15 HRU simulations, since two of the soils occurred in disjoint sets of subbasins (Hastings: subbasins 1-4; Hedville: subbasins 6-9), allowing HRUs with these soils to be combined.

=2: This is a two-region scheme (uplands and alluvial valley: set numreg = 2; specify upland and alluvial areal fractions for each subbasin). For SWBAVG, this option refers to regionalized land uses as follows: (1) nonalluvial dryland crops; (2) alluvial irrigated crops; (3) alluvial grassland; (4) nonalluvial grassland. Regional dependence of soils is specified by the input **ireg_sol**. For HRUAVG, land uses, subsurface characteristics, and soil types are specified as three separate, but not necessarily independent, factors. Spatial dependencies of these three factors on defined regions may be specified along with spatially independent factors. For example, a land use of irrigated corn may be associated with an alluvial region of a subbasin, whereas grassland may occur both in the alluvial valley and the uplands, and may be specified as spatially independent.

=3: A refinement of the above scheme, in which the alluvial aquifer area is divided into shallow and deep components; the shallow component is associated with evaporation from gw, based on Modflow's simulation. For **iophru**=3 and **iopshl** > 0, the shallow gw areal fraction of each subbasin is read from a file written by the SWBX package in a previous run of MODFLOW. Evaporation, given by MODFLOW results as a flow rate, is converted to a hydrologic depth (water volume per unit area of shallow gw), **evtgw**. If two regions are specified (**numreg** = 2), then the soils are associated with their respective regions.

Note: For the case that spatial heterogeneity is represented according to the HRU approach using SWAT's virtual subbasins capability, SWAT runs only one simulation. For this case with option Iopmod = 1, SWBAVG reads only one balance file written by SWAT and does no averaging, since this has been done in SWAT. SWBAVG applies the conceptual models for tributary flow and ground water recharge to the input read from the balance file and calculates flow rates for input to MODFLOW. Both SWBAVG and HRUAVG may be used for this case. However, a simpler alternative is provided by specifying Iopmod = 2, in which case the added Swat subroutine Sumstep performs the above operations so that the summary file can be read directly by Modflow, and execution of Swbavg or Hruavg may be bypassed.

iopwts: option (y>0,n=0) for SWAT to calculate HRU weights in terms of soil, land use, and subsurface factors. The procedure for doing this with program HRUAVG was incorporated into SWAT by the added subroutines

iprwts: option (y>0,n=0) to write HRU weights to data file <hrunam>.wts. Options:
=1: write HRU weights for each basin in each time step; (average is taken over subbasins).
=2: write HRU weights for each subbasin in each time step.

casavg: suffix to be used for balance file (*.bal) to be written and shallow gw file (*.shl) to be read, if nambal and namshl are read as blank from line 6 (see defs. above)

<u>7b. No. soils, subsurface classes, land uses, physiographic regions, and HRU combinations</u>
nsoils number of soil types used to represent soils of basin.
numaqf† number of subsurface types.

numuse number of land uses.
numreg: number of regions; the same regionalization applies to all subbasins.
ncombs: no. HRUs required to represent spatial heterogeneity. If the number of combinations is specified as zero (**ncombs**= 0), then the added SWAT subroutine Combwts on file Readwts (or program HRUAVG) writes a list of HRUs that are to be simulated by SWAT.

8.Soil types: areal fractions for each subbasin
soilnm(i): Column labels for areal fractions of each soil type, i=1 to nsoils.
soilwt(j,i): areal fraction of subbasin j for each soil i. Soil fractions are incorporated into HRU weights

9.Land areas as fractions of each subbasin
aqfnam(i)†: Column labels for areal fractions of each subsurface feature, i=1 to numaqf for numaqf = 3; aqfnam(1) = 'bedrock', aqfnam(2) = 'deep gw', aqfnam(3) = 'shallow gw'.
sublbl, subfrc(j): column header and subbasin areal fractions of basin for each subbasin j; denoted here by $f_{sub,j}$.
pndlbl, pndfrc(j): column header and noncontributing areal fractions of each subbasin j (not currently used by SWBAVG).
aqflbl, aqffrc(j): column header and areal fraction of each subbasin j underlain by ground water, $f_{aqf,j}$; used in land use equations for HRU schemes 2 and 3 (below). For HRU scheme 3 (iophru = 3), this is updated in each time step by reading data from a summary written by MODFLOW (SWBX package) in a prior ground water simulation.
shllbl, shlfrc(j): column header and areal fraction of each subbasin j with shallow ground water, $f_{shl,j}$; used in land use equations for HRU scheme 3 (below). The shallow ground water area is the sum over grid cells in which dtw < dext, where dext = extinction depth as specified in MODFLOW's EVT package. As with aqffrc (above), shlfrc is updated in each time step by data read from a summary of evaporation from shallow ground water that is given by a prior ground water simulation by MODFLOW (SWBX package).
sublbl, pndlbl, aqflbl, shllbl are 8-character header labels specified in free format.
The above areal fractions are used to specify the following subbasin components:

```
aqfwt(j,1) = 1. - aqfrac          !soil lies on top of bedrock
aqfwt(j,2) = aqfrac*(1.-shfrac)   !soil underlain by deep gw
aqfwt(j,3) = aqfrac*shfrac        !soil underlain by shallow gw
```

10: Land uses: areal fractions for each subbasin
usenam(i): Column labels for areal fractions of each land use, i=1 to numuse.

crplbl, crpfrc(j): column header (8 chars) and cropland as an areal fraction of each subbasin, j; denoted by fcj and used in land use equations for HRU schemes 1-3 (below).
irrlbl, dstirr(j): column header (8 chars) and irrigated land area in subbasin j as a fraction of total irrigated area in basin; denoted here by $f_{ird,j}$. = $A_{irr,j}/A_{irr}$. As an approximation to reduce data requirements, this distribution is assumed to be constant over the period of simulation period. It is used together with the time series for annual irrigated area in the basin to specify irrigated area as a fraction of each subbasin for each year (below).
urblbl†, **urbfrc**(j)†: column header (8 chars) and urban land areal fraction of subbasin j.

The above areal fractions are used to specify four land uses for each subbasin:

```
c           Land use weight components for each subbasin.
        usewt(isub,1) = crpfrc(isub) - firr(isub) !unirrig. cropland
        usewt(isub,2) = firr(isub)                !irrigated cropland
        usewt(isub,3) = 1. - (crpfrc(isub) + urbfrc(isub)) !grassland
        usewt(isub,4) = urbfrc(isub)                       !urban land
```

11. Irrigated area (pct of basin) for each year

pctirr(k): irrigated area as a percent of basin area; specified for each year, iyr, of the simulation period, **nyrs** (from line 1 of the *.COD input file). This is denoted by (below), denoted by $f_{irb}(\mathrm{iyr}) = 100A_{irr}(\mathrm{iyr})/A_{bas}$, where A_{bas} = basin area.

12.Regions: areal fractions for each subbasin

regnam(i): name (8 chars) of each region i from 1 to numreg.

regfrc(j,i): areal fraction of subbasin j for each region i. These fractions are read only if the number of regions **numreg** > 1. For HRU scheme 1 (**iophru** = 1), **numreg** = 1 and areal fractions **regfrc**(j,1) = 1 for all subbasins j.

ireg_sol(i): index to region (from list defined above) associated with each soil i. Soils may be specified as region-independent by setting this index to zero. In contrast to SWBAVG, HRUAVG allow a mix of region-dependent and region-independent soils or other factors.

ireg_aqf(i)†: index to region (from list defined above) associated with each subsurface feature i. These may be specified as region-independent by setting this index to zero.

ireg_use(i)†: index to region (from list defined above) associated with each land use i. These may be specified as region-independent by setting this index to zero.

13. Define combinations of soil, land use, and subsurface type to associate with HRUs

Item 13 identifies the soil type, land use, and subsurface model associated with each HRU as follows.

i: dummy index for numbering scheme used to identify HRUs; not used by program.

idxsol(i): index to soil type (item 8, above). If the number of regions numreg > 1, then each HRU is associated with a particular region, and this association is made through the soil type (see item 9, above).

idxuse(i): index to land use (item 10, above);

idxaqf(i): index to assumption regarding aquifer. Three options are defined as follows:

= 1: soil is underlain by bedrock (note: specified by a value of −1 in SWBAVG). Option is passed to subroutine Purk to indicate that percolation out of the root zone is blocked by bedrock, resulting in alternate routes (increased lateral subsurface flow, soil water content, and evaporation).

= 2: soil is underlain by an aquifer that is deep enough that soil and plant water uptake from ground water is negligible. (Note: specified by a value of 0 in SWBAVG).

= 3: soil is underlain by a shallow aquifer (note: specified by a value of 1 in SWBAVG). This case is associated with HRU option 3 and input file **namshl** (above), which specifies areal fraction of shallow aquifer and evaporation from shallow ground water in each time step for each subbasin according to Modflow's solution.

Note: the values of **idxaqf**(i) are related to **ipurk**, an input to SWAT that is defined for the modified *.gw data file (see instructions above), by **idxaqf** = **ipurk** + 2; that is, ipurk specifies the optional models for soil underlain by bedrock (−1), deep ground water (0), or shallow ground water (+1).

namcmb(i) name of combination of factors to be associated with HRUs. For programs SWBAVG and HRUAVG, which take averages over HRUs external to SWAT, these are the names of the HRUs simulated by separate executions of SWAT.

idxreg(i): region identifier; regions are defined above by item 12. For SWBAVG, this should be the same as the soil type's region identifer, ireg_sol, and consistent with the regional land use for schemes 2 and 3. For HRUAVG, idxreg should specify the same region as the soil, land use, and aquifer region identifiers ireg_sol, ireg_use, and ireg_aqf.

4.5. Instructions for modified ground water (*.gw) input data file (read by SWAT)

The input format for this file was modified by adding the input **ipurk**(j) for each HRU, *j*, to specify conceptual models for subsurface features underlying a soil profile. (Note: The input **ipurk** is related to the input **idxaqf** that read by SWBAVG or HRUAVG from the extended Control Codes (*.cod) input file to specify the subsurface model associated with each HRU; see instructions for SWBAVG and HRUAVG, below.)

Input format: only line 3 of the input format was modified by adding the input, **ipurk**.

```
Line 1 (80 characters): title

Line 2 (10f10.4): gwht(i),  shallst(i),   alpha_bf(i), gw_spyld(i),
     &            delay(i), gw_revap(i), rchrg_dp(i), revapmn(i)

Line 3 (10f10.4):  deepst(i), gwqmn(i), ipurk(i)
```

Example: file hru_deep.gw

```
Groundwater Data File ! 1/9  gw(19): h2.gw (gwht= 2m)  (zero perc to "deep" aqf)
       2.0       0.0       0.0       .15        0.      0.00      0.00       0.0
         0         0         0
```

Modified input for record 3:

ipurk(j): This option was added to the ground water input data file (*.gw) for HRU or subbasin **j** to specify the conceptual model for soil water movement. Code changes have been made to implement alternative conceptual models for ipurk(j) ≠ 0.

ipurk(j) = 0: soil profile is underlain by an aquifer with ground water that is deep enough that uptake from ground water by capillary or evaporative processes into the soil profile can be neglected. This is the default case represented by SWAT, and is invoked by an input file (*.gw) in standard format if the numeric field for **ipurk** is blank.

ipurk(j) = −1: soil profile is underlain by bedrock (no aquifer). In this case, no water percolates out of the root zone. This conceptual model is implemented in subr. Purk by setting the variable **sep** to zero after percolation out of the root zone has been calculated.

ipurk(j) = 1: soil profile is underlain by an aquifer with ground water that is shallow enough that uptake into the soil profile is signficant. Subroutine Subbasin was modified to implement this conceptual model by calling subr. Evap_gw to distribute this uptake over the soil profile. This uptake is specified by MODFLOW using a form of successive approximation in which the SWAT-MODFLOW linkage is first applied with the initial assumption of deep ground water in SWAT, and MODFLOW revises this initial assumption by summarizing the area of shallow ground water within each subbasin and the corresponding flow rate into the soil profile based on MODFLOW's evapotranspiration model. This revised estimate of uptake from shallow ground water can be used in a second application of the SWAT-MODFLOW linkage. MODFLOW's results from the second application of the linkage can be used in a third pass and so on in order to examine convergence properties of the solution.

4.6. Instructions for modified Management Codes (*.mgt) input data file

The previous version of the SWAT-MODFLOW linkage included modifications to SWAT (v.94.2) to specify a daily maximum irrigation limit, **wsfmax**, and an option, **iopswm**, to simulate irrigation based on a soil water content threshold, **swminf**, expressed as a fraction of available water capacity. These options are available as part of changes to SWAT v.99.2 through the Management Codes input file as follows.

SWAT v.99.2 has the capability to specify a soil water content threshold for irrigation in the Management Codes input file (~.mgt) as part of its initialization of automatic irrigation (mgt_op = 10). Subroutines Readmgt and Subbasin were modified to expand on this capability so that the Management Codes input file can specify both a soil water content threshold as a fraction of available soil water capacity and a maximum daily irrigation limit. These options were incorporated into the management input data file (*.mgt) using the format described below and illustrated by the following file, corn.mgt, which is part of the data set for the Lower Republican River basin model:

```
Management Data File ! 1/17 mgt(17): corn.mgt (wsf=.990)
0  1   0   0   5   0   0
   5  07           10              0.990            0.65      12.7
   5  07            1   1900.   2
   9  07            5           2
```

In this example, automatic irrigation (mgt_op=10) is specified by record 3, and occurs when plant water stress factor falls to 0.99, if the standard version of SWAT 99.2 is applied. Subroutine Readmgt reads mgt_op as mgt2i, and the stress factor threshold as mgt3, which is then assigned to auto_wstr.

SWAT v.99.2 already has the capability for automatic irrigation triggered by a soil water content threshold, but this capability is not documented in the Management codes input file description. If the desired irrigation triggering threshold is given by swtrig (mm) < sol_sumfc(j), where sol_sumfc(j) is available field capacity (mm), then the soil water deficit threshold for subbasin j can be represented as a negative soil water depth by

deficit (mm) = swtrig – sol_sumfc(j)

The plant stress factor threshold, specified in the *.mgt input file and read by subr. Readmgt, is interpreted instead by the standard version of subr. Subbasin to represent a soil water content threshold if it is a negative number, which represents a soil water deficit in the above form. Subroutines Readmgt and Subbasin were modified to allow specifying the following as part of the Management (*.mgt) input file:

(a) soil water threshold as a fraction of available capacity, **auto_swf** (cols. 49-56);
(b) maximum allowed daily irrigation (mm), **auto_dmx** (cols. 61-66).

Variables auto_swf and auto_dmx are arrays that are analogous to auto_wstr, the plant stress factor (cols. 33-40), but are currently declared in module swtmod99 instead of module parms, and are allocated in subr. alloc_swtmod instead of subr. alloca_parms. The added variables have no modifying effect if they are specified as zero. They are stored in arrays auto_swf and auto_dmx by subr. Readmgt, and are then applied as follows in subr. Subbasin if they are nonzero. These options are implemented as follows.

(a) With the modified versions of subroutines Readmgt and Subbasin, if **auto_swf** > 0, it is converted into a soil water deficit threshold in subr. Subbasin by

deficit (mm) = (**auto_swf** – 1)·sol_sumfc(j)

This form of the soil water content threshold is substituted for the plant water stress threshold, **auto_wstr**, which is then interpreted by the original version of subroutine Subbasin as described above. The initializing code to do the above in subr. Subbasin is the following:

```
          if (auto_wstr(nro(j),nair(j),j).ge.0.) then                !!spp
            swminf = auto_swf(nro(j),nair(j),j)                      !!spp
            if (0. < swminf .and. swminf < 1.)                       !!spp
     1        auto_wstr(nro(j),nair(j),j) = sol_sumfc(j)*(swminf - 1.) !!spp
          end if                                                     !!spp
```

In this code, **swminf** is a scalar version of the element of interest in array **auto_swf**. The above initialization would be more appropriately done in subr. Readmgt, but this is prevented because the call to subr. Readmgt precedes the call to Readsol, where sol_sumfc is initialized (see subr. Readinpt).

(b) The daily maximum irrigation limit, **auto_dmx**, is applied as an added constraint on the supply source, divmax, for irrigation sources irr > 2 in subroutine Subbasin as follows:

```
!!      Adjust Aquifer Storages for Irrigation Withdrawals
        if (irr(j).gt.2) then
c           wsfmax = daily irrig. max (input from modified *.mgt,
c                    subr. Readmgt) through Swtmod99 module):
          wsfmax = auto_dmx(nro(j),nair(j),j)
          if (1.+wsfmax > 1.) divmax(j) = amin1(divmax(j),wsfmax)
```

4.7. Swbmerge (input and example)

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.

<u>7. No. subbasins; HRU scheme and options to calculate and write HRU weights</u>

```
Data (FREE) iophru iopwts iprwts nsubs casnam                    (7
```

<u>8. File names of summary results for separate simulations of subbasins by SWAT</u>

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"):

```
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   2
                                                                          Ipdvar      3
                                                                          Ipdvab      4
                                                                          Ipdvas      5
   0   1   1 ' '  ' '  ! '(3i4,2a)': iopshl itmuni Itmuni nambal namshl               6
   1   1   1   9 'hru1x'  ! '(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'
```

5. MODFLOW-96

This chapter provides input data requirements for packages that are used in a coordinated SWAT-MODFLOW simulation. It begins with a summary of input requirements for using SWAT's simulation results as input to Modflow.

5.1. Using SWAT's simulation results as input to MODFLOW-96

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).

5.2. MODFLOW-96 changes to invoke added packages

The method used to specify packages for MODFLOW-88 was replaced by the NAME file in MODFLOW-96. An example of the NAME file, Hru1.nam, is listed below for the Lower Republican River basin model; "Operation sequence for HRU scheme 1."

Unlike MODFLOW-88, only the mainline of MODFLOW-96 was modified; no changes were made to the standard packages in MODFLOW-96. However, both standard and modified versions of the Well and Stream packages were incorporated into MODFLOW-96. In the mainline, the data statement identifying linked packages was modified to identify added packages SWBX, RSDX, and POSTX with 'swb', 'rsd', and 'pos' respectively, as shown below. RSDX and POSTX are in-line postprocessing packages that are documented separately (P&S, 2000d).

```
      DATA CUNIT/'BCF ','WEL ','DRN ','RIV ','EVT ','TLK ','GHB ',       1-7
     1           'RCH ','SIP ','DE4 ','SOR ','OC  ','PCG ','GFD ',       8-14
     2           '    ','HFB ','RES ','STR ','IBS ','CHD ','FHB ',      15-21
     3           'SWB ','RSD ','POS ','    ','    ','    ','    ',      22-24
     4           '    ','    ','    ','    ','    ','    ','    ',
     5           '    ','    ','    ','    ','    ','    '/
```

Added or modified packages are indicated by the data statement as follows:

```
 index      abbrev      package
     2      wel   standard (WEL5) or modified (WEL2) Well package
    18      str   standard (STR1) or modified (STR2) Stream package
Added:
    22      swb   SWBX: Soil water balance package
    23      rsd   RSDX: residuals package
    24      pos   POSTX: postprocessing package
```

Invoking modified versions of the Well and Stream packages

The identifiers 'WEL' and 'STR' do not distinguish between the standard packages and the modified versions WELX and STRX, which are invoked instead of the standard packages in either of two ways. First, SWBX is invoked if the package is specified in the NAME file (see the example mentioned above). If SWBX is invoked, then WELX and STRX are both invoked internally (by setting variables Iopwel and Iopstr both equal to 1), since these packages were modified to provide coordination with the SWBX packages. Second, if SWBX is not invoked, the WELX and STRX packages may be invoked as follows. The added input Iopwel is read from the first record of the Well input file, and the added input Iopstr is read from the first record of the Stream input file. If Iopwel > 0 or if the SWBX package is invoked, then the nonstandard WELX package is used. If Iopstr > 0 or if either of the SWBX and WELX packages are invoked, then the nonstandard STRX package is invoked. The nonstandard STRX package is required if the nonstandard WELX package is invoked because WELX provides the capability to represent water rights that pump from streams, which requires association with corresponding stream reaches. STRX provides the added indexing array Idxstr for directly referencing stream reaches given their grid cell locations.

Only minor changes were required to incorporate the added or modified packages SWBX, WELX, and STRX, RSDX, and POSTX into MODFLOW-96. These packages were documented previously as part of MODFLOW-88 in Perkins and Sophocleous (1999b-c).

SWBX data files

- *.swb (In): Associate grid cells with geographical extent of subbasins simulated by SWAT, and subbasin outflows ("pour points") with stream reaches specified by the STRX package.
- *.bal (In): For each time step, specify flow rates for recharge, tributary inflow, irrigation demand, and potential evaporation for each subbasin, to be spatially distributed over corresponding grid domain to specify flux conditions for MODFLOW's solution.
- *.shl (Out): For each time step of MODFLOW's solution, summarize evapotranspiration and the corresponding area of shallow ground water in each subbasin. This can be used as input to SWAT and SWBAVG in a subsequent simulation to provide a two-way hydrologic coupling of SWAT and MODFLOW using a successive approximation approach.

5.3. Instructions for the SWBX package input data files (*.swb and *.bal)

The SWB input file is read by subroutines Swb1al and Swb1rp of the Modswb package. It specifies some modeling options, associates subbasin pour points with aquifer grid cell locations and thereby stream reaches; and associates the extent of each subbasin with underlying aquifer grid cells. The SWB package is coordinated with modified versions of the WELL package, WELX, and the STREAM package, STRX.

For stand-alone execution of Modflow (**iopswt** = 0), the balance file is read beginning in Swb2rp and continuing in Swb2fm in each time step. The balance (*.BAL) input file contains the results of Swat's simulations which are converted in subroutine Preswb, called by Swat, from Swat's units for hydrologic depths (mm), i.e., volumes per unit area, to flow rates; and averaged over HRUs by program Swbavg to represent spatial heterogeneity within subbasins. In a future version of this linkage, the role played by Swbavg should be internalized as part of Swat, which should allow Swat to call Modflow as a subroutine at the end of each time step and passing the data contained in the balance file by reference to arrays as subroutine arguments instead.

The model for the Swat-Modflow linkage has been implemented with some interdependencies among the SWB package and associated packages WELX and STRX:

1. Runoff simulated by Swat is specified as tributary inflows to the stream network with STRX;
2. Irrigation demand simulated by Swat is supplied with pumping from both surface and ground water points of diversion with WELX.

Some additional modeling capabilities have been incorporated in these packages that are described in the input instructions for the respective packages.

*.swb input file:

For each simulation (Read items 1-7 once to initialize linkage, then item 8 each time step):

<Open *.swb input file>

SWB2AL (allocate memory requirements at the beginning of the simulation):

```
1. Data (FREE):      nwshed
```

SWB2RP (data read in the first stress period):

```
2. Data (FREE):      irropt,ievopt,ioprch,rchmpy,welmpy,iadcod,frseep

3. Data (TEXT)       (heading: data to associate subbasin outflows with stream reaches)
  do j=1,nwshed
    Data (FREE):     idx,isact,irow,icol,isbnxt
  end do

4.Data (U2DINT):     locat, iconst, fmtbnd, iprn  (U2DINT: MODFLOW arrays)
  Format:            (2i10,a20,i10)
 do ir=1,nrow
    Data:            (ibshed(ic,ir),ic=1,ncol)  (subbasin-grid association)
    Format:          specified by fmtbnd (above)
```

end do

<Close *.swb input file>
<Open *.bal input file>

*.bal input file:

```
      SWB2RP (continued from above):
1. Data (FREE):      nyrs iopmod  bsarea  fpd  Idxhru  Numhru  (Namhru)

2. Data (TEXT)       (heading for the following)
  do j=1,nwshed
    Data (FREE):     idx,subfrc(j),pndfrc(j),
                     wthru(j),soilwt(j),cropwt(j), isolhr, iusehr
  end do

3. Data (TEXT)       (heading for the following)
            SWB2FM (data read for each time step):
   do j=1,nwshed
   Data (FREE):      iyr imon ndays, (shed(i,j),i=10,22),
                     shed(6,j), shed(5,j), wthru(j)
```

Definitions: Soil Water Balance input file (*.swb)

1. nwshed: number of subbasins in watershed

2. Options for irrigation, evaporation, recharge, scenarios; sensitivity analysis.

irropt = option (y>0,n=0) to specify irrigation pumping rates for both ground and surface water diversions with results of watershed simulation.

=1: Scale Qapp, appropriations for irrigation diversions within each subbasin, by the total irrigation demand for the subbasin according to the watershed simulation; i.e., apply the scaling factor s = Qirr/Qapp to the appropriated rate of each individual diversion.

=2: define scaling factor in terms of totals for entire basin rather than individual subbasins.

ievopt = option (y=1,n=0) to specify potential evap from groun surface (array EVTR in MODFLOW's EVT package) with the potential evaporation flux from watershed simulation. (applicable if MODFLOW's EVT package is invoked): if ievopt > 0, evaporation from the water table is controlled by potential evaporation at ground surface as calculated by Swat. Otherwise (ievopt ≤ 0), potential evaporation is specified by standard Modflow input to array evtr in the EVT module.

ioprch = option for distributing recharge over grid cells:

=0: use recharge as read into the recharge array RECH at the beginning of the stress period. This option is also applied to grid cells not associated with a subbasin, i.e., those cells for which isub = ibshed(icol,irow)=0 (see definition of array ibshed, below).

>0: distribute recharge specified by shed(17,isub) over grid cells of the subbasin according to a spatial distribution that is specified in by the initial recharge array RECH for the first stress period in MODFLOW's Recharge package. The spatial distribution Rchdst is evaluated in terms of the array RECH by subr. SWB2RCH, and is normalized so that the elements of Rchdst add to one when summed over the active grid cells within each subbasin.

rchmpy = multiplier to be applied to recharge array for sensitivity analysis; to leave the recharge array unchanged, set `rchmpy = 1`.

welmpy = multiplier to be applied to pumping rates for sensitivity analysis and for water use scenarios specified by the scenario code **iadcod**, below; to leave pumping rates unchanged, set **welmpy** = 1.

iadcod = administrative option scenario code for irrigation water use scenarios; applied by subroutine USEMGT to groundwater diversions in subr WELZ2FM of the modified WELL package. USEMGT uses the scenario codes **iadcod**, and how they are used in conjunction with the multiplier **welmpy** (above) and input data for the diversion points passed from the modified WELL package that specifies the distance from diversion point to stream, **dsstrm**, and application number, **iappno**.

frseep = fraction of "evaporation from shallow ground water" to be treated as seepage face flow to the stream channel. This is performed by subr. EVT2STR in the MODSWB package, called from Modflo(), the main subroutine. Frseep is read by subr SWB2RP from the MODSWB input file.

This is an experimental option applied to HRU scheme 2 for an ad hoc partitioning of "evaporation from shallow ground water" between a component of seepage face flow to streams for grid cells coupled to stream reaches, and the remainder which, in the case of HRU scheme 2, is assumed to disappear by evaporation, whereas in scheme 3 it is redistributed over the soil profile by the coupling of Swat and Modflow, so that irrigated crop requirements are apparently supplied in part by uptake from shallow ground water. This option is not operational for a coupled simulation as in HRU scheme 3, for which the seepage face flow to the stream network would presumably be subtracted from the water that is to be redistributed over the soil profile.

iwtsub (dropped) = option (Walnut Creek) to scale irrig. diversions according to simulated irrigation for either (=0) the total basin or (>0) individual subbasins. For the Republican River basin model, scale for the total basin.

3. Association between subbasin outflows and grid cells corresponding to stream reaches defined by the STREAM package. After a header record, the following columns of data are read:

idx subbasin index from 1 to nwshed subbasins

isact indicates whether (y=1,n=0) index refers to an active subbasin, i.e., whether data are to be read for this subbasin index in each time step in SWB2FM; isact is stored in ished(1,idx). The sum of isact over all subbasins gives the number of "active" subbasins; the remainder are just placeholders.

(irow,icol) grid location assigned for subbasin runoff to stream network; irow and icol are stored in ished(4,idx) and ished(5,idx).

isbnxt next subbasin in lateral flow routing sequence; stored in ished(3,idx).

A stream reach corresponding to the grid location (irow,icol) must be defined as part of the stream network in Modstr, the modified Stream package.

4. **ibshed** array: association between subbasins and grid cells of aquifer. This is a 2-D integer array that is read by MODFLOW's U2DINT subroutine (see Modflow manual); also used to read MODFLOW's **ibound** array from the Basic package input file. Each nonzero entry in the array is an index, j, in the range [1, nwshed], associating the grid cell with subbasin j.

<u>Definitions: Balance input file (*.bal)</u>

1. Summary of options specified in Swat's Control Codes (*.cod) file: No. years; time step and hydrologic flux conversion options; basin area and noncontributing fraction; HRU index, total number, and name.

nyrs = no. years of simulation as specified in Swat's Control Codes (*.cod) input file; should agree with no. stress periods, nper, in basic package input file.
iopmod = time step option (0=avg annual, 1=annual, 2=monthly, 3=daily)
bsarea = basin area, Modflow's units; Swat units are km^2.
fpd = noncontributing fraction of basin
idxhru = index to HRU (see list on modified Swat input file *.cod)
numhru = total number of HRUs
namhru = name of HRU corresponding to idxhru.

2. read (FREE) for each subbasin: areal fractions for subbasin; initial HRU fraction; identifiers for soil type and land use associated with the HRU.

idx = subbasin index
fract = subbasin area as fraction of basin
noncontrib = noncontributing fraction of basin, i.e., fraction of subbasin area that drains to ponds.
swinit = initial soil water content (mm)
pndinit = initial pond volume (cu. m)
wthru = initial HRU weight based on soil and land use area fractions:
soilwt = initial HRU's soil areal fraction
cropwt = initial HRU's crop (land use) areal fraction
isolhr = index to HRU's soil type
iusehr = index to HRU's crop (land use)

SWB2FM

3. Summary of Swat's simulation for each active subbasin j (isact > 0) in each time step:

icalyr,imo,ndays,isub, (shed(i,j),i=10,22),shed(6,j),shed(5,j), wthru(j)

icalyr: calendar year
imo: month
ndays: number of days in time step
isub: subbasin index

shed(5,j), shed(6,j), and (shed(i,j),i=10,22) are flow rates in Modflow's units, e.g. cfs.
i= 5: time rate of change in pond storage
i= 6: time rate of change in soil water storage
i=10: (Overall balance): precipitation

i=11: (Input): irrigation
i=12: (Overall balance): "actual" evaporation
i=13: surface runoff
i=14: transmission losses along ephemeral stream channels
i=15: subsurface lateral flow
i=16: percolation out of root zone to ground water
i=17: (Input): ground water recharge, given by sum of transmission losses(15), percolation(16), and pond seepage(20).
i=18: (Output): evaporation from shallow ground water, calculated in Modflow's Evaporation package; uses potential evaporation rate(20) as maximum.
i=19: (Output): baseflow, calculated in modified Stream package.
i=20: pond seepage
i=21: (Input): potential evaporation
i=22: (Input): tributary flow, given by sum of surface runoff(13) and subsurface lateral flow(15) in subr. Preswb called by Swat.
wthru(j): HRU weight for subbasin j, given by product of areal fractions for corresponding soil type and land use fraction according to the Control Codes input file (above).

Definitions of other vectors in the Shed(i,j) array for subbasins j=1 to nwshed:

(1) **Areal frc** areal fraction of subbasin; read in SW1RP.
(2) area[L^2] area of subbasin [L^2]: product of bsarea and (1); SWB1RP.
(3) **GrdArea[L^2]** gridded subbasin area; see also (7); SWB1RP.
(4) **Irr_use[L]** irrigation [L^3/T]: total irrigation pumping accumulated for each subbasin from WELL module input at beginning of each stress period; SWB1RP.
(5)
(6)
(7) **AreGrd/Act** gridded active subbasin area as fraction of actual subbasin area, (3)/(2); SWB1RP; passed back to SWAT to be written in the balance file (~.bal) by HYDBAL in a combined SWAT-MODFLOW run (iopswt>0).
(8) **Pond fract** noncontributing areal fraction of subbasin, which contributes instead to ponds; read from ~.balance file; SWB1FM.
(9) **Irr_use** irrigation flux based on total pumping in subbasin for the stress period, (4); SWB1RP.
i=23: (Output): depth to water [L]
i=24: (Output): Irrigation assigned in Modflow: includes both surface and ground water components.
i=25: (Output): Recharge specified by Swat for subbasins with no aquifer and which is not assigned to a downstream subbasin.

Definition of vectors in integer watershed subbasin array ished(10,mxshed):

```
(1) isact: 1 indicates active subbasin.
(2) istrec:  index to record for stream segment, reach.
(3) device number for reading subbasin hydrograph file
(4) soil id for subbasin
(5) no. soil layers for subbasin
(6) no. cells in each subbasin with nonzero value for ibound(ic,ir,1); evaluated in subr
SHALLOW as vector numshd(*), and corresponds to gridded area of each subbasin given by
shed(3,*).
(7) subset of ished(6,*) w/ shallow gw, defined by (dtw(ic,ir) < exdp(ic,ir), where exdp =
extinction depth, defined in MODEVT; ished(7,*) is evaluated in subr SHALLOW as vector nshzon.
(10) no. pumping wells (Qw < 0)in each subbasin for the stress period
```

Definition of array SHED in SWBX for Swat-Modflow data transfer

Swat's hydrologic summary is expressed as a depth (mm) accumulated over the number of days in the aquifer time step, dtswat. The hydrologic summary in vectors 10-20 of array SHED is obtained either directly from arrays in Swat (through Hydbal subroutine Swt2mod) in the case of a linked Swat-Modflow run (**iopswt** > 0), or from a balance file written by Swat and read by Modswb subroutine Swb1fm.

(18)GW ET mm evaporation from water table ("revap" in Swat); the value from SWAT is superseded by results from MODFLOW's EVT package, summarized in SWB1BD.

(19)Baseflow mm baseflow; the value from SWAT is superseded by the negative of streambed leakage, calculated by MODFLOW's STREAM package and summarized for watershed subbasins in SWB1BD.

(20)PndSeep mm pond seepage into aquifer

(21) **POT ET mm** potential et; used to define maximum evaporation rate from water table if EVT is invoked; see options iopet and ievopt.

(22) **Tribflow mm** tributary inflow to streams from subbasins given by the contributing sum of surface and subsurface runoff. Defining c = 1 - pond fraction(8),

Qtrib(22) =c*[SURQ(13) + LATQ(15)]

unless **jkkopt** > 0; SWB1FM.

(23) **DTW [L]** avg depth to water for shallow nodes if EVT is invoked; SWB1BD.

(25) **Recharge mm** groundwater recharge flux is defined for MODFLOW by the sum

RchMod(25) =xmloss(14) +perc(16) +pond seepage(20)

unless **jkkopt** > 0; SWB1FM.

(26) **RchInp mm** recharge depth (mm) corresponding to initial array RECH as read from Modflow input file if ioprch > 0; flux is for initial time step duration, **delt0**, and with respect to area of active nodes in subbasin; SWB1FM.

Example: input file rptest96.swb (data items 1-4) for Republican River Basin

```
 9, nwshed                                                                      (1)
    1    3    1    1 0.00    1    0 0.0   irropt,ievopt,ioprch,rchmpy,
                                              evapir,welmpy,iadcod,frseep       (2)
   sub  act  row col sbnxt     tributary                                        (3)
    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       (4)
 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 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 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 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 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 3 5 5 5 3 7 7 7 7 7 7 9 9 9
```

2	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	3	7	7	7	7	7	9	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	3	3	7	7	7	7	9	9	9	9	9
0	0	0	0	0	0	0	0	2	2	2	2	3	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	0	3	3	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	3	8	8	3	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	3	3	8	8	8	8	8	8	3	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	3	8	8	8	8	8	8	8	8	8	3	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	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	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	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	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	0	8	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	0	0	8	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	0	0	0	8	8	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	0	0	0	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0

Example: input file rptest.bal (data items 1-3) for Republican River Basin

```
18    2   27658944500. 0.0199367   18   18 rptest                        (1)
  sub sub fract noncontrb   sw,mm   pond vol sum HRU fracts               (2)
    1 0.2201500 0.0343000  212.01     388068. 1.0000000
    2 0.0490900 0.0031000  191.57      85943. 0.9990000
    3 0.2043500 0.0064000  269.54     117622. 0.9999999
    4 0.0872900 0.0268000  224.17      90259. 1.0010002
    5 0.0528200 0.0021000  274.68      28503. 1.0000000
    6 0.0824700 0.0000000  241.92          0. 0.9999999
    7 0.1094500 0.0131000  290.13      36806. 0.9990000
    8 0.1178800 0.0413900  231.15     376117. 1.0000000
    9 0.0764900 0.0282700  297.42     166526. 0.9990000                   (3, below:)
```

Year	mon	days	delt (sec)	sub	precip	irrig	ETact	runoff	XMloss	QLAT	PERC	recharg	et-gw	baseflo	pondsep	ETpot	tribflo	dSW/dt	dPND/dt	HRU fract
1977	1	31	2678400.	1	138.73	0.00	98.43	33.89	1.71	0.03	24.19	31.91	0.00	0.00	6.01	100.38	33.91	-16.40	-3.12	1.0000000
1977	1	31	2678400.	2	27.25	0.00	18.34	1.16	0.77	0.00	13.68	15.60	0.00	0.00	1.15	18.60	1.17	-5.26	-1.13	0.9990000
1977	1	31	2678400.	3	113.54	0.00	79.34	14.39	3.73	0.00	4.95	10.42	0.00	0.00	1.75	80.37	14.39	18.35	-1.55	0.9999999
1977	1	31	2678400.	4	48.55	0.00	37.42	11.13	1.91	0.00	1.60	5.14	0.00	0.00	1.63	38.08	11.13	0.21	-1.15	1.0010002
1977	1	31	2678400.	5	28.27	0.00	14.92	3.45	0.66	0.00	0.00	1.05	0.00	0.00	0.40	14.98	3.45	10.50	-0.38	1.0000000
1977	1	31	2678400.	6	44.15	0.00	22.92	4.56	0.68	0.00	0.00	0.68	0.00	0.00	0.00	23.05	4.56	17.24	0.00	0.9999999
1977	1	31	2678400.	7	58.53	0.00	36.38	5.61	1.34	0.00	0.00	1.34	0.00	0.00	0.00	36.76	5.61	17.70	0.39	0.9990000
1977	1	31	2678400.	8	104.64	0.00	38.02	28.98	0.93	0.01	17.75	25.25	0.00	0.00	6.57	38.39	29.00	20.59	-4.77	1.0000000
1977	1	31	2678400.	9	67.83	0.00	19.88	20.85	0.75	0.01	12.59	16.02	0.00	0.00	2.68	20.25	20.87	15.09	-1.88	0.9990000
1977	2	28	2419200.	1	4.13	0.00	174.52	0.00	0.00	0.00	12.13	14.27	0.00	0.00	2.14	333.08	0.00	-182.53	-2.21	1.0000000
1977	2	28	2419200.	2	1.47	0.00	43.10	0.00	0.00	0.00	1.32	1.32	0.00	0.00	0.00	70.38	0.00	-42.95	0.00	0.9990000
1977	2	28	2419200.	3	6.13	0.00	172.01	0.00	0.00	0.01	10.94	10.94	0.00	0.00	0.00	271.80	0.01	-176.83	0.00	0.9999999
1977	2	28	2419200.	4	2.62	0.00	73.92	0.00	0.00	0.00	1.37	1.41	0.00	0.00	0.04	138.04	0.00	-72.67	-0.04	1.0010002
1977	2	28	2419200.	5	3.96	0.00	54.67	0.00	0.00	0.01	6.40	6.40	0.00	0.00	0.00	82.79	0.01	-57.12	0.00	1.0000000
1977	2	28	2419200.	6	6.19	0.00	80.44	0.00	0.00	0.00	3.54	3.54	0.00	0.00	0.00	131.84	0.00	-77.79	0.00	0.9999999
1977	2	28	2419200.	7	8.20	0.00	101.58	0.00	0.00	0.00	1.16	1.16	0.00	0.00	0.00	149.93	0.00	-94.54	-0.03	0.9990000
1977	2	28	2419200.	8	3.54	0.00	108.38	0.00	0.00	0.01	15.31	15.50	0.00	0.00	0.20	187.05	0.01	-120.16	-0.20	1.0000000
1977	2	28	2419200.	9	2.30	0.00	70.24	0.00	0.00	0.00	13.60	13.94	0.00	0.00	0.34	119.77	0.00	-81.55	-0.35	0.9990000
1977	3	31	2678400.	1	572.08	0.00	377.73	95.19	3.84	0.03	25.85	30.74	0.00	0.00	1.04	659.67	95.22	77.12	2.29	1.0000000
1977	3	31	2678400.	2	87.06	0.00	69.30	11.83	1.26	0.00	2.42	3.72	0.00	0.00	0.03	143.99	11.83	4.78	0.00	0.9990000
1977	3	31	2678400.	3	362.79	0.00	315.88	62.85	5.52	0.01	5.92	11.65	0.00	0.00	0.21	621.68	62.86	-16.35	0.14	0.9999999
1977	3	31	2678400.	4	155.12	0.00	122.97	24.20	2.08	0.01	4.94	7.18	0.00	0.00	0.16	247.58	24.21	5.08	0.42	1.0010002
1977	3	31	2678400.	5	138.69	0.00	98.77	29.52	0.92	0.00	2.71	3.68	0.00	0.00	0.05	174.79	29.52	8.60	0.01	1.0000000
1977	3	31	2678400.	6	216.54	0.00	141.87	47.54	1.15	0.00	7.50	8.65	0.00	0.00	0.00	260.21	47.54	20.78	0.00	0.9999999
1977	3	31	2678400.	7	287.09	0.00	190.06	68.28	3.48	0.00	6.94	10.42	0.00	0.00	0.00	351.33	68.28	25.30	0.67	0.9990000
1977	3	31	2678400.	8	238.83	0.00	164.97	38.05	1.67	0.01	8.91	11.37	0.00	0.00	0.79	419.09	38.05	28.57	0.90	1.0000000
1977	3	31	2678400.	9	154.82	0.00	108.11	27.50	1.60	0.00	4.29	6.18	0.00	0.00	0.29	262.03	27.51	16.51	0.48	0.9990000
1977	4	30	2592000.	1	483.25	0.00	737.64	21.74	2.84	0.03	36.75	42.51	0.00	0.00	2.92	1046.63	21.77	-310.06	-2.37	1.0000000
1977	4	30	2592000.	2	103.70	0.00	147.53	3.33	0.99	0.00	5.89	6.89	0.00	0.00	0.01	208.19	3.33	-52.05	0.00	0.9990000
1977	4	30	2592000.	3	432.11	0.00	640.14	17.09	5.28	0.02	26.77	32.31	0.00	0.00	0.26	870.20	17.10	-246.63	-0.15	0.9999999
1977	4	30	2592000.	4	184.76	0.00	262.84	7.01	1.56	0.02	12.00	14.13	0.00	0.00	0.57	366.33	7.03	-95.54	-0.44	1.0010002
1977	4	30	2592000.	5	121.86	0.00	190.95	14.42	0.86	0.00	6.45	7.34	0.00	0.00	0.03	247.21	14.42	-89.11	-0.01	1.0000000
1977	4	30	2592000.	6	190.27	0.00	267.69	25.44	0.95	0.00	13.12	14.07	0.00	0.00	0.00	369.26	25.45	-115.04	0.00	0.9999999
1977	4	30	2592000.	7	252.26	0.00	386.16	34.26	3.04	0.00	15.75	18.79	0.00	0.00	0.00	506.39	34.27	-180.87	-0.42	0.9990000
1977	4	30	2592000.	8	392.88	0.00	374.61	48.55	1.74	0.02	42.04	46.70	0.00	0.00	2.92	518.67	48.57	-70.60	-0.93	1.0000000
1977	4	30	2592000.	9	254.68	0.00	247.18	33.97	1.61	0.01	28.89	31.81	0.00	0.00	1.31	347.84	33.98	-53.78	-0.41	0.9990000
1977	5	31	2678400.	1	1006.93	0.00	818.13	108.77	5.40	0.07	68.47	76.04	0.00	0.00	2.16	1191.53	108.84	16.89	1.41	1.0000000
1977	5	31	2678400.	2	253.72	0.00	179.08	28.69	2.94	0.02	25.63	28.66	0.00	0.00	0.09	259.40	28.70	23.25	0.00	0.9990000
1977	5	31	2678400.	3	1057.20	0.00	836.02	124.64	13.91	0.04	64.08	78.66	0.00	0.00	0.67	1067.22	124.68	46.33	0.11	0.9999999
1977	5	31	2678400.	4	452.04	0.00	329.02	53.63	4.12	0.06	36.15	41.11	0.00	0.00	0.84	460.06	53.69	37.31	0.52	1.0010002
1977	5	31	2678400.	5	357.37	0.00	235.48	66.12	1.97	0.03	18.36	20.46	0.00	0.00	0.14	289.18	66.15	39.35	0.00	1.0000000
1977	5	31	2678400.	6	557.98	0.00	328.72	120.84	2.34	0.03	41.67	44.01	0.00	0.00	0.00	448.77	120.86	69.08	0.00	0.9999999
1977	5	31	2678400.	7	739.78	0.00	458.67	156.56	6.67	0.02	39.62	46.29	0.00	0.00	0.00	567.90	156.58	91.57	0.52	0.9990000
1977	5	31	2678400.	8	718.08	0.00	422.98	199.56	3.02	0.04	68.75	74.81	0.00	0.00	3.03	637.09	199.60	29.78	5.55	1.0000000
1977	5	31	2678400.	9	465.48	0.00	293.74	129.06	2.50	0.02	38.49	42.20	0.00	0.00	1.22	427.75	129.09	6.67	2.49	0.9990000
1977	6	30	2592000.	1	1445.90	1.70	1087.68	362.87	7.33	0.10	67.26	78.43	0.00	0.00	3.84	1412.20	362.98	-63.00	6.00	1.0000000
1977	6	30	2592000.	2	219.59	0.70	221.19	47.03	2.21	0.01	11.18	13.53	0.00	0.00	0.14	305.09	47.04	-56.91	0.00	0.9990000
1977	6	30	2592000.	3	915.02	0.53	1044.10	201.20	7.76	0.02	33.07	41.70	0.00	0.00	0.87	1357.04	201.23	-355.09	0.35	0.9999999

1977	6	30	2592000.	4	391.25	1.00	406.07	88.23	2.99	0.04	20.78	24.98	0.00	0.00	1.22	551.60	88.27	-119.88	0.75	1.0010002
1977	6	30	2592000.	5	152.19	0.28	290.40	13.41	0.66	0.00	5.23	5.91	0.00	0.00	0.03	357.88	13.41	-155.90	0.00	1.0000000
1977	6	30	2592000.	6	237.62	1.08	437.20	23.67	0.79	0.00	11.33	12.12	0.00	0.00	0.00	550.94	23.67	-232.72	0.00	0.9999999
1977	6	30	2592000.	7	315.04	0.17	639.29	30.98	2.03	0.00	15.23	17.27	0.00	0.00	0.00	780.75	30.98	-368.26	-0.44	0.9990000
1977	6	30	2592000.	8	547.23	1.37	695.53	89.66	2.25	0.01	9.67	17.75	0.00	0.00	5.83	825.27	89.67	-244.01	-2.59	1.0000000
1977	6	30	2592000.	9	354.73	0.11	456.67	66.59	2.01	0.00	6.55	10.91	0.00	0.00	2.36	532.01	66.60	-172.97	-0.83	0.9990000
1977	7	31	2678400.	1	763.03	32.81	808.93	158.77	2.46	0.03	18.33	25.77	0.00	0.00	4.97	1711.83	158.80	-187.77	-0.78	1.0000000
1977	7	31	2678400.	2	98.36	6.83	185.71	0.38	0.25	0.00	0.00	0.26	0.00	0.00	0.00	366.05	0.38	-80.64	0.00	0.9990000
1977	7	31	2678400.	3	409.87	27.19	822.54	0.83	0.66	0.00	0.00	1.05	0.00	0.00	0.40	1582.05	0.83	-385.66	-0.45	0.9999999
1977	7	31	2678400.	4	175.26	12.92	345.48	0.62	0.42	0.00	0.00	1.36	0.00	0.00	0.93	692.07	0.62	-157.51	-1.07	1.0010002
1977	7	31	2678400.	5	136.18	9.38	173.48	10.74	0.54	0.00	0.00	0.56	0.00	0.00	0.02	420.70	10.75	-38.12	0.00	1.0000000
1977	7	31	2678400.	6	212.63	16.06	294.07	16.14	0.57	0.00	0.04	0.61	0.00	0.00	0.00	678.88	16.14	-81.00	0.00	0.9999999
1977	7	31	2678400.	7	281.91	20.66	405.24	22.72	1.43	0.00	0.00	1.44	0.00	0.00	0.00	900.72	22.72	-123.97	0.02	0.9990000
1977	7	31	2678400.	8	213.67	20.82	446.73	27.50	0.61	0.00	0.10	4.22	0.00	0.00	3.51	963.18	27.51	-239.24	-3.03	1.0000000
1977	7	31	2678400.	9	138.50	12.06	360.91	17.19	0.54	0.00	0.00	2.25	0.00	0.00	1.70	618.98	17.19	-227.01	-1.52	0.9990000
1977	8	31	2678400.	1	2041.45	2.00	943.32	641.60	7.45	0.19	136.34	149.87	0.00	0.00	6.09	1334.31	641.80	329.44	5.73	1.0000000
1977	8	31	2678400.	2	452.77	1.28	193.98	102.60	3.71	0.03	26.98	31.03	0.00	0.00	0.35	257.59	102.62	134.18	0.00	0.9990000
1977	8	31	2678400.	3	1886.63	4.75	817.69	378.65	15.71	0.09	19.14	36.22	0.00	0.00	1.38	1098.30	378.73	691.52	1.20	0.9999999
1977	8	31	2678400.	4	806.70	1.50	362.14	177.09	4.90	0.11	35.92	42.34	0.00	0.00	1.52	488.28	177.19	237.85	2.22	1.0010002
1977	8	31	2678400.	5	502.33	0.11	221.13	91.57	1.93	0.05	8.19	10.33	0.00	0.00	0.20	320.08	91.62	183.43	0.00	1.0000000
1977	8	31	2678400.	6	784.30	0.20	349.88	153.34	2.21	0.05	35.06	37.27	0.00	0.00	0.00	469.33	153.39	248.39	0.00	0.9999999
1977	8	31	2678400.	7	1039.85	0.03	441.62	182.52	6.47	0.05	4.76	11.23	0.00	0.00	0.00	612.57	182.56	417.40	0.77	0.9990000
1977	8	31	2678400.	8	1341.91	4.47	525.15	380.50	3.24	0.06	57.83	65.08	0.00	0.00	4.01	715.64	380.57	386.06	10.96	1.0000000
1977	8	31	2678400.	9	869.87	2.10	344.30	209.48	2.47	0.03	6.27	10.32	0.00	0.00	1.57	451.58	209.51	314.36	3.92	0.9990000
1977	9	30	2592000.	1	534.89	1.04	651.03	41.92	3.78	0.04	50.12	59.97	0.00	0.00	6.08	1021.26	41.96	-203.41	-7.81	1.0000000
1977	9	30	2592000.	2	89.45	0.00	137.61	11.08	0.78	0.00	7.56	8.38	0.00	0.00	0.03	230.02	11.09	-66.03	0.00	0.9990000
1977	9	30	2592000.	3	372.73	0.00	559.32	46.68	4.02	0.02	5.50	10.92	0.00	0.00	1.40	994.81	46.70	-234.77	-1.21	0.9999999
1977	9	30	2592000.	4	159.38	0.00	245.05	18.95	1.14	0.02	7.40	10.24	0.00	0.00	1.70	427.76	18.98	-110.91	-1.63	1.0010002
1977	9	30	2592000.	5	155.33	0.00	142.07	25.74	0.77	0.02	5.38	6.21	0.00	0.00	0.06	254.57	25.76	-17.11	0.00	1.0000000
1977	9	30	2592000.	6	242.53	0.00	246.56	36.25	0.80	0.02	11.15	11.95	0.00	0.00	0.00	387.85	36.27	-50.64	0.00	0.9999999
1977	9	30	2592000.	7	321.55	0.00	316.50	52.21	2.56	0.02	8.33	10.89	0.00	0.00	0.00	532.97	52.23	-52.95	-0.85	0.9990000
1977	9	30	2592000.	8	355.33	0.00	377.76	40.95	2.00	0.04	60.91	69.97	0.00	0.00	7.05	580.29	40.98	-122.32	-7.31	1.0000000
1977	9	30	2592000.	9	230.34	0.00	258.01	23.44	1.46	0.02	31.56	35.71	0.00	0.00	2.70	371.12	23.46	-81.24	-2.98	0.9990000
1977	10	31	2678400.	1	366.22	0.00	362.39	80.62	1.30	0.02	28.94	35.30	0.00	0.00	5.06	698.32	80.64	-104.45	-2.62	1.0000000
1977	10	31	2678400.	2	93.55	0.00	85.06	6.68	0.64	0.00	4.14	4.80	0.00	0.00	0.02	146.82	6.68	-1.70	0.00	0.9990000
1977	10	31	2678400.	3	389.79	0.00	360.25	35.12	3.61	0.01	8.69	12.56	0.00	0.00	0.26	600.27	35.13	-10.67	-0.03	0.9999999
1977	10	31	2678400.	4	166.67	0.00	146.15	12.99	0.94	0.01	6.52	8.56	0.00	0.00	1.10	240.19	13.00	1.94	-0.77	1.0010002
1977	10	31	2678400.	5	114.53	0.00	101.55	24.54	0.43	0.01	7.33	7.81	0.00	0.00	0.05	183.17	24.54	-18.45	0.00	1.0000000
1977	10	31	2678400.	6	178.82	0.00	165.16	31.52	0.48	0.01	10.00	10.48	0.00	0.00	0.00	260.86	31.52	-27.38	0.00	0.9999999
1977	10	31	2678400.	7	237.08	0.00	217.96	49.46	1.44	0.01	13.29	14.73	0.00	0.00	0.00	358.25	49.47	-42.19	0.03	0.9990000
1977	10	31	2678400.	8	252.81	0.00	236.59	43.40	0.68	0.01	11.32	16.79	0.00	0.00	4.79	386.04	43.40	-37.82	-3.16	1.0000000
1977	10	31	2678400.	9	163.88	0.00	166.10	28.84	0.59	0.00	6.14	8.26	0.00	0.00	1.53	240.04	28.85	-36.62	-0.78	0.9990000
1977	11	30	2592000.	1	454.73	0.00	193.73	121.25	2.03	0.02	19.04	25.01	0.00	0.00	3.93	333.20	121.26	122.74	0.06	1.0000000
1977	11	30	2592000.	2	75.54	0.00	49.37	8.55	0.59	0.00	4.86	5.47	0.00	0.00	0.03	82.36	8.55	13.35	0.00	0.9990000
1977	11	30	2592000.	3	314.78	0.00	217.01	44.85	2.29	0.01	13.14	15.72	0.00	0.00	0.27	333.28	44.86	42.07	0.00	0.9999999
1977	11	30	2592000.	4	134.59	0.00	92.62	16.29	0.75	0.01	8.64	9.85	0.00	0.00	0.45	130.21	16.30	17.79	-0.04	1.0010002
1977	11	30	2592000.	5	80.81	0.00	51.45	23.91	0.43	0.00	5.17	5.65	0.00	0.00	0.05	100.61	23.92	0.70	0.00	1.0000000
1977	11	30	2592000.	6	126.17	0.00	78.27	31.51	0.45	0.00	6.83	7.28	0.00	0.00	0.00	159.26	31.51	10.00	0.00	0.9999999
1977	11	30	2592000.	7	167.28	0.00	106.37	48.19	1.40	0.00	9.78	11.18	0.00	0.00	0.00	209.04	48.19	4.34	-0.08	0.9990000
1977	11	30	2592000.	8	189.84	0.00	114.62	35.79	0.93	0.01	10.24	13.26	0.00	0.00	2.09	199.91	35.79	30.13	-0.77	1.0000000
1977	11	30	2592000.	9	123.06	0.00	75.51	23.21	0.84	0.00	5.39	7.37	0.00	0.00	1.13	133.10	23.21	19.78	-0.53	0.9990000
1977	12	31	2678400.	1	3.73	0.00	98.93	0.00	0.00	0.00	0.00	2.00	0.00	0.00	2.00	191.47	0.00	-95.20	-2.05	1.0000000
1977	12	31	2678400.	2	1.83	0.00	22.10	0.00	0.00	0.00	0.08	0.08	0.00	0.00	0.00	43.11	0.00	-20.68	0.00	0.9990000
1977	12	31	2678400.	3	7.62	0.00	92.46	0.00	0.00	0.00	3.90	3.90	0.00	0.00	0.00	192.56	0.00	-90.17	0.00	0.9999999
1977	12	31	2678400.	4	3.25	0.00	39.95	0.00	0.00	0.00	1.29	1.29	0.00	0.00	0.00	80.85	0.00	-38.57	0.00	1.0010002
1977	12	31	2678400.	5	0.00	0.00	20.73	0.00	0.00	0.00	0.38	0.38	0.00	0.00	0.00	49.63	0.00	-21.11	0.00	1.0000000
1977	12	31	2678400.	6	0.00	0.00	32.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	67.73	0.00	-32.31	0.00	0.9999999
1977	12	31	2678400.	7	0.00	0.00	42.59	0.00	0.00	0.00	0.74	0.74	0.00	0.00	0.00	102.60	0.00	-43.33	-0.22	0.9990000
1977	12	31	2678400.	8	2.40	0.00	52.85	0.00	0.00	0.00	0.37	0.37	0.00	0.00	0.00	103.09	0.00	-50.82	0.00	1.0000000
1977	12	31	2678400.	9	1.55	0.00	33.64	0.00	0.00	0.00	0.63	0.63	0.00	0.00	0.00	77.24	0.00	-32.73	0.00	0.9990000

5.4. STRX: modified Stream package

Input data differences in STRX from the STREAM package (Prudic, 1989)

Changes to the STREAM package (Prudic, 1989) are summarized as follows.

1) As the first record of each stream reach is read in STR2RP, an indexing array, Idxstr, is defined that allows directly referencing each stream reach in terms of the aquifer grid cell coordinates (icol, irow, ilay).

2) The Stream package was modified to allow inflow data to be specified for each time step within a stress period without having to specify a complete set of data as described for the standard options (see Numinp).

3) The standard package requires streambed conductance C to be read for each reach based on an assumed rectangular channel geometry with steady flow. Alternatively (for irdcnd > 0), streambed hydraulic conductivity K' and reach length L may also be read and used to calculate conductance, C, given by $C = K' \cdot L \cdot P / b'$, where:

K' = streambed saturated hydraulic conductivity;

L = stream reach length;

P = wetted perimeter;

b' = streambed thickness.

4) Stream channel geometry can be specified as trapezoidal (icalc=2), in which case reciprocal side slope is read, or as natural, using power functions to represent stream channel characteristics (icalc=3). In either case, a modified version of Prudic's stream routing procedure (subr STR1DW) is used. The natural channel option is used for the Wet Walnut Creek model (Ramireddygari et al., 2000), in which data from USGS gaging stations at Alexander, Nekoma, and Albert were compared. Those for the Albert station were found to represent measurements at all three stations satisfactorily, and are used to approximate stream depth, width, and cross sectional area as functions of flow rate for all reaches of the stream network.

5) The Stream package was modified to incorporate a diffusive wave routing option, although this option is limited to experimental use, for which it was designed and has been applied (Perkins and Koussis, 1996).

Input data changes from the standard STR package in STRX

(subroutines STR2AL, STR2RP, STR2STP, STR2FM, STR2BD)

Record 1:
Additional items Iopstr, Itoprc, Ibotrc, and Adjbed are read.

Iopstr specifies whether the standard (STR) or modified (STRX) version of the Stream package is to be used as follows:
- If iopstr = 0 and neither the SWBX package nor the WELX package have been invoked, then the standard Stream package (STR) subroutines are called except for STR2AL; however, arrays are dimensioned the same as for the standard package.
- Otherwise (iopstr > 0 or either of the SWBX and WELX packages is invoked), subroutines in the modified STRX package are called in place of the standard package routines.

Itoprc, Ibotrc: identified as top and bottom reaches of the main channel; the difference in their outflow is taken to represent stream yield for the basin.
Adjbed: change that is to be applied to bottom elevation for every stream reach of the network: a calibration adjustment.

Record 2:
itmp > or = 0: no. reaches active during the current stress period;
 = -1: use stream data from the previous stress period;
 = -2: except for NUMINP stream nodes, use stream data from the previous stress period.

numinp: This option allows stream inflows to be updated in each time step. If ITMP = -2 (above), then for each time step of a stress period (step 1 in STR2RP and remaining steps in STR2STP), streamflow data are read for NUMINP stream nodes, in the standard format used for the first six variables in the first record read for each reach, as follows:

```
READ(IN,'(5i5,f15.0)') ilay, irow, icol, iseg, irch, strflo
```

irdcnd: stream channel geometry options.
If irdcnd = 0 (default): streambed conductance, C, is applied as read from the first record for each reach. As described in the STREAM manual, a rectangular channel with steady flow is assumed, and input data values for streambed conductance is approximated by

$$C = Ks*Ls*P/T = strm(3,*),$$

where:

Ks = streambed saturated hydraulic conductivity;
Ls = stream reach length;

P = wetted perimeter;
T = strm(5,*)-strm(4,*) = streambed thickness.

If irdcnd > 0, then Ks is applied as read from field 51-60 of the second record for each reach, and conductance C is calculated as shown above. For this option, data are read from f10 fields 4 and 5 (columns 31-40 and 41-50) of the second record of stream reach input data as described below;

Field 4: Reach length, Ls=strm(12,*);

Field 5:

if icalc=2, read reciprocal side slope for a symmetrical trapezoidal channel, 1/c = strm(13,*); then subr YQ calculates depth given discharge for a trapezoidal channel under unsteady flow conditions. P is approximated by the stream surface top width, B, if iperim=0, which is set internally in subr STR2RP; otherwise, P is based on a trapezoidal channel.

if icalc=3, read a gaging station identifier as follows:

1=Concordia, 2=Clay Center on Repub. R., 3=Albert KS gage on Walnut Creek. subr YQGAGE calculates depth given discharge.

iroute: streamflow routing options.

0 or 1: Apply stream routing procedure by Prudic, subr STR2FM;

2: Apply diffusive wave routing where Cr-Pe conditions are met.

nrstep: (not read):

Number of streamflow routing time steps for each aquifer time step: this is assumed to be 1 for all routing options (above). In the case of routing option 2, the Cr-Pe conditions are checked for each stream reach and time step; if these conditions are met, diffusive routing is applied; otherwise, the modified Prudic routing procedure (option 1) is followed. The tradeoff is that while flood wave travel time is neglected for each reach handled this way, there's no worry over solution errors that can occur for nrstep > 1 under conditions of strong coupling, i.e. for large conductance, C, as described elsewhere (Perkins and Koussis, 1996).

Notes regarding stream-aquifer solution

The optional calculation of streambed conductance (irdcnd > 0) allows greater modeling accuracy, but care must be taken regarding solution convergence. Streambed leakage is given by

flobot = cstr*hygrad,

where hygrad is the head across the streambed based on Qavg (above), and cstr is the streambed conductance, given by

cond = rkeqv*perim*strm(12,L)/bedthk,

where perim = wetted perimeter, calculated by subr. STRDEP;

bedthk = streambed thickness, given by input data, i.e.,

bedthk = strm(5,L) - strm(4,L).

Equivalent hydraulic conductivity, rkeqv, is based on different hydraulic conductivity vlaues for main and side channels, and is described for flow through parallel layers (see Freeze and Cherry, Groundwater, 1979, Prentice-Hall, eq. 2.32).

```
        wdmain = strm(19,L)              !main channel maximum width
        C=Ks_low*perim*dx/T              conductance based on Ks for main channel
        if (perim.lt.wdmain) then        !stream width < max. main channel width
                rkeqv = strm(14,L)       !use low Ks within main channel
        else
                equiv. conductivity through parallel layers:
        rkeqv = (wdmain*strm(14,L) + (perim-wdmain)*strm(15,L))/perim
end if
```

The greater modeling accuracy provided by variable conductance can produce solution instability due to the coupling of the conductance value to the solution through stream width, which may vary with stream depth. Other such couplings include streambed leakage and, in the modified Well package, pumping rates that vary with saturated thickness if the saturated thickness is small. This problem is avoided for these wells by evaluating variable pumping rates implicitly, i.e., on the basis of heads in the previous time step, hold. For the modified STREAM package, the following measures are taken to improve solution convergence.

First, streambed leakage is driven by a gradient across the streambed that is based on a stream stage calculated from average streamflow, Qavg, which is both time- and space-centered in the reach, i.e., the average of inflow and outflow for both the current solution iteration and the solution for the previous time step,

Qavg = (strm(9,L) + strm(10,L) + strm(23,L) + strm(24,L))/4.

Qavg is used to evaluate stream depth (in subr STRDEP); stream stage, hstr = strm(2,L) (in STR2FM); the hydraulic head across the streambed (STR2FM) and streambed leakage (subr STRLKG.

The solution for the previous time step is also used for diffusive wave routing (IROUTE=2). Outflow from each reach is based on the same components used to compute Qavg, above, but with a different weighting scheme based on Courant and Peclet conditions in subr ROUTE.

Second, both streambed conductance and streambed leakage are calculated as shown above, except that an average is taken over the current and previous iterations of the current time step. These are calculated in subr STRLKG as follows:

Conductance:

```
        cond = rkeqv*perim*strm(12,L)/bedthk
        if (kkiter.le.1) then
                strm(3,L) = cond
        else
                strm(3,L) = (strm(3,L) + cond)/2.
        end if
```

Streambed leakage:

```
        if (kkiter.le.1) then
                flobot = cstr*hygrad
        else
```

```
        flobot = (strm(11,L) + cstr*hygrad)/2.
    end if
```

Third: to avoid oscillating between coupled and uncoupled states of stream reaches with water table close to the bottom of the streambed, whichever state a given reach is in for the second iteration is assigned to that reach for the remaining iterations of the solution for a given time step. This is coded in Strlkg as follows:

STRX: Input instructions (revisions in **bold**)

```
For each simulation (STR2AL):
1. Data:    MXSTRM,NSS,NTRIB,NDIV,ICALC,CONST,ISTCB1,ISTCB2,
            IOPSTR,ITOPRC,IBOTRC,ADJBED
   Format: (5I10,F10.0,2I10,3i5,F10.0)

For each stress period (STR2RP):
2. Data:  ITMP,IRDFLG,IPTFLG,IRDCND,NUMINP,IROUTE,ISGTOP
   Format: (7I10)

Segments for which inflows to top reaches are to be read for each time step:'

  if (numinp.gt.0) read (in,*) (inpseg(j),j=1,numinp)

if (itmp = -1) then
            <use stream data from previous stress period>

else if (itmp = -2) then
            update inflow to top reaches of numinp designated segments:
      do ii = 1,numinp
            Data:   layer row column segment reach inflow
            Format: (5i5,f15.0)

            Note: the following inverse reference to each reach is also defined:
            Idxstr(icol,irow,ilay) = ireach
      end do

else if (itmp > 0) then
            read stream segment and reach data (items 3-6):
```

3. Read NSTREM records (item 3) corresponding to NSTREM stream reaches in sequential order from upstream to downstream, first by segments, and then by reaches. This ordering is necessary for streamflow to be routed downstream properly.

```
      DO II=1,NSTREM
            Data: layer row column segment reach flow stage cond sbot stop
            Format: (5I5,F15.0,4F10.0)
            Array: (ISTRM(j,ii), j=1,5); (STRM(j,ii), j=1,5)
      end do

4.    If stream stages are to be calculated (Icalc > 0), read a second set of
NSTREM records in the same order as the set in item 3:
      do ii=1,nstrem:
            Data:             width  slope  rough length   side Ks_main, Ks_side
```

```
        Format: (7f10.0)
        Array: (STRM(j,ii), j=6      7       8      12      13      14       15
    end do
```

5. If NTRIB > 0 (maximum number of tributaries joining a segment), read one record per segment in the same sequence the segment data are read above (items 3 and 4). Include records for all segments, even those without tributaries, for which blank records, or records with all zeroes, are read.

```
    do Iseg=1,nss
        Data:   (ITRBAR(Iseg,JK),JK=1,NTRIB)
        Format: (10I5)
    end do
```

6. if (ndiv > 0) then read a record for each segment in the same sequence followed for items 3-5. For each segment that is a diversion, read the upstream segment number; for segments that are not diversions, enter a blank or zero:

```
    do Idiv=1,nss
        Data:   IDIVAR(Idiv)
        Format: (I10)
    end do
```

end if (itmp>0)

For each time step istep = 2 to Nstep (**STR2FM**):

if (numinp > 0) then

```
        update inflow to top reaches of numinp designated segments:
    do ii = 1,numinp
        Data:   layer row column segment reach inflow
        Format: (5i5,f15.0)
        Array: (ISTRM(j,ii), j=1,5); STRM(1,ii)
    end do
```

Definition of input data

Line 1:

mxstrm maximum number of stream reaches during simulation; used to allocate array space.
nss maximum number of segments during simulation.
ntrib maximum number of tributary segments
ndiv flag: if ndiv>0, diversions from segments are to be simulated.

icalc flag: if icalc>0, stream stages in reaches are to be calculated. Options for channel description are as follows; all options account for lateral surface inflow and allow streambed hydraulic conductivity to be specified; see IRDCND (2).

icalc = 1: rectangular channel geometry; consistent with model in STR1 (Prudic, 1990). For each stream reach, given streamflow, Q, under steady flow conditions for a rectangular channel, solve Manning's equation for depth, d. Manning's equation is given by

$$Q(d) = (c_m/n)AR^{2/3}S^{1/2},$$

where c_m = unit conversion constant (CONST); n = Manning's roughness (ROUGH), A = area of transverse flow section, R = A/P, hydraulic radius; P = wetted perimeter, and S = friction slope, approximated by bed slope for steady flow. For a rectangular channel, $A = wd$, $P = w + 2d$; and the inverse, d(Q), is approximated by

$$d = [nQ/(c_m w S^{1/2})]^{3/5}.$$

icalc = 2: Solve Manning's equation for stream depth in each reach under conditions of unsteady flow for a trapezoidal channel. Read reciprocal side slope (SIDE = 1/c) to define a symmetrical trapezoidal, using WIDTH (4) as the trapezoid's base. Subr YQ calculates depth given discharge for a trapezoidal channel, allowing unsteady flow conditions. Wetted perimeter P is approximated by the stream surface top width B if iperim=0, which is set internally in subr STR1DW; otherwise, P is based on a trapezoidal channel.

icalc = 3: read a gaging station identifier from **side** (see Line 4, STRM vector 13) as follows: 1=Concordia, 2=Clay Center (both on Republican R., calc. by YQGAGE); 3=Albert KS (on Walnut Creek). Subr YQGAGE calculates depth given discharge, y(Q), using empirical fits to USGS rating curves for these stations. YQGAGE also calculates top width B(y) and transverse flow area A(y) based on flow rate calibration measurements by USGS.

const unit conversion constant c_m:for Manning's equation: $c_m = 1$ for SI units (flow rate Q in m^3/s), $c_m = 1.486$ for English units (Q in cfs); see ICALC.

istcb1 flag: if istcb1<0 and icbcfl≠0, print streamflow and streambed leakage for each reach.
istcb2 flag regarding writing results to a file.

iopstr an option to determine whether to use the modified STRX package (if **iopstr** > 0) or the standard STR1 package in Modflow-96 (if **iopstr** = 0). The default, a blank field, invokes the standard package. NOTE: This option is overriden and the modified STRX package is invoked if either of the SWBX or WELX packages are invoked, since these three packages are coordinated to provide a linkage with a watershed simulation model. An analogous option, **iopwel**, is specified on the first line of the WELL input package to choose between the modified WELX and standard WEL5 packages.

itoprc index to top reach for stream yield summary (see ibotrc).
ibotrc index to bottom reach for stream yield summary. Stream yield is taken to be the increase in calculated streamflow from the top reach to the bottom reach.
adjbed: streambed elevation adjustment: a constant to be added to both top and bottom elevations of each stream reach in the network. This was installed to allow for sensitivity analysis of streambed elevation; see Perkins and Sophocleous (1999).

<u>Line 2:</u>
itmp flag and counter:
itmp > 0: number of reaches active during the current stress period;
itmp = −1: use stream data from the previous stress period;
itmp = −2: except for NUMINP stream nodes, use stream data from the previous stress period. For each of NUMINP segments, inflow to the top reach is read for each time step.

irdflg flag: if <0, print input data.

iptflg flag: if <0, print results.

irdcnd stream channel geometry option:

irdcnd = 0: (default) streambed conductance, COND (below), is applied as read from the input file. As described in Prudic (1989), a rectangular channel with steady flow is assumed, and input data values for streambed conductance are approximated by COND = K_sL_sP/T, where K_s = streambed saturated hydraulic conductivity; L_s = stream reach length; P = wetted perimeter; and T = streambed thickness, given by STOP – SBOT (below).

irdcnd > 0: COND is read as for irdcnd = 0, but is calculated for each time step. Additional data are read from item 4 for stream reach length, a geometry parameter (side), and hydraulic conductivity (K_{sm} and K_{ss}).

numinp If ITMP = -2, then for each time step (STR1RP for step 1 and in STR1FM or STR1DW for remaining steps), streamflow data are read for NUMINP previously defined stream nodes at (7) or (8). This allows inflow hydrographs to be updated in each time step.

iroute streamflow routing options:

iroute ≤ 1: Apply Prudic's streamflow routing (STR2FM);

iroute = 2: Apply Muskingum-Cunge (diffusive wave) routing in reaches where Cr-Pe conditions are met (STR2FM). These conditions are checked for each stream reach and time step; if these conditions are not met, Prudic's routing procedure is applied. Prudic routing neglects travel time of a flood wave, while diffusive routing does not.

isgtop: if > 0, isgtop is the index to the top segment of a sequence of segments going downstream for which profiles of stream depth, streambed leakage, and tributary inflows are to be displayed graphically during the simulation. This applies only if the custom Modplt package is invoked.

Data for lines 3 and 4:

```
3. Data:              layer row column segment reach flow stage cond sbot stop
   ISTRM vectors:       1    2    3      4       5
   STRM vectors:                                       1    2     3    4    5

4. Data:            width  slope  rough length   side Ks_main, Ks_side
   STRM vectors:      6      7      8     12      13     14        15
```

<u>Data stored in Istrm:</u>

1 Layer (line 3)
2 Row (line 3)
3 Column (line 3)
4 Segment (line 3)
5 Reach (line 3)

<u>Additional array ISTRM vectors (increased from 5 to 10)</u>

6 no. of pumping wells for which this is closest stream reach.
7 indicates whether reach is active this time step.
8 indicates whether Muskingum-Cunge (1) or Prudic-type (0) routing was applied to the reach.
9 IQFLG, assigned for each reach in STR2FM as follows:

0: if head in aquifer is above the streambed bottom elevation;

1: if either (a) head in aquifer is below the streambed bottom elevation or (b) leakage from streambed to aquifer exceeds reach inflow + surface lateral inflow to reach, in which case leakage is reset to the sum of these.

NOTE: the value of IQFLG assigned in the second iteration of the solution is used to determine the state of coupling (0 for coupled, 1 for uncoupled) for succeeding iterations in a given time step.

10 indicates whether subbasin ISUB's point of outflow is associated with this stream reach (irec) and, if so, istrm(10,irec) = isub.

Definitions for array STRM (expanded from 11 to 30 vectors)

<u>Data stored in Strm: read 1-5 (line 3); 6-8 and 12-15 (line 4).</u>
1 Flow: streamflow input (specified for segment's top reach).
2 Stage: stage (computed if icalc > 0): avg for reach based on Qavg.
3 Cond: streambed hydraulic conductance; if irdcnd > 0, computed from stream width, length, hydraulic conductivity, and streambed thickness.
4 Sbot: streambed bottom elevation
5 Stop: streambed top elevation
6 Width: stream channel width; variable if Icalc > 1.
7 Slope: stream channel slope
8 Rough: If icalc <= 2, Manning roughness, n; if icalc = 3, index to a set of natural stream channel characteristics based on USGS gaging station data.
9 reach outflow
10 reach inflow
11 ql = streambed leakage. Revised as space- and time-centered , based on strm(9,*) and strm(10,*) for the end of the current time step, and strm(24,*) and strm(23,*) for the beginning of the time step.

<u>Additional array STRM vectors (12 to 30)</u>
12 L = reach length
13 if icalc=2 (call subr YQ for depth): reciprocal side slope for symmetrical trapezoidal channel (cot alpha);
if icalc=3 (call subr YQGAGE for depth): index to gaging station as follows for now: 1=Concordia, 2=Clay Center on Republican R., 3=Albert KS gage on Walnut Creek.
14 Ks = streambed hydraulic conductivity, applied to flow in main channel (perim < wdmain); see strm(3,*)
15 Ks_high: hydraulic conductivity applied to flow outside main channel, perim > wdmain, where perim = wetted perimeter, and wdmain is width specified for low hydraulic conductivity channel.
16 not used. Possible use: a 2nd Manning coefficient for flow in side channels when perim > wdmain as applied in (15).
17 stream depth (STR2FM)

18 qs = net lateral inflow due to surface runoff and interflow; includes diversions for appropriated water use (see SURFACE package), but not baseflow; see strm(11,L).
19 main channel width: set to twice the base width, strm(6,L), in STR2RP.
20 hydraulic gradient: if iqflg=0, hygrad = hstr-hnew; otherwise, hstr-strm(4,*)
21 potential evaporation for time step as depth[L] = rate[L/T]*delt
22 evaporation for time step subtracted from reach as flow rate (STR2FM)
23 (*) reach outflow for previous time step's solution
24 (*) reach inflow for previous time step's solution
25 orig. streambed top elevation
26 fraction of subbasin drained by this reach
27 head on streambed (Str2rp, 410)
28 total diversions without considering constraint on inflows
30 total diversions considering inflow constraints as fraction of total without considering inflow constraints (Str2fm)

(*): STRM vectors 23 and 24 provide reach outflow and inflow from the beginning of the current time step, allowing streambed leakage, strm(11,*), to be time- and space-centered.

Stream package input example from base case: file rptest.str

```
     77         1         0         0         3      1.49         0         0   1  12    73  -2.
     77         0         0         1         1         1         1             77"itmp
1    1   2  1   1            74.387    1378.0         0     1375.0    1378.0   5s 4w 5
1    2   3  1   2              0.00    1373.2         0     1370.2    1373.2   5s 4w 9
1    2   4  1   3              0.00    1368.0         0     1365.0    1368.0   5s 4w10
1    2   5  1   4              0.00    1363.2         0     1360.2    1363.2   5s 4w11
1    3   5  1   5              0.00    1358.3         0     1355.3    1358.3   5s 4w14
1    4   5  1   6              0.00    1356.3         0     1353.3    1356.3   5s 4w23
1    3   6  1   7              0.00    1353.9         0     1350.9    1353.9   5s 4w13
1    4   6  1   8              0.00    1350.3         0     1347.3    1350.3   5s 4w24
1    5   6  1   9              0.00    1348.0         0     1345.0    1348.0  Buffalo Cr
1    4   7  1  10              0.00    1346.5         0     1343.5    1346.5   5s 3w19
1    5   7  1  11              0.00    1342.1         0     1339.1    1342.1  Wolf Cr
1    5   8  1  12              0.00    1338.0         0     1335.0    1338.0   5s 3w29
1    5   9  1  13              0.00    1332.7         0     1329.7    1332.7   5s 3w28
1    5  10  1  14              0.00    1328.6         0     1325.6    1328.6   5s 3w27
1    5  11  1  15              0.00    1325.3         0     1322.3    1325.3   5s 3w26
1    5  12  1  16              0.00    1322.4         0     1319.4    1322.4   5s 3w25
1    4  12  1  17              0.00    1320.7         0     1317.7    1320.7   5s 3w24
1    4  13  1  18              0.00    1318.0         0     1315.0    1318.0   5s 2w19
1    4  14  1  19              0.00    1316.3         0     1313.3    1316.3   5s 2w20
1    5  14  1  20              0.00    1313.9         0     1310.9    1313.9   5s 2w29
1    6  14  1  21              0.00    1310.8         0     1307.8    1310.8  Plum Cr
1    6  15  1  22              0.00    1308.2         0     1305.2    1308.2  stream from
1    5  15  1  23              0.00    1307.7         0     1304.7    1307.7   5s 2w28
1    6  16  1  24              0.00    1306.4         0     1303.4    1306.4  stream (inte
1    5  16  1  25              0.00    1303.8         0     1300.8    1303.8   5s 2w27
1    4  16  1  26              0.00    1301.5         0     1298.5    1301.5  Salt Cr
1    4  17  1  27              0.00    1297.6         0     1294.6    1297.6   5s 2w23
1    4  18  1  28              0.00    1293.5         0     1290.5    1293.5  Upton Cr
1    4  19  1  29              0.00    1289.9         0     1286.9    1289.9   5s 1w19
1    4  20  1  30              0.00    1287.5         0     1284.5    1287.5   5s 1w20
1    5  20  1  31              0.00    1284.2         0     1281.2    1284.2   5s 1w29
1    6  21  1  32              0.00    1279.2         0     1276.2    1279.2  Elm Cr
1    5  21  1  33              0.00    1277.7         0     1274.7    1277.7   5s 1w28
1    5  22  1  34              0.00    1275.3         0     1272.3    1275.3   5s 1w27
1    5  23  1  35              0.00    1273.3         0     1270.3    1273.3   5s 1w26
1    6  23  1  36              0.00    1270.9         0     1267.9    1270.9   5s 1w35
1    6  24  1  37              0.00    1265.4         0     1262.4    1265.4   5s 1w36
1    5  24  1  38              0.00    1265.6         0     1262.6    1265.6  Elk Cr
1    7  24  1  39              0.00    1259.7         0     1256.7    1259.7  Beaver Cr
1    8  25  1  40              0.00    1257.2         0     1254.2    1257.2   6s 1e 7
1    8  26  1  41              0.00    1253.1         0     1250.1    1253.1   6s 1e 8
1    7  26  1  42              0.00    1254.1         0     1251.1    1254.1   6s 1e 5
1    8  27  1  43              0.00    1249.0         0     1246.0    1249.0   6s 1e 9
1    8  28  1  44              0.00    1246.2         0     1243.2    1246.2   6s 1e10
1    8  29  1  45              0.00    1241.3         0     1238.3    1241.3   6s 1e11
1    8  30  1  46              0.00    1235.9         0     1232.9    1235.9   6s 1e12
1    7  30  1  47              0.00    1234.3         0     1231.3    1234.3  Parsons Cr
1    8  31  1  48              0.00    1231.1         0     1228.1    1231.1   6s 2e 7
1    9  31  1  49              0.00    1228.7         0     1225.7    1228.7   6s 2e18
1   10  31  1  50              0.00    1226.0         0     1223.0    1226.0   6s 2e19
1   11  31  1  51              0.00    1224.0         0     1221.0    1224.0   6s 2e30
1   11  32  1  52              0.00    1221.3         0     1218.3    1221.3  Peats Cr
1   12  32  1  53              0.00    1217.8         0     1214.8    1217.8   6s 2e32
1   13  32  1  54              0.00    1214.2         0     1211.2    1214.2   7s 2e 5
1   13  33  1  55              0.00    1213.7         0     1210.7    1213.7  Peet Cr
1   14  32  1  56              0.00    1209.9         0     1206.9    1209.9  Mulberry Cr
1   14  33  1  57              0.00    1208.2         0     1205.2    1208.2   7s 2e 9
1   15  33  1  58              0.00    1207.3         0     1204.3    1207.3   7s 2e16
1   15  32  1  59              0.00    1202.8         0     1199.8    1202.8   7s 2e17
1   16  32  1  60              0.00    1198.7         0     1195.7    1198.7   7s 2e20
1   17  32  1  61              0.00    1196.4         0     1193.4    1196.4   7s 2e29
1   17  33  1  62              0.00    1193.2         0     1190.2    1193.2   7s 2e28
1   18  33  1  63              0.00    1188.6         0     1185.6    1188.6   7s 2e33
1   19  33  1  64              0.00    1187.0         0     1184.0    1187.0   8s 2e 4
1   19  34  1  65              0.00    1184.7         0     1181.7    1184.7   8s 2e 3
1   19  35  1  66              0.00    1181.0         0     1178.0    1181.0   8s 2e 2
1   20  35  1  67              0.00    1177.9         0     1174.9    1177.9   8s 2e11
1   21  35  1  68              0.00    1176.0         0     1173.0    1176.0   8s 2e14
1   21  36  1  69              0.00    1173.2         0     1170.2    1173.2  Five Cr
1   20  36  1  70              0.00    1172.0         0     1169.0    1172.0   8s 2e12
1   20  37  1  71              0.00    1170.5         0     1167.5    1170.5   8s 3e 7
1   21  37  1  72              0.00    1167.9         0     1164.9    1167.9  Huntress Cr
1   21  38  1  73              0.00    1165.8         0     1162.8    1165.8   8s 3e17
1   22  38  1  74              0.00    1164.2         0     1161.2    1164.2   8s 3e20
1   21  39  1  75              0.00    1161.1         0     1158.1    1161.1  Finney Cr
1   22  39  1  76              0.00    1158.2         0     1155.2    1158.2   8s 3e21
1   23  39  1  77              0.00    1156.3         0     1153.3    1156.3   8s 3e28
   100 0.0007137       0.03    5483.1         1 6.2304e-6 6.2305e-6   54627.7   1
   100 0.0006155       0.03    7716.9         1 6.2304e-6 6.2305e-6   62344.6   2
   100 0.0009655       0.03    7107.7         1 6.2304e-6 6.2305e-6   69452.3   3
```

100	0.0009655	0.03	4264.6	1	6.2304e-6	6.2305e-6	73716.9	4
100	0.0005726	0.03	6498.5	1	6.2304e-6	6.2305e-6	79098.5	5
100	0.0005726	0.03	4467.7	1	6.2304e-6	6.2305e-6	83566.2	6
100	0.0005726	0.03	2640	1	6.2304e-6	6.2305e-6	87323.1	7
100	0.000566	0.03	7513.8	1	6.2304e-6	6.2305e-6	94836.9	8
100	0.000566	0.03	2843.1	1	6.2304e-6	6.2305e-6	97680	9
100	0.000566	0.03	2640	1	6.2304e-6	6.2305e-6	100320	10
100	0.000566	0.03	9341.5	1	6.2304e-6	6.2305e-6	109661.5	11
100	0.0006746	0.03	5787.7	1	6.2304e-6	6.2305e-6	115449.2	12
100	0.0006746	0.03	8630.8	1	6.2304e-6	6.2305e-6	124080	13
100	0.0005129	0.03	5990.8	1	6.2304e-6	6.2305e-6	130070.8	14
100	0.0005129	0.03	6701.5	1	6.2304e-6	6.2305e-6	136772.3	15
100	0.0005129	0.03	5381.5	1	6.2304e-6	6.2305e-6	142153.8	16
100	0.0005129	0.03	2640	1	6.2304e-6	6.2305e-6	144793.8	17
100	0.0005103	0.03	6092.3	1	6.2304e-6	6.2305e-6	150886.2	18
100	0.0005103	0.03	2436.9	1	6.2304e-6	6.2305e-6	153323.1	19
100	0.0005103	0.03	5483.1	1	6.2304e-6	6.2305e-6	158806.2	20
100	0.0005411	0.03	6295.4	1	6.2304e-6	6.2305e-6	165101.5	21
100	0.0005411	0.03	3147.7	1	6.2304e-6	6.2305e-6	166929.3	22
100	0.0005411	0.03	3046.1	1	6.2304e-6	6.2305e-6	169975.4	23
100	0.0005411	0.03	507.7	1	6.2304e-6	6.2305e-6	171803.1	24
100	0.0005411	0.03	6295.4	1	6.2304e-6	6.2305e-6	178098.5	25
100	0.0005411	0.03	3553.8	1	6.2304e-6	6.2305e-6	181652.3	26
100	0.0006354	0.03	7513.9	1	6.2304e-6	6.2305e-6	189166.2	27
100	0.0006354	0.03	6092.3	1	6.2304e-6	6.2305e-6	195258.5	28
100	0.0005828	0.03	5584.6	1	6.2304e-6	6.2305e-6	200843.1	29
100	0.0005828	0.03	3655.4	1	6.2304e-6	6.2305e-6	204498.5	30
100	0.0005828	0.03	6295.4	1	6.2304e-6	6.2305e-6	210793.9	31
100	0.0005352	0.03	9341.5	1	6.2304e-6	6.2305e-6	220135.4	32
100	0.0005352	0.03	609.2	1	6.2304e-6	6.2305e-6	220744.6	33
100	0.0005352	0.03	5889.2	1	6.2304e-6	6.2305e-6	226633.9	34
100	0.0005352	0.03	3046.2	1	6.2304e-6	6.2305e-6	229680	35
100	0.0005352	0.03	4873.8	1	6.2304e-6	6.2305e-6	234553.9	36
100	0.0005183	0.03	11169.3	1	6.2304e-6	6.2305e-6	239935.4	37
100	0.0005183	0.03	4772.3	1	6.2304e-6	6.2305e-6	244707.7	38
100	0.0004191	0.03	6193.8	1	6.2304e-6	6.2305e-6	256689.3	39
100	0.0004191	0.03	5889.2	1	6.2304e-6	6.2305e-6	262578.5	40
100	0.0004191	0.03	5686.2	1	6.2304e-6	6.2305e-6	264000	41
100	0.0004191	0.03	5889.3	1	6.2304e-6	6.2305e-6	269889.3	42
100	0.0004602	0.03	8224.6	1	6.2304e-6	6.2305e-6	282378.5	43
100	0.0004602	0.03	5584.6	1	6.2304e-6	6.2305e-6	287963.1	44
100	0.0005352	0.03	12793.8	1	6.2304e-6	6.2305e-6	300756.9	45
100	0.0005352	0.03	7818.5	1	6.2304e-6	6.2305e-6	306240	46
100	0.0005352	0.03	5787.7	2	6.2304e-6	6.2305e-6	312027.7	47
100	0.0005352	0.03	3046.2	2	6.2304e-6	6.2305e-6	317409.3	48
100	0.0004875	0.03	5178.5	2	6.2304e-6	6.2305e-6	322587.7	49
100	0.0004875	0.03	5686.2	2	6.2304e-6	6.2305e-6	328273.9	50
100	0.0004875	0.03	3553.8	2	6.2304e-6	6.2305e-6	331827.7	51
100	0.0004875	0.03	6092.3	2	6.2304e-6	6.2305e-6	337920	52
100	0.0004875	0.03	7716.9	2	6.2304e-6	6.2305e-6	345636.9	53
100	0.0004875	0.03	7615.4	2	6.2304e-6	6.2305e-6	350713.9	54
100	0.0004875	0.03	1726.2	2	6.2304e-6	6.2305e-6	352440	55
100	0.0006437	0.03	6498.5	2	6.2304e-6	6.2305e-6	361476.9	56
100	0.0006437	0.03	1218.5	2	6.2304e-6	6.2305e-6	362695.4	57
100	0.0006437	0.03	1523.1	2	6.2304e-6	6.2305e-6	364218.5	58
100	0.0006437	0.03	8833.8	2	6.2304e-6	6.2305e-6	373052.3	59
100	0.0005077	0.03	6193.9	2	6.2304e-6	6.2305e-6	379246.2	60
100	0.0005077	0.03	4061.5	2	6.2304e-6	6.2305e-6	383307.7	61
100	0.0005077	0.03	7107.7	2	6.2304e-6	6.2305e-6	390415.4	62
100	0.00049	0.03	9646.2	2	6.2304e-6	6.2305e-6	400061.6	63
100	0.00049	0.03	1218.5	2	6.2304e-6	6.2305e-6	401280	64
100	0.00049	0.03	5889.2	2	6.2304e-6	6.2305e-6	407169.3	65
100	0.00049	0.03	8021.5	2	6.2304e-6	6.2305e-6	415190.8	66
100	0.0005253	0.03	5381.6	2	6.2304e-6	6.2305e-6	420572.3	67
100	0.0005372	0.03	3046.1	2	6.2304e-6	6.2305e-6	423618.5	68
100	0.0005372	0.03	5889.3	2	6.2304e-6	6.2305e-6	429507.7	69
100	0.0005372	0.03	1218.5	2	6.2304e-6	6.2305e-6	430726.2	70
100	0.0005372	0.03	3147.7	2	6.2304e-6	6.2305e-6	433873.9	71
100	0.0005897	0.03	4975.4	2	6.2304e-6	6.2305e-6	438849.3	72
100	0.0005897	0.03	3046.2	2	6.2304e-6	6.2305e-6	441895.4	73
100	0.0005897	0.03	2640	2	6.2304e-6	6.2305e-6	444535.4	74
100	0.0005897	0.03	6193.8	2	6.2304e-6	6.2305e-6	450729.3	75
100	0.0004646	0.03	5584.6	2	6.2304e-6	6.2305e-6	456313.9	76
100	0.0004646	0.03	3452.3	2	6.2304e-6	6.2305e-6	459766.2	77

1	1	2	1	1		189.643	1378	0	1375	1378	31.678	2	77
1	1	2	1	1		156.677	1378	0	1375	1378	63.42	3	77
1	1	2	1	1		140.2	1378	0	1375	1378	34.733	4	77
1	1	2	1	1		223.516	1378	0	1375	1378	192.936	5	77
1	1	2	1	1		734.733	1378	0	1375	1378	611.634	6	77
1	1	2	1	1		364.613	1378	0	1375	1378	-37.774	7	77
1	1	2	1	1		1113.677	1378	0	1375	1378	1126.581	8	77
1	1	2	1	1		1160.5	1378	0	1375	1378	337	9	77
1	1	2	1	1		276.258	1378	0	1375	1378	63.645	10	77
1	1	2	1	1		264.833	1378	0	1375	1378	69.9	11	77
1	1	2	1	1		216.419	1378	0	1375	1378	23.807	12	77
	-2		0		0	1	1	1	1		78"itmp irdflg iptflg		
1	1	2	1	1		164.516	1378	0	1375	1378	7.742	1	78

1	1	2	1	1	175.714	1378	0	1375	1378	16.429	2	78
1	1	2	1	1	1104.419	1378	0	1375	1378	730.162	3	78
1	1	2	1	1	411.733	1378	0	1375	1378	159.334	4	78
1	1	2	1	1	380.129	1378	0	1375	1378	617.903	5	78
1	1	2	1	1	213.367	1378	0	1375	1378	109.9	6	78
1	1	2	1	1	450.71	1378	0	1375	1378	263.613	7	78
1	1	2	1	1	514.903	1378	0	1375	1378	97.387	8	78
1	1	2	1	1	571.7	1378	0	1375	1378	346.533	9	78
1	1	2	1	1	178.935	1378	0	1375	1378	63.13	10	78
1	1	2	1	1	191.3	1378	0	1375	1378	53.433	11	78
1	1	2	1	1	143.613	1378	0	1375	1378	41.839	12	78

5.5. WELX: modified Well package

The WELL package was modified

Water rights are distinguished both by source (surface or ground water) and by type (irrigation, domestic, municipal, etc., including imaginary wells used to represent boundary conditions). The inclusion of both surface and ground water rights for MODWEL simplifies data preparation and coordination with the simulation of irrigation demand. If surface water sources are specified, a stream network must also be specified using MODSTR such that each diversion's grid cell location is associated with a stream reach.

This package incorporates the capability to represent water rights that pump from stream reaches, which requires invoking STRX, the modified Stream package.

Background of the WELX package

As part of an earlier project to model the Lower Republican River Basin, a SURFACE package was written to be called by MODFLOW. The SURFACE package provided an operational model of irrigation that could be supplied by both ground and surface water rights, represented by the WELL and SURFACE packages, respectively. The area of the basin under irrigation according to DWR water rights records and monthly irrigation demand specified as a depth by SWAT's simulations for each subbasin were used by the SWB package to determine the total irrigation demand as a flow rate for the basin. This total monthly demand was supplied by distributing it over both ground and surface water rights appropriated for irrigation. This irrigation model and its application to the Lower Republican Basin are described in Volume 1 of the study report (Sophocleous et al., 1997b) and in Perkins and Sophocleous (1999); the SURFACE package is documented in Volume 2 of the study (Perkins and Sophocleous, 1997).

In a more recent application to Walnut Creek Basin, a computer code for a comprehensive watershed model was developed based on MODFLOW and POTYLDR (Koelliker, 1994), which was used to replace SWAT's functions for daily simulations of watershed hydrology. Monthly irrigation demand is specified by POTYLDR and distributed over both ground and surface water diversions using an earlier version of the SWBX package. For this computer code, MODFLOW's WELL package was modified to represent both ground and surface water diversions, a change that eliminated the need for the separate SURFACE package, simplifying both the computer code and input data preparation. The development and application of the computer model to Walnut Creek is described in Sophocleous and Perkins (1998). These improvements have been incorporated into the present version of the Swat-Modflow linkage.

Summary of modified Well package WELX

For each well, READ LAYER,ROW,COLUMN, appropriated FLOW RATE, maximum pumping rate, distance to stream, stream reach index, year of water right, and codes indicating whether the well represents an actual water right or a boundary condition; and if it is a water right, its type (vested or appropriated), source (ground or surface water), and use, particularly whether it is an irrigation water right. Appropriations as given by the input file may be modified according to a set of scenarios for water use management (subr USEMGT). In each time step, appropriations for irrigation may be scaled to meet simulated irrigation demand (for IRROPT > 0; see Modswbwc package), within optional constraints given by each water right's maximum pumping rate (PMPRAT), global pumping rate limits (RATGND and RATSRF, line 1); and an optional criterion based on saturated thickness (for IOPSAT > 0, line 1). These options are implemented in each time step by subr WELZ2FM, which is called just before execution enters the loop on iterations for a solution. Welz2fm is based on Wel2fm, which is called for each iteration on the solution. Welz2fm was intended to be called as an alternative to Wel2fm, but the dependence of the variable pumping rate on the solution produces oscillations. To avoid this, Welz2fm is called prior to the solution loop, where pumping rates may be reduced as a function of saturated thickness at the beginning of the time step. Currently, Welz2fm is called only if the MODSWBWC package is invoked.

Input instructions for modified Well package (WELX)

```
For each simulation (WEL1AL):
1.     Data:     MXWELL  IWELCB  iopwel  iopsat  satlo  sathi  ratgnd  ratsrf
       Columns:    1-10   11-20   21-30   31-40  41-50  51-60   61-70   71-80
       Format:   (8I10)

For each stress period (WEL2RP):
2.     Data:     ITMP,nwread
       Columns: 1-10  11-20
       Format:   (2I10)
C
For each water right (WEL2RP):
       DO II=1,nwread
3.     Data:    layer   row column   Qwr pmprat dsstrm istrch  iwryr codes
       Columns: 1-10 11-20  21-30 31-40  41-50  51-60  61-65  66-70 71-80
       Format:   (3i10,3f10.0,2i5,a10)
```

Definitions of modified Well package input data

Line 1 (for each simulation).

MXWELL maximum number of wells used at any time.

IWELCB flag: print(<0) or save(>0) cell-by-cell flow rates.

iopwel: option to determine whether to use the modified WELX package (if **iopwel** > 0) or the standard WEL5 package in Modflow-96 (if **iopwel** = 0). The default, a blank field, invokes the standard package. NOTE: This option is overriden and the modified WELX package is invoked if the SWBX packages is invoked, which is coordinated with the WELX and STRX packages to provide a linkage with a watershed simulation model. Although STRX may be used without WELX, invoking WELX automatically invokes STRX, which is needed to support the added capability in WELX to model water rights that pump from streams. The option **iopstr**, analogous to **iopwel**, is specified on the first line of the STREAM input package to choose between the modified STRX and standard STR1 packages.

iopsat an option to curtail pumping based on saturated thickness thresholds satlo and sathi (below) as follows.

=0: this option is ignored.

>0: pumping rate is reduced linearly from q to qr as a function of saturated thickness ys between limits yL = satlo and yH = sathi according to

$$qr = q(ys-yL)/(yH-yL),\ yL < ys < yH,$$
$$= q,\ ys > yH,$$
$$= 0,\ ys < yL.$$

See the Final Report for a more detailed description of this option and the incorporation of the resulting head-dependent fluxes when saturated thickness is between the thresholds satlo and sathi.

In an earlier version of this package, a variation was on this option, specified by iopsat = 2, specified the pumping rate to be a hysteretic function of the saturated thickness ys between yL = satlo and yH = sathi as follows. Pumping rate is unaffected until the saturated thickness falls below the lower threshold, i.e. ys < yL, when pumping is reduced abrubtly from q to 0. For a well that has been so curtailed, its pumping rate is held at zero until saturated thickness recovers to that given by the upper threshold, i.e. ys > yH. This option was eliminated in favor of the linearly varying pumping rate (iopsat = 1), which was incorporated into the solution with less risk of adverse effects on the solution, i.e., oscillatory behavior.

satlo, sathi: lower and upper threshold on saturated thickness; see **iopsat** (above).

ratgnd, ratsrf: upper limits on scaling factors to be applied to annual appropriations for irrigation from ground and surface water diversions, respectively. The product of one of these and the appropriation for a particular point of diversion is represented by pmpmax, defined below, which is used as an upper limit on the water right's pumping rate if a specific limit for the water right given by **pmprat** (line 3) is not specified.

<u>Line 2 (for each stress period).</u>

ITMP flag:

> 0: NWELLS = ITMP, the number of wells active during the current stress period.

< 0: use well data from the previous stress period, with the following exception.

=-2: The assigned pumping rate for each well is taken to be the well's appropriation Qwr (Line 3) specified in the previous stress period times the water use fraction, frcuse (below). This option is used in particular to represent water use in the scenario study period of 18 years beginning in 1995, when water use is represented by the 1994 appropriations times the water use fractions for the corresponding years of the 1977-1994 study period.

nwread **flag:** added to allow all appropriated water rights to be read only once for a simulation time period.

> or = nwells: number of wells to be read; the first nwells of the list are taken to be the active set of wells for the stress period. This works as follows. For the first stress period, all wells to be simulated, a total of NWREAD wells, are read in chronological order of their year of appropriation. Then in each stress period, the first NWELLS in the list are the rights that have been appropriated by the time of the calendar year corresponding to the stress period.

= 0 indicates wells have been read for a previous stress period, and only nwells was adjusted.

<u>Line 3 (for each point of diversion from surface or ground water): WEL2RP</u>

Fields: revised water use input file format:

Layer	1:10, layer number of model cell containing the well.
Row	11:20, row number of model cell containing the well.
Column	21:30, column number of model cell containing the well.
Qwr	volumetric recharge rate [L^3/T], e.g. cfs; negative Qwr indicates discharge.

codes 71:80, character codes, including the following:

bndcnd = codes(1:1): '*' indicates boundary condition well; used as convention for Rattlesnake Creek watershed model; otherwise ignored.

wrtype = codes(2:2), water right type: 'V'=vested, 'A'=appropriated (seniority based on year of right); 'T'=temporary.

source = codes(3:3): 'G'=groundwater, 'S'=surface water (streamflow diversion).

usecod = codes(4:6), water use code: 'IRR'=irrigation. Rights with irrigation water use are subject to scaling to meet irrigation demand; see option Iopirr in the SWBX package.

codes(7:10): ignored by program.

pmprat If (pmprat > 0): pmprat = maximum pumping rate;
If (pmprat <= 0): maximum pumping rate is given as follows:
if source = 'G', max. pumping rate = Abs(Qwr)*ratgnd;
if source = 'S', max. pumpint rate = Abs(Qwr)*ratsrf.

Dsstrm (*) distance to stream (grid units)

Istrch (*) index to stream reach (order in which stream reach is read). This can be left blank or zero, in which case the program will attempt to associate the water right with a stream reach; see note 2 (below).

Iwryr year of application for water right, interpreted as the first year of water use.

<u>(*) Notes on associating a surface water right with a stream reach, Istrch.</u>

1. If a water right is specified with a surface water source (source = 'S'), then the water right must be associated with a stream reach, Istrch, in order that the water required to supply the flow rate demanded by the water right can be diverted from streamflow. This is represented as a subtraction from the stream reach in the modified routing procedure of the STRX package.

2. If Dsstrm or Istrch are given as zero, an attempt is made by subr SRF2RP to find reasonable values for them. For a stream network that is defined for the STRX (modified Stream) package, the indexing array **Idxstr** will attempt to look up the stream reach ID corresponding to the grid cell indices given for the water right. Second, if a stream reach does not correspond to the water right's grid cell, Subr SRF2RP searches array Idxstr for a grid cell with a stream reach within a specified radius (grid cell units) of the water right. The primary objective of this association is to supply surface water diversions; a secondary objective is to estimate the distance between the point of diversion and a stream reach for the purpose of simulating scenarios for management of irrigation water use (see subr. Srf2rp).

Definitions of modified array WELL (expanded from 4 to 15 vectors)

The Well array was expanded from 4*mxwell to 15*mxwell to add some options that are coordinated with the SWBX and STRX packages. These include varying the pumping rate in each time step (5) for irrigation wells (8), and representing recharge/b.c. conditions (6):

(1) layer
(2) row
(3) column
(4) pumping rate as specified by Qwr subject to change in Wel2stp to reflect irrigation demand, and in Wel2fm to prevent depletion below a minimum saturated thickness (see satlo, sathi, above).
(5) Qwr = pumping rate: appropriation.
(6) bccode: read as '*', retain as 1 to identify flux b.c. wells not to be weighted by fluxes in module modswb; otherwise (default), set to zero.
(7) source: read as 'S' or 'G', retain as 1:surface, 0:ground water
(8) usecod: numeric version of DWR use codes (3:irrigation)
(9) dsstrm distance to stream
(10) istrch: identifer for closest stream reach; index to order in which the stream reach was read; required for surface water diversions.
(11) iwryr: water right year
(13) pmprat: appropriated maximum pumping rate [L^3/T]
(14) areair: appropriated area for irrigation (acres)

Specified-flow boundary conditions

Wells can be used to represent specified boundary flow conditions. These wells are distinguished from actual wells that represent pumping wells. Wells used to specify boundary conditions are distinguished from actual wells in the input data an asterisk in column 71.

Example Well input data file: wrrepub.wel for Lower Republican River Basin

Fields for individual water rights are as follows:

```
     lay        row        col        Qwr       pmprat    dsstrm Istrch iyr codes          rwr      cwr  Wellid
```

Listing of input data file wrrepub.wel:

```
     390         -1          1         1.          8.         15.         13.          32.  Mxwell,iwelcb,iopwel,...
     277        388       1977     1.0000     36.1760                                 Itmp,nwread,iwelyr,frcuse,Qwrtot
       1          7         29   -0.04241     0.00000       1.08     47 1941 VG  4            6.20    28.33 VCY00010006S01E020642003550
       1          7         29   -0.04241     0.00000       1.08     47 1941 VG  4            6.20    28.32 VCY00010006S01E020542003600
       1          5         23   -0.05065     0.00000       0.61     35 1941 VG  4            4.33    22.68 VCD00010005S01W260235351700
       1          5         23   -0.05065     0.00000       0.61     35 1941 VG  4            4.34    22.68 VCD00010005S01W260434951700
       1          5         23   -0.05065     0.00000       0.61     35 1941 VG  4            4.33    22.68 VCD00010005S01W260335201700
       1         13         34   -0.01483     0.00000       1.03     55 1941 VG  4           12.99    33.07 VCY00030007S02E030100504920
       1         20         37   -0.14412     0.00000       0.51     71 1941 VG  4           19.38    36.60 VCY00040008S03E071233002100
       1         20         37   -0.14412     0.00000       0.68     71 1941 VG  4           19.48    36.91 VCY00040008S03E070127500500
       1          6          9   -0.20600     0.00000       0.83     13 1941 VG  4            5.42     8.48 VCD00040005S03W330330752769
       1         20         37   -0.14412     0.00000       0.65     71 1941 VG  4           19.58    36.93 VCY00040008S03E070222000350
       1          7         30   -0.15853     0.00000       0.38     47 1941 VG  2            6.38    29.01 VCY00080006S01E011232505230
       1          5         18   -0.13813     0.00000       1.19     28 1941 VG  3            4.56    17.06 VCD00110005S02W2501NWNWSW
       1          5         14   -0.17818     0.00000       0.48     20 1941 VS  3            4.13    13.19 VCD00090005S02W290146004260
       1          5         14   -0.17818     0.00000       0.37     20 1941 VS  3            4.48    13.13 VCD00090005S02W290227254600
       1          6         26   -0.12086     0.00000       0.90     42 1942 VG  3            5.69    25.25 VWS00280005S01E3201NCS2N2SW
       1         20         35   -0.12293     0.00000       0.32     67 1952 AG  3           19.18    34.78 A0009050008S02E110743501150
       1          5         18   -0.15194     0.00000       1.21     28 1953 AG  3            4.69    17.81 A0011520005S02W2502SWNESE
       1          7         30   -0.11021     0.00000       0.43     47 1953 AG  2            6.36    29.01 A0012990006S01E010234005230
       1          4         16   -0.10774     0.00000       0.51     26 1953 AG  3            3.56    15.31 A0015050005S02W2201NWNESW
       1          6         12   -0.13537     0.00000       0.74     16 1953 AG  3            5.16    11.51 A0015450005S03W360144502600
(Note: only the first 20 of 388 water rights in the data file wrrepub.wel are shown here)
     287          0       1978     1.0000     37.4270                                 Itmp,nwread,iwelyr,frcuse,Qwrtot
     295          0       1979     1.0000     38.5350
     298          0       1980     1.0000     38.8670
     309          0       1981     1.0000     40.6950
     310          0       1982     1.0000     41.2030
     316          0       1983     1.0000     42.2060
     318          0       1984     1.0000     42.3300
     318          0       1985     1.0000     42.3300
     323          0       1986     1.0000     42.8260
     329          0       1987     1.0000     43.8290
     345          0       1988     1.0000     47.6500
     355          0       1989     1.0000     48.8230
     375          0       1990     1.0000     51.3110
     379          0       1991     1.0000     51.8400
     386          0       1992     1.0000     52.2620
     387          0       1993     1.0000     52.2670
     388          0       1994     1.0000     52.4890
```

6. Representing spatial variability with SWBAVG or HRUAVG

We recently extended SWAT's virtual subbasin capability to include calculating HRU weights and to account for both time-varying HRU factors and spatial dependencies. These recent developments are presented in the companion report. Previously, these added capabilities were provided by first simulating each HRU with a single execution of SWAT. This was followed by running SWBAVG to take a spatially weighted average over the subbasins for each HRU; summarize recharge to groundwater and tributary inflow to a stream network; and convert each hydrologic term from SWAT's units as a water volume per unit area (mm) to MODFLOW's units as a flow rate. Despite recent developments, the previous approach may still be applied in case it is preferred. This approach is covered in this chapter.

Fig. 6.1 outlines the procedure for coordinating SWAT and MODFLOW simulations according to this three-step approach, in which one of the two programs SWBAVG or HRUAVG can be used for the middle step. These steps are summarized as follows; equation numbers refer to the companion report.

1. Hydrologic terms for SWAT's soil water balance are accumulated and written to a file to be used in specifying fluxes for MODFLOW's solution in each time step. This is implemented by subroutine SUMSTEP, which is called by modified versions of SWAT's subroutines Writed, Writem, and Writea, to summarize SWAT's results for daily, monthly, and annual time steps.

2. The second component of the linkage applies the HRU concept to represent the hydrologic effects of spatial heterogeneity within subbasins simulated by SWAT. A statistical model for spatial heterogeneity is provided by coordinating the execution of SWAT with a separate program, SWBAVG. Alternatively, this function can be performed in SWAT by making use of SWAT's virtual subbasin capability. We have extended This capability by installing options to calculate virtual subbasin areas and to update these calculated areas during the simulation to reflect changing areas of HRU factors. One of these is the area of shallow groundwater. By incorporating its temporal variation into the virtual subbasin areas, the SWAT-MODFLOW linkage can be used to simulate a two-way coupling. SWAT's Control Codes input file was extended to provide the data required for SWAT to evaluate spatial weights for the HRUs.

SWBAVG (or, alternatively, HRUAVG) can apply three intermediate operations to coordinate SWAT and MODFLOW. These can now be incorporated into execution of SWAT, which simplifies the overall procedure for linking SWAT and MODFLOW. These intermediate steps are the following:

1. Soil water-atmosphere simulation: SWAT (v. 99.2)

For each HRU, run SWAT as follows:
- For each day of the simulation period:
  - At beginning of aquifer solution time step: If Iopshl > 0, read evap. from shallow gw summary written by MODFLOW For each subbasin;
  - For each subbasin:
    - Run lumped watershed model code;
    - Accumulate results over aquifer solution time step;
  - At the end of each aquifer solution time step (daily, monthly, or annual, specified by Control Code Ipd), call **Sumstep** to write HRU summary (called from modified subr. Writed, Writem, or Writea,

2. Take average over HRUs: SWBAVG

Read extended version of Control Codes input file to specify areal fractions of soils, land uses, and land forms, used to calculate spatial weights for HRUs;

For each aquifer solution time step:
- If shallow gw is represented by the HRUS (scheme 3): Read shallow gw fraction for each subbasin from the summary written by MODFLOW;
- Calculate spatial weights (subr. SUBWTS) for each subbasin;
- For each HRU:
  - Read balance file written by SWAT (subr. Sumstep) for each subbasin;
  - For each subbasin:
    - For each hydrologic component:
      - Accumulate a weighted average over all HRUs;

- Specify terms for MODFLOW (tributary inflow, recharge, irrigation demand) in terms of the HRU averages; and convert to flow rates; Write HRU-averaged flow rates for each subbasin;

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 and SWBAVG on a subsequent run (subr. SWB2BD);
- Call optional packages (invoked in Name file): RSDX (calculate residuals for simulated heads) and POSTX (write postprocessing results).

Fig. 2.2. Procedure to coordinate SWAT (v.99.2) and MODFLOW-96 using SWBAVG or HRUAVG as an intermediate program to average HRUs and convert results for input to MODFLOW.

a) Apply an optional procedure for the HRU method of representing spatial heterogeneity as an alternative to SWAT's "virtual subbasin" approach. This procedure includes calculating HRU weights with subroutine Subwts and taking a spatially weighted average over HRUs simulated by SWAT. This alternative method is used as the basis for three HRU schemes that are presented below. SWBAVG reads an extended form of SWAT's Control Codes input file to specify areal fractions for HRU factors (soils, land uses, and geomorphic features)

b) Transform the terms simulated by SWAT from cumulative volumes per unit area [L] to flow rates [L/T^3] in the system of units specified for MODFLOW's simulation. 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

$$cQ\Delta t = dfA, \tag{2.8}$$

where c is a length conversion factor. This operation is combined with item 3

c) Combine hydrologic terms simulated by SWAT for each subbasin 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.

3. The third component uses the spatially averaged results given by SWBAVG for each subbasin to specify boundary conditions over the grid of MODFLOW's spatially distributed stream-aquifer solution (Section 5). This component is provided by the package SWBX, which was written for this purpose, in conjunction with the packages WELX and STRX, which are modified versions of MODFLOW's WELL and STREAM packages, respectively.

In each time step of MODFLOW's simulation, the added package SWBX reads the HRU-averaged results from SWBAVG as flow rates for each subbasin, and distributes the flow rates over the corresponding stream reaches and aquifer grid cells. WELX and STRX are coordinated with SWBX to supply the irrigation pumping demand simulated by SWAT with spatially distributed diversions from surface and ground water sources.

Input and output files for SWBAVG and HRUAVG

An extended version of the Control Codes input data file is read by SWBAVG or HRUAVG. In addition to the first six records read by SWAT, SWBAVG reads data required to calculate spatial weights for each HRU and to identify the HRUs and associated "balance" files (*.bal) produced by SWAT. HRUAVG provides the additional capability to determine whether specified HRUs are either missing or unnecessary.

SWBAVG takes a spatially weighted average over the HRUs, converts the resulting hydrologic components from SWAT's units (volume/area) to flow rates for input to MODFLOW. Four files may be written, based on a name associated with the HRU scheme, such as "hru1".

*.cod (In): see input instructions in the User's Manual.

*.bal (Out): same form as the input *.bal files written by subr. Sumstep in SWAT; spatially weighted averages are taken over the HRUs for each subbasin in each time step and converted from volumes per unit area (SWAT's units) to flow rates (MODFLOW's units).

*.dep (Out): same form as the *.dep files written in SWAT; spatially weighted averages are taken over the HRUs. Basinwide averages of the hydrologic components of soil water balance (volumes per unit area) in each time step.

*.sum (Out): basinwide average of the HRU-averaged flow rates written to the *.bal file.

*.wts (Out): summary of spatial weights corresponding to each HRU in each time step; written if the extended Control Codes input option **Iprwts** > 0. If **Iprwts** = 1, write a basinwide average for each weight in each time step; if **Iprwts** = 2, write the HRU weights for each subbasin in each time step. These weights are written for comparisons and analysis, and are not used as input to the other programs.

6.1. SWBAVG

SWBAVG is very similar to the form in which it was documented in User and Programmer manuals for the previous SWAT-MODFLOW linkage based on SWAT-94.2 and MODFLOW-88 (Perkins and Sophocleous, 1999a and 1999b). SWBAVG has been demonstrated for the three HRU schemes that were applied to the Lower Republican River basin schemes as described in the Progress Report (January 2000). However, these HRU schemes were based on assumptions that are specific to the Lower Republican River basin and which are not necessarily applicable to other basins. Applying these three HRU schemes to other basins required generalizing assumptions relevant to those basins.

Program SWBAVG reads a slight variation on the extended Control Codes (*.cod) input file read by Swat and Hruavg; the revised set of instructions is given below. The extended Control Codes input file specifies the type of HRU scheme (Iophru = 1, 2, or 3; see definitions below), areal fractions of subbasins used to calculate HRU weights, number of HRUs, names of HRUs, and identification of each HRU's soil type, land use, and aquifer status (no aquifer, deep aquifer, or shallow aquifer). For each time step, SWBAVG calculates HRU weights and writes them to a file (*.wts). SWBAVG uses these weights to calculate a weighted average over the HRUs for each time step, subbasin, and hydrologic component. SWBAVG is run for HRU scheme 1, redirecting keyboard responses from file hruf1.cod as follows:

Swbavg <hru1.cod >hru1.jnl

The input variable **casavg** is read from the Control Codes input file to specify the names of both the weights file (*.wts) written by Swat and the balance file (*.bal) to be written by SWBAVG (or HRUAVG) containing the weighted averages of the component HRUs simulated by Swat. The resulting balance file can be read by MODFLOW (SWBX package). For example, if casavg is given as "hru1", the balance file name = "hru1.bal". Format of the output file is given by Input Instructions for the added Modflow package, SWBX.

Input data for either program SWBAVG or HRUAVG is provided by Swat's modified Control Codes input file to specify the number of HRUs and their names. Instructions are provided above; see "Instructions for Control Codes input file."

SWBAVG calculates the HRU weights, which may optionally be written to a file, and uses the weights to take a weighted average over the HRUs simulated by SWAT and written to balance files. Subroutine Subwts sums the weights over HRUs for each subbasin as a check on the HRU scheme specified by the Control Codes input file. Weights for each subbasin should add to 1 The HRU-averaged hydrologic components are then used to calculate flow rates for ground water recharge, tributary inflow, irrigation pumping, potential evaporation, and change in watershed storage. Theas are written to a balance file that is read by the SWBX package of MODFLOW.

The recently developed program HRUAVG provides a more general means of specifying spatial heterogeneity for a watershed than SWBAVG, which was designed primarily for application to a particular watershed, the Lower Republican River Basin. If the reader is interested in the more general approach of HRUAVG, the section reviewing SWBAVG may be skipped without loss of continuity. Input instructions for HRUAVG are the same as for SWAT, as provided above (Ch. 4).

In addition to records 1-6 that are read by SWAT (see previous chapter under "Input instructions for modified control codes"), SWBAVG reads data records 7-13 as labeled in the example shown below (file hru1.cod). These data are used by SWBAVG to take spatially weighted averages over HRUs simulated by SWAT to represent spatial heterogeneity with respect to soil type and land use within subbasins.

Record items 7-13 specify the HRU scheme, individual HRUs, and their properties as they pertain to the calculation of HRU weights, spatial averaging of HRUs simulated by SWAT for each hydrologic component, combination of hydrologic components to specify ground water recharge and tributary inflow; and conversion of HRU-averaged results simulated by SWAT from hydrologic depths (volumes per unit area) to flow rates for input to MODFLOW.

Extended Control Codes (*.cod) input (items 7 to 13)

In addition to records 1-6, SWAT, SWBAVG, or HRUAVG can read data records 7-13 (below) These data are used to calculate HRU weights, take spatially weighted averages over HRUs simulated by SWAT, and to specify flux conditions for MODFLOW's stream-aquifer solution as flow rates.

Record items 7-13 specify the HRU scheme, individual HRUs, and their properties as they pertain to the calculation of HRU weights, spatial averaging of HRUs simulated by SWAT for each hydrologic component, combination of hydrologic components to specify ground water recharge and tributary inflow; and conversion of HRU-averaged results simulated by SWAT from hydrologic depths (volumes per unit area) to flow rates for input to MODFLOW.

Item 7a is read if Iopmod > 0; the remaining items are read if Iopwts > 0.

If Iopwts > 0, all of the the following input data are read by the added SWAT subroutine Readwts from the extended Control Codes input file. If Iopwts = 0, these data may be read instead by program SWBAVG or HRUAVG. The first of these options is based on recent changes to incorporate the capability of HRUAVG into SWAT, allowing spatial weights to be calculated by SWAT in terms of soil, land use, and subsurface factors as the simulation proceeds.

SWBAVG example. Control codes input file hru1.cod: HRU scheme 1

```
hru1.cod (15 HRUs, cn2=72) 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   1
                                                                                Ipdvar
                                                                                Ipdvab
                                                                                Ipdvas
   0   1   1 ' '  ' '   !(3i4,2a)': iopshl itmuni Itmuni nambal namshl
   1   1   2   9 'hru1' !(3i4,a)': iophru iopwts iprwts nsubs hrunam (read in SWBAVG)
5,2,3,1,15,nsoils,numaqf,numuse,numreg,numhru
'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !(soilnm(j),j=1,nsoils)
   1      0.092   0.471    0.099     0.338      0.
   2      0.191   0.064    0.402     0.342      0.
   3      0.098   0.637    0.132     0.052    0.081
   4      0.126   0.543    0.054     0.274    0.004
   5      0.043   0.745      0.      0.086    0.126
   6         0.   0.741    0.176     0.059    0.024
   7         0.   0.869    0.022        0.    0.108
   8         0.   0.697    0.279        0.    0.024
   9         0.   0.630    0.021        0.    0.348
    'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! land fractions fsub, fp, faqf, fshl
 1    0.22015   0.0343    0.0733    0.1875
 2    0.04909   0.0031    0.2053    0.2
 3    0.20435   0.0064    0.2368    0.0625
 4    0.08729   0.0268    0.0924    0.
 5    0.05282   0.0021    0.2106    0.09091
 6    0.08247   0.0000    0.0122    0.
 7    0.10945   0.0131    0.0829    0.
 8    0.11788   0.04139   0.0257    0.
```

```
9     0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd'   ! (usenam(j),j=1,numuse)
     'crpfrc'  'dstirr'               !cropland fractions fc, firr
1     0.5962    0.139694
2     0.5463    0.060835
3     0.6281    0.315519
4     0.5737    0.039543
5     0.7164    0.100748
6     0.6113    0.010547
7     0.6753    0.094522
8     0.5316    0.039287
9     0.4991    0.182079
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.9 4.2 4.3 4.5 4.4 4.8 4.7
  hru Soil  Mgt  Aqf   namhru      HRU description
    1    1    1    2  'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.) (case, file name)
    2    1    2    2  'carr-irm'          (irrigated corn)
    3    1    3    2  'carr-pam'          (grass: range and pasture)
    4    2    1    2  'cret-wsm'   soil 2
    5    2    2    2  'cret-irm'
    6    2    3    2  'cret-pam'
    7    3    1    2  'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
    8    3    2    2  'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
    9    3    3    2  'hshd-pam'
   10    4    1    2  'kips-wsm'   soil 4
   11    4    2    2  'kips-irm'
   12    4    3    2  'kips-pam'
   13    5    1    2  'muir-wsm'   soil 5
   14    5    2    2  'muir-irm'
   15    5    3    2  'muir-pam'
```

Specifying a case that incorporates SWAT's "virtual subbasin" approach

If the model executed by Swat represents spatial variability by way of virtual subbasins, as described by Mamillapalli et al. (1996), then the simplest means of providing a data link to Modflow is to set Iopmod = 2 in the modified Control Codes input file, in which case the added Swat subroutine Sumstep writes a summary file that can be read by the added Modflow package, SWBX, thereby eliminating the need to run SWBAVG as an intermediate step.

Alternatively, the input data for this file can also be used to specify cases in which SWAT's "virtual subbasin" capability is used to represent spatial heterogeneity in the modeled basin. In this case, the HRU averaging function of SWBAVG is not needed, since this is done in SWAT. The remaining functions of SWBAVG are applied to convert SWAT's hydrologic summary to a form for input to MODFLOW. This approach is also presented in Ch. 2 of the Final Report in the section entitled "SWAT's virtual subbasin capability and the SWAT-MODFLOW linkage." This is illustrated by the example input file (below), and by the final example in the Readme file (readme99.doc) for HRU scheme 1. Affected input data to specify this option are the following (also identified in the "Readme" file example):

b) set **numhru** = 1, which refers in this case to the single balance file written by SWAT that is to be read, not to the number of HRUs simulated by SWAT;
c) use **namhru**(1) to specify the name of the HRU-averaged case simulated by SWAT instead of the name of the first HRU for cases in which SWBAVG calculates spatial weights and takes a weighted average over HRUs that are simulated separately by

SWAT. The associated indices, defined for line item 13c of Input Instructions mentioned above, can all be set to 1 and are ignored for this case.

The three HRU schemes 1-3 have all been tested and appear to function correctly for the Lower Republican River basin model.

SWBAVG example. Control codes input file hru1v.cod

The following example represents cases in which Swat applies the virtual subbasin approach to represent spatial variability within subbasins, and SWBAVG is used to combine hydrologic terms to specify tributary flows and recharge, and convert depths (volumes per unit area) to flow rates for input to Modflow.

```
hru1v.cod (1 HRU, 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   1
                                                                                Ipdvar
                                                                                Ipdvab
                                                                                Ipdvas
   0   1   1 ' '   ' '   ! '(3i4,2a)': iopshl itmuni Itmuni nambal namshl
   1   1   2   9 'hru1v' ! '(3i4,a)': iophru iopwts iprwts nsubs hrunam (read in SWBAVG)
5,2,3,1,1,nsoils,numaqf,numuse,numreg,numhru
'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !(soilnm(j),j=1,nsoils)
   1      0.092    0.471     0.099     0.338      0.
   2      0.191    0.064     0.402     0.342      0.
   3      0.098    0.637     0.132     0.052   0.081
   4      0.126    0.543     0.054     0.274   0.004
   5      0.043    0.745       0.      0.086   0.126
   6         0.    0.741     0.176     0.059   0.024
   7         0.    0.869     0.022        0.   0.108
   8         0.    0.697     0.279        0.   0.024
   9         0.    0.630     0.021        0.   0.348
     'subfrc'   'pndfrc'   'aqffrc'   'shlfrc'   ! land fractions fsub, fp, faqf, fshl
 1    0.22015    0.0343     0.0733     0.1875
 2    0.04909    0.0031     0.2053     0.2
 3    0.20435    0.0064     0.2368     0.0625
 4    0.08729    0.0268     0.0924     0.
 5    0.05282    0.0021     0.2106     0.09091
 6    0.08247    0.0000     0.0122     0.
 7    0.10945    0.0131     0.0829     0.
 8    0.11788    0.04139    0.0257     0.
 9    0.07649    0.02827    0.2504     0.
'nonirrig','irrig','grasslnd'   ! (usenam(j),j=1,numuse)
     'crpfrc'   'dstirr'                 !cropland fractions fc, firr
 1    0.5962     0.139694
 2    0.5463     0.060835
 3    0.6281     0.315519
 4    0.5737     0.039543
 5    0.7164     0.100748
 6    0.6113     0.010547
 7    0.6753     0.094522
 8    0.5316     0.039287
 9    0.4991     0.182079
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.9 4.2 4.3 4.5 4.4 4.8 4.7
  hru Soil  Mgt  Aqf    namhru       HRU description
    1    1    1    2   'carr-wsm'    soil 1 (wheat/sorghum/fallow rot.) (case, file name)
[end of input]


Other HRUs left out of the above (artificial) example:
    2    1    2    2   'carr-irm'           (irrigated corn)
    3    1    3    2   'carr-pam'           (grass: range and pasture)
    4    2    1    2   'cret-wsm'    soil 2
    5    2    2    2   'cret-irm'
    6    2    3    2   'cret-pam'
    7    3    1    2   'hshd-wsm'    soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
    8    3    2    2   'hshd-irm'   (collapses 6 hrus for the two soils into 3 hrus)
```

```
 9    3    3    2  'hshd-pam'
10    4    1    2  'kips-wsm'    soil 4
11    4    2    2  'kips-irm'
12    4    3    2  'kips-pam'
13    5    1    2  'muir-wsm'    soil 5
14    5    2    2  'muir-irm'
15    5    3    2  'muir-pam'
```

Use of extended Control Codes input data by SWBAVG

Some regional differences exist within subbasins for the model of the Lower Republican River basin, which the SWAT-MODFLOW code was designed to simulate. These differences are associated with the alluvial and upland components of the basin as summarized in the table below. The approaches taken to represent these spatial heterogeneities within subbasins are designated as HRU schemes 1-3, which are reviewed here.

Table 6.1. Summary of regional characteristics within each subbasin

	Region 1	Region 2
Region characteristics	Uplands	Alluvial valley
basin areal fraction (approx.)	0.875	0.125
land uses	dryland crops, grassland	irrigated crops, grassland
soil types	Crete, Hasting, Hedville, Kipson	Carr, Muir
subsurface underlying soils	bedrock	alluvial aquifer

6.2. HRUAVG: a more general version of SWBAVG

A comparison of the methods implemented by SWBAVG and HRUAVG is presented in the Final Report. Some of the following description of HRUAVG was taken from the same report. This program is intended to allow generalizing the HRU schemes 1-3 from the specific application to the Lower Republican River basin using SWBAVG, although it has only been tested by comparison with SWBAVG for this basin. Further testing by application to other watersheds may uncover problems with the approach implemented by HRUAVG or may otherwise show that program revisions are indicated.

Comparison of input format for HRUAVG and SWBAVG

In addition to records 1-6 that are read by SWAT (above), SWBAVG reads data records 7-13 as labeled in the example shown below (file hru1.cod). These data are used by SWBAVG to take spatially weighted averages over HRUs simulated by SWAT to represent spatial heterogeneity with respect to soil type and land use within subbasins. Record items 7-13 specify the HRU scheme, individual HRUs, and their properties as they pertain to the calculation of HRU weights, spatial averaging of HRUs simulated by

SWAT for each hydrologic component, combination of hydrologic components to specify ground water recharge and tributary inflow; and conversion of HRU-averaged results simulated by SWAT from hydrologic depths (volumes per unit area) to flow rates for input to MODFLOW.

The input data formats for the two programs SWBAVG and HRUAVG are very similar. Additions to the input format are identified by bold type (below). Differences between the two are the following.

1. The land use and subsurface features are specified as separate factors (items 9-10 of input instructions); special combinations of the two factors are not devised as they are for SWBAVG, which was designed for application to a specific watershed (Lower Republican River basin).

2. Each type of soil, land use and subsurface feature can be associated either with a particular region or be specified as spatially independent, which is denoted by a region index of zero (items 12d-12f). The table of properties associated with each HRU also identifies the region (item 13c). For SWBAVG, only a restricted case of regionalized soil types can be specified; SWBAVG cannot represent a mix of spatially dependent and spatially indendent soil types.

3. HRUAVG provides a check on the list of defined HRUs by making an initial pass through all combinations of HRU factors and writing a list of all HRUs with nonzero spatial weights. This list identifies any HRUs that are missing from the user-specified list that should be included, as well as any unnecessary HRUs with zero or negligible weights that may be eliminated. In fact, HRUAVG may be run in order to automatically identify the HRUs that must be simulated with SWAT. If the number of HRUs is specified as zero (**numhru** = 0, item 13), HRUAVG writes a list of HRUs that are to be simulated by SWAT.

Section 2.5 of the SWAT-MODFLOW Integration Report describes how the data read from the extended Control Codes input file (*.cod) are used by HRUAVG to represent spatial variability.

HRUAVG example. Control codes input file hru1gen.cod: HRU scheme 1

```
hru1gen.cod (15 HRUs, 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    1
                                                                                  Ipdvar
                                                                                  Ipdvab
                                                                                  Ipdvas
   0   1   1  ' '  ' '  ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl              (6
   1   1   2   9 'hru1gn2' ! '(3i4,a)': nsubs iophru iprwts hrunam (read in HRUAVG)   (7
5,3,4,1,15,                         nsoils,numaqf,numuse,numreg,numhru                (8
 'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !(soilnm(j),j=1,nsoils)
 1  0.092    0.471    0.099     0.338   0.
 2  0.191    0.064    0.402     0.342   0.
 3  0.098    0.637    0.132     0.052   0.081
 4  0.126    0.543    0.054     0.274   0.004
 5  0.043    0.745    0.        0.086   0.126
 6  0.       0.741    0.176     0.059   0.024
```

```
7  0.        0.869    0.022     0.        0.108
8  0.        0.697    0.279     0.        0.024
9  0.        0.630    0.021     0.        0.348
'bedrock','deep gw','shallow gw'              !(aqfnam(j),j=1,numaqf)
     'subfrc'   'pndfrc'   'aqffrc'   'shlfrc'   ! land fractions
1     0.22015    0.0343     0.0733     0.1875
2     0.04909    0.0031     0.2053     0.2
3     0.20435    0.0064     0.2368     0.0625
4     0.08729    0.0268     0.0924     0.
5     0.05282    0.0021     0.2106     0.09091
6     0.08247    0.0000     0.0122     0.
7     0.10945    0.0131     0.0829     0.
8     0.11788    0.04139    0.0257     0.
9     0.07649    0.02827    0.2504     0.
'nonirrig','irrig','grasslnd','urban'      !(usenam(j),j=1,numuse)
     'crpfrc'   'dstirr'    'urbfrc'
1     0.5962     0.139694     0.
2     0.5463     0.060835     0.
3     0.6281     0.315519     0.
4     0.5737     0.039543     0.
5     0.7164     0.100748     0.
6     0.6113     0.010547     0.
7     0.6753     0.094522     0.
8     0.5316     0.039287     0.
9     0.4991     0.182079     0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.9 4.2 4.3 4.5 4.4 4.8 4.7
  hru Soil  Use  Aqf      namhru (read region ID only if Numreg>1) HRU description
    1    1    1    2     'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.) (case, file name)
    2    1    2    2     'carr-irm'          (irrigated corn)
    3    1    3    2     'carr-pam'          (grass: range and pasture)
    4    2    1    2     'cret-wsm'   soil 2
    5    2    2    2     'cret-irm'
    6    2    3    2     'cret-pam'
    7    3    1    2     'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
    8    3    2    2     'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
    9    3    3    2     'hshd-pam'
   10    4    1    2     'kips-wsm'   soil 4
   11    4    2    2     'kips-irm'
   12    4    3    2     'kips-pam'
   13    5    1    2     'muir-wsm'   soil 5
   14    5    2    2     'muir-irm'
   15    5    3    2     'muir-pam'
```

6.3. Coordinating execution of SWAT, SWBAVG, and MODFLOW

The test shown below may be run to demonstrate execution of programs SWAT, SWBAVG, HRUAVG, and MODFLOW. Commands shown in brackets are implied and do not need to be entered. The syntax for the COPY command in the DOS window may vary between operating systems. Batch files hru1.bat, hru2.bat, and hru3.bat presume that the command "copy <source> <destination>" will overwrite files without protest. If the form "copy/y <source> <destination>" is required, use the alternative batch files hru1y.bat, hru2y.bat, and hru3y.bat.

From directory \gh\test99_2\, run:

```
hru1[.bat]      Run SWAT and SWBAVG for HRU scheme 1.
..\swbavg  <hru1.cod  >>hru1.jnl      (run SWBAVG by itself)
..\hruavg  <hru1gen.cod  >>hru1gen.jnl      (run HRUAVG)
hru2[.bat]      Run HRU scheme 2 (after running hru1)
hru3[.bat]      Run HRU scheme 3 (after hru2 and modflx96 for hru2, below)
```

From directory \gh\test99_2\modflw\, run Modflow-96 and specify Name file:

```
\gh\modflx96          (enter hru1.nam, hru2.nam, or hru3.nam)
```

HRU scheme 1, Lower Republican R.: a one-way coupling of SWAT and MODFLOW

The sequence of operations followed to simulate HRU scheme 1 is outlined in terms of program execution and the key input files associated with the scheme. This procedure is outlined in Fig. 2.2 and in Fig. 2.5 of the Final Report, Ch. 2.

1.Run SWAT (swt99opt.exe) to simulate 15 HRUs, all of which are based on Control Codes input file HRU1.COD.

2. Run SWBAVG to prepare input to MODFLOW; use the extended version of Swat's Control Codes input file (*.cod) as input to Swbavg to specify the HRU scheme. Specify input file as redirected keyboard input. To run Swbavg for HRU scheme 1 from \gh\test99_2\, enter "swbavg <hru1.cod" as shown in batch file (below). Note: HRUAVG can replace SWBAVG in this step. To run Hruavg for HRU scheme 1 from \gh\test99_2, enter "hruavg <hru1gen.cod". Swbavg with Hru1.cod and Hruavg with Hru1gen.cod produce equivalent results. Both files Hru1.cod and Hru1gen specify the case names associated with the HRUs executed by SWAT; see listing of Hru1.cod (below).

2 (alternate). HRUAVG may be used in place of SWBAVG. This may be desirable, particularly for applying HRU schemes 2 and 3 or similar schemes to represent spatial heterogeneity in watersheds other than those for which SWBAVG was designed. In the present example, file hru1gen.cod would be used as input to HRUAVG in place of file hru1.cod, which is read by SWBAVG; see the User's Manual for a description of input to HRUAVG and a listing of file hru1gen.cod as an example.

3. Run MODFLOW-96 (modflx96.exe) as modified for the SWAT-MODFLOW linkage.

Steps 1 and 2 of HRU scheme 1 are executed by running the batch file HRU1.BAT, listed below, from the directory \gh\test99_2\. This HRU scheme consists of fifteen simulations of HRUs to be run by SWAT, beginning with the HRU named "carr-wsm" (below). SWBAVG is then run to take a spatially weighted average over the HRUs. The extended Control Codes input file, hru1.cod, specifies the names of the HRUs to be averaged, and is also listed below.

Note: The batch file shown below is executed by entering "hru1" in a DOS window. Note that the "copy /y" syntax may not be defined in all DOS environments, and may need to be replaced by "copy".

File HRU1.BAT:

```
rem  HRU scheme 1: Simulate hrus with deep aquifer. file hru_deep.gw
rem  sets Ipurk(j)=0 for each subbasin; file hru1.cod specifies HRU
rem  scheme 1 for SWAT and SWBAVG which are executed below.

copy /y hru_deep.gw h2.gw
```

```
copy /y   hru1.cod hru.cod

copy /y   carr-wsm.cio file.cio
..\swt99opt >hru1.jnl
copy /y   carr-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   carr-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   cret-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   cret-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   cret-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   hshd-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   hshd-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   hshd-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   kips-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   kips-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   kips-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   muir-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   muir-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   muir-pam.cio file.cio
..\swt99opt >>hru1.jnl

..\swbavg <hru1.cod >>hru1.jnl
```

The above batch file executed in approximately 25 minutes on a 90 MHz pc, and produced file hru1.bal for input to MODFLOW.

<u>Example File.cio for case carr-irm</u>

This file specifies the input files associated with the second case executed by the above batch file, including the land use (file corn.mgt) and soil type (file carr.sol) associated with the HRU. This file is documented in the SWAT v.99.2 manual.

```
Republican River Project, KS case carr-irm irrig99.mco(wsf=.99), h2.gw(gwht=2m)
hru.cod; ponds

 carr-irm.std    out10.sbs    out10.rch    out10.rsv    out10.lqo    out10.pso
   out10.eve      crop.dat     till.dat     pest.dat     hru.cod      in10.bsn
    lwqfile       in10.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
     corn.mgt optional.wus   h2.gw       in10.wgn      WQLDAT      1   1
  2  0       0   slp102.sub   in102.rte      in2.pnd     in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn      WQLDAT      4   3
  3  0       0   slp103.sub   in103.rte      in3.pnd     in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn      WQLDAT      4   3
  4  0       0   slp104.sub   in104.rte      in4.pnd     in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn      WQLDAT      4   3
```

```
5  0        0  slp105.sub    in105.rte      in5.pnd     in101.chm    carr.sol
    corn.mgt optional.wus    h2.gw       in10.wgn       WQLDAT       9   4
6  0        0  slp106.sub    in106.rte      in6.pnd     in101.chm    carr.sol
    corn.mgt optional.wus    h2.gw       in10.wgn       WQLDAT       9   4
7  0        0  slp107.sub    in107.rte      in7.pnd     in101.chm    carr.sol
    corn.mgt optional.wus    h2.gw       in10.wgn       WQLDAT       9   4
8  0        0  slp108.sub    in108.rte      in8.pnd     in101.chm    carr.sol
    corn.mgt optional.wus    h2.gw       in10.wgn       WQLDAT       5   2
9  0        0  slp109.sub    in109.rte      in9.pnd     in101.chm    carr.sol
    corn.mgt optional.wus    h2.gw       in10.wgn       WQLDAT       5   2
```

7. Examples: HRU schemes 1-3 (Lower Republican R. Basin)

These three schemes are run under the control of batch files assuming that scheme 1 is run first, followed by scheme 2 and then scheme 3. HRU schemes 1 and 2 are independent, but one or the other must precede HRU scheme 3 so that MODFLOW produces a summary of shallow ground water evaporation and areal extent; this summary is required as input to SWAT and SWBAVG for HRU scheme 3.

The following directories are used; see Readme99.doc for a more complete summary of the directories used for the updated SWAT-MODFLOW linkage.

d:\gh\ location of executable files:

- swt99opt.exe: SWAT (v.99.2, modified for SWAT-MODFLOW linkage);
- swbavg.exe: SWBAVG: HRU averaging; meets requirements for model of Lower Republican River basin.
- hruavg.exe: HRUAVG: HRU averaging; a more general version of SWBAVG that is intended for use with other watersheds; hru schemes 1-3 for the Lower Repub. R. have been run with HRUAVG for comparison, and show small differences from results of SWBAVG.
- modflx96.exe MODFLOW-96 (v.3.3), with packages for SWAT-MODFLOW linkage.

d:\gh\test99_2\ location of input files and for running SWAT and SWBAVG using batch files HRU1.BAT, HRU2.BAT, and HRU3.BAT corresponding to HRU schemes 1-3.
d:\gh\test99_2\inbase\ location of input files to MODFLOW-96 for HRU schemes 1-3.
d:\gh\test99_2\modflw\ location to run MODFLOW-96 for HRU schemes 1-3

7.1. Specifying hydrologic response unit (HRU) schemes 1-3

The land use/land form classification is the distinguishing feature of the three HRU schemes, and are alternatives for representing spatial heterogeneity with respect to both land use and the bedrock or aquifer underlying the soil profile. Soil type, land use, and land form classes for each of the three HRU schemes are listed below.

In HRU scheme 1, soil type and land use are treated as independent factors, and all HRUs are simulated by SWAT with the assumption that the soil profile is underlain by an aquifer with deep ground water over the entire domain of each subbasin. This assumption is then modified in SWBAVG, where contributions of hydrologic components to recharge and tributary flow depend on the areal fractions of each subbasin with a soil profile underlain by bedrock or ground water. The inconsistency between conceptual models applied in SWAT and SWBAVG regarding the material underlying the soil profile may represent a source of distortion in the simulation.

In HRU schemes 2 and 3, the conceptual models of a soil profile with underlying bedrock or ground water are consistent between SWAT and SWBAVG. HRUs simulated by SWAT are distinguished by a soil profile either underlain by bedrock or by ground water. This distinction is specified by the added input **ipurk** in the *.gw input file for SWAT, and by the input **idxaqf** in the extended *.cod input file for SWBAVG (or the more general HRUAVG). The case of bedrock is represented by a modification to subroutine purk() in which percolation out of the soil profile is conditionally set to zero, depending on the value of **ipurk**. If percolation out of the soil profile is held to zero, then soil water content, lateral subsurface flow, and evaporation show compensating increases.

HRU scheme 3 further distinguishes HRUs with ground water underlying the soil profile as either deep or shallow ground water. This distinction is also specified by **ipurk** in the *.gw input file for SWAT and by **idxaqf** for SWBAVG or HRUAVG. Deep ground water is assumed to have a negligible effect on soil water content due to upflow from ground water. This scheme requires specifying the following: (a) for SWAT, the rate of upflow from ground water for corresponding HRUs with shallow ground water; (b) for SWBAVG, the areal fractions of shallow and deep ground water components within each subbasin, which are used to calculate HRU weights. The data necessary for both SWAT and SWBAVG is provided by previous execution of MODFLOW. This procedure is a form of successive approximation that can be initialized by HRU schemes 1 or 2, in which all ground water is assumed to be deep. In SWAT, the upflow from ground water given by MODFLOW is converted to a daily volume per unit area for each subbasin and distributed over the soil profile in subroutine Evap_gw, which is called by a modified version of subroutine Subbasin. SWBAVG calculates HRU weights in each time step, which allows the weights to vary over time with the areal fraction of shallow ground water in each subbasin as the ground water elevation responds to hydrologic conditions.

<u>HRU Scheme 1</u>

18 combinations: 6 soils, 3 land uses, 1 subsurface type (alluvial valley and uplands are not distinguished by HRUs. Entire basin is assumed to be underlain by deep gw for SWAT simulation; areal fraction of each subbasin actually underlain by groundwater is used to determine whether flux out of soil profile is treated as groundwater recharge or as additional tributary inflow.

Soils (*.sol)	Land uses (*.mgt)	Subsurface (*.gw)
1 Carr.sol	1 3-wsf.mgt	1 deep_hru.gw (Ipurk = 0)
2 Crete.sol	2 corn.mgt	
3 Hastings.sol	3 pasture.mgt	
4 Hedville.sol		
5 Kipson.sol		
6 Muir.sol		

<u>HRU Scheme 2</u>

Spatial dependence of land uses, soil types, and subsurface features with respect to the alluvial valley, which occupies about 1/8 of the basin land area, is recognized as follows

4 alluvial valley combinations: 2 soils, 2 land uses, 1 subsurf. type

Soils (*.sol)	Land uses (*.mgt)	Subsurface (*.gw)
Carr.sol	corn.mgt	deep_hru.gw
Muir.sol	pasture.mgt	

8 combinations outside the alluvial valley: 4 soils, 2 land uses, 1 subsurf. type

Crete.sol	3-wsf.mgt	shal_hru.gw (Ipurk = – 1)
Hastings.sol	pasture.mgt	
Hedville.sol		
Kipson.sol		

<u>HRU Scheme 3</u>

This builds on scheme 2 by dividing alluvial gw into deep and shallow components. HRUs outside the alluvial valley are the same as for HRU scheme 2.

8 alluvial valley combinations: 2 soils, 2 land uses, 2 subsurf. types

Soils (*.sol)	Land uses (*.mgt)	Subsurface (*.gw)
Carr.sol	corn.mgt	deep_hru.gw (Ipurk = 0)
Muir.sol	pasture.mgt	shal_hru.gw (Ipurk = 1)

Scheme 1.soil types and land uses are treated as spatially independent

The following illustrates the procedure followed to simulate HRU schemes 1-3 for the Lower Republican River basin with the updated version of the SWAT-MODFLOW linkage based on SWAT v.99.2 and MODFLOW v.88.

<u>Conditions specified for SWAT-MODFLOW linkage by file HRU1.COD:</u>

ipd=0 (hru1.cod): monthly time steps for stream-aquifer solution

numhru=15 (hru1.cod): number of HRUs to be simulated by SWAT and averaged by SWBAVG

iophru=1 (hru1.cod): basic HRU scheme (soils and land uses assumed independent; alluvial/upland heterogeneity is ignored.

ipurk(j)=0 (hru_deep.gw): an aquifer is assumed to underlie the entire basin (standard SWAT assumption);

auto_swf(j) = 0.65 (corn.mgt): set soil water content threshold equal to 0.65 as a fraction of available soil water capacity; irrigation is triggered if soil water content is below this threshold during the growing season.

auto_dmx = 12.7 (corn.mgt): limit daily irrigation depth to a maximum of 12.7 mm.

nsoils=5 (hru1.cod): six soils are defined for SWAT, but for SWBAVG, Hasting and Hedville soils are combined, since they occur in separate subbasins (Hasting in subbasins 1-4, Hedville in subbasins 6-9, neglecting the small component in subbasin 3). By combining these two soils for SWBAVG, the number of required simulations is reduced from 18 to 15 (five soils, three land uses; see below).

numuse=3

Modified input files for SWAT are listed below. See the SWAT v.99.2 manual for their descriptions; modifications of the files are documented above under "Modified SWAT input instructions."

Simulating HRU schemes 1-3 using SWBAVG

The following HRUs from scheme 1, the cases with a soil profile underlain by deep groundwater, also apply to scheme 2 and don't need to be re-run under SWAT to be used in the average taken by SWBAVG; however, they are associated with region 2, the alluvial valley, in HRU scheme 2, whereas only one region is defined for HRU scheme 1.

hru	Soil	Mgt	Aqf	namhru	Reg	HRU1	HRU2	HRU description
2	1	2	2	'carr-irm'	2	y	y	alluvial: (irrigated corn)
3	1	3	2	'carr-pam'	2	y	y	(grass: range, pasture)
5	5	2	2	'muir-irm'	2	y	y	alluvial: (irrigated corn)
6	5	3	2	'muir-pam'	2	y	y	(grass: range, pasture)

Similarly, the following HRUs from scheme 2, the cases for uplands with a soil profile underlain by bedrock, also apply to scheme 3 and don't need to be rerun under SWAT:

hru	Soil	Mgt	Aqf	namhru	Reg	HRU1	HRU2	HRU description
9	2	1	1	'cret-wsb'	1	n	y	upland: wheat/sorghum/fallow
10	2	4	1	'cret-pab'	1	n	y	grass (range and pasture)
11	4	1	1	'kips-wsb'	1	n	y	upland: wheat/sorghum/fallow
12	4	4	1	'kips-pab'	1	n	y	grass (range and pasture)
13	3	1	1	'hshd-wsb'	1	n	y	upland: wheat/sorghum/fallow
14	3	4	1	'hshd-pab'	1	n	y	grass (range and pasture)

This leaves only the following four HRUs, the cases for a soil profile underlain by shallow ground water, to be run with SWAT for HRU scheme 3:

hru	Soil	Mgt	Aqf	namhru	Reg	HRU1	HRU2	HRU description
1	1	5	3	'carr-irs'	2	n	n	shallow gw, alluv: irrigated corn
3	1	6	3	'carr-pas'	2	n	n	shallow gw, alluv: grass (range/pasture)
5	5	5	3	'muir-irs'	2	n	n	shallow gw, alluv: irrigated corn
7	5	6	3	'muir-pas'	2	n	n	shallow gw, alluv: grass (range/pasture)

Program HRUAVG, the more general successor to SWBAVG, can automate the identification of HRUs required for the above HRU schemes; for further explanation, see the Final Report, Methodology: HRUAVG.

<u>Description of land use class names corresponding to HRU schemes 1-3</u>

The following land use class labels were used for the Lower Republican River basin model, but are otherwise arbitrary input labels (item 10, above).

HRU scheme 1 (iophru = 1): 1 region (numreg = 1) and 3 land uses (numuse =3):

    usenam(1) = 'nonirrig' !no irrig. e.g. wheat,sorghum,fallow rotation
    usenam(2) = 'irrig'   !irrigated crops
    usenam(3) = 'noncrop'   !range, pasture, and other noncrop land uses

HRU scheme 2 (iophru = 2): 2 regions (numreg = 2) and 4 land uses (numuse =4) to distinguish alluvial and upland components of basin:

    usenam(1) = 'wsf-upld' !non-irrigated crops in upland, no aquifer
    usenam(2) = 'irr-aqfr' !irrigated cropland over alluvial aquifer
    usenam(3) = 'grs-aqfr' !grasslands over alluvial aquifer
    usenam(4) = 'grs-upld' !grass in upland, no aquifer

HRU scheme 3 (iophru = 3): 2 regions (numreg = 2) and 6 land uses (numuse =6) to further distinguish deep and shallow ground water in alluvial component of basin:

    usenam(1) = 'wsf-upld' !non-irrigated crops in upland, no aquifer
    usenam(2) = 'irr-aqdp' !irrigated cropland, deep alluvial aquifer
    usenam(3) = 'grs-aqdp' !grasslands, deep alluvial aquifer
    usenam(4) = 'grs-upld' !grass in upland, no aquifer
    usenam(5) = 'irr-aqsh' !irrigated cropland, shallow alluvial aquifer
    usenam(6) = 'grs-aqsh' !grasslands, shallow alluvial aquifer

<u>File Hru1.cod: input to SWAT and SWBAVG for HRU scheme 1</u>

File Hru1.cod is listed above as an example to illustrate the input instructions for SWBAVG. Items 1-6 are read only by SWAT; the entire file (items 1-13) is read by SWBAVG.

<u>File Hru1gen.cod: input to SWAT and HRUAVG for HRU scheme 1</u>

If the more general program HRUAVG is used in place of SWBAVG, the input file Hru1.cod is replaced by Hru1gen.cod, which is listed above as an example to illustrate the input instructions for HRUAVG. Items 1-6 are read only by SWAT; the entire file (items 1-13) is read by HRUAVG.

<u>File hru_deep.gw: specifies default subsurface features assumption (ipurk(j) = 0)</u>

```
Groundwater Data File ! 1/9  gw(19): h2.gw (gwht= 2m)  (zero perc to "deep" aqf)
       2.0       0.0       0.0       .15        0.      0.00      0.00       0.0
         0         0         0


      read (19,5000) titldum
      read (19,'(10f10.4)') gwht(i), shallst(i), alpha_bf(i), gw_spyld(i),     &
     &                delay(i), gw_revap(i), rchrg_dp(i), revapmn(i)
      read (19,'(10f10.4)',iostat=eof) deepst(i), gwqmn(i) !! ,ipurk(i)

record 1: (8f10.4)
      gwht   shallst  alpha_bf  gw_spyld     delay  gw_revap  rchrg_dp   revapmn
record 2: (2f10.4,i10)
    deepst     gwqmn      ipurk
```

<u>File Hru_bedr.gw, input to SWAT for HRUs with bedrock underlying soil profile</u>

```
Groundwater Data File ! 1/9  gw(19): h2.gw (gwht= 2m)  (zero perc to "deep" aqf)
       2.0       0.0       0.0       .15        0.      0.00      0.00       0.0
         0         0        -1
```

File Hru_shal.gw, input to SWAT for HRUs with shallow ground water

```
Groundwater Data File ! 1/9  gw(19): h2.gw (gwht= 2m)  (zero perc to "deep" aqf)
       2.0      0.0      0.0      .15      0.      0.00      0.00      0.0
       0        0        1
```

File 3-wsf.mgt: specifies 3-year rotation of wheat, sorghum and fallow (no irrigation)

```
Crop Data for Wheat-Sorghum-Fallow: 3-wsf.mgt
1  3   0   0   5   0  10    0.05    100.     90.
   6  25           5           10

   5   1           1 1650.00   3
  10  10           5           3

   9  20           1 1650.00  10
```

```
Winter crops are represented as follows.  Set igro=1 to indicate plants
are growing from the first of the year.  Specify the harvest operation
(5) first; follow this with the planting operation (1)
```

File corn.mgt: specifies daily irrigation limit and soil water content threshold

```
Management Data File ! 1/17 mgt(17): corn.mgt
0  1   0   0   5   0   0
   5  07          10                 0.98            0.65      12.7
   5  07           1   1900.   2
   9  07           5           2
```

File pasture.mgt: represents uncultivated land

```
Management Data File ! 1/17 mgt(17): pasture.mgt: pasture
0  1   0   0   5   0   0
   3   1           1   1650.  37
  10  31           5          37

crop code 37: summer pasture
```

Operation sequence for HRU scheme 1

0. Prior to setting up and running SWAT, if the HRU scheme is sufficiently complex, it may be desirable to run HRUAVG (the more general successor to SWBAVG) in order to automate the identification of HRUs and the spatial weight each contributes. For further explanation, see Final Report, Methodology: HRUAVG.

1.Run SWAT to simulate 15 HRUs, all of which are based on Control Codes input file HRU1.COD.

2. Run SWBAVG to prepare input to MODFLOW:

a) Read file HRU1.COD. In addition to data read by SWAT, this file contains the data necessary to identify the HRUs simulated by SWAT that are to be averaged, and specifies the areal fractions for soil types, land use, and alluvial valley for each subbasin.

For each time step of MODFLOW's stream-aquifer simulation, do the following:

b) Based on the areal fractions read from HRU1.COD, SWBAVG calls subr. Subwts to calculate the HRU weights for each subbasin.
c) Take a weighted average over the HRUs.
d) Combine HRU-averaged hydrologic components into tributary inflows, ground water recharge, and irrigation demand for each subbasin; and convert these into flow rates for input to MODFLOW.

2 (alternate). HRUAVG may be used in place of SWBAVG. This may be desirable, particularly for applying HRU schemes 2 and 3 or similar schemes to represent spatial heterogeneity in watersheds other than those for which SWBAVG was designed. In the present example, file hru1gen.cod would be used as input to HRUAVG in place of file hru1.cod, which is read by SWBAVG.

3. Run MODFLOW as modified for the SWAT-MODFLOW linkage.

The above steps 1 and 2 are executed by running the following batch file hru1.bat from directory \gh\test99_2\. In this batch file, copies are made of files hru_deep.gw, hru1.cod, and carr-wsm.cio with generic names. After SWAT has been executed for all HRUs, SWBAVG is run to calculate weighted averages for each hydrologic component of the HRUs.

```
rem simulate hrus with deep aquifer: set ipurk(j) = 0 for each subbasin

copy /y hru_deep.gw h2.gw

copy /y   hru1.cod hru.cod

copy /y   carr-wsm.cio file.cio
..\swt99opt >hru1.jnl
copy /y   carr-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   carr-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   cret-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   cret-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   cret-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   hshd-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   hshd-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   hshd-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   kips-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   kips-irm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   kips-pam.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   muir-wsm.cio file.cio
..\swt99opt >>hru1.jnl
copy /y   muir-irm.cio file.cio
```

```
..\swt99opt >>hru1.jnl
copy /y   muir-pam.cio file.cio
..\swt99opt >>hru1.jnl

..\swbavg <hru1.cod >>hru1.jnl
```

Example File.cio: file carr-irm.cio

See the SWAT v.99.2 manual for a description of this file.

```
Republican River Project, KS case carr-irm irrig99.mco(wsf=.99), h2.gw(gwht=2m)
hru.cod; ponds

 carr-irm.std    out10.sbs    out10.rch    out10.rsv    out10.lqo    out10.pso
    out10.eve    crop.dat     till.dat     pest.dat     hru.cod      in10.bsn
     lwqfile     in10.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
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      1   1
  2  0      0   slp102.sub   in102.rte     in2.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      4   3
  3  0      0   slp103.sub   in103.rte     in3.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      4   3
  4  0      0   slp104.sub   in104.rte     in4.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      4   3
  5  0      0   slp105.sub   in105.rte     in5.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      9   4
  6  0      0   slp106.sub   in106.rte     in6.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      9   4
  7  0      0   slp107.sub   in107.rte     in7.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      9   4
  8  0      0   slp108.sub   in108.rte     in8.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      5   2
  9  0      0   slp109.sub   in109.rte     in9.pnd    in101.chm   carr.sol
     corn.mgt optional.wus   h2.gw       in10.wgn     WQLDAT      5   2
```

Execution time for the above batch file was approximately 25 minutes on a 90 MHz pc. This produced file hru1.bal for input to MODFLOW.

Step 3: execution of MODFLOW given results on file Hru1.bal:

Step 3, execution of MODFLOW, is shown for the latest version of MODFLOW-96. Here, the input file HRU1.BAL is produced by the modified version of SWAT 99.2 and SWBAVG, and is used for input to both versions of MODFLOW. Execution time for this run of MODFLOW on the 90 MHz pc was approx. 1 minute. MODFLOW-96 was executed for the same case with the following command:

```
\gh\test99_2\modflw> \gh\modflx96
```

MODFLOW prompts for the NAME file, and the name Hru1.nam is given. File Hru1.nam, below, is analogous to the response file shown above for running Modflow-88. Additional postprocessing packages, RSD and POS, and the associated files invoked under the "Postprocessor" comment line were optional and are independent of the SWAT-MODFLOW linkage, and are documented separately (P&S, 2000d).

```
LIST 6   hru1.lst                        case name (~.log, ~.prn, ~.rsp)
BAS   1  ..\inbase\bcase_t4.bas                Monthly Basic package
OC   69  ..\inbase\rpbase.oc                   Output control
BCF  61  ..\inbase\kbase20b.bcf                Block-centered flow
RCH  67  ..\inbase\matrix1.rch                 67 Recharge
EVT  65  ..\inbase\repsurf.evt                 Evapotranspiration
PCG  68  ..\inbase\model1bs.pcg                preconditioned conjugate gradient
#
# Non-standard Modflow-88 modules substituted for standard Modflow-96 modules,
# modified for coordination with the added SWB module:
#
WEL  62  ..\inbase\wrrepub.wel                 Well: groundwater use
STR  70  ..\inbase\rptest.str                  monthly Streamflow, Ks=0.54 ft/day
#
# If invoking WELX and STRX to be used with SWB (below), open:
#   2, iostrm: Str2fm (stream routing details for istrbd = 0 or 2)
DATA 117   hru1.stm
#   3, ioreg: Str2fm, Wel2stp: record of pumping rates that have been
#       reduced due to low saturated thickness or streamflow.
DATA 218   hru1.reg
#
#               Modules added to Modflow-96:
#
#               SWB: 2 input files are specified, *.swb and *.bal:
SWB  66  ..\inbase\rptest96.swb               Soil water balance
#   1, iobal: Soil Water Balance simulation produced by SWAT and SWBAVG:
DATA  116   hru1cn72.bal
#   5, ioshl: Swb2bd, summary of evaporation from shallow gw for each subbasin.
#   This file can be used as input to a subsequent watershed simulation
#   (e.g. by SWAT) to implement a two-way coupling by successive approximation.
DATA 220   hru1.shl
#   4, ioswm: Swb2bd, combined surface & gw budget terms
DATA 219   hru1.swm
```

Execution under the modified MODFLOW-88 version, which was used in the linkage with SWAT 94.2 as described in Perkins and Sophocleous (1999a,b), is shown for comparison with the updated version (above). The modified version of MODFLOW-88 was executed as follows:

d:\gh\test99_2\hru1> \gh\modflow <hru1.rsp >hru1.jnl

<u>Response file Hru1.rsp contents:</u>

File hru1.rsp specifies MODFLOW input files, located in directory d:\gh\ars\swat99_2\inbase\: File hru1.rsp is listed as follows:

```
hru1                                 case name (~.log, ~.prn, ~.rsp)
..\inbase\bcase_t4.bas               .bas unit   1 Monthly Basic pkg
..\inbase\kbase20b.bcf               .bcf unit  61 Block-centered flow
..\inbase\wrrepub.wel                .wel unit  62 Well: gw, surf. use
..\inbase\repsurf.evt                .evt unit  65 Evaporation from gw
..\inbase\rptest.swb                 .swb unit  66 Soil water balance
..\inbase\matrix1.rch                .rch unit  67 Recharge
..\inbase\model1bs.pcg               .pcg unit  68 precond. conj. grad.
..\inbase\rpbase.oc                  .oc  unit  69 Output control
..\inbase\rptest.str                 .str unit  70 Stream package
```

Input file for the SWBX package

The following input file is read for the updated HRU schemes 1-3 by the SWBX package, which is documented above. It specifies execution options and initializes associations of subbasin outflows with stream reaches, and subbasin domains with grid cells.

```
9,    nwshed   (balance file: use case name); file c:\gh\test\inbase\rptest.swb
' ',     1     3     1     1 0.00     1     0 0.0    nambal,irropt,ievopt,ioprch,rchmpy,
                                                    evapir,welmpy,iadcod,frseep
  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 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 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 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 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 3 5 5 5 3 7 7 7 7 7 7 9 9 9
 2 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 3 7 7 7 7 7 9 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 3 3 7 7 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 0 2 2 2 2 3 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 0 3 3 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 3 8 8 3 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 3 3 8 8 8 8 8 8 3 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 3 8 8 8 8 8 8 8 8 8 3 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 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 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 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 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 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 0 0 8 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 0 0 0 8 8 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 0 0 0 8 8 8 8 8 8 8 8 8 8 8 0 0 0 0
```

Scheme 2. represent alluvial valley and upland as separate regions

numhru=10 (hru2.cod): number of HRUs simulated by SWAT and averaged by SWBAVG.

iophru=2 (hru2.cod): alternate HRU scheme: disaggregate alluvial and upland components of subbasin; associate soil types and land uses with alluvial/upland heterogeneity.

Table 7.1 shows the land use areal fractions given by equations 2.27a-d.

Table 7.1. HRU scheme 2 land use fractions

sub-basin	upland, dry crop c1	alluv, irrig c2	alluv, grass c3	upland, grass c4	=sum
1	0.566024	0.030176	0.043124	0.360676	1
2	0.461782	0.084518	0.120782	0.332918	1
3	0.530614	0.097486	0.139314	0.232586	1
4	0.535661	0.038039	0.054361	0.371939	1
5	0.629700	0.086700	0.123900	0.159700	1
6	0.606277	0.005023	0.007177	0.381523	1

7	0.641172	0.034128	0.048772	0.275928	1
8	0.521020	0.010580	0.015120	0.453280	1
9	0.396015	0.103085	0.147315	0.353585	1

Batch file Hru2.bat to run SWAT and SWBAVG for HRU scheme 2:

```
rem file hru2.bat: to run HRU scheme 2.

rem   Note: HRUs with deep aquifer have already been run as part of
scheme 1;
rem   only the additional HRUs with bedrock underlying soil profile need
to
rem   be run.  For these, set ipurk(j) = -1 by copying file hru_bedr.gw
rem   onto h2.gw:

copy /y hru_bedr.gw h2.gw

rem   Note: file hru2.cod differs from hru1.cod only for data read by
Swbavg;
rem   data read by SWAT are the same for all three schemes except
rem   possibly for title in line 1.  For Swbavg, Hru2.cod identifies
rem   four HRUs previously run as part of scheme 1 with deep gw and six
rem   additional HRUs that are run with bedrock underlying soil.

rem copy /y   hru2.cod hru.cod

copy /y   cret-wsb.cio file.cio
..\swt99opt  >hru2.jnl
copy /y   cret-pab.cio file.cio
..\swt99opt >>hru2.jnl

copy /y   kips-wsb.cio file.cio
..\swt99opt >>hru2.jnl
copy /y   kips-pab.cio file.cio
..\swt99opt >>hru2.jnl

copy /y   hshd-wsb.cio file.cio
..\swt99opt >>hru2.jnl
copy /y   hshd-pab.cio file.cio
..\swt99opt >>hru2.jnl

..\swbavg <hru2.cod >>hru2.jnl
```

File Hru2.cod, input to SWAT and SWBAVG

```
hru2.cod (10 HRUs, cn2=72) iophru=2; swminf=0.65,ipet=0(Priestley-Taylor) iopshl=0
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
                                                                                Ipdvar
                                                                                Ipdvab
                                                                                Ipdvas
   0   1   1 ' '  ' '     !free (3i4,2a): iopshl itmuni Lenuni nambal namshl          (6
   2   1   2   9 'hru2'   !(4i4,a): iophru iopwts iprwts nsubs hrunam                  (7
5,2,4,2,10,nsoils,numaqf,numuse,numreg,numhru                                          (8
'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir'  !(soilnm(j),j=1,nsoils)
   1      0.092   0.471    0.099     0.338     0.
   2      0.191   0.064    0.402     0.342     0.
   3      0.098   0.637    0.132     0.052   0.081
   4      0.126   0.543    0.054     0.274   0.004
   5      0.043   0.745      0.      0.086   0.126
   6         0.   0.741    0.176     0.059   0.024
```

```
   7        0.   0.869   0.022        0.   0.108
   8        0.   0.697   0.279        0.   0.024
   9        0.   0.630   0.021        0.   0.348
    'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! land fractions fsub, fp, faqf, fshl
 1   0.22015  0.0343   0.0733   0.1875
 2   0.04909  0.0031   0.2053   0.2
 3   0.20435  0.0064   0.2368   0.0625
 4   0.08729  0.0268   0.0924   0.
 5   0.05282  0.0021   0.2106   0.09091
 6   0.08247  0.0000   0.0122   0.
 7   0.10945  0.0131   0.0829   0.
 8   0.11788  0.04139  0.0257   0.
 9   0.07649  0.02827  0.2504   0.
'wsf-upld','irr-aqfr','grs-aqfr','grs-upld' !numuse, (crpnam(j),j=1,numuse)
    'crpfrc'  'dstirr'                !cropland fractions fc, firr
 1   0.5962   0.139694
 2   0.5463   0.060835
 3   0.6281   0.315519
 4   0.5737   0.039543
 5   0.7164   0.100748
 6   0.6113   0.010547
 7   0.6753   0.094522
 8   0.5316   0.039287
 9   0.4991   0.182079
'Uplands','Alluvial'  !numreg, (regnam(j),j=1,numreg): HRU schemes 2,3
 1  0.908    0.092    !alluvial area given by sum of Carr & Muir soil areas
 2  0.808    0.191
 3  0.821    0.179
 4  0.871    0.130
 5  0.831    0.169
 6  0.976    0.024
 7  0.891    0.108
 8  0.976    0.024
 9  0.651    0.348
          2       1        1       1       2     !(ireg_sol(j),j=1,nsoils)
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.3 4.2 4.3 4.5 4.4 4.8 4.7
 hru  Soil  Use  Aqf  Reg    namhru  part of HRU1?  HRU description
   2    1    2    2  'carr-irm'  2     y  alluvial:  (irrigated corn)
   3    1    3    2  'carr-pam'  2     y  (deep gw)  (grass: range and pasture)
   5    5    2    2  'muir-irm'  2     y  alluvial:  (irrigated corn)
   6    5    3    2  'muir-pam'  2     y  (deep gw)  (grass: range and pasture)
   9    2    1    1  'cret-wsb'  1     n   upland: wheat/sorghum/fallow
  10    2    4    1  'cret-pab'  1     n           grass (range and pasture)
  11    4    1    1  'kips-wsb'  1     n   upland: wheat/sorghum/fallow
  12    4    4    1  'kips-pab'  1     n           grass (range and pasture)
  13    3    1    1  'hshd-wsb'  1     n   upland: wheat/sorghum/fallow
  14    3    4    1  'hshd-pab'  1     n           grass (range and pasture)
```

Execution of MODFLOW given SWAT and SWBAVG results (file Hru2.bal):

c:\gh\modflow <Hru2.rsp >Hru2.jnl

Response file Hru2.rsp contents:

(same as file Hru1.rsp with case name = hru2)

Scheme 3. disaggregate deep and shallow ground water within alluvial region

Table 7.2, below, shows the areal fractions of shallow ground water that can be used with the land use fractions shown in Table 7.1 for HRU scheme 2 to obtain those required for HRU scheme 3 according to equations (2.28a-f). Coupling of Swat and Modflow is based on shallow ground water evaporation and area given on file Hru2.shl resulting from the uncoupled HRU scheme 2 (case Hru2, above).

Table 7.2. Beginning subbasin areal fractions of shallow ground water

sub-basin	active cells	shallow cells	shallow fraction	active fraction	areal fraction	noncon-trib. fract.	evap-gw,cfs	shallow dtw,ft	deep dtw,ft
1	16	3	0.18750	0.07325	0.22015	0.0343	6.58	3.91	22.2
2	10	2	0.20000	0.20532	0.04909	0.0031	1.52	3.56	19.29
3	48	4	0.08333	0.23675	0.20435	0.0064	1.14	4.98	27.23
4	8	0	0	0.09238	0.08729	0.0268	0	0	28.26
5	11	1	0.09091	0.20991	0.05282	0.0021	0.79	2.54	23.75
6	1	0	0	0.01222	0.08247	0	0	0	35.88
7	9	0	0	0.08288	0.10945	0.0131	0	0	17.56
8	3	0	0	0.02565	0.11788	0.0414	0	0	37.6
9	19	0	0	0.25037	0.07649	0.0283	0	0	20.48
basin	125	10	0.07293	0.12599	1	0.01994			

numhru=14 number of HRUs simulated by SWAT and averaged by SWBAVG.

iophru=3 alternate HRU scheme as variation on scheme 2: further disaggregate deep and shallow alluvial ground water components of subbasin; associate soil types and land uses with alluvial/upland heterogeneity as in HRU scheme 2.

<u>Batch file Hru3.bat to run SWAT and SWBAVG for HRU scheme 3:</u>

```
rem run HRU scheme 3, recognizing areas with bedrock, deep gw, and
shallow gw.
rem Notes:
rem 1. This batch file was run after HRU schemes 1 and 2 were run,
rem    so that HRUs run as part of those schemes are not run again.
rem 2. indiv. cio files refer to hru.cod and h2.gw.
rem    simulate hrus with shallow aquifer: set ipurk(j) = -1 for each
rem    subbasin
copy /y hru_shal.gw h2.gw
copy /y   hru3.cod hru.cod

copy /y   carr-irs.cio file.cio
..\swt99opt >hru3.jnl
copy /y   carr-pas.cio file.cio
..\swt99opt >>hru3.jnl
copy /y   muir-irs.cio file.cio
..\swt99opt >>hru3.jnl
copy /y   muir-pas.cio file.cio
..\swt99opt >>hru3.jnl


..\swbavg <hru3.cod >>hru3.jnl
```

<u>File Hru3.cod, input to Swat and Swbavg for HRU scheme 3</u>

```
hru3.cod (14 HRUs, cn2=72) iophru=3; swminf=0.65,ipet=0(Priestley-Taylor) iopshl=1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
                                                                                   Ipdvar
                                                                                   Ipdvab
                                                                                   Ipdvas
   1   1   1   ' '  'hru2.shl'     !free (3i4,2a): iopshl itmuni Lenuni nambal namshl (6
   3   1   2   9 'hru3'   !(4i4,a): iophru iopwts iprwts nsubs hrunam                (7
5,2,6,2,14,nsoils,numaqf,numuse,numreg,numhru                                         (8
'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir'         !(soilnm(j),j=1,nsoils)
   1      0.092   0.471    0.099     0.338      0.
```

```
   2      0.191   0.064    0.402     0.342      0.
   3      0.098   0.637    0.132     0.052    0.081
   4      0.126   0.543    0.054     0.274    0.004
   5      0.043   0.745      0.      0.086    0.126
   6         0.   0.741    0.176     0.059    0.024
   7         0.   0.869    0.022        0.    0.108
   8         0.   0.697    0.279        0.    0.024
   9         0.   0.630    0.021        0.    0.348
    'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! land fractions fsub, fp, faqf, fshl
 1    0.22015   0.0343   0.0733   0.1875
 2    0.04909   0.0031   0.2053   0.2
 3    0.20435   0.0064   0.2368   0.0625
 4    0.08729   0.0268   0.0924   0.
 5    0.05282   0.0021   0.2106   0.09091
 6    0.08247   0.0000   0.0122   0.
 7    0.10945   0.0131   0.0829   0.
 8    0.11788   0.04139  0.0257   0.
 9    0.07649   0.02827  0.2504   0.
'wsf-upld','irr-aqdp','grs-aqdp','grs-upld','irr-aqsh','grs-aqsh' !(usenam(j),j=1,numuse)
    'crpfrc'  'dstirr'                  !cropland fractions fc, firr
 1    0.5962    0.139694
 2    0.5463    0.060835
 3    0.6281    0.315519
 4    0.5737    0.039543
 5    0.7164    0.100748
 6    0.6113    0.010547
 7    0.6753    0.094522
 8    0.5316    0.039287
 9    0.4991    0.182079
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.3 4.2 4.3 4.5 4.4 4.8 4.7
'Uplands','Alluvial'  !(regnam(j),j=1,numreg): HRU schemes 2,3
 1  0.908     0.092   !alluvial area given by sum of Carr & Muir soil areas
 2  0.808     0.191
 3  0.821     0.179
 4  0.871     0.130
 5  0.831     0.169
 6  0.976     0.024
 7  0.891     0.108
 8  0.976     0.024
 9  0.651     0.348
          2       1        1        1       2     !(ireg_sol(j),j=1,nsoils)
  hru Soil  Mgt  Aqf  Reg    namhru   HRU1 HRU2  HRU description
    2    1    2    2  'carr-irm'   2     y y alluvial:  (irrigated corn)
    3    1    3    2  'carr-pam'   2     y y            (grass: range and pasture)
    5    5    2    2  'muir-irm'   2     y y alluvial:  (irrigated corn)
    6    5    3    2  'muir-pam'   2     y y            (grass: range and pasture)
    1    1    5    3  'carr-irs'   2     n n shallow gw, alluv: irrigated corn
    3    1    6    3  'carr-pas'   2     n n shallow gw, alluv:  grass (range/pasture)
    5    5    5    3  'muir-irs'   2     n n shallow gw, alluv: irrigated corn
    7    5    6    3  'muir-pas'   2     n n shallow gw, alluv: grass (range/pasture)
    9    2    1    1  'cret-wsb'   1     n y upland: wheat/sorghum/fallow
   10    2    4    1  'cret-pab'   1     n y         grass (range and pasture)
   11    4    1    1  'kips-wsb'   1     n y upland: wheat/sorghum/fallow
   12    4    4    1  'kips-pab'   1     n y         grass (range and pasture)
   13    3    1    1  'hshd-wsb'   1     n y upland: wheat/sorghum/fallow
   14    3    4    1  'hshd-pab'   1     n y         grass (range and pasture)
[end of input]
```

Execution of MODFLOW given SWAT and SWBAVG results (file Hru3.bal):

```
c:\gh\modflow <Hru3.rsp >Hru3.jnl
```

Response file Hru3.rsp contents:

This is the same as file Hru1.rsp with case name = hru3. MODFLOW writes file Hru3.shl, summary of shallow ground water area and evaporation flow rate, which could be used to update the results on file Hru2.shl that was used to run Swat (batch file Hru3.bat).

rptest.shl: summary of evaporation from shallow ground water

This file is written in Modflow by subroutine Swb2bd, part of the SWBX package. In Swat, it is opened and data for the first time step are read by subroutine Init_shl (called by subr. Simulate). At the end of each time step, data for the next time step are read by subroutine Sumstep after results for the current time step have been summarized. In the following listing, only data for the first time step, January 1977, are shown.

```
year  per   stp   sub   act shal  frc shall  frc activ   evap-gw  shal dtw  deep dtw
 1977     1     1     1   16     3 0.1875000 0.0732544      0.57       3.29      22.16
 1977     1     1     2   10     2 0.2000000 0.2053238      0.34       3.30      19.25
 1977     1     1     3   48     4 0.0833333 0.2367548      0.28       4.92      27.20
 1977     1     1     4    8     0 0.0000000 0.0923757      0.00       0.00      28.24
 1977     1     1     5   11     1 0.0909091 0.2099068      0.17       2.44      23.74
 1977     1     1     6    1     0 0.0000000 0.0122218      0.00       0.00      35.84
 1977     1     1     7    9     0 0.0000000 0.0828818      0.00       0.00      17.54
 1977     1     1     8    3     0 0.0000000 0.0256515      0.00       0.00      37.56
 1977     1     1     9   19     0 0.0000000 0.2503694      0.00       0.00      20.44
```

7.2. Using HRUAVG instead of SWBAVG to specify HRU schemes 1-3

Ex. 1. Control codes input file hru1gen.cod (specify HRU scheme 1 for HRUAVG)

```
hru1gen.cod (15 HRUs, 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   1
                                                                                  Ipdvar
                                                                                  Ipdvab
                                                                                  Ipdvas
   0   1   1  ' '  ' '  ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl                 (6
   1   1   2   9 'hru1gn2' ! '(3i4,a)': nsubs iophru iprwts hrunam (read in HRUAVG)    (7
5,3,4,1,15,nsoils,numaqf,numuse,numreg,numhru
 'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !(soilnm(j),j=1,nsoils)
 1  0.092   0.471    0.099     0.338   0.
 2  0.191   0.064    0.402     0.342   0.
 3  0.098   0.637    0.132     0.052   0.081
 4  0.126   0.543    0.054     0.274   0.004
 5  0.043   0.745    0.        0.086   0.126
 6  0.      0.741    0.176     0.059   0.024
 7  0.      0.869    0.022     0.      0.108
 8  0.      0.697    0.279     0.      0.024
 9  0.      0.630    0.021     0.      0.348
'bedrock','deep gw','shallow gw'        !(aqfnam(j),j=1,numaqf)
     'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! land fractions
 1     0.22015   0.0343    0.0733    0.1875
 2     0.04909   0.0031    0.2053    0.2
 3     0.20435   0.0064    0.2368    0.0625
 4     0.08729   0.0268    0.0924    0.
 5     0.05282   0.0021    0.2106    0.09091
 6     0.08247   0.0000    0.0122    0.
 7     0.10945   0.0131    0.0829    0.
 8     0.11788   0.04139   0.0257    0.
 9     0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd','urban'     !(usenam(j),j=1,numuse)
     'crpfrc'  'dstirr'   'urbfrc'
 1     0.5962    0.139694   0.
 2     0.5463    0.060835   0.
 3     0.6281    0.315519   0.
 4     0.5737    0.039543   0.
 5     0.7164    0.100748   0.
 6     0.6113    0.010547   0.
 7     0.6753    0.094522   0.
 8     0.5316    0.039287   0.
 9     0.4991    0.182079   0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.3 4.2 4.3 4.5 4.4 4.8 4.7
  hru Soil  Use  Aqf      namhru (read region ID only if Numreg>1) HRU description
    1    1    1    2     'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.) (case, file name)
    2    1    2    2     'carr-irm'          (irrigated corn)
    3    1    3    2     'carr-pam'          (grass: range and pasture)
    4    2    1    2     'cret-wsm'   soil 2
    5    2    2    2     'cret-irm'
    6    2    3    2     'cret-pam'
    7    3    1    2     'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
    8    3    2    2     'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
    9    3    3    2     'hshd-pam'
   10    4    1    2     'kips-wsm'   soil 4
   11    4    2    2     'kips-irm'
   12    4    3    2     'kips-pam'
   13    5    1    2     'muir-wsm'   soil 5
   14    5    2    2     'muir-irm'
   15    5    3    2     'muir-pam'
```

Ex. 2. Control codes input file hru2gen.cod (specify HRU scheme 2 for HRUAVG)

The regions associated with land uses and subsurface features are identified by the index arrays ireg_use and ireg_aqf, in addition to association of regions with soils given by ireg_sol as in SWBAVG. In addition, an urban land use fraction is specified.

```
hru2gen.cod (10 HRUs, cn2=75) iophru=2; swminf=0.65,ipet=0(Priestley-Taylor) iopshl=0
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
                                                                                     Ipdvar
                                                                                     Ipdvab
                                                                                     Ipdvas
   0    1    1   ' '  ' '   ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl             (6
   2    1    2    9 'hru2gn2'   ! '(3i4,a)':  nsubs iophru iprwts hrunam (read in HRUAVG) (7
5,3,4,2,10,                                nsoils,numaqf,numuse,numreg,numhru            (8
 'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !(soilnm(j),j=1,nsoils)
 1  0.092   0.471    0.099     0.338   0.
 2  0.191   0.064    0.402     0.342   0.
 3  0.098   0.637    0.132     0.052   0.081
 4  0.126   0.543    0.054     0.274   0.004
 5  0.043   0.745    0.        0.086   0.126
 6  0.      0.741    0.176     0.059   0.024
 7  0.      0.869    0.022     0.      0.108
 8  0.      0.697    0.279     0.      0.024
 9  0.      0.630    0.021     0.      0.348
'bedrock','deep gw','shallow gw'         !(aqfnam(j),j=1,numaqf)
     'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! aqfbas=0.1261
 1     0.22015   0.0343    0.0733    0.1875
 2     0.04909   0.0031    0.2053    0.2
 3     0.20435   0.0064    0.2368    0.0625
 4     0.08729   0.0268    0.0924    0.
 5     0.05282   0.0021    0.2106    0.09091
 6     0.08247   0.0000    0.0122    0.
 7     0.10945   0.0131    0.0829    0.
 8     0.11788   0.04139   0.0257    0.
 9     0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd','urban'     !(usenam(j),j=1,numuse)
     'crpfrc'  'dstirr'   'urbfrc'
 1     0.5962    0.139694    0.
 2     0.5463    0.060835    0.
 3     0.6281    0.315519    0.
 4     0.5737    0.039543    0.
 5     0.7164    0.100748    0.
 6     0.6113    0.010547    0.
 7     0.6753    0.094522    0.
 8     0.5316    0.039287    0.
 9     0.4991    0.182079    0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.3 4.2 4.3 4.5 4.4 4.8 4.7
'Uplands','Alluvial'  !(regnam(j),j=1,numreg): HRU schemes 2,3
 1  0.9267  0.0733    !alluvial area given by gw areal fraction of subbasin
 2  0.7947  0.2053
 3  0.7632  0.2368
 4  0.9076  0.0924
 5  0.7894  0.2106
 6  0.9878  0.0122
 7  0.9171  0.0829
 8  0.9743  0.0257
 9  0.7496  0.2504
      2        1        1        1      2      !(ireg_sol(j),j=1,nsoils)
      1        2        2                      !(ireg_aqf(j),j=1,numaqf)
      1        2        0        0             !(ireg_use(j),j=1,numuse)
  hru Soil  Mgt  Aqf  namhru      Region
    2    1    2    2  'carr-irm'    2 soil 1 deep alluvial: irrigated corn
    4    1    3    2  'carr-pam'    2        deep alluv.:  grass (range and pasture)
    6    5    2    2  'muir-irm'    2 soil 2 deep alluvial: irrigated corn
    8    5    3    2  'muir-pam'    2        deep alluv.: grass (range and pasture)
    9    2    1    1  'cret-wsb'    1 soil 3 upland: wheat/sorghum/fallow rotation
   10    2    3    1  'cret-pab'    1                grass (range and pasture)
   11    4    1    1  'kips-wsb'    1 soil 4 upland: wheat/sorghum/fallow rotation
   12    4    3    1  'kips-pab'    1                grass (range and pasture)
   13    3    1    1  'hshd-wsb'    1 soil 5 upland (Hasting 1-4, Hedville 6-9)
   14    3    3    1  'hshd-pab'    1                grass (range and pasture)
```

Ex. 3. Control codes input file hru3gen.cod (specify HRU scheme 3 for HRUAVG)

```
hru3gen.cod (14 HRUs, cn2=75) iophru=3; swminf=0.65,ipet=0(Priestley-Taylor) iopshl=1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
                                                                                 Ipdvar
                                                                                 Ipdvab
                                                                                 Ipdvas
   1   1   1  ' '  'hru2.shl'  ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl          (6
   3   1   2   9 'hru3gn2' ! '(3i4,a)': nsubs iophru iprwts hrunam (read in HRUAVG)    (7
5,3,4,2,14,nsoils,numaqf,numuse,numreg,numcmb (no. specified HRU factor combinations) (8
'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !(soilnm(j),j=1,nsoils)
 1  0.092   0.471    0.099     0.338   0.
 2  0.191   0.064    0.402     0.342   0.
 3  0.098   0.637    0.132     0.052   0.081
 4  0.126   0.543    0.054     0.274   0.004
 5  0.043   0.745    0.        0.086   0.126
 6  0.      0.741    0.176     0.059   0.024
 7  0.      0.869    0.022     0.      0.108
 8  0.      0.697    0.279     0.      0.024
 9  0.      0.630    0.021     0.      0.348
'bedrock','deep gw','shallow gw'                !(aqfnam(j),j=1,numaqf)
    'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! aqfbas=0.1261
 1     0.22015   0.0343    0.0733    0.1875
 2     0.04909   0.0031    0.2053    0.2
 3     0.20435   0.0064    0.2368    0.0625
 4     0.08729   0.0268    0.0924    0.
 5     0.05282   0.0021    0.2106    0.09091
 6     0.08247   0.0000    0.0122    0.
 7     0.10945   0.0131    0.0829    0.
 8     0.11788   0.04139   0.0257    0.
 9     0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd','urban'     !(usenam(j),j=1,numuse)
    'crpfrc'  'dstirr'   'urbfrc'
 1     0.5962    0.139694    0.
 2     0.5463    0.060835    0.
 3     0.6281    0.315519    0.
 4     0.5737    0.039543    0.
 5     0.7164    0.100748    0.
 6     0.6113    0.010547    0.
 7     0.6753    0.094522    0.
 8     0.5316    0.039287    0.
 9     0.4991    0.182079    0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.3 4.2 4.3 4.5 4.4 4.8 4.7
'Uplands','Alluvial'  !(regnam(j),j=1,numreg): HRU schemes 2,3
 1  0.9267  0.0733  !alluvial area given by active gridded aquifer area
 2  0.7947  0.2053
 3  0.7632  0.2368
 4  0.9076  0.0924
 5  0.7894  0.2106
 6  0.9878  0.0122
 7  0.9171  0.0829
 8  0.9743  0.0257
 9  0.7496  0.2504
     2        1        1        1       2        !(ireg_sol(j),j=1,nsoils)
     1        2        2                         !(ireg_aqf(j),j=1,numaqf)
     1        2        0        0                !(ireg_use(j),j=1,numuse)
  hru Soil  Mgt  Aqf    namhru    Reg HRU1 HRU2  HRU description
   2    1    2    2  'carr-irm'    2    y y   deep gw, alluv: irrig. corn
   3    1    3    2  'carr-pam'    2    y y            (grass: range and pasture)
   5    5    2    2  'muir-irm'    2    y y deep gw, alluv: irrigated corn
   6    5    3    2  'muir-pam'    2    y y            (grass: range and pasture)
   1    1    2    3  'carr-irs'    2    n n shallow gw, alluv: irrigated corn
   3    1    3    3  'carr-pas'    2    n n shallow gw, alluv:  grass (range/pasture)
   5    5    2    3  'muir-irs'    2    n n shallow gw, alluv: irrigated corn
   7    5    3    3  'muir-pas'    2    n n shallow gw, alluv: grass (range/pasture)
   9    2    1    1  'cret-wsb'    1    n y upland: wheat/sorghum/fallow
  10    2    3    1  'cret-pab'    1    n y         grass (range and pasture)
  11    4    1    1  'kips-wsb'    1    n y upland: wheat/sorghum/fallow
  12    4    3    1  'kips-pab'    1    n y         grass (range and pasture)
  13    3    1    1  'hshd-wsb'    1    n y upland: wheat/sorghum/fallow
  14    3    3    1  'hshd-pab'    1    n y         grass (range and pasture)
```

7.3. Example input for the Lower Republican R. model as virtual subbasins

The following data files are listed here as a supplement to the discussion of the Lower Republican River basin model in Chapter 4 of the SWAT-MODFLOW Integration Report, and also serve here as examples for the User's Manual.

SWAT input:
- Definition of HRUs: extended Control Codes (*.cod) input file for SWAT
- Routing of HRUs: Configuration (*.fig) input file for SWAT
- Specification of files for running SWAT: excerpt from SWAT File Control (*.cio) file.
- SWAT files specifying special model options: Corn.mgt and *.gw
- Summary of results from SWAT for input to Modflow: excerpt from *.bal file.

MODFLOW input:
- Input file for SWBX
- Excerpt from STREAM input file
- Excerpt from WELL input file
- Output from SWBX: summary of shallow gw depth/evap for each subbasin.

SWAT data files for HRU schemes 1-3 as virtual subbasins

Because of the space it takes, only the *.cio file for HRU scheme 1 is listed below, but with the *.fig and *.cod files it references, it illustrates how the *.cio files for HRU schemes 2 and 3 might be assembled. For a given geographically defined subbasin, all virtual subbasins refer to the same subbasin input files except for the files associated with the distinguishing features of the HRUs to be simulated. For the Lower Republican River basin model, these include up to six soils (*.sol), three land uses (*.mgt), and three groundwater (*.gw) input files. The subbasin (*.sub) input files specify the area associated with each virtual subbasin. Specifying these could be a tedious process for a model with a large number of virtual subbasins. For this model under HRU schemes 1-3, the number of virtual subbasins is 105, 70, and 90, respectively. This task was automated, as summarized at the beginning of Ch. 3.

File control input file Hru1virt.cio

```
Republican River Project, KS case hrultest irrig99.mco(wsf=.99), h2.gw(gwht=2m)
hru.cod; ponds

 hru1virt.std    out10.sbs    out10.rch    out10.rsv    out10.lqo    out10.pso
    out10.eve     crop.dat     till.dat     pest.dat hru1virt.cod     in10.bsn
     lwqfile  hru1virt.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  slp101a.sub   in101.rte      in1.pnd     in101.chm   carr.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   2  0        0  slp101b.sub   in101.rte      in1.pnd     in101.chm   carr.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   3  0        0  slp101c.sub   in101.rte      in1.pnd     in101.chm   carr.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   4  0        0  slp101d.sub   in101.rte      in1.pnd     in101.chm   crete.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   5  0        0  slp101e.sub   in101.rte      in1.pnd     in101.chm   crete.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   6  0        0  slp101f.sub   in101.rte      in1.pnd     in101.chm   crete.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   7  0        0  slp101g.sub   in101.rte      in1.pnd     in101.chm hastings.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   8  0        0  slp101h.sub   in101.rte      in1.pnd     in101.chm hastings.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
   9  0        0  slp101i.sub   in101.rte      in1.pnd     in101.chm hastings.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
  10  0        0  slp101j.sub   in101.rte      in1.pnd     in101.chm   kipson.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
  11  0        0  slp101k.sub   in101.rte      in1.pnd     in101.chm   kipson.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
  12  0        0  slp101l.sub   in101.rte      in1.pnd     in101.chm   kipson.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      1   1
  13  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   carr.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  14  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   carr.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  15  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   carr.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  16  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   crete.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  17  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   crete.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  18  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   crete.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  19  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm hastings.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  20  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm hastings.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  21  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm hastings.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  22  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   kipson.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  23  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   kipson.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  24  0        0   slp102.sub   in102.rte      in2.pnd     in101.chm   kipson.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  25  0        0   slp103.sub   in103.rte      in3.pnd     in101.chm   carr.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  26  0        0   slp103.sub   in103.rte      in3.pnd     in101.chm   carr.sol
      corn.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  27  0        0   slp103.sub   in103.rte      in3.pnd     in101.chm   carr.sol
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  28  0        0   slp103.sub   in103.rte      in3.pnd     in101.chm   crete.sol
     3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn      WQLDAT      4   3
  29  0        0   slp103.sub   in103.rte      in3.pnd     in101.chm   crete.sol
```

```
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
30  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  crete.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
31  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm hastings.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
32  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm hastings.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
33  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm hastings.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
34  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  kipson.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
35  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  kipson.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
36  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  kipson.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
37  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  muir.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
38  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  muir.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
39  0        0    slp103.sub   in103.rte     in3.pnd  in101.chm  muir.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
40  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  carr.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
41  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  carr.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
42  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  carr.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
43  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  crete.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
44  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  crete.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
45  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  crete.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
46  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm hastings.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
47  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm hastings.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
48  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm hastings.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
49  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  kipson.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
50  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  kipson.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
51  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  kipson.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
52  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  muir.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
53  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  muir.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
54  0        0    slp104.sub   in104.rte     in4.pnd  in101.chm  muir.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
55  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  carr.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
56  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  carr.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
57  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  carr.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
58  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  crete.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
59  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  crete.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
60  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  crete.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
61  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  kipson.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
62  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  kipson.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
63  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  kipson.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
64  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  muir.sol
    3-wsf.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
65  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  muir.sol
     corn.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
66  0        0    slp105.sub   in105.rte     in5.pnd  in101.chm  muir.sol
  pasture.mgt optional.wus  hru_deep.gw  in10.wgn     WQLDAT     4   3
67  0        0    slp106.sub   in106.rte     in6.pnd  in101.chm  crete.sol
```

```
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 68 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  crete.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 69 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  crete.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 70 0       0   slp106.sub   in106.rte     in6.pnd in101.chm hedville.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 71 0       0   slp106.sub   in106.rte     in6.pnd in101.chm hedville.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 72 0       0   slp106.sub   in106.rte     in6.pnd in101.chm hedville.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 73 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  kipson.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 74 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  kipson.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 75 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  kipson.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 76 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  muir.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 77 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  muir.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 78 0       0   slp106.sub   in106.rte     in6.pnd in101.chm  muir.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 79 0       0   slp107.sub   in107.rte     in7.pnd in101.chm  crete.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 80 0       0   slp107.sub   in107.rte     in7.pnd in101.chm  crete.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 81 0       0   slp107.sub   in107.rte     in7.pnd in101.chm  crete.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 82 0       0   slp107.sub   in107.rte     in7.pnd in101.chm hedville.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 83 0       0   slp107.sub   in107.rte     in7.pnd in101.chm hedville.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 84 0       0   slp107.sub   in107.rte     in7.pnd in101.chm hedville.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 85 0       0   slp107.sub   in107.rte     in7.pnd in101.chm  muir.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 86 0       0   slp107.sub   in107.rte     in7.pnd in101.chm  muir.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 87 0       0   slp107.sub   in107.rte     in7.pnd in101.chm  muir.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     9  4
 88 0       0   slp108.sub   in108.rte     in8.pnd in101.chm  crete.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 89 0       0   slp108.sub   in108.rte     in8.pnd in101.chm  crete.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 90 0       0   slp108.sub   in108.rte     in8.pnd in101.chm  crete.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 91 0       0   slp108.sub   in108.rte     in8.pnd in101.chm hedville.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 92 0       0   slp108.sub   in108.rte     in8.pnd in101.chm hedville.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 93 0       0   slp108.sub   in108.rte     in8.pnd in101.chm hedville.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 94 0       0   slp108.sub   in108.rte     in8.pnd in101.chm  muir.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 95 0       0   slp108.sub   in108.rte     in8.pnd in101.chm  muir.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 96 0       0   slp108.sub   in108.rte     in8.pnd in101.chm  muir.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 97 0       0   slp109.sub   in109.rte     in9.pnd in101.chm  crete.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 98 0       0   slp109.sub   in109.rte     in9.pnd in101.chm  crete.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
 99 0       0   slp109.sub   in109.rte     in9.pnd in101.chm  crete.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
100 0       0   slp109.sub   in109.rte     in9.pnd in101.chm hedville.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
101 0       0   slp109.sub   in109.rte     in9.pnd in101.chm hedville.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
102 0       0   slp109.sub   in109.rte     in9.pnd in101.chm hedville.sol
  pasture.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
103 0       0   slp109.sub   in109.rte     in9.pnd in101.chm  muir.sol
    3-wsf.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
104 0       0   slp109.sub   in109.rte     in9.pnd in101.chm  muir.sol
     corn.mgt optional.wus hru_deep.gw in10.wgn    WQLDAT     5  2
105 0       0   slp109.sub   in109.rte     in9.pnd in101.chm  muir.sol
```

```
   pasture.mgt optional.wus  hru_deep.gw  in10.wgn       WQLDAT       5   2
```

Land use management input files for HRU schemes 1-3

1. 3-wsf.mgt: a three-year rotation of wheat, sorghum, and fallow; no irrigation.

```
Rattlesnake Creek Watershed - Crop Data for Wheat-Sorghum-Fallow: 3-wsf.mgt
1  3   0   0   5   0  10    0.05     100.     90.
   6  25           5           10

   5   1           1 1650.00   3
  10  10           5           3

   9  20           1 1650.00  10
```

2. corn.mgt: irrigated corn.

```
Management Data File ! 1/17 mgt(17): corn.mgt; assoc. w/ irrig99.mco(wsf=.999)
0  1   0   0   5   0   0
   5  07          10                  0.98              0.65      12.7
   5  07           1    1900.   2
   9  07           5            2

  mo ida     husc itill    hu ncrp   airg    anit     phos inpest pamt cn2up
  i4  i4     f8.3  i4    f8.3  i4    f8.3    f8.3     f8.3  i4   f6.3  f6.3

set igro=1 to indicate that plants are growing from the first of the year;
    specify the harvest operation (5) first; follow this with the planting
    operation (1).
```

3. pasture.mgt: grasslands (range and pasture).

```
Management Data File ! 1/17 mgt(17): pasture.mgt: pasture
0  1   0   0   5   0   0
   3   1           1    1650.  37
  10  31           5           37

  mo ida     husc itill    hu ncrp   airg    anit     phos inpest pamt cn2up
  i4  i4     f8.3  i4    f8.3  i4    f8.3    f8.3     f8.3  i4   f6.3  f6.3
```

Control Codes input files for HRU schemes 1-3

HRU scheme 1: file hru1virt.cod

```
hru1virt.cod (15 HRUs, cn2=75) iophru=1; swminf=0.65,ipet=0(Priestley-Taylor)
  181977   0   0   1   1   0   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   1   2             ! '(2i4)': iophru iopwts iprwts (read in Readwts)
5,3,4,1,15,nsoils,numaqf,numuse,numreg,numcmb (no. specified HRU factor combinations)
   'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !nsoils, (soilnm(j),j=1,nsoils)
 1  0.092   0.471   0.099    0.338  0.
 2  0.191   0.064   0.402    0.342  0.
 3  0.098   0.637   0.132    0.052  0.081
 4  0.126   0.543   0.054    0.274  0.004
 5  0.043   0.745   0.       0.086  0.126
 6  0.      0.741   0.176    0.059  0.024
 7  0.      0.869   0.022    0.     0.108
 8  0.      0.697   0.279    0.     0.024
 9  0.      0.630   0.021    0.     0.348
'bedrock','deep gw','shallow gw'          !numaqf,(aqfnam(j),j=1,numaqf)
     'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! land fractions
 1     0.22015   0.0343    0.0733    0.1875
 2     0.04909   0.0031    0.2053    0.2
 3     0.20435   0.0064    0.2368    0.0625
 4     0.08729   0.0268    0.0924    0.
 5     0.05282   0.0021    0.2106    0.09091
 6     0.08247   0.0000    0.0122    0.
 7     0.10945   0.0131    0.0829    0.
 8     0.11788   0.04139   0.0257    0.
```

```
 9    0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd','urban'    !numuse, (usenam(j),j=1,numuse)
     'crpfrc'  'dstirr'   'urbfrc'
 1    0.5962    0.139694    0.
 2    0.5463    0.060835    0.
 3    0.6281    0.315519    0.
 4    0.5737    0.039543    0.
 5    0.7164    0.100748    0.
 6    0.6113    0.010547    0.
 7    0.6753    0.094522    0.
 8    0.5316    0.039287    0.
 9    0.4991    0.182079    0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.2 4.2 4.3 4.5 4.4 4.8 4.7,IrrigPct
  hru Soil  Use  Aqf     namhru (read region ID only if Numreg>1) HRU
    1    1    1    2     'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.)
    2    1    2    2     'carr-irm'          (irrigated corn)
    3    1    3    2     'carr-pam'          (grass: range and pasture)
    4    2    1    2     'cret-wsm'   soil 2
    5    2    2    2     'cret-irm'
    6    2    3    2     'cret-pam'
    7    3    1    2     'hshd-wsm'   soil 3 subs: Hastings(1-5), Hedville(6-9)
    8    3    2    2     'hshd-irm'  (represent 6 hrus for two soils as 3 hrus)
    9    3    3    2     'hshd-pam'
   10    4    1    2     'kips-wsm'   soil 4
   11    4    2    2     'kips-irm'
   12    4    3    2     'kips-pam'
   13    5    1    2     'muir-wsm'   soil 5
   14    5    2    2     'muir-irm'
   15    5    3    2     'muir-pam'
```

HRU scheme 2: file hru2virt.cod

```
hru2virt.cod (10 HRUs, cn2=75) iophru=2; swminf=0.65,ipet=0(Priestley-Taylor) iopshl=0
  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
   2   1   2             ! '(2i4)': iophru iopwts iprwts (read in Readwts)
5,3,4,2,10,nsoils,numaqf,numuse,numreg,numcmb (no. specified HRU factor combinations)
'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !nsoils, (soilnm(j),j=1,nsoils)
 1  0.092   0.471    0.099     0.338   0.
 2  0.191   0.064    0.402     0.342   0.
 3  0.098   0.637    0.132     0.052   0.081
 4  0.126   0.543    0.054     0.274   0.004
 5  0.043   0.745    0.        0.086   0.126
 6  0.      0.741    0.176     0.059   0.024
 7  0.      0.869    0.022     0.      0.108
 8  0.      0.697    0.279     0.      0.024
 9  0.      0.630    0.021     0.      0.348
'bedrock','deep gw','shallow gw'          !numaqf,(aqfnam(j),j=1,numaqf)
     'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! aqfbas=0.1261
 1    0.22015   0.0343    0.0733    0.1875
 2    0.04909   0.0031    0.2053    0.2
 3    0.20435   0.0064    0.2368    0.0625
 4    0.08729   0.0268    0.0924    0.
 5    0.05282   0.0021    0.2106    0.09091
 6    0.08247   0.0000    0.0122    0.
 7    0.10945   0.0131    0.0829    0.
 8    0.11788   0.04139   0.0257    0.
 9    0.07649   0.02827   0.2504    0.
'nonirrig','irrig','grasslnd','urban'    !numuse, (usenam(j),j=1,numuse)
     'crpfrc'  'dstirr'   'urbfrc'
 1    0.5962    0.139694    0.
 2    0.5463    0.060835    0.
 3    0.6281    0.315519    0.
 4    0.5737    0.039543    0.
 5    0.7164    0.100748    0.
 6    0.6113    0.010547    0.
 7    0.6753    0.094522    0.
 8    0.5316    0.039287    0.
 9    0.4991    0.182079    0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.2 4.2 4.3 4.5 4.4 4.8 4.7,IrrigPct
'Uplands','Alluvial'  !(regnam(j),j=1,numreg): HRU schemes 2,3
 1  0.9267  0.0733    !alluvial area given by gw areal fraction of subbasin
```

```
2  0.7947  0.2053
3  0.7632  0.2368
4  0.9076  0.0924
5  0.7894  0.2106
6  0.9878  0.0122
7  0.9171  0.0829
8  0.9743  0.0257
9  0.7496  0.2504
    2      1       1        1      2     !(ireg_sol(j),j=1,nsoils)
    1      2       2                     !(ireg_aqf(j),j=1,numaqf)
    1      2       0        0            !(ireg_use(j),j=1,numuse)
 hru Soil  Mgt  Aqf  namhru      Region
   2    1    2    2  'carr-irm'    2 soil 1 deep alluvial: irrigated corn
   4    1    3    2  'carr-pam'    2        deep alluv.:  grass (range and pasture)
   6    5    2    2  'muir-irm'    2 soil 2 deep alluvial: irrigated corn
   8    5    3    2  'muir-pam'    2        deep alluv.: grass (range and pasture)
   9    2    1    1  'cret-wsb'    1 soil 3 upland: wheat/sorghum/fallow rotation
  10    2    3    1  'cret-pab'    1                grass (range and pasture)
  11    4    1    1  'kips-wsb'    1 soil 4 upland: wheat/sorghum/fallow rotation
  12    4    3    1  'kips-pab'    1                grass (range and pasture)
  13    3    1    1  'hshd-wsb'    1 soil 5 upland (Hasting 1-4, Hedville 6-9)
  14    3    3    1  'hshd-pab'    1                grass (range and pasture)
```

HRU scheme 3: file hru3virt.cod

```
hru3virt.cod (14 HRUs, cn2=75) iophru=3; swminf=0.65,ipet=0(Priestley-Taylor)
iopshl=1,ixmlos=0
  181977  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  2
                                                                   Ipdvar
                                                                   Ipdvab
                                                                   Ipdvas
   1   1   1  ' '  'hru2virt.shl'  ! '(3i4,2a)': iopshl itmuni Lenuni nambal namshl
   3   1   2            ! '(3i4)': iophru iopwts iprwts (read in Readwts)
5,3,4,2,14,nsoils,numaqf,numuse,numreg,numcmb (no. specified HRU factor combinations)
   'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !nsoils, (soilnm(j),j=1,nsoils)
 1  0.092   0.471    0.099     0.338   0.
 2  0.191   0.064    0.402     0.342   0.
 3  0.098   0.637    0.132     0.052   0.081
 4  0.126   0.543    0.054     0.274   0.004
 5  0.043   0.745    0.        0.086   0.126
 6  0.      0.741    0.176     0.059   0.024
 7  0.      0.869    0.022     0.      0.108
 8  0.      0.697    0.279     0.      0.024
 9  0.      0.630    0.021     0.      0.348
   'bedrock','deep gw','shallow gw'         !numaqf,(aqfnam(j),j=1,numaqf)
    'subfrc'  'pndfrc'  'aqffrc'  'shlfrc'  ! aqfbas=0.1261
 1    0.22015   0.0343    0.0733    0.0137352
 2    0.04909   0.0031    0.2053    0.0411059
 3    0.20435   0.0064    0.2368    0.0147972
 4    0.08729   0.0268    0.0924    0.00001
 5    0.05282   0.0021    0.2106    0.02
 6    0.08247   0.0000    0.0122    0.
 7    0.10945   0.0131    0.0829    0.008
 8    0.11788   0.04139   0.0257    0.
 9    0.07649   0.02827   0.2504    0.025
  'nonirrig','irrig','grasslnd','urban'     !numuse, (usenam(j),j=1,numuse)
    'crpfrc'   'dstirr'    'urbfrc'
 1    0.5962    0.139694    0.
 2    0.5463    0.060835    0.
 3    0.6281    0.315519    0.
 4    0.5737    0.039543    0.
 5    0.7164    0.100748    0.
 6    0.6113    0.010547    0.
 7    0.6753    0.094522    0.
 8    0.5316    0.039287    0.
 9    0.4991    0.182079    0.
3.1 3.3 3.4 4.2 4.1 3.5 3.6 3.7 3.5 3.6 3.8 4.2 4.2 4.3 4.5 4.4 4.8 4.7,IrrigPct
'Uplands','Alluvial'  !(regnam(j),j=1,numreg): HRU schemes 2,3
 1  0.9267  0.0733  !alluvial area given by active gridded aquifer area
 2  0.7947  0.2053
 3  0.7632  0.2368
 4  0.9076  0.0924
 5  0.7894  0.2106
 6  0.9878  0.0122
 7  0.9171  0.0829
```

```
8  0.9743  0.0257
9  0.7496  0.2504
     2       1        1        1        2      !(ireg_sol(j),j=1,nsoils)
     1       2        2                        !(ireg_aqf(j),j=1,numaqf)
     1       2        0        0               !(ireg_use(j),j=1,numuse)
 hru Soil  Mgt   Aqf      namhru     Reg HRU1 HRU2  HRU description
   1    1    2     2   'carr-irm'     2    y y   deep gw, alluv: irrig. corn
   2    1    3     2   'carr-pam'     2    y y           (grass: range and pasture)
   3    5    2     2   'muir-irm'     2    y y deep gw, alluv: irrigated corn
   4    5    3     2   'muir-pam'     2    y y           (grass: range and pasture)
   5    2    1     1   'cret-wsb'     1    n y upland: wheat/sorghum/fallow
   6    2    3     1   'cret-pab'     1    n y         grass (range and pasture)
   7    4    1     1   'kips-wsb'     1    n y upland: wheat/sorghum/fallow
   8    4    3     1   'kips-pab'     1    n y         grass (range and pasture)
   9    3    1     1   'hshd-wsb'     1    n y upland: wheat/sorghum/fallow
  10    3    3     1   'hshd-pab'     1    n y         grass (range and pasture)
  11    1    2     3   'carr-irs'     2    n n shallow gw, alluv: irrigated corn
  12    1    3     3   'carr-pas'     2    n n shallow gw, alluv:  grass (range/pasture)
  13    5    2     3   'muir-irs'     2    n n shallow gw, alluv: irrigated corn
  14    5    3     3   'muir-pas'     2    n n shallow gw, alluv: grass (range/pasture)
```

Configuration input files (*.Fig) for HRU schemes 1-3

HRU scheme 1: file hru1virt.fig

```
* from subr. Readfig:
*         read (9,5000) a, icodes(idum), ihouts(idum), inum1s(idum),     &
*    &    inum2s(idum), inum3s(idum), rnum1s(idum), inum4s(idum)
*5000 format (a1,9x,5i6,f6.3,i9)
*
*           command hyd  hru          sub last hru   gis code
*             code   no.  no.          no. (1=last)   (not used)
*          icodes ihouts inm1   inm2   inm3 rnm1       inm4
*
* Subbasin  Cmd Hyd_stor Hru_num Sub_num Final_flag GIS idcmb   soil     use
subbasin      1     1      1          1     0.        1     1   Carr     3-wsf
subbasin      1     2      2          1     0.        1     2   Carr     corn
subbasin      1     3      3          1     0.        1     3   Carr     pasture
subbasin      1     4      4          1     0.        1     4   Crete    3-wsf
subbasin      1     5      5          1     0.        1     5   Crete    corn
subbasin      1     6      6          1     0.        1     6   Crete    pasture
subbasin      1     7      7          1     0.        1     7   Hastings 3-wsf
subbasin      1     8      8          1     0.        1     8             corn
subbasin      1     9      9          1     0.        1     9             pasture
subbasin      1    10     10          1     0.        1    10   Kipson    3-wsf
subbasin      1    11     11          1     0.        1    11             corn
subbasin      1    12     12          1     1.        1    12             pasture
subbasin      1    13     13          2     0.        2     1   Carr     3-wsf
subbasin      1    14     14          2     0.        2     2   Carr     corn
subbasin      1    15     15          2     0.        2     3   Carr     pasture
subbasin      1    16     16          2     0.        2     4   Crete    3-wsf
subbasin      1    17     17          2     0.        2     5   Crete    corn
subbasin      1    18     18          2     0.        2     6   Crete    pasture
subbasin      1    19     19          2     0.        2     7   Hastings 3-wsf
subbasin      1    20     20          2     0.        2     8             corn
subbasin      1    21     21          2     0.        2     9             pasture
subbasin      1    22     22          2     0.        2    10   Kipson    3-wsf
subbasin      1    23     23          2     0.        2    11             corn
subbasin      1    24     24          2     1.        2    12             pasture
subbasin      1    25     25          3     0.        3     1   Carr     3-wsf
subbasin      1    26     26          3     0.        3     2   Carr     corn
subbasin      1    27     27          3     0.        3     3   Carr     pasture
subbasin      1    28     28          3     0.        3     4   Crete    3-wsf
subbasin      1    29     29          3     0.        3     5   Crete    corn
subbasin      1    30     30          3     0.        3     6   Crete    pasture
subbasin      1    31     31          3     0.        3     7   Hastings 3-wsf
subbasin      1    32     32          3     0.        3     8             corn
subbasin      1    33     33          3     0.        3     9             pasture
subbasin      1    34     34          3     0.        3    10   Kipson    3-wsf
subbasin      1    35     35          3     0.        3    11             corn
subbasin      1    36     36          3     0.        3    12             pasture
subbasin      1    37     37          3     0.        3    13    Muir     3-wsf
subbasin      1    38     38          3     0.        3    14             corn
```

```
subbasin        1    39    39         3    1.        3    15           pasture
subbasin        1    40    40         4    0.        4     1   Carr     3-wsf
subbasin        1    41    41         4    0.        4     2   Carr     corn
subbasin        1    42    42         4    0.        4     3   Carr     pasture
subbasin        1    43    43         4    0.        4     4   Crete    3-wsf
subbasin        1    44    44         4    0.        4     5   Crete    corn
subbasin        1    45    45         4    0.        4     6   Crete    pasture
subbasin        1    46    46         4    0.        4     7   Hastings 3-wsf
subbasin        1    47    47         4    0.        4     8            corn
subbasin        1    48    48         4    0.        4     9            pasture
subbasin        1    49    49         4    0.        4    10   Kipson    3-wsf
subbasin        1    50    50         4    0.        4    11            corn
subbasin        1    51    51         4    0.        4    12            pasture
subbasin        1    52    52         4    0.        4    13    Muir     3-wsf
subbasin        1    53    53         4    0.        4    14            corn
subbasin        1    54    54         4    1.        4    15            pasture
subbasin        1    55    55         5    0.        5     1   Carr     3-wsf
subbasin        1    56    56         5    0.        5     2   Carr     corn
subbasin        1    57    57         5    0.        5     3   Carr     pasture
subbasin        1    58    58         5    0.        5     4   Crete    3-wsf
subbasin        1    59    59         5    0.        5     5   Crete    corn
subbasin        1    60    60         5    0.        5     6   Crete    pasture
subbasin        1    61    61         5    0.        5    10   Kipson    3-wsf
subbasin        1    62    62         5    0.        5    11            corn
subbasin        1    63    63         5    0.        5    12            pasture
subbasin        1    64    64         5    0.        5    13    Muir     3-wsf
subbasin        1    65    65         5    0.        5    14            corn
subbasin        1    66    66         5    1.        5    15            pasture
subbasin        1    67    67         6    0.        6     4   Crete    3-wsf
subbasin        1    68    68         6    0.        6     5   Crete    corn
subbasin        1    69    69         6    0.        6     6   Crete    pasture
subbasin        1    70    70         6    0.        6     7   Hastings 3-wsf
subbasin        1    71    71         6    0.        6     8            corn
subbasin        1    72    72         6    0.        6     9            pasture
subbasin        1    73    73         6    0.        6    10   Kipson    3-wsf
subbasin        1    74    74         6    0.        6    11            corn
subbasin        1    75    75         6    0.        6    12            pasture
subbasin        1    76    76         6    0.        6    13    Muir     3-wsf
subbasin        1    77    77         6    0.        6    14            corn
subbasin        1    78    78         6    1.        6    15            pasture
subbasin        1    79    79         7    0.        7     4   Crete    3-wsf
subbasin        1    80    80         7    0.        7     5   Crete    corn
subbasin        1    81    81         7    0.        7     6   Crete    pasture
subbasin        1    82    82         7    0.        7     7   Hastings 3-wsf
subbasin        1    83    83         7    0.        7     8            corn
subbasin        1    84    84         7    0.        7     9            pasture
subbasin        1    85    85         7    0.        7    13    Muir     3-wsf
subbasin        1    86    86         7    0.        7    14            corn
subbasin        1    87    87         7    1.        7    15            pasture
subbasin        1    88    88         8    0.        8     4   Crete    3-wsf
subbasin        1    89    89         8    0.        8     5   Crete    corn
subbasin        1    90    90         8    0.        8     6   Crete    pasture
subbasin        1    91    91         8    0.        8     7   Hastings 3-wsf
subbasin        1    92    92         8    0.        8     8            corn
subbasin        1    93    93         8    0.        8     9            pasture
subbasin        1    94    94         8    0.        8    13    Muir     3-wsf
subbasin        1    95    95         8    0.        8    14            corn
subbasin        1    96    96         8    1.        8    15            pasture
subbasin        1    97    97         9    0.        9     4   Crete    3-wsf
subbasin        1    98    98         9    0.        9     5   Crete    corn
subbasin        1    99    99         9    0.        9     6   Crete    pasture
subbasin        1   100   100         9    0.        9     7   Hastings 3-wsf
subbasin        1   101   101         9    0.        9     8            corn
subbasin        1   102   102         9    0.        9     9            pasture
subbasin        1   103   103         9    0.        9    13    Muir     3-wsf
subbasin        1   104   104         9    0.        9    14            corn
subbasin        1   105   105         9    1.        9    15            pasture
*
* Route      Cmd Hydsto Rchnm Hydnm Subnm Flovn
route           2   106    12    12     1     0
* Add        Cmd Hyd_stor Hyd_num1 Hyd_num2
add             5   107   106    12
route           2   108    24    24     2     0
add             5   109   108    24
route           2   110    39    39     3     0
add             5   111   110    39
```

```
route          2   112    54    54     4      0
add            5   113   112    54
route          2   114    66    66     5      0
add            5   115   114    66
route          2   116    78    78     6      0
add            5   117   116    78
route          2   118    87    87     7      0
add            5   119   118    87
route          2   120    96    96     8      0
add            5   121   120    96
route          2   122   105   105     9      0
add            5   123   122   105
finish         0
```

HRU scheme 2: file hru2virt.fig

```
* from subr. Readfig:
*         read (9,5000) a, icodes(idum), ihouts(idum), inum1s(idum),     &
*    &    inum2s(idum), inum3s(idum), rnum1s(idum), inum4s(idum)
*5000 format (a1,9x,5i6,f6.3,i9)
*
*
*           command hyd  hru         sub last hru   gis code
*            code   no.  no.         no. (1=last)   (not used)
*         icodes ihouts inm1   inm2  inm3 rnm1      inm4
*
* Subbasin  Cmd Hyd_stor Hru_num Sub_num Final_flag GIS idcmb   soil     use
subsurface
subbasin      1    1      1           1    0.       1     1   carr     corn    deep
subbasin      1    2      2           1    0.       1     2   carr     past    deep
subbasin      1    3      3           1    0.       1     5   crete    3-wsf   deep_gw
subbasin      1    4      4           1    0.       1     6   crete    pasture deep_gw
subbasin      1    5      5           1    0.       1     7   kipson   3-wsf   bedrock
subbasin      1    6      6           1    0.       1     8   kipson   pasture bedrock
subbasin      1    7      7           1    0.       1     9   hastings 3-wsf   bedrock
subbasin      1    8      8           1    1.       1    10   hastings pasture bedrock
subbasin      1    9      9           2    0.       2     1   carr     corn    deep
subbasin      1   10     10           2    0.       2     2   carr     past    deep
subbasin      1   11     11           2    0.       2     5   crete    3-wsf   deep_gw
subbasin      1   12     12           2    0.       2     6   crete    pasture deep_gw
subbasin      1   13     13           2    0.       2     7   kipson   3-wsf   bedrock
subbasin      1   14     14           2    0.       2     8   kipson   pasture bedrock
subbasin      1   15     15           2    0.       2     9   hastings 3-wsf   bedrock
subbasin      1   16     16           2    1.       2    10   hastings pasture bedrock
subbasin      1   17     17           3    0.       3     1   carr     corn    deep
subbasin      1   18     18           3    0.       3     2   carr     past    deep
subbasin      1   19     19           3    0.       3     3   muir     corn    deep
subbasin      1   20     20           3    0.       3     4   muir     past    deep
subbasin      1   21     21           3    0.       3     5   crete    3-wsf   deep_gw
subbasin      1   22     22           3    0.       3     6   crete    pasture deep_gw
subbasin      1   23     23           3    0.       3     7   kipson   3-wsf   bedrock
subbasin      1   24     24           3    0.       3     8   kipson   pasture bedrock
subbasin      1   25     25           3    0.       3     9   hastings 3-wsf   bedrock
subbasin      1   26     26           3    1.       3    10   hastings pasture bedrock
subbasin      1   27     27           4    0.       4     1   carr     corn    deep
subbasin      1   28     28           4    0.       4     2   carr     past    deep
subbasin      1   29     29           4    0.       4     3   muir     corn    deep
subbasin      1   30     30           4    0.       4     4   muir     past    deep
subbasin      1   31     31           4    0.       4     5   crete    3-wsf   deep_gw
subbasin      1   32     32           4    0.       4     6   crete    pasture deep_gw
subbasin      1   33     33           4    0.       4     7   kipson   3-wsf   bedrock
subbasin      1   34     34           4    0.       4     8   kipson   pasture bedrock
subbasin      1   35     35           4    0.       4     9   hastings 3-wsf   bedrock
subbasin      1   36     36           4    1.       4    10   hastings pasture bedrock
subbasin      1   37     37           5    0.       5     1   carr     corn    deep
subbasin      1   38     38           5    0.       5     2   carr     past    deep
subbasin      1   39     39           5    0.       5     3   muir     corn    deep
subbasin      1   40     40           5    0.       5     4   muir     past    deep
subbasin      1   41     41           5    0.       5     5   crete    3-wsf   deep_gw
subbasin      1   42     42           5    0.       5     6   crete    pasture deep_gw
subbasin      1   43     43           5    0.       5     7   kipson   3-wsf   bedrock
subbasin      1   44     44           5    1.       5     8   kipson   pasture bedrock
subbasin      1   45     45           6    0.       6     3   muir     corn    deep
subbasin      1   46     46           6    0.       6     4   muir     past    deep
subbasin      1   47     47           6    0.       6     5   crete    3-wsf   deep_gw
subbasin      1   48     48           6    0.       6     6   crete    pasture deep_gw
```

```
subbasin        1    49    49          6    0.        6     7   kipson    3-wsf    bedrock
subbasin        1    50    50          6    0.        6     8   kipson    pasture  bedrock
subbasin        1    51    51          6    0.        6     9   hedville  3-wsf    bedrock
subbasin        1    52    52          6    1.        6    10   hedville  pasture  bedrock
subbasin        1    53    53          7    0.        7     3   muir      corn     deep
subbasin        1    54    54          7    0.        7     4   muir      past     deep
subbasin        1    55    55          7    0.        7     5   crete     3-wsf    deep_gw
subbasin        1    56    56          7    0.        7     6   crete     pasture  deep_gw
subbasin        1    57    57          7    0.        7     9   hedville  3-wsf    bedrock
subbasin        1    58    58          7    1.        7    10   hedville  pasture  bedrock
subbasin        1    59    59          8    0.        8     3   muir      corn     deep
subbasin        1    60    60          8    0.        8     4   muir      past     deep
subbasin        1    61    61          8    0.        8     5   crete     3-wsf    deep_gw
subbasin        1    62    62          8    0.        8     6   crete     pasture  deep_gw
subbasin        1    63    63          8    0.        8     9   hedville  3-wsf    bedrock
subbasin        1    64    64          8    1.        8    10   hedville  pasture  bedrock
subbasin        1    65    65          9    0.        9     3   muir      corn     deep
subbasin        1    66    66          9    0.        9     4   muir      past     deep
subbasin        1    67    67          9    0.        9     5   crete     3-wsf    deep_gw
subbasin        1    68    68          9    0.        9     6   crete     pasture  deep_gw
subbasin        1    69    69          9    0.        9     9   hedville  3-wsf    bedrock
subbasin        1    70    70          9    1.        9    10   hedville  pasture  bedrock
*
* Route       Cmd Hydsto Rchnm Hydnm Subnm Flovn
route           2    71     8     8     1     0
add             5    72    71     8
route           2    73    16    16     2     0
add             5    74    73    16
route           2    75    26    26     3     0
add             5    76    75    26
route           2    77    36    36     4     0
add             5    78    77    36
route           2    79    44    44     5     0
add             5    80    79    44
route           2    81    52    52     6     0
add             5    82    81    52
route           2    83    58    58     7     0
add             5    84    83    58
route           2    85    64    64     8     0
add             5    86    85    64
route           2    87    70    70     9     0
add             5    88    87    70
finish          0
```

HRU scheme 3: file hru3virt.fig

```
* from subr. Readfig:
*        read (9,5000) a, icodes(idum), ihouts(idum), inum1s(idum),     &
*    &   inum2s(idum), inum3s(idum), rnum1s(idum), inum4s(idum)
*5000 format (a1,9x,5i6,f6.3,i9)
* variation on case hru2virt: set up HRUs for shallow gw as follows:
* carr, (corn, pasture), shallow gw: subbasins 1,2,3,4,5
* muir, (corn, pasture), shallow gw: subbasins     3,4,5,7,9
*
*
*            command hyd  hru          sub last hru   gis code
*              code   no.  no.          no. (1=last)   (not used)
*          icodes ihouts inm1   inm2  inm3 rnm1       inm4
*
* Subbasin    Cmd Hyd_stor Hru_num Sub_num Final_flag GIS idcmb   soil      use
subsurface
subbasin        1     1     1          1    0.        1     1   carr      corn     deep_gw
subbasin        1     2     2          1    0.        1     2   carr      past     deep_gw
subbasin        1     3     3          1    0.        1     5   crete     3-wsf    deep_gw
subbasin        1     4     4          1    0.        1     6   crete     pasture  deep_gw
subbasin        1     5     5          1    0.        1     7   kipson    3-wsf    bedrock
subbasin        1     6     6          1    0.        1     8   kipson    pasture  bedrock
subbasin        1     7     7          1    0.        1     9   hastings  3-wsf    bedrock
subbasin        1     8     8          1    0.        1    10   hastings  pasture  bedrock
subbasin        1     9     9          1    0.        1    11   carr      corn     deep
subbasin        1    10    10          1    1.        1    12   carr      past     deep
subbasin        1    11    11          2    0.        2     1   carr      corn     deep
subbasin        1    12    12          2    0.        2     2   carr      past     deep
subbasin        1    13    13          2    0.        2     5   crete     3-wsf    deep_gw
subbasin        1    14    14          2    0.        2     6   crete     pasture  deep_gw
subbasin        1    15    15          2    0.        2     7   kipson    3-wsf    bedrock
```

subbasin	1	16	16	2	0.	2	8	kipson	pasture	bedrock
subbasin	1	17	17	2	0.	2	9	hastings	3-wsf	bedrock
subbasin	1	18	18	2	0.	2	10	hastings	pasture	bedrock
subbasin	1	19	19	2	0.	2	11	carr	corn	deep
subbasin	1	20	20	2	1.	2	12	carr	past	deep
subbasin	1	21	21	3	0.	3	1	carr	corn	deep
subbasin	1	22	22	3	0.	3	2	carr	past	deep
subbasin	1	23	23	3	0.	3	3	muir	corn	deep
subbasin	1	24	24	3	0.	3	4	muir	past	deep
subbasin	1	25	25	3	0.	3	5	crete	3-wsf	deep_gw
subbasin	1	26	26	3	0.	3	6	crete	pasture	deep_gw
subbasin	1	27	27	3	0.	3	7	kipson	3-wsf	bedrock
subbasin	1	28	28	3	0.	3	8	kipson	pasture	bedrock
subbasin	1	29	29	3	0.	3	9	hastings	3-wsf	bedrock
subbasin	1	30	30	3	0.	3	10	hastings	pasture	bedrock
subbasin	1	31	31	3	0.	3	11	carr	corn	deep
subbasin	1	32	32	3	0.	3	12	carr	past	deep
subbasin	1	33	33	3	0.	3	13	muir	corn	deep
subbasin	1	34	34	3	1.	3	14	muir	past	deep
subbasin	1	35	35	4	0.	4	1	carr	corn	deep
subbasin	1	36	36	4	0.	4	2	carr	past	deep
subbasin	1	37	37	4	0.	4	3	muir	corn	deep
subbasin	1	38	38	4	0.	4	4	muir	past	deep
subbasin	1	39	39	4	0.	4	5	crete	3-wsf	deep_gw
subbasin	1	40	40	4	0.	4	6	crete	pasture	deep_gw
subbasin	1	41	41	4	0.	4	7	kipson	3-wsf	bedrock
subbasin	1	42	42	4	0.	4	8	kipson	pasture	bedrock
subbasin	1	43	43	4	0.	4	9	hastings	3-wsf	bedrock
subbasin	1	44	44	4	0.	4	10	hastings	pasture	bedrock
subbasin	1	45	45	4	0.	4	11	carr	corn	deep
subbasin	1	46	46	4	0.	4	12	carr	past	deep
subbasin	1	47	47	4	0.	4	13	muir	corn	deep
subbasin	1	48	48	4	1.	4	14	muir	past	deep
subbasin	1	49	49	5	0.	5	1	carr	corn	deep
subbasin	1	50	50	5	0.	5	2	carr	past	deep
subbasin	1	51	51	5	0.	5	3	muir	corn	deep
subbasin	1	52	52	5	0.	5	4	muir	past	deep
subbasin	1	53	53	5	0.	5	5	crete	3-wsf	deep_gw
subbasin	1	54	54	5	0.	5	6	crete	pasture	deep_gw
subbasin	1	55	55	5	0.	5	7	kipson	3-wsf	bedrock
subbasin	1	56	56	5	0.	5	8	kipson	pasture	bedrock
subbasin	1	57	57	5	0.	5	11	carr	corn	deep
subbasin	1	58	58	5	0.	5	12	carr	past	deep
subbasin	1	59	59	5	0.	5	13	muir	corn	deep
subbasin	1	60	60	5	1.	5	14	muir	past	deep
subbasin	1	61	61	6	0.	6	3	muir	corn	deep
subbasin	1	62	62	6	0.	6	4	muir	past	deep
subbasin	1	63	63	6	0.	6	5	crete	3-wsf	deep_gw
subbasin	1	64	64	6	0.	6	6	crete	pasture	deep_gw
subbasin	1	65	65	6	0.	6	7	kipson	3-wsf	bedrock
subbasin	1	66	66	6	0.	6	8	kipson	pasture	bedrock
subbasin	1	67	67	6	0.	6	9	hedville	3-wsf	bedrock
subbasin	1	68	68	6	1.	6	10	hedville	pasture	bedrock
subbasin	1	69	69	7	0.	7	3	muir	corn	deep
subbasin	1	70	70	7	0.	7	4	muir	past	deep
subbasin	1	71	71	7	0.	7	5	crete	3-wsf	deep_gw
subbasin	1	72	72	7	0.	7	6	crete	pasture	deep_gw
subbasin	1	73	73	7	0.	7	9	hedville	3-wsf	bedrock
subbasin	1	74	74	7	0.	7	10	hedville	pasture	bedrock
subbasin	1	75	75	7	0.	7	13	muir	corn	deep
subbasin	1	76	76	7	1.	7	14	muir	past	deep
subbasin	1	77	77	8	0.	8	3	muir	corn	deep
subbasin	1	78	78	8	0.	8	4	muir	past	deep
subbasin	1	79	79	8	0.	8	5	crete	3-wsf	deep_gw
subbasin	1	80	80	8	0.	8	6	crete	pasture	deep_gw
subbasin	1	81	81	8	0.	8	9	hedville	3-wsf	bedrock
subbasin	1	82	82	8	1.	8	10	hedville	pasture	bedrock
subbasin	1	83	83	9	0.	9	3	muir	corn	deep
subbasin	1	84	84	9	0.	9	4	muir	past	deep
subbasin	1	85	85	9	0.	9	5	crete	3-wsf	deep_gw
subbasin	1	86	86	9	0.	9	6	crete	pasture	deep_gw
subbasin	1	87	87	9	0.	9	9	hedville	3-wsf	bedrock
subbasin	1	88	88	9	0.	9	10	hedville	pasture	bedrock
subbasin	1	89	89	9	0.	9	13	muir	corn	deep
subbasin	1	90	90	9	1.	9	14	muir	past	deep

*

* Route	Cmd	Hydsto	Rchnm	Hydnm	Subnm	Flovn
route	2	91	10	10	1	0
add	5	92	91	10		
route	2	93	20	20	2	0
add	5	94	93	20		
route	2	95	34	34	3	0
add	5	96	95	34		
route	2	97	48	48	4	0
add	5	98	97	48		
route	2	99	60	60	5	0
add	5	100	99	60		
route	2	101	68	68	6	0
add	5	102	101	68		
route	2	103	76	76	7	0
add	5	104	103	76		
route	2	105	82	82	8	0
add	5	106	105	82		
route	2	107	90	90	9	0
add	5	108	107	90		
finish	0					

File Hru1virt.dep (excerpt): summary of SWAT simulation

SWAT's simulation results for each gw time step are averaged over all HRUs for each subbasin by subr. Sumhrus. Subr. Sumstep operates on these HRU-averaged results. File Hru1virt.dep summarizes these results as averages taken over the subbasins. An excerpt of this file is shown below for 1977. Results are shown in SWAT's units of volumes per unit area (mm). A second, analogous summary file is also written, Hru1virt.sum, which gives the results as flow rates in the units used by MODFLOW (see below).

```
Year  mon days  sub  PRECIPmm      IRRmm      ETmm     SURQmm   TLOSSmm    LATQmm    PERCmm DA_RCHGmm   REVAPmm    GW_Qmm   PNDSEPmm
                PETmm PND_OUTmm  PNDEVPmmdSol_sw,mm  dPnd_mm Et_gw(mm) Egwuna,mm Sol_sw,mm NetInf_mm Balanc_mm  qtrib,mm  qrech,mm cn
 1977    1  31            18.81      0.00     10.75      0.03      0.03      0.00      0.00      0.00      0.00      0.00      0.00
             12.13        0.03      0.05      5.69      0.04      0.00      0.00    178.74      8.03      2.34      0.06      0.00  59.
 1977    2  28             1.20      0.00     29.46      0.03      0.03      0.00      0.00      0.00      0.00      0.00      0.00
             57.81        0.00      0.10    -25.96     -0.10      0.00      0.00    152.78    -28.29     -2.34      0.03      0.00  74.
 1977    3  31            63.88      0.00     40.82      0.45      0.24      0.00      0.08      0.08      0.00      0.00      0.00
            105.17        0.00      0.02     21.41     -0.01      0.00      0.00    174.19     22.54      1.12      0.50      0.03  74.
 1977    4  30            65.20      0.00     73.91      1.51      0.93      0.00      0.71      0.71      0.00      0.00      0.00
            143.44        0.00      0.01    -10.00      0.00      0.00      0.00    164.20    -10.94     -0.94      2.11      0.12  79.
 1977    5  31           157.95      0.13     97.85      5.63      1.48      0.00      5.88      5.88      0.00      0.00      0.00
            195.99        0.00      0.01     45.96      0.00      0.00      0.00    210.15     48.72      2.77     10.92      0.59  78.
 1977    6  30           135.19      0.22    113.62     18.96      3.08      0.00     13.35     13.35      0.00      0.00      0.00
            219.90        0.00      0.01    -16.92      0.00      0.00      0.00    193.24    -10.51      6.40     30.57      1.73  76.
 1977    7  31            73.22      5.19     88.91     10.32      3.15      0.00      1.25      1.25      0.00      0.00      0.00
            236.89        0.00      0.01    -18.38      0.00      0.00      0.00    174.86    -22.06     -3.68     11.03      0.53  69.
 1977    8  31           274.80      0.40    108.65     51.32      3.03      0.01     44.97     44.97      0.00      0.00      0.00
            202.68        0.00      0.00     51.46      0.00      0.00      0.00    226.32     70.25     18.78     90.45      5.86  77.
 1977    9  30            64.02      0.21     68.27     25.63      3.79      0.00      4.89      4.89      0.00      0.00      0.00
            157.31        0.00      0.00    -14.53      0.00      0.00      0.00    211.79    -34.57    -20.04     29.41      1.11  85.
 1977   10  31            56.94      0.00     43.92      8.77      3.19      0.00      1.12      1.12      0.00      0.00      0.00
            104.13        0.00      0.00      5.48      0.00      0.00      0.00    217.28      3.14     -2.35      9.42      0.47  84.
 1977   11  30            47.28      0.00     26.47      7.74      3.50      0.00      3.24      3.24      0.00      0.00      0.00
             55.77        0.00      0.00      8.89      0.00      0.00      0.00    226.16      9.82      0.94     10.32      0.66  85.
 1977   12  31             0.54      0.00     12.26      1.36      1.22      0.00      0.00      0.00      0.00      0.00      0.00
             35.16        0.00      0.00    -10.39      0.00      0.00      0.00    215.77    -13.07     -2.68      1.21      0.15  84.
```

File Hru1virt.sum (excerpt): summary of SWAT simulation

This file summarizes SWAT's results as flow rates in the units used by MODFLOW.

Year	mon	days	delt (sec)	sub	precip	irrig	ETact	runoff	XMloss	QLAT	PERC	recharg	et-gw
			baseflo	pondsep	ETpot	tribflo	dSW/dt	dPND/dt	et-gw(un)	cn_av	c*A/dt		
1977	1	31	2678400.		637.17	0.00	365.69	0.91	0.89	0.00	0.00	0.08	0.00
			0.00	0.15	411.08	2.02	192.86	1.26	0.00	58.9	33.8801422		
1977	2	28	2419200.		44.91	0.00	1108.81	1.21	1.21	0.00	0.00	0.10	0.00
			0.00	0.07	2168.62	1.18	-973.61	-3.76	0.00	74.2	37.5101585		
1977	3	31	2678400.		2164.16	0.00	1383.43	15.15	8.12	0.02	2.55	0.92	0.00
			0.00	0.01	3563.01	16.80	725.53	-0.19	0.00	73.7	33.8801422		
1977	4	30	2592000.		2282.49	0.00	2587.71	52.89	32.72	0.04	25.02	4.10	0.00
			0.00	0.00	5021.65	73.85	-349.95	-0.09	0.00	78.6	35.0094795		
1977	5	31	2678400.		5351.36	4.57	3315.29	190.65	49.97	0.09	199.37	20.02	0.00
			0.00	0.00	6640.20	370.09	1556.98	0.01	0.00	77.9	33.8801422		
1977	6	30	2592000.		4732.95	7.73	3977.99	663.65	107.74	0.14	467.22	60.62	0.00
			0.00	0.00	7698.60	1070.39	-592.28	-0.06	0.00	75.9	35.0094795		
1977	7	31	2678400.		2480.79	175.77	3012.34	349.60	106.87	0.09	42.24	18.09	0.00
			0.00	0.00	8025.94	373.84	-622.74	-0.10	0.00	69.1	33.8801422		
1977	8	31	2678400.		9310.24	13.47	3681.09	1738.74	102.53	0.24	1523.72	198.41	0.00
			0.00	0.00	6866.94	3064.30	1743.61	0.09	0.00	76.7	33.8801422		
1977	9	30	2592000.		2241.32	7.22	2390.26	897.32	132.70	0.16	171.23	38.92	0.00
			0.00	0.00	5507.44	1029.79	-508.62	-0.06	0.00	84.9	35.0094795		
1977	10	31	2678400.		1929.16	0.05	1487.95	297.17	108.14	0.09	37.82	16.00	0.00
			0.00	0.00	3528.08	319.08	185.77	-0.02	0.00	84.0	33.8801422		
1977	11	30	2592000.		1655.13	0.00	926.79	270.85	122.63	0.07	113.54	23.19	0.00
			0.00	0.00	1952.31	361.28	311.08	0.00	0.00	85.2	35.0094795		
1977	12	31	2678400.		18.40	0.00	415.27	45.91	41.45	0.04	0.00	5.09	0.00
			0.00	0.00	1191.30	40.87	-352.12	-0.02	0.00	84.4	33.8801422		

File Hru1virt.bal (excerpt): written by SWAT for input to Modflow

SWAT simulation results can be summarized for each groundwater time step either in SWAT's units (volume per unit subbasin area, mm) by setting Iopmod = 1, or in MODFLOW's units (flow rate, specified by Itmuni and Lenuni) by setting Iopmod = 2. The first option is chosen if HRU averaging and conversion to flow rates are performed externally by program HRUAVG or SWBAVG. Alternatively, with Iopmod = 2, SWAT's simulation results are converted to flow rates; the balance file written by SWAT can then be read by MODFLOW. Additionally, by setting Iopwts = 1, HRU weights can be calculated in SWAT using the same procedure followed in HRUAVG for externally calculated weights; see instructions for modified Configuration (*.Fig) and Control Codes

(*.Cod) input files in the User's Manual. Below are shown the first month's results in the converted form for input to Modflow as flow rates (cfs), specified by setting Iopmod = 2.

```
18    2  0.2765894E+11 0.0199353    1  105 hrulvirt
  sub sub fract noncontrb aqf_fr(j)    subpnd sol_sw,mm    pnd_vol,m^3
    1 0.2201500 0.0343000
    2 0.0490409 0.0031000
    3 0.2043500 0.0064000
    4 0.0873773 0.0268000
    5 0.0528200 0.0021000
    6 0.0824700 0.0000000
    7 0.1093406 0.0131000
    8 0.1178800 0.0413900
    9 0.0764135 0.0282700
 Year  mon days       delt (sec)  sub    precip     irrig      ETact      runoff     XMloss       QLAT       PERC    recharg       et-gw    baseflo
pondsep      ETpot    tribflo    dSW/dt   dPND/dt et-gw(un) cn_av        c*A/dt
 1977    1   31        2678400.    1    138.73      0.00      64.79        0.00       0.00       0.00       0.00       0.00       0.00       0.00
0.06     67.18        0.34     -3.72     0.60      0.00  58.4      7.4587131
 1977    1   31        2678400.    2     27.25      0.00      17.75        0.00       0.00       0.00       0.00       0.00       0.00       0.00
0.01     20.40        0.07      9.64     0.06      0.00  59.1      1.6615131
 1977    1   31        2678400.    3    113.54      0.00      76.02        0.00       0.00       0.00       0.00       0.01       0.00       0.00
0.03     89.38        0.30     37.81     0.00      0.00  59.1      6.9234066
 1977    1   31        2678400.    4     48.55      0.00      32.84        0.00       0.00       0.00       0.00       0.00       0.00       0.00
0.01     38.77        0.03     15.79     0.04      0.00  59.1      2.9603546
 1977    1   31        2678400.    5     29.35      0.00      19.42        0.00       0.00       0.00       0.00       0.00       0.00       0.00
0.01     22.97        0.07     10.01     0.02      0.00  59.1      1.7895490
 1977    1   31        2678400.    6     44.15      0.00      29.10        0.00       0.00       0.00       0.00       0.00       0.00       0.00
0.00     35.51        0.00     15.04     0.00      0.00  59.0      2.7940950
 1977    1   31        2678400.    7     58.53      0.00      38.70        0.00       0.00       0.00       0.00       0.00       0.00       0.00
0.00     47.54        0.00     19.84     0.01      0.00  59.1      3.7044735
 1977    1   31        2678400.    8    107.43      0.00      52.68        0.73       0.71       0.00       0.00       0.02       0.00       0.00
0.04     53.84        1.06     53.58     0.50      0.00  59.1      3.9937916
 1977    1   31        2678400.    9     69.64      0.00      34.37        0.18       0.17       0.00       0.00       0.04       0.00       0.00
0.00     35.50        0.14     34.86     0.05      0.00  59.0      2.5889006
```

Key MODFLOW file listings

Name file Hru1virt.nam

```
LIST 6   hru1virt.lst                          case name (~.log, ~.prn, ~.rsp)
BAS   1  ..\inbase\bcase_t4.bas                  Monthly Basic package
OC   69  ..\inbase\rpbase.oc                     Output control
BCF  61  ..\inbase\kbase20b.bcf                  Block-centered flow
RCH  67  ..\inbase\matrix1.rch                   67 Recharge
EVT  65  ..\inbase\repsurf.evt                   Evapotranspiration
PCG  68  ..\inbase\model1bs.pcg                  preconditioned conjugate gradient
#
# Non-standard Modflow-88 modules substituted for standard Modflow-96 modules,
# modified for coordination with the added SWB module:
#
WEL  62  ..\inbase\wrrepub.wel                   Well: groundwater use
STR  70  ..\inbase\rptest.str                    monthly Streamflow, Ks=0.54 ft/day
#
# If invoking WELX and STRX to be used with SWB (below), open:
#   2, iostrm: Str2fm (stream routing details for istrbd = 0 or 2)
DATA 117   hru1virt.stm
#   3, ioreg: Str2fm, Wel2stp: record of pumping rates that have been
#       reduced due to low saturated thickness or streamflow.
DATA 218   hru1virt.reg
#
#               Modules added to Modflow-96:
#
#               SWB: 2 input files are specified, *.swb and *.bal:
SWB  66  ..\inbase\rptest96.swb                  Soil water balance
#   1, iobal: Soil Water Balance simulation produced by SWAT and SWBAVG:
DATA  116 hru1virt.bal
#   5, ioshl: Swb2bd, summary of evaporation from shallow gw for each subbasin.
#   This file can be used as input to a subsequent watershed simulation
#   (e.g. by SWAT) to implement a two-way coupling by successive approximation.
DATA 220   hru1virt.shl
#   4, ioswm: Swb2bd, combined surface & gw budget terms
DATA 219   hru1virt.swm

#               RSD: Calculate gw residuals during simulation.
RSD  72  ..\inbase\gwuadmnu.obs                  gw level measurements
#      Output files associated with the RSD package:
#  11, iorsd: Rsd1wl, annual summary of residuals for measured water levels
DATA 226   hru1virt.rsd
#  12, iomeas: Rsd1wl, observed and simulated heads and difference for each obs.
DATA 227   hru1virt.mea
#
#               POS: Postprocessor
POS  64  ..\inbase\nozones.pos                   Postprocessor
#   6, iobud: Post1rp, Post1ot: Summary of budget terms
DATA 221   hru1virt.bud
#   7, ionet: Post1rp, Post1ot: Summary of net budget terms
DATA 222   hru1virt.net
#   8, ionetz: net budget terms requires ZoneBudget option to be installed)
DATA 223   hru1virt.ntz
#   9, iohyd: Hyd1rp, Hyd1ot: time series of heads and flow rates
DATA 224   hru1virt.hyd
#  10, iodat: Hyd1ot: solution arrays for specified time steps
DATA 225   hru1virt.dat
#
```

SWBX package input file rptest96.swb

The SWBX package reads this and hru1virt.bal, which was written by SWAT (above).

```
9,    nwshed  (balance file: use case name); file c:\gh\test\inbase\rptest.swb
    1    3    1    1 0.00    1     0 0.0
irropt,ievopt,ioprch,rchmpy,evapir,welmpy,iadcod,frseep
  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 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 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 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 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 3 5 5 5 3 7 7 7 7 7 7 9 9 9
 2 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 3 7 7 7 7 7 9 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 3 3 7 7 7 7 9 9 9 9 9
 0 0 0 0 0 0 0 0 2 2 2 2 3 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 0 3 3 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 3 8 8 3 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 3 3 8 8 8 8 8 8 3 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 3 8 8 8 8 8 8 8 8 8 3 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 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 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 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 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 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 0 0 8 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 0 0 0 8 8 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 0 0 0 8 8 8 8 8 8 8 8 8 8 8 0 0 0 0
```

SWBX package output file hru1virt.shl

This file, written by subroutine Swb2bd, summarizes Modflow's results for evaporation from shallow groundwater for each subbasin simulated by SWAT. The data columns are the following: Here, shallow groundwater is defined as dtw < d_{ext}, where d_{ext} is specified by input to Modflow's Evaporation module. For the Lower Republican River basin model, d_{ext} = 6 ft; see Ch. 2 for details of conceptual model for evaporation from shallow groundwater. File output format and definitions are as follows:

icalyr (i5): year
kkkper (i5): stress period
kkstp (i5): time step
j (i5): subbasin index
shlfrc (f10.7): subbasin area underlain by shallow groundwater, fraction of total basin area
shed(7,j); (f10.7): subbasin area underlain by all groundwater, fraction of total basin area
shed(28,j); (f10.2): mean depth to water over the area underlain by shallow groundwater
shed(29,j); (f10.2): mean depth to water over total area underlain by groundwater
frcpot; (f10.6): evaporation from shallow groundwater as a fraction of potential evaporation, which is specified in each time step by input from the balance file (above).

```
 year   per   stp   sub frc shall frc activ  shal dtw    avg dtw    frcpot
 1977     1     1     1 0.0137352 0.0732544      3.72      19.03  0.340127
 1977     1     1     2 0.0411059 0.2055294      3.44      16.37  0.426068
 1977     1     1     3 0.0147972 0.2367549      5.32      25.65  0.113346
```

1977	1	1	4	0.0000000	0.0922834	0.00	28.58	0.000000
1977	1	1	5	0.0190824	0.2099068	3.02	22.07	0.497465
1977	1	1	6	0.0000000	0.0122218	0.00	36.51	0.000000
1977	1	1	7	0.0000000	0.0829647	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	0.2506201	0.00	20.64	0.000000
1977	1	2	1	0.0045784	0.0732544	0.23	19.58	0.961596
1977	1	2	2	0.0411059	0.2055294	4.07	16.90	0.322411
1977	1	2	3	0.0098648	0.2367549	5.65	26.09	0.057554
1977	1	2	4	0.0000000	0.0922834	0.00	29.11	0.000000
1977	1	2	5	0.0190824	0.2099068	3.74	22.53	0.376447
1977	1	2	6	0.0000000	0.0122218	0.00	37.34	0.000000
1977	1	2	7	0.0000000	0.0829647	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	0.2506201	0.00	21.10	0.000000
1977	1	3	1	0.0045784	0.0732544	1.38	19.86	0.770470
1977	1	3	2	0.0205529	0.2055294	3.19	17.20	0.467953
1977	1	3	3	0.0098648	0.2367549	5.79	26.30	0.035723
1977	1	3	4	0.0000000	0.0922834	0.00	29.39	0.000000
1977	1	3	5	0.0190824	0.2099068	4.01	22.80	0.332465
1977	1	3	6	0.0000000	0.0122218	0.00	37.53	0.000000
1977	1	3	7	0.0000000	0.0829647	0.00	18.70	0.000000
1977	1	3	8	0.0000000	0.0256515	0.00	39.68	0.000000
1977	1	3	9	0.0000000	0.2506201	0.00	21.38	0.000000
1977	1	4	1	0.0045784	0.0732544	2.33	20.11	0.610881
1977	1	4	2	0.0205529	0.2055294	3.93	17.48	0.345675
1977	1	4	3	0.0098648	0.2367549	5.89	26.46	0.017980
1977	1	4	4	0.0000000	0.0922834	0.00	29.61	0.000000
1977	1	4	5	0.0190824	0.2099068	4.20	23.04	0.299357
1977	1	4	6	0.0000000	0.0122218	0.00	37.66	0.000000
1977	1	4	7	0.0000000	0.0829647	0.00	18.89	0.000000
1977	1	4	8	0.0000000	0.0256515	0.00	39.87	0.000000
1977	1	4	9	0.0000000	0.2506201	0.00	21.61	0.000000
1977	1	5	1	0.0045784	0.0732544	3.19	20.23	0.468861
1977	1	5	2	0.0205529	0.2055294	4.55	17.66	0.241796
1977	1	5	3	0.0098648	0.2367549	5.65	26.49	0.057871
1977	1	5	4	0.0000000	0.0922834	0.00	29.66	0.000000
1977	1	5	5	0.0190824	0.2099068	4.12	23.15	0.312771
1977	1	5	6	0.0000000	0.0122218	0.00	37.43	0.000000
1977	1	5	7	0.0000000	0.0829647	0.00	18.86	0.000000
1977	1	5	8	0.0000000	0.0256515	0.00	39.61	0.000000
1977	1	5	9	0.0000000	0.2506201	0.00	21.71	0.000000
1977	1	6	1	0.0137352	0.0732544	5.00	19.88	0.165890
1977	1	6	2	0.0205529	0.2055294	4.95	17.52	0.174493
1977	1	6	3	0.0147972	0.2367549	4.95	26.07	0.175761
1977	1	6	4	0.0000000	0.0922834	0.00	29.23	0.000000
1977	1	6	5	0.0190824	0.2099068	3.18	22.83	0.469825
1977	1	6	6	0.0000000	0.0122218	0.00	36.24	0.000000
1977	1	6	7	0.0000000	0.0829647	0.00	18.35	0.000000
1977	1	6	8	0.0000000	0.0256515	0.00	38.49	0.000000
1977	1	6	9	0.0000000	0.2506201	0.00	21.54	0.000000

STRX (modified STREAM) package input file rptest.str

The input file listing below is complete except for monthly inflows at Clay Center, which are shown only for the first two years (1977-1978).

```
77         1         0         0         3      1.49         0         0    1   12    73  -2.    file rptest.str jun 14 96
        77         0         0         1         1         1         1          77"itmp irdflg iptflg irdcnd numinp iroute isgtop
    1    1    2    1    1        74.387    1378.0         0    1375.0    1378.0   5s 4w 5
    1    2    3    1    2          0.00    1373.2         0    1370.2    1373.2   5s 4w 9
    1    2    4    1    3          0.00    1368.0         0    1365.0    1368.0   5s 4w10
    1    2    5    1    4          0.00    1363.2         0    1360.2    1363.2   5s 4w11
    1    3    5    1    5          0.00    1358.3         0    1355.3    1358.3   5s 4w14
    1    4    5    1    6          0.00    1356.3         0    1353.3    1356.3   5s 4w23
    1    3    6    1    7          0.00    1353.9         0    1350.9    1353.9   5s 4w13
    1    4    6    1    8          0.00    1350.3         0    1347.3    1350.3   5s 4w24
    1    5    6    1    9          0.00    1348.0         0    1345.0    1348.0  Buffalo Cr
    1    4    7    1   10          0.00    1346.5         0    1343.5    1346.5   5s 3w19
    1    5    7    1   11          0.00    1342.1         0    1339.1    1342.1  Wolf Cr
    1    5    8    1   12          0.00    1338.0         0    1335.0    1338.0   5s 3w29
    1    5    9    1   13          0.00    1332.7         0    1329.7    1332.7   5s 3w28
    1    5   10    1   14          0.00    1328.6         0    1325.6    1328.6   5s 3w27
    1    5   11    1   15          0.00    1325.3         0    1322.3    1325.3   5s 3w26
    1    5   12    1   16          0.00    1322.4         0    1319.4    1322.4   5s 3w25
    1    4   12    1   17          0.00    1320.7         0    1317.7    1320.7   5s 3w24
    1    4   13    1   18          0.00    1318.0         0    1315.0    1318.0   5s 2w19
    1    4   14    1   19          0.00    1316.3         0    1313.3    1316.3   5s 2w20
    1    5   14    1   20          0.00    1313.9         0    1310.9    1313.9   5s 2w29
    1    6   14    1   21          0.00    1310.8         0    1307.8    1310.8  Plum Cr
    1    6   15    1   22          0.00    1308.2         0    1305.2    1308.2  stream from
    1    5   15    1   23          0.00    1307.7         0    1304.7    1307.7   5s 2w28
    1    6   16    1   24          0.00    1306.4         0    1303.4    1306.4  stream (inte
    1    5   16    1   25          0.00    1303.8         0    1300.8    1303.8   5s 2w27
    1    4   16    1   26          0.00    1301.5         0    1298.5    1301.5  Salt Cr
    1    4   17    1   27          0.00    1297.6         0    1294.6    1297.6   5s 2w23
    1    4   18    1   28          0.00    1293.5         0    1290.5    1293.5  Upton Cr
    1    4   19    1   29          0.00    1289.9         0    1286.9    1289.9   5s 1w19
    1    4   20    1   30          0.00    1287.5         0    1284.5    1287.5   5s 1w20
    1    5   20    1   31          0.00    1284.2         0    1281.2    1284.2   5s 1w29
    1    6   21    1   32          0.00    1279.2         0    1276.2    1279.2  Elm Cr
    1    5   21    1   33          0.00    1277.7         0    1274.7    1277.7   5s 1w28
    1    5   22    1   34          0.00    1275.3         0    1272.3    1275.3   5s 1w27
    1    5   23    1   35          0.00    1273.3         0    1270.3    1273.3   5s 1w26
    1    6   23    1   36          0.00    1270.9         0    1267.9    1270.9   5s 1w35
    1    6   24    1   37          0.00    1265.4         0    1262.4    1265.4   5s 1w36
    1    5   24    1   38          0.00    1265.6         0    1262.6    1265.6  Elk Cr
    1    7   24    1   39          0.00    1259.7         0    1256.7    1259.7  Beaver Cr
    1    8   25    1   40          0.00    1257.2         0    1254.2    1257.2   6s 1e 7
    1    8   26    1   41          0.00    1253.1         0    1250.1    1253.1   6s 1e 8
```

1	7	26	1	42	0.00	1254.1	0	1251.1	1254.1	6s 1e 5
1	8	27	1	43	0.00	1249.0	0	1246.0	1249.0	6s 1e 9
1	8	28	1	44	0.00	1246.2	0	1243.2	1246.2	6s 1e10
1	8	29	1	45	0.00	1241.3	0	1238.3	1241.3	6s 1e11
1	8	30	1	46	0.00	1235.9	0	1232.9	1235.9	6s 1e12
1	7	30	1	47	0.00	1234.3	0	1231.3	1234.3	Parsons Cr
1	8	31	1	48	0.00	1231.1	0	1228.1	1231.1	6s 2e 7
1	9	31	1	49	0.00	1228.7	0	1225.7	1228.7	6s 2e18
1	10	31	1	50	0.00	1226.0	0	1223.0	1226.0	6s 2e19
1	11	31	1	51	0.00	1224.0	0	1221.0	1224.0	6s 2e30
1	11	32	1	52	0.00	1221.3	0	1218.3	1221.3	Peats Cr
1	12	32	1	53	0.00	1217.8	0	1214.8	1217.8	6s 2e32
1	13	32	1	54	0.00	1214.2	0	1211.2	1214.2	7s 2e 5
1	13	33	1	55	0.00	1213.7	0	1210.7	1213.7	Peet Cr
1	14	32	1	56	0.00	1209.9	0	1206.9	1209.9	Mulberry Cr
1	14	33	1	57	0.00	1208.2	0	1205.2	1208.2	7s 2e 9
1	15	33	1	58	0.00	1207.3	0	1204.3	1207.3	7s 2e16
1	15	32	1	59	0.00	1202.8	0	1199.8	1202.8	7s 2e17
1	16	32	1	60	0.00	1198.7	0	1195.7	1198.7	7s 2e20
1	17	32	1	61	0.00	1196.4	0	1193.4	1196.4	7s 2e29
1	17	33	1	62	0.00	1193.2	0	1190.2	1193.2	7s 2e28
1	18	33	1	63	0.00	1188.6	0	1185.6	1188.6	7s 2e33
1	19	33	1	64	0.00	1187.0	0	1184.0	1187.0	8s 2e 4
1	19	34	1	65	0.00	1184.7	0	1181.7	1184.7	8s 2e 3
1	19	35	1	66	0.00	1181.0	0	1178.0	1181.0	8s 2e 2
1	20	35	1	67	0.00	1177.9	0	1174.9	1177.9	8s 2e11
1	21	35	1	68	0.00	1176.0	0	1173.0	1176.0	8s 2e14
1	21	36	1	69	0.00	1173.2	0	1170.2	1173.2	Five Cr
1	20	36	1	70	0.00	1172.0	0	1169.0	1172.0	8s 2e12
1	20	37	1	71	0.00	1170.5	0	1167.5	1170.5	8s 3e 7
1	21	37	1	72	0.00	1167.9	0	1164.9	1167.9	Huntress Cr
1	21	38	1	73	0.00	1165.8	0	1162.8	1165.8	8s 3e17
1	22	38	1	74	0.00	1164.2	0	1161.2	1164.2	8s 3e20
1	21	39	1	75	0.00	1161.1	0	1158.1	1161.1	Finney Cr
1	22	39	1	76	0.00	1158.2	0	1155.2	1158.2	8s 3e21
1	23	39	1	77	0.00	1156.3	0	1153.3	1156.3	8s 3e28

100	0.0007137	0.03	5483.1	1	1.2461e-5	6.2304e-5	54627.7	1
100	0.0006155	0.03	7716.9	1	1.2461e-5	6.2304e-5	62344.6	2
100	0.0009655	0.03	7107.7	1	1.2461e-5	6.2304e-5	69452.3	3
100	0.0009655	0.03	4264.6	1	1.2461e-5	6.2304e-5	73716.9	4
100	0.0005726	0.03	6498.5	1	1.2461e-5	6.2304e-5	79098.5	5
100	0.0005726	0.03	4467.7	1	1.2461e-5	6.2304e-5	83566.2	6
100	0.0005726	0.03	2640	1	1.2461e-5	6.2304e-5	87323.1	7
100	0.000566	0.03	7513.8	1	1.2461e-5	6.2304e-5	94836.9	8
100	0.000566	0.03	2843.1	1	1.2461e-5	6.2304e-5	97680	9
100	0.000566	0.03	2640	1	1.2461e-5	6.2304e-5	100320	10
100	0.000566	0.03	9341.5	1	1.2461e-5	6.2304e-5	109661.5	11
100	0.0006746	0.03	5787.7	1	1.2461e-5	6.2304e-5	115449.2	12
100	0.0006746	0.03	8630.8	1	1.2461e-5	6.2304e-5	124080	13
100	0.0005129	0.03	5990.8	1	1.2461e-5	6.2304e-5	130070.8	14

100	0.0005129	0.03	6701.5	1	1.2461e-5	6.2304e-5	136772.3	15
100	0.0005129	0.03	5381.5	1	1.2461e-5	6.2304e-5	142153.8	16
100	0.0005129	0.03	2640	1	1.2461e-5	6.2304e-5	144793.8	17
100	0.0005103	0.03	6092.3	1	1.2461e-5	6.2304e-5	150886.2	18
100	0.0005103	0.03	2436.9	1	1.2461e-5	6.2304e-5	153323.1	19
100	0.0005103	0.03	5483.1	1	1.2461e-5	6.2304e-5	158806.2	20
100	0.0005411	0.03	6295.4	1	1.2461e-5	6.2304e-5	165101.5	21
100	0.0005411	0.03	3147.7	1	1.2461e-5	6.2304e-5	166929.3	22
100	0.0005411	0.03	3046.1	1	1.2461e-5	6.2304e-5	169975.4	23
100	0.0005411	0.03	507.7	1	1.2461e-5	6.2304e-5	171803.1	24
100	0.0005411	0.03	6295.4	1	1.2461e-5	6.2304e-5	178098.5	25
100	0.0005411	0.03	3553.8	1	1.2461e-5	6.2304e-5	181652.3	26
100	0.0006354	0.03	7513.9	1	1.2461e-5	6.2304e-5	189166.2	27
100	0.0006354	0.03	6092.3	1	1.2461e-5	6.2304e-5	195258.5	28
100	0.0005828	0.03	5584.6	1	1.2461e-5	6.2304e-5	200843.1	29
100	0.0005828	0.03	3655.4	1	1.2461e-5	6.2304e-5	204498.5	30
100	0.0005828	0.03	6295.4	1	1.2461e-5	6.2304e-5	210793.9	31
100	0.0005352	0.03	9341.5	1	1.2461e-5	6.2304e-5	220135.4	32
100	0.0005352	0.03	609.2	1	1.2461e-5	6.2304e-5	220744.6	33
100	0.0005352	0.03	5889.2	1	1.2461e-5	6.2304e-5	226633.9	34
100	0.0005352	0.03	3046.2	1	1.2461e-5	6.2304e-5	229680	35
100	0.0005352	0.03	4873.8	1	1.2461e-5	6.2304e-5	234553.9	36
100	0.0005183	0.03	11169.3	1	1.2461e-5	6.2304e-5	239935.4	37
100	0.0005183	0.03	4772.3	1	1.2461e-5	6.2304e-5	244707.7	38
100	0.0004191	0.03	6193.8	1	1.2461e-5	6.2304e-5	256689.3	39
100	0.0004191	0.03	5889.2	1	1.2461e-5	6.2304e-5	262578.5	40
100	0.0004191	0.03	5686.2	1	1.2461e-5	6.2304e-5	264000	41
100	0.0004191	0.03	5889.3	1	1.2461e-5	6.2304e-5	269889.3	42
100	0.0004602	0.03	8224.6	1	1.2461e-5	6.2304e-5	282378.5	43
100	0.0004602	0.03	5584.6	1	1.2461e-5	6.2304e-5	287963.1	44
100	0.0005352	0.03	12793.8	1	1.2461e-5	6.2304e-5	300756.9	45
100	0.0005352	0.03	7818.5	1	1.2461e-5	6.2304e-5	306240	46
100	0.0005352	0.03	5787.7	2	1.2461e-5	6.2304e-5	312027.7	47
100	0.0005352	0.03	3046.2	2	1.2461e-5	6.2304e-5	317409.3	48
100	0.0004875	0.03	5178.5	2	1.2461e-5	6.2304e-5	322587.7	49
100	0.0004875	0.03	5686.2	2	1.2461e-5	6.2304e-5	328273.9	50
100	0.0004875	0.03	3553.8	2	1.2461e-5	6.2304e-5	331827.7	51
100	0.0004875	0.03	6092.3	2	1.2461e-5	6.2304e-5	337920	52
100	0.0004875	0.03	7716.9	2	1.2461e-5	6.2304e-5	345636.9	53
100	0.0004875	0.03	7615.4	2	1.2461e-5	6.2304e-5	350713.9	54
100	0.0004875	0.03	1726.2	2	1.2461e-5	6.2304e-5	352440	55
100	0.0006437	0.03	6498.5	2	1.2461e-5	6.2304e-5	361476.9	56
100	0.0006437	0.03	1218.5	2	1.2461e-5	6.2304e-5	362695.4	57
100	0.0006437	0.03	1523.1	2	1.2461e-5	6.2304e-5	364218.5	58
100	0.0006437	0.03	8833.8	2	1.2461e-5	6.2304e-5	373052.3	59
100	0.0005077	0.03	6193.9	2	1.2461e-5	6.2304e-5	379246.2	60
100	0.0005077	0.03	4061.5	2	1.2461e-5	6.2304e-5	383307.7	61
100	0.0005077	0.03	7107.7	2	1.2461e-5	6.2304e-5	390415.4	62
100	0.00049	0.03	9646.2	2	1.2461e-5	6.2304e-5	400061.6	63
100	0.00049	0.03	1218.5	2	1.2461e-5	6.2304e-5	401280	64

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     100    0.00049       0.03      5889.2          2 1.2461e-5 6.2304e-5  407169.3   65
     100    0.00049       0.03      8021.5          2 1.2461e-5 6.2304e-5  415190.8   66
     100 0.0005253        0.03      5381.6          2 1.2461e-5 6.2304e-5  420572.3   67
     100 0.0005372        0.03      3046.1          2 1.2461e-5 6.2304e-5  423618.5   68
     100 0.0005372        0.03      5889.3          2 1.2461e-5 6.2304e-5  429507.7   69
     100 0.0005372        0.03      1218.5          2 1.2461e-5 6.2304e-5  430726.2   70
     100 0.0005372        0.03      3147.7          2 1.2461e-5 6.2304e-5  433873.9   71
     100 0.0005897        0.03      4975.4          2 1.2461e-5 6.2304e-5  438849.3   72
     100 0.0005897        0.03      3046.2          2 1.2461e-5 6.2304e-5  441895.4   73
     100 0.0005897        0.03        2640          2 1.2461e-5 6.2304e-5  444535.4   74
     100 0.0005897        0.03      6193.8          2 1.2461e-5 6.2304e-5  450729.3   75
     100 0.0004646        0.03      5584.6          2 1.2461e-5 6.2304e-5  456313.9   76
     100 0.0004646        0.03      3452.3          2 1.2461e-5 6.2304e-5  459766.2   77
  1    1    2    1    1          189.643        1378         0       1375      1378    31.678    2    77
  1    1    2    1    1          156.677        1378         0       1375      1378     63.42    3    77
  1    1    2    1    1            140.2        1378         0       1375      1378    34.733    4    77
  1    1    2    1    1          223.516        1378         0       1375      1378   192.936    5    77
  1    1    2    1    1          734.733        1378         0       1375      1378   611.634    6    77
  1    1    2    1    1          364.613        1378         0       1375      1378   -37.774    7    77
  1    1    2    1    1         1113.677        1378         0       1375      1378  1126.581    8    77
  1    1    2    1    1           1160.5        1378         0       1375      1378       337    9    77
  1    1    2    1    1          276.258        1378         0       1375      1378    63.645   10    77
  1    1    2    1    1          264.833        1378         0       1375      1378      69.9   11    77
  1    1    2    1    1          216.419        1378         0       1375      1378    23.807   12    77
      -2         0         0          1           1         1          1         1  78"itmp irdflg iptflg irdcnd numinp iroute nrstep
  1    1    2    1    1          164.516        1378         0       1375      1378     7.742    1    78
  1    1    2    1    1          175.714        1378         0       1375      1378    16.429    2    78
  1    1    2    1    1         1104.419        1378         0       1375      1378   730.162    3    78
  1    1    2    1    1          411.733        1378         0       1375      1378   159.334    4    78
  1    1    2    1    1          380.129        1378         0       1375      1378   617.903    5    78
  1    1    2    1    1          213.367        1378         0       1375      1378     109.9    6    78
  1    1    2    1    1           450.71        1378         0       1375      1378   263.613    7    78
  1    1    2    1    1          514.903        1378         0       1375      1378    97.387    8    78
  1    1    2    1    1            571.7        1378         0       1375      1378   346.533    9    78
  1    1    2    1    1          178.935        1378         0       1375      1378     63.13   10    78
  1    1    2    1    1            191.3        1378         0       1375      1378    53.433   11    78
  1    1    2    1    1          143.613        1378         0       1375      1378    41.839   12    78
```

WELX (modified WELL) package input file wrrepub.wel (excerpt)

Both surface and groundwater rights, primarily for irrigation, are listed in this file in order of their first year of appropriation. Rights are shown here only through 1954; the complete version of the file extends to 1994.

```
390         0         1        1.        4.        8.       15.       30. wrrepub.wel
       277       388      1977    1.0000   36.1760
         1         7        29  -0.04241   0.00000      1.08    47 1941 VG  4        6.20    28.33 VCY00010006S01E020642003550
         1         7        29  -0.04241   0.00000      1.08    47 1941 VG  4        6.20    28.32 VCY00010006S01E020542003600
```

1	5	23	-0.05065	0.00000	0.61	35	1941	VG	4	4.33	22.68	VCD00010005S01W260235351700
1	5	23	-0.05065	0.00000	0.61	35	1941	VG	4	4.34	22.68	VCD00010005S01W260434951700
1	5	23	-0.05065	0.00000	0.61	35	1941	VG	4	4.33	22.68	VCD00010005S01W260335201700
1	13	34	-0.01483	0.00000	1.03	55	1941	VG	4	12.99	33.07	VCY00030007S02E030100504920
1	20	37	-0.14412	0.00000	0.51	71	1941	VG	4	19.38	36.60	VCY00040008S03E071233002100
1	20	37	-0.14412	0.00000	0.68	71	1941	VG	4	19.48	36.91	VCY00040008S03E070127500500
1	6	9	-0.20600	0.00000	0.83	13	1941	VG	4	5.42	8.48	VCD00040005S03W330330752769
1	20	37	-0.14412	0.00000	0.65	71	1941	VG	4	19.58	36.93	VCY00040008S03E070222000350
1	7	30	-0.15853	0.00000	0.38	47	1941	VG	2	6.38	29.01	VCY00080006S01E011232505230
1	5	18	-0.13813	0.00000	1.19	28	1941	VG	3	4.56	17.06	VCD00110005S02W2501NWNWSW
1	5	14	-0.17818	0.00000	0.48	20	1941	VS	3	4.13	13.19	VCD00090005S02W290146004260
1	5	14	-0.17818	0.00000	0.37	20	1941	VS	3	4.48	13.13	VCD00090005S02W290227254600
1	6	26	-0.12086	0.00000	0.90	42	1942	VG	3	5.69	25.25	VWS00280005S01E3201NCS2N2SW
1	20	35	-0.12293	0.00000	0.32	67	1952	AG	3	19.18	34.78	A0009050008S02E110743501150
1	5	18	-0.15194	0.00000	1.21	28	1953	AG	3	4.69	17.81	A0011520005S02W2502SWNESE
1	7	30	-0.11021	0.00000	0.43	47	1953	AG	2	6.36	29.01	A0012990006S01E010234005230
1	4	16	-0.10774	0.00000	0.51	26	1953	AG	3	3.56	15.31	A0015050005S02W2201NWNESW
1	6	12	-0.13537	0.00000	0.74	16	1953	AG	3	5.16	11.51	A0015450005S03W360144502600
1	5	17	-0.06699	0.00000	0.78	27	1953	AG	3	4.19	16.94	A0017090005S02W2601SENENE
1	5	17	-0.06699	0.00000	0.78	27	1953	AG	3	4.19	16.69	A0017090005S02W2602SENWNE
1	19	35	-0.17957	0.00000	0.15	66	1953	AG	3	18.81	34.19	A0019620008S02E0201NESWSW
1	21	35	-0.04144	0.00000	0.27	68	1953	AS	3	20.69	34.31	A0020410008S02E1401SWNESW

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Appendix: SWAT Help files modified for SWAT-MODFLOW linkage

These documents are in html format, and are to be found in the subdirectory \ghdoc\Swat_htm\ after running the self-extracting file swtmddoc.exe; please refer to Installation Notes (Ch. 4 of the Guide to Coordinating Swat and Modflow). They show the additional data required for input to Swat to invoke the Swat-Modflow linkage.

Control Codes (*.Cod): linkage options and HRU component fractions

Configuration (*.Fig): routing for virtual subbasins

Management (*.Mgt): land uses

Groundwater (*.Gw): variations on deep groundwater assumption