Documentation of a combined watershed and stream-aquifer modeling program based on Swat and Modflow

Vol. 1. Users' manual

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Preface

The purpose of this report is to document a watershed modeling program, referred to here as SWATMOD, which incorporates both Swat (Arnold et al., 1994), a watershed modeling program, and Modflow (McDonald et al., 1988), a stream-aquifer modeling program. This report is intended to serve as a user's manual for the program, to document its application to the Lower Republican River Basin as described by Perkins (1999), and to provide a starting point for an update of the Swat-Modflow linkage scheduled for completion July, 2000 that is to incorporate the latest versions of Swat and Modflow.

The program is based on code development efforts from three separate projects. In each of these we have linked Modflow to a watershed model code and then applied the combined code to develop calibrated computer models for use in examining watershed management questions. Sophocleous and Perkins (1999) present an overview of these studies. This report describes the latest version of this program, which benefits from the experience gained in the course of thes projects. The code incorporates the capabilities developed for these studies, yet is simpler and easier to apply than earlier versions.

Initial tests of the combined SWAT-MODFLOW computer code were based on a model of a small watershed with an area of 1.23 km^2 at Riesel, TX that is gaged and operated by USDA-ARS and identified as Y7. A SWAT-based model of Y7 was used by ARS for SWAT program verification; results from this model are summarized in the SWAT manual (Arnold et al., 1994). Results from our tests of Y7 are described in progress reports to KWO for a study of the Lower Republican River Basin (Sophocleous et al., 1995a and b).

Swat and Modflow were combined for application to Rattlesnake Creek watershed in south central Kansas and to the Lower Republican River Basin in north central Kansas. Similar but separate versions of the combined code were developed on parallel schedules, and are documented separately. The version applied to the Rattlesnake Creek watershed is documented in Perkins and Sophocleous (1998: KGS Open-File Report 98-59), which is an update of Appendix I to the Combined KSU/KGS Final Report (Sophocleous et al., 1997a). In this study, KSU provided the expertise to develop a watershed model based on

Swat, while KGS developed the Swat-Modflow linkage and the calibrated stream-aquifer model. The combined Swat-Modflow code was applied to the Lower Republican River Basin in a study for the Kansas Water Office, and is documented in Perkins and Sophocleous (1997: KGS Open-File Report 97-9) as a companion volume to the study's final report (Sophocleous et al., 1997: KGS Open-File Report 97-8). The development and application of these computer codes to Rattlesnake Creek and Lower Republican River basins, respectively, are also reported in Sophocleous et al. (1998) and in Perkins and Sophocleous (1999).

We drew on our experience and computer codes from these studies to develop a combined code for a study of Wet Walnut Creek watershed. In this case Swat was replaced by the program POTYLDR ("Potential Yield Revised", Koelliker, 1994). This was again a collaborative effort in which KSU applied Potyldr to develop a calibrated watershed model, while KGS applied Modflow to develop a calibrated stream-aquifer model, and the two groups coordinated closely to produce a combined calibrated model.

This report is supplemented by appendices as follows. Appendix A was written as an extension to Chapter 3 of Swat's manual (version 2), added as Section 3.4, to describe the format for input data files read by Swat, including additional input required for coordinating Swat with Modflow. Appendix B provides operational details of running the combined programs of Swat and Modflow, and coordinating file device numbers. Appendix C describes input changes made to MODFLOW for its application to the combined watershed-stream-aquifer models. Volume 2 describes compiling and linking the programs, and lists the source code that was written or modified to implement the linkage.

Introduction

This document describes a revised Swat-Modflow linkage with application to the Lower Republican River Basin. The main objectives of the revisions are to simplify and generalize the linkage, both in terms of the code's maintenance and its application to watershed modeling. The version of MODFLOW used in the POTYLDR-MODFLOW linkage for application to Wet Walnut Creek (Sophocleous and Perkins, 1998) was revised by substituting SWAT v.'94 for POTYLDR for application to the Lower Republican River Basin. The calibrated model previously developed for this basin was updated to run under this simplified version of SWATMOD. The base case of our study of the Lower Republican River Basin is used as an example for input data file instructions and in procedures for running the linked program and examining simulation results.

This version is an improvement in several aspects over the original linkage used for the Lower Republican River basin study (Sophocleous et al., 1997) and documented in Perkins and Sophocleous (P&S, 1997):

1. Techniques for passing data between SWAT and MODFLOW are simpler but more flexible, whether data are passed by file or by reference as subroutine arguments.

2. Conceptual models for hydrologic connections between the two model codes satisfy continuity more accurately. This is shown by improvements in calibration residuals and in overall watershed water balances (Perkins, 1999).

3. Two alternatives to the original conceptual model for spatial heterogeneity (HRU scheme) have been installed as options to account for areal fractions of subbasins underlain by bedrock with no aquifer; and to further distinguish between deep and shallow areas of ground water. The two-way coupling between unsaturated and saturated zones arising from shallow ground water is represented by one of the alternative schemes. This coupling of SWAT and MODFLOW solutions was implemented with separate execution

of SWAT and MODFLOW and required relatively minor changes to the two programs. Its implementation utilizes the techniques of (a) time-varying HRU weights to reflect ground water response to weather cycles, and (b) successive approximation to pass MODFLOW's results concerning shallow ground water to SWAT. Section 4 of this report discusses options for representing this two-way coupling

4. The operating procedure for applying the SWAT-MODFLOW linkage to simulations has been simplified by using a single instance of SWAT's Control Codes (~.cod) input file to show in a table how the component HRUs of a scheme are organized to represent spatial heterogeneity. This ~.cod file is used as input to all of the HRU simulations by SWAT and by program SWBAVG, which takes an average over SWAT's results.

5. The procedure for representing spatial heterogeneity with SWAT as originally developed for application to the Lower Republican River basin has been retained. In this procedure, SWAT, SWBAVG, and MODFLOW are executed separately. This is favored over the procedure outlined in Fig. 1 of the proposal (S&P, 1999), in which SWAT calls MODFLOW as a subroutine. However, the technique employed here of simulating HRUs individually with SWAT and averaging them externally is considered to be an optional mode of operation that should not interfere with alternative approaches that make use of SWAT's capabilities to simulate and average HRUs internally.

6. The preliminary version of the updated SWAT-MODFLOW linkage incorporates the latest versions of MODFLOW packages developed for the linkage of POTYLDR (Koelliker, 1994) to MODFLOW for application to the Wet Walnut Creek watershed (Sophocleous et al., 1998).

Input data requirements for the combined Swat-Modflow program (SwatMod)

Most of the input data for the combined Swat-Modflow program are described by the respective manuals for Swat (Arnold et al., 1994) and Modflow (McDonald et al., 1988; Prudic, 1989). The manual for Swat describes input for the program but not the format in which it is read, under the assumption that input files are written by a preprocessor available with Swat that runs under GRASS, a public domain, raster-based graphical interface system (GIS). However, Arc-Info is the GIS used here in Kansas by the parties interested in the combined Swat-Modflow program (KGS, KU, KSU, DWR, and KWO). Because a preprocessor for Swat that runs under Arc-Info was not available, a preliminary version of one was developed (L. Bian, personal communication), although it does not take into account revisions to input data format for Swat (v. 2).

Revisions to Swat's original input data format are restricted primarily to its input control file (~.cod), where options regarding variations on original Swat procedures and coordination of Swat and Modflow are specified. Some format revisions were made to input files for soils and weather data to be consistent with formats for version 1 of Swat (1993).

For the combined Swat-Modflow program, an extension to the Swat manual has been written to describe Swat's input format, including revisions. This extension, reproduced here as Appendix A (also inserted after Section 3.3 of the Swat manual as Section 3.4), provides some rudimentary instructions for input files that are to be constructed without the aid of a GIS-based preprocessor. For the purpose of data entry, some preprocessing assistance can be provided by spreadsheet templates for exporting text files that conform to Swat input file formats described by Appendix A.

Changes to Modflow input format have been made that allow the program to operate as expected, given standard input as described by Modflow's manual. The Stream package contains some nonstandard input options, although only standard input is used for the Rattlesnake Creek watershed model. The Well package was modified to allow pumping wells to be distinguished from model wells used to represent nonzero flow boundary conditions.

The Modswb package reads an input file primarily to associate (a) subbasin outflow locations with reaches of a stream network represented by Modflow's Stream package; and (b) the domain of each subbasin with grid cells of the aquifer through an integer array, IBSHED, similar to the IBOUND array read from the input file for Modflow's Basic package.

If Swat and Modflow are executed separately, Modswb also reads a hydrologic summary of results from Swat for each aquifer time step from a balance input file. Alternatively, Swat can make subroutine calls to Modflow, and Swat's results are passed to Modflow by reference; see overviews for linked Swat-Modflow execution control, Preswb, and Modswb.

Methodology

1. 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. 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 based on separate execution of SWAT and MODFLOW is illustrated in Fig. 2. This coordination relies on three additional components of code in addition to SWAT and MODFLOW. The essential features of these components are summarized here, and described in more detail in Perkins and Sophocleous (1999b-c).

The first component of the SWAT-MODFLOW linkage, presented in Section 2, specifies hydrologic connections between the respective control volumes simulated by SWAT and MODFLOW. These connections include tributary inflow, ground water recharge, potential evaporation, and irrigation requirements. At the end of each aquifer solution time step, SWAT calls subroutine PRESWB (formerly HYDBAL) to transform the

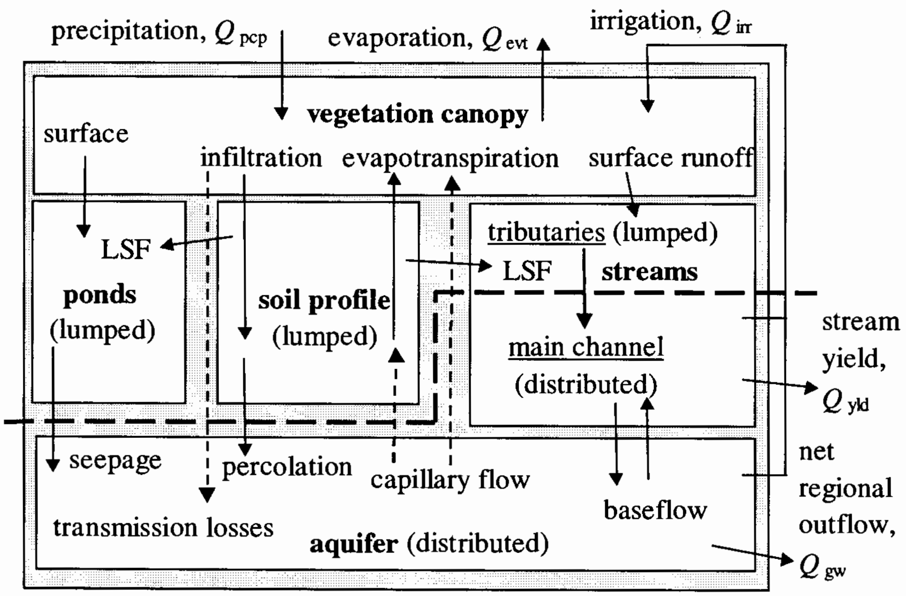

Figure 1. SWAT and SWBAVG simulate watershed control volume components above the dashed line (vegetation canopy, soils, and ponds), and MODFLOW those below (stream and aquifer); LSF = lateral subsurface flow. (from P&S, 1999a)

hydrologic depths, or cumulative volumes per unit area simulated by SWAT, to average flow rates over the aquifer time step to represent these connections for each subbasin. These flow rates are written to a file to summarize SWAT's simulation results for MODFLOW. SWAT also calls subroutine SUBWTS (formerly WEIGHTS) to calculate HRU weights, based on soil type and land use areal fractions in each subbasin

The second component of the linkage applies the HRU concept to represent the hydrologic effects of spatial heterogeneity within subbasins simulated by SWAT (Sections 3-4). A statistical model for spatial heterogeneity is provided by coordinating the execution of SWAT with a separate program, SWBAVG. SWAT simulates a set of representative homogeneous cases, referred to as hydrologic response units (HRUs). SWBAVG then takes an areally weighted average over the HRU simulation results. Weight functions for the averages taken over HRUs are calculated in calls by SWAT to subroutine SUBWTS. SWAT's Control Codes input file was modified to specify the HRUs and corresponding areal weights for SWAT and SWBAVG, respectively.

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 MODSWB, which was written for this purpose, in conjunction with the packages

1. Soil water-atmosphere simulation: SWAT

```
For each HRU, run SWAT as follows:
    For each day of the simulation period:
        At beginning of each aquifer solution time step, calculate (HRU scheme 3)
            Daily capillary uptake from shallow ground water (from MODFLOW)
        For each subbasin:
            Run lumped watershed model code;
            Accumulate results over each groundwater simulation time step;
        end do
        At end of each aquifer solution time step, calculate:
            Flow rates for each HRU and subbasin (subr. PRESWB);
            Spatial weights (subr. SUBWTS) to be used in average over HRUS
    end do
end do
```

2. Take average over HRUs: SWBAVG

```
For each aquifer solution time step:
    Read spatial weights written by subr. SUBWTS for each subbasin;
    For each HRU:
        Read flow rates written by subr. PRESWB for each subbasin;
        For each subbasin:
            For each hydrologic component:
                Accumulate a weighted average over all HRUs;
            end do
        end do
    end do
    Write HRU-averaged flow rates for each subbasin;
end do
```

3. Stream-aquifer simulation: MODFLOW

```
For each aquifer solution time step:
    Distribute HRU-averaged flow rates for each subbasin over grid cells to specify recharge, tributary flow, surface and ground water diversions, and max. evaporation for shallow ground water (MODSWB, MODSTR and MODWEL packages).
    Formulate and solve finite difference equations (FM_ and solver routines);
    Write summary of evaporation from shallow ground water (SWB2BD)
    Calculate residuals for simulated heads (MODRSD package);
    Write optional "postprocessed" results (MODPOST package);
end do
```

Figure 2. Procedure to coordinate separate execution of SWAT and MODFLOW for simulation of the Lower Republican River basin's watershed hydrology.

MODWEL and MODSTR, which are modified versions of MODFLOW's WELL and STREAM packages, respectively. MODSWB distributes the flow rates simulated by SWAT and SWBAVG for HRU-averaged hydrologic connections over the appropriate grid cells of the stream and aquifer domain in each time step. MODWEL and MODSTR are coordinated with MODSWB to represent irrigation requirements specified by SWAT as spatially distributed diversions from surface and ground water supplies.

2. Lumped conceptual models for hydrologic connections

SWAT uses an excess rainfall method to simulate the soil water budget of each subbasin separately with daily time steps in the form

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

On the left-hand side is the change in soil water content after t days; on the right are terms integrated over time for precipitation, d_{pcp}, which includes snowmelt and applied irrigation; runoff, d_{ro}; transmission losses, d_{xm}; percolation from the soil profile, d_{perc}; and evapotranspiration, d_{et}. Fig. 3 is a block diagram showing the hydrologic connections to be represented by the SWAT-MODFLOW linkage.

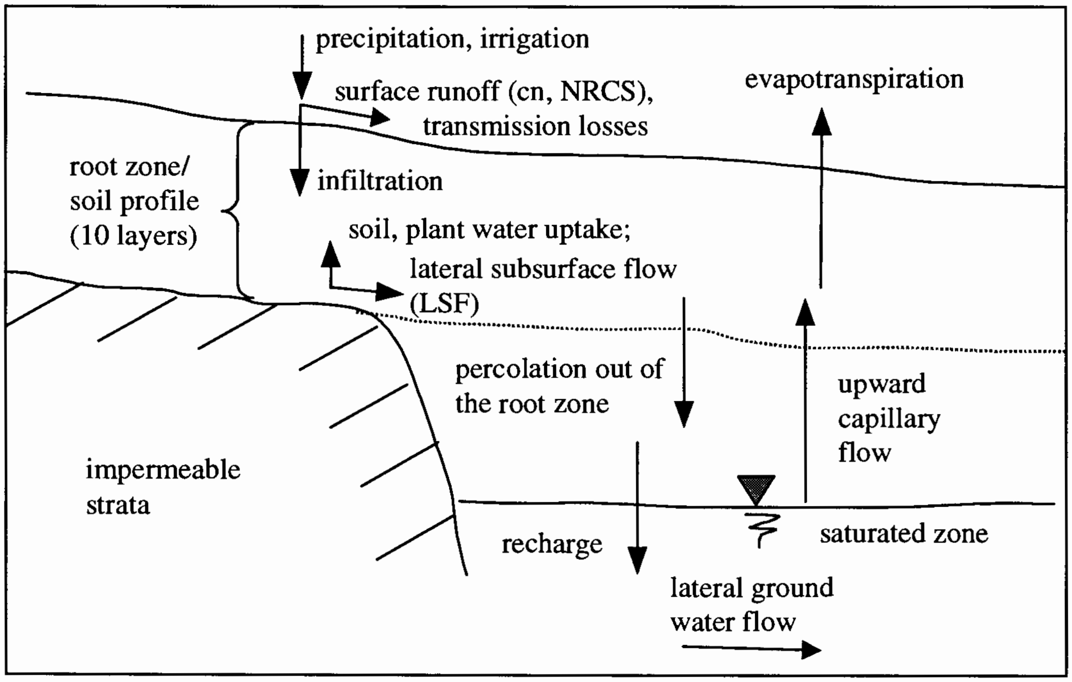

Figure 3. Conceptual model for soil water hydrology simulated by SWAT.

Equation (1) expresses each of these components as a depth, d, based on a geometrical interpretation of volume given by $V = dfA$, where f is the areal fraction of watershed area, A, to which the hydrologic component applies. This volume is also given by integrating flow rate over time. For average flow rate, Q, and time step, Δt, $V = Q\Delta t$. Combining these relates the hydrologic flow rates, Q, and depths, d, by

$$cQ\Delta t = dfA, \qquad (2)$$

where c is a length conversion factor.

SWAT calls subroutine PRESWB to calculate flow rates from each subbasin representing contributions for a single HRU to tributary inflows to the Republican River, aquifer recharge, surface and ground water diversions, and evapotranspiration from shallow ground water. Calculation of these flow rates involves combining terms simulated by SWAT, reviewed below, and conversion from hydrologic depths (cumulative volumes per unit area of the watershed) into flow rates according to equation (2).

Irrigation water use, recharge, tributary flow, and evaporation

Irrigation demand is simulated as summarized above for SWAT's soil water balance simulation. This is converted to a flow rate according to equation (2) by

$$Q_{irr} = d_{irr} f_{irr} A / c\Delta t. \tag{3}$$

The areal fraction of the watershed appropriated for irrigation, f_{irr}, is factored into the spatial weight functions associated with the averages taken over HRUs to represent spatial heterogeneity as discussed below.

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

$$Q_{rech} = (d_{perc} + d_{xm} + d_{psep}) A / c\Delta t. \tag{4}$$

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

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

$$Q_{trib} = (d_{sro} + d_{lat}) f_{con} A / c\Delta t + Q_{po} + Q_{rbed} \tag{5}$$

Overall, the watershed fraction contributing runoff directly to streams is estimated to be 0.98, based on USGS streamflow data reports. The remaining noncontributing component of the watershed drains to ponds, from which water may overflow with a flow rate Q_{po}, or seep to streams. The last term in equation (5), Q_{rbed}, is related to equation (4) as follows.

SWAT simulates percolation, transmission losses, and pond seepage, the terms included for recharge by equation (4), based on the assumption that the full areal extent of a subbasin's soil profile is underlain by an alluvial aquifer. To represent a subbasin only partially underlain by an aquifer, several alternatives are available. A somewhat simplistic method is to partition recharge according to equation (4) into two components,

$$Q_{rech} = Q_{raqf} + Q_{rbed} \tag{6}$$

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

$$Q_{raqf} = Q_{rech} f_{aqf} \tag{7a}$$

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

$$Q_{\mathrm{rbed}} = Q_{\mathrm{rech}}(1 - f_{\mathrm{aqf}}) \tag{7b}$$

This term is added into tributary flow as shown in equation (5).

These ad hoc schemes are based on the partitioning of equation (4) to satisfy continuity, but equation (6) is inconsistent with the hydrologic model simulated by Swat, in which the full extent of the subbasin is assumed to be underlain by an aquifer. More hydrologically consistent alternatives are provided by refined conceptual models of spatial heterogeneity, which are introduced below; see "Spatial heterogeneity of the alluvial aquifer: hydrologic effects" (Section 4).

Potential evaporation simulated by SWAT is passed to MODFLOW for use as a maximum rate of evapotranspiration from shallow ground water, described in Perkins (1999, Ch. 4, "Distributed model of hydrologic connections," the third component of the SWAT-MODFLOW linkage as outlined in Fig. 2. The coupling of the soil water profile to shallow ground water is based on refinements to Swat's hydrologic model and the conceptual model for spatial heterogeneity for HRU scheme 3 (Section 4). Unlike the hydrologic connections for irrigation, recharge, and tributary flow, this coupling requires information to flow from MODFLOW to SWAT. This requirement is met with only minor changes to SWAT and MODFLOW by the use of successive approximation (Section 4).

3. Heterogeneity: spatial averages for hydrologic connections

For the basic conceptual model of spatial heterogeneity (or HRU scheme) represented by the SWAT-MODFLOW linkage, the hydrologic connections between SWAT and MODFLOW provided an improved accounting for continuity, primarily by including a term that had been neglected in the original SWAT-MODFLOW version as applied to the Lower Republican River basin. This term represents the constituents of ground water recharge (deep percolation, transmission losses, and pond seepage) corresponding to the basin uplands lying outside the alluvial valley. Since the uplands constitute 87 percent of the basin area, this was a potentially significant hydrologic term to have neglected. Because the soil profile in the basin uplands is underlain by bedrock instead of a vadose zone and aquifer, the areal fraction of the above recharge constituents corresponding to the uplands are assumed to flow to tributaries instead of ground water. By including this previously neglected hydrologic component, cumulative stream yield for a recalibrated simulation of the model was found to match observations much closer, and a more satisfactory rainfall-runoff parameter was obtained with a curve number value of 75.

The required assumption of homogeneity within each subbasin presents a conflict with a variety of hydrologic factors that are spatially heterogeneous, including drainage areas determined by hillslope, precipitation, soil type, land use, and hydrogeological properties. Spatial heterogeneity within the Lower Republican Basin was accounted for both by disaggregating geographically distinct regions and by statistical techniques. The basin was partitioned into nine subbasins along hydrologic divides corresponding to eleven-digit hydrologic unit codes (HUC-11) in the USGS river basin system (Seaber et al., 1987). SWAT represents each subbasin with a single, homogeneous set of characteristics and a lumped model of its water budget that is simulated with daily time steps. Each subbasin's topography determines its areal fraction contributing runoff directly to streamflow from the subbasin; the remainder of the subbasin contributes runoff to pond storage. SWAT uses these complementary areal fractions to simulate the magnitude of runoff to streams and ponds, respectively.

Three conceptual models of spatial heterogeneity, or HRU schemes, are presented here. The first HRU scheme is a simple scheme that accounts for variability of soil type and land use, and is the scheme that has been applied to our models of the Lower Republican River, Rattlesnake Creek, and Wet Walnut Creek watersheds. The second and third HRU schemes also disaggregate each subbasin into components that have a soil profile underlain by either bedrock or an aquifer. The third HRU scheme further disaggregates the component underlain by an aquifer into deep and shallow components. It is the third HRU scheme that provides the means of representing a two-way coupling between unsaturated and saturated components. The methodology for the three HRU schemes and their implementation were presented and demonstrated as part of sensitivity analysis in Perkins (1999). The three schemes are summarized here.

HRU scheme 1: spatial heterogeneity of soil type and land use

In the basic HRU scheme, SWAT simulates the watershed hydrology for each combination of the major soil types and land use management schemes, holding other conditions constant. The set of hydrological parameters associated with each of these combinations characterizes a hydrologic response unit (HRU). The Lower Republican River basin model is represented by six soil types and three major land uses. Assuming the land use categories and soil types to be independent, the product $n_h = 18$ combinations exist. The hydrologic fluxes simulated by SWAT for a given HRU contributes a fractional weight, w_k, to the average of hydrologic fluxes taken over all HRUs, k, from 1 to n_h. For each subbasin, the HRU-averaged value for a given hydrologic component, d_i, is given by

$$d_i = \sum_{k=1}^{n_h} d_{ik} w_k \tag{8a}$$

$$w_k = s_m c_n \tag{8b}$$

Each HRU weight, w_k, is given by the product of the subbasin's areal fractions associated with soil type, s_m, and land use, c_n. Areal fractions for the land use classes in each subbasin, c_{mj}, are expressed as follows:

$$c_{1j} = f_{cj} - c_{2j} \qquad \text{(non-irrigated cropland);} \tag{9a}$$

$$c_{2j} = f_{\text{irr}} \qquad \text{(irrigated cropland);} \tag{9b}$$

$$c_{3j} = 1 - c_{2j} \qquad \text{(grassland);} \tag{9c}$$

The areal fraction of cropland is denoted by f_{cj} for each subbasin, j, in equation (9a). The non-irrigated areal fraction is given by subtracting from cropland the irrigated areal fraction, f_{irr} (9b); grassland represents the remaining areal fraction of the subbasin (9c). Table 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 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.

4. Spatial heterogeneity of the alluvial aquifer: hydrologic effects

A preceding discussion of the conceptual model for ground water recharge (equation 4) notes that SWAT's model for the soil profile presumes the existence of a vadose zone and underlying aquifer, the destination of water that percolates below the root zone. But approximately 87 percent of the study area lies outside the alluvial valley, where the soil profile is underlain by bedrock. A conceptual model for these features and their hydrologic effects are illustrated by Figs. 4 and 5. Figure 4 shows a hypothetical watershed, part of which is underlain by an alluvial aquifer with a corridor of shallow ground water along the stream. Irrigated cropland is signified by the green circles. Fig. 5 shows the vertical profile for watershed transect A-A'. Along this transect, the segment b-b' spans the alluvial valley, and the segment c-c' spans the corridor of shallow ground water near the stream. Three HRU-based approaches to modeling the hydrologic effects of this spatial heterogeneity are presented here.

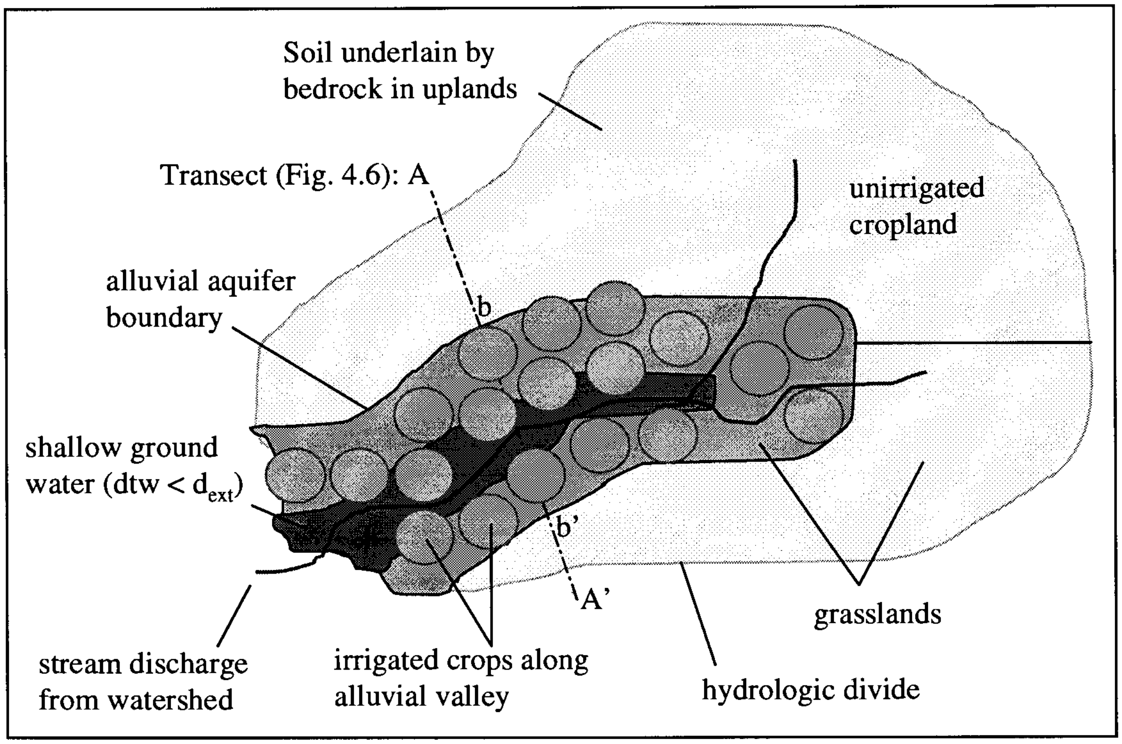

Figure 4. Conceptual model for spatial heterogeneity with respect to a subbasin's geomorphology. HRU schemes 2 and 3 disaggregate the alluvial aquifer from the uplands, and deep from shallow ground water (scheme 3).

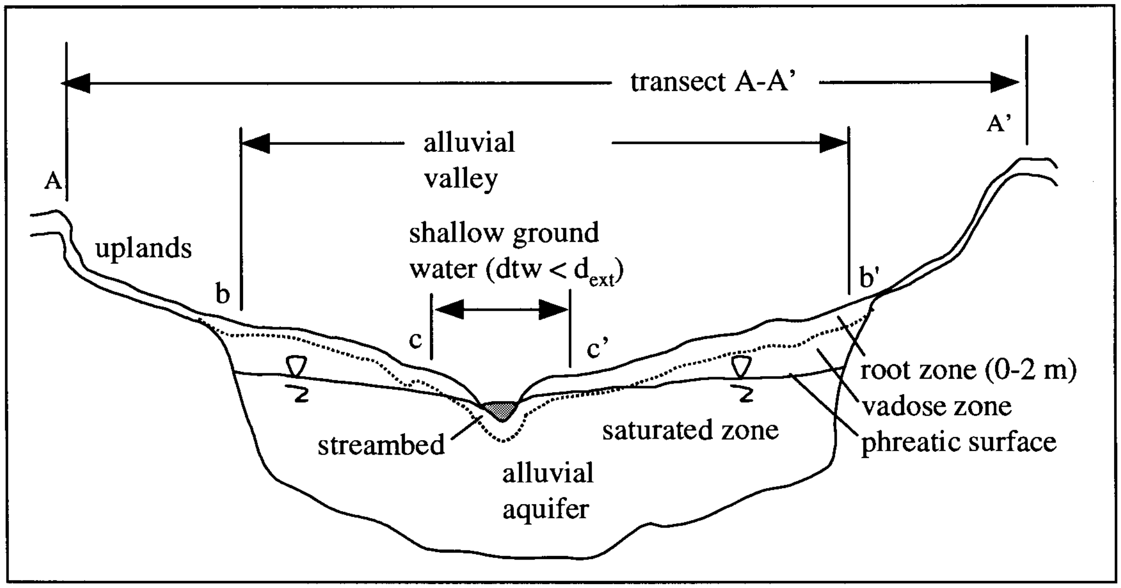

Figure 5. Profile of subbasin shown in Fig. A.2 along an arbitrary transect A-A'.

Applying HRU scheme 1 to a watershed partially underlain by an alluvial aquifer

HRU scheme 1 represents the hydrologic effects of a watershed partially underlain by an aquifer as follows. First, HRUs are simulated on a daily basis by SWAT assuming that the soil profile is underlain by an aquifer. Irrigation, recharge, tributary flow, and potential evaporation are based on equations (3-9). Ground water recharge includes percolation, transmission losses, and pond seepage for the areal fraction of the watershed underlain by an aquifer, f_{aqf} (equation 7a). For the remainder of the watershed outside the alluvial valley, these components are assumed to contribute to streamflow (equation 7b). This scheme is intended to preserve continuity, but is inconsistent with assumption of an underlying aquifer in SWAT's simulation. Effects of this inconsistency were examined in Perkins (1999) by comparison with alternative HRU schemes 2 and 3, described below.

HRU schemes 2 and 3: disaggregating areas with an underlying aquifer

HRU schemes 2 and 3 provide a more hydrologically consistent approach in which the soil profile for a given HRU is underlain completely by either an aquifer or bedrock, according to an option specified by SWAT's modified Control Codes input file (*.cod). For the subbasin component outside the alluvial valley, percolation out of the root zone is held to zero, producing increases in lateral subsurface flow, soil moisture, and evaporation. These alternate flow paths are illustrated in Fig. 3. SWAT's subroutine Purk18, which simulates percolation through the soil layers, was modified to implement this option. The hydrologic connections for ground water recharge and tributary inflow (equations 4-7) still apply, taking $f_{\text{aqf}} = 1$ for HRUs with an underlying aquifer, and $f_{\text{aqf}} = 0$ with underlying bedrock. Then for a soil profile underlain by bedrock, components that would otherwise contribute to ground water recharge are treated as components of tributary flow.

Land use heterogeneity for HRU scheme 2

Two simplifying assumptions are made, illustrated in Fig. 4, that (a) all irrigated cropland lies within the alluvial valley, where the surface and ground water diversions are located; and (b) all unirrigated cropland lies outside the alluvial valley with bedrock under the soil profile. 13 percent of the Lower Republican River basin lies within the alluvial valley, about 1/3 of which is irrigated cropland, according to analysis of DWR water rights data. The remaining 2/3 of the alluvial valley is assumed to be grassland.

HRU scheme 2 allows the hydrology of the alluvial valley with an underlying aquifer to be distinguished from that of the uplands with bedrock under the soil profile, but without distinguishing deep and shallow ground water as in the case of HRU scheme 3 (below). Dependencies with respect to both land use and soils are considered in defining the HRUs. Four land use classes are defined that also denote landform and land resources:

1. Non-irrigated crop rotations outside the alluvial valley (no aquifer);
2. Irrigated cropland within the alluvial valley (with aquifer);
3. Grassland within the alluvial valley (with aquifer);
4. Grassland outside the alluvial valley (no aquifer).

Areal fractions for these land classes in each subbasin, *j*, are expressed as follows:

$$c_{1j} = f_{cj} - c_{2j} \quad \text{(non-irrigated cropland, no aquifer);} \tag{10a}$$

$$c_{2j} = \left(\frac{A_{\mathrm{aqf},j}}{A_{\mathrm{aqf}}} \right) f_{\mathrm{irr}} \quad \text{(irrigated cropland, alluvial aquifer);} \tag{10b}$$

$$c_{3j} = f_{\mathrm{aqf},j} - c_{2j} \quad \text{(grassland, alluvial aquifer);} \tag{10c}$$

$$c_{4j} = 1 - f_{\mathrm{aqf},j} - c_{1j} \quad \text{(grassland, no aquifer).} \tag{10d}$$

This scheme builds on that given by equations (9a-c) for HRU scheme 1. The areal fraction of cropland within each subbasin, *j*, is denoted by f_{cj} in equation (10a). The alluvial cropland component, c_{2j}, is given for each subbasin in equation (10b) by distributing the irrigated fraction of the watershed, f_{irr}, over the subbasins based on their relative contributions to the total watershed area with an underlying aquifer, $(A_{\mathrm{aqf},j}/A_{\mathrm{aqf}})$. This determines the remaining areal fraction of cropland for the subbasin outside the alluvial valley (equation 10a). In equations (10c-d), the areal fractions of grasslands are given by subtracting the cropland areal fractions, c_{1j} and c_{2j}, from the subbasin areal fractions inside and outside the alluvial valley, respectively.

The above land use scheme is justified mathematically by showing that the coefficients for a given subbasin add to 1. Similarly, the areal fractions for the six soil types add to 1 for a given subbasin. If the soils and land uses are assumed to be independent as in the case of the basic HRU scheme 1, their combinations yield 24 HRUs to be simulated and averaged according to equations (9a-b). But by recognizing dependencies between soil types and land classes, spatial heterogeneity within each subbasin can be more accurately represented, and the required number of HRUs can be reduced significantly as follows.

The two alluvial land use schemes given by equations (10b-c) are associated only with Carr and Muir soils (see Table 1); their combinations are represented by four HRUs. Combinations of the remaining two land uses and four soil types can be represented by eight HRUs, for a total of 12 HRUs. The number of required simulations can be further reduced to 10. Noting that two of the soils outside the alluvial valley, Hastings and Hedville, do not occur together within subbasins (Table 1), execution of their HRUs can be combined.

HRU scheme 3: disaggregating areas with shallow ground water

HRU scheme 3 further distinguishes deep and shallow aquifer components as illustrated in Fig. 4. For HRUs representing areas with shallow ground water, SWAT and MODFLOW solutions are coupled by uptake of shallow ground water into the soil profile. These schemes are implemented by modifications to SWAT's simulation of the component HRUs and to the SWAT-MODFLOW linkage (Fig. 2).

Here shallow ground water is considered to be at a depth $z < z_{\text{ext}}$, where z_{ext} is the extinction depth as defined for MODFLOW's Evaporation package. MODFLOW represents evaporation from shallow ground water as a linearly varying function of depth to water, where the maximum rate can be specified by potential evaporation calculated by SWAT. This model is presented in Section 5, "Distributed model of HRU-averaged hydrologic connections."

SWAT simulates components of a soil water balance using the SCS curve number procedure (USDA, 1972) to determine excess rainfall, and storage routing techniques (Arnold et al., 1994) to determine infiltration, percolation,subsurface lateral flow, upward capillary flow, and plant water uptake. In addition, SWAT defines "revap" as flow from shallow ground water to the soil profile, but treats revap as water that evaporates directly from ground water to the atmosphere, bypassing the soil water balance. Note that equation (4.8) neglects upward movement of water into the soil profile, while accounting for downward movement out of the soil profile by percolation. Revap is given simply by the product of the "actual" evaporation rate and a constant (Arnold et al., 1994).

HRU scheme 3 provides a means for coupling the soil water balance in SWAT to upward flow from shallow ground water simulated by MODFLOW. The soil water balance (equation 1) can be rewritten to include a term for capillary uptake from shallow ground water, denoted here as d_{cap}:

$$d_{\text{sw}}(t) - d_{\text{sw}}(0) = \sum_{i=1}^{t} \left(d_{\text{pcp}} - d_{\text{ro}} - d_{\text{xm}} - d_{\text{perc}} - d_{\text{et}} + d_{\text{et-gw}} \right) \tag{11}$$

For an HRU-averaged soil water balance, capillary uptake into the soil profile, $d_{\text{et-gw}}$, is expressed in equation (11) as a daily volume per unit area of subbasin. This depends on simulation results from MODFLOW for "evaporation from shallow ground water," expressed as a flow rate, and the area of shallow ground water. This area is also used to calculate weights for HRUs with shallow ground water in each solution time step.

The dependence of the term $d_{\text{et-gw}}$ in equation (11) on MODFLOW's results implies that a simultaneous solution is needed for SWAT and MODFLOW. This was originally assumed to require linked execution of SWAT and MODFLOW as outlined by Fig. 1 of S&P (1999). HRU scheme 3 provides an alternate means of coupling these solutions based on separate execution of SWAT and MODFLOW using successive approximation, a technique that is discussed below.

In each aquifer solution time step and for each subbasin, MODFLOW's MODSWB package summarizes evaporation from shallow ground water as a flow rate and the corresponding area of shallow ground water within the active grid domain. These results are summarized by subroutine SWB2BD for each corresponding time step to a file that can be read in a subsequent execution of SWAT. They are used to calculate (a) time-varying spatial weight functions (subroutine SUBWTS) for the HRU scheme 3 that distinguishes deep and shallow ground water components, and (b) daily capillary uptake into the soil profile from shallow ground water, converting flow rates given by MODFLOW into volumes per unit area according to equation (2) in subroutine PRESWB.

SWAT's subroutine Subbasin was modified to distribute the daily uptake over the soil profile, beginning with the bottom layer, limited by each layer's available water capacity. This incorporates capillary uptake from shallow ground water, $d_{\text{et-gw}}$, into the soil water balance (equation 11). The routing approach taken to this redistribution in subroutine Subbasin is ad hoc but appropriate to the essentially ad hoc models implemented in MODFLOW for evaporation from shallow ground water and in SWAT for soil water movement.

The HRUs of scheme 3 are modified by dividing each of the two alluvial land uses of irrigated cropland and grassland into components with deep and shallow ground water as illustrated in Fig. 4, while treating the soil types the same as in the case of the above HRU scheme 2. The land use areal fractions for the resulting six land uses in each subbasin, *j*, are as follows:

$$c_{1j} = f_{cj} - c_{2j} \qquad \text{(non - irrigated cropland, no aquifer)} \tag{12a}$$

$$c_{2j} = \left(\frac{A_{\text{aqf},j}}{A_{\text{aqf}}} \right) f_{\text{irr}} \left(1 - f_{\text{shl},j} \right) \qquad \text{(irrigated cropland, deep alluvial aquifer)} \tag{12b}$$

$$c_{3j} = \left(f_{\text{aqf},j} - c_{2j} \right)\left(1 - f_{\text{shl},j} \right) \qquad \text{(grassland, deep alluvial aquifer)} \tag{12c}$$

$$c_{4j} = 1 - f_{\text{aqf},j} - c_{1j} \qquad \text{(grassland, no aquifer)} \tag{12d}$$

$$c_{5j} = \left(\frac{A_{\text{aqf},j}}{A_{\text{aqf}}} \right) f_{\text{irr}} f_{\text{shl},j} \qquad \text{(irrigated cropland, shallow alluvial aquifer)} \tag{12e}$$

$$c_{6j} = \left(f_{\text{aqf},j} - c_{2j} \right) f_{\text{shl},j} \qquad \text{(grassland, shallow alluvial aquifer)} \tag{12f}$$

In this land use/resource scheme, $f_{\text{shl},j}$ represents the shallow aquifer's areal fraction of the gridded aquifer area within subbasin *j*. Land use components representing the alluvial valley for HRU scheme 2 (equations 10b-c) have simply been divided into two components each, corresponding to deep aquifer components (equations 12b-c) and shallow aquifer components (equations 12e-f). Outside the alluvial valley, land uses and soil types are represented by six HRUs as before. Within the alluvial valley, the four land use components and two associated soil types are represented by eight HRUs, requiring a total of 14 HRUs. This is still fewer that the number required for the basic HRU scheme 1, which can be reduced to 15 if HRUs associated with Hastings and Hedville soils (Table 1) are combined as described for HRU schemes 2 and 3.

HRU weights, w_k, for this scheme are given by the products of soil type and land use (equation 8a-b), and are calculated by subroutine SUBWTS in each aquifer solution time step. This accounts for time-varying changes in the area of shallow ground water in response to drought-flood cycles. As illustrated by Figs. 4-5, the rise and fall of the water table with wet and dry seasons and with irrigation pumping affects not only the direction of flow across the streambed into or out of the stream channel, but also the width of the aquifer extent with a depth less than the extinction depth, d_{ext}. This is taken to be the lower limit for shallow ground water based on MODFLOW's conceptual model for evapotranspiration, which is assumed to contribute to upward capillary flow through the soil profile and to plants. The temporal variation of the spatial extent of shallow ground water results in time-varying HRU weights, which are consequently evaluated for each time step.

Evaporation from shallow ground water, denoted by $Q_{i,j}$ and corresponding to hydrologic component i and subbasin j, is converted in subroutine PRESWB to a daily volume per unit area of shallow ground water, $d_{i,j}$ (mm). This is given by integrating the flow rate over a day's time step and dividing by the shallow aquifer area, i.e.,

$$d_{i,j} = cQ_{i,j}\Delta t / f_{s,j}A \tag{13}$$

For a given HRU associated with shallow ground water, the area of shallow ground water as a fraction of the watershed, $f_{s,j}$, is given by the product

$$f_{s,j} = f_{\mathrm{sub},j} f_{\mathrm{aqf},j} f_{\mathrm{shl},j} \tag{14}$$

for subbasin j. Factors on the right-hand side are $f_{\mathrm{sub},j}$, subbasin area as a fraction of the watershed; $f_{\mathrm{aqf},j}$, aquifer area as a fraction of subbasin, j; and $f_{\mathrm{shl},j}$, shallow ground water area as a fraction of total aquifer area within a subbasin. Subroutine Subbasin was modified bay adding subr. Capflow that distributes uptake from shallow ground water over the soil profile, beginning with the bottom soil layer; redistribution to each layer is limited by the difference between available water capacity and soil water content.

Two-way coupling of SWAT and MODFLOW solutions by successive approximation

Results from MODFLOW's simulation of evaporation from shallow ground water and the associated area are passed to SWAT in each time step using the technique of successive approximation. This is used routinely for numerical solutions that depend on a converging sequence of approximations, such as MODFLOW's solution for aquifer heads. Here, HRU scheme 2 provides an initial solution for the coupled SWAT-MODFLOW simulation, following the procedure outlined by Fig. 2 and with $d_{\text{et-gw}} = 0$ in the soil water balance (equation 11). A summary of results for evaporation from shallow ground water for each time step of this simulation can be used in a subsequent pass through the procedure of Fig. 2 based on HRU scheme 3, with $d_{\text{et-gw}} \neq 0$ for HRUs with shallow ground water. Results for HRU schemes 2 and 3 corresponding to the first two passes through the simulation procedure (Fig. 2) are presented in Perkins (1999).

5. Distributed model of HRU-averaged hydrologic connections

While revisions to MODFLOW address specific modeling requirements of the Lower Republican River basin study, earlier versions have been used to develop calibrated models of Rattlesnake Creek and Walnut Creek basins in Kansas. Documentation of the simulation code for the Lower Republican River basin in Perkins and Sophocleous (1999b-c) reflects the latest versions of the packages developed for this linkage.

The MODSWB package was written to provide a means of specifying conditions for MODFLOW's stream-aquifer solution in terms of results from a watershed simulator.

SWAT and SWBAVG provide HRU-averaged, lumped quantities as flow rates from each subbasin to simulate these conditions for each solution time step. Simulated recharge and potential evaporation for each subbasin are distributed over the corresponding grid cells of arrays for MODFLOW's Recharge and Evapotranspiration packages. Simulated tributary inflows from each subbasin are associated with corresponding stream reaches, and irrigation demand is distributed over surface and ground water points of diversion. The associations of tributary inflows and diversions involve modified versions of MODFLOW's STREAM and WELL packages, referred to as MODSTR and MODWEL, respectively, which provide features necessary for the SWAT-MODFLOW linkage.

Overall mass balance check

The conceptual model for the SWAT-MODFLOW connections should be examined carefully for consistency, and checked against overall mass balances that can be evaluated by combining results from both SWAT and MODFLOW according to

$$dS / dt = Q_{\mathrm{pcp}} - Q_{\mathrm{yld}} - Q_{\mathrm{evap}} + Q_{\mathrm{gw}} \qquad (15)$$

where:
Q_{pcp} = precipitation (inflow),
Q_{yld} = stream yield (net outflow),
Q_{evt} = evapotranspiration (outflow),
Q_{gw} = net ground water inflow (net regional inflow).

The storage term on the left includes components for soil water, ponds, ground water, and surface water. Terms for storage in soil water and ponds, and fluxes on the right for precipitation and evaporation, are passed from SWAT to MODFLOW through the balance file (or by argument lists for linked execution). MODFLOW calculates change in ground water storage and neglects change in surface water storage, assuming steady streamflow for monthly time steps. Stream yield is based on MODFLOW's solution for streamflow, and net regional inflow is given by MODFLOW as the net inflow at specified heads. If time steps were shorter than the travel time for streamflow through the watershed, surface water storage should be included.

MODFLOW's Evaporation package represents evaporation from shallow ground water as a linearly varying function of depth, $q_{\mathrm{ET}}(d)$, from a maximum value at the ground surface, $q_{\mathrm{ET}}(0) = q_{\max}$, to a value of zero at the extinction depth, $q_{\mathrm{ET}}(d_{\mathrm{ext}}) = 0$. For a given grid cell, this is expressed in terms depth to water, d,

$$q_{\mathrm{ET}}(d) = q_{\max}\left(1 - d / d_{\mathrm{ext}}\right), \quad 0 < d < d_{\mathrm{ext}}$$

or as a function of hydraulic head, h, by

$$q_{\mathrm{ET}}(h) = \begin{cases} q_{\max} & h > z_s, \\ q_{\max}\left(\dfrac{h - z_{\mathrm{ext}}}{z_s - z_{\mathrm{ext}}}\right) & z_s > h > z_s - d_{\mathrm{ext}}, \\ 0 & h < z_s - d_{\mathrm{ext}} \end{cases} \qquad (16)$$

where z_s = surface elevation and $z_{\mathrm{ext}} = z_s - d_{\mathrm{ext}}$, elevation at extinction depth. The maximum value, $q_{\max}$, is provided by SWAT as the potential evaporation rate. The evaporation rate given by equation (16) is head-dependent, and is treated implicitly in MODFLOW's solution; see also Appendix A, "Head-dependent fluxes." The strength of coupling due to shallow ground water evaporation varies both with the area of shallow ground water and the depth to water. Subroutine SWB2BD in the MODSWB package writes a summary of shallow ground water, including its area, mean depth, and evaporation rate for each subbasin. These results can be used as input to a subsequent execution of the linked SWAT-MODFLOW procedure outlined in Fig. (2), thereby coupling SWAT and MODFLOW's solution by the method of successive approximation. This approach is applied in HRU scheme 3 that disaggregates shallow and deep ground water (Section 4, above).

Associating watershed subbasins with stream-aquifer grid

To initialize an association between MODFLOW's stream-aquifer grid with the subbasins simulated by SWAT, MODSWB reads the following two items.

1. The point of exit for runoff, or pour point, from each subbasin is associated with a reach of the stream network based on its grid cell coordinates and an association matrix in the MODSTR package, Idxstr (described below and in Appendix B).
2. Associate the geographical extent of each subbasin with the grid cells of the aquifer and stream. A two-dimensional integer-valued array associates each grid cell with the subbasin enclosing the cell's center, and follows MODFLOW's convention for reading arrays. The approximate areal fraction of each subbasin underlain by an aquifer is based on the area of active grid cells corresponding to positive-valued elements of MODFLOW's IBOUND array.

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

In each time step, MODSWB reads tributary inflows, ground water recharge, irrigation demand, and potential evaporation for each subbasin as HRU-averaged flow rates from a data file written by SWBAVG. In addition, "actual" evaporation and rates of change in storage for soil water and ponds are passed, allowing evaluation of an overall water balance according to equation (4.1) based on these and MODFLOW's results. Pumping rates from surface and ground water diversions are specified to meet the irrigation demand simulated by SWAT, but are constrained to stay within operating limits imposed on individual water rights, and within supply limits imposed by available streamflow and aquifer saturated thickness. The modified packages MODSTR and MODWEL are both involved in satisfying these constraints.

MODSTR, the modified version of the STREAM package, uses a modified routing procedure to account for net lateral surface inflows in each reach, which represents the sum of any tributary inflows, surface water diversions (outflows), and optional evaporation from the stream surface that might be specified for the reach. In addition, an indexing array, Idxstr, is a feature added to look up a stream reach that is to be associated with grid coordinates specified for subbasin outflows (item 1, above) and surface water diversions.

Meeting irrigation demand with surface and ground water diversions

MODWEL, the modified version of the WELL package, represents diversions from both ground and surface water, which are distinguished by a source indicator. Locations of both types of sources are given by grid coordinates. The indexing array, Idxstr, defined in MODSTR, is used to look up corresponding reaches of a stream network that is specified by input to MODSTR. Diversions are further distinguished by type of use, (irrigation, domestic, municipal, etc., including fictitious wells to represent boundary conditions. Irrigation demand simulated by SWAT is distributed only over points of diversion associated with irrigation water use. The method of this distribution is described as follows.

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

$$Q_{app} = \Sigma q_{gk} + \Sigma q_{sk} \tag{17}$$

The first summation on the right is taken over the appropriations for n_g individual ground water rights, and the second for n_s individual surface water rights. For a given time period of interest, if water use is known for the individual water rights, total water use can be similarly expressed. Otherwise, the irrigation demand simulated by SWAT and given as a flow rate, Q_{irr}, by equation (3) can be distributed over water rights appropriated for irrigation. This is done by defining the factor, $s = Q_{irr}/Q_{app}$, which is used to scale the annual appropriations of the individual diversions, expressed as pumping rates. Multiplying equation (17) by s gives

$$Q_{irr} = sQ_{app} = s(\Sigma q_{gk} + \Sigma q_{sk}) = \Sigma s q_{gk} + \Sigma s q_{sk} \tag{18}$$

Here, the normalized spatial distribution of appropriations is given by dividing equation (17) by Q_{app}, and is used in place of one for water use in the absence of sufficient information regarding water use by individual water rights.

In the case of the Lower Republican River basin model, irrigation demand was simulated in SWAT on a daily basis, summarized for monthly time steps Δt, and averaged over the eighteen HRUs for each subbasin using equations (8-9) to give the average depth

$d_{\text{irr}}f_{\text{irr}}$. The average irrigated area fraction of the basin was $f_{\text{irr}} \approx 0.04$ for years 1977-1994. The flow rate corresponding to this monthly demand is given by equation (4.3). The total annual appropriations for ground and surface water rights meet this demand by distributing the scaling factor, s, which is zero except during the growing season, over the individual water rights according to equation (18). Variations on this approach were also applied to water use models for the Rattlesnake and Wet Walnut Creek basin models. In all three cases, data from DWR were used to develop estimates of water use, particularly for irrigation. In addition, predictive models of irrigation water use were developed for all three basins, based on total precipitation during the growing season. These water use models are described for the Lower Republican River basin in the next chapter. Similar precipitation-based water use models were developed for Rattlesnake and Wet Walnut Creek basins.

Operational and supply limits on surface and ground water diversions

Pumping limits may be specified for MODWEL in terms of both operating and supply limits. Operating limits with respect to pumping capacity are specified as maximum scaling factors for ground and surface water diversions, s_g and s_s, as a variation on equation (18) given by

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

$$q'_{gk} = \min(s, s_g)\, q_{gk}, \tag{19}$$

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

The supply for surface water diversions is limited by the sum of channel and lateral surface inflows to its associated stream reach. This limit is applied as part of the modified stream routing procedure in MODSTR. The supply for ground water diversions is limited by the aquifer's saturated thickness, $d_s(h) = h - z_b$, where h = hydraulic head and z_b = bedrock elevation. Above an upper limit, d_u , and corresponding elevation, z_u, the specified pumping rate is unaffected; below this limit, the pumping rate decreases linearly with saturated thickness to zero at a lower limit, d_l. For the base case, these limits are set at d_u = 4.6 m and d_l =3.1 m. This is expressed by

$$q''_{\text{gk}}(h) = \begin{cases} q'_{\text{gk}} & h > z_u, \\ q'_{\text{gk}}\left(\dfrac{h - z_l}{z_u - z_l}\right) & z_u > h > z_l, \\ 0 & h < z_l \end{cases} \tag{20}$$

This technique provides a realistic means of preventing grid cells from going "dry" as a result of excessive pumping from wells. But equation (20) makes the affected pumping rates head-dependent components of the forcing function $R(\mathbf{x})$ in equation (4.6), which can adversely affect solution convergence if not handled properly. This and other side effects of model refinements are discussed at the end of Chapter 4 in Perkins (1999).

Converting fluxes from Swat to flow rates for Modflow: Lower Republican River basin.

Most hydrologic results from SWAT are given as depths, i.e., volumes per unit area of subbasin. An exception is in SWAT's simulation of ponds in which results are maintained as volumes.

Regarding units, MODFLOW's main requirement is that the set of units be consistent (homogeneous). We've used English for our linkages, using time steps of days in the case of Rattlesnake Creek, and seconds for the Lower Republican River and Wet Walnut Creek basins. Whether the conversions described below are implemented on the Swat or Modflow sides of the linkage is a matter involving some choice.

The conversions to flow rates are handled in subroutine Preswb, and depend on a conversion factor specified in the *.cod file for the units of length used for the stream-aquifer model in Modflow.

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

$$Q = k_q f d A / \Delta t,$$

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.

Conversion from hydrologic depths in SWAT (mm) to flow rates in MODFLOW (cfs):

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

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

Input data requirements to specify the Swat-Modflow linkage

Data associated with the Swat-Modflow linkage

Swat accumulates its hydrologic results for a monthly time step in array ssub, which is analogous to Modflow's Shed array. The correspondence between vectors in Swat's array ssub and Modflow's array Shed for hydrologic components of interest for the linkage are shown in Table 2. This also shows a separate correspondence to Swat's array ssb, which accumulates basin-wide averages of hydrologic fluxes, but the correspondence between Swat's array ssub and Modflow's array Shed for individual subbasins serves the purposes of the linkage.

Table 2. Hydrologic flux array vector locations in Swat and Modflow

item i	hydrologic flux	term id	Swat basin array ssb vector loc: idxssb(i)	Swat subbasin array ssub vector loc: idxsub(i)	Modswb array shed vector location: idxmod(i) = i + 9
1	precipitation	pcp	1	1	10
2	irrigation	irr		22	11
3	evap (actual)	et	7	12	12
4	surface runoff	surq	3	4	13
5	transmission loss	xmLoss	38	13	14
6	subsurf. lateral flow	Latq	4	5	15
7	percolation	perc	5	11	16
8	gw recharge	gwre	107	9	17
9	evap from water table	rev	105	7	18
10	baseflow	gwq	104	6	19
11	pond seepage	psep	20	16	20
12	evap (potential)	etpot	108	25	21
13	tributary inflows	qtrib			22
Storage terms (not included in Swat's flux arrays ssub and ssb)					
	soil water content	(sw)			
	pond volume	(pnd)			

The components listed in Table 2 can be classified into the following four groups:

1. Essential data required by Modflow from Swat for hydrologic connections between Swat and Modflow:
   time step (s)
   irrigation
   recharge

tributary inflow
potential evaporation

The balance file passed to Modflow would be much smaller if it contained only the essential data listed above.

2. Data required from Swat to calculate an overall hydrologic balance in Modflow:
    precipitation
    evaporation
    time rate of change in pond storage
    time rate of change in soil water storage

3. Data to pass back from Modflow to Swat in the case of linked execution:
evaporation from shallow ground water
    baseflow
    depth to water
    fraction of subbasin with underlying ground water
    fraction of subbasin with shallow ground water

4. Informational data not required by Modflow, but of interest:
    surface runoff
    subsurface lateral flow
    transmission losses
    pond seepage
    percolation

Data files associated with the SWAT-MODFLOW linkage

The key data files involved in this linkage are those for Swat's Control Codes input file (~.cod), the balance files that summarize Swat's simulation of each hydrologic response unit (HRU); the balance file written by Swbavg containing HRU-averaged results; and theModswb package input file (~.swb). Instructions for these input files are provided below.

Swat's modified Control Codes input file (*.cod)

The data involved in linking Swat and Modflow are contained in the following files:

a) *.cod, read by both SWAT and SWBAVG, specifies linkage options and spatial weights used by SWBAVG to represent spatial heterogeneity within subbasins by averaging HRUs simulated by SWAT.

Modswb package input files (*.swb and *.bal)

Instructions for the Modswb package input file (~.swb) and the balance file (~.bal) are organized as a single sequence of instructions corresponding to the order in which the data are read by the Modswb package. The balance files written by Swat and Swbavg have the same format and are described by one set of instructions.

Data are either read from the balance file by Modswb in a subsequent run of Modflow (**iopswt** = 0) or, in the case of a linked Swat-MODFLOW simulation (**iopswt** > 0), copied directly between Swat and Modflow arrays. An abbreviated version of the example file is the following.

b) *.swb, read by MODSWB, to associate each subbasin's areal domain and outflow (pour point) in SWAT with aquifer grid cells and stream network reaches, respectively, in MODFLOW's stream-aquifer model (see example input file rptest.swb).

c) *.bal, written by SWAT to allow MODSWB to specify boundary conditions for MODFLOW in each time step in terms of SWAT's simulation (see example input file rptest.bal).

Input files for modified Well and Stream packages (*.wel and *.str):

d) *.wel, input file to the modified Well package (Modwel), allows specifying pumping from both surface and ground water points of diversions. Irrigation demand specified by Swat is supplied by scaling both surface and ground water diversions that are associated with irrigation use. Surface water diversions are associated with stream reaches, hence the interdependency with the modified Stream package (Modstr).

e) *.str, input file to the modified Stream package (Modstr), includes some added modeling capabilities, e.g. specifying streambed hydraulic conductivity for main and side channels, and specifying inflows from selected stream reaches for each solution time step. The routing procedure has been modified to incorporate surface lateral flow components representing tributary inflows, surface water diversions, and stream surface evaporation from each reach.

As an alternative to the assumption of a rectangular channel, stream channel characteristics for gaged stream reaches have been incorporated for specific cases, using power functions fitted to stream measurements to represent relationships for depth, stream width, and cross sectional area as functions of flow rate.

Observation well input file (*.rsd): see MODRSD package.

Postprocessing input file (*.pos): see MODPOST package.

Summary of Swat-Modflow options

Options added to Swat

Several options have been added to Swat, both to coordinate Swat with Modflow and to revise Swat's watershed model. These options are read from Swat's options input file (Appendix A). Those used for the Rattlesnake Creek watershed model are defined below, keyed to their order in the input control file description. They include Swat-Modflow coordination options **iopmod** and **iopswt**, and Swat model revision options **iopswm**, **iopet**, and **iopwea**:

iopmod (2): option for Swat to summarize hydrologic results on an annual(1), monthly(2) or daily(3) basis for each subbasin and call Hydbal to write results to a "balance" file named below (nambal, rec. 4) that can be read by Modflow on a subsequent run; see **iopswt**.

iopswt (3): This is a Swat option (read from Swat's ~.cod input file) that defines how Swat and Modflow are to be coordinated. A zero value signifies separate execution for both Swat and Modflow, in which case Swat calls Hydbal to write the balance file without input from Modflow; on a subsequent run of Modflow, the balance file is read by Swb1fm in Modswb. Otherwise (iopswt > 0), Swat and Modflow are coordinated in the following manner.

iopwea (16): option (y=1,n=0 to read, rather than synthesize, daily values for insolation (ly/d), relative humidity (pct) and wind speed (m/s at 10 m above ground surface) in that order from an input file with name namrad (rec. 4) in format fmtrad (rec.7). The default option (**iopwea**=0) is to generate them as in the standard Swat program.

Options for the MODSWB package

Options **irropt**, **ioprch**, and **ievopt** affect the conditions of the groundwater solution in Modflow, which are set up in Swb1fm. These options are read by SWB2RP from the SWB input file. Option **iopmod** specifies aquifer solution time step to be a day, month, or year in length.

irropt: option (y=1,n=0) to scale the pumping rates of irrigation wells read from MODFLOW's ~.WEL input for a stress period so that subbasin j's total pumping flow rate varies according to the flux specified by SWAT for each time step; otherwise (irropt=0), use the rate specified in Modflow's well input file ~.wel (SWB1FM; shed vectors 4,9,11,24; well vectors 4,5).

ioprch: option (y=1,n=0) to maintain the recharge distribution within each subbasin according to the recharge input file array RECH, but scale the recharge within each subbasin for each time step according to the sum of fluxes to the aquifer given by shed vector 25. Note: option jkkopt determines which components are included in this sum. (SWB1FM: shed vectors 25 and 26)

ievopt: option (y=1,n=0), 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. However, it is coded below using Swat's actual evaporation, shed (12); potential evaporation will have to be entered into SHED(21), which is not currently being done. The next version of Swat-Modflow, i.e. SwatMod96, is a little further along than this version representing evapotranspiration from the water table. Otherwise (**ievopt** < or = 0), evaporation at ground surface is specified by standard Modflow input to array evtr in the Evt module.

Instructions for Swat's modified Control Codes (*.cod) input data file

Contents for the options input control file were modified to specify options for (1) Swat-Modflow coordination; (2) Swat revisions regarding weather input data and irrigation simulation; and (3) data requirements for simulating multiple HRUs and taking a spatially weighted average over the HRUs.

1. Options regarding Swat-Modflow coordination include the following:
(a) **iopmod** (line 3): Specify stream-aquifer solution time step for Modflow. 0: use average results over entire simulation period for a steady state run; 1: annual; 2: monthly; 3: daily.

(b) **iophru** (line 3): Specify HRU scheme, i.e., the conceptual model for spatial heterogeneity on which the simulations are based.

2. Weather and irrigation options:
(a) Daily measurements of additional weather variables, including wind speed, relative humidity, and solar radiation, may be read for use in the simulation, particularly for calculation of potential evaporation by the added Penman method (below). To use this option, set **iopmea**=1 (line 3), and specify the data file name (**namrad**, line 4). This option was implemented by modifying Swat's subroutine Clicon (source file Cliconsp.for).

(b) The Penman method for potential evaporation was added as an option, specified by setting **Ipet**=3 (line 2 of the *.cod input data file). To implement this option, Swat's subroutine Evap8 was modified to call subrouting Penman, which we wrote to follow the procedure recommended by Shuttleworth in Handbook of Hydrology (Maidment, ed., 1993); see source files Evap8.for and Penman.for.

(c) Automatic irrigation has been modified such that by setting **iopswm** =1 (line 3), automatic irrigation is triggered by soil water content threshold, **swminf** (fraction of available soil water capacity, line 3), as an alternative to plant water stress factor threshold, **wsf**. Automatic irrigation is specified by setting **irr**(j)=1 in the management codes input file (*.mco) for subbasin j, which is also where **wsf** is specified for each subbasin.

(d) A maximum daily application of irrigation water, **wsfmax** (mm, line 3), can be specified that limits automatic irrigation for either form of triggering threshold (c).

Parameters **iopswm**, **swminf**, and **wsfmax** were passed through argument lists of subroutines Subbasin and Crpmd, the latter of which was modified to implement items (c) and (d).

3. Conversion from Swat's units of length for simulated hydrologic fluxes in terms of depths (mm), i.e. cumulative volumes per unit area of subbasin, to Modflow's units of length for flow rates given as volumes per second.

cnvlen (line 3): specify factor to convert from Modflow's standard length unit to Swat's standard length unit (meters). If the model for Modflow uses ft for length unit, then **cnvlen** = 0.3048. Two additional factors are defined on file Swatmod2.h that are used in conjunction with this conversion factor:
depmpy = 10^{-3} m/mm to convert Swat's hydrologic depth units to standard length units;
and **widmpy** = 1000 m/km to convert Swat's units for basin area to standard length units.

Based on these length conversion factors and the time step (sec) given by Δt = ndays·86400 sec/day, Swat calls subroutine Preswb at the end of each such time step, where depths (cumulative volumes per unit area) are converted to flow rates for each simulated hydrologic component according to
(equation for fluxes here)

Subroutine Preswb treats storage components of soil water and pond volumes separately in order to convert them into units of rate of change in storage.
(equations for pond volume and soil water content)

4. In addition, the areal fractions corresponding to the various soil types and land uses within each subbasin that are required to apply the HRU method are read from the *.cod input file if the number of HRUs exceeds 1 (numhru > 1). These areal fractions are used in subroutine Subwts to calculate the areal weights for each subbasin and time step and write the weights to a file. Once all HRUs have been simulated by Swat and a balance file of results has been written for each HRU, the program Swbavg takes the spatially weighted average of these results for each hydrologic component, subbasin, and time step. The modified *.cod input data file used by Swat is also used for input to Swbavg.

(give equations for weights and the weighted average here)

The following data records are read by code included in Swat's mainline as file swatmod2.h. The first two records and the first entry of the third record, ilog, are the original data on the *.cod input file. These are defined in the Swat manual, section 3.2, pp. 5-8, and summarized below; the added options are described more fully.

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

title: input description line.

```
Data (20i4) nbyr,iyr,Lu,ipd,nsim,msim,ign,iwst,isst,ires,igraf,
            irain,itemp,iresq,idaf,idaL,iprn,iprp,iopt,ipet         (2
```

fields:	1	2	3	4	5	6	7	8	9	10
data:	nbyr	iyr	lu	ipd	nsim	msim	ign	iwst	isst	ires
fields:	11	12	13	14	15	16	17	18	19	20
data:	igraf	irain	itemp	iresq	idaf	idal	iprn	iprp	iopt	ipet

nbyr: number of years of runoff simulation.
iyr: beginning year of runoff simulation.
Lu: number of subbasins.
ipd: print code for standard output file (0: monthly, 1: daily, 2: yearly).
nsim: code for daily total rainfall (mm) input data options.
1, 2: read or simulate, resp., daily rainfall (mm) at a single rain gage station that represents the entire basin;
3, 4: read or simulate, resp., daily rainfall (mm) at a set of rain gage stations that are associated with individual subbasins.
msim: code for daily minimum and maximum temperature options; analogous to nsim.
1, 2: read or simulate, resp., daily temperature maximum and minimum (deg C) at a single station that represents the entire basin;
3, 4: read or simulate, resp., daily temperature maximum and minimum (deg C) at a set of stations that are associated with individual subbasins.
ign: initialization option for random number generators; see manual.
iwst: option (y=1,n=0) to compare simulated monthly stream water yield with measurements.
isst: option (y=1,n=0) to compare simulated monthly stream sediment yield with measurements.
Note regarding input variables iwst, isst and iopt:

> If iwst or isst > 0, then iopt must be specifed as the reach for which observed and calculated yields are to be compared via subr vald25 for both streamflow and sediment yields. A valid reach index must be specified; reaches are referenced on the routing configuration file (~.rte). For more clues regarding comparison of observed and calculated yields, see the chapter in Swat's manual on routing.

ires: reservoir input data option; see manual.
igraf: graphics option; see manual.
irain: option (y=1, n=0) to write measured or generated rainfall data to a file.
itemp: option (y=1, n=0) to write measured or generated temperature data to a file.

iresq: option (y=1, n=0) to simulate reservoir water quality.
idaf: beginning Julian day of simulation.
idaL: ending Julian day of simulation.
iprn: option (y=0, n=1) to print the standard file.
iprp: option (y=1, n=0) to print the pso file (daily pesticide loadings for each subbasin).
iopt: reach of measured water and sediment yields.
ipet: choice of method for calculating potential evaporation; see manual for explanation of original options 0-2:

- 0: Priestley-Taylor;
- 1: Penman-Monteith;
- 2: Hargreaves;
- 3: (added choice): Penman method as recommended by Handbook of Hydrology (Maidment, ed., 1993), including terms for both short- and long-wave radiation; see Appendix on the added Penman subroutine.

Added Swat-Modflow coordination options

```
Data (FREE) ilog,iopmod,numhru,iophru,iopwea,iopwfl,iprirr,
     1      iprevt,iopswm,swminf,wsfmax,cnvlen !(9i4,2f6.0,f8.0) (3

   0   2  14   3   0   1   1   1   1  0.50   12.7   0.3048 ! '(10i4,2f6.0)': ilog iopmod
numhru iopwea iopwfl iophru iopswm swminf wsfmax cnvlen
```

ilog: an original Swat option (y=1, n=0): give the log (base 10) of simulated streamflow as output to the rch file; see Swat manual, 3.2, p. 8. Note: for SWAT99.2, this is removed from line 3, since it is specified on line 2 as part of standard SWAT input.

iopmod: option for Swat to summarize hydrologic results on an annual(1), monthly(2) or daily(3) basis for each subbasin and call Hydbal to write results to a "balance" file named below (**nambal**, rec. 4) that can be read by Modflow on a subsequent run; see iopswt.

numhru: no. HRUs (hydrologic response units) that must be run and then averaged for a complete simulation of this case. Note: items 5-10 are read only if **numhru** > 1.

iophru: option for one of three HRU schemes (conceptual models for spatial heterogeneity within subbasins):

=1: original 18-HRU scheme for 6 soils and 3 land use types (dryland crop, irrigated crop, and grassland); can also be represented by a 15-HRU scheme in which HRUs based on Hastings and Hedville soils are combined as described below for iophru=2, option b.

=2: 2 possible schemes, depending on how soils are handled. Land use definitions are the same for both of these: (c1: nonalluvial dryland crops; c2: alluvial irrigated crops; (c3: alluvial grassland; c4: nonalluvial grassland).

a) 24-HRU scheme for 6 soils and 4 land use/landform types: The six soils are assumed to be independent of the land uses, which account for the alluvial/upland heterogeneity within each subbasin. Alluvial component of subbasin is restricted to land uses of irrigated corn and grasslands; the remainder of the subbasin in the uplands is restricted to the non-irrigated crop rotation and grassland land uses.

b) 10-HRU scheme taking into account soil and land use dependencies. Alluvial land uses (irrigated corn and grasslands) are associated only with alluvial soils (1:Carr and

2:Muir); upland land uses (dryland crop rotation and grassland) are associated only with non-alluvial soils 3:Crete, 4:Kips, and 5:(Hastings and Hedville). Hastings and Hedville are combined into one HRU soil factor with Hastings soils only in subbasins 1-4 and Hedville soils in subbasins 6-9.

=3: refinement of the above scheme, dividing the alluvial aquifer area into shallow and deep components; the shallow component is associated with evaporation from gw according to Modflow's simulation. For iophru=3, this is read from file device ioshl at the end of this subroutine for the following time step; values for initial time step are read in swatmod3.h (included in main). Evaporation, given by Modflow results as a flow rate, is converted to a hydrologic depth, evtgw, with respect to the shallow aquifer area.

iopwea: option (y=1,n=0 to read, rather than synthesize, daily values for direct solar radiation (ly/d), relative humidity (pct) and wind speed (m/s at 10 m above ground surface) in that order from an input file with name namrad (rec. 4) in format **fmtrad** (rec.7). The default option (**iopwea**=0) is to generate them as in the standard Swat program.

iopwfl: option (y=1,n=0) to read daily precipitation data for all stations from the same file, and to do similarly with temperature data. Weather stations are identified in the ~.cio file by an integer i from 1 to n corresponding to the order of data columns from left to right. Data format for temperature and precipitation data are defined in records 5-6, below. (Note: option **iopwfl** will be removed for the SWAT 99.2 version, which provides this capability in the FILE.CIO input file; see input variables NRGAGE through NTGFIL.)

iprirr: option (y=1,n=0) to write daily results describing for automated irrigation and associated soil water conditions and precipitation.

iprevt: option (y=1,n=0) to write daily results of potential evaporation calculations by subroutine Penman, which was added to SWAT as part of this work.

iopswm: option (y=1,n=0) to use soil water content, **swminf** (below), as the threshold for triggering irrigation automatically, as an alternative to plant stress factor threshold, **wsf**, Swat's original and default means of triggering irrigation. Either alternative is invoked by setting the irrigation option **irr**(j) = 1 in the management codes (***.mco**) file for subbasin j, where **wsf** for the default plant stress factor method is also specified. Both automatic irrigation options are subject to the added daily limit, **wsfmax** (below). (Note: option **iopswm** will be removed for the SWAT 99.2 version. We will provide an equivalent capability through input variable MGT_OP in the ~.mgt input file. Use an undefined value, maybe MGT_OP = 13, to represent this as a variation on MGT_OP = 10, which signifies automatic irrigation triggered by plant stress factor.)

swminf (relevant only for irrigation option **irr**(j)=1 and **iopswm**=1, above): available soil water content threshhold, below which irrigation is applied during the growing season (indicated during daily simulation by the internal code **igro**(j)=1 for subbasin j). If **iopswm**=0 and **irr**(j) = 1, then **swminf** is ignored, and the plant stress factor also specified in the *.mco file, controls irrigation according to Swat's original version.

wsfmax: daily maximum allowable irrigation as a depth (mm), i.e., volume per unit area irrigated. This applies only to automatic irrigation (**irr**(j)=1 in the *.mco file), and not to irrigation according to a specified schedule (**irr**(j)=0). NOTE: For SWAT99.2, this will most likely be removed from the ~.cod input file and specified as a parameter for the operation MGT_OP = 13 (see note on **iopswm**, above) added to the ~.mgt file.

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). The following two conversion factors are also used in the conversions, but are defined on file Swatmod2.h:

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 here to convert the basin area to Modflow's units, e.g. from km^2 in Swat to ft^2 for Modflow; and to convert simulated hydrologic fluxes from depths (mm), i.e. volume per unit area [L], to flow rates $[L^3/T]$ in Modflow's units (e.g., cfs). The added subroutine Preswb makes this conversion.

Data formats and additional weather file name

```
Data (FREE) fmttmp, fmtpcp, fmtrad, namrad, namshl                (4
     (read as free format for character variables 3a20, a13)
```

Formats are up to 20 chars each; file name up to 13 chars (read as ‘FREE’):

fmttmp temperature data format

fmtpcp rainfall data format

fmtrad format for radiation, rel. humidity & wind speed data

namrad input file name for measured daily radiation (ly/d), relative humidity (pct) and wind speed (m/s) 10 m above land surface (ALS).

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.

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.

If **numhru** > 1, read items 5-9:

Items 5-9 are used to produce HRU-averaged simulations that represent spatial heterogeneity statistically with respect to soil type and land use within subbasins. The inclusion of this data helps organize the simulations required for linking Swat and Modflow simulations where spatial heterogeneity within subbasins must be represented.

`Data (FREE) nsoils                                        (5`

nsoil number of soil types used to represent soils of basin.

`Data (FREE) crplbl, (soilnm(j),j=1,nsoils)                (6`

crplbl, soilnm(j): Column labels for areal fractions of cropland and each soil type, j.

Read for each subbasin i:
`Data (FREE)  aqffrc(i), crpfrc(i), (soilwt(i,j),j=1,nsoils)      (7`

aqffrc(i)   area of aquifer underlying soil as a fraction of subbasin i
crpfrc(i)   cropland as fraction of subbasin i
soilwt(i,j) fraction of subbasin i covered by each soil type j

`Data (FREE) (pctirr(k), k=1,nyrs)                          (8`

pctirr(k) irrigated land as pct of entire basin for each year of simulation.

`Data (text) header                                          (9`

Read for each HRU i=1 to numhru (see item 3, above):
`Data (FREE) idx, idxsol(i), idxuse(i), idxaqf(i), namhru(i)`

idx index to identify HRU
idxsol(i) soil type associated with HRU *i*
idxuse(i) land use associated with HRU *i*
idxaqf(i) aquifer status associated with HRU *i*. Definitions:
=0: soil is underlain by bedrock. Option is passed to subr. 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).
=1: soil is underlain by an aquifer that is deep enough that soil and plant water uptake from ground water is negligible.
=2: soil is underlain by a shallow aquifer. 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.
namhru(i) name of HRU, up to 8 characters; compared with case name for match to determine which HRU is represented by the simulation.

The following line is read by both Swat and Swbavg, but is used only in Swbavg:

```
Data (FREE)  casavg                                                    (10
```

casavg: suffix for balance file containing average over all HRUs, to be written by Swbavg.

Specifying hydrologic response units (HRUs) and HRU scheme

numhru: no. HRUs required to represent spatial heterogeneity; specified on extended *.cod input file, read from swatmod2.h

idxhru: index to HRU; specified by matching item from list of HRU names on file *.cod with case name on file *.cio.

iophru: option for one of three HRU schemes (conceptual models for spatial heterogeneity within subbasins): definitions are given above.

iaqufr: indicates (y>0,n=0) that soil water can percolate out of the soil profile to an underlying aquifer; otherwise, the soil profile is assumed to be underlain by bedrock, blocking percolation below soil.

Evaporation from gw is zero except for hrus with shallow aquifer, which are distinguished for the third hru scheme (option **iophru**=3). For the three HRU options, the input option **iaqufr** indicates aquifer presence; see Preswb for definition. as follows:
0: soil is underlain by bedrock, not by an aquifer, so that percolation stops at the bottom of the soil profile;
1: soil is underlain by a deep aquifer, i.e., one that does not contribute to plant or soil water uptake; aquifer areal fraction of subbasin is read from the *.cod input file.
2: soil is underlain by a shallow aquifer; plant or soil water uptake is based on Modflow's model of evapotranspiration from shallow ground water. For option iophru=3, Modflow's results for areal fractions and evapotranspiration are read by Swat in each time step.

isolhr: index to soil type associated with this HRU (**idxhru**).
iusehr: index to land use (or crop rotation) assoc. w/ the HRU
Note: **isolhr** and **iusehr** are values from index arrays **idxsol** and **idxuse** that identify the soil type and land use associated with the HRU idxhru; these associations are read from the extended *.cod input file if numhru > 1.

Test cases simulating Lower Republican River basin

SWAT was modified to provide options for coordinating its simulation with MODFLOW and some additional capabilities. These options are specified by SWAT's Option Codes (*.cod) and Management Codes (*.mco) input files, documented in Perkins and Sophocleous, 1999b). Options used for the Lower Republican River Basin model include **iopmod**, **iophru**, **iopwfl**, **iopet**, **iopwea**, and **irr**$_j$. The last is read from the management code file (~.mco) corresponding to subbasin j. Selected options are defined as follows.

iopmod: Specify the aquifer solution time step duration (1=annual, 2=monthly, and 3=daily) for the hydrologic summary of results to be passed between SWAT and MODFLOW and written to a balance file.

irr$_j$: a previously existing irrigation control option, read from the management code file (~.mco) for subbasin j. Original options 0, -1, 1, and added option 3 are defined as follows:

0: no irrigation;

-1: irrigation schedule, including date and depth (mm), are to be read from the corresponding management file for the subbasin (~.mgt);

1: irrigation is to be applied if plant water stress level falls below the threshold, wsf, also specified in the ~.mco file;

3: irrigation is to be applied if either (a) plant water stress level falls below threshold **wsf** (i.e. same as option 1 above); or (b) soil moisture content sw$_j$ falls below a threshold, swtrig, which is specified in terms of available soil water capacity by **swminf** (read from the ~.cod file).

ipet: option (ipet = 3) to calculate potential (reference crop) evaporation according to the Penman method recommended in the Handbook of Hydrology (Eq. 4.2.31, Maidment, ed., 1993) as an alternative to SWAT's options; see also Appendix A (Perkins, 1999) regarding the canopy control volume in SWAT, and the following related option, **iopwea**.

iopwea: option (y=1,n=0 to read, rather than synthesize, daily values for direct solar radiation (ly/d), relative humidity (pct) and wind speed (m/s at 10 m above ground surface) in that order from an input file with name namrad (rec. 4) in format fmtrad (rec.7). The default option (iopwea=0) is to generate them as in the standard Swat program.

The three HRU schemes described above and identified in the Control Codes input file by option **iophru** are illustrated by examples of Swat's modified control codes input file (*.cod). Each of these examples specifies the data required for complete simulations, including Swat, Swbavg, and Modflow components.

```
Land-use    HRU schemes (1-3):
codes 1-6
HRU scheme:             1               2                     3
Code  Land use:
  1               dry crops       bedrock, dry crops       bedrock, dry crops
  2         irrig. crops   aquifer, irrig. crops    deep aquifer, irrig. crops
  3         grassland      aquifer, grasslands      deep aquifer, grasslands
  4                        bedrock, grasslands      bedrock, grasslands
  5                                                 shallow aquifer, irrig. crops
  6                                                 shallow aquifer, grasslands
```

Example 1: Control Codes input file for HRU scheme 1 (18 HRUs)

Conditions specified for SWAT-MODFLOW linkage by file HRU1.cod:

ipet=3	calculate potential evaporation based on added subroutine Penman (accounts for long wave radiation)
iopmod=2	monthly time steps for stream-aquifer solution
numhru=18	number of HRUs to be simulated by SWAT and averaged by SWBAVG
iophru=1	basic HRU scheme (soils and land uses assumed independent; alluvial/upland heterogeneity is ignored.
iopwea=0	additional daily weather data (solar radiation, wind speed, relative humidity) are not available and are not read.
iopwfl=1	read daily precipitation totals for all weather stations from the same data file (the first precipitation data file read from the "file.cio" file); do the same for daily temperature max and min data.
iopswm=1	use soil water content as the threshold to trigger irrigation instead of SWAT's default threshold of plant water stress factor.
swminf=0.65	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.
wsfmax=12.7	limit daily irrigation depth to a maximum of 12.7 mm.
nsoils=6	six soils are specified; specifying Hasting and Hedville separately results in distinct HRUs; in schemes shown below these are combined, since Hasting and Hedville soils are disaggregated by subbasins (Hasting in subbasins 1-4, Hedville in subbasins 6-9, neglecting the small component in subbasin 3).

```
Control File ! hru1.cod (15 HRUs, iophru=1; swminf=0.65,iopet=3 aquifr=1
  181977   9    0    3    3    0    0    0    0    0    0    0    0    0    0    0    0    9    3
   0    2  15    1    0    1    0    0    1  0.65  12.7  0.3048 ! '(9i4,3f6.0)': ilog iopmod
numhru iophru iopwea iopwfl iprirr iprevt iopswm swminf wsfmax cnvlen
'FREE', 'FREE', ' ',' ',' '  ! fmttmp, fmtpcp, fmtrad, namrad, namshl (3a20,2a13)
   5, 0.1261, nsoils, aqfbas
      'aqffrc' 'crpfrc' 'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir'
   1     0.0733  0.5962   0.092   0.471     0.099      0.338       0
   2     0.2053  0.5463   0.191   0.064     0.402      0.342       0
   3     0.2368  0.6281   0.098   0.637     0.132      0.052   0.081
   4     0.0924  0.5737   0.126   0.543     0.054      0.274   0.004
   5     0.2106  0.7164   0.043   0.745         0      0.086   0.126
   6     0.0122  0.6113       0   0.741     0.176      0.059   0.024
   7     0.0829  0.6753       0   0.869     0.022          0   0.108
   8     0.0257  0.5316       0   0.697     0.279          0   0.024
   9     0.2504  0.4991       0   0.630     0.021          0   0.348
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28
4.21  4.31  4.52  4.42  4.77  4.70
  hru soil  use aquifr namhru
    1     1     1     1  'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.) (file name)
    2     1     2     1  'carr-irm'          (irrigated corn)
    3     1     3     1  'carr-pam'          (grass: range and pasture)
    4     2     1     1  'cret-wsm'   soil 2
    5     2     2     1  'cret-irm'
    6     2     3     1  'cret-pam'
    7     3     1     1  'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
    8     3     2     1  'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
    9     3     3     1  'hshd-pam'
   10     4     1     1  'kips-wsm'   soil 4
   11     4     2     1  'kips-irm'
   12     4     3     1  'kips-pam'
   13     5     1     1  'muir-wsm'   soil 5
   14     5     2     1  'muir-irm'
   15     5     3     1  'muir-pam'
'hru1', namcas (this line is read by Swbavg, not Swat)
```

Batch file HRU1.BAT to run SWAT and SWBAVG for HRU scheme 1:

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

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

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

Execution of MODFLOW given results on file Hru1.bal:

```
c:\gh\modflow <Hru1.rsp >Hru1.jnl
```

Response file Hru1.rsp contents:

```
hru1                                         case name (~.log, ~.prn, ~.rsp)
..\inbase\bcase_t4.bas                      .bas unit   1 Monthly Basic package
..\inbase\kbase20b.bcf                      .bcf unit  61 Block-centered flow
..\inbase\wrrepub.wel                       .wel unit  62 Well: groundwater use
..\inbase\repsurf.evt                       .evt unit  65
..\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 monthly Streamflow
..\inbase\basecase.pos                      .pos unit  64 Postprocessor: budgets
..\inbase\gwuadmnu.obs                      .obs unit  72 gw level observations
```

Input file to MODSWB package

This input file is read for the updated HRU schemes 1-3 by the MODSWB package, summarized in Chapter 4, "Associating watershed subbasins with stream-aquifer grid." It specifies execution options and initializes associations of subbasin outflows with stream reaches, and subbasin domains with grid cells. Also specified is the "Frseep" option discussed at the end of Chapter 5 regarding the partitioning of uptake from shallow ground water between evaporation and seepage flow to streams for grid cells coupled to stream reaches. For further documentation, see Perkins and Sophocleous (1999b-c).

```
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
```

Example 2a: Control Codes input file for HRU scheme 2 (24 HRUs)

```
Control File ! rpbase.cod: 18yrs, 24 hrus, swminf=0.50,iopet=3 cn=75)
  181977   9   0   3   3   0   0   0   0   0   0   0   0   0   0   1   0   9   3
   0   2  24   1   0   1   0   0   1  0.65  12.7  0.3048 ! '(9i4,3f6.0)': ilog iopmod
               numhru iophru iopwea iopwfl iprirr iprevt iopswm swminf wsfmax cnvlen
'FREE', 'FREE', ' ',' ',' ' ! fmttmp, fmtpcp, fmtrad, namrad, namshl (3a20,2a13)
   6, 0.1261, nsoils, aqfbas
      'aqffrc' 'crpfrc' 'Carr' 'Crete' 'Hasting' 'Hedville' ' Kipson' 'Muir'
   1    0.0733  0.5962   0.092   0.471    0.099         0     0.338        0
   2    0.2053  0.5463   0.191   0.064    0.402         0     0.342        0
   3    0.2368  0.6281   0.098   0.637    0.125     0.007     0.052    0.081
   4    0.0924  0.5737   0.126   0.543    0.054         0     0.274    0.004
   5    0.2106  0.7164   0.043   0.745        0         0     0.086    0.126
   6    0.0122  0.6113       0   0.741        0     0.176     0.059    0.024
   7    0.0829  0.6753       0   0.869        0     0.022         0    0.108
   8    0.0257  0.5316       0   0.697        0     0.279         0    0.024
   9    0.2504  0.4991       0   0.630        0     0.021         0    0.348
3.13   3.32   3.42   4.18   4.06   3.54   3.61   3.66   3.51   3.55   3.76   4.28
4.21   4.31   4.52   4.42   4.77   4.70
  hru soil  use aquifr namhru
   1     1     1    0   'carr-wsm'   soil 1 upland: wheat/sorghum/fallow rotation
   2     1     2    1   'carr-irm'          alluvial: irrigated corn
   3     1     3    1   'carr-alg'          alluvial: grass (range and pasture)
   4     1     4    0   'carr-upg'          upland: grass (range and pasture)
   5     2     1    0   'cret-wsm'   soil 2 upland: wheat/sorghum/fallow rotation
   6     2     2    1   'cret-irm'          alluvial: irrigated corn
   7     2     3    1   'cret-alg'          alluvial: grass (range and pasture)
   8     2     4    0   'cret-upg'          upland: grass (range and pasture)
   9     3     1    0   'hast-wsm'   soil 3 upland: wheat/sorghum/fallow rotation
  10     3     2    1   'hast-irm'          alluvial: irrigated corn
  11     3     3    1   'hast-alg'          alluvial: grass (range and pasture)
  12     3     4    0   'hast-upg'          upland: grass (range and pasture)
  13     4     1    0   'hedv-wsm'   soil 4 upland: wheat/sorghum/fallow rotation
  14     4     2    1   'hedv-irm'          alluvial: irrigated corn
  15     4     3    1   'hedv-alg'          alluvial: grass (range and pasture)
  16     4     4    0   'hedv-upg'          upland: grass (range and pasture)
  17     5     1    0   'kips-wsm'   soil 5 upland: wheat/sorghum/fallow rotation
  18     5     2    1   'kips-irm'          alluvial: irrigated corn
  19     5     3    1   'kips-alg'          alluvial: grass (range and pasture)
```

```
  20    5    4    0  'kips-upg'          upland: grass (range and pasture)
  21    6    1    0  'muir-wsm'   soil 6 upland: wheat/sorghum/fallow rotation
  22    6    2    1  'muir-irm'          alluvial: irrigated corn
  23    6    3    1  'muir-alg'          alluvial: grass (range and pasture)
  24    6    4    0  'muir-upg'          upland: grass (range and pasture)
'rpbase24', namcas (this line is read by Swbavg, not Swat)
```

Example 2b: Control Codes input file for HRU scheme 2 (10 HRUs)

```
Control File ! hru2.cod: 18yrs, 10 hrus (hru option 2), swminf=0.50,iopet=3 cn=75)
  181977   9   0   3   3   0   0   0   0   0   0   0   0   0   0   1   0   9   3
   0   2  10   2   0   1   0   0   1  0.65  12.7  0.3048 ! '(9i4,2f6.0)': ilog iopmod
numhru iophru iopwea iopwfl iprirr iprevt iopswm swminf wsfmax cnvlen
'FREE', 'FREE', ' ',' ','hru2.shl'  ! fmttmp, fmtpcp, fmtrad, namrad, namshl (3a20,2a13)
   5, 0.1261, nsoils, aqfbas
      'aqffrc' 'crpfrc' 'Carr' 'Muir'  'Crete' 'Kipson' 'HastHedv'
  1    0.0733    0.5962         1         0  0.518722  0.372247  0.109031
  2    0.2053    0.5463         1         0  0.079208  0.423267  0.497525
  3    0.2368    0.6281  0.547486  0.452514  0.775883  0.063337  0.160780
  4    0.0924    0.5737  0.969231  0.030769  0.623421  0.314581  0.061998
  5    0.2106    0.7164  0.254438  0.745562  0.896510  0.103490         0
  6    0.0122    0.6113         0         1  0.759221  0.060451  0.180328
  7    0.0829    0.6753         0         1  0.975309         0  0.024691
  8    0.0257    0.5316         0         1  0.714139         0  0.285861
  9    0.2504    0.4991         0         1  0.967742         0  0.032258
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28
4.21  4.31  4.52  4.42  4.77  4.70
  hru soil  use aquifr namhru
    2    1    2    1  'carr-ird' soil 1 deep alluvial: irrigated corn
    4    1    3    1  'carr-agd'        deep alluv.:  grass (range and pasture)
    6    2    2    1  'muir-ird' soil 2 deep alluvial: irrigated corn
    8    2    3    1  'muir-agd'        deep alluv.: grass (range and pasture)
    9    3    1    0  'cret-wsm' soil 3 upland: wheat/sorghum/fallow rotation
   10    3    4    0  'cret-upg'               grass (range and pasture)
   11    4    1    0  'kips-wsm' soil 4 upland: wheat/sorghum/fallow rotation
   12    4    4    0  'kips-upg'               grass (range and pasture)
   13    5    1    0  'hast2wsm' soil 5 upland (Hasting 1-4, Hedville 6-9)
   14    5    4    0  'hast2upg'               grass (range and pasture)
'hru2', casavg (name of HRU-averaged results calculated by Swbavg, not Swat)
```

Example 3: Control Codes input file for HRU scheme 3 (14 HRUs)

```
Control File ! hru3.cod: 18yrs, 14 hrus (hru option 3), swminf=0.50,iopet=3 cn=75)
  181977   9   0   3   3   0   0   0   0   0   0   0   0   0   0   1   0   9   3
   0   2  14   3   0   1   0   0   1  0.65  12.7  0.3048 ! '(9i4,2f6.0)': ilog iopmod
numhru iophru iopwea iopwfl iprirr iprevt iopswm swminf wsfmax cnvlen
'FREE', 'FREE', ' ',' ','hru2.shl'  ! fmttmp, fmtpcp, fmtrad, namrad, namshl (3a20,2a13)
   5, 0.1261, nsoils, aqfbas
      'aqffrc' 'crpfrc' 'Carr' 'Muir'  'Crete' 'Kipson' 'HastHedv'
  1    0.0733    0.5962         1         0  0.518722  0.372247  0.109031
  2    0.2053    0.5463         1         0  0.079208  0.423267  0.497525
  3    0.2368    0.6281  0.547486  0.452514  0.775883  0.063337  0.160780
  4    0.0924    0.5737  0.969231  0.030769  0.623421  0.314581  0.061998
  5    0.2106    0.7164  0.254438  0.745562  0.896510  0.103490         0
  6    0.0122    0.6113         0         1  0.759221  0.060451  0.180328
  7    0.0829    0.6753         0         1  0.975309         0  0.024691
  8    0.0257    0.5316         0         1  0.714139         0  0.285861
  9    0.2504    0.4991         0         1  0.967742         0  0.032258
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28
4.21  4.31  4.52  4.42  4.77  4.70
  hru soil  use aquifr namhru
    1    1    5    2  'carr-irs' soil 1 shallow alluvial: irrigated corn
    2    1    2    1  'carr-ird'           deep alluvial: irrigated corn
    3    1    6    2  'carr-ags'   shallow alluvial: grass (range and pasture)
    4    1    3    1  'carr-agd'        deep alluv.:  grass (range and pasture)
    5    2    5    2  'muir-irs' soil 2 shallow alluvial: irrigated corn
    6    2    2    1  'muir-ird'           deep alluvial: irrigated corn
    7    2    6    2  'muir-ags'        shallow alluv.: grass (range and pasture)
    8    2    3    1  'muir-agd'              deep alluv.: grass (range and pasture)
    9    3    1    0  'cret-wsm' soil 3 upland: wheat/sorghum/fallow rotation
   10    3    4    0  'cret-upg'               grass (range and pasture)
```

```
   11    4    1    0  'kips-wsm' soil 4 upland: wheat/sorghum/fallow rotation
   12    4    4    0  'kips-upg'                grass (range and pasture)
   13    5    1    0  'hast2wsm' soil 5 upland (Hasting 1-4, Hedville 6-9)
   14    5    4    0  'hast2upg'                grass (range and pasture)
'hru3', casavg (name of HRU-averaged results calculated by Swbavg, not Swat)

Example sequence for successive approximation of unsat-sat coupling:
Case HRU3: shallow wt coupling is based on results for HRU2 (file hru2.shl);
Case HRU3b: shallow wt coupling is based on results for HRU3 (file hru3.shl).

Land-use     HRU schemes (1-3):
codes 1-6
                1              2                        3
1          dry crops      bedrock, dry crops       bedrock, dry crops
2          irrig. crops   aquifer, irrig. crops    deep aquifer, irrig. crops
3          grassland      aquifer, grasslands      deep aquifer, grasslands
4                         bedrock, grasslands      bedrock, grasslands
5                                                  shallow aquifer, irrig. crops
6                                                  shallow aquifer, grasslands
```

Defunct input option definition:

The option **iopswt** is not read, since the option for Swat to call Modflow as a subroutine is not fully implemented, and may not be necessary if the HRU scheme 3 provides a satisfactory way to represent the coupling of SWAT and MODFLOW by way of evaporation from shallow ground water.

Input data requirements for program Swbavg

Program Swbavg reads the same Codes (*.cod) input file read by Swat for execution of all HRUs that are to be averaged by Swbavg. For Swat, the 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). On execution of the first HRU, Swat writes a file of HRU weights (*.wts). After simulation of all HRUs, Swbavg can be run, reading the Codes input file as redirected keyboard responses, such as

```
Swbavg        <hru1.cod             >hru1.jnl
```

The input variable casavg is read from the 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 containing the weighted averages of the component HRUs simulated by Swat. Once Swbavg has been run, the resulting balance file can be read by Modflow (Modswb package).

Input data for program Swbavg is provided by Swat's modified Control Codes input file to specify the number of HRUs and their names. Swbavg reads the HRU weights from the separate weights file written by Swat and takes a weighted average over the component HRU balance files. The weights are calculated in Swat subroutine Subwts at the end of each time step just prior to calling Preswb, where flow rates are calculated to specify recharge, tributary inflow, irrigation pumping, potential evaporation, and change in watershed storage. 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.

Instructions for the Modswb 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.

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 Modswb package and modified versions of the Well package (Modwel) and the Stream package (Modstr). Two of the key interdependencies serve to associate runoff simulated by Swat with tributary inflows to the stream network modeled by Modstr; and tor supply irrigation demand simulated by Swat with pumping from both surface and ground water points of diversion. Some additional modeling capabilities have been incorporated in these packages. Input instructions are given below for these modified 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):      nambal,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.

nambal = name of the balance file with results of hydrologic model. If nambal = ' ', then use the default based on the case name with extension '.BAL'. This allows the same SWB file to be used for all cases if balance file names are based on the case names.

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 (y=1,n=0) to distribute recharge within each subbasin according to the recharge package input file array RECH. If = 1, maintain the recharge distribution within each subbasin according to the recharge input file array RECH, but scale the recharge within each subbasin for each time step.

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 for Swat-Modflow data transfer

Modflow array SHED stores data related to subbasins; vectors 6 and 27–30 are not currently used. Dimensions for the Rattlesnake Creek aquifer model are in feet [L] and days [T], so flow rates are expressed in ft^3/day, and velocities (e.g. hydraulic conductivity and evaporation rates) in ft/day. 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 rptest.swb (data items 1-4) for Republican River Basin

```
 9, nwshed                                                              (1)
' ',     1     3     1     1 0.00     1     0 0.0   nambal,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
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 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
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 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
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 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
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 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
  sub sub fract noncontrb       sw pond volume HRU fract  soilwt  cropwt soil crop
    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
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
```

Modstr: modified Stream package

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

1) 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.

2) The standard package requires streambed conductance C to be read for each reach based on an assumed rectangular channel geometry with steady flow. Alternatively, streambed hydraulic conductivity K' and reach length L may also be read, in which case C is calculated according to $C = K' \cdot L \cdot P / b'$, where:

K' = streambed saturated hydraulic conductivity;

L = stream reach length;

P = wetted perimeter;

b' = streambed thickness.

3) 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 Walnut Creek model, 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.

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 (in 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:

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

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

For each stress period (STR2RP):
2. Data:  ITMP,IRDFLG,IPTFLG,IRDCND,NUMINP,IROUTE,NRSTEP,ISGTOP
   Format: (8I10)

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)
      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: 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.
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; can be used for sensitivity analysis of streambed elevation.

Line 2:

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 $COND = K_s L_s P/T$, 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.

nrstep (not used currently): number of streamflow routing time steps for each aquifer time step; nrstep = 1 is assumed for all routing options (above). This simplification eliminates 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).

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
```

Data stored in Istrm:

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

Additional array ISTRM vectors (increased from 5 to 10)

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.

Data stored in Strm: read 1-5 (line 3); 6-8 and 12-15 (line 4).

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 = leakage (rev.: calculate as time-centered.)

Additional array STRM vectors (increased from 11 to 25)

12 L = reach length
13 if icalc=2 (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; currently, 1=Concordia, 2=Clay Center on Republican R., 3=Albert KS gage on Walnut Creek.
14 Ks_main = 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 possibly a 2nd Manning coefficient for flow in side channels when perim > wdmain as in (15).
17 stream depth (STR2FM)
18 qs = net lateral inflow due to surface runoff and interflow; includes surface water diversions for appropriated water use (see modified WELL 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; initialized for each time step in SWB2FM of the Modswb package.
22 evaporation for time step subtracted from reach as flow rate if ievopt > 0 (STR2FM).
23 reach outflow for previous time step's solution (see note below).
24 reach inflow for previous time step's solution (see note below).
25

Vectors 23 and 24, retained from previous time step for reach inflow and outflow, are used to calculate streambed leakage and, for iroute = 2, streamflow.

Added array STRMAD vectors 1 to 7 for stream reaches L=1 to mxstrm:

1 top width B
2 wetted perimeter P

3 cross-sectional area of flow A
4 avg flow velocity v = Q/A
5 residence time tr = dx/v, where dx = reach length
6 kinematic wave speed ck = dQ/dA
7 hydraulic diffusion Dh = Q/(2*B*S0)

c STREAM package input data changes:

irdcnd: stream channel geometry options

irdcnd = 0 (default): streambed conductance, C, is applied as read from field 51:60 of 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 can be 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 STR1DW; 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.

numinp:

If ITMP = -2 (see above), then for each time step (step 1 in STR1RP and remaining steps in STR2FM), streamflow data are read for NUMINP previously defined 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)') (istrm2(j),j=1,5),strflo
```

This allows inflow hydrographs to be updated in each time step.

iroute: streamflow routing options:

iroute ≤ 1: Apply modified stream routing procedure by Prudic;
iroute = 2: Apply diffusive wave routing where Cr-Pe conditions are met. In this case, 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 is less opportunity for solution errors occurring for nrstep > 1 under conditions of strong coupling, i.e. for large conductance, C, as described elsewhere (Perkins and Koussis, 1996).

nrstep: number of streamflow routing time steps for each aquifer time step: this is assumed to be 1 for all routing options (above).

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

```
        77         1         0         0         3      1.49         0         0 12   73        -2
        77         0         0         1         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         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
```

Modwel: modified Well package

As part of the project to model the Lower Republican River Basin, the 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 MODSWB 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 a version of MODSWB. 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 in the present version of the Swat-Modflow linkage.

Summary of modified Well package

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 (Modwel)

```
For each simulation (WEL1AL):
1.     Data:    MXWELL,IWELCB,iopsat,satlo,sathi,ratgnd,ratsrf,welmpy,iadcod
       Format:  (*) or (2I10,6f10.0,I10) with space-delimited fields.

For each stress period (WEL2RP):
2.     Data:    ITMP,nwread,iyrper,frcuse
       Format:  (*) or (3I10,2f10.0) with space-delimited fields.
c
For each water right (WEL2RP):
       DO II=1,nwread
3.         Data:      ilay,irow,icol,Qwr,pmprat,dsstrm,idxrch,iwryr,codes
101        Format:    (3i10,3f10.0,2i5,a10)
```

Definition 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.

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

=0: this option is ignored.

=1: 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

$$\begin{aligned} qr &= q(ys-yL)/(yH-yL), \quad yL < ys < yH, \\ &= q, \quad ys > yH, \\ &= 0, \quad ys < yL. \end{aligned}$$

=2: pumping rate is 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.

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.

pmpmax maximum pumping rate for any irrigation well (ignored if zero) affects how irrigation assigned in SWAT is distributed over the basin as follows. In a given month, the pumping rate q_k of each well k as specified on Line 3 (above) is scaled by the ratio of total irrigation assigned by SWAT Q_s to the total specified for irrigation diversions in the Well and Surface input files Qm; i.e. for each irrigation well and surface diversion k, $q_{sk} = s \cdot q_k$, where $s = Q_s/Q_m$. If the maximum scaled pumping rate for any well exceeds pmpmax in a given month, then the wells are all assigned a scaled average pumping rate $q_{sk} = s \cdot Q_m/n$, letting n represent the total number of ground and surface water diversions for irrigation.

dtwmax include only water level observations with dtw < dtwmax. Default value: if dtwmax = 0, reset to dtwmax = 40 ft (a special case for the Republican River basin model).

Line 2 (for each stress period).

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.

iyrper calendar year corresponding to stress period.

frcuse (dropped): total estimated water use as a fraction of appropriations; this is based on analysis of water use reports available for years 1980-1993, and on precipitation models derived from these reports for the remaining years of the 1977-1994 study.

Line 3 (for each point of diversion from surface or ground water): WEL2RP
Fields: revised water use input file format:

c 1-10: i10 ilay layer
c 11-20: i10 irow row
c 21-30: i10 icol column
c 31-40: f10.0 Qwr annual avg estimated water use [L^3/T], e.g. cfs
c 41-50 f10.0 pmprat appropriated maximum pumping rate
c 51-60 f10.0 dsstrm (*) distance to stream (grid units)
c 61-65 i5 idxrch (*) index to stream reach (order in which stream reach is read)

(*) If dsstrm or idxrch are given as zero, an attempt is made by subr SRF2RP to find reasonable values for them. First, array idxstr identifies the stream reach, if one exists, associated with each grid cell. 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)

c 66-70 i5 iwryr year of application for water right (taken as 1st yr of use)
c 71-80 a10 codes
c 71 a1 bndcnd '*' indicates b.c. well if iopbc>0 (Rattlesnake model convention)
c 72 a1 wrtype V: vested; A: appropriated; (others, e.g. T=temporary)
c 73 a1 source G=ground (well(7,*)=0), S=surface, i.e., streamflow (well(7,*)=1)
c 74-76 a3 usecod DWR use code: 3 for irrigation (default)

Additional data fields not currently read:
c 81-88 y_r grid row coordinate
c 89-96 x_c grid column coordinate
c 98-124 a20 wellid

previous definitions:
iappno water right application number; used as selection criterion in water use scenarios

Definitions of modified array WELL (expanded from 4 to 20 vectors)

```
c       changed from 4*mxwell to 20*mxwell to accommodate (5) variation in
c       pumping rate with time step, to be determined in the watershed
c       module MODSWB, subr SWBHYD; and (6) distinguishing between
c       irrigation wells (=0) and recharge/b.c. wells (=1); see below.
c       (1) layer
c       (2) row
c       (3) column
c       (4) pumping rate as orig. unless irropt>0 (MODSWB), in which
c          case well(5)=rate read for stress period and well(4) is
c          scaled according to subbasin irrigation flux.
c       (5) pumping rate: appropriation.
c       (6) bccode: read as '*', retain as 1 to identify flux b.c. wells
c          not to be weighted by fluxes in module modswb; otherwise (default),
c          set to zero.
c       (7) SOURCE: read as 'S' or 'G', retain as 1:surface, 0:ground water
c       (8) usecod: numeric version of DWR use codes (3:irrigation)
c       (9) dsstrm distance to stream
c      (10) istrch: identifer for closest stream reach; index to order in
c          which the stream reach was read; required for surface water diversions.
c      (11) iwryr: water right year
c      (13) pmprat:  appropriated maximum pumping rate [L^3/T]
c      (14) areair:  appropriated area for irrigation (acres)
c      (15) qappr:   appropriated annual volume of water for irrigation (acre-ft)
```

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.        8.       15.       13.       32.   Mxwell,iwelcb,iopsat,satlo,sathi,ratgnd,ratsrf
       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
```

Modrsd: Residuals package (ground water level observations)

For each stress period, available observations of piezometric heads in the aquifer are read from the input file to this package. Then for each time step, MODFLOW's solution is compared with measurements taken during the time step at corresponding grid locations. Results of this comparison are written to two files. (a) Individual residuals are written to [case].mea; (b) Statistics of residuals are written to [case].rsd. Statistics include residual mean and standard deviation, which are summarized for each stress period and over the cumulative time period of the simulation.

Input instructions for the Residuals package

1. For each simulation (RSD1AL):
   Data: mxobs,iobscb,ioprsd,dtwmax
   Format: (2I10,f10.0)

2. For each stress period (RSD1RP), read number of water level observations and year:
   Data: **numobs, iyrper**
   Format: (2I10)

3. For each observation from 1 to numobs (RSD1RP):
   Data: ilay,irow,icol,iyrdtw,imodtw,zw,dtw,elevls
   Format: (FREE) --see note below (*) regarding format used to write data set

Definition of Residual package input data

Line 1 (for each simulation).
mxobs: maximum number of water level observations in a stress period.

iobscb: print(<0) simulated heads, measured water levels, and residuals (sim. – meas.)

ioprsd: (option) if ioprsd > 0 (or igroup > 1; see def. below); then calculate a residual based on each measurement for which dtw < dtwmax.

dtwmax include only water level observations with dtw < dtwmax.

Line 2 (for each stress period).
numobs number of observations to be read for comparison with simulated heads in this stress period.
iyrper calendar year corresponding to stress period.

Line 3 (for each observation of piezometric heads in aquifer): RSD2RP
Definitions of input data, with reference to location in array Gwobs(25)

lay: (1) layer index

row: (2) row index (= row containing rwr; i.e., rwr rounded up)
col: (3) column index (= column containing cwr; i.e., cwr rounded up)
iyrdtw (8) year of measurement (4 digits, e.g. 1992), prev. well(11)
imodtw (9) month of measurement (1=Jan,...,12=Dec), prev. well(12)
zw (4) measured water level, prev. well(10)
dtw (6) depth to water, prev. well(14)
elevwr (5) land surface elevation, prev. well(9)

Additional data included in set (for reference)
cwr (13) column coordinate, prev. well(8)
rwr (12) row coordinate, prev. well(7)
src (10) data source ID (for your own use; codes here are for Wet Walnut Creek): 'KGS' (KGS measurements 1960-1996); 'WL' (interpolated water level distributions for 1981 and 1996); 'DWR' (taken from DWR water use reports). 'KGS' and 'WL1981' data sets (1960-1990) were used for calibration; the 'DWR' and 'WL1996' data sets (1991-1996) were used for verification.
idwell Well ID associated with data base or spreadsheet from which input file was exported.
daydtw day of month of measurement

Other data given for Republican River Basin data set
(14) iappno = application no. (taken from well identifier), prev. well(15)
(15) calculated head at this node (hnew; see WEL1WR), prev. well(16)
(16) istrch = identifer for closest stream reach: index to order in which the reach was read, prev. well(21); not defined.
(17) dsstrm = approx. distance to stream reach, prev. well(22); not defined.
(18) elev. difference: meas. water level - calc. stream stage, prev. well(24)
(19) elev. difference: calc. water level - calc. stream stage, prev. well(25)
grid cell elev. variation = surf. elev. at center of node - surf. elev. at well

(*) Note: Data are exported from a data base or spreadsheet in the following format; the first few fields may then be read in free format as indicated above:
Data: ilay,irow,icol,iyrdtw,imodtw,zw,dtw,elevls, cwr,rwr,datsrc,idwell,idaywl,legloc
Format: (5i5,5f8.0,1x,a6,2i5,1x,a)

Example Residuals input data file: gwuadmnu.obs for Lower Republican River basin

Excrpts from the file are shown, including observations from two data sources: DWR (1981 water use reports) and KGS (1994 field survey).

```
Column headings corresponding to input:
  lay  row  col   yr  mon       zw      dtw ls_elev     cwr      rwr src   idwel day  Loc.(PLSS)

Input:
220        -1         1        40 mxobs iobscb ioprsd dtwmax   gwuadmnu.obs
         0       1977     0.293    36.176     1.000         0 numobs year
         0       1978     0.520    37.427     1.000         0
         0       1979     0.560    38.535     1.000         0
         3       1980     1.001    38.867     1.000         0
         1          5        18      1288 1310   22   80 1980   12    1 3    4.31   17.19 A0041870005S02W2505NCSWNW
         1         11        31      1222 1242   20   57 1980    6    1 3   10.56   30.69 A0045860006S02E3001NENWSE
         1         11        31      1222 1242   20   59 1980    6    1 3   10.31   30.44 A0054750006S02E3002NESENW
       104       1981     0.356    40.695     1.000         0
         1          7        29      1241 1268   27   62 1900    0    1 4    6.20   28.33 VCY00010006S01E020642003550
         1          7        29      1241 1268   27   62 1900    0    1 4    6.20   28.32 VCY00010006S01E020542003600
         1         13        34      1203 1229   26   55 1977    1    1 4   12.99   33.07 VCY00030007S02E030100504920
        79       1994     0.590    52.489     1.000         0
         1          1         4    1380.9 1393   12      1994   11      3    0.59    3.59           5S 4W 3 dbbd    s2    KACKLEY       "
         1          1         4    1373.5 1381    8      1994   11      3    0.97    3.34           5S 4W 3 cdcd    s2a   KACKLEY       "
         1          2         2    1372.2 1392   20      1994   11      3    1.66    1.91           5S 4W 8 dadb    s6a   KACKLEY       "
         1          3         2    1375.0 1389   14      1994   11      3    2.03    1.97           5S 4W17 aaaa    s6b   JAMESTOWN     "
         1          3         3    1370.7 1380    9      1994   11      3    2.03    2.97           5S 4W16 aaaa    s9a   JAMESTOWN     "
         1          4         4    1367.1 1380   13      1994   11      3    3.03    3.59           5S 4W22 abba    s10   JAMESTOWN     "
         1          1         4    1366.4 1385   19      1994   11      3    0.97    3.59           5S 4W 3 dccd    s1a   CONCORDIA NW  "
         1          4        10    1328.6 1337    8      1994   11      3    3.53    9.97           5S 3W22 daaa    55    CONCORDIA     "
         1          4         7    1356.8 1370   13      1994   11      3    3.09    6.34           5S 3W19 babd    50    CONCORDIA     "
         1          3         5    1356.9 1365    8      1994   11      3    2.66    4.84           5S 4W14 daca    s7    CONCORDIA     "
         1          4         6    1350.4 1362   12      1994   11      3    3.59    5.03           5S 4W24 cbbc    s12a  CONCORDIA     "
         1          3         4    1366.0 1375    9      1994   11      3    2.16    3.59           5S 4W15 abca    s8    JAMESTOWN     "
         1          3         7    1353.0 1375   22      1994   11      3    2.97    6.16           5S 3W18 ccdc    47    CONCORDIA     "
         1          3         7    1356.7 1382   25      1994   11      3    2.47    6.03           5S 3W18 bccc    47a   CONCORDIA     "
         1          3         6    1349.7 1377   27      1994   11      3    2.72    5.97           5S 4W13 dadd    47b   CONCORDIA     "
         1          4         7    1347.1 1359   12      1994   11      3    3.84    6.66           5S 3W19 dcac    49    CONCORDIA     "
         1          4         8    1341.5 1350    9      1994   11      3    3.78    7.66           5S 3W20 dcab    49a   CONCORDIA     "
         1          4         9    1328.0 1370   42      1994   11      3    3.03    8.28           5S 3W21 babb    49b   CONCORDIA     "
         1          4         8    1348.3 1370   22      1994   11      3    3.09    7.03           5S 3W20 bbbc    49c   CONCORDIA     "
         1          4        16    1299.7 1312   12      1994   11      3    3.66   15.47           5S 2W22 cada    21a   RICE          "
         1          6        17    1300.5 1323   23      1994   11      3    5.28   16.03           5S 2W35 bcbb    39a   RICE          "
         1          6        14    1309.3 1335   26      1994   11      3    5.53   13.53           5S 2W32 dbbb    39b   RICE          "
         1          4        15    1306.5 1320   14      1994   11      3    3.72   14.03           5S 2W21 cbcc    17a   RICE          "
         1          5        13    1317.0 1327   10      1994   11      3    4.91   12.22           5S 2W30 ccda    69a   RICE          "
         1          4        12    1319.1 1333   14      1994   11      3    3.91   11.03           5S 3W24 cccb    27a   RICE          "
         1          4        12    1315.6 1330   14      1994   11      3    3.84   11.41           5S 3W24 cdac    27b   RICE          "
         1          5        18    1297.7 1317   19      1994   11      3    4.53   17.03           5S 2W25 cbbb    24a   CLYDE         "
         1          5        20    1283.8 1294   10      1994   11      3    4.16   19.03           5S 1W29 bbcb    A     CLYDE         "
         1          5        22    1278.9 1288    9      1994   11      3    4.41   21.59           5S 1W27 acca    Cc    CLYDE         "
         1          6        23    1270.9 1280    9      1994   11      3    5.09   22.22           5S 1W35 bbad    Cd    CLYDE         "
         1          7        23    1270.8 1280    9      1994   11      3    6.09   22.59           6S 1W 2 abbd    Ce    CLYDE         "
         1          6        22    1273.9 1285   11      1994   11      3    5.91   21.53           5S 1W34 dccb    Da    CLYDE         "
```

```
    1        6        20     1282.8 1307   24       1994   11      3    5.84   19.53          5S 1W32  dcbc    Db     CLYDE          "
    1        5        23     1241.0 1291   50       1994   11      3    4.47   22.84          5S 1W26  adcd    Ca     CLYDE          "
    1        4        22     1258.3 1308   50       1994   11      3    3.03   21.72          5S 1W22  abaa    Cb     CLYDE          "
    1        9        31     1229.9 1245   15       1994   11      3    8.72   30.16          6S 2E18  cbdc    R9a    CLIFTON        "
    1        9        31     1230.4 1245   15       1994   11      3    8.84   30.22          6S 2E18  ccad    R9b    CLIFTON        "
    1        9        30     1230.1 1259   29       1994   11      3    8.47   29.22          6S 1E13  bcdd    5      CLIFTON        "
    1        9        30     1231.6 1248   16       1994   11      3    8.22   29.53          6S 1E13  abcc    5a     CLIFTON        "
    1        9        29     1232.5 1259   27       1994   11      3    8.97   28.53          6S 1E14  dccc    C4     CLIFTON        "
    1       10        29     1233.5 1265   32       1994   11      3    9.47   28.16          6S 1E23  bcdc    C4a    CLIFTON        "
    1       10        30     1227.5 1253   26       1994   11      3    9.22   29.22          6S 1E24  bbdd    C4b    CLIFTON        "
    1        7        29     1245.5 1264   19       1994   11      3    6.22   28.53          6S 1E 2  abcc    C3a    CLIFTON        "
    1        8        28     1246.0 1255    9       1994   11      3    7.28   27.47          6S 1E10  bdaa    21a    CLIFTON        "
    1        8        27     1253.0 1262    9       1994   11      3    7.03   26.66          6S 1E 9  abab    21b    CLIFTON        "
    1        8        28     1248.9 1259   10       1994   11      3    7.34   27.03          6S 1E10  bcbc    21c    CLIFTON        "
    1        6        28     1250.3 1274   24       1994   11      3    5.97   27.53          5S 1E34  dccc    21d    CLIFTON        "
    1        7        26     1254.2 1267   13       1994   11      3    6.09   25.03          6S 1E 5  bbbc    C1a    CLIFTON        "
    1        7        25     1260.4 1269    9       1994   11      3    6.47   24.53          6S 1E 6  accc    C1b    CLIFTON        "
    1        7        25     1261.8 1275   13       1994   11      3    6.03   24.09          6S 1E 6  bbba    C1c    CLIFTON        "
    1       10        32     1224.9 1236   11       1994   11      3    9.78   31.03          6S 2E20  ccbb    R14a   LINN SW        "
    1       10        31     1225.4 1240   15       1994   11      3    9.28   30.66          6S 2E19  acab    R14b   LINN SW        "
    1       18        34     1189.8 1200   10       1994   11      3   17.22   33.03          7S 2E34  bbcc    97     CLAY CTR NW    "
    1       17        33     1186.3 1198   12       1994   11      3   16.97   32.97          7S 2E28  dddd    97a    CLAY CTR NW    "
    1       17        34     1193.8 1218   24       1994   11      3   16.78   33.47          7S 2E27  cdaa    90     CLAY CTR NW    "
    1       18        34     1191.6 1215   23       1994   11      3   17.03   33.72          7S 2E34  abaa    90a    CLAY CTR NW    "
    1       17        34     1189.3 1215   26       1994   11      3   16.84   33.97          7S 2E27  ddad    90b    CLAY CTR NW    "
    1       18        34     1189.1 1209   20       1994   11      3   17.28   33.97          7S 2E34  adaa    90c    CLAY CTR NW    "
    1       18        34     1181.3 1201   20       1994   11      3   17.84   33.97          7S 2E34  ddad    90d    CLAY CTR NW    "
    1       19        35     1179.9 1209   29       1994   11      3   18.03   34.91          8S 2E 2  aaab    201    CLAY CTR NW    "
    1       19        36     1178.7 1203   24       1994   11      3   18.31   35.69          8S 2E 1  aca     200    CLAY CTR NW    "
    1       19        36     1180.4 1206   26       1994   11      3   18.28   35.28          8S 2E 1  bdbb    200a   CLAY CTR NW    "
    1       19        36     1182.2 1207   25       1994   11      3   18.72   35.28          8S 2E 1  cacc    200b   CLAY CTR NW    "
    1       19        36     1180.4 1205   25       1994   11      3   18.03   35.72          8S 2E 1  abaa    200c   CLAY CTR NW    "
    1       16        34     1202.5 1220   17       1994   11      3   15.22   33.91          7S 2E22  aadc    79     CLAY CTR NW    "
    1       15        33     1204.8 1215   10       1994   11      3   14.22   32.41          7S 2E16  badc    70     CLAY CTR NW    "
    1       15        33     1207.3 1225   18       1994   11      3   14.72   32.97          7S 2E16  dadd    70a    CLAY CTR NW    "
    1       15        34     1205.9 1223   17       1994   11      3   14.69   33.44          7S 2E15  cad     64     CLAY CTR NW    "
    1       15        34     1208.9 1225   16       1994   11      3   14.34   33.03          7S 2E15  bcbc    64a    CLAY CTR NW    "
    1       14        35     1212.0 1227   15       1994   11      3   13.94   34.06          7S 2E11  ccc     57a    CLAY CTR NW    "
    1       14        35     1212.9 1231   18       1994   11      3   13.47   34.03          7S 2E11  bccc    57n    CLAY CTR NW    "
    1       13        33     1214.3 1240   26       1994   11      3   12.72   32.34          7S 2E 4  cacd    51a    CLAY CTR NW    "
    1       13        34     1214.1 1235   21       1994   11      3   12.34   33.03          7S 2E 3  bcbc    51b    CLAY CTR NW    "
    1       17        36     1183.9 1210   26       1994   11      3   16.97   35.09          7S 2E25  cccd    85     CLAY CTR NW    "
    1       21        36     1184.8 1198   13       1994   11      3   20.69   35.81          8S 2E13  dac     216    CLAY CTR SW    "
    1       20        36     1170.6 1200   29       1994   11      3   19.59   35.53          8S 2E12  dbbc    213    CLAY CTR SW    "
    1       20        36     1177.6 1205   27       1994   11      3   19.28   35.53          8S 2E12  acbb    213a   CLAY CTR NW    "
    1       20        36     1178.3 1205   27       1994   11      3   19.03   35.53          8S 2E12  abbb    213b   CLAY CTR NW    "
    1       21        36     1177.8 1190   12       1994   11      3   20.56   35.56          8S 2E13  dbb     W      CLAY CTR SW    "
layer      row    column     wlevel zlnd  dtw  dtb   iyr    mon nobs u     row  column file_id--TspRngSc  Subsec obs. map
   79 observations written to file dtw94nov.obs
```

Basic package input data changes to invoke added packages

Line 4 of input requirements for the Basic package was modified to allow added packages to be invoked. Except for Line 4, input requirements for the Basic package are the same as described in the MODFLOW manual (McDonald and Harbaugh, 1988). The following additional packages are to be invoked to simulate the Rattlesnake base case with surface water diversions using SWATMOD2:

(a) The Soil Water Balance (SWB) package connects hydrologic flow paths from a watershed, calculated on a daily basis by SWAT (Arnold et al., 1990), to groundwater and streamflow represented by MODFLOW (McDonald et al., 1988).

The modified format for line 4 follows.

```
4. Data: iunit(24)
    Format: 24I3
    (bcf wel drn riv evt swb ghb rch sip pcg sor  oc str srf)
```

index	abbrev	package
	bas	basic package
1	bcf	Block-centered flow
2	wel	Modwel: modified Well package
3	drn	Drain
4	riv	River
5	evt	Evapotranspiration
6	swb	Modswb: Soil water balance package
7	ghb	General head boundary
8	rch	Recharge
9	sip	Strongly implicit solver
10	pcg	Preconditioned conjugate gradient
11	sor	Successive overrelaxation
12	oc	Output control
13	str	Modstr: modified Stream package
14	xxx	
15	pos	Modpost: postprocessing package
16	rsd	Modrsd: residuals package

In the following partial listing of base case input file **srfc.bas**, line 4 identifies the packages invoked according to the above definition. This input file also defines array IBOUND, the boundary conditions and the active domain of the solution; array STRT, the starting heads for the solution (only the first row of the array is listed); and the duration (s) and number of time steps for each stress period.

Basic package input file example

```
1 LAYER ,23 ROWS, 39 COLUMNS (1mi x 1mi grid); monthly 77-94          (1
 pcg .01 ft; 6" RCH, '77 wells No EVT; SWB; SURF case b               (2
```

```
        1        23        39       18         1                  (3
61 62 00 00 65 66 00 67 00 68 00 69 70 00 64 72 00            22  (4
        0         1                               iapart, istrt   (5
        1         1 (39i2)                     2                  (6
```

Modpost package: postprocessing during Modflow execution

Introduction

MODFLOW presents a difficult task in data interpretation, due to the complexity of both the data and the model. To help simplify this task, we have developed a MODFLOW package with postprocessing functions to provide results of interest in formats convenient for further analysis and display. The postprocessing functions are based on earlier versions which were designed to extract results from MODFLOW's standard output format. These functions have been combined into a package and revised to provide results in the desired formats as an auxiliary function during MODFLOW's execution, and are written from memory at the end of each solution time step. This eliminates the need for the sometimes cumbersome intermediate steps of first writing MODFLOW's results in its standard format and then reading desired results from the standard output, although MODFLOW's options are kept intact for writing results in its standard format.

Results of interest provided by MODPOST include arrays of aquifer heads or drawdowns; time series (hydrographs) of aquifer heads or drawdowns at nodes of interest, or of streamflow or streambed leakage at specified reaches; and aquifer hydrologic budgets. Results are written in formats for import into commercial packages for further analysis and visualization of results.

MODPOST is invoked according to MODFLOW's standard conventions, and the user specifies its postprocessing tasks with an input data file, which is described here. MODPOST includes some capabilities that take advantage of data available in memory during the simulation that are not written to the standard output file, but would otherwise require invoking MODFLOW's binary output option. These capabilities include writing vectors that describe flow and velocity fields, and zone budgets as defined for the ZONEBUDGET program (McDonald, 1989), which we revised for incorporation into MODPOST as a subroutine.

Scope

This package is based on earlier versions of postprocessing programs that operated on standard Modflow output. By invoking this package, some common postprocessing tasks can be accomplished during execution of MODFLOW as an alternative to these postprocessors. These tasks and related postprocessors include the following:

1. volumetric budgets for the entire solution domain (shown in the standard output file under the control of Output Control option **ibudfl**): files are written for import into spreadsheet programs, showing separate sets of columns for elapsed simulated time and for input and output terms of each budget component (constant heads, recharge, evaporation, pumping, streambed leakage (baseflow), etc.). These results are written

either as rates Q [L^3/T] or as cumulative volumes ΣQΔt [L^3]1. These options are also accomplished by posprocessor POSTMD3, which reads the overall hydrologic budgets from MODFLOW's standard output.

Volumetric budgets for zones, i.e. subsets of the grid domain; similar results can be produced by program ZONEBUDGET (specifying that MODFLOW write a binary output file (i.e., "save" results) ;

2. hydrographs (time series), similar to results of postprocessor program MODHYD;
3. solution arrays for selected time steps, similar to results of postprocessor programs POSTMOD (for 2-D, i.e. single layer models), POSTMD3 (for multilayer models), and some related versions.

In addition to calculating zone budgets and Darcy flow rates or velocities, MODPOST provides the functions of several postprocessors to summarize volumetric budgets, time series, and solution arrays on files in formats that allow import into spreadsheets and contouring programs. These functions are similar to those served by postprocessors that operate on MODFLOW's standard output file with some assistance from the corresponding input, esp. the *.BAS and *.BCF files; see programs POSTMOD, POSTMD3, and MODHYD.

Modpost also calculates volumetric budgets for grid subsets (zones) to produce results comparable to those of program ZONEBUDGET (Harbaugh, 1990), which reads grid cell flow rates from a binary output file written by MODFLOW.

The functions of MODPOST are described below.

1. Volumetric budgets for the entire gridded solution domain and for subareas (zones):

MODPOST writes mass balance components either as rates Q [L^3/T] to file <case>.rat or as cumulative volumes $\Sigma Q\Delta t$ [L^3] to file <case>.vol. Columns correspond to budgets as read from standard output, showing separate sets of columns for input and output for each budget component (constant heads, recharge, evaporation, pumping, streambed leakage, etc). The same function can be performed by the preprocessor POSTMD3, which reads MODFLOW's standard output file <case>.prn to extract the volumetric budget written by MODFLOW.

MODFLOW's function of calculating the volumetric budget for the total grid domain in each time step is extended to calculating separate volumetric budgets for grid subsets, or zones, including the interactions, i.e. flow rates, between adjacent zones. This function is also served by the postprocessing program ZONEBUDGET, which operates on a binary output file written by MODFLOW for a given case. The example case that accompanies ZONEBUDGET is also run using MODPOST to verify that the same results are obtained, and is described below as Example 1. MODPOST's version of zone budget calculation also prepares summaries of results for plotting and analysis that are not provided by ZONEBUDGET, including the following:

a) a matrix of interzonal transfers;
b) a summary table for all zones and the total grid domain showing input and output flow rates for each hydrologic component;

c) a separate budget table for each zone (analogous to the standard overall budget table) showing both cumulative volumes and flow rates;
d) files that may be imported into a spreadsheet program (e.g. Excel or Quattro) for plotting and analysis, and where the file may be sorted by zone to allow fast plotting of budget results for specified zones. These files include the following:
  i) file CASE.vlz (cumulative volumes) or CASE.rtz (flow rates) containing input and output terms for each hydrologic component for all zones and for every time step. Analogous summaries of the overall budget are written to CASE.vol (cumulative volumes) or CASE.rat (flow rates).
  ii) file CASE.ntz containing net flow rates for each hydrologic component for all zones and for every time step. Net flow rates for the overall budget are written to the analogous file CASE.net.

2. Hydrographs, i.e. time series of values at specified aquifer grid or stream reach nodes.
3. Solution arrays for selected time steps

Input instructions for the MODPOST package input file (*.pos)

MODPOST is invoked in the Basic package input file by IUNIT field 15 (cols. 43-45); subroutines POST1AL, POST1RP, and HYD1RP read the input file described below.

```
subroutines POST1AL, POST1RP, HYD1RP, POST1OT, POST1OZ.  Regarding format requirements:
"FREE" refers to the format used for some numerical inputs;
"TEXT" identifies records read as alphanumeric text;
"U2DINT" refers to MODFLOW's standard input format for 2-D integer arrays.

Y       opttim: years (show time in sec, min, hrs, days, or yrs?)
3,      numser (3 time series of values)
R       optvol: write file of [R]ates, cumulative [V]olumes, or [N]either?
0,                 iopzon (option to write zone budgets)
   21   69    6    streamflow at Nekoma or Rush Ctr (row,col, hydrograph type; see below)
   19   89    6    streamflow at Nekoma or Rush Ctr (row,col, hydrograph type; see below)
   21  135    6    streamflow at Albert (row,col, hydrograph type; see below)
 2,1,1,0           istper,idaxis,islice, iopvec (vector option for cell-by-cell flow)

Data for each simulation:
               POST1AL
(TEXT):opttim            time units for budgets: S M H D Y (sec min hour day year)
(FREE):numser            !no. time series (hydrographs)
(TEXT):optvol     budget option: cumulative [V]olumes, [R]ates, or [N]either
if Zone Budget option is installed (instzn > 0, set in MODFLOW mainline):
  (FREE):  iopzon      max. budget zone index (zones defined from 0 to iopzon)
  (U2DINT):     IZONEBD                      !2-D array of zone indices (0 to numzon)
end if
               HYD1RP
    do for each time series i=1 to numser:   !identify location and type of hydrograph
      (FREE):
      if NLAY = 1: irowid, icolid, idser
      if NLAY > 1: layer, irowid, icolid, idtype
    end do
(FREE): istper, idaxis, islice, iopfmt
        if (iopfmt = 3) THEN   ! proposed option for use with Arc Grid; see limitations
(FREE):     XLLCORNER, YLLCORNER, CELL_SIZE, NODATA_VALUE
        if (istper = 1 AND stress period kper = 1) THEN
(FREE)      itmstp, iperio, idtype
        if istper = 2) THEN
            DO for every stress period:
(FREE):         (iopstp(j), j=1,nstep)
```

Input definitions

opttim (TEXT): S M H D Y = time units for budgets (sec, min, hour, day, year)

optvol (TEXT): V = cumulative volumes, R = flow rates, N = none. This controls an option to write separate files describing the overall budget and, optionally, budgets for specified subareas, or zones (see **iopzon**). This optional budget output is in addition to that written to the standard output file, which is controlled by option ibudfl from the Output Control file (*.OC); the definition of option **ibudfl** has been extended as described below to control zone budget output.

For options **optvol** = V or R, separate files are written that may be imported into a spreadsheet program (e.g. Excel or Quattro) for plotting and analysis. Files describing the overall hydrologic budget include the following:

i) file <CASE>.bud: input and output terms for each hydrologic component are given as a flow rate or volume, as in Modflow's volumetric budget summary;

ii) file <CASE>.net: each hydrologic component is summarized as a net flow rate or volume (input – output).

These files describe the volumetric budget for the entire gridded solution domain in each time step.

iii) If zones are specified (see **iopzon**), budget summaries analogous to those above for each zone are written to file <CASE>.vlz (cumulative volumes) or <CASE>.rtz (flow rates).

numser: number of time series (hydrographs); $0 \leq$ numser ≤ 15.

iopzon: option to calculate zone budgets (see output option **ibudfl** definition below):

=0: no zone budgets are calculated;

>0: maximum number of budget zones mxzone = **iopzon** + 1 with allowable indices from 0 to **iopzon**; zone 0 is treated the same as zones 1 through **iopzon**. (Note: this is consistent with tests of postprocessing program ZONEBUDGET (Harbaugh, 1990), in spite of ZONEBUDGET documentation that states the contrary.) Zone budget results are optionally summarized on MODFLOW's standard output file under the control of output option **ibudfl**, specified in the output control (*.OC) input file, with the extended definition shown below.

ibudfl: This budget output option is set in MODFLOW's output control (*.OC) input file. Its definition has been modified as shown below.

= 0: no budget summary output to standard output file.

= 1: write overall budget summary table to standard output;

= 2: in addition to the above, write zone budget summary arrays to standard output showing interzone transfers and hydrologic components of budget;

≥ 3: in addition to the above, write a budget summary table to standard output for each zone.

izonbd: 2-D integer array of budget zone indices, with allowable values from 0 to **iopzon**; read only if **iopzon** > 0. This array is read using MODFLOW's U2DINT utility routine in the same way as array **ibound** from the Basic package input file (*.BAS) and array **ibshed** from the soil water balance input file (*.SWB).

(**layer,irowid,icolid**): indices to grid cell location of hydrograph j for j = 1 to numser.

idtype: index to type of results (0 to 8):

0: no results
1: head h(**x**,t), **x** = (x,y,z)
2: change in head h(**x**,t)- h(**x**,0), where h(**x**,0) represents starting heads;
3: drawdown h(**x**,0)- h(**x**,t), the negative of (2);
4: saturated thickness
5: baseflow (streambed leakage)
6: streamflow
7: flow rate through cells, Q = KAdh/dl
8: Darcy velocity (specific flow rate) through cells,q=Q/A

istper: option for specifying when to write solution arrays to a separate file according to a format specified by **iopfmt** (below):
0: Write solution for NO time steps according to option **iopfmt**;
1: Specify solution option for only one time step (**itmstp**, **iperio**, **idtype**);
2: Specify option **iopstp**(j) for each time step j=1 to nstp in each stress period;
3: Write results for ALL time steps.

idaxis: option to write a LAYER (idaxis=1), ROW (idaxis=2), or COLUMN (idaxis=3) of the solution array for each specified time step according to option **istper**.

islice: index to the layer (1 to nlay), row (1 to nrow), or column (1 to ncol) of the plane to be written, depending on option **idaxis**.

iopfmt: format option for solution arrays:
iopfmt = 0: matrix form, Modflow input format; see also iopfmt=3, below.

iopfmt = 1: single node/record as follows:
if nlay = 1: "x, y, f(x,y)";
if nlay > 1: "x, y, z, f(x,y,z)"

iopfmt = 2: flow vector format (applicable only for **idtype** = 7 or 8) as follows:
The flow rate for each cell is described by a magnitude (for either flow rate Q or darcy velocity q) and direction indicated by unit vector components (ux,uy,uz); both magnitude and direction are written for options **iopfmt** > 0. For **iopfmt** = 2, a position vector's beginning and ending points are written to represent each flow vector in a format that can be imported into a spreadsheet and plotted as a flow field. The vector originates at the center of node (j,i,k) for column j, row i, and layer k at location (xc,yr,zl), where xc=xx(j), location of column j center, yr=yy(i), row i center, and zl = location of layer k center, represented by zl=(nlay-k+1)-0.5. The vector ends at location (xc+xq,yr+yq,zl+zq), where xq=ux*delx(j)/2, yq=uy*dely(i)/2, and zq=uz*dz/2, where dz = 1 represents layer k thickness.

iopfmt = 3 (proposed option): Arc Grid format for import using the command AsciiGrid. This option is not implemented yet, but is planned as part of the Swat-Modflow upgrade. One way to implement this option is described as follows. If **iopfmt** = 3, then four additional data records will be read to specify the data required for import to Arc Grid. These four lines are denoted by items b-d in the description given below of the required format for an Ascii file to be imported to Arc

Grid; items a and e are not specified in the Modpost input file, since they are passed to Modpost from Modflow for the case being simulated. Note: this option is available only for a regular grid of square cells, since that is the only option for representing a cell grid in Arc Grid.

Required format of Ascii file for import to Arc Grid as a grid coverage using AsciiGrid is listed below, and describes the format Modpost must follow in writing an array for import to Arc Grid. Note: a-e refer to explanations below; for further explanation, see ArcInfo's documentation on the AsciiGrid command. Angle brackets (<) refer to required input (to Arc Grid); the other brackets ({) refer to optional input.

```
<NCOLS xxx> (a*)
<NROWS xxx> (a*)
<XLLCENTER xxx | XLLCORNER xxx> (b)
<YLLCENTER xxx | YLLCORNER xxx> (b)
<CELLSIZE xxx> (c)
{NODATA_VALUE xxx} (d)
row 1 (e)
row 2 (e)
...
row n (e)
```

Notes on definitions for writing results as Ascii files for import to Arc Grid:

(a) no. grid rows and columns. (*) Note: these are not to be specified in the Modpost input file, since they are already known for the case being run according to their definition in the Basic package.

b) (x,y) coordinates for either the center or lower left corner of the lower left grid cell, in terms of the projection coordinates to be used for the grid coverage in ArcInfo.

c) cell size, i.e., cell side length for a regular grid of square cells, in terms of units to be used for the grid coverage. Note: this should equal the column and row widths as specified in the BCF file, but does not need to be in the same units; e.g., for the Republican River basin case, column and row widths are specified as 5280 ft in the BCF file, but may correspond to a cell size of 1609 m if the ArcInfo grid coverage has units of meters.

(d) optional; NODATA_VALUE defaults to -9999)

(e) Cell value in row order (all cells of row 1, then all cells of row 2,..., to row n), with values delimited by a space. Carriage return is not required at the end of each row.

itmstp: time step for solution option idtype for istper = 1;

iperio: stress period for solution option idtype for istper = 1;

iopstp(j), j = 1 to nstep: vector of solution options (idtype) for each time step; read for each stress period kper = 1 to nper.

Modpost examples

1. Base case from Republican River Basin study

This example illustrates many of the capabilities of Modpost, including zone budgets for all nine subbasins, hydrographs (time series) for nodes of interest; and solution arrays for time steps of interest.

Ex. 1 Result files:

Basecase.net: net flow into aquifer for each overall budget component, i.e. the input and output columns shown in file basecase.bud are subtracted as (input - output).

Basecase.ntz net flow into aquifer for each zone and budget component.

Basecase.hyd: hydrographs for streamflow, head, and change in head at various nodes of interest. Up to 20 hydrographs may be written to this file.

Basecase.dat (concatenated files h00s00p.dat): solutions for each time step s and stress period p, written in "x,y,f(x,y)" format (results for one node per record).

Columns of file:

1 x-coordinate of cell
2 y-coordinate of cell
3 head
4 head change
5 saturated thickness
6 row index
7 column index
(additional columns for long form)
8 cell activity (value of ibound array)
9 delx (column width)
10 dely (row width)

Example 1. Base case for Lower Republican River Basin study

The response file for the base case, rpbase.rsp, specifies input file names for each package, the unit device number to be associated with the input file, an abbreviation for the package, and a description of the package; In its 1988 version, we modified Modflow to read the file names; the corresponding unit device numbers are specified by input to the Basic package to be read into the Iunit array. In the standard 1996 version of MODFLOW, both the file name and associated unit device number may be specified by a response file in essentially the format of the one shown below.

The case name, rpbase, given by the first record of the response file, is incorporated into the names of files written by MODFLOW. The local directory should contain the response file and a subdirectory , inbase, which contains the input files named in the response file. Two additional input files to be read during execution but not named in the response file are inbase\rpbase.bal, identified at the bottom of the SWB package input file (rpbase.swb); and ..\exe\newbase, identified in the PLT package input file (basecase.plt). The executable file MODFLOW.EXE and associated files (f77l3.eer) are assumed to be in the directory ..\exe, specified relative to the area where MODSWB96 is executed.

```
rpbase                                      case name (~.log, ~.prn, ~.rsp)
inbase\bcase_t4.bas                          1 BAS, Monthly Basic package
inbase\kbase20b.bcf                         61 BCF, Block-centered flow
inbase\gwuadmnu.wel                         62 WEL, groundwater use
inbase\repsurf.evt                          65 EVT, evap. from shallow gw
inbase\rpbase.swb                           66 SWB, Soil water balance
inbase\matrix1.rch                          67 RCH, groundwater Recharge
inbase\model1bs.pcg                         68 PCG, preconditioned conjugate grad
inbase\rpbase.oc                            69 OC,  Output control
inbase\rpmon.str                            70 STR, Streamflow, Ks=0.54 ft/day
inbase\swuadmnu.wel                         63 SRF, surface water use [1]
inbase\basecase.pos                         64 POS, Postprocessor: budgets
inbase\gwuadmnu.obs                         72 OBS, gw level observations
inbase\basecase.plt                         73 PLT, interactive graphical display
```

Basic package input file bcase_t.bas invokes the modpost input file basecase.pos (unit 64 on line 4); part of file bcase_t.bas follows:

```
1 LAYER ,23 ROWS, 39 COLUMNS (1mi x 1mi grid); monthly 77-94
 pcg .01 ft; 6" RCH, '77 wells No EVT; SWB; SURF case b
         1         23         39         18         1  nlay nrow ncol nper itmuni
 61 62 00 00 65 66 00 67 00 68 00 69 70 63 64                       22
         0         1                                   iapart, istrt
         1         1 (39i2)                             2  \sp\basin27\ibrepub.3/21/96
 0-1-1-1-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0-1-1-1-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0-1-1-1-1-1-1-1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
-1-1-1-1-1-1-1-1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
-1-1-1-1-1-1-1-1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0-1-1-1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1-1 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

The postprocessor input file basecase.pos (below) specifies the following:
a) 11 time series are to be written (to file basecase.hyd);
b) 9 budget zones corresponding to the subbasins on input file basecase.swb;
c) the following solution arrays are to be written:
i) Darcy velocity at the end of the first time step (Jan 1977);
ii) heads at the end of a drought month (Aug 1991),
iii) heads at the end of a flood month (Aug 1993).

```
y                              opttim: years (show time in sec, min, hrs, days, or yrs?)
r                              optvol: write file of [R]ates or cumulative [V]olumes?
11,9  numser (11 time series of values), iopzon (option to write zone budgets)
        64         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
   5    9    6    streamflow at Clay Ctr (row,col, hydrograph type; see below)
  21   38    6    streamflow at Concordia
   4   15    1    heads          (node in subbasin 1)
   4   15    2    change in heads
   6   13    2    (subbasin 2)
   4   20    2         "    4
   7   29    2         "    5
   9   30    2         "    3   Taddiken well in this cell
  13   34    2         "    7
  19   35    2         "    3   Munson well in this cell
  20   37    2         "    9
2,1,1,0    istper,idaxis,islice, iopvec (vector option for cell-by-cell flow)
7 0 0 0 0 0 0 0 0 0 0 0        1977    first time step
0 0 0 0 0 0 0 0 0 0 0 0        1978
0 0 0 0 0 0 0 0 0 0 0 0        1979
0 0 0 0 0 0 0 0 0 0 0 0        1980
0 0 0 0 0 0 0 0 0 0 0 0        1981
0 0 0 0 0 0 0 0 0 0 0 0        1982
0 0 0 0 0 0 0 0 0 0 0 0        1983
0 0 0 0 0 0 0 0 0 0 0 0        1984
0 0 0 0 0 0 0 0 0 0 0 0        1985
0 0 0 0 0 0 0 0 0 0 0 0        1986
0 0 0 0 0 0 0 0 0 0 0 0        1987
0 0 0 0 0 0 0 0 0 0 0 0        1988
0 0 0 0 0 0 0 0 0 0 0 0        1989
0 0 0 0 0 0 0 0 0 0 0 0        1990
0 0 0 0 0 0 0 1 0 0 0 0        1991    Aug '91  (drought)
0 0 0 0 0 0 0 0 0 0 0 0        1992
0 0 0 0 0 0 0 1 0 0 0 0        1993    Aug '93  (flood)
0 0 0 0 0 0 0 0 0 0 0 0        1994

j f m a m j j a s o n d       (months corresponding to time steps)
```

Results:
basecas3.hyd: hydrographs;
basecas3.net: net flow rates for overall budget components in each time step;
basecas3.ntz: net flow rates for budget components of each zone in each time step;
Darcy velocity for first time step;
Hydraulic heads in Aug '91 (drought);
Hydraulic heads in Aug '93 (flood).

2. Test case for ZoneBudget (Harbaugh, 1990)

This example compares (a) MODFLOW results that accompany the test case (zbtest_m.Lst) with results written by MODSWB96 (zbtest.prn); and (b) ZoneBudget results (zbtest.Lst) with those written by the postprocessing package Modpost called by MODSWB96.

The following is the response file to run MODSWB96 (Repub. R. Basin model).

```
         1         2         3         4         5         6
123456789012345678901234567890123456789012345678901234567890

zbtest                                              case name
zbtest                                              BAS 5 zbtest.bas
zbtest                                              BCF 11 zbtest.bcf
zbtest                                              WEL 12 zbtest.wel
zbtest                                              DRN 13 zbtest.drn
zbtest                                              RCH 18 zbtest.rch
zbtest                                              SIP 19 zbtest.sip
zbtest                                              OC  22 zbtest.oc
zbtest                                              DATA(BINARY) 30 zbtest.bud
zbtest                                              POS 24 zbtest.pos ("postprocessor"
input data)
```

File zbtest.bas (below) was changed (iunit(15) on line 4, cols. 43-45) to invoke MODPOST:

```
1         2         3         4         5         6
123456789012345678901234567890123456789012345678901234567890

SAMPLE----3 LAYERS, 15 ROWS, 15 COLUMNS; STEADY STATE; CONSTANT HEADS COLUMN 1,
LAYERS 1 AND 2; RECHARGE, WELLS AND DRAINS
         3        15        15         1         1
 11 12 13  0  0  0  0 18 19  0  0 22       24
         0         0         0    IAPART,ISTRT,izone
         1         1(15I3)                       3    IBOUND-1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
         1         1(15I3)                       3    IBOUND-2
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
 -1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
         0         1                                  IBOUND-3
    999.99
         0        0.                                  HEAD-1
         0        0.                                  HEAD-2
         0        0.                                  HEAD-3
    86400.         1        1.     PERLEN,NSTP,TSMULT
```

The MODPOST package reads input file zbtest.pos (below) to define the budget zones using MODFLOW's standard 2-d array input format, which is similar but not identical to the format of program ZONEBUDGET's input file zbtest.zon. File zbtest.pos follows:

```
1         2         3         4         5         6
123456789012345678901234567890123456789012345678901234567890

s       sec (show time in sec, min, hrs, days, or yrs?)
r       write file of [R]ates, cumulative [V]olumes, or [N]either?
0  4    numser=no. time series, iopzon=no. budget zones (FREE format)
        24         1(15I2)                     3    IBOUND-1 (c,r,1)=(5,15,3)
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1
        24         1(15I2)                     3    IBOUND-2 (c,r,1)=(5,15,3)
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
 4 2 2 2 2 2 2 2 2 2 2 2 2 2 2
         0         3                             3    IBOUND-3 (c,r,1)=(5,15,3)
0,0,1,1 istper,idform,idaxis,islice
```

Results (excerpts from budget summary on output file zbtest.prn; set ibudfl = 3 in *.oc):

```
         1         2         3         4         5         6         7         8         9
10        11        12
123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
123456789012345678901234567890

1                    U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER MODEL
0SAMPLE----3 LAYERS, 15 ROWS, 15 COLUMNS; STEADY STATE; CONSTANT HEADS COLUMN 1, LAYERS 1
AND 2; RECHARGE, WELLS AND DRAINS
    3 LAYERS        15 ROWS          15 COLUMNS
   1 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS SECONDS
0I/O UNITS:
 ELEMENT OF IUNIT:   1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
         I/O UNIT:  11 12 13  0  0  0  0 18 19  0  0 22  0  0 24  0  0  0  0  0  0  0  0  0

 Volumetric budget summary for zones 1 to  4 AT END OF TIME STEP  1 IN STRESS PERIOD  1

 Flow between zones, vbznfl(i,col,row): i=1(in) or 2(out);
 columns: adjacent zones;  rows:    zone of control volume (c.v.)
 cells       0         210         210         225          30
 zone       0           1           2           3           4
    1
 in   0.0000      0.0000       7.590      0.0000      0.0000
 out  0.0000      0.0000       30.09      0.0000       42.58
    2
 in   0.0000       30.09      0.0000       5.844      0.0000
 out  0.0000       7.590      0.0000       15.69       2.648
    3
 in   0.0000      0.0000       15.69      0.0000      0.0000
 out  0.0000      0.0000       5.844      0.0000       4.850
    4
 in   0.0000       42.58       2.648       4.850      0.0000
 out  0.0000      0.0000      0.0000      0.0000      0.0000

 ZONE  TOTAL   ADJ ZONES         STO         CON         WEL         DRN         RCH
    1
 in     165.1      7.590      0.0000      0.0000      0.0000      0.0000       157.5
 out    165.1      72.67      0.0000      0.0000       60.00       32.42      0.0000
    2
 in     35.93      35.93      0.0000      0.0000      0.0000      0.0000      0.0000
 out    35.93      25.93      0.0000      0.0000       10.00      0.0000      0.0000
    3
 in     15.69      15.69      0.0000      0.0000      0.0000      0.0000      0.0000
 out    15.69      10.69      0.0000      0.0000       5.000      0.0000      0.0000
    4
 in     50.08      50.08      0.0000      0.0000      0.0000      0.0000      0.0000
 out    50.08     0.0000      0.0000       50.08      0.0000      0.0000      0.0000
 TOTAL
 in     157.5                 0.0000      0.0000      0.0000      0.0000       157.5
 out    157.5                 0.0000       50.08       75.00       32.42      0.0000


                             Volumetric budget for zone 1 AT END OF TIME STEP  1 IN STRESS PERIOD  1 (    210 grid cells)
                             ---------------------------------------------------------------------------------
0                  CUMULATIVE VOLUMES      L**3                                      RATES FOR THIS TIME STEP      L**3/T
                   ------------------                                                ------------------------

                         IN:                                                               IN:
                         ---                                                               ---
                             STORAGE =    0.00000                                              STORAGE =    0.00000
                       CONSTANT HEAD =    0.00000                                        CONSTANT HEAD =    0.00000
                               WELLS =    0.00000                                                WELLS =    0.00000
                              DRAINS =    0.00000                                               DRAINS =    0.00000
                            RECHARGE =    0.13608E+08                                         RECHARGE =     157.50
0                FROM ADJACENT ZONES =    0.65575E+06                              FROM ADJACENT ZONES =     7.5897
0                           TOTAL IN =    0.14264E+08                                         TOTAL IN =     165.09
0                       OUT:                                                              OUT:
                        ----                                                              ----
                             STORAGE =    0.00000                                              STORAGE =    0.00000
                       CONSTANT HEAD =    0.00000                                        CONSTANT HEAD =    0.00000
                               WELLS =    0.51840E+07                                            WELLS =     60.000
                              DRAINS =    0.28011E+07                                           DRAINS =     32.420
                            RECHARGE =    0.00000                                             RECHARGE =    0.00000
0                  TO ADJACENT ZONES =    0.62785E+07                                TO ADJACENT ZONES =     72.667
0                          TOTAL OUT =    0.14264E+08                                        TOTAL OUT =     165.09
0                           IN - OUT =     208.00                                             IN - OUT =    0.23804E-02
0                PERCENT DISCREPANCY =                0.00                         PERCENT DISCREPANCY =
0.00
```

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

                           IN:                                                                    IN:
                           ---                                                                    ---
                             STORAGE =   0.00000                                                   STORAGE =   0.00000
                       CONSTANT HEAD =   0.00000                                             CONSTANT HEAD =   0.00000
                               WELLS =   0.00000                                                     WELLS =   0.00000
                              DRAINS =   0.00000                                                    DRAINS =   0.00000
                            RECHARGE =   0.13608E+08                                              RECHARGE =    157.50
0                           TOTAL IN =   0.13608E+08                                              TOTAL IN =    157.50
0                        OUT:                                                                    OUT:
                         ----                                                                    ----
                             STORAGE =   0.00000                                                   STORAGE =   0.00000
                       CONSTANT HEAD =   0.43265E+07                                         CONSTANT HEAD =    50.075
                               WELLS =   0.64800E+07                                                 WELLS =    75.000
                              DRAINS =   0.28011E+07                                                DRAINS =    32.420
                            RECHARGE =   0.00000                                                  RECHARGE =   0.00000
0                          TOTAL OUT =   0.13608E+08                                             TOTAL OUT =    157.50
0                           IN - OUT =    397.00                                                  IN - OUT =   0.45929E-02
0                PERCENT DISCREPANCY =                0.00                             PERCENT DISCREPANCY =
0.00

          TIME SUMMARY AT END OF TIME STEP  1 IN STRESS PERIOD  1
                                SECONDS        MINUTES        HOURS          DAYS           YEARS
                            ----------------------------------------------------------------------------

       TIME STEP LENGTH         86400.0        1440.00        24.0000        1.00000       0.273785E-02
     STRESS PERIOD TIME         86400.0        1440.00        24.0000        1.00000       0.273785E-02
  TOTAL SIMULATION TIME         86400.0        1440.00        24.0000        1.00000       0.273785E-02
```

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Appendix A: SWAT input data format (manual supplement)

This was written to be a supplement to SWAT's manual (v. 2), added to Chapter 3 as Section 3.4, describing the format for input data files read by SWAT. Input files are described roughly in order of their appearance in Sections 3.1 and 3.2 of the SWAT manual, which summarizes the contents of all input and output files associated with program SWAT. This also describes changes and additions to input file format and to SWAT program procedures as described below.

3.4. Preparing input data for Swat without an operational GIS front end

This format description is especially useful for creating and modifying input data files for SWAT if a preprocessor is not available to handle the formats. A preprocessor for SWAT is available that is based on the GRASS system, a public domain graphical information system (GIS). However, Arc-Info is used at the University of Kansas, Kansas Geological Survey, and the Kansas state agencies that have an interest in SWAT and its connection to MODFLOW. A preliminary version of a preprocessor for SWAT based on Arc-Info has been developed (L. Bian, personal communication). However, the scope of that project has thus far been limited to the original SWAT (v. 2) program, and has not considered changes made to SWAT input for some of the reasons mentioned below.

3.4.1. Summary of changes to Swat94.2

a) Input data file changes

Input file formats are for the most part in original Swat (v. 2) format, with some exceptions. The codes data file (~.cod) includes options relevant to our revision of Swat and its linkage with Modflow. The general basin file (~.bsn) was changed to correct a problem in v. 2's initialization of soil moisture profiles. Formats for the soils data files (~.sol) and weather data files (rf and tmp) were changed back to those used in v. 1 of Swat. This change was made partly in order to allow data files made for v. 1 to be used in both versions, thereby making comparison of results easier; but also in part to remedy apparent bugs in v. 2 as described below, or to make file handling easier for the user, e.g. an option to read weather data either from one file for all stations or from individual files for each station.

b) Addition of log files to track data input:

1. Swat.Log, unit iolog=81, to which a log is written of input file openings and readings during program execution; opened in Main and written in Main, Open, Open2, Open3, Read, Readinpt.
2. Weather.Log, unit iomeas=82, to which a record is written showing rainfall for each station for rainy days only; opened in Main and written in Clicon.

c) Compile-time bugs under Lahey Fortran (likely allowed by Microsoft Fortran)

1. **blockd**: comment out data statements for variables with the prefix "thr" not in common.
2. comment out **$debug** in **main**, **readinpt**, **subbasin**, **swata-e**.

3. **main**: fix 12301 format (ln 266) by adding a comma to separate fields.
4. **swata-e**: subr **apply** (ln 73) and **clgen4** (ln 141): fix illegal transfers from outside a **do** range into the range.
5. **swatp-r**: comment out data statements for the following arrays in subr **resis**: storec, releasec, storek, releasek, and initialize them in block data (file **blockd.for**)

d) Execution time bugs:

1. General basin (**bsn**) data bug: input variable **ffcb** is read but is not passed from subr **read** to **readinpt**, where it is used, and it is not used properly in **readinpt**; a description of the bug and correction follows.

General basin input variable **ffcb**, called ffc in Swat manual, is supposed to allow specifying a nonzero initial fraction of field capacity; if input as zero, then an initial fraction is calculated on the basis of the rainfall statistics file (wgn). However, in the original source code for Swat (v. 94.2), ffcb was not passed from Read to Readinpt, and Readinpt did not handle ffcb properly anyway.

The fraction of field capacity calculation was revised to do what was apparently intended, which is to base it on avg annual rainfall (r(8)=sum of smy, above), to be overridden by fraction ffcb read from file ~.bsn, subr Read. ffc in '93 version was passed from Read() to Readinpt() via arg lists. For '94.2 version, ffc expanded to subbasin resolution and moved to common; ffc was changed to ffcb in Read(), but ffcb was not passed to Readinpt().--spp jun 95

2. **weather** (rf and tmp) data bug: daily rainfall and temperatures from multiple stations were not read and assigned properly to subbasins; a description of this bug and correction follows.

2. weather (rf and tmp) data bug: daily rainfall and temperatures from multiple stations were not read and assigned properly to subbasins in the '94.2 version. The weather data reading code in Clicon was changed (by ARS) from a form in the '93 version that worked to one that does not appear to work for multiple weather stations in the '94.2 version, so the code from Swat's '93 version was used instead to read one daily rainfall value per record and two daily temperature values (max and min). The (5x,2f10.1) format used here (5000 format) is the same as the '93 version's 10300 format. --spp jun 11 95, KGS

3. Soils data (sol)

The '93 version of silt percentage SIL as read from the soils input files (~.sol) appears to have included clay, but in the '94 version the SIL just includes silt. For example, the Swat Y7 test case shows apparently unchanged data from the '93 version, with SIL=92; results for this case show a negative sand percentage, which is calculated by sand = 100 - (silt + clay).

Soils input data are read according to the same format used in the '93 program version, and not the form provided by the Runsoil program, which extracts soils data from database files; see soil hydraulics (~.sol) data file description.

4. Certain conditions result in the Swat program to reference zero-valued array indices, notably in subr crpmd and one or two others. These were encountered during execution as a result of routinely using Lahey Fortran's bounds checking option for compiling all source files, and verified by successful execution without the bounds

checking option for the routines where the error occurred. This problem was remedied by checking for zero-valued indices in these subroutines, rather than allowing the condition to occur by executing without bounds checking.

e) Swat program user manual bugs

Certain equations were found to be incorrect in the manual, including equations (103) and (108). The coding of these equations in the program is consistent with their expression in SWWRB by Arnold et al., 1990. This indicates that the remainder of the manual's model description should be compared with the book's description for consistency.

3.4.2. Specifying a Swat case with files (~.cio) and options (~.cod)

The file named "file.cio" specifies most file names associated with a particular simulation case to be run, and is read on device number 2 by Swat routines Open, Main and Open2. Certain other file names associated with Swat-Modflow coordination and Swat revisions are specified on the ~.cod file. In both cases, file names of up to 13 characters in length are read from these input files. Regarding weather files, option iopwfl on the ~.cod file allows all precipitation data stations to be read from the same file, and similarly for temperature data stations. See also added option iopwea (~.cod file) to read daily values for solar radiation, relative humidity, and wind speed.

cio(2): Swat input control "file.cio" (Open, Main, Open2) ex. corn90dc.cio

part 1 in subr open (on source file swatf-o.for):

```
      open (70,file='kevin.out',status='unknown')
      open (2,file='file.cio')
      3 lines of text for a case description:
read (2,'(20a4)') (title(j),j=1,60)                                    (1
      basin file names:
read (2,'(6a)') stdout,sbsout,rchout,rsvout,lwqout,pestout             (2
read (2,'(6a)') event,cropdb,tilldat,pestidat,codedat,basndat          (3
read (2,'(6a)') lwqdat,routin,statin,bigsub,watqal,wqout               (4
open files:
(3,sbsout) (8,rchout);(1,rsvout); (4,lwqout); (5,pestout); (6,stdout);
(7,event); (10,codedat); (11,basndat) (77,bigsub);(14,lwqdat)
(9,routin);
(15,cropdb=crop.dat: crop data base);
(16,tilldat=till.dat: tillage data base);
(17,pestidat=pest.dat: pesticide data base)
```

part 2 in main (main.for)

```
      no. rainfall and temperature gaging stations (see notes on options
      iopwfl and iopwea, above):
read (2,'(2i4,1x,a)') nrgage, ntgage                                   (5
      18 fields for precipitation file names: (3 records):
read (2,'(6a13)') (rfile(j),j = 1,18)                                  (6
      18 fields for temperature file names: (3 records):
read (2, '(6a13)') (tfile(j),j = 1,18)                                 (7
      18 fields for reservoir file names: (3 records):
read (2, '(6a13)') (resvo(j),j = 1,6)                                  (8
```

part 3 in subr open2 (swatf-o.for)

```
For each subbasin I=1 to Lu:
    read (2,'(i4,i2,i4,i2,i3,5a)') isb, id2, id6, id8, icnty,          (9
     1        subdat, routdat, ponddat,chemdat, soildat
    read (2, '(2x,4a,2i4)') mgtdat, mcodat, gwdat, wgendat,           (10
     1    irgage(i), itgage(i)
open (10,subdat); (11,routdat); (12,ponddat); (13,chemdat);
(14,soildat); (17,mgtdat); (18,mcodat); (19,gwdat); (20,wgendat)
end do
```

Example corn90dc.cio (rename as file.cio for execution)

```
Rattlesnake Creek Watershed: 29 subbasins  corn90dc.cio: decoupled ET(ioprev=0)         (1
corn-fallow rotation: cornfall.mgt; stress factor=0.90, ioplim=1,iopwea=1
oct 26 95 ponds, 5% noncontributing area; k=1 mm/h 1960-1993: 34 yrs
 corn90dc.std   case23.sbs      rat.rch      rat.rsv      rat.1qo    rat.pso            (2
      rat.eve     crop.dat     till.dat     pest.dat corn90dc.cod    snake.bsn          (3
      rat.1wq      rat.fig      rat.sta      rat.bsb                                    (4
   8   6  ,nrgage, ntgage                                                               (5
   rs6093.pcp                                                                           (6


      all.tmp                                                                           (7

                                                                                        (8
   1 0   0 0  0    rat01.sub    rat01.rte    p5011.pnd chemical.chm  pratt.sol          (9
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         1   2                           (10
   2 0   0 0  0    rat02.sub    rat02.rte    p5012.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         1   2
   3 0   0 0  0    rat03.sub    rat03.rte    p5013.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         1   2
   4 0   0 0  0    rat04.sub    rat04.rte    p5014.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         3   2
   5 0   0 0  0    rat05.sub    rat05.rte    p5015.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         3   2
   6 0   0 0  0    rat06.sub    rat06.rte    p5016.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         3   2
   7 0   0 0  0    rat07.sub    rat07.rte    p5017.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         3   2
   8 0   0 0  0    rat08.sub    rat08.rte    p5018.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   2
   9 0   0 0  0    rat09.sub    rat09.rte    p5019.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   2
  10 0   0 0  0    rat10.sub    rat10.rte   p50110.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         5   2
  11 0   0 0  0    rat11.sub    rat11.rte   p50111.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         5   4
  12 0   0 0  0    rat12.sub    rat12.rte   p50112.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   6
  13 0   0 0  0    rat13.sub    rat13.rte   p50113.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   4
  14 0   0 0  0    rat14.sub    rat14.rte   p50114.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   4
  15 0   0 0  0    rat15.sub    rat15.rte   p50115.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         5   4
  16 0   0 0  0    rat16.sub    rat16.rte   p50116.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   6
  17 0   0 0  0    rat17.sub    rat17.rte   p50117.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   4
  18 0   0 0  0    rat18.sub    rat18.rte   p50118.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   6
  19 0   0 0  0    rat19.sub    rat19.rte   p50119.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         8   5
  20 0   0 0  0    rat20.sub    rat20.rte   p50120.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         6   5
  21 0   0 0  0    rat21.sub    rat21.rte   p50121.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
  22 0   0 0  0    rat22.sub    rat22.rte   p50122.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
  23 0   0 0  0    rat23.sub    rat23.rte   p50123.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
  24 0   0 0  0    rat24.sub    rat24.rte   p50124.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
  25 0   0 0  0    rat25.sub    rat25.rte   p50125.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         6   5
  26 0   0 0  0    rat26.sub    rat26.rte   p50126.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
  27 0   0 0  0    rat27.sub    rat27.rte   p50127.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
  28 0   0 0  0    rat28.sub    rat28.rte   p50128.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         2   1
  29 0   0 0  0    rat29.sub    rat29.rte     p501.pnd chemical.chm  pratt.sol
      3-wsf.mgt    rat90.mco     rat.gw rat.wgn         4   3
```

3.4.3. Data base input files (~.dat, read by subr Readinpt)

<u>dat(15): Crop data base file crop.dat</u>

Example (excerpt from crop.dat):

```
 1  SOYB    25.0     .30    25.0    10.0     5.0     .90  15.010  50.950     1.0
     1.0     3.0   .0100     .85    35.0      .8    2.00  660.31    .200   .0650
   .0091    .220     .60    .330  370.00    .130   .0524   .0265   .0258   .0074
   .0037   .0035   1.266    .633    .729      1.   5.010   15.95    5.00     .50
    4.75    1.00    0.40    0.20   52.20    1.00
 2  CORN    40.0     .50    25.0     8.0     5.0     .80  15.050  50.950  1.0000
    1.00     3.0   .0070     .85    20.0     2.0    2.00  660.44    .200   .0175
   .0025     .01     .60   2.510  100.00    .150   .0440   .0164   .0128   .0062
   .0023   .0018    .433    .433    .213      4.   5.010   15.95    8.00     .50
    4.75    2.00    0.40    0.20   47.60   1.000
```

```
c****icnum = crop number
c     cpnm = crop name
c     be = biomass-energy ratio
c     hi = harvest index
c     to = optimal temperature for plant growth degrees c
c     tb = base temperature for plant growth degrees c
c     blai = max lai for subbasin j
c     dlai = fraction of growing season when leaf area declines
c     dlp1 = 1st point on optimal leaf development curve
c     dlp2 = 2nd point on optimal leaf area development curve
c     gsi = maximum stomatal conductance
c     chtmx = maximum canopy height (m)
c     rdmx = maximum root depth(m)
c     pt2 = co2 concentraion in future atmosphere/resulting WA value
c     cvm = minimum value of C factor for water erosion
c     wsyf = water stress yield factor
c     wvap = parm relating vapor press deficit to WA
c     vpth = threshold VPD (SPA) (F=1.)
c     vpd2 = VPD  value (KPA) / F2  1
c     ird = vegetation for crop (1) annual (2) perennial

* Alternative reading using a text buffer incrop for debugging:
      do 1112 ic = 1, mcrdb
        write (iolog,'(/,1x,a,i3)') 'ic=',ic
        do j=1,5
            read (15,'(a)') incrop(j)
            if (j.eq.1) print '(1x,a)',incrop(j)(1:16)
        end do
        read (incrop(1),'(i2,2x,a4,8f8.3)')
     1      icnum(ic), cpnm(ic), be(ic), hi(ic), to(ic),
     *      tb(ic), blai(ic), dlai(ic), dlp1(ic), dlp2(ic)
        read (incrop(2),'(16x,f8.3,16x,4f8.3)')
     *      gsi(ic), chtmx(ic), rdmx(ic), pt2(ic), cvm(ic)
        read (incrop(3),'(8x,f8.3)') wsyf(ic)
        read (incrop(4),'(64x,2f8.3)') wavp(ic), vpth(ic)
        read (incrop(5),'(f8.3,64x,i8)') vpd2(ic), ird(ic)
* spp  The above replaces this previous, more obscured version:
*spp    read (15,1111) icnum(ic), cpnm(ic), be(ic), hi(ic), to(ic),
*spp *      tb(ic), blai(ic), dlai(ic), dlp1(ic), dlp2(ic),
*spp *      gsi(ic), chtmx(ic), rdmx(ic), pt2(ic), cvm(ic),
```

```
*spp *       wsyf(ic),
*spp *       wavp(ic), vpth(ic),
*spp *       vpd2(ic), ird(ic)
 1111    format (i2,2x,a4,8f8.3,/,16x,f8.3,16x,4f8.3,8x,/,8x,f8
     *       .3,64x,/,64x,2f8.3,/,f8.3,64x,i8)
```

Calculations after reading crop.dat:

```
        cvm(ic) = alog(cvm(ic))
        if (be(ic).gt.0.) then
        temp = vpd2(ic) - int(vpd2(ic))
        vpd2(ic) = (1.-vpd2(ic)) / (temp-vpth(ic))
        vpd2(ic) = -1. / vpd2(ic)
        wac21(ic) = be(ic) * .01
        co21 = 330.
        co22 = pt2(ic)
        wac22(ic) = pt2(ic) - int(pt2(ic))
        call ascrv(wac21(ic),wac22(ic),co21,co22)
        pt1max = .01 * int(dlp1(ic))
        pt2max = .01 * int(dlp2(ic))
        dlp1(ic) = dlp1(ic) - int(dlp1(ic))
        dlp2(ic) = dlp2(ic) - int(dlp2(ic))
        call ascrv(dlp1(ic),dlp2(ic),pt1max,pt2max)
```

dat(16): Tillage data base file till.dat

Example (excerpt from till.dat):

```
   1    LISTRPLT   19.77     .15    10.00    40.00    75.00     1.00     .00     .00
   2    ROW PLT    20.00     .05     5.00    60.00    10.00      .86     .00     .00
   3    PLANT DR   17.54     .25    10.00    40.00    25.00      .17     .00     .00
   4    TRSPLANT   19.77     .15    10.00   500.00    75.00     1.00     .00     .00
   5                 .00     .00      .00      .00      .00      .00     .00     .00
   6    INJECT-P     .00     .00      .00     75.0      .00      .00     .00     .00
   7                 .00     .00      .00      .00      .00      .00     .00     .00
   8                 .00     .00      .00      .00      .00      .00     .00     .00
   9    IRSTRSCH     .00     .00      .00      .00      .00      .00     .00     .00
  10    SPREADER    7.66     .00      .00      .00      .00      .00     .00     .00
  11    SPRAYER     6.80     .00      .00      .00      .00      .00     .00     .00
  12    ANHYD AP    4.94     .15    13.00    75.00    25.00      .30     .00     .00
  13    --------     .00     .00      .00      .00      .00      .00     .00     .00
  14    --------     .00     .00      .00      .00      .00      .00     .00     .00
  15    LISTER      9.14     .80    25.00   100.00   150.00     1.00     .00     .00
  16    DISK BED    9.74     .70      .00   100.00    75.00     1.00     .00     .00
  17    ROWBUILD     .00     .50    15.00   350.00   300.00     1.78     .00     .00
  18    CULTPACK     .00     .10     5.00    40.00    25.00     1.78     .00     .00
  19    ROW CULT   13.52     .30    15.00    25.00   100.00     1.00     .00     .00
  20    FLD CULT   12.36     .30     6.00    50.00    25.00      .25     .00     .00
```

```
c***itnum = tillage number
c     till = tillage name
c     effmix = mixing efficiency of operation
      do 1113 it = 1, 83
        read (16,1114) itnum(it), till(it), effmix(it)
 1114   format (i4,4x,a8,8x,f8.3)
 1113 continue
```

dat(17): Pesticide data base file pest.dat

Example (excerpt from pest.dat):

```
  1 Aldrin             20000.0     .05     2.0    28.0    0.75     0.1
  2 Balan              10700.0    1.00    24.0    24.0    0.75    50.0
  3 Banvel                 8.0     .65     9.0     8.0    0.75  4500.0
  4 Basagran              35.0     .60     2.0    10.0    0.75500000.0
  5 Benlate              200.0     .25     6.0    10.0    0.75     0.1
  6 Benzex             55000.0     .05     3.0   600.0    0.75     0.1
  7 Bidrin                20.0     .70    20.0     7.0    0.75 10000.0
  8 Bladex               168.0     .60     2.0    14.0    0.75   165.0
  9 Bolstar              550.0     .55     0.5    14.0    0.75    45.0
 10 Bravo               4000.0     .50    10.0    18.0    0.75     0.6
 11 Carbofos            1800.0     .90     3.0    25.0    0.75   145.0
 12 Chlordane         100000.0     .05     2.5   100.0    0.75     0.1
 13 Cotoran              100.0    1.00    12.0    12.0    0.75    90.0
 14 Counter             1000.0     .60     2.5     5.0    0.75    15.0
 15 Cygon                  9.0     .95     3.0     7.0    0.75 25000.0
 16 2,4-D                 74.0     .45     9.0    10.0    0.75   900.0
 17 Dasanit            10000.0    1.00    24.0    24.0    0.75     .01
 18 DDT               240000.0     .05     4.0   120.0    0.75     0.1
 19 DEF                 5000.0     .25     7.0    10.0    0.75     1.0
 20 Dieldrin           50000.0     .05     5.0  1400.0    0.75     0.1
```

```
c*****pnum = pesticide number
c     pname = pesticide name
c     skoc = soil partition coefficient
c     wof = wash off fraction
c     hl = half-life on foliage(days)
c     skk = half-life on ground (days)
c     efa = application efficiency
c     wsol = water solubility(ppm)
      do 1115 ip = 1, mpdb
        read (17,1116) ipnum(ip), pname(ip), skoc(ip), wof(ip), hl(ip),
     *        skk(ip), efa(ip), wsol(ip)
 1116   format (i3,a16,f11.1,f8.2,2f8.1,f8.2,f8.1)
        hl(ip) = exp(-.693/hl(ip))
        skk(ip) = exp(-.693/skk(ip))
        pab(ip) = 0.
 1115 continue
```

3.4.4. Daily weather input data (subr Clicon)

Input file names for daily rainfall and temperature measurements are given on the input control file (File.cio), which also associates measurement stations with subbasins. Input format for temperature, precipitation, radiation, relative humidity and wind speed are specified by records 5-7 on the options input control file (~.cod); an example is shown below. The options input control file also includes a choice, **iopwea**, to read precipitation data from separate files for each station or all stations from one file; and similarly for temperature data.

Weather data are either read (subr Clicon) or generated (subroutines Clicon, CLGEN4, Alpha9). Case control input File.cio (above) contains the number of rain (nrgage) and temperature (ntgage) stations, and the names of daily precipitation and temperature data files, which are read from devices rf(9+*k*) for *k*=1 to **nrgage** and tmp(27+*k*) for *k*=1 to **ntgage** in subr Clicon. Option **iopwfl** (see options input file ~.cod) allows all rainfall data to be read from one file, and all temperature data on another. If data are missing,daily values are generated by subroutines Clicon, Clgen4, and Alpha9 (which estimates fraction of total rainfall in 1/2 hour). See also notes on input bug fixes below.

In SWAT's standard version, daily radiation, relative humidity, wind speed and [CO2] are only simulated (subr CLGEN4). With added option **iopwea** (~.cod file), daily values for the first three of these can be read from a data file.

Daily weather values for subbasin k:	read?	generate?	options (*)
subp(k) = rainfall (mm)	yes	yes	1
tmx(k) maximum temperature (deg C)	yes	yes	1
tmn(k) minimum temperature (deg C)	yes	yes	1
ra(k) radiation (langleys)	yes(*)	yes	2
rhd(k) relative humidity	yes(*)	yes	2
wind speed	yes(*)	yes	2
co2(k) carbon dioxide conc?		yes	

(*) Note on options **iopwfl**(1) and **iopwea**(2):

The options input file corn90dc.cod specifies (with **iopwfl**>0) that precipitation and temperature data are to be consolidated into one file each for pcp and tmp; and (with **iopwea**>0) that solar radiation, relative humidity, and wind speed are to be read from file sand6092.rad. Input format for weather data files are given on the options input file as follows (which may also be given as 'FREE'):

```
(5x,12f5.0)            temperature data format (file all.tmp)          (5
(4x,8f6.0)             rainfall data format (file rs6093.pcp)          (6
(14x,f5.0,12x,2f6.0)   rad(ly/d), relhum(%), wind(m/s) (sand6092.rad) (7
```

Input control codes **nsim** and **msim** (read in ~.cod) control rain and temperature input as follows (for daily rainfall input) and msim (for daily max and min temperature input):

1 or 2: read or simulate , respectively, for entire basin
3 or 4: read or simulate, respectively, for each sub-basin

If a daily value < -97 is read, then it is replaced by a simulated value (subr CLGEN4); see also note on weather (rainfall and temperature) input data file bug (p. 88).

Theissen polygon weights

The following Theissen polygon weight data are not read by Swat from this data file or otherwise used, but were originally used to avg precip & temp stations for each subbasin, and are included for historical reference.

```
  2  1  4       0.589 0.411                PRECIP  1  belle conwt
```

```
1  4          1.                                2  conw
3  3  7  4    0.441 0.309 0.249                 3  clif milv conw
3  3  6  1    0.484 0.372 0.144                 4  clif hadd bell
2  3  6       0.852 0.148                       5  clif hadd
2  3  6       0.600 0.400                       6  clif hadd
4  3  9  5  2 0.488 0.198 0.154 0.151           7  clif wash fact clay
2  2  7       0.540 0.459                       8  clay milv
3  2  5       0.647 0.353                       9  clay fact
2  1  3       0.685 0.315               TEMP    1 bell conc
1  3          1.0                               2 conc
2  3  2       0.722 0.278                       3 conc clay
2  1  3       0.551 0.449                       4 bell conc
4  3  4  2  1 0.412 0.281 0.192 0.115           5 conc wash clay belle
2  4  2       0.846 0.154                       6 wash clay
2  2 7        0.491 0.509                       7 clay wash
1             1.0                               8 clay
1             1.0                               9 clay
```

tmp(27+k): Read daily temperature min and max (ex. file all.tmp)

```
          if (iopwfl.eq.0) then
            do k=1,ntgage
              if (itfree.gt.0) then
                read (27+k,*) txmeas(k),tnmeas(k)
              else
                read (27+k,fmttmp) txmeas(k),tnmeas(k)
              end if
            end do
          else
            if (itfree.gt.0) then
                read (27+1,*) (txmeas(kfld),tnmeas(kfld),
     1                kfld=1,ntgage)
            else
                read (27+1,fmttmp) (txmeas(kfld),tnmeas(kfld),
     1                kfld=1,ntgage)
            end if
          end if
```

Example: temperature input file all.tmp (excerpt)

Format: (5x,12f5.1)

Contents: year; (tmn(j),tmx(j),j=1,6)

Begin:

```
1960   3.3 -1.1  8.9  -.6  8.9   .6  7.8  -.6  8.9 -1.1 10.0  1.7
1960  -1.1 -7.2  1.1 -8.3  1.7 -7.2   .6 -8.3 -1.1 -7.8  2.8 -7.2
1960  -2.2-10.0  2.2-10.6  -.6 -9.4   .6-10.0   .6 -9.4   .6-10.0
1960    .0-11.7   .6-12.2   .0-10.6   .6-12.2  -.6-12.8  1.1-12.2
1960  -2.8 -8.9  -.6 -8.9 -2.2 -8.9 -1.7 -9.4  2.8 -8.9 -1.7 -8.3
1960   9.4 -7.8  8.9 -9.4  8.9 -8.3  8.9 -9.4  8.3 -8.3  9.4 -8.9
1960  12.2 -5.0 13.3 -6.7 11.7 -5.0 13.9 -5.0 11.7 -3.9 15.0 -6.1
1960  13.3 -3.9 14.4 -4.4 12.2 -3.9 14.4 -5.6 12.8 -5.0 11.7 -6.1
1960   8.9 -3.9 16.1 -3.9 11.7 -3.3 14.4 -5.6 11.7 -3.9 15.0 -3.9
1960  10.0 -3.9 13.3 -3.9 11.7 -3.3 11.7 -4.4 10.6 -3.3 12.2 -3.3
1960  13.3 -1.7 13.9 -2.2 13.3 -1.7 13.9 -1.7 12.2 -2.2 13.3 -1.1
1960  14.4  7.2 15.6  7.8 15.6  7.8 14.4  7.2 13.9  6.1 18.3  9.4
1960   7.2  1.1  7.8  -.6  7.8  2.8  7.2   .0  6.7   .0 10.0  2.8
1960   3.9 -5.6  5.0 -5.0  5.6 -5.0  5.6 -3.9  5.6 -5.0  8.9 -2.8
1960  -3.9 -7.8  1.1 -6.1 -2.2 -6.7  -.6 -5.6 -1.7 -8.3   .6 -5.0
1960  -2.2-10.0 -2.2 -7.8 -1.7 -9.4 -2.8 -8.9 -2.2 -9.4 -1.1 -7.8
```

```
1960  -3.3 -9.4 -2.2-11.1 -1.7 -8.3 -2.8 -9.4 -2.2-11.1 -1.1 -7.2
1960  -7.8-12.2 -8.9-13.3 -7.2-12.2 -7.2-13.3 -5.6-12.8 -6.7-12.2
1960  -5.6-15.6 -4.4-17.8 -5.0-15.6 -2.8-16.1 -5.6-16.1 -3.9-16.1
1960  -3.3-16.1  -.6-17.2 -2.8-15.6 -1.1-17.2 -2.8-15.0  1.1-15.0
1960  -4.4-15.0  -.6-13.3 -3.3-13.3 -2.2-15.0 -2.2-13.3 -1.1-12.2
```

rf(9+k): Read daily precipitation (ex. file rs6093.pcp)

```
if (iopwfl.eq.0) then
  do k=1,nrgage
    if (irfree.gt.0) then
      read (9+k,*) rmeas(k)
    else
      read (9+k,fmtpcp) rmeas(k)
    end if
  end do
else
  if (irfree.gt.0) then
      read (9+1,*) (rmeas(kfld),kfld=1,nrgage)  ! -spp
  else
      read (9+1,fmtpcp) (rmeas(kfld),kfld=1,nrgage)  ! -spp
  end if
end if
```

Example: precipitation input data rs6093.pcp (excerpt)
Format: (i4,8f6.1)
(Format is specified by fmtpcp on input control file corn90dc.cod)
Contents: year; daily precipitation at eight stations:
Buckl Grbnd Grns Hudson Kinsley Larned Pratt Trusd
Begin:

```
1960   2.5   1.3   2.3   1.5   1.3   1.0   1.0    .8
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0   1.8   1.3    .0    .0    .0    .5    .5
1960    .0    .0    .0    .0   1.0   1.0    .0    .0
1960  18.8  26.7  26.2  20.3  22.9  20.1  24.1  23.4
1960   4.6   7.6    .0   5.1   4.1   2.5   2.5   2.3
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960  12.4  11.4  10.2   7.4  12.2   8.4   8.4   8.1
1960    .0   1.3    .0   2.8   2.3    .8   1.3    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
1960    .0    .0    .0    .0    .0    .0    .0    .0
```

rad: Read radiation, rel. humidity and wind speed (ex. file sand6092.rad)

These data are read subject to added option **iopwea** (see options file ~.cod); previously, Swat only generated these data as described in the Swat manual.

Whether read or generated, wind speed measurements are assumed by Swat to be taken 10 m above land surface (ALS). The measurement at 10 m is used in Swat as u_{10}(j) for subbasin j to evaluate evaporation in subr evap8 according to the Ritchie model as described in the Swat manual. From these, wind speed at 2 m ALS is estimated to be given by $u_2=f*u_{10}$ for a reduction factor f=0.749 according to a logarithmic wind speed profile described in Appendix E.

Read radiation (ly/d), relative humidity (pct) and wind speed (m/s) measured 10m above land surface (ALS):

```
if (iopwea.gt.0) then
    if (isfree.gt.0) then
        read (iorad,*) radmea,relhum,wndspd
    else
        read (iorad,fmtrad) radmea,relhum,wndspd
    end if
    if (relhum.gt.-97. .and. relhum.le.100.) relhum = relhum/100.
    do k=1,Lu
        if (radmea.gt.-97. .and. radmea.lt.9999.) ra(k) = radmea
        if (relhum.gt.-97. .and. relhum.lt.9999.) rhd(k) = relhum
        if (wndspd.gt.-97. .and. wndspd.lt.9999.) u10(k) = wndspd
    end do
end if
do j=1,Lu
    u2(j) = 0.749*u10(j)
end do
```

Example: radiation, rel. humidity and wind speed, sand6092.rad
Begin: (excerpt):

```
1  1 1960   1 203.    6.   -7.   97. 10.43    .0
1  2 1960   2 239.   -2.   -8.   75.  8.24    .0
1  3 1960   3 239.    0.   -9.   75.  5.00    .0
1  4 1960   4 166.    1.  -12.   90.  4.35    .0
1  5 1960   5 162.   -1.   -9.   87.  4.60    .0
1  6 1960   6 248.    7.   -9.   84.  5.02    .0
1  7 1960   7 233.   12.   -6.   67.  5.15    .0
1  8 1960   8 243.   13.   -1.   66.  5.32    .0
1  9 1960   9 248.   14.   -3.   85.  4.52    .0
1 10 1960  10 200.   10.   -2.   87.  4.73    .0
1 11 1960  11  73.   13.   -3.  100.  7.38    .0
1 12 1960  12 194.   12.    3.   96.  6.24   1.0
1 13 1960  13  70.    5.   -1.  100.  4.71   7.4
1 14 1960  14 147.    3.   -6.  100. 11.58  10.9
1 15 1960  15 255.   -1.   -9.   84.  7.19    .0
1 16 1960  16  40.   -3.   -9.   95.  4.37   5.8
1 17 1960  17 150.   -4.  -11.   92.  8.56   4.3
1 18 1960  18 187.   -9.  -14.   88. 11.58    .0
1 19 1960  19 266.   -7.  -18.   85.  6.08    .0
1 20 1960  20 276.   -2.  -16.   77.  5.13    .0
1 21 1960  21 258.   -6.  -13.   63.  5.95    .0
```

3.4.5. Basin input files

bsn(11): general basin input (subr Read); ex. snake.bsn

See note on input variable **ffcb** data bug fix (3.4.1, "Changes to Swat").

Example: general basin input file snake.bsn

```
Rattlesnake basin            file snake.bsn (approx.)                  (1
 5302.40    1.00    1.000    0.00     0.33   0   0   0                 (2
```

Instructions for general basin input

```
character*80 title
      real mumax, kl, kn, kp, lambda0, lambda1, lambda2
C     DA = BASIN AREA (KM**2)
C     P2=RAINFALL CORRECTION(RATIO OF AVE AN RAINFALL TO AVE AN FOR GAGE
C     TP5 = TP-40 10 YR FREQ .5H RAINFALL(MM)
C     TP6 = TP-40 10 YR FREQ 6H  RAINFALL(MM)
C     TP24= NO YRS RECORD MAX .5H RAIN
C     YLT = LATITUDE
C     BRT = BASIN LAG TIME(D)
C     FFC = FRACTION OF FIELD CAP--INITIAL WATER STORAGE (0. ALLOWS
C     SWRRB TO ESTIMATE FFC)
      read (11,'(a)') title                                          (1
      read (11,5000) da, p2(1), bff, brt, ffcb,(npno(k),k=1,10)      (2
5000 format (f10.3,f6.3,3f8.3,10i4)
      write (kw,5600) bff, brt ! baseflow factor, basin lag time (days)
      write (kw,6000) ign      ! generator cycles
      write (kw,5800) iwst, isst ! water stats, sediment stats
      write (kw,6100) k1, k2, k3, k4, k5, k6, k7, k8, k9  ! random seeds
      af = 1000. * da
      da9 = 100. * da
      if (brt.lt..01) brt = 1.
      brt = 1. - exp(-1./brt)
      uob = 1. - exp(-ub)
C     IF MULT RAINGAGES ARE TO BE GENERATED, READ CENTROID COORDINATES
C     OF SUB-BASINS (KM).  (reads are commented out)
CREAD
c     read (11,6500) (xij(i),i = 1,lu)
c     read (11,6500) (yij(i),i = 1,lu)
*
c spp   if (ffcb.eq.0) ffc(i) = xx / (xx+exp(9.043-.002135*xx))
* The above line is replaced by the code below, which assigns ffcb to
ffc(i) for positive-valued ffcb as presumably intended
        if (ffcb.gt.0.) then
            ffc(i) = ffcb
        else
            xx = r(8)
            ffc(i) = xx / (xx+exp(9.043-.002135*xx))
        end if
```

lwq(8): Lake water quality input (subr Readlk)

Input instructions:

```
Input for lake toxic balance and lake phosphorus balance:
C      CPEST1 = INITIAL PESTICIDE CONCENTRATION (MG/M3)
C      VREAC = REACTION COEFFICIENT              (1/DAY)
C      VVOL = VOLATILIZATION COEFFICIENT         (M/DAY)
C      VPART = PARTITION COEFFICIENT             (M**3/G)
C      VSETL = SETTLING VELOCITY                 (M/DAY)
C      VRSUP = RESUSPENSION VELOCITY             (M/DAY)
C      VMIX = MIXING VELOCITY (DIFFUSION)        (M/DAY)
       read (8,5300) cpest1, vreac, vvol, vpart, vsetl, vrsup, vmix
5300 format (10f8.3)
C      CPEST2 = INITIAL PESTICIDE CONCENTRATION IN BOTTOM
C      SEDIMENTS (MM/M3)
C      VREAC2 = REACTION COEFFICIENTS      (1/DAY)
C      VBURY  = BURIAL VELOCITY            (M/DAY)
C      DACT   = DEPTH OF ACTIVE SEDIMENT LAYER (M)
       read (8,5300) cpest2, vreac2, vbury, dact
C      VSETLP = PHOSPHORUS SETTLING RATE (M/DAY)
C      PHOSL  = INITIAL TOTAL PHOSPHORUS CONCENTRATION IN LAKE (mg/L)
       read (8,5300) vsetlp, phosl
C      ISUBL = SUBBASINS WEATHER TO USE IN LAKE BALANCE
       read (8,5700) isubl
5700 format (20i4)
C      UMW = AVERAGE MONTHLY WIND SPEED (M/S)
C      EFFLQ(12) = AVERAGE DAILY EFFLUENT FLOW BY MONTH (M3/DAY)
C      EFFLT(12) = AVERAGE TEMP OF EFFLUENT BY MONTH (DEG C)
C      FLOWT(12) = AVERAGE TEMP OF NATURAL INFLOW BY MONTH (DEG C)
C      TD(12) = AVE MONTHLY DEWPOINT POINT TEMP (DEG C)
C      TLAKE = INTIAL LAKE TEMP (DEG C)
       read (8,6500) (umw(i),i = 1,12)
       read (8,6500) (efflq(i),i = 1,12)
       read (8,6500) (efflt(i),i = 1,12)
       read (8,6500) (flowt(i),i = 1,12)
       read (8,6500) (td(i),i = 1,12)
       read (8,5300) tlake
6500 format (12f6.2)
```

fig(9): Watershed configuration input (Main); ex. file rat.fig

Example input file rat.fig:

```
subbasin       1     1     1     1
subbasin       1     2     2     2
subbasin       1     3     3     3
subbasin       1     4     4     4
dsubbasin       1     5     5     5
subbasin       1     6     6     6
subbasin       1     7     7     7
subbasin       1     8     8     8
subbasin       1     9     9     9
subbasin       1    10    10    10
subbasin       1    11    11    11
subbasin       1    12    12    12
subbasin       1    13    13    13
subbasin       1    14    14    14
subbasin       1    15    15    15
subbasin       1    16    16    16
subbasin       1    17    17    17
subbasin       1    18    18    18
subbasin       1    19    19    19
subbasin       1    20    20    20
subbasin       1    21    21    21
subbasin       1    22    22    22
subbasin       1    23    23    23
subbasin       1    24    24    24
subbasin       1    25    25    25
subbasin       1    26    26    27
subbasin       1    27    27    27
subbasin       1    28    28    28
subbasin       1    29    29    29
route          2    30     2     1
add            5    31     2    30
route          2    32     3    31
add            5    33     3    32
route          2    34     5    33
add            5    35     5    34
add            5    36     4    35
route          2    37     6    36
add            5    38     6    37
add            5    39     7    38
route          2    40     8    39
add            5    41     8    40
route          2    42     9    41
add            5    43     9    42
add            5    44    11    10
route          2    45    14    44
add            5    46    14    45
route          2    47    13    46
add            5    48    13    47
add            5    49    43    48
route          2    50    12    49
add            5    51    12    50
route          2    52    16    51
add            5    53    16    52
route          2    54    18    53
add            5    55    18    54
add            5    56    19    55
route          2    57    21    56
add            5    58    21    57
route          2    59    20    15
add            5    60    20    59
add            5    61    17    60
route          2    62    22    61
add            5    63    22    62
add            5    64    58    63
route          2    65    25    64
add            5    66    25    65
route          2    67    24    66
add            5    68    24    67
```

```
route          2    69    23    68
add            5    70    23    69
add            5    71    26    70
route          2    72    27    71
add            5    73    27    72
route          2    74    28    73
add            5    75    28    74
route          2    76    29    75
add            5    77    29    76
finish         0
```

Instructions for watershed configuration input

```
c     CALCULATE THE NUMBER OF SUBBASINS, REACHES, AND RESERVOIRS
      nrch = 0
      nres = 0
      lu = 0
      lubtot = 0
      do idum = 1, mhyd
        read (9,'(a10,5i6,f6.3,i9)') a,
     *      icodes(idum), ihouts(idum), inum1s(idum),
     *      inum2s(idum), inum3s(idum), rnum1s(idum), inum4s(idum)
        if (a(1:1).eq.'*') go to 90
        if (icodes(idum).eq.0) go to 100
      end do
100   continue
c
c       icode = 1  subbasin command
c       icode = 2  route command
c       icode = 3  route reservoir command
c       icode = 7  read monthly flows (avg daily cms) from monthin(18)
        if (icodes(idum).eq.7) then
          read (9,(10x,6a)) monthin
          open (18,file=monthin)
          read (18,(a)) title
          read (18,5202) noyrs
5202      format (i6)
         'for each year, read 2 records of monthly flows (6e12.4)'
          do iy = 1, noyrs
c***format changed for pc swat from  1 rec/yr (12e12.4) to 2 recs/yr:
            read(18,5204)(flomon(inum1s(idum),iy,mo),mo=1,6)
            read(18,5204)(flomon(inum1s(idum),iy,mo),mo=7,12)
5204        format(6e12.4)
          end do
        end if
c
c       icode = 8  read in EPIC daily epd file
        if (icodes(idum).eq.8) then
          dart(ihouts(idum)) = rnum1s(idum)
          read (9,5201) dayin
5201      format (10x,6a)
          open (45+inum1s(idum),file=dayin)
          do ii = 1, 6
              read (45+inum1s(idum),’(a)’) title
          end do
        end if
c
c       icode = 9  output to eve file for input to another SWAT run
        if (icodes(idum).eq.9) then
          do ii = 1, 6
```

```
            write (7,9900) title
          end do
        end if
c
c       icode = 10  read daily values with water in cms and rest in tons
        if (icodes(idum).eq.10) then
          read (9,5201) dayin
          call caps(dayin)
          open (55+inum1s(idum),file=dayin)
          do ii = 1, 6
              read (55+inum1s(idum),9900) title
          end do
        end if
```

sta(9): Measured streamflow and sediment yield at gaged station (Main)

```
      open (9,file=statin)
      if (iwst.ne.0.or.isst.ne.0) then
        kk = nbyr * 12
        sump = 0.
        summ = 0.
        do 810 i = 1, kk
          read (9,8400) wob(i), sob(i)
8400      format (10e12.4)
          wob(i) = wob(i) * 86400 / 35.3146
          sob(i) = sob(i) / 35.3146
c         convert m^3/month to m^3/s
c         wob(i) = wob(i) / 2592000.
c         wpd(i) = wpd(i) / 2592000.
c         write(7,777) wob(i), wpd(i)
c         777     format(2f16.6)
          summ = summ + wob(i)
          sump = sump + wpd(i)
  810   continue
COMPUTE STATS ON MEASURED AND PREDICTED MONTHLY WATER YIELDS
          if (summ.gt.0.) call vald25(wob,wpd,kk)
COMPUTE STATS ON MEASURED AND PREDICTED MONTHLY SEDIMENT YIELDS
          if (sump.gt.0.) call vald25(sob,spd,kk)
        end if
      end if
c     close(9)
```

3.4.6. Subbasin input data files (read by subr. Readinpt)

Example: files for the first subbasin are specified in file.cio as follows:

```
1 0    0 0  0    rat01.sub    rat01.rte    p5011.pnd chemical.chm  pratt.sol
     3-wsf.mgt     rat90.mco       rat.gw rat.wgn           1   2
```

These files are used to illustrate the input data descriptions given below.

sub(10): General input data (ex. rat01.sub)

Example: file rat01.sub

```
Rattlesnake Creek - Subbasin Data - #1                                          (1
.0426246   65.000            .000  42.297    .001    5.000  75.000    .060      (2
    .200    .000    .000    .000    .500  50.000    .030    .000                (3







                                                   .000                         (13
```

```
C******READ BASIN DATA
C        FLU = FRACTION OF BASIN IN EACH SUBAREA
C        CN2 = II COND. SCS CURVE NUMBER
C        SALB = SOIL ALBEDO
C        SNO = INITIAL WATER CONTENT OF SNOW(MM)
C        CHL = MAIN CHANNEL LENGTH (KM)
C        CHS = MAIN CHANNEL SLOPE (M/M)
C        CHW = AVERAGE WIDTH OF MAIN CHANNEL (M)
C        CHK = EFF HYD CONDUCTIVITY OF MAIN CHANNEL
C        CHN = CHANNEL N VALUE
C        OVN = OVERLAND FLOW N VALUE
C        ELEV = MEAN ELEVATION ABOVE SEA LEVEL (M)
read (10,(a)) title
c****format change for swat pc
c         read (10,10301) flu(i), cn2(i), co2(i), sno(i), chl(1,i),
c     *       chs(i), chw(1,i), chk(1,i), chn(i), ovn(i), elev(i)
c         read (10,10302) ovn(i), elev(i)
c10301    format(f9.7,10f8.3)
   new version:
read (10,10301) flu(i), cn2(i), co2(i), sno(i), chl(1,i),
     *      chs(i), chw(1,i), chk(1,i), chn(i)
10301    format(f9.7,8f8.3)
if (co2(i).le.0.) co2(i) = 330.
         if (flu(i).le.0.) flu(i) = .000001
         if (chs(i).le.0.) chs(i) = .0001
         cn2(i) = cn2(i) + incrcn
         dx(i) = da * flu(i)
C RT = RETURN FLOW TRAVEL TIME (D).
C ENTERING ZERO ALLOWS SWRRB TO CALCULATE RT.
C CSS = SEDIMENT CONC IN RETURN FLOW
C ECP = USLE EROSION CONTROL PRACTICE FACTOR P.
C SL = AVERAGE SLOPE LENGTH FOR SUBBASIN I (M)
C STP = AVERAGE SLOPE STEEPNESS FOR SUBBASIN I (M/M)
```

```
C RSDIN = INTIAL RESIDUE COVER (KG/HA) - 0 ALLOWS SWRRB TO ESTIMATE
        read (10,10300) ovn(i),elev(i),rt(i), css(i), ecp(i), sl(i),
    1         stp(i), rsdin(i)
10300    format(10f8.3)
        if (stp(i).le.0.) stp(i) = .0002
        slsoil(i) = sl(i)
c****format change for swat pc
c        read (10,10300) (rfinc(i,mo),mo=1,12)
c        read (10,10300) (tmpinc(i,mo),mo=1,12)
c        read (10,10300) (radinc(i,mo),mo=1,12)
c        read (10,10300) (huminc(i,mo),mo=1,12)
c        read (10,10300) (co2inc(i,mo),mo=1,12)
         read (10,10300) (rfinc(i,mo),mo=1,6)
         read (10,10300) (rfinc(i,mo),mo=7,12)
         read (10,10300) (radinc(i,mo),mo=1,6)
         read (10,10300) (radinc(i,mo),mo=7,12)
         read (10,10300) (huminc(i,mo),mo=1,6)
         read (10,10300) (huminc(i,mo),mo=7,12)
         read (10,10300) (co2inc(i,mo),mo=1,6)
         read (10,10300) (co2inc(i,mo),mo=7,12)
```

rte(11): Routing input data (ex. rat01.rte)

Example: file rat01.rte

```
Subbasin Routing Data for #1 - Rattlesnake Creek Water shed                   (1
   5.000   1.000    .001  22.297    .060  75.000    .500    .500              (2
```

```
C       CHW = CHANNEL WIDTH(M)
C       CHD = CHANNEL DEPTH(M)
C       CHSS = CHANNEL SLOPE(M/M)
C       CHL2 = CHANNEL LENGTH(KM)
C       CHNN = CHANNEL N
C       CHK2 = EFF HYD CONDUCTIVITY OF ALLUVIUM (MM/H)
C       CHXK = CHANNEL USLE K FACTOR
C       CHC = CHANNEL USLE C FACTOR
        read (11,'(a)') title
        read (11,10300) chw(2,i), chd(i), chss(i), chl(2,i), chnn(i),
     *      chk(2,i), chxk(i), chc(i)
10300    format(10f8.3)
        if (chss(i).le.0.) chss(i) = .0001
c       if (chl(2,i).le.0.) chl(2,i) = .0010
```

pnd(12): Pond/reservoir data (ex. p5011.pnd)

Example: file p5011.pnd

```
p5011.pnd                                                   15:25 11:11 27Aug92  (1
    .150 109.000 100.000 110.000 200.000    .001    .000    .001    .001   1.000 (2
   1  12  10                                                                     (3
    .000    .000    .000    .000    .000    .000    .000    .000    .000    .000 (4
```

```
C       FP = FRACTION OF SUBBASIN THAT FLOWS INTO PONDS
C       SAX = TOTAL SURFACE AREA OF ALL PONDS IN SUBBASIN TO
C       PRINCIPLE SPILLWAY(HA)
C       VMX = RUNOFF VOLUME FROM POND CATCHMENT AREA REQUIRED TO
C       FILL EMPTY PONDS AT PRINCIPLE SPILLWAY(MM).
C       SAE = TOTAL SURFACE AREA OF ALL PONDS IN SUBBASIN AT
C       EMERGENCY SPILLWAY(HA)
C       VMX = RUNOFF VOLUME FROM POND CATCHMENT AREA REQUIRED TO
C       FILL EMPTY PONDS AT EMERGENCY SPILLWAY(MM).
C       V = INITIAL POND VOLUMES(MM)
C       SEPP = SEEPAGE THROUGH DAM (CONTRIBUTES TO FLOW) (M**3/DAY)
C       CS = INITIAL SEDIMENT CONCENTRATION IN PONDS (PPM)
C       CFP = NORMAL SEDIMENT CONCENTRATION IN PONDS (PPM)
C       HC = HYDRAULIC CONDUCTIVITY OF POND BOTTOMS (MM/H)
        read (12,'(a)') title
        read (12,10303) fp(i), sax(i), vmx(i), sae(i), vme(i), v(i),
     *      sepp(i), cs(i), cfp(i), hc(i)
        read (12,10304) iflod1(i), iflod2(i),
     *      ndtarg(i)
10303   format (10f8.3)
10304   format (3i4)
C******READ WETLAND DATA
C FW = FRACTION OF SUBBASIN THAT FLOWS INTO WETLANDS
C SAXW = TOTAL SURFACE AREA OF ALL WETLANDS IN SUBBASIN TO
C         PRINCIPAL SPILLWAY(HA)
```

```
C VMXW = RUNOFF VOLUME FROM WETLANDS CATCHMENT AREA REQUIRED TO
C        FILL EMPTY PONDS AT PRINCIPLE SPILLWAY(MM).
C SAEW = TOTAL SURFACE AREA OF ALL WETLANDS IN SUBBASIN AT
C        EMERGENCY SPILLWAY(HA)
C VMXW = RUNOFF VOLUME FROM WETLANDS POND CATCHMENT AREA REQUIRED TO
C        FILL EMPTY WETLANDS AT EMERGENCY SPILLWAY(MM).
C VW = INITIAL WETLANDS VOLUMES(MM)
C SEPW = SEEPAGE THROUGH DAM (CONTRIBUTES TO FLOW) (M**3/DAY)
C CSW = INITIAL SEDIMENT CONCENTRATION IN WETLANDS (PPM)
C CFW = NORMAL SEDIMENT CONCENTRATION IN WETLANDS (PPM)
C HCW = HYDRAULIC CONDUCTIVITY OF WETLANDS BOTTOMS (MM/H)
        read (12,10300) fw(i), saxw(i), vmxw(i), saew(i), vmew(i),
     *      vw(i), sepw(i), csw(i), cfw(i), hcw(i)
10300    format(10f8.3)
```

chm(13): Top ten pesticides input data (ex. chemical.chm)

Note: the basin file bsn(11) specifies up to ten pesticides in array npno.

Example: file chemical.chm

```
dummy chemical data file                                            (1
    .000    .000    .000                                            (2
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000
    .000    .000    .000                                            (3
```

Input instructions for ~.chm:

```
read (13,'(a)') title                                               (1
        do 20 j = 1, 10
C******READ PESTICIDE DATA
C         FFP = INITIAL PESTICIDE ON FOLIAGE (KG/HA)
C         GP = INITIAL PESTICIDE ON GROUND (KG/HA)
C         ERP = ENRICHMENT RATIOS FOR PESTICIDES
For each pesticide j=1,10:
          read (13,10300) ffp(j,i), gp(j,i,1), erp(j,i)             (2
C******READ NUTRIENT AND PESTICIDE DATA
C       WN = ORGANIC N CONCENTRATION IN UPPER LAYER(G/T)
C       WPO = PHOSPHORUS CONCENTRATION IN UPPER LAYER(G/T)
C       AP = CONCENTRATION OF LABILE (SOLUABLE) P IN UPPER LAYER (G/T)
        read (13,10300) wn(1,i), wpo(1,i), ap(1,i)                  (3
```

sol(14): Soil input data (ex. pratt.sol; houston.s93)

Example: pratt.sol

```
PRATT                                                                        (1
  4     .17    25.00PRATT                                                    (2
  10.00  304.80 1016.00 1524.00      .00      .00      .00 depth mm to layer bottom(3
   1.47    1.47    1.50    1.52      .00      .00      .00     bulk density  T/m^3 (4
    .11     .11     .10     .10      .00      .00      .00     avail water cap m/m (5
 330.20  330.20  330.20  330.20      .00      .00      .00          Sat. Cond. mm/h (6
   5.00    5.00    7.00    4.00      .00      .00      .00          Clay cont. %    (7
    .47     .47                                                     organic C       (8
  10.00   10.00    5.00    5.00                                     Init. [NO3]     (9
    .00     .00     .00     .00      .00                            part. size dist(10
1524.00                                                             max root depth  (11
```

The soils data files extracted from the soils data base via program Runsoils is not in the format read below, so Runsoils output must be converted to the format shown below, at least for this PC version of Swat. Examples of these two forms are shown below. --spp

```
C       READ SOIL HYDRAULIC PROPERTIES FOR EA SUB-BASIN.  SOIL IN EACH
SUB-BASIN IS DIVIDED VERTICALLY INTO A MAXIMUM OF 10 LAYERS.  EACH
HYDRAULIC PROPERTY REQUIRES 1 RECORD.

*   input format:
5200    format(i4,2f8.3,a)
5300    format(10f8.3)
read (14,'(a)') title                                                   (1
*   no. soil layers, USLE erosion K-factor, silt content (%), soil name:
read (14,5200) ns(i), ek(i),sil(i),snam(i)                              (2
        nn = ns(i)
read (14,5300) (z(j,i),j = 1,nn)    !depth to bottom of layers (mm)     (3
read (14,5300) (por(j,i),j = 1,nn)  !bulk density (T/m^3)               (4
read (14,5300) (awc(j,i),j = 1,nn)  !available water capacity (m/m)     (5
read (14,5300) (sc(j,i),j = 1,nn)   !saturated conductivity (mm/h)      (6
read (14,5300) (cla(j,i),j = 1,nn)  ! clay content (pct)                (7
read (14,5300) (cbn(j,i),j = 1,nn)  ! organic carbon content (pct)      (8
read (14,5300) (wno3(j,i),j = 1,nn) !initial [NO3] (g/T)                (9
read (14,5300) (psz(j,i),j=1,5)     !particle size distribution        (10
read (14,5300) zmx(i)               !maximum rooting depth (mm)        (11

            Calculation of soil properties:
        san(i)=0.  !sand content (pct)
        rock(i)=0.  !rock fragments (pct)
        salb(i)=.15  !moist soil albedo
        do 877 j = 1,nn
          if (por(j,i).le.1.e-6) por(j,i) = 1.3  !default bult density
 877    continue
        rock(i) = exp(-.053*rock(i))
        if (nn.eq.1) then
          z(2,i) = z(1,i)
          z(1,i) = 10.
          por(2,i) = por(1,i)
          awc(2,i) = awc(1,i)
          sc(2,i) = sc(1,i)
```

```
          cbn(2,i) = cbn(1,i)
          cla(2,i) = cla(1,i)
          wno3(2,i) = wno3(1,i)
          ns(i) = 2
          nn = 2
        endif
c5300 format (27x,10f12.2)
        if (cbn(3,i).le.0) then
C****CALCULATE CBN FOR LOWER LAYERS IF ONLY HAVE UPPER LAYER
          xx = z(2,i)
          do 40 l = 3, nn
            dg = (z(l,i)-xx)
            if (cbn(l,i).eq.0.) cbn(l,i) = cbn(l-1,i) * exp(-.001*dg)
            xx = z(l,i)
   40     continue
        end if
        cv(i) = rsd(i)
        sil(i) = sil(i) / 100.
        cla(1,i) = cla(1,i) / 100.
        san(i) = 1.0 - cla(1,i) - sil(i)
        psz(1,i) = (1.-cla(1,i)) ** 2.49 * san(i)
        psz(2,i) = .13 * sil(i)
        psz(3,i) = .20 * cla(1,i)
        if (cla(1,i).le..5) then
          if (cla(1,i).lt..25) go to 140
          psz(4,i) = .28 * (cla(1,i)-.25) + .5
          go to 150
        end if
        psz(4,i) = .57
        go to 150
  140   psz(4,i) = 2. * cla(1,i)
  150   psz(5,i) = 1. - psz(1,i) - psz(2,i) - psz(3,i) - psz(4,i)
        do 160 j = 1, nn
          if (j.eq.1) cla(1,i) = 100. * cla(1,i)
          wp(j,i) = 0.4 * cla(j,i) * por(j,i) / 100.
          up(j,i) = wp(j,i) + awc(j,i)
          por(j,i) = 1. - por(j,i) / 2.65
          if (up(j,i).ge.por(j,i)) then
            up(j,i) = por(j,i) - .05
            wp(j,i) = up(j,i) - awc(j,i)
            if (wp(j,i).le.0.) then
              up(j,i) = por(j,i) * .75
              wp(j,i) = por(j,i) * .25
            end if
          end if
  160   continue
```

<u>Example 2: soil data file Houston.s93</u>

```
Soils Data
   3   0.320  92.000HOUSTON BLACK   D
  10.000 609.6002032.000
   1.400   1.400   1.500
   0.170   0.170   0.170
   1.524   1.524   1.524
  50.000  50.000  50.000
   1.744   1.744
  10.000  10.000   5.000
```

```
    0.00    0.00    0.00    0.00    0.00
2032.000
```

The following (below the column numbers) shows the form of the Houston Black soil data extracted from the soils data base via Runsoils (file houston.s94):

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 HOUSTON BLACK
 2HOUSTON BLACK
 Maximum rooting depth              .00
 Texture                            .00
 Depth (mm)                      609.60     2032.00         .00         .00
 Bulk Density (t/m**3)             1.40        1.50         .00         .00
 Available Water Cap (m/m)          .17         .17         .00         .00
 Sat. Cond. (mm/h)                 1.52        1.52         .00         .00
 Organic Carbon Content(%)         1.74
 Clay Content (%)                 50.00       50.00         .00         .00
 Silt Content(%)**                  .00
 Sand Content(%)**                  .00
 Rock Fragments(%)**                .00
 Moist Soil Albedo**                .00
 Dry Soil Albedo**                  .00
 USLE Erosion K-Factor              .32
 Salinity                           .00
 Initial NO3 Conc (g/t)           10.00        5.00
```

mgt(17): Management input data, i.e. schedules (ex. 3-wsf.mgt)

Example: file 3-wsf.mgt

```
Rattlesnake Creek Watershed - Crop Data for Wheat-Sorghum-Fallow: 3-wsf.mgt
1  3        0      0
   6  25           5 1650.00   4    1.00  660.00     .00   0     0     0

   5   1           1 1650.00   3            0.00   30.00   0     0     0
  10  10           5 1650.00   3            0.00   30.00   0     0     0

   9  20           1 1650.00   4            0.00   30.00   0     0     0
```

```
File format:
title                   (a)
igro,nrot,nmgt,nptot    (i1,i3,2i4)
for iro=1,nrot:         (2i4,2(f8.3,i4),3f8.3,i4,2f6.3)
--mo ida  husc itill       hu ncrp   airg    anit    phos inp  pamt cn2up
```

Note: For winter crops, do the following, as shown above.
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).

```
C IF PERENNIAL VEGETATION, ENTER START AND END OF GROWING SEASON
C       IN PLACE OF PLANTING AND HARVEST
c       nrot =number of years of rotation in simulation
c       mo = month of planting
c       ida = day of planting
c       husc = heat unit scheduling
c       itill =operation/tillage code number
```

```
c       hu = heat units to maturity
c       ncrp = crop identification number
c       airg = amount of irrigation applied(mm)
c       anit = amount of nitrogen applied (kg/ha)
c       phos = amount of phosphorus applied (kg/ha)
c       inpest = pesticide number
c       pamt = pesticide amount applied(kg/ha)
c       cn2up = SCS runoff curve number update
      read (17,'(a)') title
      read (17,5802) igro(i), nrot(i), nmgt(i), nptot(i)
5802  format (i1,i3,12i4)
      if (igro(i).eq.1) then
          alai(i) = 1.
          dm(i) = 3.
          g(i) = .2
          npl = 1
      end if
      do iro = 1, nrot(i)
          read (17,5800) mo, ida, husc, itill, hu, ncrp, airg, anit,
     *        phos, inpest, pamt, cn2up
5800     format (2i4,f8.3,i4,f8.3,i4,3f8.3,i4,2f6.3)
      end do
ITILL   operation
1     plant
2     irrigate
3     fertilize
4     apply pesticide
5     harvest and kill
6     till
7     harvest only
8     kill only
9     grace
0     initialize cumulative operations for all classes (1-9) to zero.
```

mco(18): Mgmt codes, i.e. stress factor threshholds:(ex. rat90.mco)

Specify stress factor threshholds for rrigating and fertilizing "automatically" during crop growth seasons.

Example: file90.mco

```
Rattlesnake Creek Watershed - MCO file for Subbasin 1                             (1
   1     0.9    0.15       0      0.       0                                      (2
    .500         1.000    21   2   1                                              (3
         0         0         0         0         0         0  wures(mo,i)  1-6    (4
         0         0         0         0         0         0  wures(mo,i) 7-12    (5
         0         0         0         0         0         0  wurch(mo,i)  1-6    (6
         0         0         0         0         0         0  wurch(mo,i) 7-12    (7
         0         0         0         0         0         0  wushal(mo,i)  1-6   (8
         0         0         0         0         0         0  wushal(mo,i) 7-12   (9
         0         0         0         0         0         0  wudeep(mo,i)  1-6  (10
         0         0         0         0         0         0  wudeep(mo,i) 7-12  (11
```

title record

irr wsf efi irrsub wurtn irtnsb (i4,2f8.3,i8,f8.3,i8)

ansf fnmx anmx idmn ipman lafert forgn forgp (3f8.3,3i4,2f8.3)

< then 8 records as above, (6f10.1) >

```
        read (18,'(a)') title
```

```
c    irr = irrigation = 1 automatic by water stress
c       = -1 input date and amount
c       = 0 no irrigation
c    wsf = if irr=1, wsf = water stress factor
c    efi = irrigation runoff ratio
c    irrsub = subbasin to remove the water from
c    wurtn = fraction of water use that returns to stream
c    irtnsb = subbasin that the flow returns to
c    ansf = nitrogen stress factor to trigger fertilization
c    fnmx = soil N level to fertilize to (kg/ha)
c    anmx = max amount of N that can be applied in one year (kg/ha)
c    idmn = minimum interval between fertilizations (days)
c    ipman = P fertilizer management for auto fertilization
c    ipman = 3, high management-restores P in upper 2 layers to 30 ppm
c    ipman = 2 medium management-restores P in upper 2 layers to 20 ppm
c    ipman = 1 low management-restores P in upper 2 layers to 10 ppm
c    lafert = soil layer that fertilizer is applied to
c    forgn = fraction of organic N in fertilizer
c    forgp = fraction of organic P in fertilizer
c    wures, wurch, wushal, wudeep are average monthly water use
c    from the reservoir, reach, shallow and deep aquifer storages (ha-m)
*   Formats:
7200  format (i4,2f8.3,i8,f8.3,i8)
7201  format (3f8.3,3i4,2f8.3)
7203  format (6f10.1)  ! ****format change for swat pc
*
read (18,7200) irr(i), wsf(i), efi(i), irrsub(i), wurtn(i), irtnsb(i)
read (18,7201) ansf(i), fnmx(i), anmx(i), idmn(i), ipman(i),
     *       lafert(i), forgn(i), forgp(i)
read (18,7203) (wures(mo,i),mo = 1,6)
read (18,7203) (wures(mo,i),mo = 7,12)
read (18,7203) (wurch(mo,i),mo = 1,6)
read (18,7203) (wurch(mo,i),mo = 7,12)
read (18,7203) (wushal(mo,i),mo = 1,6)
read (18,7203) (wushal(mo,i),mo = 7,12)
read (18,7203) (wudeep(mo,i),mo = 1,6)
read (18,7203) (wudeep(mo,i),mo = 7,12)
```

gw(19): Groundwater input data (ex. rat.gw)

Results based on data from this file, evaporation from groundwater, can be replaced by results from Modflow if Swat and Modflow are coordinated.

Example: file rat.gw

```
DUMMY GROUNDWATER DATAFILE                                                         (1
    .00000    .00000    .00000    .15000   1.00000    .00000   1.00000    .00000   (2
 100.00000                                                                         (3
```

```
C       GWHT = INITIAL GROUNDWATER HEIGHT (M)
C       GWQ = INITIAL GROUNDWATER FLOW CONTRIBUTION TO STREAMFLOW
C       ABF = ALPHA FACTOR FOR GROUNDWATER
C       SYLD = SPECIFIC YIELD
C       DELAY = GROUNDWATER DELAY (DAYS)
C       RCHRGC = FRACTION (0-1) OF ROOT ZONE PERC THAT PERCOLATES
C       PAST SHALLOW GW INTO DEEP GW
C       REVAPC = REVAP COEFF-FRACTION OF RECHARGE (ROOT ZONE PERC)
C       THAT GOES TO REVAP
C       REVAPMN = REVAP STORAGE
```

```
        read (19,'(a)') title
        read (19,5301) gwht(i), gwq(i), abf(i), syld(i), delay(i),
     *      revapc(i), rchrgc(i), revapmn(i)
        read (19,5301)  deepst(i)
5301  format(8f10.4)  ! c*****format change for swat pc
        abf1(i) = exp(-abf(i))
        delay(i) = exp(-1./(delay(i)+1.e-6))
        rchrg(i) = gwq(i)
```

wgn(20): Weather generation input (ex. rat.wgn)

Example: file rat.wgn

```
  KS   PRATT KS                                                                  (1
  72.900 125.730  45.000  37.600 330.000   1                                     (2
  6.20  9.50 14.50 21.20 25.70 31.40 34.50 33.70 28.90 23.00 14.00  8.10          (3
 -6.80 -4.40  -.20  6.30 11.60 17.00 19.80 18.80 14.10  7.90   .30 -4.70          (4
   .40   .34   .27   .18   .13   .10   .07   .08   .13   .17   .23   .32          (5
249.00315.00414.00516.00563.00639.00636.00573.00486.00368.00279.00229.00          (6
  8.13  2.54  8.13 42.16 24.38 34.04 41.66 29.97 29.72 12.95 19.56  9.40          (7
   .09   .11   .13   .17   .22   .20   .19   .18   .15   .11   .09   .09          (8
   .26   .31   .33   .34   .43   .43   .37   .35   .35   .42   .37   .32          (9
   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00   .00         (10
  4.57  7.11  8.13  9.14 10.67 11.94 10.41 10.41 10.92 12.19  7.11  6.35         (11
  5.08  8.38  9.40 14.73 12.95 14.48 12.45 12.95 14.22 17.27  9.14  7.62         (12
  1.30  1.36   .67  4.95   .98  1.03   .98  1.71  1.58  2.65  2.32  1.08         (13
 -6.34 -3.88 -2.01  4.20 11.20 15.77 17.58 16.47 12.12  6.56  -.20 -4.31         (14
  5.57  5.65  6.47  6.27  5.65  5.91  5.11  4.94  5.32  5.47  5.46  5.46         (15
```

```
C       TP5 = TP-40 10 YEAR FREQ. .5 H RAINFALL (MM)
C       TP6 = TP-40 10 YEAR FREQ. .6 H RAINFALL (MM)
C       TP24 = NO YEARS RECORD MAX .5 H RAINFALL (MM)
C       YLT = LATITUDE
        read (20,'(a)') title                                 ! (1
        read (20,(4f8.3)) tp5(i), tp6(i), tp24(i), ylt(i)     ! (2
C       OBMX = AV MO MAX TEMP C; OBMN = AV MO MIN TEMP C
        read (20,(12f6.3)) (obmx(mo,i),mo = 1,12)             ! (3
        read (20,(12f6.3)) (obmn(mo,i),mo = 1,12)             ! (4
C       CVT = COEF OF VAR FOR MO TEMP
        read (20,(12f6.3)) (cvt(mo,i),mo = 1,12)              ! (5
        do 777 mo = 1, 12
777          if (cvt(mo,i).gt.0.36) cvt(mo,i) = 0.36
C       OBSL = AV MO SOL RA
        read (20,(12f6.3)) (obsl(mo,i),mo = 1,12)             ! (6
C       WI = MO MAX .5H RAIN FOR PERIOD OF RECORD(MM)
        read (20,(12f6.3)) wim                                ! (7
nsim  condition
1     measured single raingage
2     simulated single raingage
3     measured multiple raingages
4     simulated multiple raingages
msim  condition
1     measured single temperature for entire basin
2     simulated single temperature for entire basin
3     measured temperature for each sub-basin
4     simulated temperature for each sub-basin
C PRW(1)= MONTHLY PROBABILITY  OF WET DAY AFTER DRY DAY.
C PRW(2)= MONTHLY PROBABILITY OF WET DAY AFTER WET DAY.
C RST = MONTHLY MEAN EVENT, ST DEV, AND SKEW COEF OF DAILY RAINFALL.
        read (20,(12f6.3)) (prw(1,mo,i),mo = 1,12)            ! (8
        read (20,(12f6.3)) (prw(2,mo,i),mo = 1,12)            ! (9
        read (20,(12f6.3)) (wvl(mo,i),mo = 1,12)              !(10
        read (20,(12f6.3)) (rst(mo,1,i),mo = 1,12)            !(11
        read (20,(12f6.3)) (rst(mo,2,i),mo = 1,12)            !(12
        read (20,(12f6.3)) (rst(mo,3,i),mo = 1,12)            !(13
        read (20,(12f6.3)) (dewpt(mo,i),mo = 1,12)            !(14
        read (20,(12f6.3)) (uavm(mo,i),mo = 1,12)             !(15
c       do 1701 j = 2, 10
c       read (20,(12f6.3)) (vobmx(mo,j),mo = 1,12)
```

```
c        read (20,(12f6.3)) (vobmn(mo,j),mo = 1,12)
```

Appendix B: coordinating Swat and Modflow programs

Data file device numbers used for Swat and Modflow

A large number of input and output data files are coordinated for a combined execution of Swat and Modflow. The Fortran code for these programs is compiled and linked under Lahey Fortran, which was installed with an allowable maximum of 255 data files open concurrently on device numbers from 1 to 255. Swat file device numbers run from 1 to 57, except for 70, 77, and 80-81, as listed below. Modflow currently uses device numbers 1 (Basic package input file), 116 (standard output ~.prn), 117 (log file ~.log), 150-161 (unformatted output files for "saving" results), 217-220 (summary files), and a set of device numbers specified by the model input files. For these, the range 61-74 is recommended to avoid conflict with other data files. Although many numbers within the range 1-255 could be chosen other than those already mentioned above, the range 61-74 is recommended as one safe set of choices. The main hazard is in specifying a number that coincides with an output file device number so that your input file is written over. The input files shown in the "response" file corn90do.rsp for the Rattlesnake Creek watershed model in the above example refer to numbers outside this range with no apparent conflict.

Swat and Modflow file device numbers are listed below, categorized by program location and source file in which data files were opened.

<u>Swat file device numbers:</u>

Main program (file swatmod1.h, "included" in file swatmain.for): these were added as part of changes to Swat and coordination with Modflow.

- 50 iobal: output to hydrologic balance file (~.bal), named in ~.cod file, written in subr Hydbal, to be read by Modflow's Modswb package.
- 51 iolog
- 52 iopcp
- 53 iotmp
- 54 iomat
- 55 iosol
- 56 ioet
- 57 iorad

Subr open (file swatf-o.for): mainly basin-wide input

- 1 rsvout
- 2 file.cio
- 3 sbsout
- 4 Lwqout
- 5 pestout
- 6 stdout (~.std): Swat's standard output file
- 7 event
- 8 rchout
- 10 codedat (~.cod)

11 basndat (~.bsn)
70 kevin.out
77 bigsub

Subr open2 (file swatf-o.for): data base (~.dat) and subbasin input files

10 subdat (~.sub)
11 routdat (~.rte)
12 ponddat (~.pnd)
13 chemdat
14 soildat (~.sol)
15 cropdat: file crop.dat, crop data base
16 napdat
17 mgtdat (~.mgt): crop management
18 mcodat (~.mco): management codes (stress factor threshholds)
19 gwdat (~.gw): groundwater, but input is superseded by results from Modflow.
20 wgendat (~.wgn): historical basis for synthesized weather data
9+j for j=1 to 18 (10 to 27): daily rainfall (mm) for up to 18 stations
27+j for j=1 to 18 (28 to 45): daily min & max temperature (deg C) for up to 18 stations.

<u>Modflow file device numbers:</u>

Subr Modflo (file modflo.for):

1 inbas (~.bas): input for basic package
116 iout (~.prn): standard output
117 iolog (~.log): log file
217 iodwl
218 iomeas (~.mea): residuals (calculated - measured heads)
219 iomea2 (~.me2): summary of residuals
220 iorsd1 (~.rsd): another residual file

Device numbers specified as input (array iunit in file ~.bas and in array header records): suggested numbers that should not conflict with any of those specified in Swat or Modflow as described above:

61 ~.bcf
62 ~.wel
63 ~.drn
64 ~.riv
65 ~.evt
66 ~.swb
67 ~.ghb
68 ~.rch
69 ~.sip
70 ~.pcg
71 ~.sor
72 ~.oc

73 ~.str
74 ~.div surface water diversions

Appendix C. Extensions to Modflow input instructions

Unformatted output file options

The table below shows the scheme used to implement the unformatted output options in Modflow. These options are described in the Modflow manuals under the input instructions for the respective packages; see McDonald and Harbaugh (1988) for all but the stream package documentation, which is documented separately by Prudic (1989). Contents of the table columns are as follows.

Column	Contents of table column
input flag:	name of Modflow input flag to specify unformatted output;
device:	file device number to which unformatted output is written;
file prefix:	file name is formed by attaching the extension ".unf";
package:	the group of subroutines in Modflow associated with the flag;
subroutine:	which routine in Modflow's package's that reads the flag;
output:	description of some of the unformatted file's contents.

input flag	j: device(j)	file prefix	package	subroutine	output
ihedun	1 (151)	modhed	oc	bas1rp	heads
iddnum	2 (152)	modddn	oc	bas1rp	drawdown
ibcfcb	3 (153)	modbcf	bcf	bcf1rp	storage, flow rates
iwelcb	4 (154)	modwel	wel	wel1al	
idrncb	5 (155)	moddrn	drn	drn1al	
irchcb	6 (156)	modrch	rch	rch1al	
ievtcb	7 (157)	modevt	evt	evt1al	
irivcb	8 (158)	modriv	riv	riv1al	
istcb1	9 (159)	modst1	str	str1al	streambed leakage
istcb2	10 (160)	modst2	str	str1al	streamflow
ighbcb	11 (161)	modghb	ghb	ghb1al	

Consistent with the Modflow manuals, setting any of these flags to a positive number results in unformatted output, contingent on assigning a nonzero value to the overriding flag, **icbcfl**, which is described in the output control (**oc**) instructions. Contrary to the manual, however, the positive values assigned to these flags do not serve double duty as output file unit numbers; column 2 shows the unit numbers in parentheses that are used to write these files if the corresponding input flags have a positive value (e.g., 1). Column 3 shows the names, all of which have the extension ".unf", of the resulting unformatted files.

Appendix D. MODFLOW postprocessing programs

Programs POSTMOD and MODHYD were written to extract results of interest from MODFLOW's standard output for further data analysis and display. POSTMOD extracts heads or drawdowns for specified time steps of interest. MODHYD extracts a time series of results at an aquifer node (heads or drawdowns) or a stream node (streamflow, streambed leakage, or stream stage); or a time series of results along a row, column, or stream as described below.

POSTMOD and MODHYD are both based on FORTRAN's intrinsic INDEX character function, used to search for character strings that are part of standard MODFLOW output and serve as guideposts to locate the desired data. The MODFLOW manual (McDonald & Harbaugh, 1988) provides details of output format. Source code excerpts from MODFLOW were adapted for use in POSTMOD and MODHYD by changing WRITE statements into READ statements.

POSTMOD with example to extract drawdown arrays

Program POSTMOD (executable file postmod.exe) reads a standard MODFLOW output file to copy arrays of heads or drawdowns (or others listed below if written by MODFLOW) to separate files for specified time steps. Heads or drawdowns may be extracted (i.e. copied to a separate file) for any given time step and stress period for which the heads or drawdowns of interest were printed. Other arrays listed below are not printed in MODFLOW's standard output except through use of nonstandard options added to MODFLOW.

The file extension (shown as "ext" below) depends on the file format chosen, with the following options. First, the format may be that of a spreadsheet (ext = "srf"), in which each array element is described by a file record specifying grid coordinates and array element value (row i, column j, a_{ij}). Second, the format may be a wrapped matrix format (ext = "dat") as defined in the Utilities chapter of MODFLOW's manual (McDonald et al., 1988). File name prefixes correspond to the type of extracted array as follows:

HEADn.ext - heads from stress period n;
DRAWn.ext - drawdowns from stress period n.
THCKn.ext - saturated thickness, stress period n;
VSTGn.ext - volumetric storage, stress period n.
DSDTn.ext - rate of change of storage, stress period n.
CFLOn.ext - constant head cell flow rates, stress period n.
FFLOn.ext - front face cell flow rates, stress period n.
RFLOn.ext - right face cell flow rates, stress period n.
LFLOn.ext - lower face cell flow rates, stress period n.

As shown in an example below, the program prompts the user to specify the stress period and layer, whether an array of heads, drawdowns or other array is to be extracted, and the format in which the array is written, according to the MODFLOW output control codes. POSTMOD is normally able to find these control codes from MODFLOW's output; if not, POSTMOD asks for the format.

Example: use POSTMOD to extract drawdown arrays.

Run POSTMOD at the DOS prompt with redirected input from file postmod.rsp and redirected output to file postmod.jou as follows:

```
----------------------------------------------------------------------
   postmod <postmod.rsp >postmod.jou

----------------------------------------------------------------------
```

Redirected input file postmod.rsp is as follows:

```
----------------------------------------------------------------------
corn90cp.prn
c              continue or exit
y              subst. value for dry nodes ok?
1,1            enter time step, stress period of interest
h              extract heads or drawdowns?
s              [S]urfer, [A]rc-Info, or [M]atrix (wrapped) format?
y              exclude zero-valued array elements?
y              use unit cell dimensions?
n              extract another array?


----------------------------------------------------------------------
```

POSTMOD redirected output file postmod.jou with queries and responses (in **bold**):

```
----------------------------------------------------------------------
Program POSTMOD
Extract head or drawdown arrays from MODFLOW output file.

 Enter MODFLOW output file name [MODFLOW.PRN]: corn90cp.prn
0Pre-dev transient '60-'84 DWR Rattlesnake Creek 1/12/96 w/ Swat: 6061swat.bas
  1 layer(s),  47 rows, 190 columns,    2 stress periods,
Head format code   2 = (5x,9g14.6)
Drawdown format code   2 = (5x,9g14.6)
Note: Cell-by-cell flow format code not found.
Scan for dry nodes; write list to file corn90cp.DRY
   14 instances of dry nodes are listed on file corn90cp.DRY
C[ontinue POSTMOD] or E[xit]?[C]: C
Default Substitution value =   0.0000000     for dry nodes.
Is substitute dry node value ok?[Y]: Y

           2 stress periods.
Enter time step, stress period (negative no. to STOP):    1    1
Find STRESS PERIOD  1
Options:
HEADn [H]eads
DRAWn [D]rawdowns
Enter choice: [H]: H
nput format = (5x,9g14.6)
Output format: [S]urfer input, [A]rc/info input, [M]atrix[S]: S
Exclude zero values from output?[Y]: Y
Use unit cell dimensions (row,col widths)?[Y]: Y
  layer timstp strper period:
     1      1      1      1

HEAD IN LAYER                1 AT END OF TIME STEP  1 IN STRESS PERIOD  1
write to file HEAD1.srf
Use format (5x,9g14.6)
Write file HEAD1.srf

Extract row:
   1   2   3   4   5   6   7   8   9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47
Array written to file HEAD1.srf
Extract another array? [Y]: N
```

```
------------------------------------------------------------------------
Excerpt from results on file head1.srf, giving (row, column, head) for each record:
------------------------------------------------------------------------
    7.500        46.50        2365.030
    8.500        46.50        2364.720
    9.500        46.50        2364.190
    10.50        46.50        2363.520
    11.50        46.50        2362.760
    12.50        46.50        2362.000
    13.50        46.50        2361.310
    14.50        46.50        2360.700
    15.50        46.50        2360.240
    52.50        46.50        2235.240
```

MODHYD with example to extract streamflow time series

Program MODHYD (executable file modhyd95.exe) reads a standard MODFLOW output file and extracts (i.e., copies to a separate file) a time series of results for either individual nodes or for a profile of a row, column or stream. Each element in the time series corresponds to printed results for a time step in the MODFLOW output.

For an aquifer MODHYD will extract either heads or drawdowns, and profiles may be extracted along either a row or a column.

For a stream MODHYD will extract stage, depth, leakage or aquifer head at a stream node. If stream profiles are specified then all the above stream results will be extracted.

If time series for individual nodes are specified, then up to 20 such series may be extracted in succession. They will be written to a file after all have been extracted, such that columns in the file correspond to nodes, and rows correspond to time steps. Optional columns at the left hand side label time step and stress periods.

If profiles (for aquifer rows or columns, or for stream reaches) are specified, then the file is written as follows:

```
do for each time step:
   do for each node along the row, column or stream:
      write time, location and corresponding results;
   end do
   write a blank line to separate profiles for successive time steps (*);
end do.
```

(*) The files are written to be imported into a spreadsheet for analysis and plotting. In the case of Quattro Pro™, the blank line between time steps produces the equivalent of a raised pen directive between coordinate pairs so that successive profiles may be superimposed on a plot.

Example: use MODHYD95 to extract streamflow time series

Stream reaches are designated by (row,column) grid coordinates.

```
------------------------------------------------------------------------
```

Run modhyd95 at the DOS prompt with redirected input from file modhyd95.rsp and redirected output to file modhyd95.jou as follows:

```
modhyd95 <modhyd95.rsp >modhyd95.jou
```

Redirected input file modhyd95.rsp is as follows:

```
corn90cp.prn                    MODFLOW output file name
y                               use unit cell dimensions?
s                               extract heads, drawdowns, or stream
o                               write [S]:streambed leakage or [O] streamflow?
corn90cp.hot                    enter the hydrograph output file name
p                               extract row, column, stream or point values?
3                               enter no. series (max=20, min=1)
2,25                            enter (row, col) for time series 1
3,36                                                          series 2
4,45                                                          series 3
y                               include time step, stress period columns on left?
n                               run again?
```

MODHYD95 redirected output file modhyd95.jou with queries and responses (in **bold**):

```
Program MODHYD
Extract head or drawdown arrays from MODFLOW output file.

NOTE: Arrays must be WRAPPED (rather than STRIPPED).
 (See MODFLOW manual, Ch. 14, "Utility Modules")

 Enter MODFLOW output file name [MODFLOW.PRN]: corn90cp.prn
0Pre-dev transient '60-'84 DWR Rattlesnake Creek 1/12/96 w/ Swat: 6061swat.bas
  1 layer(s),  47 rows, 190 columns,   2 stress periods,
Head format code =   2 Drawdown format code =   2
Use unit cell dimensions (row,col widths)?[Y]: Y
 Extract H[eads] D[rawdowns] S[tream] or Q[uit]: [H]: S
   775 STREAM NODES  nstrem=    775
Write S[tream flow into aquifer] or O[utflow into reach]? [S]: O
outfmt = (2(1x,i3),1x,11g11.3)
fmthdg = (1x,a6,t10,11(2x,i5,4x))
Enter the hydrograph output file name corn90cp.hot
Extract R[ow], C[olumn] S[tream] or P[oint values]?[P]: P
Enter no. series (max=20): 3

Enter (row,col) for time series  1:    2   25
Enter (row,col) for time series  2:    3   36
Enter (row,col) for time series  3:    4   45
Extract    3 hydrographs:
   2    25STRM
   3    36STRM
   4    45STRM
 layer  row  col  str  rchinto aquifer  outflow
    8 ITERATIONS FOR TIME STEP   1 IN STRESS PERIOD  1 WITH SIP SOLVER
    8 ITERATIONS FOR TIME STEP   2 IN STRESS PERIOD  1 WITH SIP SOLVER
    7 ITERATIONS FOR TIME STEP   3 IN STRESS PERIOD  1 WITH SIP SOLVER
   13 ITERATIONS FOR TIME STEP   4 IN STRESS PERIOD  1 WITH SIP SOLVER
end of file: stream reach index L=    0 time step    4    4    1
Extracted     4 series (mxser=   20 ) from corn90cp.prn
Include time step, stress period columns on left? (y/n)[Y]: Y
Write hydrograph output file corn90cp.hot
Again?[Y]: N
```

Output file corn90cp.hot specified by response file modhyd95.rsp is as follows:

```
-----------------------------------------------------------------------
0Pre-dev transient '60-'84 DWR Rattlesnake Creek 1/12/96 w/ Swat: 6061swat.bas

              1          2          3
              2          3          4
             25         36         45
 1   1    0.000      0.000      0.000
 1   2    0.000      0.000      0.000
 1   3    0.000      0.000      0.000
 1   4    0.000      0.000      0.000
```

Superseded Swat options

iopwfl (7): option (y=1,n=0) to read daily precipitation data for all stations from the same file, and to do similarly with temperature data. Weather stations are identified in the ~.cio file by an integer, *i*, from 1 to n corresponding to the order of data columns from left to right. Data format for temperature and precipitation data are defined in records 5-6, below.

ioplim (10): option (y>0,n=0) to limit daily irrigation pumping by wsfdmx (mm/day) and annual irrigation pumping by groundwater appropriation pmpmax (mm/yr), reduced by pumping efficiency pmpeff; wsfdmx, pmpmax and pmpeff are defined in records 8-9, below, subject to the following conditions. If Swat does not call Modflow (specified by **iopswt**=0 and **ioplim**>0), annual irrigation limits are read from record 9 (below). If Swat calls Modflow (specified by **iopswt**>0 and ioplim>0), Swat calls subr Passflx to obtain annual maximum pumping flux rates (mm/yr) for each subbasin, based on Modflow's ~.WEL input file.

iopet (15): option (y=1,n=0) to use the reference crop evaporation calculated by subr Penman instead of the value calculated by Swat's subroutine EVAP8, the default option. Subroutine Penman was written and linked with Swat by SPP, and calculates reference crop evaporation according to the method recommended in the Handbook of Hydrology (Maidment, ed., 1993). This method includes the effect of long-wave emission in calculating net radiation, in contrast to Swat's subroutine; see also the following related option, **iopwea**.

jkkopt (19): an option passed to Swb1fm, where it determines how terms from Swat's hydrologic summary are combined to define groundwater recharge (25) and tributary flow (22) for Modflow. The default Swat option for these combinations corresponds to **jkkopt** = 0; the exception, **jkkopt** > 0, is a special case formulated for the Rattlesnake Creek watershed model by Prof. Jim Koelliker, Kansas State University. Defining c = 1 - pond fraction(8), these definitions are as follows.

tributary inflow (22) $= c\cdot[\text{surq}(13) + \text{latq}(15)]$, default
$= -(1/c)\cdot\text{xmloss}(14) + c\cdot\text{latq}(15)$, jkkopt > 0

Recharge (25) = xmloss(14)+perc(16)+pond seepage(20), (default)

$= \text{xmloss}(14)+c\cdot\text{latq}(15)+\text{perc}(16)+\text{pond seepage}(20), \qquad \text{jkkopt} > 0$

Superseded Control Codes input data requirements for program Swat

Definitions for options and data from earlier versions of rec. 3 but not read from this file nor otherwise used in the current simplified Swat-Modflow linkage:

6 **iopsol**: option to show initial and final states of soil on hydrologic balance file after avg annual results have been calculated; Swat calls SoilStat after last call to Hydbal.

7 **iopwfl**: option (y=1,n=0) to read daily precipitation data for all stations from the same file, and to do similarly with temperature data. Weather stations are identified in the ~.cio file by an integer i from 1 to n corresponding to the order of data columns from left to right. Data format for temperature and precipitation data are defined in records 5-6, below.

8 **ithpcp**: option (y=1,n=0) to use Theissen weights to calculate spatial averages of daily precipitation reported at weather stations. Theissen polygon weights are read from file (**namths**) specified on record 4.

9 **ithtmp**: option (y=1,n=0) to use Theissen weights to calculate spatial averages of daily temperature at weather stations. Theissen polygon weights are read from file **namths** specified on record 4.

10 **ioplim**: option (y>0,n=0) to limit daily irrigation pumping by **wsfdmx** (mm) and annual irrigation pumping by groundwater appropriation **pmpmax** (mm), reduced by pumping efficiency **pmpeff**; these are defined in records 8-9, below, subject to the following conditions. If Swat and Modflow are run independently (specified by setting **iopswt**=0 and **ioplim**>0), annual irrigation limits are read from record 9 (below). Otherwise, i.e., if Swat calls Modflow (specified by **iopswt**>0 and **ioplim**>0), Swat calls subroutine Passflx at the beginning of each year (stress period) to obtain annual maximum pumping flux rates (mm) for each subbasin, based on Modflow's ~.WEL input file and summarized by Modswb subroutine Swb1rp.

Note: based on option **irropt** specified by input to the Modswb package, subroutine Swb1fm either assigns pumping rates specified by the ~.WEL input file (**irropt**=0), or scales these pumping rates to correspond to the irrigation depths assigned by Swat for each subbasin (**irropt**>0); see "Definition of options for the Modswb package."

11 **iopqtl**: option (y=1,n=0) to include transmission loss with infiltration as input to soil profile (passed to subroutine purk18 with transmission loss).

12 **iopcmp**: option (y=1,n=0) to write daily results of evaporation calculations to file <casename>.ET. If **iopcmp**=1, daily results are written for the entire period of simulation; if **iopcmp**=0, daily results are restricted to the range of years given by **iopyrF** and **iopyrL** (below); set both to zero to prevent writing daily results. Output includes independent calculation of reference ET by subroutine Penman (see option **iopet**, below).

13 **iopyrF**: first year of writing daily evaporation results (see **iopcmp**, above);

14 **iopyrL**: last year of writing daily evaporation results (see **iopcmp**, above);

15 **iopet**: option (y=1,n=0) to use the reference crop evaporation calculated by subr Penman instead of the value calculated by Swat's subroutine EVAP8, the default

option. Subroutine Penman (Appendix F) was written and linked with Swat by SPP, and calculates reference crop evaporation according to the method recommended by Shuttleworth (1993). This method includes the effect of long-wave emission in calculating net radiation, in contrast to Swat's subroutine; see also the following related option, **iopwea**.

17 **ioprev**: option (y=1,n=0) to reduce evaporative demand on soil moisture by the depth evtgw evaporated from the water table according to Modflow.

18 **itrace**: trace option (y=1,n=0) to print the Julian day at the top of the daily loop.

19 **jkkopt**: option (y=1,n=0) to evaluate groundwater recharge and watershed contribution to streamflow according to a scheme conceived by Prof. James K. Koelliker at KSU for the Rattlesnake basin study, hence the option's name (see "Definition of options for the Modswb package").

pmpeff: pumping efficiency fraction: applied irrigation/water pumped; the loss is assumed to be evaporative.

phideg =latitude (deg); rlamdg = longitude (deg)

Rec. 9: read max. annual irrigation depth (mm/yr) subject to ioplim (above) as follows.

If ioplim=1, annual pumping limits are read from the ~.cod input file for each subbasin from within the annual loop in the mainline for every year as follows:

```
read (10,*) iyr, (pmpmax(j),j=1,lu)
```

if ioplim=2, read irrigation limits for each subbasin as above but only in the first year; these limits then apply to every year.

If ioplim=3, read irrigation limit, constant over all subbasins, for each year.

read (10,*) (pmpmax(k),k=1,nyrs) (9)