

LOWER REPUBLICAN STREAM-AQUIFER PROJECT, FINAL REPORT  
VOL. 2 DEVELOPMENT AND DOCUMENTATION OF A COMBINED  
WATERSHED AND STREAM-AQUIFER MODELING PROGRAM

by

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# LOWER REPUBLICAN STREAM-AQUIFER PROJECT FINAL REPORT

## VOL. 2. DEVELOPMENT AND DOCUMENTATION OF A COMBINED WATERSHED AND STREAM-AQUIFER MODELING PROGRAM

Sam P. Perkins and Marios Sophocleous  
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## Preface

Volume Two of this report is intended to describe the methods and procedures followed in our study of the Lower Republican River Basin; and documents the programs developed to integrate existing watershed and groundwater modeling programs, SWAT and MODFLOW, into a coordinated computer model, SWATMOD, that we applied in our study. We begin by presenting overviews of the integrated computer model in Section 1, methods applied in the integrated model in Section 2, procedures followed to obtain data describing the basin in Section 3, and input data required for the model in Section 4. Sections 5-7 document the program "packages" (i.e., functionally related groups of subroutines, a term borrowed from MODFLOW) that were modified (marked by a heavy dot) or developed (marked with an asterisk) and added to SWAT and MODFLOW to integrate them into a combined watershed-stream-aquifer modeling program. The key packages or programs developed at KGS to integrate SWAT and MODFLOW include HYDBAL (Section 5), SWBAVG (Section 6), and MODSWB

(Section 7). Section 5 documents major changes or additions to SWAT in order to integrate the programs into a coordinated model. How to run the combined programs of SWAT and MODFLOW (i.e., SWATMOD) and coordinating file device numbers are documented in the description of SWAT's modified mainline. Section 5 also describes HYDBAL, which writes the hydrologic balance file to be read by either SWBAVG or MODFLOW; and subroutine PENMAN, written to calculate potential evaporation based on the Penman method, and added to SWAT to be called as an alternative to SWAT's original options. Section 6 documents the specially-written program SWBAVG, which approximates the effects of spatial heterogeneities in the watershed that cannot be represented correctly with a lumped model such as SWAT. Section 7 documents the added and modified MODFLOW packages. Operational details of running MODFLOW as a stand-alone program and coordinating file device numbers are documented in the description of MODFLOW's modified mainline. Section 8 describes compiling and linking SWAT and MODFLOW. Section 9 documents programs used as preprocessors to prepare input data for MODFLOW, and Section 10 documents postprocessors used to assist in evaluating standard output written by MODFLOW either as a stand-alone program or as a subroutine called by SWATMOD. Section 11, which provides format instructions for SWAT input data files, serves two purposes. First, it documents additional input to SWAT required to coordinate SWAT and MODFLOW, especially its Options Codes input file (~.cod). Second, it supplements Chapter 3 of the SWAT manual, which lacked format instructions for its input data, since it was assumed that SWAT would be run with a front end (user interface) based on the GRASS GIS system. Sections 1-11 are followed by references and an index to files on accompanying disks, which provide input data and summary results for the base case (1977-1994), baseline, and water-use scenarios (1995-2012) described in volume 1; and the data files and source code corresponding to the sections of the report.

## 1. Overview of SWAT-MODFLOW coordination

We have developed a combined watershed-groundwater modeling program referred to as SWATMOD that integrates SWAT (Arnold et al., 1994), a lumped watershed modeling program, and MODFLOW (McDonald et al., 1988), a distributed stream-aquifer modeling program. This report documents the program's development at Kansas Geological Survey (KGS), and application to a model of the Lower Republican River Basin for the Kansas Water Office (KWO).

Development of SWATMOD was motivated by a need for a combined watershed-stream-aquifer model of the Lower Republican River watershed (Koussis et al., 1994). Initial tests (Sophocleous et al., 1995) were based on a model of a small part of a watershed designated as Y7 at Riesel, TX, with an area of 1.23 km<sup>2</sup> that is gaged and operated by USDA-ARS and used by ARS for SWAT program verification in the SWAT manual (Arnold et al., 1994). During its development, SWATMOD was also chosen to model the Rattlesnake Creek basin in south-central Kansas (Sophocleous et al., 1994) for a joint study by Kansas State University (KSU) and KGS for the Division of Water Resources (DWR), Kansas Department of Agriculture. Consequently, the program's development reflects the requirements of both watershed models, and has benefited significantly from the expertise of those involved in these studies. Although SWATMOD is sufficiently general to accommodate models of both the Rattlesnake Creek and Lower Republican River watersheds, separate versions of the program were applied to each to provide reasonably stable platforms for the separate modeling projects. The Rattlesnake Creek version, referred to as SWATMOD95, is documented in Appendix I of the final report to DWR by the KGS and KSU teams (unpublished as of this writing); and the Lower Republican River version, referred to as SWATMOD96, is documented here in Vol. 2 of our report to KWO. Where a distinction between the two versions is unnecessary, the integrated program is referred to simply as SWATMOD.

Most of the component input data for SWATMOD are described by the respective manuals for SWAT (Arnold et al., 1994) and MODFLOW (McDonald et al., 1988;

in which it is read, under the assumption that input files are maintained by a user interface accompanying SWAT that runs under GRASS, a public domain, raster-based graphical interface system (GIS). However, ArcInfo™ is the GIS used 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 ArcInfo was not available during program development, a preliminary version of one has been developed (L. Bian, personal communication), although it does not take into account revisions to input data format for SWAT, which are summarized as follows.

Revisions to SWAT's original input data format include its input control file (\*.cod), where options are specified regarding coordination of SWAT and MODFLOW, and variations on original SWAT procedures; and input files for soils and weather data, whose formats were revised to conform more closely to version 1 of SWAT (1993).

An extension to the SWAT manual has been written to describe SWAT's input format, including these revisions. This extension is included in this report as "SWAT input data format", and inserted after Section 3.3 of the SWAT manual as Section 3.4, to assist in preparation of input files in the absence of a GIS-based preprocessor. As an alternative, spreadsheet templates can be set up to export text files conforming to SWAT input file formats described by this extension.

Changes to MODFLOW input format are intended not to interfere with standard input as described by MODFLOW's manual. Both the STREAM and WELL packages contain nonstandard input options which have been put to use for the Lower Republican River Basin model, and which are summarized below (see Section 4, p. 28).

The MODSWB package, written by the authors, associates (a) subbasin outflows with reaches of a stream network specified with MODFLOW's STREAM package; and (b) the areal extent of each subbasin with grid cells of the aquifer, which is accomplished with the integer array, IBSHED, in a fashion similar to the use of the IBOUND array in MODFLOW's BASIC package. If SWAT and MODFLOW are executed separately, MODSWB also reads a hydrologic summary of results for each aquifer time step from a balance input file written either by SWAT, through the specially-written subroutine

HYDBAL, or by SWBAVG, which calculates a weighted average of balance files written by SWAT to represent the watershed's heterogeneity.

SWAT and MODFLOW are coordinated either by independent execution with data transfer by file, or by linked execution with data transfer by access to common memory. Their interaction is handled by two sets of subroutines developed for this purpose, which are HYDBAL, a "package", or set of subroutines called by SWAT; and MODSWB, a package called by MODFLOW. A third program, SWBAVG, combines results from SWAT to represent spatial heterogeneity existing within the watershed with respect to soil type and land use based on the "hydrologic response unit" (HRU) concept summarized below ( see also Section 2, p. 13).

SWAT begins by reading the input files associated with a particular case, and opening those with daily values (weather data). SWAT calculates hydrologic fluxes for each subbasin of the watershed on a daily basis and accumulates them over the aquifer time step, designated to be a day, month, or year; an average over all years of simulation is also calculated. At the end of each aquifer time step, SWAT calls subroutine HYDBAL to summarize recharge, irrigation, evaporation, and tributary flow to streams for each subbasin; to calculate a mass balance on soil, stream, and aquifer control volumes; and to write a hydrologic summary to a "balance" file.

SWBAVG represents spatial heterogeneities existing within a watershed by producing a composite of eighteen combinations of the six soil types and three land use/management schemes used to characterize the watershed. A "hydrologic response unit" is defined for each of these combinations, i.e., a separate case of the watershed model is simulated by SWAT in which the watershed is assumed to be homogeneous in the characteristics of that soil-land use combination. A composite of the HRUs is produced by calculating an areally weighted average of the HRUs. Separate composites are calculated for each subbasin and hydrologic depth calculated by SWAT. The resulting weighted average is written to a balance file in the same format as the eighteen components on which it is based for input to MODFLOW. The weight functions used to calculate the averages are given by the areal fractions of the watershed represented by the

HRUs. The weight functions are distinct for each subbasin and time step, and are calculated by program WEIGHTS.

The Soil Water Balance (MODSWB) package was written for MODFLOW to provide an interface between SWAT's lumped parameter model of a watershed and MODFLOW's distributed parameter model of an aquifer. MODSWB consists of four subroutines whose names and functions conform to the conventions followed in MODFLOW. SWB1AL allocates memory in MODFLOW for the watershed-aquifer interface. SWB1RP maps the geographical extent of a watershed's subbasins onto a gridded aquifer domain, and the subbasin outflows onto a stream network. SWB1FM converts results obtained from SWAT for each subbasin into conditions for MODFLOW's aquifer solution, including recharge, evaporation, and tributary flow to streams; irrigation is handled similarly by the modified WELL and SURFACE packages.

If SWAT and MODFLOW are to be run separately, MODFLOW's subroutine SWB1FM reads a hydrologic summary from a balance file written either by SWAT or SWBAVG; for linked execution in which SWAT calls MODFLOW as a subroutine, the hydrologic summary is passed through memory by subroutines in the HYDBAL package. SWB1BD summarizes baseflow and evaporation from the water table for each subbasin. Both SWB1FM and SWB1BD make necessary conversions between SWAT's hydrologic depths (mm), i.e. flow rates divided by subbasin area, and MODFLOW's flow rates [ $L^3/T$ ].

## 2. METHODOLOGY

The conceptual basis for the integrated watershed model of the Lower Republican River Basin (SWATMOD) is shown schematically in Fig. 5.2 (Vol. 1), and reproduced here as Fig. 1. Watershed control volumes are roughly associated with SWATMOD's component programs as follows. The atmosphere, soil and vadose zones are represented by SWAT. Groundwater is represented by MODFLOW, and the stream network is

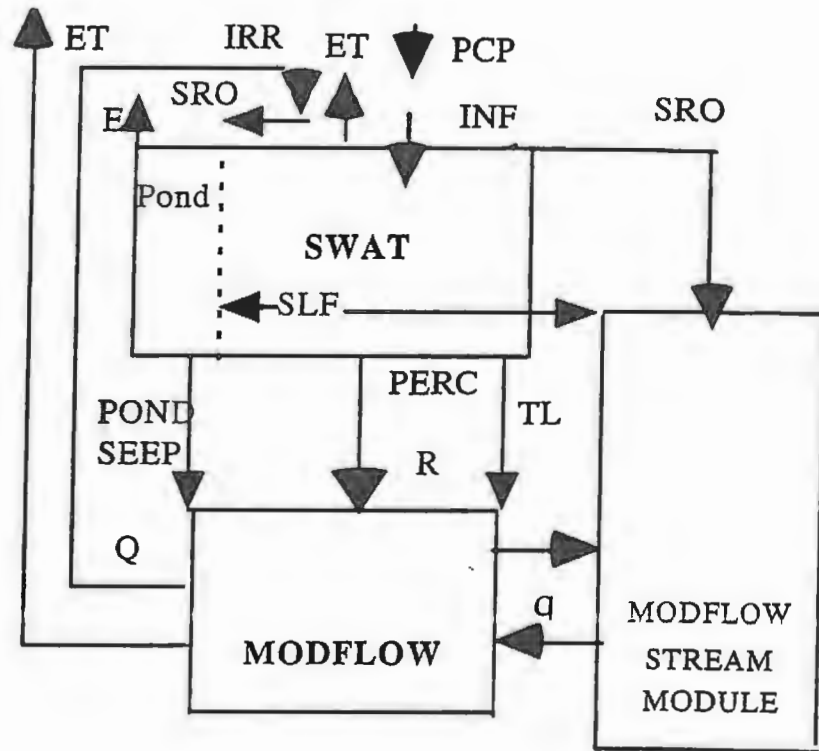


Fig. 1 Schematic block diagram of SWAT/MODFLOW linkages.

represented by MODFLOW's STREAM package. The hydrologic flow paths connecting the control volumes for soil, vadose, aquifer, and stream components are summarized at the end of each aquifer time step as hydrologic depths and written to a hydrologic balance file by the HYDBAL package, specifically written to be incorporated in the SWAT model. This summary, or an average of a number of summaries written by program SWBAVG to represent spatial heterogeneity in the watershed, is passed to MODFLOW through its Soil Water Balance (MODSWB) package, which converts the hydrologic depths to flow rates. For each hydrologic component, the flow rate depends on the depth, the area to which the depth applies, and the solution time step  $\Delta t$  (s). We first give a brief definition of hydrologic terms used in the model, and describe the control volumes in terms of their hydrologic components. We then discuss the relationships used to convert between hydrologic depths for SWAT and flow rates for MODFLOW, the areas to which the depths are applied, and how spatial heterogeneity in the watershed is represented.

## Definition of hydrologic terms used in watershed model

We begin by defining hydrologic terms used in the SWAT model, with reference to corresponding vectors in array SHED (Section 5, p. 97), which stores the values associated with these terms for each subbasin in the MODSWB package. Array vectors 1, 7, and 8 represent areal fractions; and 10–25 represent various hydrologic components as depths, which are calculated by SWAT on a daily basis for each subbasin and accumulated over each aquifer solution time step. Hydrologic depths,  $d$  (mm) represent flow rates per unit area over a time step  $\Delta t$  by  $d = cQ\Delta t/A$ , where  $c$  is a units conversion factor; see p. 13 regarding the relationship between hydrologic depths  $d$  (mm) in SWAT, the areas of the basin to which the depths apply, and the corresponding flow rates in MODFLOW.

These data are passed from SWAT to MODFLOW by a hydrologic balance file (Section 5, p. 49). Some of these hydrologic depths are combined in MODFLOW and converted to flow rates to represent tributary flow to streams and groundwater recharge (array vectors 22 and 25). Evaporation from the water table and baseflow, which are coupled to MODFLOW's solution for aquifer heads, are calculated as flow rates and

converted to depths in MODFLOW (array vectors 18 and 19). The sum of surface and ground water irrigation use (array vector 24) is based on 1) annual estimates of water use and irrigated area; 2) SWAT's revised model of daily irrigation triggered by soil moisture, and 3) MODFLOW's model of diversions from streamflow and from the aquifer for each solution time step (p. 15).

The following hydrologic terms are defined with reference to the vector location in array SHED which stores a value for each subbasin. These terms are then used to define control volumes for the watershed (p. 8).

1  $f_{sj}$  = areal fraction of basin,  $A_j/A$ , for each subbasin area  $A_j$ ;

7  $f_{aj}$  = areal fraction of each subbasin with an underlying aquifer represented by MODFLOW;

8  $f_{pj}$  = areal fraction of each subbasin for which runoff contributes to ponds; the remainder,  $f_{con} = 1 - f_{pond}$  contributes to streamflow (22). Pond seepage (20) appears to be the only hydrologic term calculated by SWAT that is affected by the inclusion of pond contributing areas.

10  $d_{precip}$  = precipitation, input data from National Weather Service (NWS).

11  $d_{irrig}$  = irrigation, specified by management schedule or triggered by conditions of soil moisture or plant stress factor, and subject to daily and annual maximum limits.

12  $d_{et}$  = evaporation from the ground surface to the atmosphere; given by potential evaporation (21), reduced by soil water deficiency.

13  $d_{surf-runoff}$  = surface runoff, based on NRCS (SCS) procedures;

14  $d_{xmloss}$  = transmission loss, calculated as a fraction of surface runoff (13);

15  $d_{lateral-flow}$  = subsurface (lateral) flow, calculated as part of infiltration routing procedure;

16  $d_{perc-rz}$  = percolation from the root zone; the component of infiltration which remains after lateral flow(15) and soil moisture increases to each soil layer have been assigned by the infiltration routing procedure.

17  $d_{perc-vz}$  = percolation out of the vadose zone into the water table; this is taken to equal  $d_{perc-rz}$  rather than attempting to represent water movement processes in this zone.

18  $d_{\text{et-gw}}$  = evaporation from the water table, based on MODFLOW's EVT package, in which the evaporation decreases linearly with depth to the water table  $d_{\text{drw}}$  to zero at the extinction depth  $d_{\text{drw}}$  from a maximum given by potential evaporation  $d_{\text{et-pot}}$  (21) according to  $d_{\text{et-gw}} = (1 - d_{\text{drw}}/d_{\text{ext}}) \cdot d_{\text{et-pot}}$  for each aquifer grid cell.

19  $d_{\text{baseflow}}$  = baseflow, water flowing from the aquifer to the stream through the streambed as a result of the hydraulic gradient between the stream and aquifer according to Darcy's law. Baseflow is taken to be the negative of streambed leakage as calculated by MODFLOW's STREAM package (Prudic, 1989).

20  $d_{\text{pond-seep}}$  = pond seepage to the aquifer as represented by SWAT, which is approximately a linear function of the pond contributing fraction  $f_{\text{pond}}$ (8).

21  $d_{\text{et-pot}}$  = potential evaporation, calculated according to the Penman procedure recommended by Shuttleworth in Maidment et al. (1993) as an alternative to SWAT's implementation of Penman-Monteith, Priestley-Taylor, and Hargreaves-Samani methods.

22  $d_{\text{trib}}$  = tributary flow to streams:  $d_{\text{trib}} = f_{\text{con}} \cdot d_{\text{runoff}}$ , where  $f_{\text{con}} = 1 - f_{\text{pond}}$ (8), and  $d_{\text{runoff}} = d_{\text{surf-runoff}}$ (13) +  $d_{\text{lateral-flow}}$ (15). Remaining runoff  $f_{\text{pond}} \cdot d_{\text{runoff}}$  goes to ponds.

24  $d_{\text{irrig}}$  = irrigation depth, given by  $d_{\text{irrig}} = d_{\text{irr-gw}} + d_{\text{irr-surf}}$ , includes gw and surface components, and represents the depth assigned by MODFLOW as the result of coordination of water use estimates specified as input to SWAT, SWBAVG, and MODFLOW; SWAT's daily irrigation model; and MODFLOW's aquifer model for each solution time step.

25  $d_{\text{rech}}$  = groundwater recharge:  $d_{\text{rech}} = d_{\text{xmloss}}$ (14) +  $d_{\text{perc-vz}}$ (17) +  $d_{\text{pond-seep}}$ (20).

## Soil moisture balance calculated by SWAT

SWAT's daily simulation of watershed hydrology is reviewed for each component of a mass balance as follows. The change in soil moisture as a depth can be expressed as a sum of flow components into the soil profile  $Q_i$  over basin area  $A$  for time step  $\Delta t$  given

by  $ds = (1/A)\Sigma Q_i \Delta t$ , or as a corresponding sum of depths. The daily change in soil moisture is represented in SWAT by

$$ds_{\text{soil}} = d_{\text{precip}} + d_{\text{irrig}} - d_{\text{runoff}} - d_{\text{xmloss}} - d_{\text{et}} - d_{\text{perc-rz}} + d_{\text{et-gw}},$$

where  $ds_{\text{soil}}$  is the change in soil-profile moisture over a specified time period (day?), and

$$d_{\text{runoff}} = d_{\text{surf-runoff}} + d_{\text{lateral-flow}}.$$

At time  $t$ , soil moisture is given by  $s(t) = s_0 + \Sigma ds$ , the sum of initial soil moisture  $s_0$  and the accumulation of the daily changes  $ds_{\text{soil}}$ . Daily precipitation is given by NWS data. Irrigation may be specified by a schedule or triggered by conditions of either soil moisture or plant stress factor, and is subject to daily and annual maximum limits.

The annual maximum irrigation depth is based on water use estimates derived from analysis of water use reports from the Division of Water Resources, Kansas Department of Agriculture. Surface runoff, determined in SWAT by the SCS curve-number procedure, varies with the SCS curve number, which is related empirically to soil moisture, surface conditions and land use. Transmission loss is calculated as a fraction of surface runoff. At the top of the soil profile, infiltration is represented by the sum of the first four terms on the right-hand side, i.e.

$$d_{\text{infiltr}} = d_{\text{precip}} + d_{\text{irrig}} - d_{\text{surf-runoff}} - d_{\text{lateral-flow}} - d_{\text{xmloss}}.$$

The infiltration process is represented by a routing procedure downward through each soil layer in which the infiltrate is divided among an increase in soil moisture, lateral flow (subsurface runoff), and percolation to the layer below. Percolation out of the bottom layer  $d_{\text{perc-rz}}$  is assumed to pass through the vadose zone into the aquifer.

Evapotranspiration is represented similarly by a routing procedure upward through each soil layer in which evaporative demand represented by potential evaporation  $d_{\text{et-pot}}$  is divided between soil moisture loss and plant root extraction, both of which are subject to reductions due to soil moisture deficiency. This routing procedure has been modified to include the effect of evaporation from a shallow water table  $d_{\text{et-gw}}$ , calculated by MODFLOW for each solution time step as a linearly decreasing function of depth to zero at the extinction depth, with a maximum given by potential evaporation for a water table at the ground surface. In a linked execution of SWAT and MODFLOW, an approximation of this model is applied in SWAT on a daily basis. A procedure to

calculate potential evaporation as recommended by Shuttleworth in Maidment (1993) has been added to SWAT, primarily so that the effects of not only (short-wave) absorption but also (long-wave) emission are included. The change in soil moisture  $ds_{\text{soil}}$  given by the equation above includes the errors introduced by the approximations and routing procedures used to represent the terms on the right-hand side of the equation.

If pond contributing fractions are nonzero, the corresponding component of runoff  $f_{\text{pond}} \cdot d_{\text{runoff}}$  goes to ponds, with the remainder treated as tributary flow to streams. The evident result of this is to produce pond seepage, which increases with noncontributing fraction  $f_{\text{pond}}$ , and is treated as a component of groundwater recharge. Since recharge contributes to baseflow, this “noncontributing” component can ultimately contribute to streamflow. Pond seepage, as simulated by SWAT, is not included in the above soil balance, since it goes directly to groundwater without passing through the soil profile.

## Moisture flow in the vadose zone

A simplified model of moisture flow processes in the vadose zone is used in which percolation from the root zone is taken to equal percolation out of the vadose zone. Similarly, any uptake from the water table is assumed to flow upward, without change in storage within the vadose zone, into the root zone as  $d_{\text{et-gw}}$ .

## Mass balances for groundwater and streamflow

Mass balances are calculated by MODFLOW for groundwater and streamflow in terms of flow rates. MODFLOW’s groundwater mass balance (“budget summary”) is calculated for each solution time step. As a flow rate  $dS/dt$ , this balance is expressed in terms of the net inflow to the aquifer for each hydrologic component by

$$(dS/dt)_{\text{gw}} = Q_{\text{const}} + Q_{\text{rech}} - Q_{\text{irr-gw}} - Q_{\text{et-gw}} - Q_{\text{baseflow}}$$

On the right-hand side are terms for constant heads, recharge, irrigation pumping, evapotranspiration from groundwater, and baseflow; their sum is the change in storage on the left-hand side. MODFLOW has its own idiosyncratic definition for storage given by  $S_{\text{mod}} = -S_{\text{gw}}$ , so that the above mass balance is expressed as

$$E_{gw} = dS_{mod} + Q_{const} + Q_{rech} - Q_{irr-gw} - Q_{et-gw} - Q_{baseflow},$$

where  $E_{gw}$  is the mass balance error. The streamflow mass balance, also expressed as a net inflow for each component, is given by

$$(dS/dt)_{str} = (Q_{in} - Q_{out}) + Q_{trib} - Q_{irr-surf} + Q_{baseflow}.$$

On the right-hand side are terms for net inflow ( $Q_{in} - Q_{out}$ ), tributary flow  $Q_{trib}$ , surface water diversion  $Q_{irr-surf}$ , and baseflow  $Q_{baseflow}$ . MODFLOW's STREAM package (Prudic, 1989) routes streamflow essentially by applying the above equation to each stream reach, with the storage term on the left-hand side set to zero as a result of neglecting flood wave travel time. Stream yield (net outflow) is given by rearranging this equation, holding the storage term to zero:

$$Q_{out} - Q_{in} = Q_{trib} - Q_{irr-surf} + Q_{baseflow}.$$

## Watershed connections to groundwater and streamflow

Groundwater recharge, tributary flow to the Republican River, and irrigation are calculated by SWAT as hydrologic depths and converted to flow rates to be used as input to MODFLOW's solution, while baseflow and evaporation from groundwater are results of MODFLOW's solution. The basis of each of these terms is summarized below.

Recharge is given by the sum of transmission losses, percolation, and pond seepage calculated in SWAT as

$$d_{rech} = d_{xmloss} + d_{perc-vz} + d_{pond-seep}$$

Tributary flow from subbasins to the Republican River is the contributing fraction of the sum of surface and subsurface runoff,  $d_{trib} = f_{con} d_{runoff}$  (p. 8). Irrigation depth calculated by SWAT is supplied in MODFLOW by a combination of diversion points from groundwater and the Republican River, i.e.  $d_{irrig} = d_{irr-gw} + d_{irr-surf}$  (p. 15); corresponding components are shown above in the mass balances for groundwater and streamflow.

Evaporation from groundwater and baseflow to the stream are both coupled to MODFLOW's solution for the aquifer's hydraulic head, and are solved simultaneously with the head distribution. Evaporation from groundwater is solved in the EVT package for each grid cell according to

$$q_{et-gw} = (1 - d_{drw}/d_{ext}) \cdot q_{et-pot},$$

which decreases linearly with depth to water  $d_{drw}$  from a maximum given by the potential evaporation rate to zero at the extinction depth,  $d_{ext}$ .

Baseflow depends on the hydraulic gradient between the aquifer and the stream stage across the streambed according to Darcy's law, and is calculated in MODFLOW's STREAM package (Prudic, 1989). Evaporation from groundwater and baseflow are converted to hydrologic depths as described below.

## Hydrologic pathways and heterogeneities within the watershed

If the Lower Republican River basin were spatially homogeneous, depth  $d_i$  and flow rate  $Q_i$  for each hydrologic component (i) would be related by the equation  $Q_i \Delta t = d_i A / c$ , where  $A$  = basin area and  $c$  = units conversion factor. However, the basin's geomorphology possesses important heterogeneities, including the alluvial valley aquifer, various soil types, and the basin's contributing and noncontributing component (with respect to runoff), which combine to produce heterogeneities associated with land use, including crop type and irrigation. The alluvial aquifer in the Republican River valley underlies approximately 13 percent of the basin. The hydrologic pathways of recharge, baseflow, and evaporation from shallow groundwater are defined only for this part of the basin. Both the alluvial aquifer's presence and soil type affect land use. Crops that are heavily dependent on irrigation, primarily corn, are grown mostly in this part of the basin. Irrigated cropland, which represents approximately 4 percent of the basin, is supplied primarily by the alluvial aquifer and streamflow; water use supplied by the deeper Dakota aquifer plays a relatively minor and more homogeneous role in the basin. Within the noncontributing component of the basin (approximately 2 percent), surface and subsurface runoff flows to ponds instead of the river.

Heterogeneities within the Lower Republican River basin are represented by a combination of methods by the three model programs of SWAT, SWBAVG, and MODFLOW. First, for a given lower Republican River valley case represented by SWAT, the watershed is broken into nine subbasins along hydrologic divides. Each subbasin is characterized primarily by data for weather, soil type, land use, and ponds.

Second, heterogeneities that exist within subbasins with respect to soil types and land use/management, which includes irrigation, are represented using SWAVG that is based on the “hydrologic response unit” (HRU) concept. Third, MODFLOW applies hydrologic depths for recharge and baseflow only to the aquifer fraction of the basin, and runoff to streamflow only to the contributing fraction of the basin. This is done as an alternative to the HRU concept, to which its approximate equivalence is described below.

## **Representing heterogeneity with a lumped model of a watershed**

The Lower Republican River Basin is represented by six soil types summarized as Carr, Crete, Hastings, Hedville, Kipson, and Muir; and three land use/management schemes summarized as irrigated corn; a nonirrigated rotation of wheat, sorghum and fallow; and pasture. These are represented by eighteen combinations of soil type and land use. Each combination (or “case”) of soil type and land use defines a “hydrologic response unit” (HRU), in which all subbasins represented by input data to SWAT are assigned the characteristics of that soil type and land use, and execution of SWAT for each case results in a hydrologic summary written for each aquifer time step and subbasin to a balance file (Section 5, p. 49). The balance files for all HRUs are then averaged by program SWBAVG for each subbasin and hydrologic component to represent the combined effect of soil types and land uses within the watershed. The averages are based on weight functions, one per subbasin, representing the set of areal fractions corresponding to the combinations of soil type and land use existing within the subbasin. The weight functions, calculated by program WEIGHTS, are updated as land use (i.e. area irrigated) changes over time.

MODFLOW obtains hydrologic fluxes as depths (mm) either directly from SWAT or indirectly by way of averages calculated by SWBAVG; each depth is converted to a flow rate that corresponds to the relevant areal fractions of the basin. This relationship is expressed in the equation  $Q_i c \Delta t = d_i f_i A$ , where  $A$  = basin area ( $m^2$ ),  $f_i$  = fraction  $A_i/A$  of basin area to which depth  $d_i$  pertains, and  $c$  = units conversion factor (described above). The areal basin fractions  $f_i$  are summarized as follows for the watershed connections:

<u>hydrologic connection</u>	<u>relevant areal fraction, <math>f_i = A_i/A</math></u>	
tributary flow (runoff to streams):	contributing area	$f_{con} = 0.98$
recharge, baseflow, $et_{gw}$	aquifer area	$f_{aqf} = 0.126$
<u>irrigation</u>	<u>irrigated area</u>	<u><math>f_{irr} = 0.039</math> (avg annual)</u>

Contributing and aquifer areas vary over the subbasins but are constant over time.

Irrigated area is constant over all subbasins but varies slightly over time with a range from 3.13 to 4.77 percent, according to our estimate based on water use reports (Vol. 1). For a 365-day year, depth  $d_i$  corresponds to a flow rate given by  $Q_i = 2.8775d_i f_i$ . Going the other direction, the total basin flow rate  $Q_i$  is converted to an average depth  $d_i$  with respect to subarea  $A_i$  by  $d_i = Q_i(c\Delta t / A_i)$ ; and the average depth with respect to the entire basin area is given by  $d_i f_i = Q_i(c\Delta t / A)$ .

## Relating hydrologic depths and flow rates for each subbasin

Each of the contributing, aquifer, and irrigation areas as fractions of the basin area can be expressed as a mean taken over the subbasins,  $f_i = \sum f_{ij} f_{sj}$ , in which weight functions are subbasin areal fractions,  $f_{sj} = A_{sj}/A$ , and  $f_{ij} = A_{ij}/A_{sj}$  are the component fractions being averaged.

Similarly, the flow rate for hydrologic component  $i$  and subbasin  $j$  is given in terms of depth  $d_{ij}$  by  $Q_{ij} = d_{ij} f_{ij} f_{sj} A / (c\Delta t)$ , and the total basin flow rate for component  $i$  is given by  $Q_i = \sum Q_{ij}$ . The mean basin depth  $d_i$  is given either in terms of the basin-wide expression  $d_i f_i = Q_i(c\Delta t / A)$  or by substituting into it the above expressions for  $Q_i$  and  $Q_{ij}$  to obtain  $d_i = (1 / f_i) \sum d_{ij} f_{ij} f_{sj}$ .

While the application of different areal fractions  $f_i$  to different hydrologic components  $i$  to calculate flow rates in MODFLOW may appear inconsistent, suggesting violation of mass conservation, this procedure is instead a consequence of the heterogeneities existing within the basin. In the case of irrigation ( $i = 3$ ), individual SWAT cases represent each subbasin as homogeneously irrigated to an annual depth  $d_{ij}$  that is tied to annual estimates described below. The combination of HRUs in SWB AVG incorporates the irrigated area fraction into the irrigation depths for each subbasin as

$d_{ij}f_{ij}$ , which are then multiplied by  $f_{sj}A/(c\Delta t)$  in MODFLOW to obtain  $Q_{ij}$ . In the case of hydrologic terms associated with contributing and aquifer area fractions ( $i = 1$  and  $2$ ), SWBAVG is not used to factor these areal fractions  $f_{ij}$  into the hydrologic depths  $d_{ij}$ ; instead, MODFLOW factors does this, multiplying  $d_{ij}$  by  $f_{ij}f_{sj}A/(c\Delta t)$  to again obtain  $Q_{ij}$ . Presumably, these heterogeneities could be represented equivalently according to the HRU concept in SWBAVG. A test of this possible equivalence is described below.

The forward model represented by the combined use of SWAT, SWBAVG, and MODFLOW introduces approximation errors due not only to the various methods of handling heterogeneity within the watershed, but also to the methods used in SWAT and MODFLOW to represent the various components of watershed hydrology. These errors are countered by the calibration process, in which errors are minimized for the target parameters of aquifer head, stream yield, and irrigation water use.

## Relating irrigation depths in SWAT and SWBAVG to flow rates for MODFLOW

Annual estimates of water use  $Q_i$  and corresponding irrigated area  $f_iA$  and depth  $d_i$  according to the equation  $Q_i c\Delta t = d_i f_i A$  are based on analysis of water rights and water use data from DWR for both surface and ground water irrigation (Vol. 1). These estimates are used to specify data for SWAT, SWBAVG, and MODFLOW to represent irrigation water use as follows.

First, the annual water use estimates are specified by MODFLOW's input data as average annual pumping rates for irrigation wells and surface water diversions; let  $Q_A = \sum q_{gk} + \sum q_{sk}$  denote the sum of average annual use over all ground and surface water points of diversion for irrigation represented by  $q_{gk}$  and  $q_{sk}$ .

Second, for the HRUs with irrigation, SWAT input data ( $\sim$ .cod files) specify annual irrigation depth limits  $d_i$  that are given by the water use estimates. These annual depth limits apply to SWAT's daily simulation in which irrigation can be applied as a result of schedules in the management ( $\sim$ .mgt) files and soil moisture deficiency or plant stress factor thresholds ( $\sim$ .cod and  $\sim$ .mco files).

Third, annual estimates of irrigated area fractions  $f_i$  are incorporated by program WEIGHTS into weight functions, which are then applied by program SWBAVG to average the HRUs calculated by SWAT as daily, monthly, or annual summaries of accumulated depths for each subbasin as  $d_{ij}f_{ij}$ . The resulting depths for each hydrologic component are read by MODFLOW's soil water balance (SWB) package and converted to flow rates  $Q_i$  over the appropriate areas  $f_iA$  according to  $Q_i c \Delta t = d_i f_i A$  as described above for representing heterogeneities in the basin.

For monthly aquifer solution time steps, the heterogeneous irrigation depths calculated by SWAT and SWBAVG as  $d_{ij}f_{ij}$  are read by MODFLOW's MODSWB package from the balance file, and converted to a total pumping rate  $Q_i$  for the entire basin. This irrigation flow rate for the month is divided by the annual average pumping rate  $Q_A$  for the basin specified by MODFLOW's input, resulting in a scaling factor  $s = Q_i / Q_A$ . This is multiplied by the annual average rate of irrigation use specified by input to MODFLOW's Well and Surface packages for each individual point of ground and surface water diversion  $k$  as  $s \cdot q_{gk}$  and  $s \cdot q_{sk}$ , respectively. During peak irrigation months, this scaling factor may increase the average annual rates by more than an order of magnitude; in months without irrigation,  $s = 0$ . If a maximum pumping rate is specified (PMPMAX on line 1 of the Well input file, Section 5, p. 75), and the largest scaled pumping rate exceeds this maximum, each individual well is assigned a scaled value of the average pumping rate for all wells, i.e.  $s\bar{q}_g$  and  $s\bar{q}_s$ , where  $\bar{q}_g = \Sigma q_{gk}$  and  $\bar{q}_s = \Sigma q_{sk}$ . Monthly aquifer time steps provide an improvement over annual time steps in simulating the effect of irrigation use on both groundwater and streamflow, which are hydraulically coupled through streambed leakage.

The annual water use assigned in MODFLOW should match the annual estimated water use  $Q_A$  specified by MODFLOW's input, allowing for discrepancies introduced by simulation conditions in SWAT and MODFLOW as follows. In SWAT, automatic application of daily irrigation based on soil moisture (or plant stress factor) threshold may result in either using less than the annual limit or running into the annual limit part way through the growing season. In MODFLOW, irrigation pumping rates are subject to two

constraints which we have introduced into the Well package. First, a well's pumping rate  $q$  is decreased from its assigned rate  $q_r$  if the aquifer's saturated thickness  $y$  declines too much: a saturated thickness between  $y_0 = 5$  ft and  $y_1 = 10$  ft results in a linear scaling of the pumping rate by a factor of from 0 to 1 according to  $q = q_r(y - y_0) / (y_1 - y_0)$ , and  $q = 0$  for  $y < y_0$ . Second, irrigation pumping rates are limited to a maximum value set at 4 cfs (approximately 1800 gpm), which limits the scaling factor  $s$  based on irrigation assigned by SWAT as described above.

Water use is varied about the base case in sensitivity analysis and about the baseline in water management scenarios by varying  $f_{\text{irr}}$  with  $Q$  in order to maintain the equality expressed by  $Q_i c \Delta t = d_i f_i A$ . Rationale for varying irrigation fraction instead of  $d_{\text{irr}}$  is as follows. The annual irrigation depth  $d_{\text{irr}}$  is treated as an upper limit by SWAT, so that less irrigation may be simulated by SWAT than that specified by  $d_{\text{irr}}$ . With a soil moisture threshold of 0.70 (fraction of available field capacity) and a daily application rate of 0.5 in (12.7 mm), we obtain a satisfactory match between estimated water use and irrigation assigned by SWAT. Representing other scenarios for water use by varying  $f_{\text{irr}} A$  with  $Q$  instead of  $d_{\text{irr}}$  avoids (a) a mismatch in SWAT based on the assumed soil moisture threshold, and (b) rerunning the individual cases of SWAT that represent the eighteen HRUs, and instead requires only that the weight functions be recalculated by program WEIGHTS and applied to the base case HRUs by program SWBAVG.

### 3. PROCEDURES TO COLLECT, RETRIEVE, AND REDUCE DATA

We summarize procedures used to obtain data and for converting or reducing them into a form to be used in the model, and how the data are used. These procedures are carried out using preprocessors, which were used to prepare parts of the input files for the Lower Republican River Basin model, as described and illustrated below with examples from the study in Section 9.

### **Daily weather data: NWSDAT**

Daily precipitation and minimum and maximum temperatures were obtained for NWS stations in and around the Lower Republican River basin for the study period, 1977-1994. Using the cd-rom data base "NCDC Summary of the Day" (EarthInfo, 1992) from a pc, data were retrieved as text files with a table format. These files were converted into a column format using our program, NWSDAT, which also evaluated the weather files for missing data. The column-formatted daily precipitation and temperature files were read by the watershed simulation program, SWAT.

### **Daily streamflow data: ADAPS (USGS)**

Daily streamflow measurements for the Republican River were obtained for gaging stations at Concordia and Clay Center in order to allow calculated values of daily streamflow at Clay Center and stream yield between Concordia and Clay Center to be compared with measured values. Daily streamflow measurements were retrieved from the USGS ADAPS data base, which was accessed from a pc at KGS by connecting via Telnet to a computer account at USGS in Lawrence, KS. The format in which daily streamflow were retrieved (commonly referred to as USGS 2-,3-card format) was converted to a column format by program HYSEPKGS, which also calculated baseflow according to hydrograph separation techniques; only the format conversion function of this program was used. Procedures used to access ADAPS, retrieve daily streamflow measurements and convert them to a column format with HYSEPKGS are described in Perkins (1994).

Daily streamflow measurements were also obtained as described above for streams in neighboring watersheds: Mill Creek in the Blue River watershed, gaged at Washington; and Chapman Creek in the Solomon River watershed, gaged near Chapman. These data were used to approximate runoff depth (flow rate per unit area), which was compared with runoff depth calculated for the Lower Republican River basin.

### **Republican River flow rate characteristics: YQGAGE**

Flow rate characteristics were obtained for the Republican River at Concordia and Clay Center, which were used in a modified version of MODFLOW's STREAM package (Prudic, 1990), documented below. Flow rate-depth characteristics  $y(Q)$ , commonly

referred to as depth rating curves, were retrieved from ADAPS in an array format that was converted to a column format by program RATCRV. The retrieval and postprocessing of these data are described in Perkins (1994). Curve fitting was used to reduce these depth rating curves to the functional form  $y = aQ^b$ .

Flow rate calibration measurements (transverse profiles of stream depth and flow velocity) for Concordia and Clay Center, were obtained from Mr. Butch Laycock, USGS, Lawrence, KS office. These data were used to approximate stream width  $B$ , wetted perimeter  $P$ , and transverse sectional area of flow  $A$  as functions of stream depth  $y$  calculated by program PROFILE. Flow rate characteristics for Concordia and Clay Center gaging stations were coded in subroutine YQGAGE, which is called by the modified version of the STREAM package (described below) in order to represent streamflow in a natural channel.

### **Geographical and grid coordinates for legal descriptions of locations: TSTGRD**

Locations of appropriated points of diversion for both surface and ground water are given as legal descriptions (township, range, section and subsection) in data from DWR. Legal descriptions of locations taken from USGS 1:24000 scale maps were also used to identify or verify well locations in the field for our water level survey, and to identify locations of stream and river reaches. A regular grid of square cells  $1 \text{ mi}^2$  in area was used for our alluvial aquifer model area. This grid was constructed using ArcInfo™ geographical information system (GIS) based on a rectangle, 39 miles east to west and 23 miles north to south, using an Albers (equal area) projection. This rectangle was located so that its grid lines coincided approximately with township range boundaries, with an error estimated to be 50-200 m, which is no worse than the range of error associated with an indirect mapping via successive transformations through geographical and projected distance coordinates. Because of this approximate coincidence of the model grid with township section boundaries, legal descriptions of locations were mapped onto the grid by way of two separate paths. Geographical (latitude, longitude) coordinates were calculated from legal descriptions by calls to subroutine LEOCVT (Ross, 1990), and passed to ArcInfo for analysis and display on maps. Legal locations were also mapped directly onto

grid (row, column) coordinates corresponding to township sections by calls to subroutine TRGRID for such purposes of selecting water rights within the gridded aquifer domain; calculating distances between water diversion points and nearest stream reaches for comparison with similar calculations via ArcInfo; and constructing input files for MODFLOW.

Program TSTGRD first calls LGL2GEO to interpret the subsection description according to one of four possible conventions; and then calls LEOCVT and TRGRID to calculate both geographical and grid coordinates given legal coordinates. The use of TSTGRD to map well locations for our water level survey is described below. Program TSTGEO works the same way as TSTGRD, except that TRGRID is not called to calculate grid coordinates. Subroutines LEOCVT and TRGRID are also called within preprocessors STRMDATA and WRREPUB to construct input files for MODFLOW's STREAM, WELL, and SURFACE packages.

### **Stream geography and bed slope: STRMDATA**

Distance measurements along the Republican River were taken from USGS maps at 1:24000 scale along the Republican River from north of Concordia to South of Clay Center. Stream reach lengths between contours and within each township section were measured; the model grid was designed to coincide with township sections. Program STRMDATA read these measurements, approximated bed slopes based on stream length between contours, and consolidated multiple stream reaches crossing a given grid cell, so that each model grid cell represented in MODFLOW referred to no more than one stream reach in MODFLOW's Stream package. STRMDATA writes a list of consolidated stream reaches in a format to be read by a modified version of MODFLOW's STREAM package to represent stream-aquifer interaction along the Republican River from Concordia to Clay Center; and a list of correspondences between tributaries and stream reaches along the Republican River in a format to be read by the MODSWB package. Results from STRMDATA are incorporated into the following input files for these MODFLOW packages:

**rpann.str:** input file for the modified STREAM package for an annual aquifer time step;  
**rpmcn.str:** STREAM input file for a monthly aquifer time step.

rpann.swb: input file to the Soil Water Balance (MODSWB) package, to map the geographical extent of watershed subbasins onto the gridded model area; and subbasin runoff exit points representing tributaries onto Republican River reaches.

### **Ground-Water level survey during November 1994: SURFELEV**

Water levels were measured at 80 wells whose locations are distributed along the Republican River alluvial valley from north of Concordia to south of Clay Center. Program TSTGRD was used to map well locations from their legal descriptions onto grid coordinates (row, column) with subr TRGRID; and onto geographical coordinates (longitude, latitude) with subr LEOCVT (Ross, 1990).

Ground water level measurements taken in November 1994 as part of this study are listed in Appendix 3B3 (vol. 1). Program SURFELEV wrote these measurements to file dtw94nov.wel according to MODFLOW's modified WELL package input format, so that it may be simply appended to file gwuadmnu.wel, written by WUREPUB (below) to be treated as part of the 1994 water use data set and thereby included in the comparison with MODFLOW's calculated heads.

### **Water rights: WRREPUB**

A detailed description of ground and surface water rights obtained from DWR was processed by our program WRREPUB, which was used to set up lists of ground and surface water rights lying within active nodes (solution space) of gridded area in our study area along the Republican River's alluvial valley. These lists, containing location and annual appropriation of points of diversion, were used in the analysis of water use reports as described below. As with the water level survey (above), legal descriptions of well locations were mapped onto grid and geographical coordinates by calls from WRREPUB to subroutines TRGRID and LEOCVT (Ross, 1990), respectively.

Input: detailed description of ground and surface water rights from DWR (file klrpd.prm);  
Output: condensed descriptions of water rights within active nodes of aquifer model.

### **Water use estimates: WUREPUB**

With the aid of program WUREPUB, ground and surface water use for years 1977-1994 were estimated for those water rights identified to be within the alluvial

domain of interest as described above. Water use estimates are based on reported use for years 1980-1993 and on precipitation models for the remaining years.

Input: water use reports from DWR for years 1980-1993;

Output describing water use estimates for 1977-1994:

(a) annual water use estimate summaries of ground and surface water use:

gwuadmnu.sum and swuadmnu.sum.

(b) estimated annual ground (gwuadmnu.wel) and surface (swuadmnu.wel) water use for individual points of diversion.

The files describing individual points of diversion are to be read by MODFLOW according to the input instructions given in this report for the modified Well and Surface packages below. These files contain some or all of the following data for each diversion:

- 1) annual water use estimates and appropriation; used in coordination with SWAT and SWBAVG to determine annual or monthly diversion rates.
- 2) water level measurements either provided as part of the water use data from DWR for some of the wells, or based on our water level survey in November 1994; used in Modflow Well package, subr. WEL1WR to calculate residuals (solution error).
- 3) application number, distance from stream, and index to closest stream reach, which are used in Modflow Well package, subr. WEL1F0 as criteria for selection or water use scaling according to scenarios.

## **Water use management scenarios (USEMGT)**

Well pumping rates are scaled and selected according to management scenarios 1-11 (Ch. 10, vol. 1). Scenarios are specified by input to the MODSWB package, and implemented in the WELL package subroutine WEL1RP by calls to subroutine USEMGT (below). The same procedure is applied to surface water rights in the Surface package subroutine SRF1RP by calls to USEMGT. At the beginning of each stress period (year), USEMGT selects or scales individual water rights according to the scenarios, which are identified on the first line of the Soil water balance input file ~.SWB by variables *welmpy* and *iadcod*. An alternative means of representing water use scenarios would be with the preprocessors WRREPUB and WUREPUB to set up input files for the Well and Surface packages corresponding to each scenario. For this study water use scenarios

were implemented by calling subroutine USEMGT from subroutines WEL1RP and SRF1RP, which was viewed as more direct and less error prone with less data handling.

Subroutine USEMGT is listed below to show how scenarios are implemented.

```

-----
      subroutine USEMGT (iadcod,welmpy,dsstrm,iappno,Q,Qwr)
c ----      implement water use management scenarios-----
-----
c iadcod: use management option: this subroutine handles options 1-11 excepting 6-8,
defined below.
c welmpy: if iadcod > 0, scaling factor applied to water use for each water right;
c         if iadcod < 0, welmpy specifies a use fraction that is to be applied to all
c         water rights for all stress periods (years).
c dsstrm distance from water right to stream (miles)
c iappno water right application number;
c Q      estimated use for a water right (cfs for Repub. R. model);
c Qwr   appropriation for a water right (cfs for Repub. R. model).
c List of scenarios:
c 1 Reduce water rights by 25%;
c 2 Shut off all water rights junior to 3/22/74 (application numbers > 22310);
c 3 Shut off all water rights junior to 4/12/84 (application numbers > 37147);
c 4 Shut off all water rights within distance of 1/4 mi to Republican River;
c 5 Shut off all water rights within distance of 1/2 mi to Republican River;
c 6 Increase irrigated cropland area by 10%;
c 7 Decrease irrigated cropland area by 10%;
c 8 Increase pond storage by 25% (increase pond area by 25%);
c 9 Combine 2 and 4: shut off water rights junior to 3/22/74 within 1/4 mi of river;
c 10 Combine 3 and 5: shut off water rights junior to 4/12/84 within 1/2 mi of river;
c 11 Combine 9 and 10 as follows: shut off all water rights junior to 3/22/74 within
c     1/4 mi of river, and all water rights junior to 4/12/84 within 1/2 mi of river.
-----
c
      if (iadcod.eq.-1) then
        Q = welmpy*Qwr      ! use = avg use fraction times appropriation, Qwr
      else if (iadcod.gt.0) then
c         apply administrative options on water rights restrictions to Qnew:
c         > 0: multiply use and appropriation by factor welmpy:
        Q = welmpy*Q
        Qwr = welmpy*Qwr
        iadmin=0 !assume no use restriction, subject to options below:
        if (iadcod.eq.2) then
c           2: shut off add'l water rights after 3/22/74:
            if (iappno.gt.22310) iadmin=1
        else if (iadcod.eq.3) then
c           3: shut off add'l water rights after 4/12/84:
            if (iappno.gt.37147) iadmin=1
        else if (iadcod.eq.4) then
c           4: shut off water rights closer than 1/4 mile from Republican R.
            if (dsstrm.lt.0.25) iadmin=1
        else if (iadcod.eq.5) then
c           5: shut off water rights closer than 1/2 mile from Republican R.
            if (dsstrm.lt.0.5) iadmin=1
        else if (iadcod.eq.9) then
c           9: shut off add'l water rights after 3/22/74 within 1/4 mi of river
            if (iappno.gt.22310 .and. dsstrm.lt.0.25) iadmin=1
        else if (iadcod.eq.10) then
c           10: shut off add'l water rights after 4/12/84 within 1/2 mi of river
            if (iappno.gt.37147 .and. dsstrm.lt.0.5) iadmin=1
        else if (iadcod.eq.11) then
c           11: shut off add'l water rights after 3/22/74 within 1/4 mi of river;
c              shut off add'l water rights after 4/12/84 within 1/2 mi of river
            if ((iappno.gt.22310 .and. dsstrm.lt.0.25) .or.
1          (iappno.gt.37147 .and. dsstrm.lt.0.5)) iadmin=1
        end if
        if (iadmin.eq.1) then
            Q = 0.
            Qwr = 0.
        end if
      end if !iadcod > 0
      return
      end

```

## 4. OVERVIEW OF INPUT DATA REQUIRED FOR SWATMOD

### **Model input: defining a case to be run**

A specific instance, or case, of the Lower Republican River basin model is defined by data for programs SWAT, SWBAVG, and MODFLOW. Data are required for SWAT that describe the eighteen homogeneous components (HRUs) corresponding to six soil types and three land use management schemes. For each of these HRUs, a daily simulation of SWAT is run for eighteen years, and a "soil water balance" file is written that summarizes the HRU's results for each aquifer time step, subbasin, and hydrologic flux. Program SWBAVG calculates a weighted average based on the balance files for these HRU's and a weight function calculated by program WEIGHTS, and writes an average balance file that is read as part of MODFLOW's input to specify primarily recharge, tributary flow, and irrigation. The data for each of these three components are summarized below.

### **SWAT input**

The names of most input and output data files associated with a run of SWAT are summarized on a file which must be named FILE.CIO at time of SWAT's execution. Such a file corresponding to each HRU is named according to a combination of prefixes corresponding to soil type and land use management represented by the HRU, and then is renamed to the mandatory FILE.CIO just prior to executing SWAT. Soils and corresponding prefixes are Carr (CARR), Crete (CRET), Hastings (HAST), Hedville (HEDV), Kipson (KIPS), and Muir (MUIR). Land use management schemes and corresponding prefixes for annual and monthly aquifer time steps, respectively, are as follows: (1) wheat, sorghum, and fallow rotations without irrigation (WSF, WSM); (2) irrigated corn (IRC, IRM); and (3) range and pasture (PAS, PAM). For example, the annual versions for HRUs with Carr soils have the prefixes CARR-WSF, CARR-IRC, and CARR-PAS. Certain additional file names are specified in the ~.COD file, whose name is given in the ~.CIO file corresponding to a particular HRU, and which specifies most of the standard, modified, and added options for SWAT execution. Standard

SWAT output is to file ~.STD, named by the ~.CIO file. A special output file ~.BAL summarizes the hydrologic fluxes calculated by SWAT for each basin and for each aquifer time step. This file is written in a format that is to be read by both programs SWBAVG and MODFLOW. Names identifying HRUs for the base case, listed below, are used as prefixes for ~.CIO and ~.COD input files, and for ~.STD and ~.BAL output files. Separate runs are made, with names shown below, to distinguish annual and monthly summaries written to soil water balance (~.BAL) files, corresponding to annual and monthly aquifer time steps in MODFLOW.

### **Input data to coordinate SWAT and MODFLOW**

The Option Codes (~.cod) file contains most of the changes to input related to SWAT-MODFLOW coordination and SWAT revisions; the Management Codes (~.mco) file specifies an added irrigation option. Section 5 documents major changes or additions to SWAT, whose input file instructions are given in Section 11.

Contents for the Option Codes input control file (~.cod) were modified to specify options both for SWAT-MODFLOW coordination and for SWAT revisions. Several changes have been made regarding weather data, evaporation, and irrigation. If the data are available, daily measurements may be read for solar radiation, relative humidity, and wind speed (option *iopwea*). Option *iopet* specifies that evaporation is to be calculated according to the Penman method recommended in Maidment, ed. (1993). For a linked simulation in which SWAT calls MODFLOW, option *ioprev* supplies evaporative demand on soil moisture with the depth evaporated from a shallow water table calculated by MODFLOW.

Changes to irrigation include a daily maximum depth and an annual limit given by the estimated annual water use and irrigated area for the corresponding years 1977-1994, which are specified in conjunction with option *ioplim* = 3. These irrigation depths represent basinwide averages for Rattlesnake Creek based on total estimated irrigation water use divided by total estimated irrigated area.

The Management Codes (~.mco) file for each subbasin specifies an automatic irrigation option *irr*, which has been modified to specify (for *irr* = 3) a soil moisture

threshold in addition to the previously existing option for a plant stress factor threshold ( $irr = 1$ ).

Soil and weather (precipitation and temperature) input file formats from SWAT v. 1 were used rather than the formats of v. 2, which did not appear to work as well as the earlier versions.

Simulation conditions specified by SWAT options for the Lower Republican River Basin are summarized as follows.

Use monthly time steps for the aquifer solution ( $iopmod = 2$ ). Annual time steps ( $iopmod = 1$ ) are also used for preliminary runs (e.g. for scenarios) or for checks on calculations.

Run SWAT and MODFLOW separately ( $iopswt = 0$ ).

Specify daily precipitation and temperature data from one NWS station for each subbasin ( $ithpcp = 0$  and  $ithtmp = 0$ ) rather than averaging weather data based on

Theissen weights specified on file `theis.inp`; however, specify nearby stations whose data are to be substituted for any days of missing data instead of using SWAT's generated weather data.

Limit irrigation depth assigned in SWAT to an annual maximum depth based on estimated annual water use for both surface and ground water diversions ( $ioplim = 3$ ).

Simulate irrigation during the growing season based on a minimum soil water threshold ( $irr = 3$ , SWAT Subbasin Management Codes input files `~.mco`).

Calculate potential (reference crop) evaporation according to the Penman method recommended in the Handbook of Hydrology, including the effect of long-wave emission in calculating net radiation ( $iopet > 0$ ).

Daily values for insolation (ly/d), relative humidity (pct) and wind speed (m/s at 10 m above ground surface) are synthesized since measured values were not available ( $iopwea = 0$ ); daily values for these data may be read if available ( $iopwea > 0$ ).

Default definitions are used for tributary inflow to streams and groundwater recharge ( $jkkopt = 0$ ); see Option Codes definitions (Section 11) and balance file definition (p. 52).

## **SWBAVG input**

SWBAVG (Section 6) reads an input file containing the names of the balance files summarizing the HRUs calculated by SWAT, and the weight functions calculated by WEIGHTS. SWBAVG reads the balance files written by SWAT for each HRU, and applies the weight functions to calculate an areally weighted average over the HRUs for each hydrologic flux, subbasin, and time step for which MODFLOW is to be run. SWBAVG writes its average of SWAT results to a file in the same format it uses to read the component balance files written by SWAT for each HRU. The resulting composite balance file is read by the Soil Water Balance (SWB) package added to MODFLOW.

## **WEIGHTS: a preprocessor for SWBAVG**

The weight functions applied by SWBAVG are computed by program WEIGHTS (Section 6) for each year and for each subbasin on the basis of areal fractions of soil and land use within each subbasin, and of the irrigated areal fraction for the entire basin. Areal fractions are specified for cropland and six soil types for each subbasin, and are represented as constant over the study period. In addition, irrigated cropland is specified as an areal fraction of the entire basin that varies from year to year. Program WEIGHTS uses these to calculate a weight function to be applied to eighteen homogeneous components (HRUs) for each year and for each subbasin.

## **MODFLOW Input**

Program MODFLOW is run only once for a particular case of the Lower Republican River model. For convenience, a "response" file (with extension RSP, which is named for the case and analogous to the ~.CIO file for SWAT) identifies most of the input and output files associated with MODFLOW. Input files specified by the response file correspond to MODFLOW packages, some of which have been added or modified for the purpose of this integrated watershed model, and one documented in Section 7.

## **MODSWB package options**

Several options affecting the conditions of the groundwater solution in MODFLOW are specified at the top of the MODSWB package input file documented in Section 7. Options `irrept`, `toprch`, and `levopt` affect how irrigation, recharge, and

evaporation from the water table are modeled. Option **iadcod** identifies an administrative option for water use scenarios. Scaling factors **rchmpy** and **welmpy** are applied to recharge and irrigation wells for sensitivity analysis and modeling of water use scenarios. The effects of these options are summarized below; for specific definitions of these options, see description of the MODSWB package.

Several options affect MODFLOW's execution that are specified in SWAT's Codes input file (~.cod). Option **jkkopt** is passed from SWAT to MODFLOW either by way of the balance file written by HYDBAL or by subroutine argument list, depending on option **iopswt**. Option **iopmod** specifies the length of an aquifer time step as a day, month, or year. These options are defined above.

**irropt**: option ( $y>0, n=0$ ) to scale the pumping rates of irrigation wells read from MODFLOW's ~.WEL input for a stress period so that the watershed's total pumping flow rate corresponds to the irrigation depth assigned by SWAT for each time step; otherwise (**irropt**=0), use the rate specified in Modflow's WELL and SURFACE input files.

**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 the recharge depth calculated by SWAT. Note: SWAT option **jkkopt** determines which components are included in this sum.

**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. Otherwise (**ievopt** < or = 0), evaporation at ground surface is specified by standard Modflow input array EVTR in the EVT module.

**iadcod**: administrative option code used in conjunction with scaling factor **welmpy** for water use scenarios.

## STREAM package options

Changes to the STREAM package allow the following:

**itmp**: 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.

**irdcnd**: 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  $K_s$  and reach length  $L_s$  can be read instead of C, which is then calculated by the program.

**icalc:** Stream channel geometry can be specified as rectangular according to Prudic (1990); trapezoidal, in which case a value for reciprocal side slope is read; or by empirical relationships representing a natural streambed. The natural channel option is used for the Republican River model, in which data from USGS gaging stations at Concordia and Clay Center are used to approximate stream depth, width, and cross sectional area as functions of flow rate.

## **Modified WELL package options**

Changes to the WELL package allow the following:

- a) pumping wells can be distinguished from model wells used to represent nonzero flow boundary conditions.
- b) Measured water level elevations may be read as part of the irrigation well data set to allow comparison of calculated and measured heads during execution and thereby reduce data handling operations.

## **Preprocessors for MODFLOW input data files**

Several preprocessors were used to help construct input data files for the MODSWB, STREAM, WELL, and SURFACE packages, and are documented in Sections 3 and 9. Parts of input files for the Stream and Soil Water Balance packages were written by program STRMDATA, which translated a geographical description of the Republican River taken from USGS 1:24000 topographic maps into a set of stream reaches corresponding to aquifer grid cells and a list identifying reaches along the river where tributaries join.

Input files for the WELL and SURFACE packages were written by program WUREPUB, which estimates water use based on DWR use reports for appropriations in active grid nodes representing the alluvial aquifer domain, selected by program WRREPUB. The Well input file includes water level reports from DWR and water level observations from our Nov 1994 survey; these observations were written by program SURFELEV in the Well package format and appended to the Well input file.

## 5. SWAT: NEW (\*) AND MODIFIED (•) PACKAGES

### •Main program

SWAT's organization is illustrated by Fig. 2 which is reproduced from SWAT's manual. The SWAT mainline was modified primarily to summarize results of its simulation for input to MODFLOW on a daily, monthly, or annual basis, depending on option *iopmod*, and to execute SWAT either independent of MODFLOW or in a linked mode, in which SWAT calls entry points in MODFLOW at the end of each time step, depending on option *iopswt*. The path of execution in SWAT based on these options is illustrated by the narrative flow chart that follows.

```
begin
  Initialize simulation;
  if (iopswt > 0) call MODFLO to initialize the aquifer model;
  for each year:
    if (iopswt > 0) then at the beginning of each year's simulation:
      call MODPER to begin an aquifer stress period;
      call PASSFLX to retrieve annual groundwater use for each subbasin to provide
        annual limits on SWAT's automatic use of irrigation.
    end if
    Simulate watershed hydrology on a daily basis;
    for each aquifer time step (a day, month, or year, based on iopmod), do the following:
      if (iopswt > 0) then coordinate with MODFLOW as follows:
        call SWT2MOD: copy the hydrologic summary into array SHED for MODSWB;
        call MODSTP: solve hydraulic head distribution for the time step;
        call MOD2SWT: retrieve MODFLOW results (baseflow and, optionally,
          evaporation from water table);
      end if
      call HYDBAL to calculate a mass balance and write the hydrologic summary to the
        balance file, including components calculated by MODFLOW if iopswt > 0);
    end of year;
  if (iopswt > 0) call MODEND to close files used in MODFLOW;
end.
```

Options *iopswt* and *iopmod*, read from SWAT's input control file (~.cod), affect execution control as follows. For each year of a simulation, SWAT simulates watershed hydrology on a daily basis, and summarizes its results at the end of each aquifer time step

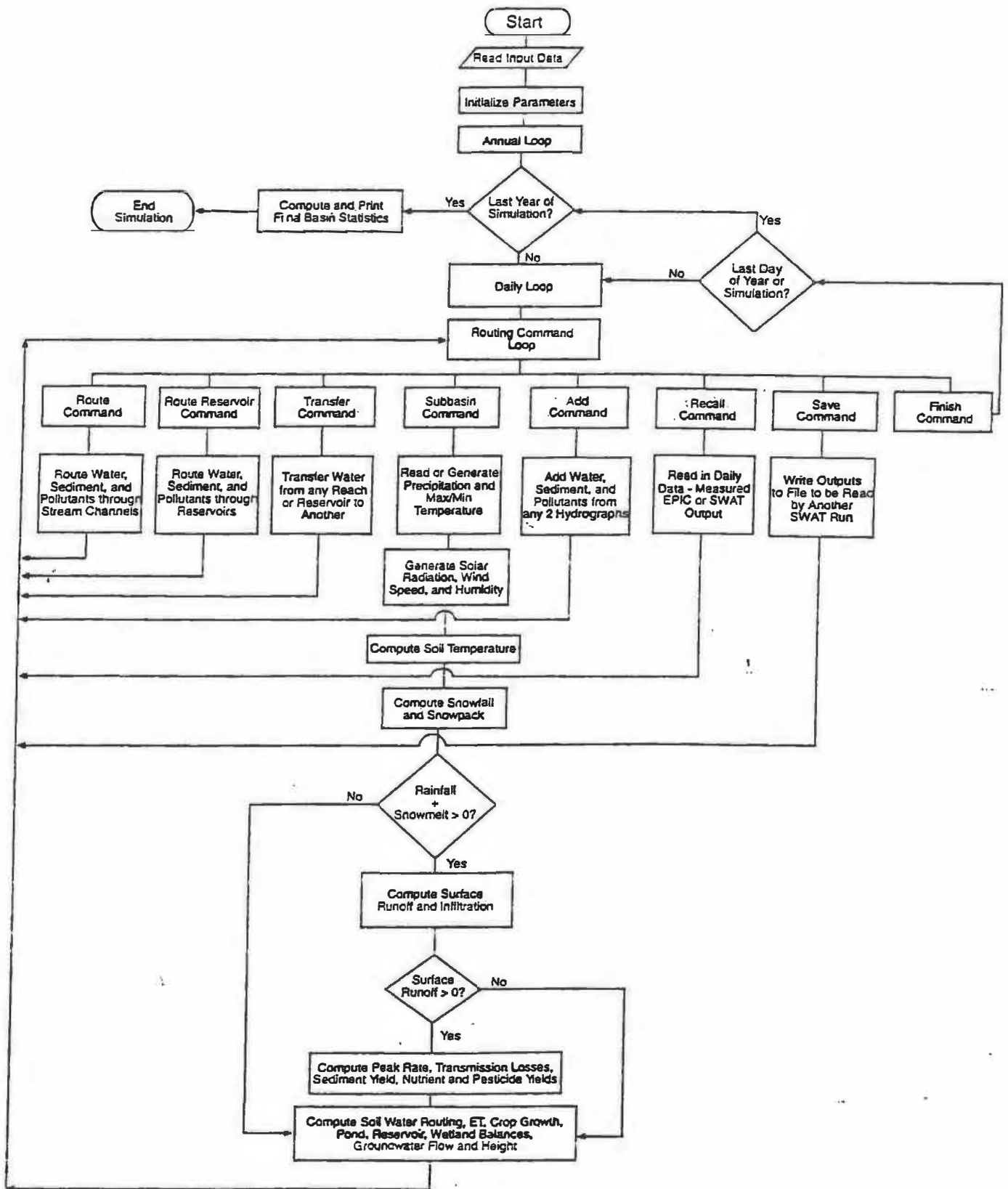


Fig. 2. SWAT program structure (reproduced from Fig. 1, Arnold et al., 1994).

of a day, month, or year, depending on `iopmod`. If `iopswt=0`, SWAT bypasses calls to MODFLOW, and calls subroutine HYDBAL at the end of each time step to write a hydrologic summary file (p. 49) to be read in a subsequent, separate run of MODFLOW. If `iopswt>0`, SWAT calls HYDBAL package subroutines PASSFLX, SWT2MOD, and MOD2SWT (p. 48) to transfer data directly between SWAT and MODFLOW arrays; and SWAT calls MODFLOW through entry points MODFLO, MODPER, MODSTP, and MODEND, shown in a flow chart of MODFLOW's modified mainline (p. 62). The functions of these entry points are as follows:

call MODFLO to allocate memory that is to be common to both programs;

call MODPER at the beginning of each stress period to update associated data;

call MODSTP at the end of each time step to convert hydrologic fluxes calculated by SWAT for the relevant basin areas into flow rates for tributary flow, diversions from surface and aquifer sources, and recharge; and solve the groundwater equations.

In this mode, illustrated below by code added to SWAT for monthly aquifer time steps, the hydrologic summary is passed from array SSUB in SWAT to array SHED in MODFLOW for each time step by subroutine SWT2MOD's argument list just prior to calling MODFLOW through entry MODSTP, whose results, including baseflow and evaporation from the water table, are retrieved by subroutine MOD2SWT via argument list. HYDBAL then writes the summary of hydrologic fluxes to a file, incorporating results from MODFLOW if called. Option `iopswt` is passed to MODFLOW through these entry points to enable return of execution control from MODFLOW back to SWAT just before the next entry point is encountered, as described for the modified MODFLOW program structure (p. 62).

The use of MODFLOW's entry points and HYDBAL's subroutines are illustrated for monthly aquifer time steps by the following excerpt of code from SWAT.

```

write (balttl, '(i4,i3,ix,a)') iyr,mol, 'monthly hydrologic balance:'
dtswat = nd !monthly SWAT time step(days)
if (iopswt.gt.0) then !does SWAT call MODFLOW?
  delt = dtswat/cnvtim !convert to MODFLOW time step
  pass monthly fluxes from SWAT to array SHED for MODFLOW:
  call SWT2MOD (lutot,x(LCSHED),ssub)
  call MODSTP (iopswt,mxcurs,icursr,jkkopt, cnvtim,delt,kper,nstp,kstp)
  retrieve monthly fluxes calculated by MODFLOW from array SHED:
  call MOD2SWT (lutot,x(LCSHED),ssub,smm,flu,tir)
end if
call HYDBAL (.iobal,balttl,lu,x(LCSHED),ssub)

```

## Examples: running SWAT and MODFLOW separately and together

SWAT (executable file SWTMOD96.exe) can be run with or without calling MODFLOW. SWAT writes a summary of hydrologic results for each aquifer time step to a balance file, which can be read on a subsequent run of MODFLOW (executable file MODSWB96.exe). As an example, SWAT and MODFLOW are executed separately at the DOS prompt for case carr-irc as follows:

```

swtmod96 >carr-irc.jou
modswb96 <carr-irc.rsp >>carr-irc.jou

```

Just prior to running SWAT, case file carr-irc.cio is renamed to file.cio to be read by SWAT; an excerpt from this file follows, showing files through only the first subbasin (lines 15 and 16).

```

Republican R. Basin, KS carr-irc Irrig95.mco (irr=3,swtrig=0.8,wsf=.95) 1
Weather: Concordia carr-irc.cod (w/et; no limit on irrig, ->carr-irc.bal),ponds 2
3
carr-irc.std out10.sbs out10.rch out10.rsv out10.lqo out10.pso 4
  out10.eve crop.dat till.dat pest.dat carr-irc.cod in10.bsn 5
  in10.lwq in10.fig in10.sta in10.bsb 6
  9 4 7
bell7794.pcp clay7794.pcp cliff7794.pcp conc7794.pcp fact7794.pcp hadd7794.pcp 8
milt7794.pcp scan7794.pcp wash7794.pcp 9
10
bell7794.tmp clay7794.tmp conc7794.tmp wash7794.tmp 11
12
13
in10.res 14
  1.0 0 0 0 slp101.sub in101.rte in1.pnd in101.chm carr.sol 15
  corn.mgt irrig95.mco h2.gw in10.wgn 1 1 16

```

The above file also names the Option Codes file on line 5, carr-irc.cod, listed below.

```

Options Control File carr-irc.cod (swmin=0.8; ioplum=3; w/et) (1
  181977 9 0 3 3 0 0 0 0 0 0 0 0 0 0 0 9 0 (2
  0 1 0 0 0 1 0 -1 -1 3 1 019871988 1 0 1 (3
carr-irc.bal 9_theis.inp scan8695.rad (4
(10x,2f6.0) temperature data format (file in10.tmp) (5
(10x,f6.0) rainfall data format (files in10x.pcp) (6
(32x,3f8.0) radiation(ly/d),rel.hum(pct),wndspd@10m(m/s) (7
12.7,0.80,1.0,39.51,-97.46, wsfdmx,swminf,pmpeff,phideg,rlamdg (8
  248 248 248 344 132 134 333 327 178 152 203 361 299 286 (9
  185 104 58 228, irrigation depth (mm) 1977-1994 (10

```

In this file, option `iopswt=0`, the third flag on line 3, tells SWAT not to call MODFLOW; SWAT writes a balance file `carr-irc.bal` (named on line 4) that can be used as input to either MODFLOW or to SWBAVG as a component (HRU) of a composite balance file to be read by MODFLOW. With `iopswt>0`, SWAT would call MODFLOW, and the command line for execution would be as follows:

```
swtmod96 <carr-irc.rsp >carr-irc.jou
```

The following is a listing of MODFLOW “response” file `carr-irc.rsp`, which is read for either of the above cases:

<code>carr-irc</code>	case name	(~.log, ~.prn, ~.rsp)
<code>bcase_t</code>	.bas unit	1 Monthly Basic package
<code>kbase20a</code>	.bcf unit	61 Block-centered flow
<code>gwuadm0</code>	.wel unit	62 Well: groundwater use
<code>repsurf</code>	.evt unit	65
<code>rpmon</code>	.swb unit	66 Soil water balance
<code>matrix1</code>	.rch unit	67 Recharge
<code>modellbs</code>	.pcg unit	68 preconditioned conjugate gradient
<code>rep7794m</code>	.oc unit	69 Output control
<code>rpmon</code>	.str unit	70 monthly Streamflow, Ks=0.54 ft/day
<code>swuadm0</code>	.div unit	63 Surf: surface water use

## Coordinating SWAT and MODFLOW data file device numbers:

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 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 file device numbers are listed below, categorized by program location and source file in which data files were opened. This set of file device numbers is coordinated with the set used in MODFLOW (p. 33).

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 pondat (~.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 thresholds)  
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.

## \*PENMAN potential evaporation

An option has been added to SWAT (`iopet` in Option Codes input file `~.cod`) to calculate potential evaporation over land according to the Penman equation 4.2.31 as recommended in the Handbook of Hydrology, D.R. Maidment, ed., 1993, McGraw-Hill, and implemented by subr PENMAN, listed below.

### Wind speed measurement height

Penman calculations are based on wind speed at 2 m above land surface (ALS), which is estimated as follows, using eq. 4.4.9 in Handbook of Hydrology, D.R. Maidment, ed., 1993. Wind speed measured at 10 m is reduced by a factor  $f$  given by  $f = 34.9648/(f_h \cdot f_w)$ , where

$$f_h = \ln[(z_h - 0.08)/0.001476], \quad f_w = \ln[(z_w - 0.08)/0.01476],$$

and  $z_h$  and  $z_w$  are heights (ALS) of humidity and wind speed measurements, respectively.

For  $z_h = 2$  m and  $z_w = 10$  m, wind speed measured at 10 m is reduced by a factor  $f = 0.749$ .

The following are excerpts taken from source code for a test program, `ettest.for`, and subroutine PENMAN, which the test program calls, to outline the procedure and equations used.

### Excerpt from test mainline ETTEST

```
* file ettest.for  spp aug 94; rev. 11/95
*
*   This program estimates daily evaporation by several methods (subr PENMAN)
*   from daily meteorological data taken either at the Sandyland station (St. John,
*   KS) or at the Konza Prairie station south of Manhattan, KS. The program reads
*   data from either of these station and converts data to SI units for calculations
*   in subr PENMAN.
*   Methods of estimating daily evaporation are summarized in subr. PENMAN
*   listing with reference to Handbook of Hydrology, 1993, D. R. Maidment, ed.,
*   esp. Ch. 4, Evaporation, W. J. Shuttleworth. Emphasis is on the
*   Penman-Monteith equation for reference crop evaporation (4.2.30).
*
* Program modules:
*   ettest.for
*       program ettest: mainline
*       integer function JULIAN (month,day,year,ndaymo,ndayr)
*       usage: julday = JULIAN(mon,iday,iyear,ndayr)
*              given date (mo, day, yr),
*              return Julian date and no. days in yr, ndayr.
*       subr's PROMPT and CPTLIZ
*   penman.for
```

```

*      penman: calculate evaporation for one day given input data (below).
*      (see subr PENMAN listing for description)
* Program linking under Lahey:
*      386link ettest,penman -symbol -exe ettest.exe
*
*      data used in the estimates are the following:
* latitude and elevation;
* daily data:
* solar radiation (langleys/day)
* wind speed (not provided with Konza data file)
* relative humidity
* air temperature (min, max, avg, 8am)
* soil temperature
*
*      Content summary of input data files for Sandyland and Konza:
*      for site (Sandyland or Konza):
*      phideg = site latitude (degrees) Note: give as negative for Southern
*      hemisphere.
*      zsite = site elevation (m) (used to est. atmospheric pressure)
*      Sandyland: for each day (written by KSU's program sndpet.bas):
*      chmon = month name (1st 3 char's)
*      iday = day of month
*      tmaxf = max daily temp (deg F)
*      tminf = min daily temp (deg F)
*      relhum = relative humidity (pct)
*      stlang = measured solar radiation (langleys/day)
*      wndrun = wind speed (mi/day)
*      pptin = daily precipitation (inches)
*      tsmaxf = max daily soil temp (deg F)
*      tsminf = min daily soil temp (deg F)
*      Konza: for each day (note: wind speed not in data set)
*      iyear = year
*      mon = calendar month index (1 to 12)
*      iday = day of month
*      julday = Julian date
*      tmax = max daily temp (deg C)
*      tmin = min daily temp (deg C)
*      tavg = avg daily temp (deg C)
*      relhum = relative humidity (pct)
*      stlang = measured solar radiation (langleys/day)
*      pptmm = daily precipitation (mm)
*      tsmax = max daily soil temp (deg C)
*      tsmin = min daily soil temp (deg C)
*      tsavg = avg daily soil temp (deg C)
*
* File name format:
* Sandyland: SNDnn.pet (nn=85 through 93, last two digits of years of
* available data);
* Konza:      KNZnn.pet (nn=93, only year of available data).
*
* Sandyland data:
* The input file described below is actually the output from program petsnd.bas
* (Mary Knapp, Kansas State University (KSU), which computes evaporation (petmm)
* from a combination Penman method (method 1 in list below), most of whose
* input is included in its output file; it lacks only 8 am air temperature and
* 8 am relative humidity. These data are used to make comparative calculations
* of evaporation.
* input format for Sandyland data (available 1 Mar 85 - 31 Dec 93):
*
* 1. rec. 1-6: headers (identifiers), with the following specifics:
*   rec. 1: year (56x,i4)
*   rec. 3: latitude elevation
*           (9x,f6.2, 15x,f5.0)
*           deg ft
* 2. daily records (66 characters, 1 record/day):
*   chmon iday tmaxf tminf relhum stlang wndrun pptin tsmaxf tsminf petmm petin
*   a3 i3 f5.0 f5.0 f6.1 f7.1 f7.1 f6.2 f5.0 f5.0 f7.2 f6.2
*   deg F deg F pct ly/day mi/day in/da deg F deg F mm/da in/da
*
* input format for Konza data (available for 1993; lacks wind speed data):
* 1. rec. 1-6: headers (identifiers), same as above for Sandyland data.
* 2. daily records (96 characters, 1 record/day):
*   iyear mon iday julday tmax tmin tavg relhum stlang pptin tsmax tsmin tsavg u2
*   5x i2 i2 i2 9x i3 10f8.0
*   degC degC degC pct ly/d in/da deg C deg C deg C m/s

```

```

-----
program ETTEST
data (moncal(j),j=1,12) /31,28,31,30,31,30,31,31,30,31,30,31/
data months/'JANFEBMARAPRMAJUNJULAUGSEPOCTNOVDEC'/
*
  default site code (SND for Sandyland, KNZ for Konza):
  data sitdft /'SND'/
* input format for Sandyland data:
*
mon day tmaxf tminf relhum stlang wndrun pptin petmm petin
data fmtinp /'(a3,i3,2f5.0,f6.1,2f7.1,f6.2,1x,2f5.0,f7.2,f6.2)'/
data fmtout /'(1x,i3,22f8.2)'/
* input format for Konza data:  iyr mon iday Julday
*
  tmax tmin tavg relhum stlang pptin tmaxf tminf tavg u2
  data fmtikz /'(6x,3i2,9x,i3,10f8.0)'/
*
  convert radiation in langleys (cal/cm^2) to MJ/m^2:
  (note: based on 1 J = 0.239 cal)
*
data radcnv /23.9/
*
  convert mph to m/s:
data spdcnv /0.44704/
*
  reference crop clipped grass height (m) (passed to subr PENMAN)
data hc /0.12/
*
  arbitrarily set minimum wind speed (m/s).  This provides some
  wind for the Konza data and takes care of wind run data missing
  from Sandyland data set (e.g. at end of Feb 1986).
*
data u2min /0.1/
*
-----
*
  statement functions:
*
1a convert temperature from Fahrenheit to Celcius:
tmpf2c(T) = (5./9.)*(T-32.)
*
1b convert temperature from Celcius to Fahrenheit:
tmpc2f(T) = 32. + (9./5.)*T
*
2. nominal atm. pressure at site (kPa): z=elev (m) (4.4.12)
pnom(z) = 101.3*((293.-0.0065*z)/293.)**5.256
*
  pressure conversions:
*
  1 atm = 101.32 kPa (kPa = kilopascal; 1 pascal = 1 N/m^2)
  = 1013.2 millibars = 760 mm Hg = 10.33 m water
  = 14.7 psia = 29.92 in Hg = 33.9 ft water
*
  saturation vapor pressure (kPa) given temperature (deg C): (4.2.2)
  (approximation for Clausius-Clapeyron eqn (3.3.3))
satvp(T) = 0.6108*EXP(17.27*T/(237.3+T))
*
print *, 'open input file '//naminp(:idxend)
open (unit=inpdev,file=naminp,status='OLD',err=500)

do while (julday.lt.ndayr.and.iostat.eq.0)
  if (irdnxt.eq.0) then
    read (inpdev,'(a)',end=600,err=600,
1      iostat=iostat) recinp
c      option to get daily avg wind speed from alternative source if
        missing from primary source (above):
    if (optwnd.eq.'Y') read (18,'(a)',end=600,err=600,
1      iostat=iostat) recdft
    irdnxt=0
  end if
  irec=irec+1

  if (irec.le.nheadr) then
    if (irec.eq.3) then
      read(recinp,'(9x,f6.0,15x,f5.0)') phideg, elevft
*      site latitude (radians):
      phirad = phideg*(pi/180.)
*      site elevation (m):
      elev = 0.3048*elevft
      patm = PNOM(elev)
      print '(1x,a,i4,3(1x,a,f8.2))', 'year=',iyear,
1      'phideg=',phideg,'elevft=',elevft,'patm=',patm
    end if
  end if
  if (site.eq.'SND') then
    read (recinp,fmtinp,err=15,iostat=iostat)
1      chmon, iday, tmaxf, tminf, relhum,
1      stlang, wndrun, pptin, tmaxf, tminf, petmm, petin
*      look up month:
      mon = 1 + (INDEX (months,chmon) - 1)/3
*****
      mon = 1+(mon-1)/3
      tavgf = (tmaxf+tminf)/2.

```

```

*       data conversions to units used in subr PENMAN:
*       convert air temperature values from Fahrenheit to Celcius:
tmin = TMPF2C(tminf)
tmax = TMPF2C(tmaxf)
tavg = (tmin+tmax)/2.
*       daily soil temperature:
tsoil = TMPF2C(tsoilf)
tsoil = TMPF2C(tsoilf)
*       convert daily avg wind speed from mi/day to m/s:
u2 = spdcnv*wndrun/24.
pptmm = 25.4*pptin !precipitation (mm)
else
*       Konza input format:
read (recinp,fmtikz,err=500,iostat=iostat)
1       iyear,mon,iday,julday,tmax,tmin,tavg,relhum,
1       stlang,pptmm,tsoil,tsoil,tsoil
tavgf = TMPC2F(tavg)
if (chu2.ne.' ') read (chu2,'(f8.0)') u2
if (cht Dew.ne.' ') then
    read (cht Dew,'(f8.0)') tdewpt
    relhum = 100.*SATVP(tdewpt)/SATVP(tavg)
end if
if (chelev.ne.' ') then
    read (chelev,'(f8.0)') elevft
*       site elevation (m):
    elev = 0.3048*elevft
    patm = PNOM(elev)
end if
if (optwnd.eq.'Y') then
    read (recdft,'(a3,i3,23x,f7.1)')
1       mondft,idadft,wndrun
*       convert daily avg wind speed from mi/day to m/s:
    u2 = spdcnv*wndrun/24.
end if
    pptin = pptmm/25.4 !precipitation (in)
end if
*       count no. days read:
idxday = idxday + 1
julday = JULIAN(mon,iday,iyear,ndaymo,ndayr)
*       mean daily soil temperature:
tsoil = (tsoil+tsoil)/2.
*       (u2min is set above in data statement)
u2 = AMAX1(u2min, u2)
c       initialize values for "previous day" to calc. soil temperature change:
if (idxday.eq.1 .and. iyrfil.eq.1) then
    tsprev = tsoil
    chmprv = chmon
    monprv = mon
    iyprv = iyear
    write (outdev,'(lx,a)')
1       'Jul AvgTmp RelHum SolRad WndSpd Precip'//
1       ' dtsoil petmm Penman Priest'//
1       ' s0 vp_def rshort rlong shflux'
    write (outdev,'(lx,a)')
1       'day deg C pct ly/d m/s mm/day'//
1       ' deg C mm/day mm/day mm/day ly/d kPa'//
1       ' MJ/m2/d MJ/m2/d MJ/m2/d'
else if (idxday.eq.2) then
    itrace = 0
end if
*       daily change in soil temperature (deg C):
dtsoil = tsoil - tsprev
*       convert observed solar radiation from langleys (cal/cm^2) to MJ/m^2:
stj = stlang/radcnv
*
data hc /0.12/ !height of reference crop: cut grass
data iopcmp/1/
data method/1/ !choose recommended Penman method (epmref);
*       routine still compares with Priestley-Taylor (aprt).
ccc rel.humidity (%) is available with weather data from both Sandyland and Konza,
c so emissivity is estimated on the basis of rel. humidity (iemiss=0);
c otherwise (iemiss=1), emissivity would be estimated on the basis of temperature.
data iemiss/0/
data albedo /0.23/

call PENMAN (itrace,method,iemiss,julday,albedo,elev,

```

```

1      patm, phi, tmin, tmax, tavg, dtsoil, stj, u2, relhum, pptmm,
1      hc, dxleaf, s0j, vpdef, rs, ra, rshort, rlong, shflux, etref)

*      convert computed extraterrestrial solar radiation s0j back
*      from MJ/m^2 to langleys (cal/cm^2):
s0lang = s0j*radcnv
c      ...the program goes on to summarize results for weeks, months,
c      and years; see code and examples with Sandyland and Konza data
c      for more details.
*      from monthly evaporation summary:
if (monacc.eq.1) then
*      monthly results:
etmon(mon) = etcref      !sp Penman-Monteith ref et (4.2.31)
petmon(mon) = petmm      !sp combination Penman (KSU)
etrad(mon) = etrval      !sp Priestley-Taylor ref et (4.2.39)
etkim(mon) = etcomb      !sp Kimberly Penman ref et (4.2.33)
etturb(mon)=et          !sp resistance-based et (4.2.27)
etmksu(mon)=etksu       !sp try to reproduce petsnd.bas (KSU)
cfmon(mon) = cfcref      !sp Priestly-Taylor coef. (alpha, eqn 4.2.37)
cccc  s0mmon(mon)=s0m      !sp extraterrest. rad. (see subr. PENMAN)
s0jmon(mon)=s0j         !sp extraterrestrial rad. (MJ/m^2/d)
stjavg(mon)=stj         !sp measured insolation (MJ/m^2/day)

*      monthly input values:
rhmon(mon) = rhmon(mon)/accmon      !sp relative humidity (pct)
tmpmon(mon)= tmpmon(mon)/accmon     !sp monthly avg air temp (deg C)
tfmon(mon) = tfmon(mon)/accmon     !sp monthly avg air temp (deg F)
radmon(mon)= radmon(mon)/accmon     !sp monthly avg radiation (ly/day)

*      est. monthly coefficients as and bs for (4.2.6), which can
*      then be used to solve for daily cloudiness fraction n/N,
*      which can be used in (4.2.12), the cloudiness factor in
*      (4.2.7) for long-wave radiation.
*      fraction of extraterrestrial radiation S0 on overcast days
*      (when bright sunshine hours n=0)
as = stjmin(mon)/s0jmon(mon)
*      fraction of extraterrestrial radiation S0 on clear days
*      (n=N, total day length, i.e. while sun is up):
cfrac = stjmax(mon)/s0jmon(mon)
bs = cfrac - as
end if
monprv = mon      ! retain for writing annual summary below.
mon = monnxt      ! month index
tsprev= tsoil     ! mean daily soil temperature (deg C)
30      continue
end do
end

```

## Excerpt from subroutine PENMAN

```

subroutine PENMAN (itrace,method,iemiss,julday,albedo,elev,patm,
1 phi, tmin, tmax, tavg, dtsoil, stj, u2, relhum, pcpmm, hc, dxleaf, s0j,
1 vpdef, rs, ra, snj, rlong, shflux, etref)
*
* Compute evaporation estimates (mm/day); numbered equations refer to
* Handbook of Hydrology, 1993, Maidment, ed., especially Ch. 4, Evaporation,
* Shuttleworth; see also sec. 13.2, pp. 13.22-13.25. This routine is designed
* to aid comparison of various methods of calculating evapotranspiration.
* Note: relative humidity value is assumed to be available.
*
* argument list
* INPUT:
* int itrace option (no=0, yes otherwise) to print most calculated values
* just prior to returning (see end of routine).
* int method 1=recommended; methods 1-4 are defined below under OUTPUT.
* int iemiss 0: relative humidity (%) is available, and is used to estimate
* emissivity; otherwise (iemiss=1), temperature would be used
* to estimate emissivity.
* int julday Julian day
* re albedo reflectivity
* re elev land surface elevation (m); used to estimate atmos. pressure, patm
* re patm atmospheric pressure (kPa)
* re phi site latitude (radians)
* re tmin day's minimum temperature (deg C)

```

```

* re tmax day's maximum temperature (deg C)
* re tavg day's avg temperature (deg C)
* re dtsoil change from previous day in soil temperature (deg C) at 0.1 m depth
* re stj incoming solar radiation (insolation) at land surface (MJ/day)
* re u2 day's avg wind speed (m/s) NOTE: set minimum at 1 m/s (arbitrary)
* re relhum relative humidity (pct)
* re hc crop height (m); used to evaluate actual et by (4.2.27): see et (below).
* re dxleaf leaf area index; if input as zero, calculated by 4.2.23 for grass.
*
* OUTPUT: intermediate calculations
* re cfcfref coefficient replacing the value 1.26 in (4.2.38) req'd for eprta
* to equal epmref (above).
* re s0j day's extraterrestrial incoming radiation (MJ/m^2/day) through a
* plane tangent to a sphere enclosing the earth's atmosphere.
*
* OUTPUT: evaporation results
* re epmref reference crop evaporation (4.2.31 or 4.4.14), version of the
*(method 1) Penman-Monteith equation recommended by the Handbook of Hydrology
* re epot potential open water evaporation (4.2.30)
*(method 2)
* re eprta reference crop evaporation (4.2.38-39), Priestley-Taylor eqn.,
*(method 3) radiation based; use cfrad=1.74 for arid locations (def. avg
* relative humidity < 60% for month of peak evaporation);
* otherwise, cfrad=1.26. Here, cfrad=1.26 is assumed.
* re ekimb reference crop evaporation (4.2.33), Penman combination eqn;
*(method 4)
* re epmnmon actual evapotranspiration, the Penman-Monteith eqn (4.2.27);
*(method 5) see also p. 13.25.
*
* This model accounts directly for the physical mechanisms of
* turbulent and molecular diffusion of water vapor as follows.
* For evaporation, i.e. transfer of water vapor from plant and
* soil surfaces, turbulent diffusion dominates, and is represented
* by aerodynamic resistance ra (4.2.25), a function of wind speed
* and crop height.
* For transpiration, i.e. transfer of water vapor from leaf
* stomata to plant surface, molecular diffusion dominates, but is
* controlled by the plant's stomatal response to soil moisture and
* other factors. This controlled transfer is represented by
* surface resistance rs, for which some empirical relationships
* are available, e.g. (4.2.22), which depends on crop height.
* When plants are wet, this surface resistance is effectively
* zero, since the water vapor source is on the plant surface rather
* than inside the leaves (see sec. 4.2.5). But evaporation
* during precipitation (and irrigation) can be represented by
* interception (and depression storage) losses, which can be
* estimated separately.
* This is a one-step method to calculate actual evapotranspiration,
* in contrast to all of the preceding methods, which estimate only
* reference evaporation, which must be multiplied by empirically
* based restrictive factors for soil moisture and vegetation to
* estimate actual evapotranspiration, and hence are referred to as
* two-step methods (sec. 4.4.8, Handbook of Hydrology).
* defunct argument: etksu
* re etksu this is an attempt (not yet successful) to reproduce calculations
* in the KSU Basic program petsnd, written circa 1985, and which
* is a Penman combination eqn. This is to be compared with petmm,
* the value computed by program petsnd and read from the Sandyland
* input data file (see etsand.txt for details on Sandyland input).
*
* Checks and notes on internal variables:
* ra aerodynamic resistance (4.2.25; see also eqn 13.2.1) checks
* for wind speed u2=5 m/s:
* crop mean height hc (m) ra (s/m)
* grass 0.1 45
* agricultural 1. 18
* forest 10. 6.5
* daymax max. possible daylight hours (N, eqn 4.4.1) accuracy is within 0.1 h.
*
* s0m extraterrestrial solar radiation S0 in MJ/m^2/day was backed out
* from (4.4.4) by multiplying by lambda (i.e. htvap): calculated
* to compare with s0j above. Note that (4.4.4) must assume a
* nominal value for heat of vaporization, so that s0j (above)
* should be more rigorous than s0m. A comparison of these two
* for 1993 Sandyland data (actually it's independent of these data)
* showed a mean error 100*(s0m-s0j)/s0j of -1.2 pct ranging from
* -2.6 pct to 0.6 pct (small compared to other error sources

```

```

*      in evaporation calculation). S0 (mm/day) by (4.4.4) is accurate
*      to within 0.1 mm.
*      Checks from Maidment (p.4.31) for April 15 (Julian day=105):
*      latitude (deg)      N (daymax, h)      S0 (mm/day)
*      30 N                 12.7          15.0
*      0                    12.0          15.1
*      30 S                 11.3          11.2
-----
dimension etref(5)
character*60 refnam(5)
data (refnam(j),j=1,5) /
1 '(4.2.31) Penman-Monteith reference crop evap',
1 '(4.2.30) Penman-Monteith potential open water evap',
1 '(4.2.39) Priestley-Taylor reference crop evap',
1 '(4.2.33) Kimberly Penman reference crop evap',
1 '(4.2.27) Penman-Monteith' /
*      coefficients for estimating incoming solar radiation st given
*      extraterrestrial solar radiation s0 and fraction of cloud cover n/N:
data as, bs /0.25, 0.50/
*      est. albedo (reflectance): (now pass as argument)
cccc data albedo /0.23/
*      Stefan-Boltzmann constant (MJ/m^2/K^4) for long-wave radiation:
data stefan /4.903e-9/
*      solar constant, langleys/min:
data gsc /1.957/
*      convert radiation in langleys (cal/cm^2) to MJ/m^2:
*      (note: based on 1 J = 0.239 cal)
data radcnv /23.9/
*      soil heat capacity (MJ/(m^3*C)) for average moist soil (Handbook,p.4.10):
data cpsoil /2.1/
*      presumed soil depth (m) for temperature change dTsoil:      (4.2.17)
data dpsoil /0.15/
*      specific heat of moist air (kJ/(kg*C)) (p. 4.13):
data cp /1.013/
*      mixing ratio (check term): ratio of molecular weight of water
*      vapor to that for dry air:
data epsiln /0.622/
*      coefficient for psychrometric constant gamma: pscoef=1.e-3*cp/epsiln
data pscoef /1.6286e-3/
data iopchk /0/ !option to write out table with entries like T. 4.4.3 !
data initlz /0/
-----
*      saturation vapor pressure (kPa) given temperature (deg C):      (4.2.2)
*      (approximation for Clausius-Clapeyron eqn (3.3.3))
satvp(T) = 0.6108*EXP(17.27*T/(237.3+T))
*      evaluate derivative delta = d(es)/dT at T (kPa/degC):      (4.2.3)
desdt(es,T) = 4098.*es/(237.3+T)**2
*      estimated density (kg/m^3) of moist air (eqn 4.2.4, Shuttleworth,
*      Ch. 4, Evaporation, Handbook of Hydrology, ed. by Maidment '93), for
*      atmospheric pressure P (kPa) and air temperature T (deg C):
airden(P,T) = 3.486*P/(275.+T)
*      estimated atmospheric pressure P (kPa) as a function of elevation z (m)
*      leaf area index for clipped grass of height 0.05 < hc < 0.15 m:
dxgrass(hc) = 24.*hc
*      leaf area index for alfalfa of height 0.10 < hc < 0.50 m:
dxalfa(hc) = 5.5 + 1.5*ALOG(hc)
*      program petsnd.bas (KSU) vapor pressure calculation:
vpksu(RH,T) = 6.11*(RH/100.)*10.**((7.5*T)/(T+237.3))
*      nominal atm. pressure at site (kPa): z=elev (m)      (4.4.12)
pnom(z) = 101.3*((293.-0.0065*z)/293. )**5.256
*      (The above function is used in the calling routine ETSAND)
*      pressure conversions:
*      1 atm = 101.32 kPa (kPa = kilopascal; 1 pascal = 1 N/m^2)
*      = 1013.2 millibars = 760 mm Hg = 10.33 m water
*      = 14.7 psia      = 29.92 in Hg = 33.9 ft water
*
if (initlz.eq.0) then
  initlz = 1
  pi = 4.*ATAN(1.)
  twopi = 2.*pi
  gscday = gsc*24.*60.
*      solar constant (MJ/m^2/day):
  gscj = gsc*24.*60./radcnv
  govрпи=gscj/pi
*      coef. used in (4.2.18) for daily change in soil heat content:
  cpdp = cpsoil*dpsoil

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```

print 110,'solar constant (MJ/m^2/day) gscj=',gscj,
1   'gscj/pi=',govrpi
print 110,'soil heat flux coef cp*dp in (4.2.17) =',cpdp
end if
*   choose 1st method if not specified (1-5):
*   if (method.lt.1.or.method.gt.5) method=1
*
*       nominal atmospheric pressure (kPa):
patm = PNOM(elev)
*       mean daily air temperature (deg K):
tavgk = tavg + 273.2
*       julday = Julian day
d julia = julday
yrfrac = djulia/365.
*       dr = earth-sun distance as fraction of (mean?)           (4.4.5)
dr = 1.+0.033*COS(twopi*yrfrac)
*       solar declination (radians)                               (4.4.3)
dlt = 0.4093*SIN(twopi*yrfrac - 1.405)
*       sunset hour angle (radians):                             (4.4.2)
ws = ACOS(-TAN(phi)*TAN(dlt))
*       max. possible daylight hours (N):                       (4.4.1)
daymax = 24.*(ws/pi)
*
*       extraterrestrial solar radiation S0 (MJ/m^2/day):       (ce751)
s0j = (ws*SIN(phi)*SIN(dlt) + COS(phi)*COS(dlt)*SIN(ws))*
1   dr*gscday/(pi*radcnv)
*
*       htvap = latent heat of vaporization (MJ/kg) (lambda):   (4.2.1)
*       base this on mean daily temperature tavg (deg C),
*       but is defined in terms of Ts, water surface temperature.
*       htvap = 2.501 - 0.002361*tavg
*       psychrometric constant (kPa/deg C):                     (4.2.28)
gamma = pscoef*patm/htvap
*       day's avg saturated water vapor pressure (kPa) (see p. 4.33):
esmin = SATVP(tmin)
esmax = SATVP(tmax)
esavg = (esmin + esmax)/2.
*       estimate avg vapor pressure deficit (kPa):              (4.4.6)
vpdef = esavg*(1.-relhum/100.)
*       sat. water vapor pressure (kPa) at day's avg temp (deg C):
es = SATVP(tavg)
cccc eschg = esavg/es
cccc desdt(es,T) = 4098.*es/(237.3+T)**2  !(copy of statement function above)
*       evaluate avg derivative delta = d(es)/dT at T (kPa/degC) (4.2.3)
delta = (DESDT(esmin,Tmin) + DESDT(esmax,Tmax))/2.
cccc dltold= 4098.*es/(237.3+tavg)**2
cccc dltchg = delta/dltold
*
*       To convert solar radiation from MJ/m^2/day to mm/day, divide by
*       htvap, the latent heat of vaporization (MJ/kg), (4.2.1).
*       Explanation (p. 4.8): for net radiation Rn (MJ/m^2/day), the
*       equivalent depth of evaporated water is Rn/(rho_w*lambda) (m),
*       where rho_w= density of water (approx. 1000 kg/m^3) and
*       lambda=latent heat of vaporization (htvap, above, MJ/kg).
*       so equivalent evaporated depth (mm) is (1000/rho_w)*Rn/lambda,
*       or approximately Rn/lambda.
*       extraterrestrial solar radiation s0m in MJ/m^2/day backed out
*       from (4.4.4) by multiplying by lambda (i.e. htvap); see
*       notes on s0m in argument list description.
cccc s0m = htvap*15.392*dr*
cccc 1   (ws*SIN(phi)*SIN(dlt) + COS(phi)*COS(dlt)*SIN(ws))
*
*       absorbed short-wave radiation:                           (4.2.5)
snj = (1.-albedo)*stj
*
*       intermediate calculations for net long-wave radiation:
*       est. fraction of available extraterrestrial solar radiation:
radfr = stj/s0j
*       estimate fraction of cloud cover dayfr (n/N) based on st and s0:
*       rearrange equation used to estimate st = s0*(as + bs*n/N) (4.2.6)
*       into the form [(st/s0) - as]/bs = n/N; nominal values for
*       coefficients as, bs are in data statement. Limit this fraction
*       to the range [0,1].
dayfr = AMIN1(1., AMAX1(0., (radfr - as)/bs ))
*       cloudiness factor f using nominal coefficients:         (4.2.12)
f = 0.9*dayfr + 0.1

```

```

*      use the alternate calculation (4.2.9) if relative humidity isn't
*      available; e.g. for Swat, temperature comes from data, but relative
*      humidity was simulated.
if (iemiss.eq.0) then
*      unsaturated vapor pressure: from def.  $RH = e(T)/es(T)$ :
      eunsat= esavg - vpdef
*      est. net emissivity from vapor pressure (kPa):           (4.2.8)
      emiss = 0.34 - 0.14*SQRT(eunsat)
else
*      alt: est. net emissivity from avg temperature (deg C):   (4.2.9)
      emiss = -0.02 + 0.261*EXP(-7.77e-4*tavg*tavg)
end if
*      net long-wave radiation (MJ/m^2/day):                   (4.2.7)
      rlong = -f*emiss*stefan*tavgk**4
*
*      est. soil heat flux (MJ/m^2/day):                       (4.2.18)
      shflux = cpdp*dtsoil
*      energy available for evaporation (mm/day) = net radiation - soil heat flux
*      net radiation (MJ/m^2/day) = snj + rlong;                 (4.2.13)
      avail = (snj + rlong - shflux)/htvap
*      available energy coefficient for potential evaporation from
*      open water (4.2.30), for the Priestley-Taylor eqn (4.2.38-39),
*      and the Kimberly Penman combination equation (4.2.33):
      flp = delta/(delta+gamma)

if (method.eq.1 .or. iopchk.gt.0 .or. itrace.gt.0) then
*      evaluate reference crop evaporation:                     (4.2.31)
*      coef's flrc and f2rc are both functions of (T,u2,z).
*      variation on psychrometric constant gamma (above):       (4.2.32)
      gstar = gamma*(1.+0.33*u2)
*      available energy coef.:                                  (4.2.15)
      flrc = delta/(delta+gstar)
*      vapor pressure deficit coef.:                            (4.2.16)
      f2rc = (gamma/(delta+gstar))*900.*u2/(tavg+275.)
*      est. reference crop evaporation (mm/day):                (4.4.14)
      etref(1) = flrc*avail + f2rc*vpdef
end if
*      est. evaporation rate from open water: potential evap by
*      Penman eqn (4.2.30), rewritten as (4.4.10):
if (method.eq.2 .or. iopchk.gt.0 .or. itrace.gt.0) then
*      energy available for evaporation from open water (mm/day),
*      assuming that data to estimate advected energy Ah (4.2.20) is
*      not available (see flowchart, Table 4.4.1, item 5b);
*      Note that albedo for open water from T. 4.2.2 is used here:
      data albh2o / 0.08/
      avlopn = (stj*(1.-albh2o) + rlong)/htvap
      f2p = gamma/(delta+gamma)*6.43*(1.+0.536*u2)/htvap
(4.4.13)
      etref(2) = flp*avlopn + f2p*vpdef           (4.4.10)
end if
*      always calculate this for now to pass back comparison w/ method 1.
cccc if (method.eq.3 .or. iopchk.gt.0 .or. itrace.gt.0) then
*      compute coef. for comparing with radiation-based eqn 4.2.38-39:
*      use cfrad=1.74 for arid locations (def. avg relative humidity < 60%
*      for month of peak evaporation); cfrad=1.26 otherwise. Here,
*      cfrad=1.26 is assumed.
*      Priestley-Taylor eqn (radiation-based evap):
      etref(3) = 1.26*flp*avail                   (4.2.39)
*      compute coef. req'd for radiation-based eqn (4.2.38-39) to match
*      value given by etref(1) from (4.2.31):
      cfcraf = etref(1)*(1.+gamma/delta)/avail
cccc end if
if (method.eq.4 .or. iopchk.gt.0 .or. itrace.gt.0) then
*      est. ref. crop evap based on the Kimberly Penman combination
*      eqn (4.2.33), so named for using a seasonal adjustment based on
*      Kimberly, Idaho data.
*      wind ftn for the Kimberly Penman combination eqn:
*      coef. aw for wind function (below):                       (4.2.35)
      awexp = ((d julia-173.)/58.)**2
      aw = 0.4 + 1.4*EXP(-awexp)
*      coef. bw for wind function (below) for Northern latitudes:(4.2.36)
*      (for Southern latitudes see variation given in Handbook)
      bwexp = ((d julia-243.)/80.)**2
      bw = 0.605 + 0.345*EXP(-bwexp)
*      wind function for Kimberly Penman eqn:                   (4.2.34)
      wndftn = aw + bw*u2

```

```

        f2k = gamma/(delta+gamma)*6.43*wndftn/htvap          (4.4.13)
        etref(4) = flp*avail + f2k*vpdef                    (4.2.33)
    end if
    *      resistance-based model, the Penman-Monteith eqn(4.2.27)
    if (method.eq.5 .or. iopchk.gt.0 .or. itrace.gt.0) then
    *      if leaf area index is not given (i.e. input as zero),
    *      use 4.2.23 to estimate leaf area index for grass:
    if (dxleaf.eq.0.) dxleaf = DXGRAS(hc)
    *      est. fraction of day that canopy is wet; use to reduce surface
    *      resistance.
    frcwet = AMIN1(1.,0.045*pcpmm)
    *      approximate surface resistance:                    (4.2.22)
    rs = frcwet*200./dxleaf
    *      von Karman constant:
    data vonkar /0.41/
    *      assumed heights (m) of wind speed and humidity measurements:
    data zu, ze /2., 2./
    *      intermediate values for aerodynamic resistance (below)
    *      for a mean crop height hc (m):
    *      roughness length (c.f. (13.2.2)):
    d = 0.67*hc
    *      zero plane displacement for wind and humidity factors (c.f. (13.2.2)):
    zom = 0.123*hc
    zov = 0.0123*hc
    wfactr = ALOG((zu-d)/zom)
    hfactr = ALOG((ze-d)/zov)
    *      assume wind speed uz(zu) (m/s) measurement height zu = 2 m:
    uz = u2
    *      aerodynamic resistance:                            (4.2.25)
    *      (see also eqn (13.2.1))
    ra = wfactr*hfactr/(vonkar*vonkar*uz)
    *      compare eqn given for the reference crop (for std u2) (4.2.26)
    rasc = 208./u2
    *      air density:                                       (4.2.4)
    rhoair = AIRDEN(patm,tavg)
    *      resistance-based model for evap: the Penman-Monteith eqn (4.2.27)
    etref(5) = ((delta*avail + rhoair*cp*vpdef/ra)/
    1      (delta+gamma*(1.+rs/ra)))/htvap
    end if
end

```

## Example: Test of evaporation calculations with Sandyland weather data for 1993

(file snd93.txt) Run test mainline to do daily Penman calculations (1993 Sandyland data):  
 ettest <snd9393.rsp >snd9393.jou

### Input:

keyboard responses on file snd9393.rsp;  
 1993 weather data from Sandyland station on file snd93.pet.

### Output:

terminal output on journal file snd9393.jou; for the first day,  
 intermediate results of calculations are shown and associated with  
 reference equations in Shuttleworth (1993);  
 annual summary: snd9393.ann  
 monthly summary: snd9393.mo2;  
 weekly summary: snd9393.wk;  
 daily results: file snd9393.out;

Redirected keyboard input, response file snd9393.rsp, is as follows:

```

-----
snd                               [SND]: 3-character code for data
collection site
93 93                             last 2 digits of beginning and ending
years
L                                  [N]: [L]ong version, [S]hort version,
or [N]o output
snd93.pet                         [SND93.PET]: input file name
-----

```

Excerpt from Sandyland weather input file snd93.pet: 1st and last 7 days of 1993

-----

SND93 DAILY WEATHER INFORMATION -- St. John, KANSAS, 1993  
SANDYLAND RESEARCH FIELD

Lat(deg): 38.00 Elev. (ft): 1905

DAY	TEMP.		AVG RH	SOLAR		WIND RUN	RAIN FALL	SOIL TEMP		PET	
	MAX	MIN		RAD	RAD			MAX	MIN	MM	INCH
JAN 1	41	54	85.0	78.2	172.3	0.00	33	35	-0.97	0.00	
JAN 2	37	41	87.7	51.7	226.1	0.00	32	34	-0.79	0.00	
JAN 3	44	51	78.0	105.3	152.4	0.00	35	33	-0.45	0.00	
JAN 4	35	43	80.1	272.0	154.6	0.00	32	32	1.30	0.05	
JAN 5	36	41	81.1	150.4	144.1	0.00	32	32	0.17	0.01	
JAN 6	33	41	87.6	89.9	135.8	0.00	32	32	-0.72	0.00	
JAN 7	33	37	89.7	31.0	177.7	0.00	32	32	-1.19	0.00	
...											
DEC 25	49	37	73.8	265.8	177.7	0.00	36	32	1.68	0.07	
DEC 26	61	39	68.7	236.6	99.9	0.00	41	33	1.60	0.06	
DEC 27	39	49	88.3	71.5	265.7	0.00	36	33	-0.28	0.00	
DEC 28	32	51	80.5	221.4	155.7	0.00	33	32	0.49	0.02	
DEC 29	41	45	73.0	277.2	143.4	0.00	32	33	1.62	0.06	
DEC 30	53	43	58.8	269.1	178.9	0.00	32	33	2.23	0.09	
DEC 31	64	32	53.5	209.4	230.4	0.00	39	32	2.08	0.08	

DATA OBTAINED FROM AUTOMATIC RECORDING STATION LOCATED AT  
EXPERIMENTAL FIELD OR STATION. THEY MAY DIFFER FROM RECORDS  
FROM 'OFFICIAL NWS STATION' LOCATED NEARBY.

DATA FURNISHED BY WEATHER DATA LIBRARY-KANSAS STATE UNIVERSITY  
CARDWELL HALL. CAMPUS PHONE 913/532-6270.

-----

Redirected terminal output, journal file snd9393.jou, is as follows:

-----

program ETTEST: evaporation for Sandyland or Konza data  
Expected input name formats:  
Sandyland: SNDnn.pet (nn = 85-93, last 2 digits of years' data);  
Konza: KNZnn.pet (nn = 93)  
enter 3-character code for data collection site [SND]:  
enter last two digits of beginning & ending years:  
open daily output file SND9393.OUT

show daily results? [L]ong, [S]hort, [N]o[N]: Enter input file name [SND93.PET]:  
open input file snd93.pet  
idxyr= 93  
year=1993 phideg= 38.00 elevft= 1905.00 patm= 94.63  
solar constant (MJ/m<sup>2</sup>/day) gscj= 117.911 gscj/pi= 37:532  
soil heat flux coef cp\*dp in (4.2.17) = 0.315  
elev,m P,kPa Tmp,C u2,m/s Flp F2p Flrc F2rc F2k delta gamma htvap  
esavg  
581. 94.6 8.6 3.2 0.554 3.142 0.377 3.083 2.705 0.077 0.062 2.481  
1.148  
1 0.82 (4.2.31) Penman-Monteith reference crop evap  
2 1.07 (4.2.30) Penman-Monteith potential open water evap  
3 0.53 (4.2.39) Priestley-Taylor reference crop evap  
4 0.89 (4.2.33) Kimberly Penman reference crop evap  
5 0.18 (4.2.27) Penman-Monteith  
es= 1.118  
s0j= 35.673 MJ/m<sup>2</sup>/d, daymax= 12.000  
vpdef= 0.172 stj= 3.272 MJ/m<sup>2</sup>/d  
stj/s0j= 0.092 dayfrc= 0.000 cloudiness factor f= 0.100 albedo= 0.230  
emiss(e)= 0.202 iemiss= 0.000  
snj= 2.519 MJ/m<sup>2</sup>/d, rlong= -0.624 MJ/m<sup>2</sup>/d  
shflux= 0.000 MJ/m<sup>2</sup>/d, avail= 0.764 mm/d  
epmref= 0.000  
Terms for resistance-based evaporation model:  
uz= 3.209 hc= 0.120  
d= 0.080 zom= 0.015 zov= 0.001  
wfactr= 4.868 hfactr= 7.171  
rs= 0.000 ra= 64.701 rasc= 54.810  
rhoair= 1.163  
frcwet= 0.000

-----

annual summary:

-----

program ETTEST output file SND9393.ann annual results

year	mo	day	Penman	Petsnd	Priest	Ekmm	Rad,ly/d	Tmp,C	RelHum,%	cfann
1993	12	365	0.82	1283.15	0.53	0.89	388.35	14.19	73.41	0.00

monthly summary:

-----  
 program ETTEST output file SND9393.mo2 monthly solar radiation (MJ/m^2/day)

year	mo	day	s0jmon	stjavg	stjmin	stjmax	as	bs	as+bs
1993	1	31	36.14	8.46	1.30	14.35	0.036	0.361	0.397
1993	2	28	37.30	11.54	1.72	18.57	0.046	0.452	0.498
1993	3	31	37.76	14.02	1.85	24.50	0.049	0.600	0.649
1993	4	30	36.69	16.62	1.91	28.89	0.052	0.735	0.787
1993	5	31	34.73	20.61	5.89	31.55	0.170	0.739	0.908
1993	6	30	33.45	24.69	4.10	32.18	0.123	0.839	0.962
1993	7	31	33.88	24.95	7.30	30.33	0.216	0.680	0.895
1993	8	31	35.61	22.07	3.93	28.79	0.110	0.698	0.809
1993	9	30	37.12	18.69	3.14	26.28	0.085	0.623	0.708
1993	10	31	37.25	14.00	2.74	20.25	0.073	0.470	0.544
1993	11	30	36.30	10.47	1.65	15.13	0.046	0.371	0.417
1993	12	31	35.62	8.59	1.24	12.00	0.035	0.302	0.337

weekly summary: excerpt (first and last few weeks)

-----  
 program ETTEST output file SND9393.wk weekly results

year	Jul	mo	wk	Penman	Priestly	relhum	ly/day	u2(m/s)	Tavg(C)
1993	7	1	1	4.2.31	4.2.39	84.17	111.21	3.09	4.72
1993	14	1	2	0.00	0.00	85.40	146.43	3.75	7.78
1993	21	1	3	0.00	0.00	86.73	196.57	2.51	6.11
...									
1993	357	12	51	0.00	0.00	79.69	213.51	3.19	4.88
1993	364	12	52	0.00	0.00	74.86	214.53	3.44	7.46
1993	365	1	53	0.00	0.00	53.50	209.40	4.29	8.89

Daily results: excerpt from file SND9393.OUT (7 days each from first and last of 1993)

-----														
program ETSAND daily output file SND9393.OUT														
Jul	AvgTmp	RelHum	SolRad	WndSpd	Precip	dTsoil	petmm	Penman	Priest	s0	vp_def	rshort	rlong	shflux
day	deg C	pct	ly/d	m/s	mm/day	deg C	mm/day	mm/day	mm/day	ly/d	kPa	MJ/m2/d	MJ/m2/d	MJ/m2/d
1	8.61	85.00	78.20	3.21	0.00	0.00	-0.97	0.82	0.53	852.58	0.17	2.52	-0.62	0.00
2	3.89	87.70	51.70	4.21	0.00	-0.56	-0.79	0.54	0.29	853.06	0.10	1.67	-0.64	-0.18
3	8.61	78.00	105.30	2.84	0.00	0.56	-0.45	1.11	0.72	853.56	0.25	3.39	-0.65	0.18
4	3.89	80.10	272.00	2.88	0.00	-1.11	1.30	1.51	1.86	854.10	0.16	8.76	-1.46	-0.35
5	3.61	81.10	150.40	2.68	0.00	0.00	0.17	1.01	1.01	854.68	0.15	4.85	-0.66	0.00
6	2.78	87.60	89.90	2.53	0.00	0.00	-0.72	0.57	0.53	855.28	0.09	2.90	-0.64	0.00
7	1.67	89.70	31.00	3.31	0.00	0.00	-1.19	0.30	0.08	855.91	0.07	1.00	-0.64	0.00
...														
359	6.11	73.80	265.80	3.31	0.00	0.83	1.60	1.78	1.81	850.23	0.25	8.56	-1.41	0.26
360	10.00	68.70	236.60	1.86	0.00	1.67	1.60	1.95	1.81	850.46	0.41	7.62	-0.98	0.52
361	6.67	88.30	71.50	4.95	0.00	-1.39	-0.28	0.74	0.56	850.73	0.12	2.30	-0.63	-0.44
362	5.28	80.50	221.40	2.90	0.00	-1.11	0.49	1.51	1.74	851.03	0.18	7.13	-0.76	-0.35
363	6.11	73.00	277.20	2.67	0.00	0.00	1.62	1.81	1.91	851.36	0.26	8.93	-1.58	0.00
364	8.89	58.80	269.10	3.33	0.00	0.00	2.23	2.58	2.02	851.74	0.48	8.67	-1.52	0.00
365	8.89	53.50	209.40	4.29	0.00	1.67	2.08	3.01	1.63	852.14	0.62	6.75	-0.69	0.53

### **\*HYDBAL package: summarize SWAT hydrologic results**

This package includes the subroutines PASSFLX, SWT2MOD, and MOD2SWT, which are called by SWAT only for a linked SWAT-MODFLOW run, and HYDBAL, which is called whether or not SWAT calls MODFLOW. The HYDBAL subroutines are described in the context of their use by SWAT.

### **Retrieve annual estimated irrigation water use from MODFLOW (PASSFLX)**

For each year, prior to beginning daily simulation, SWAT first calls MODFLOW entry point MODPER to define a stress period corresponding to a calendar year, and summarize the year's estimated irrigation use as a depth, based on input to Modflow's WELL package. Irrigation depth is calculated for each subbasin  $j$  by  $c \cdot Q_j / A_j$ , where  $Q_j$  = total pumping flow rate,  $A_j$  = subbasin area, and  $c$  = conversion factor for length and time. SWAT then calls PASSFLX to retrieve this estimated irrigation use, which can be interpreted as an annual constraint on irrigation by a modified version of SWAT's automatic irrigation procedure. If SWAT does not call MODFLOW, these annual irrigation depths can be read from SWAT's `~.cod` input file.

### **Pass SWAT's results to MODFLOW at the end of a time step (SWT2MOD)**

After simulating an aquifer time step (day, month, or year, based on option `iopmod`, `~.cod` input file) for a combined SWAT-MODFLOW run, SWAT calls SWT2MOD just prior to calling MODFLOW entry point MODSTP to pass a hydrologic summary calculated by Swat, including surface runoff, lateral flow, percolation from root zone, irrigation and surface evaporation, to Modflow's SHED array. If SWAT and MODFLOW are run separately, MODFLOW obtains the hydrologic summary by reading the balance file written by HYDBAL.

## **Retrieve MODFLOW results for SWAT's hydrologic summary (MOD2SWT)**

After calling MODSTP, SWAT calls MOD2SWT to retrieve a hydrologic summary of baseflow and groundwater evapotranspiration calculated by Modflow from the SHED array, to replace the values for these terms calculated by SWAT in the balance file written by HYDBAL. If SWAT does not call MODFLOW, the balance file includes the values calculated by SWAT for these terms.

## **Calculate mass balance and write summary of results (HYDBAL)**

After simulating the days of an aquifer time step (and calling MODFLOW if  $iopswt > 0$ ), SWAT calls HYDBAL to calculate mass balances for the control volumes of interest and (2) write the hydrologic summary and mass balance to the balance file. The mass balances for soil, vadose zone, aquifer, stream, and total control volumes provide a check on mass conservation in the combined Swat-Modflow linkage (see p. 49).

## **Structure of balance file for SWAT-MODFLOW data transfer**

A hydrologic summary is written by a call from SWAT to subroutine HYDBAL for each aquifer time step. The data contained in this summary may be either read 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. In addition, balance files summarizing the homogeneous components of a watershed may be combined into an average by program SWBAVG to be read by MODSWB. Examples of balance files written by SWAT and by SWBAVG for one time step are shown below, followed by balance file input format and definitions.

### Example: balance file written by SWAT

```

File repub.bal (first time step, 1 year) to be read by MODSWB
18 1977 9 0 file carr-ire.bal (1)
(25x,i3,a,2f7.1,10f8.2/, (t53,10f8.2)) (2)
balttl = 1977 initialize subr HYDBAL (3)
basttl = annual (4)
365. (days) 1977 annual hydrologic balance: (5)
id So Va Aq St To Sb Bas Sh component mean std d 1 2 3 4 5 6 7 8 9 (6)
2569.600 km**2 area fractions: 0.22015 0.04909 0.20435 0.08729 0.05282 0.08247 0.10945 0.11788 0.07649 (7)
ponds (areal fractions): 0.01994 0.03430 0.00310 0.00640 0.02680 0.00210 0.00000 0.01310 0.04139 0.02827 (8)
active gridded fraction: 0.12599 0.07325 0.20532 0.23676 0.09238 0.20991 0.01222 0.08288 0.02565 0.25037 (9)
1 1 0 0 0 1 1 1 10 PREC MM 993.4 107.5 1035.10 895.30 1113.80 855.70 855.70 855.70 855.70 1079.60 1079.60 (10)
2 1 0 -1 0 0 22 0 11 IRR MM 136.1 6.1 137.52 133.12 127.01 133.11 133.76 133.46 145.19 142.80 142.85 (11)
3 -1 0 0 0 -1 12 7 12 ET MM 868.9 24.9 885.77 834.88 859.75 842.52 851.06 839.14 850.67 910.92 903.16 (12)
4 -1 0 0 1 0 4 3 13 SURQ MM 100.8 39.6 124.66 63.53 152.81 55.67 48.57 50.74 51.56 111.52 113.18 (13)
5 0 0 1 0 1 13 38 14 TLOSS MM 3.8 1.7 3.29 5.23 6.80 3.43 2.06 1.42 3.25 2.64 3.43 (14)
6 -1 0 0 0 0 5 4 15 LATQ MM 0.3 0.1 0.38 0.15 0.29 0.43 0.37 0.25 0.19 0.44 0.27 (15)
7 -1 1 0 0 0 11 5 16 PERC MM 192.9 53.8 192.70 166.60 265.51 122.57 121.23 130.07 132.05 232.32 239.72 (16)
8 0 -1 1 0 0 9 107 17 GWRE MM 192.9 53.8 192.70 166.60 265.51 122.57 121.23 130.07 132.05 232.32 239.72 (17)
9 0 0 -1 0 -1 7 105 18 REV MM 6.1 6.3 9.42 22.36 8.70 0.00 17.72 0.00 2.11 0.00 0.00 (18)
10 0 0 -1 1 0 6 104 19 GW Q MM 5.1 9.6 6.79 27.36 12.86 6.04 -23.96 6.34 -0.32 1.01 -2.52 (19)
11 0 0 1 0 1 16 20 20 PSEP MM 2.5 2.2 4.67 0.87 1.18 1.92 0.36 0.00 0.00 6.07 4.08 (20)
12 0 0 0 0 0 25 108 21 ETPOT MM 1367.5 34.7 1371.68 1306.96 1322.86 1347.39 1393.00 1373.94 1375.39 1422.19 1416.17 (21)

```

### Example: average balance file written by SWBAVG for base case

```

File repbase.bal (first year of annual summary)
18 1977 9 0 (1)
(25x,i3,a,2f7.1,10f8.2/, (t53,10f8.2)) (2)
balttl = 1977 initialize subr HYDBAL (3)
basttl = monthly (4)
31. (days) 1977 1 monthly hydrologic balance: (5)
2569.600 1 2 3 4 5 6 7 8 9 (6)
0.01994 0.22015 0.04909 0.20435 0.08729 0.05282 0.08247 0.10945 0.11788 0.07649 (7)
0.00000 0.03430 0.00310 0.00640 0.02680 0.00210 0.00000 0.01310 0.04139 0.02827 (8)
0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 0.00000 (9)
10 PREC MM 18.6 3.9 18.60 16.40 16.38 16.40 15.77 15.80 15.78 26.23 26.23 (10)
11 IRR MM 0.0 0.0 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 (11)
12 ET MM 13.6 2.2 15.88 14.54 15.06 15.63 10.61 10.39 11.96 12.15 10.15 (12)
13 SURQ MM 1.3 1.4 0.60 0.05 1.18 1.13 0.56 0.38 0.22 3.86 4.35 (13)
14 TLOSS MM 0.2 0.1 0.21 0.05 0.26 0.31 0.27 0.16 0.19 0.23 0.29 (14)
15 LATQ MM 0.0 0.0 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 (15)
16 PERC MM 1.4 1.4 3.34 3.77 0.24 0.24 0.00 0.00 0.00 2.23 1.45 (16)
17 GWRE MM 1.4 1.4 3.34 3.77 0.24 0.24 0.00 0.00 0.00 2.23 1.45 (17)

```

18	REV MM	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(18)
19	GW Q MM	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(19)
20	PSEP MM	0.5	0.4	0.70	0.68	0.24	0.48	0.22	0.00	0.00	1.36	0.90	(20)
21	ETPOT MM	14.0	2.4	16.80	14.83	15.48	16.03	10.78	10.78	12.22	12.24	10.26	(21)

File records in the above examples are numbered at the right, corresponding to the following description; numbers in parentheses refer to vectors in the SHED array (below). The columns in the table of hydrologic components following line 9 are identified by the headings in line 2. In the middle of the table are the names of the hydrologic components to be passed between SWAT and MODFLOW. To the right of the component names lie columns for mean and standard deviation values for the components taken over all (nine) subbasins; to the right of these lie the component values for the first three of nine subbasins in this example. To the left of the component names, column Sh identifies vectors 10-21 of the SHED array, defined below.

## Input instructions for the balance file

These instructions describe not only how the balance file is written by subr. HYDBAL, but also how the file is both read and written in SWBAVG (p. 55) and is read by subr. SWB1FM in MODSWB (p. 87).

Items 1-21 correspond to records 1-21 in the example file repbase.bal (below).

1. Data (FREE): `nyrs, iyr, lutot, jkkopt` ! (~.bal rec. 1)
2. Data (TEXT): `fmtswb` !subbasin flux input format (~.bal rec. 2)

For each time step:

5. Scan for a record containing 'hydrologic balance'. From that record, extract the SWAT time step, `dtswat` (days); divide `dtswat` by `cnvtim` to convert `dtswat` into a MODFLOW time step, `delt`.

6. Data: `(idx, j=1, nwshed)` !column heading  
Format: `(t53, 10f8)`
7. Data: `bsarea, (shed(3, j), j=1, nwshed)` !basin area, subbasin fractions  
Format: `(f15.3, t53, 10f8.5/, (t53, 10f8.5))`
8. Data: `fpd, (shed(8, j), j=1, nwshed)` !noncontrib. areas: subbasin fractions  
Format: `225 = (t39, f8.5, 6x, 10f8.5/, (t53, 10f8.5))`
9. Data: `avgval, (subval( j), j=1, nwshed)` active gridded area fractions  
Format: `225`

10-21. Read hydrologic fluxes calculated by SWAT for all subbasins:

```
do i=10,21
  Data:      idx, coltxt, swtflx(i), flxdev(i), (shed(i, j), j=1, nwshed)
  Format:    fmtswb (from balance record 2)
end do
```

## Definitions for balance input file (ext. ~.bal)

Input records 1-21 are identified at right on listing of example files repbase.bal and repub.bal (below).

1.

nyrs no. years simulated; should equal no. of stress periods (Basic package)  
iyrbeginning calendar year of simulation  
lutot number of subbasins; should equal nwshed (~.SWB, item 1).  
jkkopt option (orig. read from SWAT input options file ~.cod, determines how hydrologic fluxes are combined to define tributary flow and recharge for MODFLOW. The default (jkkopt = 0) is applied to the Republican River model; the exception (jkkopt>0) is a special case applied to the Rattlesnake Creek watershed model (Koelliker, 1995). Letting  $c = 1 - \text{pond fraction}(8)$ , tributary flow and recharge are defined as follows (numbers identify vectors in array SHED where fluxes are retained during a time step; see example balance file below).

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

2. **fmtswb**: subbasin flux input format; used at (13).

For each time step of each stress period (SWT1FM):

Read file records until one is found containing the phrase 'hydrologic balance'.

From that record, extract the SWAT time step, **dtswat** (days); convert this into an aquifer time step **delt** (s) for MODFLOW by  $\text{delt} = \text{dtswat}/\text{cnvtim}$ .

Record contents:

5 length of time step (days), calendar year, and the phrase "hydrologic balance", used by MODSWB to identify the beginning of the summary;

6. headings that apply to columns for the hydrologic components that follow line 9:  
(idx, j=1, nwshed): column heading

7. total basin area and the areal fraction for each subbasin, SHED(1):  
avgval, (subval(j), j=1, nwshed): placeholder for subbasin fractions of basin area;  
also read from ~.SWB file (item 4).

8 noncontributing area fraction of basin and each subbasin for ponds, SHED(8):  
fpd, (shed(8, j), j=1, nwshed): noncontrib. areas: basin average and subbasin fractions

9 area fraction of basin and each subbasin corresponding to active aquifer nodes, SHED(3). In SWAT's stand-alone mode (iopswt = 0), these appear as zero, since they are defined in MODFLOW.  
avgval, (subval(j), j=1, nwshed): placeholder for active gridded area fractions;  
(calculated in MODSWB)

10-21. Read hydrologic fluxes calculated by SWAT for all subbasins into array SHED vectors 10-21 (defined below):

idx index to array SHED where hydrologic flux is retained;  
coltxt name of flux (precip, irrig., etc.)  
swtflx(i) avg flux taken over subbasins, weighted by subbasin areal fraction  
flxdev(i) std deviation taken over subbasins  
(shed(i, j), j=1, nwshed): hydrologic flux (mm) for each subbasin.

Hydrologic components read from the balance file by MODFLOW's MODSWB package into SHED vectors are defined below; see p. 97 for a complete list of definitions.

- (10) **Prec mm** precipitation
- (11) **Irr mm** irrigation [L] according to SWAT; used to scale pumping if  $irropt > 0$ .
- (12) **ET mm** "actual" evaporation calculated by SWAT [L]; see also (21).
- (13) **SURQ mm** surface runoff [L] to tributaries leaving subbasin
- (14) **TLoss mm** transmission loss [L]
- (15) **LATQ mm** lateral flow [L] to tributaries leaving subbasin
- (16) **PERC mm** percolation from the root zone
- (17) **GWRE mm** groundwater recharge. According to SWAT, this consists only of percolation from the root zone, with a possible delay time set by SWAT input. For zero time delay (i.e., no storage in the vadose zone), recharge equals percolation from the root zone. For MODFLOW definition of recharge, see (25).
- (18) **GW ET mm** evaporation from water table ("revap" in Swat); the value from SWAT is replaced calculations in MODFLOW's EVT package that are summarized for each subbasin in SWB1BD.
- (19) **Baseflow mm** baseflow; the value from SWAT is replaced 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 calculated by SWAT; if  $ievopt > 0$ , this is used to define the maximum evaporation rate from the water table for the EVT package; also see option  $ievopt$  and SWAT option  $iopet$ .

## Discussion of terms written to balance file

In the first example above, Columns **Sb** and **Bas** identify the vectors for SWAT's subbasin and basin arrays, respectively, that contain these components. At the left are vector columns corresponding to soil (**So**), vadose (**Va**), aquifer (**Aq**), stream (**St**), and total (**To**) control volumes that indicate how the components are added into a mass balance for each by subroutine HYDBAL according to the equations shown below. For each of these control volumes, mass conservation is expressed by  $ds = \sum q_i$ , i.e., the time rate of change of mass per unit area within the control volume equals the net flux into the control volume by the components  $q_i$ . The balances are evaluated as follows:

$$\text{soil/vadose: } ds(1) = \text{precip}(10) + \text{irrig}(11) - \text{runoff} - \text{xmlloss}(14) - \text{et}(12) - \text{perc}_{rz}(16) + \text{et}_{gw}(18),$$

$$\text{vadose: } ds(2) = \text{perc}_{rz}(16) - \text{perc}_{vz}(17);$$

$$\text{aquifer: } ds(3) = \text{rech}(25) - \text{irr}_{gw}(11) - \text{et}_{gw}(18) - \text{baseflow}(19);$$

$$\text{stream: } ds(4) = c \cdot \text{runoff} + \text{baseflow}(19) - \text{irr}_{surf};$$

$$\text{ponds: } ds_{pnd} = (1 - c) \cdot \text{runoff};$$

$$\text{total: } ds(5) = \text{prec}(10) - \text{et}(12),$$

where

$$\text{infiltr} = \text{precip}(10) + \text{irrig}(11) - \text{runoff} - \text{xmloss}(14);$$

$$\text{irrig} = \text{irr}_{\text{gw}}(11) + \text{irr}_{\text{surf}};$$

$$\text{runoff} = \text{runoff}_{\text{surf}}(13) - \text{runoff}_{\text{sub}}(15)$$

$$\text{rech}(25) = \text{xmloss}(14) + \text{perc}_{\text{vz}}(16) + \text{psep}(20);$$

$$c = 1 - \text{pond fraction (8); and}$$

$$\text{et}_{\text{gw}}(18) = (1 - \text{dtw}/\text{extdep}) \cdot \text{etpot}(25)$$

Abbreviations and indices for the terms in these equations correspond to the vectors in array SHED that store the components shown in the balance file examples (above); see also the description (p. 6) of control volumes in the watershed. The above equations indicate that of the total runoff (13) and subsurface flow (15) leaving the soil control volume, only their contributing fraction are shown entering the stream control volume; a balance on ponds might be useful in showing the fate of their noncontributing fraction.

A distinction is drawn between definitions for recharge in SWAT and MODFLOW. SWAT's definition of recharge (17) is restricted to soil water that has dropped through both the soil profile and the vadose zone, and is represented by SWAT as delayed percolation (16) from the soil profile. This definition is narrower than that used in MODSWB to calculate recharge for MODFLOW, which includes transmission losses, percolation and pond seepage, subject to added SWAT option **jkopt**, described in Section 11. MODFLOW's version of the recharge flux is distinguished from SWAT's definition as SHED vector 25.

\*\*\*

## 6. SWBAVG: REPRESENT WATERSHED SPATIAL HETEROGENEITY

The use of program SWBAVG is illustrated for the base case by input file `repbases.inp`. The basin is represented by eighteen cases corresponding to combinations of three land uses and six soil types, whose areal fractions are shown in Table 3.7 (Vol. 1). The product of areal fractions corresponding to a land use and a soil type, e.g. irrigated corn and Carr soil, gives the areal fraction of the basin represented by that case. A full simulation of SWAT is run (1977-1994, monthly) for each case, in which the entire areal

extent of the basin is represented homogeneously by the case's associated land use and soil type, i.e., as a hydrologic response unit (HRU). The input file shown below lists the names of balance files resulting from the eighteen runs of SWAT for these cases. Each hydrologic flux for each subbasin is averaged over these eighteen cases on the basis of the table of weight functions shown in the input file for each year. The first and last years' tables of normalized weights are shown in the input file below as percents. For each year, the rows of the matrix correspond to the nine subbasins, and the columns correspond to the eighteen cases of land use and soil type, whose sequence corresponds to the order in which the case names were read. For example, the mean of each hydrologic balance component for subbasin 1 (row 1) includes 4.9 pct of case 1 (Carr-wsf), 25 pct of case 2 (Carr-irc), 5.2 pct of case 3 (Carr-r/p), and so on, through 13.6 pct of case 17 (Muir-irc).

Program SWBAVG is illustrated by file `swbavg.inp` for the Lower Republican River Basin model. In this example, each HRU corresponds to one of 18 combinations of six soil types and three land use-management schemes used to represent The five soil types are represented by Harney, Pratt, Tivoli, Naron, and Carwile. Land use and management practices are represented by three schemes: wheat, sorghum, and fallow rotations with no irrigation (wsf); irrigated corn (irc); and range and pasture without irrigation (r/p). The initial table of weight functions used to average the HRUs are shown in the table below: the 29 rows correspond to subbasins, and the columns from left to right correspond to 15 HRUs associated with the order in which names of the balance files are read from the file.

Whereas areal fractions of soil types within each subbasin are naturally fixed with respect to time, their land use areal fractions vary from year to year. To represent this land use change, the initial table of weight functions is updated every five years.

Input data requirements for SWBAVG are described below, and are summarized as follows. Line 1 shows the name of the hydrologic balance file that is to be written by SWBAVG containing the averaged results, and which can be read in a subsequent run of MODFLOW. In addition to this file, SWBAVG writes a summary file containing an areally weighted average over all subbasins for each hydrologic component. Line 2 of the file lists the years in which the set of weight functions is to be updated, primarily

reflecting the change in land use over time. Following line 2 are the names of eighteen hydrologic balance files previously written by SWAT that represent the HRUs to be averaged; see p. 49 for a description of the balance file format as written by subr. HYDBAL, which is called from SWAT for each aquifer time step. This list is followed by an initial set of weight functions for each of 29 subbasins, used to calculate averages for each hydrologic component in each subbasin. This initial set of weights is updated in the years shown in line 2 by tables of weight functions (not shown) following the first set of weights.

For each hydrologic flux (SHED vectors 10-21) in each time step and subbasin, the corresponding weight function is used to calculate an average over all 15 HRUs read from the balance files; the results are written to file spp60-91.bal, which is written in the same format as the component balance files, so that it may be read by MODFLOW to represent a weighted average of the spatial heterogeneities in the Rattlesnake Creek watershed. The code in SWBAVG that reads the component balance files and writes the average balance file was adapted from the code in subroutine SWB1FM of the MODSWB package in MODFLOW used to read balance files.

## Input instructions for SWBAVG

The following instructions are illustrated below by file swbavg.inp; corresponding input records are numbered 1-6.

Number of subbasins, HRUs, years, weight function revisions, output file name:  
`read (in,*) nwshed,ncond,nwper,nrevis,iopsub,outbal` (1)

Years of revisions (max: one less than the number of years):  
`if (nrevis.gt.0) read (in,*) (irevyr(i),i=1,nrevis)` (2)

Balance file names for component cases (HRUs):  
 For each component case k=1,ncond:  
`read (in,*) condnm(k), inpbal(k)` (3)

Tables of weight functions: In the first year (not specified) and in subsequent years (given by line 2), read weight functions. For each table of weights, read two lines of headings: one to identify which set of weights is being read, and one to associate the columns of weights, from left to right, with the order in which the balance file names are read.

`read (in,'(a)') wthdg` (4)  
`read (in,'(a)') wthdg` (5)

Table of weight functions as pct: each row should add to 100 pct. If iopsub=0, only one weight function is read, which is applied to all subbasins.

For each subbasin j=1,nwshed:

```
if (j=1 or iopsub>0) read (in,*) (condwt(j,ic),ic=1,ncond) (6
```

## Input definitions for SWBAVG

nwshed: no. subbasins

ncond: no. component cases (HRUs) represented by balance files written by SWAT to be averaged (the number no. of combinations of soil types and land use-management schemes;

nper: no. years of study

nrevis: no. times the initial table of weight functions is updated;

iopsub: option to either (yes=1) specify a separate weight function for each subbasin; or (no=0) specify one weight function to be applied to all subbasins.

outbal: name of output balance file containing average of the HRUs; enclose name with apostrophes for free format input.

irevyr(i) = beginning year for each revision of weight functions, i from 1 to nrevis//

condnm = identifying name (10 characters) for each component case (HRU);

inpbal = name of balance file (up to 30 characters) written by SWAT for each component case (HRU); enclose with apostrophes as shown.

## Example: SWBAVG input file rpbasem.inp (for base case)

The following excerpt, showing weights for only the first and last years, is based on results from program WEIGHTS (below).

```

9,18,217,17,1,'rpbasem.bal',    nwshed,ncond,nper,nrevis,iopsub,outfil swbavg.inp
  1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990
1991 1992 1993 1994
'Carr-wsm',    'carr-wsm.bal',  soil 1 (wheat/sorghum/fallow rot.) (case, file name)
'Carr-irm',    'carr-irm.bal',  (irrigated corn)
'Carr-pam',    'carr-pam.bal',  (grass: range and pasture)
'Crete-wsm',   'cret-wsm.bal',  soil 2
'Crete-irm',   'cret-irm.bal',
'Crete-pam',   'cret-pam.bal',
'Hasting-wsm', 'hast-wsm.bal',  soil 3
'Hasting-irm', 'hast-irm.bal',
'Hasting-pam', 'hast-pam.bal',
'Hedville-wsm', 'hedv-wsm.bal',  soil 4
'Hedville-irm', 'hedv-irm.bal',
'Hedville-pam', 'hedv-pam.bal',
'Kipson-wsm',  'kips-wsm.bal',  soil 5
'Kipson-irm',  'kips-irm.bal',
'Kipson-pam',  'kips-pam.bal',
'Muir-wsm',    'muir-wsm.bal',  soil 6
'Muir-irm',    'muir-irm.bal',
'Muir-pam',    'muir-pam.bal',
normalized weights beginning year 1977  3.13 pct basin irrigated
   1   2   3   4   5   6   7   8   9   10   11   12   13   14   15   16   17   18
  1  5.20 0.29 3.71 26.61 1.47 19.02 5.59 0.31 4.00 0.00 0.00 0.00 19.09 1.06 13.65 0.00 0.00 0.00
  2  9.85 0.60 8.67  3.30 0.20  2.91 20.72 1.26 18.26 0.00 0.00 0.00 17.63 1.07 15.53 0.00 0.00 0.00
  3  5.85 0.31 3.64 38.02 1.99 23.69 7.46 0.39 4.65 0.42 0.02 0.26 3.10 0.16 1.93 4.83 0.25 3.01
  4  6.83 0.39 5.37 29.42 1.70 23.12 2.93 0.17 2.30 0.00 0.00 0.00 14.85 0.86 11.67 0.22 0.01 0.17
  5  2.95 0.13 1.22 51.04 2.33 21.13 0.00 0.00 0.00 0.00 0.00 0.00 5.89 0.27 2.44 8.63 0.39 3.57
  6  0.00 0.00 0.00 42.98 2.32 28.80 0.00 0.00 0.00 10.21 0.55 6.84 3.42 0.18 2.29 1.39 0.00 0.93
  7  0.00 0.00 0.00 56.02 2.72 28.24 0.00 0.00 0.00 1.42 0.07 0.72 0.00 0.00 0.00 6.96 0.34 3.51
  8  0.00 0.00 0.00 34.87 2.18 32.65 0.00 0.00 0.00 13.96 0.87 13.07 0.00 0.00 0.00 1.20 0.08 1.12
  9  0.00 0.00 0.00 29.50 1.97 31.59 0.00 0.00 0.00 0.98 0.07 1.05 0.00 0.00 0.00 16.30 1.09 17.45
normalized weights beginning year 1994  4.70 pct basin irrigated
   1   2   3   4   5   6   7   8   9   10   11   12   13   14   15   16   17   18
  1  5.05 0.43 3.71 25.87 2.21 19.02 5.44 0.47 4.00 0.00 0.00 0.00 18.56 1.59 13.65 0.00 0.00 0.00
  2  9.55 0.90 8.67  3.20 0.30  2.91 20.09 1.89 18.26 0.00 0.00 0.00 17.09 1.61 15.53 0.00 0.00 0.00
  3  5.69 0.46 3.64 37.02 2.99 23.69 7.26 0.59 4.65 0.41 0.03 0.26 3.02 0.24 1.93 4.71 0.38 3.01
  4  6.63 0.59 5.37 28.57 2.55 23.12 2.84 0.25 2.30 0.00 0.00 0.00 14.42 1.29 11.67 0.21 0.02 0.17
  5  2.88 0.20 1.22 49.87 3.50 21.13 0.00 0.00 0.00 0.00 0.00 0.00 5.76 0.40 2.44 8.43 0.59 3.57
  6  0.00 0.00 0.00 41.81 3.48 28.80 0.00 0.00 0.00 9.93 0.83 6.84 3.33 0.28 2.29 1.35 0.11 0.93
  7  0.00 0.00 0.00 54.65 4.09 28.24 0.00 0.00 0.00 1.38 0.10 0.72 0.00 0.00 0.00 6.79 0.51 3.51
  8  0.00 0.00 0.00 33.78 3.28 32.65 0.00 0.00 0.00 13.52 1.31 13.07 0.00 0.00 0.00 1.16 0.11 1.12
  9  0.00 0.00 0.00 28.51 2.96 31.59 0.00 0.00 0.00 0.95 0.10 1.05 0.00 0.00 0.00 15.75 1.64 17.45

```

## Program WEIGHTS: calculate weight functions for SWBAVG

Program weights is run as follows:

weights <wrpbase.inp >wrpbase.dat  
 The results, file wrpbase.dat, contain the tables of weight functions for each year that are to be used by program SWBAVG to average the hydrologic response units (HRUs) described above. These weight function tables follow the list of balance file names associated with the HRUs.

Input file wrpbase.inp (redirected from keyboard):

```
-----
file wrpbase.inp (export ak64-at71) from cropsp.wq! feb 1 96 spp
9,6,18,1977,nsubs,nsouls,numver,ibgnyr(1)
' crop%' 59.62 54.63 62.81 57.37 71.64 61.13 67.53 53.16 49.91
' Carr' 0.092 0.191 0.098 0.126 0.043 0 0 0 0
' Crete' 0.471 0.064 0.637 0.543 0.745 0.741 0.869 0.697 0.63
'Hasting' 0.099 0.402 0.125 0.054 0 0 0 0 0
'Hedville' 0 0 0.007 0 0 0.176 0.022 0.279 0.021
' Kipson' 0.338 0.342 0.052 0.274 0.086 0.059 0 0 0
' Muir' 0 0 0.081 0.004 0.126 0.024 0.108 0.024 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, irrig. area pct 1977 to 1994
-----
```

Output file wrpbase.dat (excerpt; redirected from terminal):

```
-----
Program weights: read from keyboard; write to terminal.
write weights before normalizing to file weights.prn.
file wrpbase.inp (export ak64-at71) from cropsp.wq! feb 1 96 spp
read nwshed,nsouls,nyrs; defs (incl. related variables for SWBAVG):
nwshed = no. subbasins
nsouls = no. soil combinations
nyrs = no. versions of weight ftns
(in SWBAVG: nrevis = nyrs - 1)
iopsub = option: (y=1) specify a separate weight ftn for each subbasin;
(y=0) specify one weight ftn for all subbasins.
outbal = avg balance output file name (30 char max)
nweight = ncrop*nsouls = 3* 6 = 18
read irrigated pct of basin for each year:
Bgn year: 1977 1978 1979 1980 1981 1982 1983 1984 1985
Pct Irrig: 3.130 3.320 3.420 4.180 4.060 3.540 3.610 3.660 3.510
Bgn year: 1986 1987 1988 1989 1990 1991 1992 1993 1994
Pct Irrig: 3.550 3.760 4.280 4.210 4.310 4.520 4.420 4.770 4.700
1 1977 3.13
subbasin 1 2 3 4 5 6 7 8 9
crop% 59.620 54.630 62.810 57.370 71.640 61.130 67.530 53.160 49.910
soils
Carr 0.092 0.191 0.098 0.126 0.043 0.000 0.000 0.000 0.000
Crete 0.471 0.064 0.637 0.543 0.745 0.741 0.869 0.697 0.630
Hasting 0.099 0.402 0.125 0.054 0.000 0.000 0.000 0.000 0.000
Hedvill 0.000 0.000 0.007 0.000 0.000 0.176 0.022 0.279 0.021
Kipson 0.338 0.342 0.052 0.274 0.086 0.059 0.000 0.000 0.000
Muir 0.000 0.000 0.081 0.004 0.126 0.024 0.108 0.024 0.348
Weights and sums before normalizing:
sol crp iwt 1 2 3 4 5 6 7 8 9
1 1 1 5.20 9.84 5.85 6.83 2.95 0.00 0.00 0.00 0.00
1 2 2 0.29 0.60 0.31 0.39 0.13 0.00 0.00 0.00 0.00
1 3 3 3.71 8.67 3.64 5.37 1.22 0.00 0.00 0.00 0.00
2 1 4 26.61 3.30 38.02 29.45 51.04 42.98 55.96 34.87 29.47
2 2 5 1.47 0.20 1.99 1.70 2.33 2.32 2.72 2.18 1.97
2 3 6 19.02 2.90 23.69 23.15 21.13 28.80 28.22 32.65 31.56
3 1 7 5.59 20.70 7.46 2.93 0.00 0.00 0.00 0.00 0.00
3 2 8 0.31 1.26 0.39 0.17 0.00 0.00 0.00 0.00 0.00
3 3 9 4.00 18.24 4.65 2.30 0.00 0.00 0.00 0.00 0.00
4 1 10 0.00 0.00 0.42 0.00 0.00 10.21 1.42 13.96 0.98
4 2 11 0.00 0.00 0.02 0.00 0.00 0.55 0.07 0.87 0.07
4 3 12 0.00 0.00 0.26 0.00 0.00 6.84 0.71 13.07 1.05
5 1 13 19.09 17.61 3.10 14.86 5.89 3.42 0.00 0.00 0.00
5 2 14 1.06 1.07 0.16 0.86 0.27 0.18 0.00 0.00 0.00
5 3 15 13.65 15.52 1.93 11.68 2.44 2.29 0.00 0.00 0.00
6 1 16 0.00 0.00 4.83 0.22 8.63 1.39 6.96 1.20 16.28
6 2 17 0.00 0.00 0.25 0.01 0.39 0.08 0.34 0.08 1.09
6 3 18 0.00 0.00 3.01 0.17 3.57 0.93 3.51 1.12 17.43
sums: 100.00 99.90 100.00 100.10 100.00 100.00 99.90 100.00 99.90
-----
```

Output file wrpbase.dat (continued excerpt from above)

-----The following results are to be read by program SWBAVG:  
 (Only tables for 1977 and 1994 are shown; compare tables in rpbasem.inp)

normalized weights beginning year 1977 3.13 pct basin irrigated

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	5.20	0.29	3.71	26.61	1.47	19.02	5.59	0.31	4.00	0.00	0.00	0.00	19.09	1.06	13.65	0.00	0.00	0.00
2	9.85	0.60	8.67	3.30	0.20	2.91	20.72	1.26	18.26	0.00	0.00	0.00	17.63	1.07	15.53	0.00	0.00	0.00
3	5.85	0.31	3.64	38.02	1.99	23.69	7.46	0.39	4.65	0.42	0.02	0.26	3.10	0.16	1.93	4.83	0.25	3.01
4	6.83	0.39	5.37	29.42	1.70	23.12	2.93	0.17	2.30	0.00	0.00	0.00	14.85	0.86	11.67	0.22	0.01	0.17
5	2.95	0.13	1.22	51.04	2.33	21.13	0.00	0.00	0.00	0.00	0.00	0.00	5.89	0.27	2.44	8.63	0.39	3.57
6	0.00	0.00	0.00	42.98	2.32	28.80	0.00	0.00	0.00	10.21	0.55	6.84	3.42	0.18	2.29	1.39	0.08	0.93
7	0.00	0.00	0.00	56.02	2.72	28.24	0.00	0.00	0.00	1.42	0.07	0.72	0.00	0.00	0.00	6.96	0.34	3.51
8	0.00	0.00	0.00	34.87	2.18	32.65	0.00	0.00	0.00	13.96	0.87	13.07	0.00	0.00	0.00	1.20	0.08	1.12
9	0.00	0.00	0.00	29.50	1.97	31.59	0.00	0.00	0.00	0.98	0.07	1.05	0.00	0.00	0.00	16.30	1.09	17.45

normalized weights beginning year 1994 4.70 pct basin irrigated

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	5.05	0.43	3.71	25.87	2.21	19.02	5.44	0.47	4.00	0.00	0.00	0.00	18.56	1.59	13.65	0.00	0.00	0.00
2	9.55	0.90	8.67	3.20	0.30	2.91	20.09	1.89	18.26	0.00	0.00	0.00	17.09	1.61	15.53	0.00	0.00	0.00
3	5.69	0.46	3.64	37.02	2.99	23.69	7.26	0.59	4.65	0.41	0.03	0.26	3.02	0.24	1.93	4.71	0.38	3.01
4	6.63	0.59	5.37	28.57	2.55	23.12	2.84	0.25	2.30	0.00	0.00	0.00	14.42	1.29	11.67	0.21	0.02	0.17
5	2.88	0.20	1.22	49.87	3.50	21.13	0.00	0.00	0.00	0.00	0.00	0.00	5.76	0.40	2.44	8.43	0.59	3.57
6	0.00	0.00	0.00	41.81	3.48	28.80	0.00	0.00	0.00	9.93	0.83	6.84	3.33	0.28	2.29	1.35	0.11	0.93
7	0.00	0.00	0.00	54.65	4.09	28.24	0.00	0.00	0.00	1.38	0.10	0.72	0.00	0.00	0.00	6.79	0.51	3.51
8	0.00	0.00	0.00	33.78	3.28	32.65	0.00	0.00	0.00	13.52	1.31	13.07	0.00	0.00	0.00	1.16	0.11	1.12
9	0.00	0.00	0.00	28.51	2.96	31.59	0.00	0.00	0.00	0.95	0.10	1.05	0.00	0.00	0.00	15.75	1.64	17.45

## 7. MODFLOW: NEW (\*) AND MODIFIED (•) PACKAGES

### •Main program

The original structure of MODFLOW is illustrated by the flowchart in Fig. 3 reproduced from MODFLOW's manual (McDonald et al., 1988). The modified structure of MODFLOW is summarized by the outline shown below. Calls to subroutines in the MODSWB package, added to this structure to coordinate MODFLOW and a watershed model, are identified by bold type. The MODSWB package is invoked by setting **iunit(6) > 0** in MODFLOW's basic package input; see MODFLOW manual, p. 4.9. MODFLOW may be run either as a stand-alone program or linked with the daily watershed simulation program, SWAT, as described above (p. 30). In linked execution mode, MODFLOW is called from SWAT via entry points MODFLO, MODPER, and MODSTP that were added to MODFLOW. In order to place these entry points to MODFLOW within "do" loops on stress periods and time steps, and allow jumps into these loops by calls from SWAT, the "do" loops have been rewritten as more primitive but functionally equivalent conditional jumps with counters, thereby circumventing the normally justified prohibition by Fortran compilers of jumps into a do loop.

100

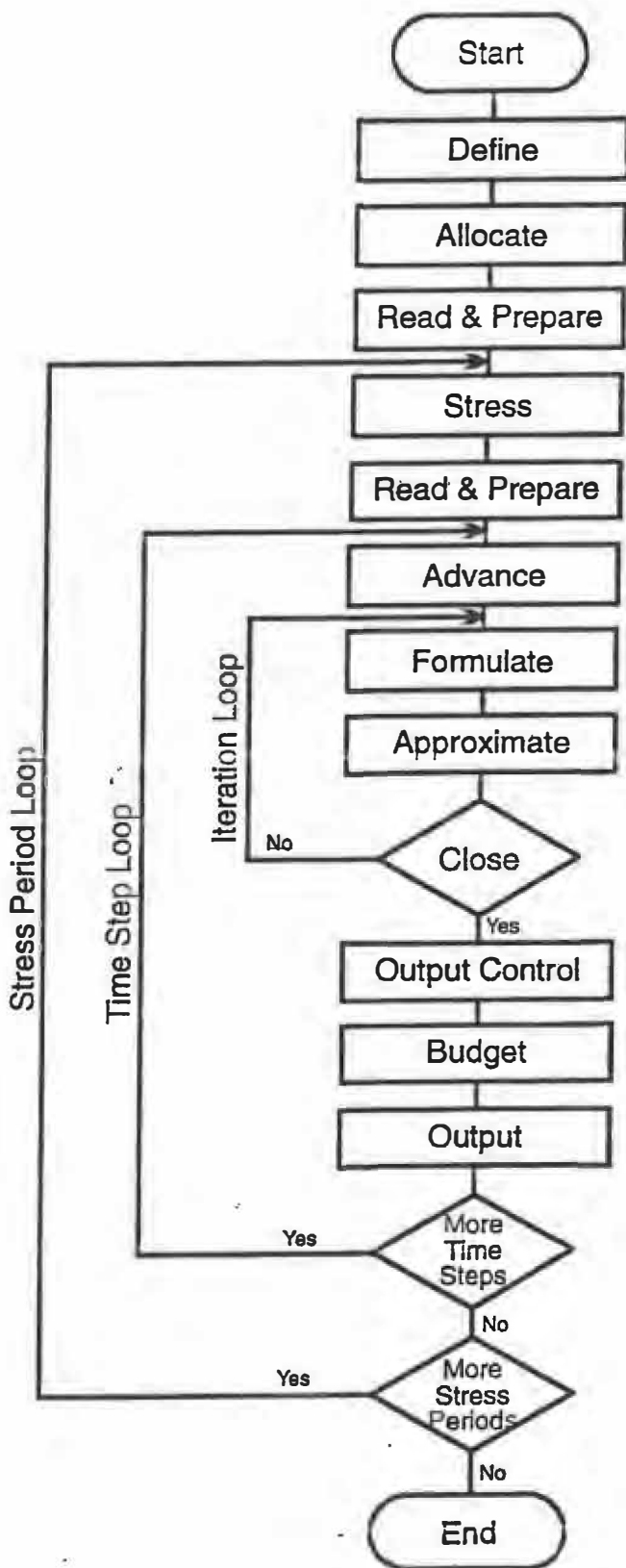
1

1

1

1

1



**DEFINE** - Read data specifying number of rows, columns, layers, stress periods, and major program options.

**ALLOCATE** - Allocate space in the computer to store data.

**READ AND PREPARE** - Read data which is constant throughout the simulation. Prepare the data by performing whatever calculations can be made at this stage.

**STRESS** - Determine the length of a stress period and calculate terms to divide stress periods into time steps.

**READ AND PREPARE** - Read data which changes from one stress period to the next. Prepare the data by performing whatever calculations can be made at this stage.

**ADVANCE** - Calculate length of time step and set heads at beginning of a new time step equal to heads calculated for the end of the previous time step.

**FORMULATE** - Calculate the coefficients of the finite difference equations for each cell.

**APPROXIMATE** - Make one cut at approximating a solution to the system of finite difference equations.

**OUTPUT CONTROL** - Determine whether results should be written or saved on disk for this time step. Send signals to the **BUDGET** and **OUTPUT** procedures to indicate exactly what information should be put out.

**BUDGET** - Calculate terms for the overall volumetric budget and calculate and save cell-by-cell flow terms for each component of flow.

**OUTPUT** - Print and save heads, drawdown and overall volumetric budgets in accordance with signals from **OUTPUT CONTROL** procedure.

Fig. 3. MODFLOW program structure (reproduced from Fig. 13, McDonald and Harbaugh, 1988).

Modified MODFLOW program structure (based on Fig. 3).  
See keys below; additions are in **bold type**.

```
begin simulation (subroutine modflo)
  Define no. rows, columns, layers, stress periods, and major options (bas1df).
  Allocate space for data (bas bcf wel drn rch evt riv str srf swb ghb sip sor) -al
  Read, prepare data for the simulation (bas bcf sip pcg sor) -rp
  do for each stress period (entry modper):
    Stress: Determine stress period length; divide it into time steps (bas1st).
    Read stress period data (wel srf drn rch evt riv str1rp str1dw ghb evtinit swb1rp)
    do for each time step (entry modstp):
      (call swb1f0)
      Advance time step and update initial heads (bas1ad wel1f0 srf1f0).
      do while solution has not yet converged:
        Formulate finite difference equations to be solved.
        Approximate solution (bas wel drn rch evt riv str str1dw ghb sip pcg sor)
      end iterative loop on solution
      Output control: determine what results are to be printed and written (bas1oc)
      Budget (bcf wel drn rch evt riv str str1dw str2dw swb1bd wellwr ghb)
      Output: print and save heads, drawdown, and overall budget (bas1ot).
    ,end time step
  end stress period
end simulation
```

Key to packages (prefixes; added packages are in **bold type**):

bas = Basic, bcf = Block-centered flow, wel = Well, drn = Drain, riv = River,  
evt = Evapotranspiration, **swb = Soil water balance**, ghb = General head boundary,  
rch = Recharge, sip = Strongly implicit procedure, pcg = Conjugate gradient,  
sor = Successive overrelaxation, oc = Output control, str = Streamflow,  
**srf = Surface water diversions**

Key to functions (suffixes): al = allocate, rp = read and prepare, fm = formulate,  
oc = output control, bd = budget, ot = output.

## Stand-alone MODFLOW execution control

In stand-alone mode, calling program MODMAIN, shown below, calls subroutine MODFLO, passing **iopswt=0** so that the complete structure of MODFLOW shown above is executed before returning to MODMAIN.

```
program modmain
  data iopswt/0/ ! set option to run modflow as stand-alone program.
```

```

data cnvtim /1./ ! time unit conversion factor (for calling MODFLOW from SWAT)
  call MODFLO (iopswt, mx curs, icursr, jkkopt, cnvtim, delt, kper, nstp, kstp)
stop
end

```

## Definition of argument list passed to MODFLOW

In the case of stand-alone execution (*iopswt*=0, above), only arguments *iopswt* and *cnvtim* need be defined by the mainline, as shown; the remaining arguments are defined within the call to subroutine MODFLO. For combined SWAT-MODFLOW execution (*iopswt*>0), the argument lists for MODFLO, MODPER, and MODSTP are the same, and are defined as follows.

- mx curs*: max. no. cursors identifying beginning locations of arrays within the x array; specifies dimension for array *icursr* (see below).
- icursr*: array of indices to arrays within x array; calculated in MODFLOW's x-array allocation routines. This allows SWAT (or other calling program) to reference any of the arrays allocated space within the x-array. Note: *inters* (10) is an internal version of array *icursr* that is equivalenced to the x-array indices for convenient copying to *icursr*.
- jkkopt*: option for defining recharge and tributary flow (see "Definition of options used in the MODSWB package"); *jkkopt* is either read from balance file if *iopswt*=0 or passed from SWAT if *iopswt*=1.
- cnvtim*: conversion from Swat time units (days) to Modflow time units [Tmd]; given by  $cnvtim = tsec(itmuni)/86400$  [days/Tmd]; *tsec* and *itmuni* are defined below. *cnvtim* is calculated in MODSWB subroutine SWB1RP and, if *iopswt*=1, is passed back to Swat via MODFLO's argument list on Swat's initial call to MODFLO.
- itmuni*: time unit option (0-5); specified in MODFLOW's Basic Package input file.
- tsec*: time unit length (sec) corresponding to *itmuni* as follows:

<i>itmuni</i>	<i>tsec(itmuni)</i>	time unit
0:	1	undefined
1:	1	second
2:	60	minute
3:	3600	hour
4:	86400	day
5:	31536000	year (365 days)

*delt*: time step [T]; not used until after the MODSTP entry point, but the argument list of the first entry point should contain all arguments of ensuing entry points. For the stand-alone option (*iopswt*=0), time step and multiplier are used as specified in MODFLOW's basic package input file, i.e. standard input is default.

*kper*: index to current stress period;

---

nstp: number of time steps for current stress period, kper;  
kstp: index to current time step.

## 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.

<u>input flag</u>	<u>j: device(j)</u>	<u>file prefix</u>	<u>package</u>	<u>subroutine</u>	<u>output</u>
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	wellal	
idrnbc	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.

### Example: base case (1977-1994) with monthly time steps

MODFLOW is invoked to run base case as follows:

```
modswb96 <basecase.rsp >basecase.jou
```

For this run, file **basecase.rsp**, listed below, contains the redirected keyboard responses to MODFLOW's queries for case name and names of files associated with packages invoked by input for the Basic package; modified or added packages are shown in **bold** type.

```
basecase          case name (-.log, -.prn, -.rsp)
bcase_t          .bas unit   1 Monthly Basic package
kbase20a         .bcf unit   61 Block-centered flow
gwradn           .wel unit   62 Well: groundwater use
repsurf          .evt unit   65
basecase         .swb unit   66 Soil water balance
recharge         .rch unit   67 Recharge
```

modellbs	.pcg unit	68	precond. conjugate gradient
rep7794m	.oc unit	69	Output control
rpmon	.str unit	70	monthly Strmflow, Ks=0.54 ft/day
swuadm	.div unit	63	Surf: surface water use

Redirected terminal output is written to file `basecase.jou`, providing a sketch of the base case simulation. Other files recording results from this simulation include `basecase.prn`, which is MODFLOW's standard output, and `basecase.me2`, an annual summary of water use, stream yield, and residuals for the base case written by the modified WELL package (WEL1WR).

## Coordinating MODFLOW and SWAT file device numbers

The file device numbers shown above in the response file listing identify the device numbers used in the individual package input files, especially for reading arrays as described in the MODFLOW manual. These device numbers are somewhat arbitrary with certain constraints. They must lie within the range allowed for the compiler (1-255 for Lahey), and a given device number can be associated with only one file at a time. The range 61-74 is recommended as a safe range for the device numbers to be used for reading input files from the various packages, as specified in the Basic package input file; although the use of many numbers outside this range may cause no harm, as with the above case. The file device numbers used by MODFLOW are as follows; they are coordinated with the file device numbers used by SWAT (p. 33).

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 `~.dm`
- 64 `~.riv`
- 65 `~.evt`
- 66 `~.swb`
- 67 `~.gbb`

- 68 ~.rch
- 69 ~.sip
- 70 ~.pcg
- 71 ~.sor
- 72 ~.oc
- 73 ~.str
- 74 ~.div surface water diversions

### •Basic package

Line 4 of input requirements for this package were modified to allow packages to be invoked that have been added to MODFLOW, including the following:

- (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).
- (b) The SURFACE package represents diversions from streamflow for irrigation. This package is analogous to the WELL package in its input format and operation.

Except for Line 4, input requirements for the Basic package are the same as described in the MODFLOW manual (McDonald and Harbaugh, 1988). The modified format for line 4 follows.

```
4. Data: iunit(24)
Format: 24I3
(bcfl wel drn riv evt swb ghb rch sip pcg sor oc str srf)
index abbrev package Preprocessors
1 bcf Block-centered flow
2 wel Well WRREPUB, WUREPUB, SURFELEV
3 drn Drain
4 riv River
5 evt Evapotranspiration
6 swb Soil water balance STRMDATA
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 Stream STRMDATA
14 srf Surface water diversions WUREPUB
```

Preprocessors used to construct input data files for MODFLOW packages are shown in the above list at the right. In the following partial listing of base case input file `bcase_t.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.

STRT  
DUR  
NSTP



31536000.	12	1.	perlen, nstp, tsmult	90
31536000.	12	1.	perlen, nstp, tsmult	91
31622400.	12	1.	perlen, nstp, tsmult	92
31536000.	12	1.	perlen, nstp, tsmult	1993
31536000.	12	1.	perlen, nstp, tsmult	94

## • WELL package

The following options have been added to the WELL package:

Measured water level elevations may be read as part of the irrigation well data set to allow comparison of calculated and measured heads during execution and thereby reduce data handling operations (*dtw*, *dtb*, *elevwr*).

Irrigation depth assigned by SWAT is assigned on the basis of schedules specified by *~.mgt* files or a threshold on either soil water or plant water stress (option *irr*, set in *~.mco* files), where water stress is the fraction of potential plant water evaporation available from the soil. SWAT's irrigation assignment is also subject to a daily limit and, if option *ioplim* > 0, an annual limit (specified in the added SWAT-MODFLOW coordination section of data in SWAT's *~.cod* input file). If SWAT calls MODFLOW, the annual limit on irrigation depth is retrieved by subr *PASSFLX* after SWAT calls *SWB1RP* at the beginning of the year as described above.

Ground and surface water diversions for irrigation (*wruse* = 3) depend on MODSWB option *irropt* as follows. If *irropt* = 0, the pumping rates are specified by MODFLOW's WELL and SURFACE package input files, independent of irrigation assigned by SWAT. If *irropt* > 0, the annual pumping rates specified by the Well and Surface input files for irrigation are scaled according to the irrigation depth assigned by SWAT, subject to a maximum set by *pmpmax*, and limited by saturated thickness *s* based on specified limits *sathi* and *satlo* as follows. For  $\text{satlo} < s < \text{sathi}$ , an irrigation well's assigned pumping rate *q* is reduced linearly to *q<sub>r</sub>* by the ratio  $q_r/q = (s - \text{satlo}) / (\text{sathi} - \text{satlo})$ ; for  $s < \text{satlo}$ ,  $q_r = 0$ .

Both annual estimated use *Q* and appropriation *Q<sub>wr</sub>* are specified for each diversion. With option *itmp* = -2, annual use can be estimated from appropriations for a previous stress period by  $Q = \text{frcuse} \cdot Q_{wr}$ , where *frcuse* = the water use fraction for the current stress period. For the scenarios in years 1995-2012, this option is used to estimate annual use for each diversion in the future by its appropriation for 1994 times the water

use fractions estimated for the years 1995-2012, which are assumed to be the same as those for years 1977-1994.

Well pumping rates are scaled and selected on the basis of application number **iappno** and distance to stream **dsstrm** according to management scenarios 1-11 (Ch. 10, vol. 1). These scenarios are specified by input options **iadcod** and **welmpy**, which are read from the MODSWB package input file. Scenarios are implemented for ground and surface water rights in the WELL and SURFACE packages by calls to subroutine USEMGT (see p. 22). At the beginning of each stress period (year), USEMGT selects or scales individual water rights according to the scenarios.

Additional data that may be read for each well at the beginning of a stress period are listed below with uses made of the data.

Option **bccode** distinguishes “boundary condition” wells that are included to represent nonzero flow boundary conditions; see example below.

Distance to stream **dsstrm**, corresponding stream reach index **idxrch**, and water right application number **iappno** are used in water scenarios as described below.

Index **iwr** associates well with lists of water rights (vol. 1, App. 3B2) and wells included in November 1994 water level survey (vol. 1, App. 3B3).

Number of measurements of depth to water (**nmeas**, **dtw**) reported at this well;

Year and month of **dtw** report (**iyrdtw** and **imodtw**), and depth to water from land surface (**dtw**, ft): used to calculate water table elevation **zw** and residuals.

Reported depth to bottom of well (**dtb**): included to allow roughly distinguishing residuals based on measured alluvial well water levels (assumed if **dtb** < 60 ft) from those based on Dakota aquifer wells.

Land surface elevation at well (**elevwr**); used to calculate measured water level from **dtw**.

measured water table elevation at well (**zw**, ft): calculated from **dtw** and **elevwr**; used to compare hydraulic head solution for grid cell (residuals).

## Calculation of residuals following solution (WEL1WR)

For each time step after solving for aquifer heads, the solution is compared with available water level measurements taken during the time step within the corresponding grid nodes. Measurements from DWR water use reports (1980-1993) and from the water level survey of November 1994 (Appendix 3B3) are read from the Well package input

file. Annual results are summarized, including estimated water use, water yield, and residual error statistics.

## Input instructions (additions or changes in bold)

```

C
For each simulation (WEL1AL):
1.  Data:  MXWELL, IWELCB, ioprsd, iopsat, satlo, sathi, pmpmax
    Format: (4I10,3F10.0)

For each stress period (WEL1RP):
2.  Data:  ITMP, iyrper, frcuse, accwr
    Format: (2I10,3F10.0,i10)
C
For each water right (WEL1RW):
DO II=1,NWELLS
3.  Data:  ilay, irow, icol, Q, bccode, Qwr, rwr, cwr, dsstzm, iappno, yidzrch,
    wruse, iwr, nmeas, iyrdtw, imodtw, dtw, dtb, elevwr, zw
    Format: (3I10, f10.0, a1, f9.0, 3f8.2, i8, i5, 4x, a, 4i5, 4f8.0)

```

## Definition of input data and vectors in arrays PUMP and WELL

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.

**ioprsd** an option for handling residuals that is read but not currently used. Residuals are handled as follows in WEL1RW for each well: the hydraulic head solution is compared with a measured water level if  $dtw > 0$ , and if the measurement was made in either the same month for a monthly solution or the same year for an annual solution. Data  $dtw$ ,  $imodtw$ , and  $iyrdtw$  are read from the Well input file (line 3, above).

**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

$$qr = q(ys - yL) / (yH - yL), \quad yL < ys < yH,$$

$$= q, \quad ys > yH,$$

$$= 0, \quad ys < yL.$$

=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 abruptly 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).

**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  $Q_m$ ; 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.

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  $Q_{wr}$  (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.

**iyrper** calendar year.  
**fruse** 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.  
**accwr** total groundwater appropriation.

Line 3. For each water right, READ LAYER,ROW,COLUMN, FLOW RATE, distance to stream, application no., reach index, and water level observation; apply scenario selection criteria and scaling (subr USEMGT). In each time step apply pumping rate limit and saturated thickness scaling criteria (subr WEL1F0).

**iappno** water right application number; used as selection criterion in water use scenarios

**c Input** Definition of vectors in array PUMP:

(1) annual assigned pumping (accum. in WEL1F0)  
 (2) use to indicate full pumping for sat. thickness > sathi  
 (3) sat. thickness at well  
**Qwr** (5) =Qwr: appropriation  
**wruse** (4) =iusdwr: numeric version of DWR use code, wruse (irrigation = 3). Apply water use management scenarios to irrigation use only:  
 if (iusdwr.eq.3) call USEMGT (iadcod,welmpy,dsstrm,iappno,Q,Qwr)

**Input** Definition of vectors in array WELL (expanded from 4 to 25):

**Layer** (1) layer index  
**Row** (2) row index  
**Column** (3) column index  
**Q** (4) pumping rate as orig. unless irropt>0 (MODSWB), in which case well(5)=rate read for stress period and well(4) is scaled according to subbasin irrigation flux.  
 (5) variation in pumping rate with time step; to be determined in the watershed module MODSWB, subr SWBHYD;  
**bccode** (6) =0 for irrigation wells;  
 =1 if (bccode.eq.'\*' or wruse.ne.'3'): not to be scaled. This is to distinguish between irrigation wells (=0) and municipal water supply or model (recharge and b.c.) wells: code (=1) to signify these wells which are not to be weighted by Swat irrigation depth in module modswb; otherwise (default), set to zero. Added code (= -1): Saturated thickness is now checked in WEL1FM. For hysteretic option lopsat=2 (see Line 1); well(6,L) = -1 indicates that well pumping is currently set to zero because of low saturated thickness.  
**rwr** (7) row coordinate, rwr(j)  
**cwr** (8) column coordinate, cwr(j)  
**elevwr** (9) land surface elevation, ielevw(j)  
**zw** (10) measured water table elevation at well (if measurement is available)  
**iyrdtw** (11) year of measurement - 1900, iyrdtw(j)  
**imodtw** (12) month of measurement (1=Jan,...,12=Dec), imodtw(j)  
**nmeas** (13) no. of measurements reported at this well, nmeas(j)  
**dtw** (14) depth to water, idtw(j) (used in WEL1WR to calculate residual if nonzero)  
**iwr** (15) record number, j, associated with water rights list (1-349 here)  
 (16) calculated head at this node (hnew, assigned in WEL1WR, below).  
**delete** (17) w.t. elev for previous measurement, nmeas(j)-1 (if nmeas(j) > 1)  
**delete** (18) calculated head corresp. to previous measurement in well(17,\*).  
**delete** (19) time (Modflow's totim) corresp. to well(18,\*)  
**delete** (20) time of reported water table measurement  
**idxrch** (21) index to closest stream reach (index = order in which reach was read).  
**dsstrm** (22) approx. distance to stream reach  
**dtb** (23) depth to bottom of well  
 (24) elevation difference: meas. water level - calc. stream stage  
 (25) elevation difference: calc. water level - calc. stream stage



## WELL package input example 2: “boundary condition” wells to specify flow rate

These do not represent actual wells, but are model constructs to represent nonzero specified-flow (derivative, or Neumann) boundary conditions. To distinguish these from actual wells, boundary condition wells are identified in the WELL input file by an asterisk in column 41, to the immediate right of the input field for flow rate. The following excerpt from input file 6084wr.wel of the Rattlesnake Creek Basin study (Sophocleous et al., 1996) shows four actual wells followed by four boundary condition wells.

```

12345678901234567890123456789012345678901
-----
layer      row      column pump rate*
1          44       56   -33773.9
1          17       21   -32222.5
1          18       21   -21959.0
1          19        9   -56091.0
1           3        7   112388.8*
1           4        6   49794.62*
1           5        5   42906.26*
1           6        4   54999.23*

```

### \*SURFACE package

This package was written to represent surface water diversions similarly to groundwater diversions. Irrigation calculated by SWAT is assigned in MODFLOW to both ground and surface water points of diversions, whose estimated annual water use as average flow rates are scaled on a monthly basis. Surface water diversions are represented as lateral outflow from stream reaches with which they are associated. This is similar to the way runoff from the watershed is represented in MODSWB (Ch. 5D) as tributary flow, which is associated with a particular stream reach as lateral inflow for each subbasin. The net lateral inflow due to tributary flow and surface water diversions is incorporated into streamflow by a modified version of the stream routing procedure in the STREAM package.

At the beginning of each stress period (year), the following data are read for each surface water diversion.

```

layer,row,column;
annual estimated use for year, Q (cfs);

```

Annual appropriation,  $Q_{wr}$  (cfs): multiplied by annual water use fraction  $frcuse$  to estimate water use for scenarios;  
 Distance to stream  $dsstrm$ , corresponding stream reach index  $idxrch$ , and water right application number  $iappno$  are used in water scenarios as described below.  
 DWR use code ( $wruse = 3$  indicates irrigation);  
 Index  $iwr$  associates well with lists of water rights (vol. 1, App. 3B2) and wells included in November 1994 water level survey (vol. 1, App. 3B3).  
 grid coordinates to precision of .01 as fraction of cell width ( $rwr, cwr$ );

Both annual estimated use  $Q$  and appropriation  $Q_{wr}$  are specified for each diversion. With option  $itmp = -2$ , annual use can be estimated from appropriations for a previous stress period by  $Q = frcuse \cdot Q_{wr}$ , where  $frcuse =$  the water use fraction for the current stress period. This option is used to estimate annual use for each surface water diversion for the 1995-2012 scenarios the same way as for the modified WELL package by multiplying its appropriation for 1994 times the water use fractions estimated for the years 1995-2012, which are assumed to be the same as those for years 1977-1994.

As with the modified WELL package, surface water diversion flow rates are scaled and selected on the basis of application number  $iappno$  and distance to stream  $dsstrm$  according to management scenarios 1-11 (Ch. 10, vol. 1; p. 22, vol. 2), which are specified by input options  $iadcod$  and  $welmpy$  in the SWB package input file (p. 87).

## Input instructions

```

For each simulation (SRF1AL):
1.   Data:   MKSURF,ISRFCB
      Format: (2I10)

For each stress period (SRF1RP):
2.   Data:   ITMP,iyrserf,frcuse,accwr
      Format: (2I10,2f10.0)

C
For each surface water right (SRF1RP):
DO II=1,NSURFS
3.   Data:   layer,row,column,Q,Qwr,rwr,cwr,dsstrm,iappno,idxrch,wruse,iwr
      Format: (3i10,2f10.0,3f8.0,i8,i5,4x,a,i5)

```

## Definition of input data and vectors in array SURF

```

Line 1 (for each simulation).
MKSURF maximum number of surface water diversions used at any time.
ISRFCB flag: print(<0) or save(>0) cell-by-cell flow rates.

Line 2 (for each stress period).
ITMP flag:

```

> 0: NSURFS = ITMP, surface water diversions active in this stress period.  
 < 0: use data from the previous stress period, with the following exception.  
 =-2: The assigned pumping rate for each diversion is taken to be the diversion's appropriation Qwr (Line 3) specified in the previous stress period times the water use fraction, frcuse (below). As in the Well package, this option is used 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.

lyrsrf calendar year.

frcuse 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.

accwr total surface water rights.

For each surface water right: READ LAYER,ROW,COLUMN, FLOW RATE, distance to stream, application no., and reach index; look up stream segment and reach; apply scenario selection criteria and scaling (subr USEMGT).

Definition of input data not stored in array SURF (below):

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

c Input Definition of vectors in array SURF:

Layer	(1)	layer
Row	(2)	row
Column	(3)	column
	(4)	water use for time step; same as in (5) unless scaled by irrigation depth passed to MODSWB.
Q	(5)	water use for current stress period
Qwr	(6)	appropriation for current stress period
idxrch	(7)	stream reach identifier, indicating which reach from which the diversion will be taken as lateral outflow. idxrch is the index to order in which stream reaches were read, and is used to look up the corresponding stream segment and reach in array ISTRM (see Stream package input instructions).
dsstrm	(8)	approx. distance from pt. of diversion to stream reach

## Input example from base case: first year from file swuadm.wel

```

40      -1
      31      1977      0.571      1.635      1.000      0      swuadm0.wel
      1      5      14      -0.10174      -0.17818      4.13      13.19      0.48      9      20      3      1
      1      5      14      -0.10174      -0.17818      4.48      13.13      0.37      9      20      3      2
      1      21      35      -0.02366      -0.04144      20.69      34.31      0.27      2041      68      3      3
      1      5      9      -0.00935      -0.01638      4.39      8.03      0.48      2668      13      3      4
      1      5      9      -0.00935      -0.01638      4.50      8.03      0.47      2668      13      3      5
      1      5      9      -0.00935      -0.01638      4.63      8.08      0.44      2668      13      3      6
      1      4      18      -0.03549      -0.06216      3.19      17.44      0.32      4572      28      3      7
      1      4      17      -0.03549      -0.06216      3.38      16.13      0.40      4572      27      3      8
      1      20      36      -0.03273      -0.05732      19.92      35.93      0.61      5679      70      3      9
      1      20      36      -0.03273      -0.05732      19.83      35.98      0.58      5679      70      3      10
      1      21      36      -0.02405      -0.04213      20.32      35.69      0.26      5961      69      3      11
      1      21      36      -0.02405      -0.04213      20.22      35.92      0.51      5961      69      3      12
      1      21      36      -0.02405      -0.04213      20.34      35.44      0.17      5961      69      3      13
      1      21      36      -0.02405      -0.04213      20.30      35.80      0.36      5961      69      3      14
      1      11      32      -0.05994      -0.10498      10.06      31.19      0.54      9928      52      3      15
      1      11      32      -0.05994      -0.10498      10.44      31.44      0.09      9928      52      3      16
      1      5      14      -0.05954      -0.10429      4.53      13.14      0.36      12425      20      3      17
      1      6      14      -0.05954      -0.10429      5.19      13.59      0.32      12425      21      3      18
      1      21      35      -0.02313      -0.04051      20.49      34.95      0.45      17109      68      3      19
      1      21      35      -0.02313      -0.04051      20.49      34.68      0.18      17109      68      3      20
      1      21      35      -0.02313      -0.04051      20.50      34.91      0.41      17109      68      3      21
      1      21      36      -0.02031      -0.03557      20.30      35.80      0.36      25983      69      3      22
      1      21      36      -0.02031      -0.03557      20.22      35.92      0.51      25983      69      3      23
      1      21      36      -0.02031      -0.03557      20.32      35.69      0.26      25983      69      3      24
      1      21      36      -0.02031      -0.03557      20.34      35.44      0.17      25983      69      3      25
      1      5      9      -0.02011      -0.03522      4.43      8.67      0.18      26381      13      3      26
      1      5      9      -0.02011      -0.03522      4.34      8.89      0.42      26381      13      3      27
      1      21      36      -0.00394      -0.00691      20.30      35.80      0.36      30394      69      3      28
      1      21      36      -0.00394      -0.00691      20.22      35.92      0.51      30394      69      3      29
      1      21      36      -0.00394      -0.00691      20.34      35.44      0.17      30394      69      3      30
      1      21      36      -0.00394      -0.00691      20.22      35.69      0.26      30394      69      3      31

```

## •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  $L$  can be read instead of  $C$ , which is then calculated by the program using  $C = K' \cdot L \cdot P / b'$ , 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 ( $icalc=3$ ). In either case, a modified version of Prudic's stream routing procedure (subr STR1DW) is used. The natural channel option is used for the Republican River model, in which data from USGS gaging stations at Concordia and Clay Center are used to approximate stream depth, width, and cross sectional area as functions of flow rate.

## Input instructions (additions or changes in bold)

(subroutines STR1AL, STR1RP, STR1FM, STR1BD, STR1DW)

For each simulation: STR1AL

1. Data: **MXSTRM, NSS, NTRIB, NDIV, ICALC, CONST, ISTCB1, ISTCB2, itopro, ibotrc**  
Format: (5I10, F10.0, 2I10, 2I5)

For each stress period: STR1RP

2. Data: **ITMP, IRDFLG, IPTFLG, irdcnd, numinp, iroute, nrstep**  
Format: (7I10)

if (itmp > 0) then READ AND PRINT DATA FOR EACH STREAM REACH:  
DO II=1, NSTREM

3. Data: **layer row column segment reach flow stage cond sbot stop**  
5 Format: (5I5, F15.0, 4F10.0)  
end do

If stream stages are to be calculated ( $icalc > 0$ ), read for each stream reach:  
do ii=1, nstrem:

4. Data: **width slope rough length side**

```

        Format: (5f10.0)
    end do

    If (ntrib > 0) then for each segment ik, read tributary segment numbers:
    do ik=1,nss
5.      Data: (ITRBAR(IK,JK),JK=1,NTRIB)
        Format: (10I5)
    end do

    if (ndiv > 0) then for each segment ik, read upstream diversion segment numbers:
6.      Data: IDIVAR(IK)
        Format: (I10)
    end do
end if (itmp>0)

if (itmp.eq.-2) then update streamflow for designated inflow reaches:
do ii = 1,numinp
7.      Data: layer row column segment reach flow
        Format: (5i5,f15.0)
    end do

For each time step except for the first; for kkstp=1, these data are read at (7):
Read stream inflow at NUMINF stream nodes: STR1FM or STR1DW.
if=(kkiter.eq.1 .and. kkstp.gt.1 .and. numinp.gt.0) then
do ii = 1,numinp
8.      Data: layer row column segment reach flow
        Format: (5i5,f15.0)
    end do
end if

```

## Definition of input and vectors in arrays ISTRM, STRM, and STRMAD

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).

=1: apply Prudic routing (STR1FM, STR1BD); for each reach, solve Manning's equation,  $Q = (c_m/n)AR^{2/3}S^{1/2}$ , 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.

=2: apply modified Prudic routing (STR1DW, STR2DW); 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.

=3: read a gaging station identifier as follows: 1=Concordia, 2=Clay Center; 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 icbcl≠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.

Line 2:

itmp flag and counter:

>0: number of reaches active during the current stress period;

-1: use stream data from the previous stress period;

-2: except for NUMINP stream nodes, use stream data from the previous stress period; see NUMINP, below.

irdflg flag: if <0, print input data.

iptflg flag: if <0, print results.

irdcnd stream channel geometry option:

- = 0: (default) COND (3) is interpreted as streambed conductance, C. As described in Prudic (1989), a rectangular channel with steady flow is assumed, and input data values for streambed conductance are approximated by  $C = K_s L_s P / T$ , where  $K_s$  = streambed saturated hydraulic conductivity;  $L_s$  = stream reach length;  $P$  = wetted perimeter; and  $T$  = streambed thickness = STOP - SBOT (3).
- > 0: COND (3) is interpreted as hydraulic conductivity  $K_s$ , from which C is calculated using values read for reach length and reciprocal side slope (4).

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:

- 0: Apply default stream routing procedure by Prudic (STR1FM and STR1BD);
- 1: Apply modified stream routing procedure by Prudic (STR1DW and STR2DW);
- 2: Apply diffusive wave routing where Cr-Pe conditions are met (STR1DW and STR2DW). 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. 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).

Lines 3 and 4: data for each stream reach; stored in vectors ISTRM or STRM

Input ISTRM vector (increased from 5 to 10)

Layer (1) layer containing stream reach

Row (2) row

Col (3) column

Seg (4) segment: a group of reaches; number the segments in downstream order.

Reach (5) reach: read the reaches in downstream order.

added vectors:

(6) no. of pumping wells for which this is closest stream reach.

(8) indicates whether Muskingum-Cunge (1) or Prudic-type (0) routing was applied.

(9) retains for each reach the value assigned to variable IQFLG in STR1FM:  
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.

Input Definition of array STRM vectors (increased from 11 to 25)

Flow (1) streamflow input (specified for segment's top reach); see also ITMP.

Stage (2) stage (computed): avg for reach

Cond (3) either streambed conductance C (if irdcnd=0) or hydraulic conductivity  $K_s$  (if irdcnd>0).

Sbot (4) streambed bottom elevation

Stop (5) streambed top elevation

Width (6) stream base width

Slope (7) bed slope

Rough (8) Manning roughness coefficient n

(9) reach outflow

(10) reach inflow

(11) streambed leakage  $q_L$

added vectors:

Length (12) L = reach length

Side (13) if icalc=2 (call subr YQ for depth): reciprocal side slope for symmetrical trapezoidal channel (cot alpha);  
if icalc=3 (call subr YQGAGE for depth): index to gaging station as follows for this version: 1=Concordia, 2=Clay Center.

(14) depth at reach outflow; see also (2) and (20).

(15) ck = wave speed

(16) D = diffusion coef.

(17)  $K_s$  = streambed hydraulic conductivity retained here; see IRDCND.

(18)  $q_s$  = lateral inflow due to surface runoff and interflow;

(19) avg cross-sectional area of flow for reach (for mass balance)

(\*) depth at reach outflow for previous time step; see also strm(14,\*).

(21) total pumping from wells associated with this reach, i.e., those for which this is the closest stream reach. istrm(6,\*) is the

number of such wells, and see strm(22,\*), below:  
 (22) distance to centroid of pumping from wells for which this is the closest stream reach.  
 (\*) (23) reach outflow at beginning of aquifer time step  
 (\*) (24) reach inflow at beginning of aquifer time step  
 (\*) (25) reach streambed leakage at beginning of aquifer time step  
 (\*): vectors retained from previous time step for diffusive wave routing (IROUTE=2).

Added array STRMAD vectors:

- (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  $Dh = Q/(2*B*S0)$

\*  
 \* added to str1dw argument list for diffusive wave routing:  
 \* hold(ic,ir,ilay) (also added for str2dw)  
 \* delt = aquifer time step

## Stream package input example from base case: first two years of file rpmon.str

77	1	0	0	3	1.49	-1	0	12	73	
77	0	0	1	1	1	1		77	itmp	
1	1	2	1	1	74.387	1378.0	6.2304e-6	1375.0	1378.0	5s 4w 5
1	2	3	1	2	0.00	1373.2	6.2304e-6	1370.2	1373.2	5s 4w 9
1	2	4	1	3	0.00	1368.0	6.2304e-6	1365.0	1368.0	5s 4w10
1	2	5	1	4	0.00	1363.2	6.2304e-6	1360.2	1363.2	5s 4w11
1	3	5	1	5	0.00	1358.3	6.2304e-6	1355.3	1358.3	5s 4w14
1	4	5	1	6	0.00	1356.3	6.2304e-6	1353.3	1356.3	5s 4w23
1	3	6	1	7	0.00	1353.9	6.2304e-6	1350.9	1353.9	5s 4w13
1	4	6	1	8	0.00	1350.3	6.2304e-6	1347.3	1350.3	5s 4w24
1	5	6	1	9	0.00	1348.0	6.2304e-6	1345.0	1348.0	Buffalo Cr
1	4	7	1	10	0.00	1346.5	6.2304e-6	1343.5	1346.5	5s 3w19
1	5	7	1	11	0.00	1342.1	6.2304e-6	1339.1	1342.1	Wolf Cr
1	5	8	1	12	0.00	1338.0	6.2304e-6	1335.0	1338.0	5s 3w29
1	5	9	1	13	0.00	1332.7	6.2304e-6	1329.7	1332.7	5s 3w28
1	5	10	1	14	0.00	1328.6	6.2304e-6	1325.6	1328.6	5s 3w27
1	5	11	1	15	0.00	1325.3	6.2304e-6	1322.3	1325.3	5s 3w26
1	5	12	1	16	0.00	1322.4	6.2304e-6	1319.4	1322.4	5s 3w25
1	4	12	1	17	0.00	1320.7	6.2304e-6	1317.7	1320.7	5s 3w24
1	4	13	1	18	0.00	1318.0	6.2304e-6	1315.0	1318.0	5s 2w19
1	4	14	1	19	0.00	1316.3	6.2304e-6	1313.3	1316.3	5s 2w20
1	5	14	1	20	0.00	1313.9	6.2304e-6	1310.9	1313.9	5s 2w29
1	6	14	1	21	0.00	1310.8	6.2304e-6	1307.8	1310.8	Plum Cr
1	6	15	1	22	0.00	1308.2	6.2304e-6	1305.2	1308.2	stream from
1	5	15	1	23	0.00	1307.7	6.2304e-6	1304.7	1307.7	5s 2w28
1	6	16	1	24	0.00	1306.4	6.2304e-6	1303.4	1306.4	stream (inte
1	5	16	1	25	0.00	1303.8	6.2304e-6	1300.8	1303.8	5s 2w27
1	4	16	1	26	0.00	1301.5	6.2304e-6	1298.5	1301.5	Salt Cr
1	4	17	1	27	0.00	1297.6	6.2304e-6	1294.6	1297.6	5s 2w23
1	4	18	1	28	0.00	1293.5	6.2304e-6	1290.5	1293.5	Upton Cr
1	4	19	1	29	0.00	1289.9	6.2304e-6	1286.9	1289.9	5s 1w19
1	4	20	1	30	0.00	1287.5	6.2304e-6	1284.5	1287.5	5s 1w20
1	5	20	1	31	0.00	1284.2	6.2304e-6	1281.2	1284.2	5s 1w29
1	6	21	1	32	0.00	1279.2	6.2304e-6	1276.2	1279.2	Elm Cr
1	5	21	1	33	0.00	1277.7	6.2304e-6	1274.7	1277.7	5s 1w28
1	5	22	1	34	0.00	1275.3	6.2304e-6	1272.3	1275.3	5s 1w27
1	5	23	1	35	0.00	1273.3	6.2304e-6	1270.3	1273.3	5s 1w26
1	6	23	1	36	0.00	1270.9	6.2304e-6	1267.9	1270.9	5s 1w35
1	6	24	1	37	0.00	1265.4	6.2304e-6	1262.4	1265.4	5s 1w36
1	5	24	1	38	0.00	1265.6	6.2304e-6	1262.6	1265.6	Elk Cr
1	7	24	1	39	0.00	1259.7	6.2304e-6	1256.7	1259.7	Beaver Cr
1	8	25	1	40	0.00	1257.2	6.2304e-6	1254.2	1257.2	6s 1e 7
1	8	26	1	41	0.00	1253.1	6.2304e-6	1250.1	1253.1	6s 1e 8
1	7	26	1	42	0.00	1254.1	6.2304e-6	1251.1	1254.1	6s 1e 5
1	8	27	1	43	0.00	1249.0	6.2304e-6	1246.0	1249.0	6s 1e 9
1	8	28	1	44	0.00	1246.2	6.2304e-6	1243.2	1246.2	6s 1e10

1	8	29	1	45	0.00	1241.3	6.2304e-6	1238.3	1241.3	6s 1e11		
1	8	30	1	46	0.00	1235.9	6.2304e-6	1232.9	1235.9	6s 1e12		
1	7	30	1	47	0.00	1234.3	6.2304e-6	1231.3	1234.3	Parsons Cr		
1	8	31	1	48	0.00	1231.1	6.2304e-6	1228.1	1231.1	6s 2e 7		
1	9	31	1	49	0.00	1228.7	6.2304e-6	1225.7	1228.7	6s 2e18		
1	10	31	1	50	0.00	1226.0	6.2304e-6	1223.0	1226.0	6s 2e19		
1	11	31	1	51	0.00	1224.0	6.2304e-6	1221.0	1224.0	6s 2e30		
1	11	32	1	52	0.00	1221.3	6.2304e-6	1218.3	1221.3	Peats Cr		
1	12	32	1	53	0.00	1217.8	6.2304e-6	1214.8	1217.8	6s 2e32		
1	13	32	1	54	0.00	1214.2	6.2304e-6	1211.2	1214.2	7s 2e 5		
1	13	33	1	55	0.00	1213.7	6.2304e-6	1210.7	1213.7	Peet Cr		
1	14	32	1	56	0.00	1209.9	6.2304e-6	1206.9	1209.9	Mulberry Cr		
1	14	33	1	57	0.00	1208.2	6.2304e-6	1205.2	1208.2	7s 2e 9		
1	15	33	1	58	0.00	1207.3	6.2304e-6	1204.3	1207.3	7s 2e16		
1	15	32	1	59	0.00	1202.8	6.2304e-6	1199.8	1202.8	7s 2e17		
1	16	32	1	60	0.00	1198.7	6.2304e-6	1195.7	1198.7	7s 2e20		
1	17	32	1	61	0.00	1196.4	6.2304e-6	1193.4	1196.4	7s 2e29		
1	17	33	1	62	0.00	1193.2	6.2304e-6	1190.2	1193.2	7s 2e28		
1	18	33	1	63	0.00	1188.6	6.2304e-6	1185.6	1188.6	7s 2e33		
1	19	33	1	64	0.00	1187.0	6.2304e-6	1184.0	1187.0	8s 2e 4		
1	19	34	1	65	0.00	1184.7	6.2304e-6	1181.7	1184.7	8s 2e 3		
1	19	35	1	66	0.00	1181.0	6.2304e-6	1178.0	1181.0	8s 2e 2		
1	20	35	1	67	0.00	1177.9	6.2304e-6	1174.9	1177.9	8s 2e11		
1	21	35	1	68	0.00	1176.0	6.2304e-6	1173.0	1176.0	8s 2e14		
1	21	36	1	69	0.00	1173.2	6.2304e-6	1170.2	1173.2	Five Cr		
1	20	36	1	70	0.00	1172.0	6.2304e-6	1169.0	1172.0	8s 2e12		
1	20	37	1	71	0.00	1170.5	6.2304e-6	1167.5	1170.5	8s 3e 7		
1	21	37	1	72	0.00	1167.9	6.2304e-6	1164.9	1167.9	Huntress Cr		
1	21	38	1	73	0.00	1165.8	6.2304e-6	1162.8	1165.8	8s 3e17		
1	22	38	1	74	0.00	1164.2	6.2304e-6	1161.2	1164.2	8s 3e20		
1	21	39	1	75	0.00	1161.1	6.2304e-6	1158.1	1161.1	Finney Cr		
1	22	39	1	76	0.00	1158.2	6.2304e-6	1155.2	1158.2	8s 3e21		
1	23	39	1	77	0.00	1156.3	6.2304e-6	1153.3	1156.3	8s 3e28		
100.0	0.0007137	0.030	5483.1	1	54627.7	0	0	0	0	1	1	1
100.0	0.0006155	0.030	7716.9	1	62344.6	0	0	0	0	1	2	1
100.0	0.0009655	0.030	7107.7	1	69452.3	0	0	0	0	1	3	1
100.0	0.0009655	0.030	4264.6	1	73716.9	0	0	0	0	1	4	1
100.0	0.0005726	0.030	6498.5	1	79098.5	0	0	0	0	1	5	2
100.0	0.0005726	0.030	4467.7	1	83566.2	0	0	0	0	1	6	1
100.0	0.0005726	0.030	2640.0	1	87323.1	0	0	0	0	1	7	1
100.0	0.0005660	0.030	7513.8	1	94836.9	0	0	0	0	1	8	1
100.0	0.0005660	0.030	2843.1	1	97680.0	0	0	1	0	1	9	1
100.0	0.0005660	0.030	2640.0	1	100320.0	0	0	0	0	1	10	1
100.0	0.0005660	0.030	9341.5	1	109661.5	0	0	1	0	1	11	1
100.0	0.0006746	0.030	5787.7	1	115449.2	0	0	0	0	1	12	1
100.0	0.0006746	0.030	8630.8	1	124080.0	1	2	0	0	1	13	1
100.0	0.0005129	0.030	5990.8	1	130070.8	1	2	0	0	1	14	1
100.0	0.0005129	0.030	6701.5	1	136772.3	1	2	0	0	1	15	1
100.0	0.0005129	0.030	5381.5	1	142153.8	1	2	0	0	1	16	1
100.0	0.0005129	0.030	2640.0	1	144793.8	1	2	0	0	1	17	1
100.0	0.0005103	0.030	6092.3	1	150886.2	1	2	0	0	1	18	1
100.0	0.0005103	0.030	2436.9	1	153323.1	1	2	0	0	1	19	1
100.0	0.0005103	0.030	5483.1	1	158806.2	1	2	0	0	1	20	1
100.0	0.0005411	0.030	6295.4	1	165101.5	1	3	2	0	1	21	1
100.0	0.0005411	0.030	3147.7	1	166929.3	1	3	1	0	1	22	2
100.0	0.0005411	0.030	3046.1	1	169975.4	1	3	0	0	1	23	1
100.0	0.0005411	0.030	507.7	1	171803.1	1	3	1	0	1	24	1
100.0	0.0005411	0.030	6295.4	1	178098.5	1	3	0	0	1	25	1
100.0	0.0005411	0.030	3553.8	1	181652.3	1	3	1	0	1	26	1
100.0	0.0006354	0.030	7513.9	1	189166.2	1	3	0	0	1	27	1
100.0	0.0006354	0.030	6092.3	1	195258.5	1	3	1	0	1	28	1
100.0	0.0005828	0.030	5584.6	1	200843.1	4	3	0	0	1	29	1
100.0	0.0005828	0.030	3655.4	1	204498.5	4	3	0	0	1	30	1
100.0	0.0005828	0.030	6295.4	1	210793.9	4	3	0	0	1	31	1
100.0	0.0005352	0.030	9341.5	1	220135.4	4	3	1	0	1	32	1
100.0	0.0005352	0.030	609.2	1	220744.6	4	3	0	0	1	33	1
100.0	0.0005352	0.030	5889.2	1	226633.9	4	3	0	0	1	34	1
100.0	0.0005352	0.030	3046.2	1	229680.0	4	3	0	0	1	35	1
100.0	0.0005352	0.030	4873.8	1	234553.9	4	3	0	0	1	36	1
100.0	0.0005183	0.030	11169.3	1	239935.4	4	3	0	0	1	37	2
100.0	0.0005183	0.030	4772.3	1	244707.7	4	3	1	0	1	38	1
100.0	0.0004191	0.030	6193.8	1	256689.3	4	3	1	0	1	39	1
100.0	0.0004191	0.030	5889.2	1	262578.5	4	3	0	0	1	40	1
100.0	0.0004191	0.030	5686.2	1	264000.0	4	3	0	0	1	41	2
100.0	0.0004191	0.030	5889.3	1	269889.3	4	3	0	0	1	42	1
100.0	0.0004191	0.030	9224.6	1	282379.5	5	3	0	0	1	43	1

100.0	0.0004602	0.030	5584.6	1	287963.1	5	3	0	0	1	44	1
100.0	0.0005352	0.030	12793.8	1	300756.9	5	3	0	0	1	45	1
100.0	0.0005352	0.030	7818.5	1	306240.0	5	3	0	0	1	46	2
100.0	0.0005352	0.030	5787.7	2	312027.7	6	3	2	0	1	47	1
100.0	0.0005352	0.030	3046.2	2	317409.3	7	3	0	0	1	48	1
100.0	0.0004875	0.030	5178.5	2	322587.7	7	3	0	0	1	49	1
100.0	0.0004875	0.030	5686.2	2	328273.9	7	3	0	0	1	50	1
100.0	0.0004875	0.030	3553.8	2	331827.7	7	3	0	0	1	51	1
100.0	0.0004875	0.030	6092.3	2	337920.0	7	3	1	0	1	52	1
100.0	0.0004875	0.030	7716.9	2	345636.9	7	3	0	0	1	53	1
100.0	0.0004875	0.030	7615.4	2	350713.9	7	3	0	0	1	54	2
100.0	0.0004875	0.030	1726.2	2	352440.0	7	3	1	0	1	55	1
100.0	0.0006437	0.030	6498.5	2	361476.9	7	3	1	0	1	56	1
100.0	0.0006437	0.030	1218.5	2	362695.4	9	3	0	0	1	57	1
100.0	0.0006437	0.030	1523.1	2	364218.5	9	3	0	0	1	58	1
100.0	0.0006437	0.030	8833.8	2	373052.3	9	3	0	0	1	59	1
100.0	0.0005077	0.030	6193.9	2	379246.2	9	3	0	0	1	60	1
100.0	0.0005077	0.030	4061.5	2	383307.7	9	3	0	0	1	61	1
100.0	0.0005077	0.030	7107.7	2	390415.4	9	3	0	0	1	62	1
100.0	0.0004900	0.030	9646.2	2	400061.6	9	3	0	0	1	63	1
100.0	0.0004900	0.030	1218.5	2	401280.0	9	3	0	0	1	64	1
100.0	0.0004900	0.030	5889.2	2	407169.3	9	3	0	0	1	65	1
100.0	0.0004900	0.030	8021.5	2	415190.8	9	3	0	0	1	66	1
100.0	0.0005253	0.030	5381.6	2	420572.3	9	3	0	0	1	67	1
100.0	0.0005372	0.030	3046.1	2	423618.5	9	8	0	0	1	68	1
100.0	0.0005372	0.030	5889.3	2	429507.7	9	8	1	0	1	69	1
100.0	0.0005372	0.030	1218.5	2	430726.2	9	8	0	0	1	70	1
100.0	0.0005372	0.030	3147.7	2	433873.9	9	8	0	0	1	71	1
100.0	0.0005897	0.030	4975.4	2	438849.3	0	0	1	0	1	72	1
100.0	0.0005897	0.030	3046.2	2	441895.4	0	0	0	0	1	73	1
100.0	0.0005897	0.030	2640.0	2	444535.4	0	0	0	0	1	74	1
100.0	0.0005897	0.030	6193.8	2	450729.3	0	0	1	0	1	75	1
100.0	0.0004646	0.030	5584.6	2	456313.9	0	0	0	0	1	76	1
100.0	0.0004646	0.030	3452.3	2	459766.2	0	0	0	0	1	77	1
1	1	2	1	1	189.643	1378	6.2304e-6	1375	1378	31.678	2	77
1	1	2	1	1	156.677	1378	6.2304e-6	1375	1378	63.42	3	77
1	1	2	1	1	140.2	1378	6.2304e-6	1375	1378	34.733	4	77
1	1	2	1	1	223.516	1378	6.2304e-6	1375	1378	192.936	5	77
1	1	2	1	1	734.733	1378	6.2304e-6	1375	1378	611.634	6	77
1	1	2	1	1	364.613	1378	6.2304e-6	1375	1378	-37.774	7	77
1	1	2	1	1	1113.677	1378	6.2304e-6	1375	1378	1126.581	8	77
1	1	2	1	1	1160.5	1378	6.2304e-6	1375	1378	337	9	77
1	1	2	1	1	276.258	1378	6.2304e-6	1375	1378	63.645	10	77
1	1	2	1	1	264.833	1378	6.2304e-6	1375	1378	69.9	11	77
1	1	2	1	1	216.419	1378	6.2304e-6	1375	1378	23.807	12	77
	-2	0		0	1	1	1	1	78"itmp			
1	1	2	1	1	164.516	1378	6.2304e-6	1375	1378	7.742	1	78
1	1	2	1	1	175.714	1378	6.2304e-6	1375	1378	16.429	2	78
1	1	2	1	1	1104.419	1378	6.2304e-6	1375	1378	730.162	3	78
1	1	2	1	1	411.733	1378	6.2304e-6	1375	1378	159.334	4	78
1	1	2	1	1	380.129	1378	6.2304e-6	1375	1378	617.903	5	78
1	1	2	1	1	213.367	1378	6.2304e-6	1375	1378	109.9	6	78
1	1	2	1	1	450.71	1378	6.2304e-6	1375	1378	263.613	7	78
1	1	2	1	1	514.903	1378	6.2304e-6	1375	1378	97.387	8	78
1	1	2	1	1	571.7	1378	6.2304e-6	1375	1378	346.533	9	78
1	1	2	1	1	178.935	1378	6.2304e-6	1375	1378	63.13	10	78
1	1	2	1	1	191.3	1378	6.2304e-6	1375	1378	53.433	11	78
1	1	2	1	1	143.613	1378	6.2304e-6	1375	1378	41.839	12	78

## \*Soil Water Balance package (MODSWB): a watershed interface

MODSWB connects MODFLOW's stream-aquifer model to a watershed hydrology model, implemented by SWAT (Arnold et al., 1990). An acronym for Soil Water Balance, the name MODSWB refers to the hydrologic summary of SWAT's results written by subroutine HYDBAL. The MODSWB package updates water rights appropriations for each subbasin at the beginning of each stress period; obtains hydrologic fluxes calculated by SWAT (recharge, tributary flow, and irrigation) for each aquifer time step either through memory or by reading a balance file written by either by SWAT (p. 49) or SWBAVG (p. 55); maps these fluxes onto the stream network and aquifer grid represented by MODFLOW; and summarizes fluxes calculated by MODFLOW (baseflow and evaporation from the water table) for each subbasin the fluxes relevant to Swat's hydrologic balance.

SWAT and MODFLOW are coordinated to represent annual water use for irrigation through input options **ioplim** for SWAT (input file ~.cod) and **irropt** for MODFLOW (input file ~.swb). If SWAT runs without calling MODFLOW but option **ioplim**>0, SWAT reads a maximum annual irrigation depth from the ~.cod input file. Then for each aquifer time step, SWAT calculates an irrigation depth (11) subject not only to specified schedules (~.mgt files) and conditions of soil water and plant stress factor (option **irr** in ~.mco files), but also, for **ioplim**>0, to specified annual use limits. In the case that SWAT calls MODFLOW (**iopswt**>0) and **ioplim**>0, SWAT obtains annual irrigation limits from MODFLOW as follows. SWAT calls MODFLOW's entry point MODPER at the beginning of each stress period (year), and MODSWB subroutine SWB1RP calculates irrigation depth (9) for each subbasin, given by total reported use according to the WELL package input file, divided by subbasin area. SWAT then retrieves these irrigation depths (subr PASSFLX) to limit annual irrigation as described above.

For each aquifer time step, SWB1FM sets up the conditions for MODFLOW's solution that are based on the hydrologic components calculated by SWAT. Irrigation

depth (11) is treated as follows, subject to limits described above. If option **irropt=0** (specified by MODSWB's input file), irrigation pumping is given as read from the WELL input file, and SWAT's irrigation depth is ignored. Otherwise (**irropt>0**), the pumping rate of each well within a subbasin is scaled by the ratio of depths given by SHED vectors (11) and (9), so that total groundwater pumping in each subbasin corresponds to that assigned by SWAT. The irrigation depth calculated by SWAT is part of SWAT's hydrologic summary that is obtained by MODFLOW as described above.

SWB1BD calculates the hydrologic components **etgw**(18) and **baseflow** (19), which depend on MODFLOW's aquifer head solution. **Etgw** ("revap" in SWAT) is based on evapotranspiration from shallow groundwater as calculated by the EVT package. **Baseflow** is given by the negative of streambed leakage as calculated by the STREAM package. For a combined SWAT-MODFLOW run, these two components are passed from MODFLOW back to SWAT and appear in the hydrologic balance file; otherwise, SWAT's version of these components, shown in the balance file, are based on a much weaker model of groundwater than MODFLOW.

## Options

Several options affecting the conditions of the groundwater solution in MODFLOW are read by SWB1AL from the SWB input file, and are summarized as follows. Options **irropt**, **ioprch**, and **ievopt** affect how irrigation, recharge, and evaporation from the water table are modeled. Option **iadcod** identifies an administrative option for water use scenarios. Scaling factors **rchmpy** and **welmpy** are applied to recharge and irrigation wells for sensitivity analysis and modeling of water use scenarios. Option **jkkopt** is passed from SWAT to MODFLOW either by way of the balance file written by HYDBAL or by subroutine argument list, depending on option **iopswt**. Option **iopmod** specifies the length of an aquifer time step as a day, month, or year. Options **jkkopt**, **iopmod**, and **iopswt** are three of several options read by SWAT and summarized below.

**jkkopt**: Components of SWAT's hydrologic summary are combined to represent tributary inflow (22) and groundwater recharge (25) for MODFLOW's stream-

aquifer model. Default definitions, used for these terms in the Republican River watershed model, are invoked by setting option **jkkopt** = 0.

**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 the basin's total pumping flow rate varies according to the flux specified by SWAT for each time step; otherwise (**irropt**=0), use the rates specified by Modflow's modified WEL and SURFACE input files, subject to water use scenarios (see **iadcod**, below).

**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.

**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. Otherwise (**ievopt** < or = ), evaporation at ground surface is specified by standard Modflow input array EVTR in the EVT module.

**rchmpy**: scaling factor for varying recharge flow rates for sensitivity analysis.

**welmpy**: scaling factor for varying irrigation pumping rates for sensitivity analysis and for water use scenarios.

**iadcod**: administrative option code used in conjunction with scaling factor **welmpy** applied to ground and surface water diversion rates for water use scenarios.

## **MODSWB package organization**

The MODSWB package consists of subroutines SWB1AL, SWB1RP, SWB1FM, and SWB1BD. MODFLOW's modified Basic package input file invokes the MODSWB package as described above. At the beginning of the simulation, array space is allocated in SWB1AL, and a geographical correspondence between the watershed represented by SWAT and the stream-aquifer system represented by MODFLOW is initialized in SWB1RP, connecting subbasin outflow points to specific reaches of the Republican

River fed by tributaries; and associating the domains of subbasins with aquifer grid cells. At the end of each time step, hydrologic depths calculated by SWAT are passed to MODSWB, and SWB1FM translates these depths into flow rates to represent recharge to groundwater, evaporation from groundwater, tributary flow due to runoff, and water diversions from both surface and aquifer water sources. If MODFLOW is run as a stand-alone program, SWB1FM reads SWAT's results the balance file written by HYDBAL; otherwise, SWAT's results are passed to MODFLOW via memory.

#### Allocate memory and specify options (SWB1AL)

At the beginning of the simulation, MODFLOW calls SWB1AL to allocate memory according to conventions used in MODFLOW's standard packages, and to specify options defined above relating to a combined watershed and stream-aquifer simulation. Key memory requirements are provided by the SHED array, defined below (balance file input instructions).

#### Associate watershed subareas with nodes of stream network and aquifer (SWB1RP)

At the beginning of the simulation, subroutine SWB1RP does the following:

- (a) associate the outflow from each subbasin of a watershed with tributaries that flow into a stream network specified by MODFLOW's STREAM package;
- (b) map the geographical extent of the watershed's subbasins onto the gridded aquifer domain specified by MODFLOW's Basic and Block-Centered Flow packages;
- (c) If the EVT package is invoked (see also option ievopt, below), calculate an initial evaporation rate from the water table for shallow nodes;
- (d) Read a length conversion factor, cnvlen, and calculate a time conversion factor; both are used in SWB1FM to convert hydrologic depths (mm) from SWAT to flow rates (cfs) in MODFLOW, and in SWB1BD to do the reverse.

#### Convert hydrologic depths from SWAT into flow rates for MODFLOW (SWB1FM)

At the end of each aquifer time step (day, month, or year), SWB1FM obtains hydrologic depths for the watershed calculated by SWAT either by reading the balance file in the format written by SWAT or copied from SWAT's memory into array SHED by

subroutine SWT2MOD, part of the HYDBAL package written for SWAT, depending on whether MODFLOW is run independently or as a series of subroutine calls from SWAT. Except for irrigation, SWB1FM converts the hydrologic depths calculated by SWAT into flow rate conditions of lateral inflow from tributaries and recharge for MODFLOW's solution. Irrigation depth is similarly converted into flow rates for individual ground and surface water rights the modified WELL package in WEL1F0 and the SURFACE package in SRF1F0. SWB1FM calculates the aquifer time step  $\text{delt} = \text{dtswat}/\text{cnvtim}$  for MODFLOW from the corresponding number of days simulated by SWAT,  $\text{dtswat}$ , where  $\text{cnvtim} = \text{SWAT-MODFLOW time units conversion factor}$  passed from SWB1RP. The correspondence between SWAT's hydrologic components and the stream and aquifer in MODFLOW is summarized below for each component.

#### Runoff

Runoff from the watershed carried by tributaries to the Republican River is represented by the sum of surface and subsurface flow as a depth (mm), SHED(22), subject to SWAT option  $\text{jkkopt}$ . This runoff is converted to a flow rate on the basis of each subbasin's contributing area (approximately 98 percent), and enters the stream network as lateral inflow from one tributary for each subbasin to the stream network as STRM (18) in the STREAM package.

#### Recharge

Groundwater recharge, SHED(25), as a depth for each subbasin is a combination of hydrologic components from SWAT subject to SWAT option  $\text{jkkopt}$ . Its distribution in MODFLOW's recharge package array RECH within each subbasin can be specified according to MODFLOW option  $\text{ioprch}$ . Recharge is calculated in SWAT as a homogeneous depth assuming an underlying aquifer; but is applied in MODFLOW only to the component of the basin with such an aquifer (approximately 13 percent).

#### Maximum evaporation from water table

If MODFLOW option  $\text{ievopt} > 0$ , maximum water table evaporation rate given by array EVTR in EVT package is based on potential evaporation calculated in SWAT, SHED(21); otherwise, array EVTR is specified by Modflow input to the EVT package.

Evaporation from the water table is then calculated by the EVT package for the alluvial aquifer component of the basin (13 percent), and is nonzero only for shallow groundwater as defined by the extinction depth in the EVT package.

### Irrigation

Irrigation depth assigned by SWAT is assigned on the basis of either schedules (in `~.mgt` files) or a threshold for either soil moisture or plant water stress (option `irr`, set in `~.mco` files). For this study, soil moisture (`irr=2`) was used as the trigger for irrigation instead of plant water stress (`irr=1`), which is defined as the fraction of potential plant water evaporation available from the soil. SWAT's irrigation assignment is subject to limits on daily and, if option `ioplim > 0`, annual use. Option `ioplim` and the daily and annual limits, which we added to SWAT, are specified in the SWAT-MODFLOW coordination section of data in SWAT's `~.cod` input file. However, if SWAT calls MODFLOW directly, the annual limit on irrigation depth is retrieved by subr PASSFLX after SWAT calls SWB1RP at the beginning of the year as described above.

Ground and surface water diversions (pumping rates) for MODFLOW depend on MODSWB option `irropt` as follows. If `irropt = 0`, the pumping rates are specified by MODFLOW's WELL and SURFACE package input files, independent of irrigation assigned by SWAT. If `irropt > 0`, the annual pumping rates specified by the Well and Surface input files for irrigation are scaled according to the irrigation depths in SHED(11) assigned by SWAT.

MODFLOW's modified WELL and SURFACE packages convert the irrigation depth calculated by SWAT into a total irrigation flow rate that corresponds to only the irrigated component of the basin area, approximately 4 percent, and distribute the total among the surface and ground water rights. The conversion maintains mass balance according to  $cQ_{irr}\Delta t = d_{irr}f_{irr}A$ , where  $Q_{irr}$  (cfs) is the sum of ground and surface water use for irrigation,  $f_{irr} = A_{irr}/A$ , the irrigated fraction of basin's area;  $A =$  basin area (2569.6 km<sup>2</sup>),  $d_{irr} =$  annual irrigation depth (mm); and  $c$  is a units conversion factor; for an annual time step ( $\Delta t = 86,400 \cdot 365$  s),  $A/(c\Delta t) = 2.8775$ . As described above, estimates of  $Q_{irr}$  and  $A_{irr}$  are based on water use data from DWR for 1980-1993;  $d_{irr}$  is derived from these,

i.e.  $d_{irr} = c\Delta t Q_{irr} / A_{irr}$ . These estimates are used to associate data for  $d_{irr}$  with SWAT, specified by SWAT's input file `~.cod`;  $f_{irr}$  with SWBAVG (specified as input to the WEIGHTS program), and  $Q_{irr}$  with MODFLOW (specified by input to the WELL and SURFACE packages). From the balance file written by SWBAVG, MODFLOW obtains the irrigation depth averaged over the basin,  $d_{irr}f_{irr}$ , which is multiplied by  $A/(c\Delta t)$  to obtain  $Q_{irr}$ . The option `irropt` is set equal to 1 to indicate that the irrigated areal fraction has already been incorporated into the depth in this way. On the other hand, a balance file written by SWAT for a homogeneous component (HRU) with irrigation, e.g. for Carr soil and irrigated corn, contains only the irrigation depth  $d_{irr}$ , which MODFLOW must multiply by  $f_{irr} \cdot A/(c\Delta t)$  to obtain  $Q_{irr}$ . In this case, indicated by `irropt=2`, the watershed's heterogeneity with respect to irrigated area would be handled in MODFLOW rather than in SWBAVG.

#### Hydrologic fluxes calculated by MODFLOW for SWAT (SWB1BD)

After the aquifer equations have been solved, MODFLOW calls SWB1BD to summarize shallow water table evaporation and baseflow for each subbasin as follows.

##### Evaporation from water table

Evaporation from the water table is summarized in SHED(18) as a depth for each subbasin, is based on array EVAP calculated in the EVT package, and replaces SWAT's calculation of "revap". Average depth to water, SHED(23), is also calculated for each subbasin. If MODFLOW's evaporation (EVT) package is invoked, the maximum evaporation rate is set by array EVTR according to option `ievopt` (see SWB1FM above); otherwise, (18) and (23) are not calculated, and SWAT's version of (18) is retained.

##### Baseflow

Baseflow from aquifer to stream, SHED(19) as a depth for each subbasin, is the negative of streambed leakage to the aquifer, which is given by adding STRM(11) in the STREAM package over all stream reaches within the subbasin.

## Input instructions for the MODSWB package input file (~.swb)

The following SWB input section numbers 1-9 refer to definitions (below) and the example input file, basecase.swb (p. 99). The SWB input file is read by subroutines SWB1AL, SWB1RP, and SWB1FM of the SWB package. For stand-alone execution of MODFLOW (iopswt = 0), SWB1FM reads the balance file name, closes the SWB input file, and opens the balance file, from which SWAT's results (or averaged results from SWBAYG) are read for each time step according to input instructions given above for subr. HYDBAL in SWAT (p. 52).

subroutines SWB1AL, SWB1RP, SWB1FM, SWB1BD. Regarding format requirements: "FREE" refers to the format used for some numerical inputs; "TEXT" identifies records read as alphanumeric text.

For each simulation:

- ```

      SWB1AL
1.  Data:  nwshed, noutfl, nsoils, mxslay, irropt, ievopt, ioprch, rchmpy, weimpy, iadcod
      Format: FREE

      SWB1RP
2.  Data (TEXT):  record      !table heading
      do i=1, nwshed
      Data (TEXT):  record      !number these records 1 to nwshed.
      end do

3.  Data (FREE):  cnvlen      ! (e.g. cnvlen=1000 mm/m, or 304.8 mm/ft)
4.  Data (FREE):  bsarea, (shed(1,i), i=1, nwshed)

5.  Data (FREE)  (ished(4,i), i=1, nwshed) !Soil id for each subbasin (not used)
      do i=1, nsoils
6.  Data (FREE):  nlsoil, (zsoil(j,i), j=1, nlsoil) !layers; depth (mm) to bottom.
      end do

7.  Data (TEXT)  record 1      !2 table heading records
      Data (TEXT)  record 2      !2 table heading records
      do j=1, nwshed
      Data (FREE):  j, j, idxseg, idxrch ! subbasin index (twice), stream segment, reach.
      end do

8.  Data:        locat, iconst, fmbnd, iprn ! MODFLOW array format
      Format:      (2i10, a20, i10)
      do ir=1, nrow
      Data:        (ibshed(ic, ir), ic=1, ncol) !map subbasins onto grid
      Format:      specified by fmbnd (above)
      end do

      SWB1FM
9.  Data (TEXT):  nambal      !hydrologic flux balance file name (--bal)

```

## Input definitions for Soil Water Balance package input file (ext. ~.swb)

1. Number of subbasins; options for irrigation, evaporation, recharge, and scenarios.
  - nwshed: no. subbasins in watershed;
  - noutfl: total no. streams leaving subbasins; now require that noutfl = nwshed (noutfl is replaced by nwshed but still read to avoid changing input for now).
  - nsoils: no. soils; each subbasin is associated with 1 soil type.
  - mxslay: max. no. soil layers
  - irrop: option (yes>0,no=0) to use irrigation flux as determined by SWAT for each subbasin to scale the pumping rates of irrigation diversions specified by the WELL and Surface package input for a stress period.
    - irrop=0: pumping rates specified in Modflow's Well and Surface input files are applied.
    - irrop>0: total irrigation in the basin varies according to the flux specified by the balance file written by SWBAVG or SWAT for each time step.
    - irrop=1: If the balance file was written by SWBAVG, the irrigation depth which it contains should represent the product  $f_{irr}d_{irr}$ , incorporating the irrigated areal fraction. This is multiplied by  $A/c\Delta t$  to obtain  $Q_{irr}$ , the total irrigation to be applied by ground and surface water diversions.
    - irrop=2: If, on the other hand, the balance file was written by SWAT, it contains the irrigation depth  $d_{irr}$  for a watershed component (hydrologic response unit, HRU) that is homogeneous with respect to irrigation. In order to incorporate the watershed heterogeneity with respect to irrigation, this must be multiplied by  $f_{irr}A/c\Delta t$  to obtain  $Q_{irr}$ .
  - ioprch: (option) If ioprch=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 according to the recharge calculated by SWAT. Note: option jkkopt determines which components calculated by SWAT are included in recharge.
  - ievopt: (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.
  - rchmpy = multiplier to be applied to recharge array for sensitivity analysis.
  - welmpy = multiplier to be applied to pumping rates for sensitivity analysis and for water use scenarios specified by the following code.
  - iadcod = administrative option code for irrigation water use scenarios; applied to groundwater diversions in subr WEL1F0 of the modified WELL package, and to surface water diversions in subr SRF1F0 of the SURFACE package.

2. list of tributaries and the subbasins from which they flow: Read list heading and then list of `nwshed` records numbered 1 through `nwshed`, i.e. one for each subbasin. Since the model is now restricted to one outflow per subbasin, this list is unnecessary but is read to avoid changing the input file format.
3. length conversion between SWAT and MODFLOW: SWAT calculates hydrologic fluxes (flow per unit area) in units of depth (mm); use `cnvlen` to convert from mm to MODFLOW's length unit `L`, corresponding to flow rates [ $L^3/T$ ]; e.g. `cnvlen = 304.8` mm/L for Modflow length unit `L=1` ft and corresponding flow rates (cfs). Similarly, subroutine `MODSWB` converts SWAT time units (days) into MODFLOW time units by `cnvtim = tsec(itmuni)/86400` (days/Modflow time unit), where `itmuni` is MODFLOW's time unit input option specified in the BASIC input file.
4. basin area and subbasin areal fractions: these should be the same values read by SWAT, except that SWAT reads the basin area in  $km^2$ , and `bsarea` should be in MODFLOW's units of [ $L^2$ ].
5. Irrigated area as a percent of the basin for each year; see `IRROPT` (above) to see how it is used.
6. Soil id for each subbasin (read but not used).
- 6a. For each soil, the number of layers and depth to bottom of each layer (mm); not used.
7. Location of subbasin outflow on the network defined by the `STREAM` package: First, read two lines of headings for location of subbasin outflow. Then, for each subbasin,  $j = 1$  to `nwshed`, read subbasin and tributary index (both equal to index  $j$ ), and the segment and reach of the stream network as defined by the `STREAM` (Prudic, 1989) input file. This list is generated by program `STRMDATA` to accompany the description of stream reaches which it writes to be used as input to the `STREAM` package.
8. `ibshed`: correspondence between subbasins and aquifer nodes: This is a 2-D integer array that is read according to MODFLOW's convention used for the `ibound` array in the MODFLOW's basic package input file (see Modflow manual). Each nonzero entry in the array is an index,  $j$ , in the range [ $1, nwshed$ ], associating the grid cell with subbasin  $j$ .
9. `nambal`: For the first time step of the first stress period, `SWB1FM` reads the hydrologic balance file name. Then, for a stand-alone run of `modswb96` (`iopswt = 0`), `SWB1FM` closes the `~.SWB` input file and opens the balance file (e.g. `rebase.bal`, p. 49); `MODSWB` reads the balance input file according to the instructions given for SWAT's subroutine `HYDBAL` (p. 52). Otherwise (`iopswt > 0`), this information is passed from SWAT to `MODSWB` (subr. `SWT2MOD` of the `HYDBAL` package added to SWAT).

## Definition of vectors in arrays ISHED and SHED for the SWB package

MODFLOW arrays ISHED and SHED contain data describing each subbasin for the connecting the watershed to the stream-aquifer system. Definitions are given below for vectors 1-10 of integer array ISHED, and vectors 1-30 or real array SHED. In these definitions, vector  $i$  is referred to as ( $i$ ) for  $i = 1$  to 30; vectors 10-21 correspond to balance file records 10-21, defined below. Dimensions for the Lower Republican River Basin aquifer model are feet [L] and seconds [T], so flow rates are expressed in  $\text{ft}^3/\text{s}$  (cfs), and velocities (e.g. hydraulic conductivity and evaporation rates) in  $\text{ft}/\text{s}$ . SWAT's hydrologic summary is expressed as a depth (mm) accumulated over the number of days in the aquifer time step,  $\text{dtswat}$ . Names of vectors shown in bold type represent data passed to MODFLOW via the balance summaries from SWAT or SWBAVG.

### Integer watershed array ISHED:

- (1) number of streams out of watershed;
- (2) index to list of streams out of watershed.
- (3) (not used)
- (4) soil id for subbasin (not used)
- (5) number of soil layers for subbasin (not used)
- (6) number of cells in each subbasin with active or specified-head nodes (nonzero values in array  $\text{ibound}$ ); evaluated in subr SHALLOW as vector  $\text{numshd}$ , and corresponds to gridded area of each subbasin given by SHED vector (3).
- (7) number of grid cells in each subbasin with shallow groundwater, defined by the condition  $\text{dtw}(\text{ic},\text{ir}) < \text{exdp}(\text{ic},\text{ir})$  for column  $\text{ic}$  and row  $\text{ir}$ , where  $\text{exdp} =$  extinction depth, defined in MODEVT;  $\text{ished}(7)$  is evaluated in subr SHALLOW as vector  $\text{nshzon}$ .
- (10) number of pumping wells ( $Q_w < 0$ ) in each subbasin for the stress period

### Real watershed array SHED:

- (1) **Areal frc** areal fraction of subbasin; read in SW1RP.
- (2) **area** [ $\text{L}^2$ ] area of subbasin [ $\text{L}^2$ ]; product of  $\text{bsarea}$  and (1); SWB1RP.
- (3) **GrdArea** [ $\text{L}^2$ ] gridded subbasin area; see also (7); SWB1RP.
- (4) **Irr\_use** [ $\text{L}$ ] irrigation [ $\text{L}^3/\text{T}$ ]; total irrigation pumping accumulated for each subbasin from WELL module input at beginning of each stress period; SWB1RP.
- (5) **IrrSwatFrc** ratio of irrigation fluxes (11)/(9); see  $\text{irropt}$ .
- (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 ( $\sim\text{.bal}$ ) by HYDBAL in a combined SWAT-MODFLOW run ( $\text{iopswt} > 0$ ).
- (8) **Pond fract** noncontributing areal fraction of subbasin, which contributes instead to ponds; read from  $\sim\text{.balance}$  file; SWB1FM.

- (9) **Irr\_use** irrigation flux based on total pumping in subbasin for the stress period, (4); SWB1RP.
- (10) **Prec mm** precipitation
- (11) **Irr mm** irrigation [L] according to SWAT; used to scale pumping if  $irropt > 0$ .
- (12) **ET mm** "actual" evaporation calculated by SWAT [L]; see also (21).
- (13) **SURQ mm** surface runoff [L] to tributaries leaving subbasin
- (14) **TLoss mm** transmission loss [L]
- (15) **LATQ mm** lateral flow [L] to tributaries leaving subbasin
- (16) **PERC mm** percolation from the root zone
- (17) **GWRE mm** groundwater recharge. According to SWAT, this consists only of percolation from the root zone, with a possible delay time set by SWAT input. For zero time delay (i.e., no storage in the vadose zone), recharge equals percolation from the root zone. For MODFLOW definition of recharge, see (25).
- (18) **GW ET mm** evaporation from water table ("revap" in Swat); the value from SWAT is replaced calculations in MODFLOW's EVT package that are summarized for each subbasin in SWB1BD.
- (19) **Baseflow mm** baseflow; the value from SWAT is replaced 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 calculated by SWAT; if  $ievopt > 0$ , this is used to define the maximum evaporation rate from the water table for the EVT package; also see option  $ievopt$  and SWAT option  $iopet$ .
- (22) **Tribflow mm** tributary inflow to streams from subbasins given by the contributing sum of surface and subsurface runoff. Defining  $c = 1 - \text{pond fraction}(8)$ ;  
 $Q_{trib}(22) = c * [SURQ(13) + LATQ(15)]$   
 unless  $jkkopt > 0$  (defined above; record 1); SWB1FM.
- (23) **DTW [L]** avg depth to water for shallow nodes if EVT is invoked; SWB1BD.
- (24) **Pumprate mm** irrigation depth (mm) calculated in SWB1FM as a check: if  $irropt > 0$ , it should equal assigned irrigation (11) from SWAT; otherwise, it should equal irrigation use (9), calculated in SWB1RP from MODFLOW's ~.WEL input.
- (25) **Recharge mm** groundwater recharge flux is defined for MODFLOW by the sum  
 $RchMod(25) = xmloss(14) + perc(16) + \text{pond seepage}(20)$   
 unless  $jkkopt > 0$  (defined above; record 1); SWB1FM.
- (26) **RchInp mm** recharge depth (mm) corresponding to initial array RECH as read from Modflow input file if  $ioprch > 0$ ; the initial array RECH is retained as a normalized distribution in array RCHINP to allow recharge flux specified by SHED vector 25 (above) to be distributed over the grid accordingly; SWB1FM.
- (27) number of dtw measurements
- (28) **QirrigAvg**: avg pumping rate of wells with nonzero pumping as specified by the ~.WEL input file for the stress period
- (29) mean residual, i.e. solution error based on dtw measurements (27).
- (30) **QirrigMax**: max pumping rate of wells as specified by the ~.WEL input file for the stress period.



## Compiler command and options

The Lahey compiler command **f77l3** is used with specified options to compile Fortran source files named “~.for”; e.g., file modmain.for is compiled by issuing the following command at the DOS prompt:

```
F77L3 modmain /n0/n7/B/nC/D/nF/H/I/nK/L/O/P/nQ1/nQ2/nQ3/R/nS/nT/V/W/X/nZ1
```

The compiler responds as follows, listing the definitions for the above options; options that are not defaults are shown in **boldface**.

Compiling modmain.for, a Standard Format Source File

| OPTION | DESCRIPTION                           | OPTION | DESCRIPTION                               |
|--------|---------------------------------------|--------|-------------------------------------------|
| /n0    | - Standard FORTRAN 77 IMPLICIT        | / L    | - <b>Line-number traceback table</b>      |
| /n2    | - Generate 387 constants and code     | / P    | - Protect constant arguments              |
| /n4    | - No 80486 optimizations              | /nQ1   | - "Unlimited" NDP stack                   |
| /n7    | - Optimize inter-statement            | /nQ2   | - No protected-mode RPC                   |
| /nA2   | - No allocatable array checking       | /nQ3   | - No real-mode RPC                        |
| / B    | - <b>Check array subscript Bounds</b> | / R    | - Remember local variables                |
| /nC    | - Ignore nonstandard usage            | /nS    | - No SOLD file created                    |
| /nC1   | - INTEGER constants 4 bytes           | /nT    | - INTEGER*4, LOGICAL*4 default            |
| / D    | - DIRECT files without headers        | / V    | - <b>VAX Fortran interpretation</b>       |
| / H    | - Hardcopy source listing             | / W    | - Display Warning messages                |
| / I    | - <b>Check subprogram Interfaces</b>  | / X    | - <b>Cross reference &amp; allocation</b> |
| /nK    | - Generate 80x87 code                 | /nZ1   | - Better SOLD debugging                   |

Compiling line 3:            program modmain

A batch file named **f77log.bat**, listed below, is actually used to accomplish the above with the command

```
f77log modmain
```

The name **modmain** on the command line above is passed as argument “%1” to batch file **f77log.bat**, which is used to direct compilation of file modmain.for and to retain results of the compilation on file modmain.log.

```
echo off
rem file f77log.bat spp jan 14 1993
if not "%1"==" " goto begin
echo Compile Fortran 77 source file under Lahey f771-em/32 v.5
echo.
echo Usage: f77log file_name
echo This invokes the Lahey v.5 compiler with a particular set of switches, i.e.
echo F77L3 file_name /n0/n7/B/nC/D/nF/H/I/nK/L/O/P/nQ1/nQ2/nQ3/R/nS/nT/V/W/X/nZ1
echo.
echo Note: specify source file name without extension ".for".
echo        Compiler diagnostics are redirected to file_name.log
echo        Compiler switch definitions will also appear there; or to see only
echo        the definitions, type:
echo            f77l3
echo.
echo Once compiled, link object modules file1.obj[, file2.obj,...] to produce
echo an executable file file1.exe as follows:
echo        386link file1[,file2,...] -symbol
echo.
echo The -symbol switch includes a symbol table in the executable module.
echo The -exe switch in the following example specifies an executable module
echo name other than the first object file's name, e.g. progrm.exe below:
echo        386link file1[,file2,...] -symbol -exe progrm.exe
echo.
```

```

echo For more information on compiling and linking see Lahey Programmer's Reference.
goto end
:begin
if exist %1.for goto compile
echo File %1.for not found.
goto end
:compile
echo Compile file %1.for under Lahey v.5; diagnostics directed to %1.log
F77L3 %1 /n0/n7/B/nC/D/nF/H/I/nK/L/O/P/nQ1/nQ2/nQ3/R/nS/nT/V/W/X/nZ1 >%1.log
:end
echo.
exit

```

## Linking SWAT and MODFLOW to run under DOS

To link SWAT and MODFLOW so that SWAT may optionally call MODFLOW, the command `lswtmd96` is issued at the DOS prompt, which produces the executable file `swtmod96.exe`. The batch file `lswtmd96.bat` refers to file `swtmod96.lnk`, which lists names of all object files associated with SWAT and MODFLOW that were produced by compiling the source files and are to be linked. Files `lswtmd96.bat` and `swtmod96.lnk` are as follows.

### a) file `lswtmd96.bat`:

```

rem file lswtmd96.bat spp 26 May 95 Link programs Swat & Modflow
rem Lahey v. 5.1:
rem note: the "%@" below refers to file swatmod0.lnk, which lists object files.

386link @swtmod96 -symbol -lib graph3 -stub runb -exe swtmod96.exe

```

### b) file `swtmod96.lnk`:

```

! file swtmod96.lnk lists object files for linked Swat and Modflow;
! invoked by lmdswt96.bat: jun 28 96 version
!
swatmain ! main (note: orig crpmd6 version is on file crpmd6.for,
! which can be substituted for crpmdspp.for (below); but
! then call statements in subr subbasin must be switched,
! as explained in the code there.
blockd,cliconsp,crpmdspp,readinpt,subbasin !individual Swat modules
penman !independent calculation of ref. ET (Penman-Monteith).
evap8sp !soil water use (subr evap8, called by subbasin)
swu19sp !plant water use (subr swu19, called by crpmd6, called by subbasin)
swata-e,swatf-o,swatp-r,swats-y ! Swat modules grouped alphabetically
hydbal,soilstat !Swat hydrologic balance; pass fluxes between Swat & Modflow
modflo ! Modflow's main routine, changed into a subroutine called by Swat
modbas
modbcf
modwel2 ! modified to compare solution with water level measurements
! and to allow turning wells off if saturated thickness is too small
modevt ! modified to summarize evap from aquifer for each subbasin
modrch
modsrfl ! version of WELL package for surface water diversions
modsub ! includes WELL module, modified to allow Q to change at each time step
modutl ! utility package
modpcg2 ! more or less standard Modflow
modswb ! module added to coordinate watershed with stream & aquifer
shallow ! set up list of cells with shallow gw for reference by
! surface water model (Swat) in calculating et.
modstrdw ! version of STREAM package w/ option for diffusive routing
strldw ! subroutines associated with diffusive routing option
indexx ! indexed sorting and ranking routines indexr,indexi,irank
! leave out for now:
! pltwav ! routine to display flood wave simulation

```

Similarly, the command `lmdswb96` links MODFLOW as a stand-alone program, producing the executable file `modswb96.exe`. The batch file `lmdswb96.bat` refers to file `modswb96.lnk`, which lists the names of all object files associated with MODFLOW. Files `lmdswb96.bat` and `modswb96.lnk` are as follows.

a) file `lmdswb96.bat`:

```
386link @modswb96 -symbol -exe modswb96.exe
```

b) file `modswb96.lnk`:

```
modmain | mainline  
modflo,modbas,modbcf,modwel2,modevt,modrch,modsub,modut1,modpcg2  
modarf,modswb,shallow,modstrdw,strldw,indexx
```

## 9. PREPROCESSORS FOR PREPARING MODFLOW INPUT DATA

Programs used in these procedures are described and illustrated by examples of their use for the Lower Republican River basin study.

### Daily weather data: NWSDAT

Convert NWS daily precipitation and temperature data from a table format for printing (1 table per year of data), to a column format for input to watershed model (SWAT) and spreadsheets. Also write a log file (ext. log) summarizing missing data, and a monthly summary file (ext. mon).

Example: precipitation and temperature data for Concordia are converted as follows from the NWS tabular format to a column format for input to SWAT:

```
NWSDAT <conc7794.rsp >conc7794.jou
```

#### File conc7794.rsp:

```
1977,1994, beginning & ending years for data conversion      conc7794.rsp
pcp
concpcp.tab          input:  NWS Concordia daily precipitation (tabular input)
concpcp.dat          output: daily precipitation, column format
tmp
conctmx.tab          input:  NWS Concordia daily maximum temperature
conctmn.tab          input:  NWS Concordia daily minimum temperature
conctmp.dat          output: daily min and max temperature, column format
stop
```

File conc7794.jou: listed are queries by program NWSDAT, to which the responses given are listed above in file conc7794.rsp.

```
enter beginning and ending years:
convert weather data for years 1977 to 1994
enter command tmp, pcp, yrs or anything else to quit:
pcp
enter NWS file name for daily precipitation:
Input files:  concpcp.tab
enter output file name:
Open output file concpcp.dat
Open missing data log file concpcp.log
Also write dry day frequency distribution to concpcp.log
year file nmiss Julian day:
nfile=      1
dry period length (days) = 7
trace precip threshold= 0.01 in, i.e. 0.25 mm
write dry period v.time to file concpcp.mdr
write dry period histogram to file concpcp.mdb
1977
1978
1979
```



```

...
1993
1994
enter command tmp, pcp, yrs or anything else to quit:
tmp
enter NWS file name for daily max temp:
enter NWS file name for daily min temp:
Input files: conctmx.tab          conctmn.tab
enter output file name:
Open output file conctmp.dat
Open missing data log file conctmx.log
Also write dry day frequency distribution to conctmx.log
year file nmiss Julian day:
nfile= 2
1977
1977
1978
1978
1979
1979
...
1993
1993
1994
1994
enter command tmp, pcp, yrs or anything else to quit:
stop

```

Excerpts from tabular input format for daily precipitation and maximum temperature as extracted from the EarthInfo cd-rom:

1. 1977 precipitation at Concordia KS (from input file **concpcp.tab**):

| DAILY                 |                      |       |       |       |       |       |       |       |       |       |       |           |            |                |         |
|-----------------------|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----------|------------|----------------|---------|
| Station               | CONCORDIA BLOSSER AP |       |       |       |       |       |       |       |       |       |       | Parameter | Prcp       | % Coverage     | 99      |
| PO Code               | KS                   |       |       |       |       |       |       |       |       |       |       | Latitude  | N39:33:00  | Begin M/Yr     | 06/1962 |
| Stn ID                | 1767                 |       |       |       |       |       |       |       |       |       |       | Longitude | W097:39:00 | End M/Yr       | 12/1994 |
| County                | CLOUD                |       |       |       |       |       |       |       |       |       |       | Elevation | 448.1      | # Record Years | 33      |
| ----- Prcp (in) ----- |                      |       |       |       |       |       |       |       |       |       |       |           |            |                |         |
| 1977                  | Jan                  | Feb   | Mar   | Apr   | May   | Jun   | Jul   | Aug   | Sep   | Oct   | Nov   | Dec       | Annual     |                |         |
| 1                     | 0.02                 | 0.00  | 0.00  | 0.03  | 0.00  | 0.00T | 0.00  | 0.20  | 0.15  | 0.00T | 0.25  | 0.00T     |            |                |         |
| 2                     | 0.09                 | 0.02  | 0.29  | 0.01  | 1.09  | 0.00  | 0.08  | 0.00T | 1.02  | 0.00T | 0.00  | 0.00      |            |                |         |
| 3                     | 0.00T                | 0.00  | 0.00  | 0.31  | 0.00  | 0.00T | 0.00  | 0.11  | 0.10  | 0.00  | 0.00  | 0.00      |            |                |         |
| 4                     | 0.19                 | 0.00  | 0.00T | 0.01  | 0.05  | 0.00  | 0.00  | 1.44  | 0.00  | 0.00  | 0.00  | 0.01      |            |                |         |
| 5                     | 0.01                 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.72  | 0.00  | 0.04  | 0.00T | 0.00T     |            |                |         |
| 6                     | 0.06                 | 0.00T | 0.00  | 0.00  | 0.00  | 0.04  | 0.00  | 0.15  | 0.00  | 0.41  | 0.01  | 0.00      |            |                |         |
| 7                     | 0.00                 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00T | 0.03  | 0.00  | 0.94  | 0.00  | 0.00      |            |                |         |
| 8                     | 0.01                 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.10  | 0.00  | 1.09  | 0.00T     |            |                |         |
| 9                     | 0.00                 | 0.00  | 0.00  | 0.00  | 0.00T | 0.00  | 0.00  | 0.00  | 0.00T | 0.00  | 0.07  | 0.00      |            |                |         |
| 10                    | 0.00                 | 0.00  | 0.39  | 0.00  | 0.00  | 0.00  | 0.50  | 0.00  | 0.00  | 0.06  | 0.00  | 0.00      |            |                |         |
| 11                    | 0.00                 | 0.00  | 0.06  | 0.00  | 0.00  | 0.00T | 0.31  | 0.63  | 0.02  | 0.00  | 0.00  | 0.00      |            |                |         |
| 12                    | 0.00                 | 0.00  | 0.05  | 0.58  | 0.00  | 0.04  | 0.00  | 0.00  | 0.44  | 0.00  | 0.00  | 0.00      |            |                |         |
| 13                    | 0.01                 | 0.00T | 0.00  | 0.00  | 0.00T | 0.51  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00      |            |                |         |
| 14                    | 0.00                 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.08  | 0.00  | 0.00  | 0.00  | 0.00      |            |                |         |
| 15                    | 0.00T                | 0.00  | 0.00  | 0.14  | 0.16  | 0.00  | 0.00  | 0.75  | 0.00  | 0.02  | 0.00  | 0.00      |            |                |         |
| 16                    | 0.00                 | 0.00  | 0.00  | 0.38  | 0.53  | 0.00  | 0.05  | 3.14  | 0.00  | 0.00  | 0.00  | 0.00T     |            |                |         |
| 17                    | 0.01                 | 0.00  | 0.00  | 0.16  | 0.00  | 2.07  | 0.00  | 0.00T | 0.00  | 0.00  | 0.00  | 0.00T     |            |                |         |
| 18                    | 0.00                 | 0.00  | 0.00T | 0.08  | 0.00T | 0.40  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00      |            |                |         |
| 19                    | 0.06                 | 0.00  | 0.11  | 0.00T | 0.41  | 0.02  | 0.00  | 0.00T | 0.00  | 0.00  | 0.00  | 0.01      |            |                |         |
| 20                    | 0.00                 | 0.00  | 0.00  | 0.41  | 0.93  | 0.09  | 0.00  | 0.20  | 0.01  | 0.00  | 0.00  | 0.00T     |            |                |         |
| 21                    | 0.00                 | 0.00  | 0.02  | 0.23  | 0.54  | 1.66  | 0.75  | 0.54  | 0.00  | 0.20  | 0.00  | 0.00T     |            |                |         |
| 22                    | 0.18                 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.11  | 1.57  | 0.00  | 0.08  | 0.00  | 0.00      |            |                |         |
| 23                    | 0.00                 | 0.01  | 0.00  | 0.00T | 0.00  | 0.00  | 0.00  | 0.00  | 0.16  | 0.02  | 0.00  | 0.00      |            |                |         |
| 24                    | 0.00                 | 0.00T | 0.00  | 0.00T | 0.00  | 0.20  | 0.02  | 0.00  | 0.00  | 0.29  | 0.00  | 0.00      |            |                |         |
| 25                    | 0.00                 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00T | 0.01  | 0.00  | 0.00  | 0.00  | 0.00      |            |                |         |
| 26                    | 0.00T                | 0.00  | 0.00  | 0.00  | 0.37  | 0.00  | 0.00  | 0.11  | 0.00  | 0.00  | 0.26  | 0.00      |            |                |         |
| 27                    | 0.00T                | 0.00  | 0.01  | 0.00  | 0.71  | 0.00  | 0.00  | 0.38  | 0.00  | 0.00  | 0.02  | 0.00      |            |                |         |
| 28                    | 0.00T                | 0.00  | 1.11  | 0.00  | 0.04  | 0.00  | 0.51  | 0.66  | 0.00T | 0.00  | 0.03  | 0.00      |            |                |         |
| 29                    | 0.00                 | ---   | 0.00  | 0.03  | 0.44  | 0.00  | 0.00  | 0.00  | 0.00  | 0.08  | 0.00T | 0.00      |            |                |         |
| 30                    | 0.00                 | ---   | 0.00  | 0.00T | 0.74  | 0.00T | 0.00T | 0.00  | 0.05  | 0.08  | 0.00T | 0.00T     |            |                |         |
| 31                    | 0.00                 | ---   | 0.02  | ---   | 0.00  | ---   | 0.00T | 0.60  | ---   | 0.00  | ---   | 0.02      |            |                |         |

|       |      |      |      |      |      |      |      |       |      |      |      |      |       |
|-------|------|------|------|------|------|------|------|-------|------|------|------|------|-------|
| Total | 0.64 | 0.03 | 2.06 | 2.37 | 6.01 | 5.03 | 2.33 | 10.72 | 2.05 | 2.22 | 1.73 | 0.04 | 35.23 |
| Extrm | 0.19 | 0.02 | 1.11 | 0.58 | 1.09 | 2.07 | 0.75 | 3.14  | 1.02 | 0.94 | 1.09 | 0.02 | 3.14  |

Example output from file `concepc.dat`: precipitation for first seven days of 1977 for

Concordia with column format (2i5,f6.1): Julian day, year, precipitation (mm)

```

1 1977 0.5
2 1977 2.3
3 1977 0.0
4 1977 4.8
5 1977 0.3
6 1977 1.5
7 1977 0.0

```

2. 1977 maximum daily temperature at Concordia KS (from file `conctmx.tab`):

DAILY

| Station CONCORDIA BLOSSER AP |     | Parameter           |     | TMax               |     | % Coverage       |     | 99                |     |     |     |     |        |
|------------------------------|-----|---------------------|-----|--------------------|-----|------------------|-----|-------------------|-----|-----|-----|-----|--------|
| PO Code KS                   |     | Latitude N39:33:00  |     | Begin M/Yr 06/1962 |     | End M/Yr 12/1994 |     | # Record Years 33 |     |     |     |     |        |
| Stn ID 1767                  |     | Longitude W97:39:00 |     | Elevation 448.1    |     |                  |     |                   |     |     |     |     |        |
| County CLOUD                 |     |                     |     |                    |     |                  |     |                   |     |     |     |     |        |
| ----- TMax (F) -----         |     |                     |     |                    |     |                  |     |                   |     |     |     |     |        |
| 1977                         | Jan | Feb                 | Mar | Apr                | May | Jun              | Jul | Aug               | Sep | Oct | Nov | Dec | Annual |
| 1                            | 17  | 31                  | 38  | 64                 | 77  | 85               | 87  | 89                | 83  | 69  | 54  | 47  |        |
| 2                            | 23  | 34                  | 48  | 56                 | 74  | 81               | 95  | 89                | 87  | 63  | 60  | 49  |        |
| 3                            | 27  | 48                  | 41  | 42                 | 80  | 87               | 98  | 85                | 81  | 68  | 60  | 43  |        |
| 4                            | 25  | 47                  | 38  | 41                 | 85  | 93               | 96  | 89                | 82  | 79  | 63  | 41  |        |
| 5                            | 20  | 48                  | 49  | 51                 | 79  | 97               | 98  | 86                | 82  | 58  | 65  | 32  |        |
| 6                            | 25  | 27                  | 54  | 76                 | 79  | 80               | 101 | 88                | 85  | 55  | 57  | 21  |        |
| 7                            | 31  | 35                  | 70  | 79                 | 75  | 82               | 87  | 95                | 85  | 73  | 59  | 34  |        |
| 8                            | 26  | 51                  | 78  | 84                 | 80  | 90               | 89  | 92                | 87  | 60  | 56  | 32  |        |
| 9                            | 8   | 62                  | 71  | 82                 | 76  | 87               | 88  | 92                | 75  | 72  | 40  | 14  |        |
| 10                           | 8   | 64                  | 67  | 79                 | 74  | 97               | 92  | 83                | 78  | 57  | 51  | 30  |        |
| 11                           | 21  | 58                  | 58  | 78                 | 73  | 90               | 89  | 75                | 82  | 56  | 51  | 46  |        |
| 12                           | 30  | 54                  | 47  | 73                 | 78  | 86               | 93  | 80                | 78  | 65  | 52  | 48  |        |
| 13                           | 37  | 64                  | 60  | 65                 | 79  | 80               | 99  | 87                | 74  | 75  | 60  | 57  |        |
| 14                           | 36  | 42                  | 70  | 75                 | 83  | 87               | 101 | 79                | 73  | 74  | 64  | 57  |        |
| 15                           | 28  | 30                  | 58  | 68                 | 84  | 92               | 95  | 93                | 70  | 59  | 61  | 59  |        |
| 16                           | 12  | 44                  | 62  | 70                 | 88  | 83               | 101 | 72                | 81  | 69  | 55  | 54  |        |
| 17                           | 27  | 65                  | 75  | 70                 | 81  | 81               | 102 | 79                | 84  | 70  | 53  | 44  |        |
| 18                           | 20  | 62                  | 58  | 69                 | 82  | 82               | 101 | 78                | 79  | 69  | 57  | 48  |        |
| 19                           | 43  | 51                  | 47  | 69                 | 79  | 82               | 99  | 81                | 74  | 73  | 66  | 32  |        |
| 20                           | 43  | 58                  | 60  | 63                 | 74  | 83               | 101 | 85                | 78  | 82  | 61  | 25  |        |
| 21                           | 40  | 74                  | 45  | 55                 | 68  | 79               | 85  | 81                | 85  | 81  | 30  | 38  |        |
| 22                           | 37  | 69                  | 67  | 64                 | 77  | 83               | 91  | 69                | 80  | 59  | 46  | 52  |        |
| 23                           | 36  | 50                  | 68  | 73                 | 80  | 87               | 94  | 79                | 85  | 51  | 45  | 54  |        |
| 24                           | 40  | 57                  | 68  | 66                 | 84  | 87               | 104 | 78                | 79  | 53  | 37  | 44  |        |
| 25                           | 38  | 49                  | 65  | 67                 | 82  | 87               | 81  | 87                | 79  | 64  | 37  | 32  |        |
| 26                           | 38  | 43                  | 72  | 74                 | 80  | 89               | 82  | 92                | 85  | 81  | 36  | 37  |        |
| 27                           | 49  | 47                  | 71  | 81                 | 75  | 93               | 88  | 82                | 76  | 75  | 42  | 32  |        |
| 28                           | 20  | 52                  | 58  | 75                 | 83  | 82               | 92  | 77                | 68  | 73  | 39  | 43  |        |
| 29                           | 32  | ---                 | 58  | 68                 | 81  | 87               | 93  | 79                | 69  | 72  | 49  | 48  |        |
| 30                           | 23  | ---                 | 47  | 67                 | 70  | 82               | 96  | 86                | 72  | 69  | 45  | 41  |        |
| 31                           | 40  | ---                 | 52  | ---                | 78  | ---              | 81  | 85                | --- | 68  | --- | 38  |        |
| Aver                         | 29  | 51                  | 59  | 68                 | 79  | 86               | 94  | 84                | 79  | 67  | 52  | 41  | 66     |
| Extrm                        | 49  | 74                  | 78  | 84                 | 88  | 97               | 104 | 95                | 87  | 82  | 66  | 59  | 104    |

Example output from file `conctmp.dat`: temperature for first seven days of 1977 for

Concordia with column format (2i5,2f6.1): Julian day, year, temperature (C) max, min

```

1 1977 -8.3 -16.7
2 1977 -5.0 -10.0
3 1977 -2.8 -6.1
4 1977 -3.9 -8.9
5 1977 -6.7 -14.4
6 1977 -3.9 -11.4

```

7 1977 -0.6 -13.9

Procedure: convert precipitation and temperature data for all weather stations of interest from the NWS tabular format to a column format for input to SWAT.

To run:

NWSDAT <nws7794.rsp >nws7794.jou

File nws7794.rsp (redirected input):

|                                             |                                         |
|---------------------------------------------|-----------------------------------------|
| 1977,1994, bgn, end yrs for data conversion | nws7794.rsp                             |
| pcp                                         | data type: precipitation                |
| BELLEPCP.tab                                | Belleville input (tabular format)       |
| bellepcp.dat                                | output (column format)                  |
| pcp                                         |                                         |
| claypcp.tab                                 | Clay Center precip                      |
| claypcp.dat                                 |                                         |
| pcp                                         |                                         |
| clifpcp.tab                                 | Clifton precip                          |
| clifpcp.dat                                 |                                         |
| pcp                                         |                                         |
| conpcp.tab                                  | Concordia precip                        |
| conpcp.dat                                  |                                         |
| tmp                                         |                                         |
| conctmx.tab                                 | Concordia daily max and min temperature |
| conctmn.tab                                 |                                         |
| conctmp.dat                                 |                                         |
| pcp                                         |                                         |
| factpcp.tab                                 | Fact precip                             |
| factpcp.dat                                 |                                         |
| pcp                                         |                                         |
| haddpcp.tab                                 | Haddam precip                           |
| haddpcp.dat                                 |                                         |
| pcp                                         |                                         |
| miltpcp.tab                                 | Miltonville precip                      |
| miltpcp.dat                                 |                                         |
| pcp                                         |                                         |
| scanpcp.tab                                 | Scandia precip                          |
| scanpcp.dat                                 |                                         |
| pcp                                         |                                         |
| washpcp.tab                                 | Washington precip                       |
| washpcp.dat                                 |                                         |
| tmp                                         |                                         |
| belletmx.tab                                | Belleville temperature                  |
| belletmn.tab                                |                                         |
| belletmp.dat                                |                                         |
| tmp                                         |                                         |
| claytmx.tab                                 | Clay Center temperature                 |
| claytmn.tab                                 |                                         |
| claytmp.dat                                 |                                         |
| tmp                                         |                                         |
| washtmx.tab                                 | Washington temperature                  |
| washtmn.tab                                 |                                         |
| washtmp.dat                                 |                                         |
| stop                                        | no more data to convert                 |

Contents of file weather.zip: NWS data extracted from cd-rom in tabular format and compressed using PKZIP. File name suffixes refer to NWS station, identified at right, and data type (pcp = precipitation (mm), tmx = max. daily temperature (C), tmn = min. daily temperature).

| Length  | Method  | Size   | Ratio | Date     | Time  | CRC-32   | Attr | Name         | NWS station |
|---------|---------|--------|-------|----------|-------|----------|------|--------------|-------------|
| 66636   | DeflatN | 11219  | 84%   | 10-25-95 | 10:33 | 91d4656e | --w- | BELLETMX.TAB | Belleville  |
| 66636   | DeflatN | 10912  | 84%   | 10-25-95 | 10:34 | 9e3fc26d | --w- | BELLETMN.TAB |             |
| 66636   | DeflatN | 7371   | 89%   | 10-25-95 | 10:36 | a19b4327 | --w- | BELLEPCP.TAB |             |
| 66636   | DeflatN | 11142  | 84%   | 10-25-95 | 10:37 | 3d06b458 | --w- | CLAYTMX.TAB  | Clay Center |
| 66636   | DeflatN | 10883  | 84%   | 10-25-95 | 10:38 | 7a0448f2 | --w- | CLAYTMN.TAB  |             |
| 66636   | DeflatN | 7125   | 90%   | 10-25-95 | 10:39 | 4683f7c1 | --w- | CLAYPCP.TAB  |             |
| 66636   | DeflatN | 7620   | 89%   | 10-25-95 | 10:41 | 345ecd40 | --w- | CLIFPCP.TAB  |             |
| 66636   | DeflatN | 6647   | 91%   | 10-25-95 | 10:46 | e7321b6a | --w- | FACTPCP.TAB  | Fact        |
| 66636   | DeflatN | 6723   | 90%   | 10-25-95 | 10:47 | 214336a1 | --w- | HADDPCP.TAB  | Haddam      |
| 66636   | DeflatN | 7501   | 89%   | 10-25-95 | 10:52 | 35166175 | --w- | MILTPCP.TAB  | Miltonvale  |
| 66636   | DeflatN | 6244   | 91%   | 10-25-95 | 10:55 | f9e5da67 | --w- | SCANPCP.TAB  | Scandia     |
| 66636   | DeflatN | 11083  | 84%   | 10-25-95 | 10:56 | 87c4c7e6 | --w- | WASHTMX.TAB  | Washington  |
| 66636   | DeflatN | 10996  | 84%   | 10-25-95 | 10:57 | 8acb62ca | --w- | WASHTMN.TAB  |             |
| 66636   | DeflatN | 7483   | 89%   | 10-25-95 | 10:58 | d9366e23 | --w- | WASHPCP.TAB  |             |
| 66636   | DeflatN | 7937   | 89%   | 10-27-95 | 10:36 | 8d2b83cf | --w- | CONCPCP.TAB  |             |
| 66636   | DeflatN | 10909  | 84%   | 10-27-95 | 10:34 | b2a9f95b | --w- | CONCTMN.TAB  |             |
| 66636   | DeflatN | 11249  | 84%   | 10-27-95 | 10:33 | 6d1b4494 | --w- | CONCTMX.TAB  |             |
| -----   |         | -----  | ----- |          |       |          |      | -----        |             |
| 1132812 |         | 153045 | 87%   |          |       |          |      |              | 17          |

## Daily streamflow data: ADAPS (USGS)

Using the USGS ADAPS data base, daily streamflow data files were obtained for gaging stations on the Republican River at Concordia (1947-1994) and Clay Center (1917-1994); for Mill Creek at Washington (1960-1995); and for Chapman Creek near Chapman (1954-1995).

## Streamflow and stream channel characteristics: YQGAGE

Analysis of depth rating curves and transverse channel profiles of streamflow obtained from USGS for the Republican River at both Concordia and Clay Center gaging stations resulted in subroutine YQGAGE, which encodes functional relationships based on least-squares curve fits for stream depth as a function of flow rate  $y(Q)$ ; and stream width  $B(y)$ , wetted perimeter  $P(y)$ , and transverse flow area  $A(y)$  as functions of depth. YQGAGE, listed below, is called by a modified version of MODFLOW's STREAM package to approximate the interaction (streambed leakage or baseflow) between the alluvial aquifer and the Republican River represented by a natural channel.

```

subroutine YQGAGE (itrace, idgage, slope, q, dqdt, y, sf,
  1          topwid, perim, area, v, ck, diffus)
*
*   this applies to Concordia (idgage=1) and Clay Center (idgage=2)
*   gaging stations on the Republican River in Kansas:
*   a) stream depth,  $y(Q)$ , is based on an average of depth rating curves
*   obtained from the ADAPS data base;
*   b) stream width,  $B(y)$ , and transverse area of flow,  $A(y)$ , are
*   based on transverse streambed profiles obtained from Butch Laycock.

```

```

*          USGS, Lawrence, KS.
* idgage  indicates whether gaging station is at Concordia (idgage=1) or
*          Clay Center (idgage=2).
* slope   =S0, streambed slope.
* q       flow rate (cfs)
* dqdt   rate of change of flow rate (does not affect results here)
* y       stream depth (ft)
* sf      friction slope; sf = slope since dq/dt is neglected.
* topwid  =B, stream width at water surface
* perim   =P, wetted perimeter; approximate by P = B (difference is negligible).
* area    =A, transverse area of flow computed by integrating dA = B*dy.
* v       =Q/A, flow velocity.
* ck      =dQ/dA, kinematic celerity (wave speed); approximate by ck = 1.6*v.
* diffus  =Dh = Q/(2*B*S0), hydraulic diffusion coefficient.
*
  if (Q.le.18000.) then
    y = 0.166*Q**0.453
  else
    y = 1.66*Q**0.217
  end if
  if (idgage.eq.1) then      ! Concordia
    if (y.le.1.6) then
      topwid = 9.7 + 70.8*y
      area = (9.7 + 35.4*y)*y
    else
      topwid = 118. + 6.28*y
      area = (118. + 3.14*y)*y - 90.69
    end if
  else if (idgage.eq.2) then !Clay Center
    if (y.le.1.6) then
      topwid = 5.66 + 58.6*y*y
      area = (5.66 + (58.6/3.)*y*y)*y
    else
      topwid = 119. + 22.*y
      area = (119. + 11.*y)*y - 129.5
    end if
  end if
  perim = topwid
  v = Q/area
  ck = 1.6*v
  diffus = Q/(2.*topwid*slope)
  return
end

```

## Mapping legal descriptions onto geographical and grid coordinates: TSTGRD

Program TSTGRD, which transforms legal coordinates onto both geographical and grid coordinates, was used to map well locations taken from USGS 1:24000 scale topographic maps for our water level survey in November 1994. For each well, TSTGRD calls LEOCVT (Ross, KGS) to calculate geographical coordinates (latitude, longitude) and TRGRID to calculate grid coordinates (row, column).

Procedure: convert well locations for water level survey of November 1994 from legal descriptions to geographical and grid coordinates using TSTGRD as follows.

```
tstgrd <dtwdat2.inp >dtwdat2.jou
```

Results are written to file latlong.out (below).

The following excerpt from input file dtwdat2.inp shows the first five water level measurements; TSTGRD converts the legal descriptions to geographical coordinates.

```

GRID
05s 04w 06
INPUT (2(i3,a) i3,4a)
  5S 4W 3dbbd s2 1393 1 11-7-94 2:50 9.5 1 e 12.13 1380.9 1.08
  5S 4W 3cdcd s2a 1381 1 11-7-94 2:35 8 1 s 7.51 1373.5 1.08
  4S 4W 33ccd s5a 1386 1 11-11-9 4:10 0 1 s 9.60 1376.4 1.08
  5S 4W 8dadab s6a 1392 2 11-8-94 12:00 0 1 s 19.80 1372.2 2.08
  5S 4W 17aaaa s6b 1389 1 11-8-94 6 2 s 14.05 1375.0 1.17

```

Results: excerpt from file latlong.out for the first five wells.

The first record after the heading identifies the township section taken as the origin grid cell with indices (row 1, column 1), with rows increasing from north to south and columns increasing from west to east. The geographical location for the origin corresponds to grid coordinates (0,0), i.e. the northwest corner of the origin cell. Geographical locations, grid coordinates, and grid cell indices are shown for the first five wells, and correspond to their legal locations given by the input file as shown above. MODFLOW's modified WELL package calculates residuals for the hydraulic head solution at the nodes identified by these indices.

|     |           | geographical coords |          | grid coords |       | grid indices |        |
|-----|-----------|---------------------|----------|-------------|-------|--------------|--------|
|     |           | longitude           | latitude | row         | col   | row          | col    |
| 05S | 04W 06    | 1                   | -97.809  | 39.646      | 0.00  | 0.00         | 25 -23 |
| 1   | KACKLEY   | 1                   | -97.751  | 39.645      | 0.59  | 3.59         | 1 4    |
| 2   | KACKLEY   | 1                   | -97.756  | 39.640      | 0.97  | 3.34         | 1 4    |
| 3   | KACKLEY   | 1                   | -97.778  | 39.655      | -0.06 | 2.19         | 0 3    |
| 4   | KACKLEY   | 1                   | -97.783  | 39.630      | 1.66  | 1.91         | 2 2    |
| 5   | JAMESTOWN | 1                   | -97.782  | 39.624      | 2.03  | 1.97         | 3 2    |

## Listing of subroutine TRGRID

The following code from subroutine TRGRID maps a legal description (township, range and section) onto grid (row, column) indices. This is a simplified version of subroutine TRGRID3, which maps a legal location to the precision of the subsection description onto grid coordinates.

```

c      character(*) tspdir, rngdir
c      township offset (0 for 1s)
      if (tspdtr.eq.'s') then
          itoff = 6*(itsp-1)
      else
          itoff = -5*itsp

```

```

      end if
c     range offset (0 for 1e)
      if (rngdir.eq.'e') then
        iroff = 6*(irng-1)
      else
        iroff = -6*irng
      end if
c     local section coordinates (ir=row, ic=column):
      ir = 1 + (isec-1)/6
      if (MOD(ir,2).eq.0) then
        ic = isec-6*(ir-1)
      else
        ic = 6*ir-(isec-1)
      end if
c     combine local section coordinates with township and range offsets:
      irow = ir + itoff
      icol = ic + iroff
c     translate with respect to grid origin:
      irow = irow - (irow0-1)
      icol = icol - (icol0-1)
      return
    end

```

## Mapping legal descriptions only onto geographical coordinates: TSTGEO

This program, the predecessor of TSTGRD described above, performs the same as TSTGRD but without mapping legal locations onto grid coordinates.

## Stream geography and bed slope: STRMDATA

Process river and stream reach data taken from USGS 1:24000 scale topographic maps; write a list of these stream reaches, one per township section, in a format that can be read by MODFLOW's STREAM package, modified as described herein. Stream lengths across each township section were measured using a map wheel; calibration measurements were made to determine the scale to be applied to wheel revolutions; see top of input file (below). Multiple traverses of the Republican River across a section are approximated by one equivalent reach whose length is the sum of the component lengths and whose streambed elevation is a weighted mean of the elevations of the components, using their lengths as the weight function. The legal location of each stream reach (township, range, and section) is mapped onto a corresponding grid of 1-mi<sup>2</sup> cells by subroutine TRGRID.

STRMDATA is a command-driven program; the geographical description of the stream and river reaches given by input file **repubhyd.inp** contains a command column that indicates how the data on each row are to be interpreted. File **repubhyd.inp** also identifies the following two files: (a) input file **aqfthk.txt**, which gives the initial aquifer thickness in 1977 for each active node; and (b) output file **repubhyd.str**, which is used to construct input files for MODFLOW's modified STREAM package and the Soil Water Balance package, described elsewhere in this report. STRMDATA is run as follows, redirecting input from **repubhyd.inp** and output to **repubhyd.jou**, which describes program execution:

```
strmdata <repubhyd.inp >repubhyd.jou
```

Data file descriptions:

```
c repubhyd.inp: input file containing stream description;
c strmdata.dat: intermediate results, including description of stream reaches
c               before consolidating multiple occurrences within grid cells;
c repubhyd.str: (named by data on file repubhyd.inp): output file for 1st part
c               of Modflow's Stream input file;
c strmdata.st2: output file for 2nd part of Modflow's Stream input file.
```

An excerpt from input file **repubhyd.inp** is listed below, followed by excerpts from **repubhyd.str**, which was used to construct annual and monthly versions of input files to MODFLOW's STREAM package, **rpann.str** and **rptomon.str**. for annual and monthly versions of the aquifer model; and redirected terminal output file **repubhyd.jou**.

| legal location | command | numeric arguments | text argument or explanation              |
|----------------|---------|-------------------|-------------------------------------------|
|                | scale   | 52 20             | inches/mile                               |
|                | cycle   | 39                | inches/cycle map scale calib.             |
| 5 s 4 w 6      | orig    |                   | define origin                             |
|                | file    |                   | <b>repubhyd.str</b> input file for STREAM |
|                | renum   |                   |                                           |
|                | aqfthk  |                   | <b>aqfthk.txt</b> aquifer thickness       |
|                | segmt   | 1                 | Republican R stream segment               |
|                | slope   | -0.00053          | nominal avg slope                         |
| 3 s 4 w 32     | mbgn n  | 0                 | Kackley KS begin 1:24000 map              |
|                | bgn n   | 0                 | enter section from north; initial loc.    |
|                | c       | 1.4 1410          | contour (distance downstream, elev.)      |
|                | end s   | 2.65              | end section (distance downstream)         |
| 4 s 4 w 5      | bgn     |                   |                                           |
|                | c       | 5.25 1405         |                                           |
|                | end     | 7.00              |                                           |
|                | 8 bgn   |                   |                                           |
|                | c       | 9.4 1400          |                                           |
|                | end     | 10.55             |                                           |
|                | 7 bgn   |                   |                                           |
|                | end     | 12.0              |                                           |
|                | 18 bgn  |                   |                                           |
|                | t       | 12.15 5           | Beaver Cr: tributary enters at loc.       |
|                | end     | 12.35             |                                           |
| 17             | bgn     |                   |                                           |
|                | c       | 13.85 1395        |                                           |
|                | end     | 15.0              |                                           |
| 20             | bgn     |                   |                                           |
|                | bridg   |                   | bridge crosses river                      |
|                | c       | 15.8 1390         |                                           |

|     |     |     |        |       |                          |
|-----|-----|-----|--------|-------|--------------------------|
|     |     | end | 18.2   |       |                          |
|     | 29  | bgn | 21.05  | 1385  |                          |
|     |     | c   | 21.1   |       |                          |
|     |     | end |        |       |                          |
|     | 32  | bgn | 21.2   |       | Oak Cr                   |
|     |     | t   | 24.2   |       |                          |
|     |     | end |        |       |                          |
| 5 s | 4 w | 5   | bgn    |       | Cloud County Line        |
|     |     |     | cnty   |       |                          |
|     |     |     | c      | 24.85 | 1380                     |
|     |     |     | end    | 26.9  |                          |
|     |     | 9   | bgn    | 28.3  | 1375                     |
|     |     |     | c      | 30.7  |                          |
|     |     |     | end    |       |                          |
|     |     | 10  | bgn    | 32.3  | 1370                     |
|     |     |     | c      | 33.2  |                          |
|     |     |     | edge   |       | Kackley/Concordia NW     |
|     |     |     | mbgn   |       | Concordia NW             |
|     |     |     | end    | 34.2  |                          |
|     |     | 11  | bgn    | 36.3  |                          |
|     |     |     | end    | 36.3  |                          |
|     |     |     | edge   | 36.3  | Concordia NW/Concordia   |
|     |     |     | offst  | 36.3  | Concordia RS             |
|     |     |     | mbgn   |       | 36.3 in. from above maps |
| 5 s | 4 w | 14  | bgn n  | 0     |                          |
|     |     |     | c      | 1.1   | 1360                     |
|     |     |     | end s  | 2.65  |                          |
|     |     | 23  | bgn n  |       |                          |
|     |     |     | end n  | 4.85  |                          |
|     |     | 14  | bgn s  |       |                          |
|     |     |     | end e  | 5.4   |                          |
|     |     | 13  | bgn w  |       |                          |
|     |     |     | end s  | 6.7   |                          |
|     |     | 24  | bgn n  |       |                          |
|     |     |     | c      | 9.7   | 1350                     |
|     |     |     | end s  | 10.4  |                          |
|     |     | 25  | bgn n  |       |                          |
|     |     |     | t s    | 10.8  | Buffalo Cr               |
|     |     |     | end ne | 11.8  |                          |
| 5 s | 3 w | 19  | bgn sw |       |                          |
|     |     |     | end s  | 13.1  |                          |
|     |     | 30  | bgn n  |       |                          |
|     |     |     | t s    | 16.7  | Wolf Cr                  |
|     |     |     | end e  | 17.7  |                          |
|     |     | 29  | bgn w  |       |                          |
|     |     |     | c      | 18.4  | 1340                     |
|     |     |     | end e  | 20.55 |                          |
|     |     | 28  | bgn w  |       |                          |
|     |     |     | wbgn n |       | 1                        |
|     |     |     | wbgn s |       | 2                        |
|     |     |     | gs     | 23.6  | Concordia                |
|     |     |     | end e  | 24.8  |                          |
|     |     | 27  | bgn w  |       |                          |
|     |     |     | c      | 25.7  | 1330                     |
|     |     |     | end e  | 27.75 |                          |
|     |     | 26  | bgn w  |       |                          |
|     |     |     | edge e | 28.8  | Concordia/Rice           |
|     |     |     | mbgn   |       | Rice                     |
| 5 s | 3 w |     | end e  | 31.05 |                          |
|     |     | 25  | bgn w  |       |                          |
|     |     |     | end n  | 33.7  |                          |
|     |     | 24  | bgn s  |       |                          |
|     |     |     | end e  | 35    |                          |
|     | 2 w | 19  | bgn w  |       |                          |
|     |     |     | c      | 35.3  | 1320                     |
|     |     |     | end e  | 38    |                          |
|     |     | 20  | bgn w  |       |                          |
|     |     |     | end s  | 39.2  |                          |
|     |     | 29  | bgn n  |       |                          |
|     |     |     | end s  | 2.9   | 39                       |
|     |     | 32  | bgn n  |       |                          |
|     |     |     | t s    | 2.95  | Oak Cr                   |
|     |     |     | t s    | 5     | Plum Cr                  |
|     |     |     | wend s |       | 2                        |
|     |     |     | wbgn s |       | 3                        |
|     |     |     | c      | 5.95  | 1310                     |

```

end e          6
33 bgn w
t s          6.8      stream from Rice (interm.)
end n          6.9

```

An excerpt from input file **aqfthk.txt**, which lists all grid nodes (both active and inactive) follows.

| row | col | bnd | shed | thickness | legal  | location |
|-----|-----|-----|------|-----------|--------|----------|
| 1   | 1   | 1   | 1    | 85        | T 5S R | 4W 6     |
| 1   | 2   | 1   | 1    | 80        | T 5S R | 4W 5     |
| 1   | 3   | 1   | 1    | 80        | T 5S R | 4W 4     |
| 1   | 4   | 1   | 1    | 39        | T 5S R | 4W 3     |
| 1   | 5   | 0   | 0    | 0         | T 5S R | 4W 2     |
| 1   | 6   | 0   | 0    | 0         | T 5S R | 4W 1     |
| 1   | 7   | 0   | 0    | 0         | T 5S R | 3W 6     |
| 1   | 8   | 0   | 0    | 0         | T 5S R | 3W 5     |
| 1   | 9   | 0   | 0    | 0         | T 5S R | 3W 4     |
| 1   | 10  | 0   | 0    | 0         | T 5S R | 3W 3     |

The following excerpts from file **repubhyd.str** written by program **STRMDATA** describe the first 21 stream reaches; headings in bold type identify the data fields that are read by the modified **STREAM** package.

**Part 1 of STREAM input file (see input instructions item 3):**

| Lay | Row | Col | Seg | Rch | Inflow | Stage  | Hyd.Cond  | Bot Elev | Top elev | Legal loc./trib. |
|-----|-----|-----|-----|-----|--------|--------|-----------|----------|----------|------------------|
| 1   | 1   | 2   | 1   | 1   | 0.00   | 1378.0 | 0.0001574 | 1375.0   | 1378.0   | 5s 4w 5          |
| 1   | 2   | 3   | 1   | 2   | 0.00   | 1373.2 | 0.0001574 | 1370.2   | 1373.2   | 5s 4w 9          |
| 1   | 2   | 4   | 1   | 3   | 0.00   | 1368.0 | 0.0001574 | 1365.0   | 1368.0   | 5s 4w10          |
| 1   | 2   | 5   | 1   | 4   | 0.00   | 1363.2 | 0.0001574 | 1360.2   | 1363.2   | 5s 4w11          |
| 1   | 3   | 5   | 1   | 5   | 0.00   | 1358.3 | 0.0001574 | 1355.3   | 1358.3   | 5s 4w14          |
| 1   | 4   | 5   | 1   | 6   | 0.00   | 1356.3 | 0.0001574 | 1353.3   | 1356.3   | 5s 4w23          |
| 1   | 3   | 6   | 1   | 7   | 0.00   | 1353.9 | 0.0001574 | 1350.9   | 1353.9   | 5s 4w13          |
| 1   | 4   | 6   | 1   | 8   | 0.00   | 1350.3 | 0.0001574 | 1347.3   | 1350.3   | 5s 4w24          |
| 1   | 5   | 6   | 1   | 9   | 0.00   | 1348.0 | 0.0001574 | 1345.0   | 1348.0   | Buffalo Cr       |
| 1   | 4   | 7   | 1   | 10  | 0.00   | 1346.5 | 0.0001574 | 1343.5   | 1346.5   | 5s 3w19          |
| 1   | 5   | 7   | 1   | 11  | 0.00   | 1342.1 | 0.0001574 | 1339.1   | 1342.1   | Wolf Cr          |
| 1   | 5   | 8   | 1   | 12  | 0.00   | 1338.0 | 0.0001574 | 1335.0   | 1338.0   | 5s 3w29          |
| 1   | 5   | 9   | 1   | 13  | 0.00   | 1332.7 | 0.0001574 | 1329.7   | 1332.7   | 5s 3w28          |
| 1   | 5   | 10  | 1   | 14  | 0.00   | 1328.6 | 0.0001574 | 1325.6   | 1328.6   | 5s 3w27          |
| 1   | 5   | 11  | 1   | 15  | 0.00   | 1325.3 | 0.0001574 | 1322.3   | 1325.3   | 5s 3w26          |
| 1   | 5   | 12  | 1   | 16  | 0.00   | 1322.4 | 0.0001574 | 1319.4   | 1322.4   | 5s 3w25          |
| 1   | 4   | 12  | 1   | 17  | 0.00   | 1320.7 | 0.0001574 | 1317.7   | 1320.7   | 5s 3w24          |
| 1   | 4   | 13  | 1   | 18  | 0.00   | 1318.0 | 0.0001574 | 1315.0   | 1318.0   | 5s 2w19          |
| 1   | 4   | 14  | 1   | 19  | 0.00   | 1316.3 | 0.0001574 | 1313.3   | 1316.3   | 5s 2w20          |
| 1   | 5   | 14  | 1   | 20  | 0.00   | 1313.9 | 0.0001574 | 1310.9   | 1313.9   | 5s 2w29          |
| 1   | 6   | 14  | 1   | 21  | 0.00   | 1310.8 | 0.0001574 | 1307.8   | 1310.8   | Plum Cr          |

**Part 2 of STREAM input file (see input instructions item 4):**

| Width | Bed slope | Manning n | Length | 1/side | slp      | total len |   |   |   |   |    |   |
|-------|-----------|-----------|--------|--------|----------|-----------|---|---|---|---|----|---|
| 100.0 | 0.0007137 | 0.030     | 5483.1 | 0.000  | 54627.7  | 0         | 0 | 0 | 0 | 1 | 1  | 1 |
| 100.0 | 0.0006155 | 0.030     | 7716.9 | 0.000  | 62344.6  | 0         | 0 | 0 | 0 | 1 | 2  | 1 |
| 100.0 | 0.0009655 | 0.030     | 7107.7 | 0.000  | 69452.3  | 0         | 0 | 0 | 0 | 1 | 3  | 1 |
| 100.0 | 0.0009655 | 0.030     | 4264.6 | 0.000  | 73716.9  | 0         | 0 | 0 | 0 | 1 | 4  | 1 |
| 100.0 | 0.0005726 | 0.030     | 6498.5 | 0.000  | 79098.5  | 0         | 0 | 0 | 0 | 1 | 5  | 2 |
| 100.0 | 0.0005726 | 0.030     | 4467.7 | 0.000  | 83566.2  | 0         | 0 | 0 | 0 | 1 | 6  | 1 |
| 100.0 | 0.0005726 | 0.030     | 1116.9 | 0.000  | 84683.1  | 0         | 0 | 0 | 0 | 1 | 7  | 2 |
| 100.0 | 0.0005726 | 0.030     | 2640.0 | 0.000  | 87323.1  | 0         | 0 | 0 | 0 | 1 | 7  | 1 |
| 100.0 | 0.0005660 | 0.030     | 7513.8 | 0.000  | 94836.9  | 0         | 0 | 0 | 0 | 1 | 8  | 1 |
| 100.0 | 0.0005660 | 0.030     | 2843.1 | 0.000  | 97680.0  | 0         | 0 | 1 | 0 | 1 | 9  | 1 |
| 100.0 | 0.0005660 | 0.030     | 2640.0 | 0.000  | 100320.0 | 0         | 0 | 0 | 0 | 1 | 10 | 1 |
| 100.0 | 0.0005660 | 0.030     | 9341.5 | 0.000  | 109561.5 | 0         | 0 | 1 | 0 | 1 | 11 | 1 |
| 100.0 | 0.0006746 | 0.030     | 5787.7 | 0.000  | 115449.2 | 0         | 0 | 0 | 0 | 1 | 12 | 1 |
| 100.0 | 0.0006746 | 0.030     | 8630.8 | 0.000  | 124080.0 | 1         | 2 | 0 | 0 | 1 | 13 | 1 |
| 100.0 | 0.0005129 | 0.030     | 5990.8 | 0.000  | 130070.8 | 1         | 2 | 0 | 0 | 1 | 14 | 1 |

|       |           |       |        |       |          |   |   |   |   |   |    |   |
|-------|-----------|-------|--------|-------|----------|---|---|---|---|---|----|---|
| 100.0 | 0.0005129 | 0.030 | 6701.5 | 0.000 | 136772.3 | 1 | 2 | 0 | 0 | 1 | 15 | 1 |
| 100.0 | 0.0005129 | 0.030 | 5381.5 | 0.000 | 142153.8 | 1 | 2 | 0 | 0 | 1 | 16 | 1 |
| 100.0 | 0.0005129 | 0.030 | 2640.0 | 0.000 | 144793.8 | 1 | 2 | 0 | 0 | 1 | 17 | 1 |
| 100.0 | 0.0005103 | 0.030 | 6092.3 | 0.000 | 150886.2 | 1 | 2 | 0 | 0 | 1 | 18 | 1 |
| 100.0 | 0.0005103 | 0.030 | 2436.9 | 0.000 | 153323.1 | 1 | 2 | 0 | 0 | 1 | 19 | 1 |
| 100.0 | 0.0005103 | 0.030 | 5483.1 | 0.000 | 158806.2 | 1 | 2 | 0 | 0 | 1 | 20 | 1 |
| 100.0 | 0.0005411 | 0.030 | 6295.4 | 0.000 | 165101.5 | 1 | 3 | 2 | 0 | 1 | 21 | 1 |

The following tributary list, showing stream, aquifer and watershed correspondence, is used to set up input to the Soil Water Balance (SWB) package (input instructions item 7) identifying the correspondence between subbasin outflow and Republican River reaches.

| trib                               | shed | side | cell | row | col | seg | rch | width | tributary                  |
|------------------------------------|------|------|------|-----|-----|-----|-----|-------|----------------------------|
| (2i5, 1x, a, 3x, 5i5, f8.2, 1x, a) |      |      |      |     |     |     |     |       |                            |
| 1                                  | 0    |      | 0    | 0   | 0   | 1   | 0   | 5.00  | Beaver Cr                  |
| 2                                  | 0    |      | 0    | 0   | 0   | 1   | 0   | 5.00  | Oak Cr                     |
| 3                                  | 0 s  |      | 709  | 5   | 6   | 1   | 9   | 5.00  | Buffalo Cr                 |
| 4                                  | 0 s  |      | 709  | 5   | 7   | 1   | 11  | 5.00  | Wolf Cr                    |
| 5                                  | 2 s  |      | 677  | 6   | 14  | 1   | 21  | 5.00  | Oak Cr                     |
| 6                                  | 2 s  |      | 677  | 6   | 14  | 1   | 21  | 5.00  | Plum Cr                    |
| 7                                  | 3 s  |      | 678  | 6   | 15  | 1   | 22  | 5.00  | stream from Rice (interm.) |
| 8                                  | 3    |      | 679  | 6   | 16  | 1   | 24  | 5.00  | stream (interm.)           |
| 9                                  | 1 n  |      | 757  | 4   | 16  | 1   | 26  | 5.00  | Salt Cr                    |
| 10                                 | 1 n  |      | 759  | 4   | 18  | 1   | 28  | 5.00  | Upton Cr                   |
| 11                                 | 3 s  |      | 684  | 6   | 21  | 1   | 32  | 5.00  | Elm Cr                     |
| 12                                 | 4 n  |      | 726  | 5   | 24  | 1   | 38  | 5.00  | Elk Cr                     |
| 13                                 | 3 s  |      | 648  | 7   | 24  | 1   | 39  | 5.00  | Beaver Cr                  |
| 14                                 | 3 s  |      | 611  | 8   | 26  | 1   | 41  | 5.00  | Mud Cr                     |
| 15                                 | 5 n  |      | 654  | 7   | 30  | 1   | 47  | 5.00  | Scribner Cr                |
| 16                                 | 6 n  |      | 654  | 7   | 30  | 1   | 47  | 5.00  | Parsons Cr                 |
| 17                                 | 7 n  |      | 500  | 11  | 32  | 1   | 52  | 5.00  | Peats Cr                   |
| 18                                 | 7 n  |      | 423  | 13  | 33  | 1   | 55  | 5.00  | Peet Cr                    |
| 19                                 | 3 s  |      | 333  | 14  | 32  | 1   | 55  | 5.00  | Mulberry Cr                |
| 20                                 | 8 s  |      | 114  | 21  | 36  | 1   | 69  | 5.00  | Five Cr                    |
| 21                                 | 9 n  |      | 115  | 21  | 37  | 1   | 72  | 5.00  | Huntress Cr (Spring & Dry) |
| 22                                 | 0 n  |      | 117  | 21  | 39  | 1   | 75  | 5.00  | Finney Cr                  |
| 23                                 | 0 n  |      | 0    | 0   | 0   | 1   | 0   | 5.00  | Lincoln Cr                 |
| 24                                 | 0 s  |      | 0    | 0   | 0   | 1   | 0   | 5.00  | Otter Cr                   |

The following list shows the beginning, end, and length (mi) of the stretch of the Republican River bordering each subbasin; the number of tributaries flowing from each subbasin, and identifiers for the tributaries corresponding to the list above:

| (1x, i2, 1x, a, 1x, 3f9.2, 11i5) |   |       |       |       |   |    |    |    |    |    |    |    |    |
|----------------------------------|---|-------|-------|-------|---|----|----|----|----|----|----|----|----|
| 0                                |   |       |       |       |   | 7  | 1  | 2  | 3  | 4  | 22 | 23 | 24 |
| 1                                | n | 21.87 | 36.98 | 15.12 | 2 | 9  | 10 |    |    |    |    |    |    |
| 2                                | s | 21.87 | 30.88 | 9.02  | 2 | 5  | 6  |    |    |    |    |    |    |
| 3                                | s | 30.88 | 80.10 | 49.21 | 6 | 7  | 8  | 11 | 13 | 14 | 19 |    |    |
| 4                                | n | 36.98 | 51.92 | 14.94 | 1 | 12 |    |    |    |    |    |    |    |
| 5                                | n | 51.92 | 58.08 | 6.15  | 1 | 15 |    |    |    |    |    |    |    |
| 6                                | n | 58.08 | 59.10 | 1.02  | 1 | 16 |    |    |    |    |    |    |    |
| 7                                | n | 59.10 | 68.46 | 9.37  | 2 | 17 | 18 |    |    |    |    |    |    |
| 8                                | s | 80.10 | 82.92 | 2.83  | 1 | 20 |    |    |    |    |    |    |    |
| 9                                | n | 68.46 | 82.92 | 14.46 | 1 | 21 |    |    |    |    |    |    |    |

Excerpts from file repubhyd.jou (written by program STRMDATA):

```

scale: 2.600000 inches/mile
offset/cycle = 39.00 inches
origin at T1s R1e 6 (row0=1,col0=1):
T 5s R 4w 6 row0= 1 col0= 1 row 25 column=23 ir= 1 ic= 1
Origin reset to irow0= 25 icol0=-23
Open stream output file repubhyd.str

```

Open strmdata.st2 to write 2nd part of STREAM input file.

```
Stream segment 1 Republican R
xloc= 0.00 ft, x= 0.00 offset= 0.00
xloc= 0.00 ft, x= 0.00 offset= 0.00
Begin reach 1
xloc= 2843.08 ft, x= 1.40 offset= 0.00
xloc= 5381.54 ft, x= 2.65 offset= 0.00
 1 -6 2 1 1 ntrib= 0 itrib= 0
Begin reach 2
xloc= 10661.54 ft, x= 5.25 offset= 0.00
xloc= 14215.38 ft, x= 7.00 offset= 0.00
 2 -5 2 1 2 ntrib= 0 itrib= 0
Begin reach 3
xloc= 19089.23 ft, x= 9.40 offset= 0.00
xloc= 21424.62 ft, x= 10.55 offset= 0.00
 3 -4 2 1 3 ntrib= 0 itrib= 0
```

distance between gages= 60.19 mi in T 8s R 3e 17  
end of input

Contour elevations and average bed slope between contours: these were interpolated to approximate river reach elevations.

| cntr | row | col | elev (ft) | dist,ft  | dz,ft | dx,ft   | slope,ft/ft | Tsp | Rng | Sect |
|------|-----|-----|-----------|----------|-------|---------|-------------|-----|-----|------|
| 1    | -6  | 2   | 1410.0    | 2843.1   | 0.0   | 0.0     | -0.0005300  |     |     |      |
| 2    | -5  | 2   | 1405.0    | 10661.5  | -5.0  | 7818.5  | -0.0006395  |     |     |      |
| 3    | -4  | 2   | 1400.0    | 19089.2  | -5.0  | 8427.7  | -0.0005933  |     |     |      |
| 4    | -3  | 2   | 1395.0    | 28126.2  | -5.0  | 9036.9  | -0.0005533  |     |     |      |
| 5    | -2  | 2   | 1390.0    | 34116.9  | -5.0  | 5990.8  | -0.0008346  |     |     |      |
| 6    | -1  | 2   | 1385.0    | 42747.7  | -5.0  | 8630.8  | -0.0005793  |     |     |      |
| 7    | 1   | 2   | 1380.0    | 50464.6  | -5.0  | 7716.9  | -0.0006479  |     |     |      |
| 8    | 2   | 3   | 1375.0    | 57470.8  | -5.0  | 7006.2  | -0.0007137  |     |     |      |
| 9    | 2   | 4   | 1370.0    | 65593.8  | -5.0  | 8123.1  | -0.0006155  |     |     |      |
| 10   | 3   | 5   | 1360.0    | 75950.8  | -10.0 | 10355.9 | -0.0009655  |     |     |      |
| 11   | 4   | 6   | 1350.0    | 93415.4  | -10.0 | 17464.6 | -0.0005726  |     |     |      |
| 12   | 5   | 8   | 1340.0    | 111083.1 | -10.0 | 17667.7 | -0.0005660  |     |     |      |
| 13   | 5   | 10  | 1330.0    | 125907.7 | -10.0 | 14824.6 | -0.0006746  |     |     |      |
| 14   | 4   | 13  | 1320.0    | 145403.1 | -10.0 | 19495.4 | -0.0005129  |     |     |      |
| 15   | 6   | 14  | 1310.0    | 165000.0 | -10.0 | 19596.9 | -0.0005103  |     |     |      |
| 16   | 4   | 17  | 1300.0    | 183480.0 | -10.0 | 18480.0 | -0.0005411  |     |     |      |
| 17   | 4   | 19  | 1290.0    | 199218.5 | -10.0 | 15738.5 | -0.0006354  |     |     |      |
| 18   | 6   | 21  | 1280.0    | 216378.5 | -10.0 | 17160.0 | -0.0005828  |     |     |      |
| 19   | 6   | 24  | 1270.0    | 235061.5 | -10.0 | 18683.1 | -0.0005352  |     |     |      |
| 20   | 7   | 24  | 1260.0    | 254353.9 | -10.0 | 19292.3 | -0.0005183  |     |     |      |
| 21   | 8   | 27  | 1250.0    | 278215.4 | -10.0 | 23861.5 | -0.0004191  |     |     |      |
| 22   | 8   | 29  | 1240.0    | 299944.6 | -10.0 | 21729.2 | -0.0004602  |     |     |      |
| 23   | 9   | 31  | 1230.0    | 318627.7 | -10.0 | 18683.1 | -0.0005352  |     |     |      |
| 24   | 12  | 32  | 1220.0    | 339138.5 | -10.0 | 20510.8 | -0.0004875  |     |     |      |
| 25   | 14  | 32  | 1210.0    | 359649.3 | -10.0 | 20510.8 | -0.0004875  |     |     |      |
| 26   | 16  | 32  | 1200.0    | 375184.6 | -10.0 | 15535.4 | -0.0006437  |     |     |      |
| 27   | 18  | 33  | 1190.0    | 394883.1 | -10.0 | 19698.5 | -0.0005077  |     |     |      |
| 28   | 20  | 35  | 1180.0    | 415292.3 | -10.0 | 20409.3 | -0.0004900  |     |     |      |
| 29   | 21  | 35  | 1176.0    | 422907.7 | -4.0  | 7615.4  | -0.0005253  |     |     |      |
| 30   | 21  | 37  | 1170.0    | 434076.9 | -6.0  | 11169.2 | -0.0005372  |     |     |      |
| 31   | 22  | 39  | 1160.0    | 451033.9 | -10.0 | 16956.9 | -0.0005897  |     |     |      |
| 32   | 25  | 41  | 1150.0    | 472560.0 | -10.0 | 21526.2 | -0.0004646  |     |     |      |
| 33   | 26  | 43  | 1144.0    | 484541.6 | -6.0  | 11981.5 | -0.0005008  |     |     |      |
| 34   | 27  | 42  | 1140.0    | 490836.9 | -4.0  | 6295.4  | -0.0006354  |     |     |      |

In the following excerpt from a list of consolidated reaches, n = number of traversals made by the Republican River across the reach; Length = total reach length of the component traversals; and Elev = mean elevation of the components, using their lengths as the weight function.

| Rech | Idx | Row | Col | n(*) | Length | Elev   |
|------|-----|-----|-----|------|--------|--------|
| 1    | 860 | 1   | 2   | 1    | 5483.1 | 1378.0 |
| 2    | 822 | 2   | 3   | 1    | 7716.9 | 1373.2 |
| 3    | 823 | 3   | 4   | 1    | 7107.7 | 1363.2 |
| 4    | 824 | 2   | 5   | 1    | 4264.6 | 1363.2 |

|    |     |   |    |   |        |        |
|----|-----|---|----|---|--------|--------|
| 5  | 785 | 3 | 5  | 2 | 6498.5 | 1358.3 |
| 6  | 746 | 4 | 5  | 1 | 4467.7 | 1356.3 |
| 7  | 786 | 3 | 6  | 1 | 2640.0 | 1353.9 |
| 8  | 747 | 4 | 6  | 1 | 7513.8 | 1350.3 |
| 9  | 708 | 5 | 6  | 1 | 2843.1 | 1348.0 |
| 10 | 748 | 4 | 7  | 1 | 2640.0 | 1346.5 |
| 11 | 709 | 5 | 7  | 1 | 9341.5 | 1342.1 |
| 12 | 710 | 5 | 8  | 1 | 5787.7 | 1338.0 |
| 13 | 711 | 5 | 9  | 1 | 8630.8 | 1332.7 |
| 14 | 712 | 5 | 10 | 1 | 5990.8 | 1328.6 |
| 15 | 713 | 5 | 11 | 1 | 6701.5 | 1325.3 |
| 16 | 714 | 5 | 12 | 1 | 5381.5 | 1322.4 |
| 17 | 753 | 4 | 12 | 1 | 2640.0 | 1320.7 |
| 18 | 754 | 4 | 13 | 1 | 6092.3 | 1318.0 |
| 19 | 755 | 4 | 14 | 1 | 2436.9 | 1316.3 |
| 20 | 716 | 5 | 14 | 1 | 5483.1 | 1313.9 |
| 21 | 677 | 6 | 14 | 1 | 6295.4 | 1310.8 |

```

***
77 reaches written to stream file
6      61.06 sum of watersheds on north
3      61.05 sum of watersheds on south
cumulative distance= 92.96 mi

```

```

distance (mi) along stream across maps:
i end loc. mi. traversed map
1 12.769 12.769 Kackley KS
2 13.962 1.192 Concordia NW
3 25.038 11.077 Concordia KS
4 35.788 10.750 Rice
5 45.865 10.077 Clyde
6 48.115 2.250 Clifton
7 62.231 14.115 Clyde
8 63.654 1.423 Linn
9 78.962 15.308 Clay Center NW
10 83.269 4.308 Clay Center SW
11 92.962 9.692 Clay Center SE

```

## Water level survey: SURFELEV

This program was used to set up input file dtw94nov.wel summarizing ground water level measurements taken in November 1994 as part of this study. This file is also written in the format used by Modflow's Well package, so that it may be simply appended to file gwuadmnu.wel, described above, to be treated as part of the 1994 water use data set and thereby included in the comparison with Modflow's calculated heads.

```
surfelev <surfelev.rsp >surfelev.jou
```

### Response file surfelev.rsp:

|              |                                        |
|--------------|----------------------------------------|
| n            | Screen grid with ibound array? [Y]     |
| rpann.str    | stream input file name                 |
| dtwdata.o    | groundwater elevations input file name |
| dtw94nov.wel | gw elevations (well) output file name  |
| repsurf.prn  | surface elevations input file name     |
| repsurf.elv  | surface elevations output file name    |

### File surfelev.jou:

```

Screen grid with ibound array? [Y]:
Enter stream input file name:
Open stream input file rpann.str

```

Enter groundwater elevations input file name:  
 Open gw elevations input file dtwdata.o  
 Enter gw elevations (well) output file name:  
 Open gw elevations (well) output file dtw94nov.wel

Water level survey summary:

| row | col | row | col   | surf.el. | dtw,ft | w.level | err    | est.  | Legal | location |
|-----|-----|-----|-------|----------|--------|---------|--------|-------|-------|----------|
| 1   | 1   | 4   | 0.59  | 3.59     | 1393   | 12.13   | 1380.9 | 1.08" | 5 S   | 4 W 3    |
| 2   | 1   | 4   | 0.97  | 3.34     | 1381   | 7.51    | 1373.5 | 1.08" | 5 S   | 4 W 3    |
| 3   | 0   | 3   | -0.06 | 2.19     | 1386   | 9.60    | 1376.4 | 1.08" | 4 S   | 4 W 33   |
| 4   | 2   | 2   | 1.66  | 1.91     | 1392   | 19.80   | 1372.2 | 2.08" | 5 S   | 4 W 8    |
| 5   | 3   | 2   | 2.03  | 1.97     | 1389   | 14.05   | 1375.0 | 1.17" | 5 S   | 4 W 17   |
| 6   | 3   | 3   | 2.03  | 2.97     | 1380   | 9.32    | 1370.7 | 1.67" | 5 S   | 4 W 16   |
| 7   | 4   | 4   | 3.03  | 3.59     | 1380   | 12.92   | 1367.1 | 1.08" | 5 S   | 4 W 22   |
| 8   | 1   | 4   | 0.97  | 3.59     | 1385   | 18.60   | 1366.4 | 1.08" | 5 S   | 4 W 3    |
| 9   | 4   | 10  | 3.53  | 9.97     | 1337   | 8.45    | 1328.6 | 1.50" | 5 S   | 3 W 22   |
| 10  | 4   | 7   | 3.09  | 6.34     | 1370   | 13.25   | 1356.8 | 1.08" | 5 S   | 3 W 19   |
| 11  | 3   | 5   | 2.66  | 4.84     | 1365   | 8.09    | 1356.9 | 1.08" | 5 S   | 4 W 14   |
| 12  | 4   | 6   | 3.59  | 5.03     | 1362   | 11.61   | 1350.4 | 1.08" | 5 S   | 4 W 24   |
| 13  | 3   | 4   | 2.16  | 3.59     | 1375   | 8.98    | 1366.0 | 1.08" | 5 S   | 4 W 15   |
| 14  | 3   | 7   | 2.97  | 6.16     | 1375   | 22.00   | 1353.0 | 1.08" | 5 S   | 3 W 18   |
| 15  | 3   | 7   | 2.47  | 6.03     | 1382   | 25.33   | 1356.7 | 1.08" | 5 S   | 3 W 18   |
| 16  | 3   | 6   | 2.72  | 5.97     | 1377   | 27.30   | 1349.7 | 1.08" | 5 S   | 4 W 13   |
| 17  | 4   | 7   | 3.34  | 6.66     | 1359   | 11.92   | 1347.1 | 1.08" | 5 S   | 3 W 19   |
| 18  | 4   | 8   | 3.78  | 7.66     | 1350   | 8.50    | 1341.5 | 1.08" | 5 S   | 3 W 20   |
| 19  | 4   | 9   | 3.03  | 8.28     | 1370   | 41.96   | 1328.0 | 1.08" | 5 S   | 3 W 21   |
| 20  | 4   | 8   | 3.09  | 7.03     | 1370   | 21.67   | 1348.3 | 1.08" | 5 S   | 3 W 20   |
| 21  | 4   | 16  | 3.66  | 15.47    | 1312   | 12.26   | 1299.7 | 2.08" | 5 S   | 2 W 22   |
| 22  | 6   | 17  | 5.28  | 16.03    | 1323   | 22.54   | 1300.5 | 1.08" | 5 S   | 2 W 35   |
| 23  | 6   | 14  | 5.53  | 13.53    | 1335   | 25.73   | 1309.3 | 1.08" | 5 S   | 2 W 32   |
| 24  | 4   | 15  | 3.72  | 14.03    | 1320   | 13.55   | 1306.5 | 1.08" | 5 S   | 2 W 21   |
| 25  | 5   | 13  | 4.91  | 12.22    | 1327   | 9.97    | 1317.0 | 4.00" | 5 S   | 2 W 30   |
| 26  | 4   | 12  | 3.91  | 11.03    | 1333   | 13.92   | 1319.1 | 3.00" | 5 S   | 3 W 24   |
| 27  | 4   | 12  | 3.84  | 11.41    | 1330   | 14.40   | 1315.6 | 1.08" | 5 S   | 3 W 24   |
| 28  | 5   | 18  | 4.53  | 17.03    | 1317   | 19.32   | 1297.7 | 1.08" | 5 S   | 2 W 25   |
| 29  | 5   | 20  | 4.16  | 13.03    | 1294   | 10.16   | 1283.6 | 1.08" | 5 S   | 2 W 25   |
| 30  | 5   | 22  | 4.41  | 21.59    | 1288   | 9.13    | 1278.9 | 1.08" | 5 S   | 1 W 27   |
| 31  | 6   | 23  | 5.09  | 22.22    | 1280   | 9.09    | 1270.9 | 1.08" | 5 S   | 1 W 35   |
| 32  | 7   | 23  | 6.09  | 22.59    | 1280   | 9.18    | 1270.8 | 1.08" | 6 S   | 1 W 2    |
| 33  | 6   | 22  | 5.91  | 21.53    | 1285   | 11.06   | 1273.9 | 1.08" | 5 S   | 1 W 34   |
| 34  | 6   | 20  | 5.84  | 19.53    | 1307   | 24.22   | 1282.8 | 1.08" | 5 S   | 1 W 32   |
| 35  | 5   | 23  | 4.47  | 22.84    | 1291   | 50.00   | 1241.0 | 1.08" | 5 S   | 1 W 26   |
| 36  | 4   | 22  | 3.03  | 21.72    | 1308   | 49.67   | 1258.3 | 1.08" | 5 S   | 1 W 22   |
| 37  | 9   | 31  | 8.72  | 30.16    | 1245   | 15.06   | 1229.9 | 1.58" | 6 S   | 2 E 18   |
| 38  | 9   | 31  | 8.84  | 30.22    | 1245   | 14.63   | 1230.4 | 1.08" | 6 S   | 2 E 18   |
| 39  | 9   | 30  | 8.47  | 29.22    | 1259   | 28.95   | 1230.1 | 1.08" | 6 S   | 1 E 13   |
| 40  | 9   | 30  | 8.22  | 29.53    | 1248   | 16.43   | 1231.6 | 1.08" | 6 S   | 1 E 13   |
| 41  | 9   | 29  | 8.97  | 28.53    | 1259   | 26.54   | 1232.5 | 1.58" | 6 S   | 1 E 14   |
| 42  | 10  | 29  | 9.47  | 28.16    | 1265   | 31.52   | 1233.5 | 1.08" | 6 S   | 1 E 23   |
| 43  | 10  | 30  | 9.22  | 29.22    | 1253   | 25.51   | 1227.5 | 1.08" | 6 S   | 1 E 24   |
| 44  | 7   | 29  | 6.22  | 28.53    | 1264   | 18.53   | 1245.5 | 1.17" | 6 S   | 1 E 2    |
| 45  | 8   | 28  | 7.28  | 27.47    | 1255   | 8.98    | 1246.0 | 1.08" | 6 S   | 1 E 10   |
| 46  | 8   | 27  | 7.03  | 26.66    | 1262   | 9.04    | 1253.0 | 1.75" | 6 S   | 1 E 9    |
| 47  | 8   | 28  | 7.34  | 27.03    | 1259   | 10.14   | 1248.9 | 1.75" | 6 S   | 1 E 10   |
| 48  | 6   | 28  | 5.97  | 27.53    | 1274   | 23.73   | 1250.3 | 1.08" | 5 S   | 1 E 34   |
| 49  | 7   | 26  | 6.09  | 25.03    | 1267   | 12.82   | 1254.2 | 1.42" | 6 S   | 1 E 5    |
| 50  | 7   | 25  | 6.47  | 24.53    | 1269   | 8.64    | 1260.4 | 1.17" | 6 S   | 1 E 6    |
| 51  | 7   | 25  | 6.03  | 24.09    | 1275   | 13.23   | 1261.8 | 1.08" | 6 S   | 1 E 6    |
| 52  | 10  | 32  | 9.78  | 31.03    | 1236   | 11.08   | 1224.9 | 1.08" | 6 S   | 2 E 20   |
| 53  | 10  | 31  | 9.28  | 30.66    | 1240   | 14.56   | 1225.4 | 1.08" | 6 S   | 2 E 19   |
| 54  | 18  | 34  | 17.22 | 33.03    | 1200   | 10.17   | 1189.8 | 1.08" | 7 S   | 2 E 34   |
| 55  | 17  | 33  | 16.97 | 32.97    | 1198   | 11.71   | 1186.3 | 1.08" | 7 S   | 2 E 28   |
| 56  | 17  | 34  | 16.78 | 33.47    | 1218   | 24.25   | 1193.8 | 1.08" | 7 S   | 2 E 27   |
| 57  | 18  | 34  | 17.03 | 33.72    | 1215   | 23.43   | 1191.6 | 1.08" | 7 S   | 2 E 34   |
| 58  | 17  | 34  | 16.84 | 33.97    | 1215   | 25.67   | 1189.3 | 1.08" | 7 S   | 2 E 27   |
| 59  | 18  | 34  | 17.28 | 33.97    | 1209   | 19.90   | 1189.1 | 1.08" | 7 S   | 2 E 34   |
| 60  | 18  | 34  | 17.84 | 33.97    | 1201   | 19.70   | 1181.3 | 1.08" | 7 S   | 2 E 34   |
| 61  | 19  | 35  | 18.03 | 34.91    | 1209   | 29.10   | 1179.9 | 1.08" | 8 S   | 2 E 2    |
| 62  | 19  | 36  | 18.31 | 35.69    | 1203   | 24.25   | 1178.7 | 1.08" | 8 S   | 2 E 1    |
| 63  | 19  | 36  | 18.28 | 35.28    | 1206   | 25.65   | 1180.4 | 1.08" | 8 S   | 2 E 1    |
| 64  | 19  | 36  | 18.72 | 35.28    | 1207   | 24.78   | 1182.2 | 1.08" | 8 S   | 2 E 1    |
| 65  | 19  | 36  | 18.03 | 35.72    | 1205   | 24.59   | 1180.4 | 1.08" | 8 S   | 2 E 1    |
| 66  | 16  | 34  | 15.22 | 33.91    | 1220   | 17.46   | 1202.5 | 1.08" | 7 S   | 2 E 22   |
| 67  | 15  | 33  | 14.22 | 32.41    | 1215   | 10.17   | 1204.8 | 1.08" | 7 S   | 2 E 16   |
| 68  | 15  | 33  | 14.72 | 32.97    | 1223   | 17.67   | 1207.3 | 1.08" | 7 S   | 2 E 16   |
| 69  | 15  | 34  | 14.69 | 33.44    | 1223   | 17.13   | 1205.9 | 1.08" | 7 S   | 2 E 15   |

```

70 15 34 14.34 33.03 1225 16.13 1208.9 1.08" 7 S 2 E 15
71 14 35 13.94 34.06 1227 15.00 1212.0 1.08" 7 S 2 E 11
72 14 35 13.47 34.03 1231 18.08 1212.9 1.08" 7 S 2 E 11
73 13 33 12.72 32.34 1240 25.67 1214.3 2.08" 7 S 2 E 4
74 13 34 12.34 33.03 1235 20.90 1214.1 1.08" 7 S 2 E 3
75 17 36 16.97 35.09 1210 26.14 1183.9 1.08" 7 S 2 E 25
76 21 36 20.69 35.81 1198 13.25 1184.8 1.08" 8 S 2 E 13
77 20 36 19.59 35.53 1200 29.44 1170.6 5.08" 8 S 2 E 12
78 20 36 19.28 35.53 1205 27.38 1177.6 1.08" 8 S 2 E 12
79 20 36 19.03 35.53 1205 26.75 1178.3 1.08" 8 S 2 E 12
80 21 36 20.56 35.56 1190 12.18 1177.8 1.08" 8 S 2 E 13

```

```

79 observations written to file dtw94nov.wel
Enter surface elevations input file name:
Open surface elevations input file repsurf.prn
Enter surface elevations output file name:
Open surface elevations output file repsurf.elv
Surface elev. format (row,col,ctr elev,ft) = (2i5,32x,f8.0)
  2  1  2 1367
  3  1  3 1390
  4  1  4 1390
  5  1  5 1405
...
163 14 35 1234
164 16 36 1270
165 17 32 1250
numgw= 22
water level comparison with stream file rpann.str
dw_avg = -1.21 dw_rms= 7.78
numsurf= 72
Surface elev. comparison with stream file rpann.str
dh_avg = 15.10 dh_rms= 20.39

```

## Water rights: WRREPUB

Set up lists of ground and surface water rights that lie within active nodes (solution space) of gridded area along the alluvial valley.

```

wrrepub <greptest.rsp >greptest.jou      !groundwater rights
wrrepub <sreptest.rsp >sreptest.jou      !surface water rights

```

### Input files:

klrpd.prn is an exported text version of a data base file obtained from DWR describing water rights.

rpann.str represents the Republican River as a series of 77 reaches that correspond to the sections through which the river flows, and is also an input file to Modflow's Stream package for the annual version of the base case for the aquifer model. This file was written by program Strmdata (above), and is based on geographical data taken directly from USGS 1:24000 quadrangle maps.

ibrepub contains the Ibound matrix, also read by Modflow's Basic package (e.g. file bcann\_t.bas for the annual base case, or bcase\_t.base for the monthly base case). Array ibound(j,i) for columns j and rows i is integer-valued: 1 = active part of the solution domain; 0 = no-flow (zero-valued derivative, i.e. Neumann, boundary condition), and -1 = constant head (specified solution, i.e. Dirichlet, boundary condition).

repsurf.elv contains the ground surface elevation matrix, Surf, also read by Modflow's Evaporation package from file repsurf.elv for the monthly or annual versions of the base case. Elevations are specified for the active nodes of the solution grid. Since the solution grid and the township section grid coincide approximately with an error on the order of 200 ft, the node elevations are specified by the elevations at the center of the corresponding township sections.

### Output files:

greptest.rc: summary of 349 groundwater rights described in DWR file klrpd.prn within active grid cells of the Republican River aquifer model, and used as input to the water use program wurepub.

sreptest.rc: analogous summary of 40 surface water rights.

These lists of ground and surface water rights appear in Appendix 3B2, Vol. 1.

#### Groundwater rights: response file greptest.rsp

```
g surface or groundwater
greptest case name
c:\sp\repub\klrpd.prn water rights input file name
rpann.str stream input file name
ibrepub. ibound matrix file name
Y select active nodes only?
repsurf.elv surface elevation matrix file name
```

#### Excerpts from file greptest.jou:

```
Origin at T 5S R 4W 6 (row0,col0): 25 -23 24.00 -24.00
G[round] or S[urface] water rights?[G]: Open file dist_geo.prn on unit 15 to read well-
stream distances for 349 wells.
Open file elevwr.prn on unit 15 to read well top elevations for 349 wells.
Enter case name (8 char max):
Enter input file name [c:\sp\repub\klrpd.prn]:
Case name = greptest Input file name = c:\sp\repub\klrpd.prn
Output: 14, greptest.sum (annual summary)
Output: 16, greptest.rc (well list)
Output: 21, greptest.grd (cells with wells)
Enter stream input file name (blank if none):
77 1 0 0 3 1.49 -1
no. stream reaches = 77
program WRrepub: 447.761 gpm/cfs
Enter ibound matrix file name (blank if none):
125 active cells in grid
Select by ibound array mask?[Y]: Enter surface elevation matrix file name (blank if none):
164 surface elevation values
File Leobase is open: unit 91
No. pts of water diversion selected= 349
197 cells with wells 575 wells in grid 60159.58 total appropriation in grid
95 cells outside active nodes with wells
226 wells in grid outside active nodes
21837.13 total appropriation in grid outside active nodes
```

#### Surface water rights: response file sreptest.rsp

```
s surface or groundwater
sreptest case name
c:\sp\repub\klrpd.prn water rights input file name
rpann.str stream input file name
ibrepub. ibound matrix file name
Y select active nodes only?
repsurf.elv surface elevation matrix file name
```

#### File sreptest.jou:

```
Origin at T 5S R 4W 6 (row0,col0): 25 -23 24.00 -24.00
G[round] or S[urface] water rights?[G]: Enter case name (8 char max):
Enter input file name [c:\sp\repub\klrpd.prn]:
Case name = sreptest Input file name = c:\sp\repub\klrpd.prn
Output: 14, sreptest.sum (annual summary)
Output: 16, sreptest.rc (well list)
Output: 21, sreptest.grd (cells with wells)
Enter stream input file name (blank if none):
77 1 0 0 3 1.49 -1
no. stream reaches = 77
program WRrepub: 447.761 gpm/cfs
Enter ibound matrix file name (blank if none):
125 active cells in grid
Select by ibound array mask?[Y]: Enter surface elevation matrix file name (blank if none):
164 surface elevation values
No. pts of water diversion selected= 40
26 cells with wells 74 wells in grid 3918.00 total appropriation in grid
13 cells outside active nodes with wells
34 wells in grid outside active nodes
1454.43 total appropriation in grid outside active nodes
```

## Water use estimates: WUREPUB

Water use was estimated for the period 1977-1994 for those ground and surface water rights identified by the lists written by WRREPUB (above) on the basis of reported use for years 1980-1993 and on the basis of precipitation models for the remaining years.

```
wurepub <gwuadmnu.rsp >gwuadmnu.jou      !groundwater rights
wurepub <swuadmnu.rsp >swuadmnu.jou      !surface water rights
```

Output describing water use estimates for 1977-1994:

(a) annual summaries of ground and surface water use (the basis for Tables 3.1 and 3.2 in Vol. 1):

```
gwuadmnu.sum      ! estimated annual ground water use
swuadmnu.sum      ! estimated annual surface water use
```

(b) estimated annual ground and surface water use for individual points of diversion (to be read by Modflow's modified Well and Surface packages, respectively):

```
gwuadmnu.wel      ! groundwater diversions: input to Well package
swuadmnu.wel      ! surface water diversions: input to Surface package
```

These files include some or all of the following data for individual points of diversion:

- 1) annual water use estimates and appropriation; used in coordination with SWAT and SWBAVG to determine annual or monthly diversion rates.
- 2) water level measurements either provided as part of the water use data from DWR for some of the wells, or based on our water level survey in November 1994; used in Modflow Well package, subr. WEL1WR to calculate residuals, i.e. compare solution with measurements.
- 3) application number, distance from stream, and index to closest stream reach; used in Modflow Well package, subr. WEL1F0 as criteria for selection or water use scaling according to scenarios.

Response file gwuadmnu.rsp for groundwater use estimates:

```
g      optsrc: source=gw(G) or surf(S); wurepub <gwuadmnu.rsp >gwuadmnu.jou
y      op7780: set use fraction to 0.63 ('80-'93 avg) for yrs before 1980
n      opt94: set use fraction for 1994? (y/n)
y      optgrd: select by grid? (y/n; if y, read ibound file next)
ibrepub.      ibound array name
gwuadmnu      case name
1977, 1994      range of years to estimate water use
greptest.rc      water rights input file name
```

Input files for groundwater use estimates:

```
water use files for 1980-1993 (listed below in file gwuadmnu.jou);
ibrepub: Ibound matrix file describing solution domain (see above);
greptest.rc: summary of groundwater rights within the solution domain; written by WRREPUB.
```

Output files for groundwater use estimates:

```
gwuadmnu.wel: input file to Modflow's modified Well package describing annual ground water
use for years 1977-1994 based on DWR water rights and water use data for years
```

1980-1993 and derived models of water use based on precipitation data for the remaining years 1977-1979 and 1994.  
 gwuadmnu.sum: annual summary of ground water use estimates.

File gwuadmnu.jou:

Basin area: 2569.60 km<sup>2</sup>, 634962.00 acres  
 Select G[round] or S[urface] water rights?[G]: Set use fraction = 0.63 (1980-1993 avg) for years before 1980?[Y]: Specify use fraction for 1994?[n]: Select by grid?[Y]: Enter ibound matrix file name:  
 Open ibound matrix file ibrepub.  
 125 active cells in grid  
 Enter case name (8 char max):  
 Enter range of water use years (e.g. 1958,1994) :  
 Range: 1977 to 1994  
 Water use input file name: c:\sp\repub\wurepYY.prn ,YY=77 to 94  
 Enter water rights input file name:  
 Case name = gwuadmnu  
 Water rights input file name = greptest.rc  
 Output: 13, gwuadmnu.wel (Modflow input)  
 Output: 14, gwuadmnu.sum (annual summary)  
 Output: 16, gwuadmnu.rc (well list)  
 program WU\_rep: 447.761 gpm/cfs  
 0.3076217E-05 acfgal = acre-ft/gal  
 Read water rights input file greptest.rc  
 349 water rights records; sum qnew= 38322.46 acre-ft/yr

| year | Nwrtot | Numrpt | Numdtw | precip | frcrpt | frcuse | frciru | depirr | use                     | report | file |
|------|--------|--------|--------|--------|--------|--------|--------|--------|-------------------------|--------|------|
| 1977 | 246    | 0      | 0      | 0.607  | 0.000  | 0.293  | 0.293  | 0.122  |                         |        |      |
| 1978 | 256    | 0      | 0      | 0.429  | 0.000  | 0.520  | 0.520  | 0.212  |                         |        |      |
| 1979 | 264    | 0      | 0      | 0.406  | 0.000  | 0.560  | 0.560  | 0.228  |                         |        |      |
| 1980 | 267    | 267    | 3      | 0.233  | 0.264  | 1.001  | 1.006  | 0.344  | c:\sp\repub\wurep80.prn |        |      |
| 1981 | 277    | 277    | 104    | 0.564  | 0.566  | 0.356  | 0.359  | 0.133  | c:\sp\repub\wurep81.prn |        |      |
| 1982 | 278    | 278    | 83     | 0.572  | 0.574  | 0.350  | 0.328  | 0.137  | c:\sp\repub\wurep82.prn |        |      |
| 1983 | 284    | 284    | 102    | 0.262  | 0.593  | 0.800  | 0.769  | 0.333  | c:\sp\repub\wurep83.prn |        |      |
| 1984 | 285    | 285    | 107    | 0.289  | 0.660  | 0.801  | 0.774  | 0.325  | c:\sp\repub\wurep84.prn |        |      |
| 1985 | 285    | 285    | 94     | 0.442  | 0.666  | 0.451  | 0.410  | 0.177  | c:\sp\repub\wurep85.prn |        |      |
| 1986 | 290    | 290    | 101    | 0.584  | 0.540  | 0.397  | 0.364  | 0.153  | c:\sp\repub\wurep86.prn |        |      |
| 1987 | 296    | 262    | 158    | 0.430  | 0.735  | 0.495  | 0.475  | 0.204  | c:\sp\repub\wurep87.prn |        |      |
| 1988 | 310    | 202    | 138    | 0.245  | 0.512  | 0.942  | 0.929  | 0.362  | c:\sp\repub\wurep88.prn |        |      |
| 1989 | 318    | 278    | 185    | 0.418  | 0.807  | 0.725  | 0.721  | 0.301  | c:\sp\repub\wurep89.prn |        |      |
| 1990 | 336    | 291    | 176    | 0.426  | 0.809  | 0.690  | 0.677  | 0.289  | c:\sp\repub\wurep90.prn |        |      |
| 1991 | 340    | 297    | 207    | 0.290  | 0.827  | 0.969  | 0.952  | 0.385  | c:\sp\repub\wurep91.prn |        |      |
| 1992 | 346    | 302    | 174    | 0.514  | 0.685  | 0.314  | 0.251  | 0.105  | c:\sp\repub\wurep92.prn |        |      |
| 1993 | 347    | 315    | 105    | 0.850  | 0.496  | 0.241  | 0.136  | 0.057  | c:\sp\repub\wurep93.prn |        |      |
| 1994 | 348    | 0      | 0      | 0.390  | 0.000  | 0.590  | 0.590  | 0.240  | c:\sp\repub\wurep93.prn |        |      |

No. report records= 18029

Response file swuadmnu.rsp for surface water use estimates:

```
s      optsrc: source=gw(G) or surf(S); wurepub <swuadmnu.rsp >swuadmnu.jou
y      op7780: set use fraction to 0.63 ('80-'93 avg) for yrs before 1980
n      opt94:  set use fraction for 1994? (y/n)
y      optgrd: select by grid? (y/n; if y, read ibound file next)
ibrepub.      ibound array name
swuadmnu      case name
1977, 1994    range of years to estimate water use
sreptest.rc  water rights input file name
```

Input files for surface water use estimates:

water use files for 1980-1993 (listed below in file swuadmnu.jou);  
 ibrepub: Ibound matrix file describing solution domain (see above);  
 sreptest.rc: summary of surface water rights in the solution domain; written by WRREPUB.

Output files for groundwater use estimates:

swuadmnu.wel: input file to Modflow's Surface package describing annual surface water use for years 1977-1994 based on DWR water rights and water use data for years 1980-1993 and derived models of water use based on precipitation data for the remaining years 1977-1979 and 1994.  
 swuadmnu.sum: annual summary of surface water use estimates.

## File swuadmnu.jou:

Basin area: 2569.60 km<sup>2</sup>, 634962.00 acres  
Select G[round] or S[urface] water rights?[G]: Set use fraction = 0.63 (1980-1993 avg) for years before 1980?[Y]: Specify use fraction for 1994?[n]: Select by grid?[Y]: Enter ibound matrix file name:  
Open ibound matrix file ibrepub.  
125 active cells in grid  
Enter case name (8 char max):  
Enter range of water use years (e.g. 1958,1994) :  
Range: 1977 to 1994  
Water use input file name: c:\sp\repub\wurepYY.prn ,YY=77 to 94  
Enter water rights input file name:  
Case name = swuadmnu  
Water rights input file name = sreptest.rc  
Output: 13, swuadmnu.wel (Modflow input)  
Output: 14, swuadmnu.sum (annual summary)  
Output: 16, swuadmnu.rc (well list)  
program WU\_rep: 447.761 gpm/cfs  
0.3076217E-05 acfgal = acre-ft/gal  
Read water rights input file sreptest.rc  
40 water rights records; sum qnew= 2463.57 acre-ft/yr

| year | Nwrtot | Numrpt | Numdtw | precip | frcrpt | frcuse | frciru | depirr | use                     | report | file |
|------|--------|--------|--------|--------|--------|--------|--------|--------|-------------------------|--------|------|
| 1977 | 31     | 0      | 0      | 0.607  | 0.000  | 0.528  | 0.528  | 0.122  |                         |        |      |
| 1978 | 31     | 0      | 0      | 0.429  | 0.000  | 1.047  | 1.047  | 0.212  |                         |        |      |
| 1979 | 31     | 0      | 0      | 0.406  | 0.000  | 1.144  | 1.144  | 0.228  |                         |        |      |
| 1980 | 31     | 31     | 0      | 0.233  | 0.046  | 2.470  | 2.470  | 0.344  | c:\sp\repub\wurep80.prn |        |      |
| 1981 | 32     | 32     | 0      | 0.564  | 0.237  | 0.921  | 0.921  | 0.136  | c:\sp\repub\wurep81.prn |        |      |
| 1982 | 32     | 32     | 0      | 0.572  | 0.378  | 0.607  | 0.607  | 0.129  | c:\sp\repub\wurep82.prn |        |      |
| 1983 | 32     | 32     | 0      | 0.262  | 0.252  | 2.402  | 2.402  | 0.368  | c:\sp\repub\wurep83.prn |        |      |
| 1984 | 33     | 33     | 0      | 0.289  | 0.370  | 2.136  | 2.136  | 0.412  | c:\sp\repub\wurep84.prn |        |      |
| 1985 | 33     | 33     | 0      | 0.442  | 0.391  | 0.949  | 0.949  | 0.217  | c:\sp\repub\wurep85.prn |        |      |
| 1986 | 33     | 33     | 0      | 0.584  | 0.402  | 0.621  | 0.621  | 0.213  | c:\sp\repub\wurep86.prn |        |      |
| 1987 | 33     | 17     | 1      | 0.430  | 0.452  | 0.923  | 0.923  | 0.155  | c:\sp\repub\wurep87.prn |        |      |
| 1988 | 35     | 17     | 0      | 0.245  | 0.306  | 1.821  | 1.821  | 0.341  | c:\sp\repub\wurep88.prn |        |      |
| 1989 | 37     | 22     | 0      | 0.418  | 0.451  | 1.750  | 1.750  | 0.357  | c:\sp\repub\wurep89.prn |        |      |
| 1990 | 39     | 26     | 0      | 0.426  | 0.433  | 1.359  | 1.359  | 0.330  | c:\sp\repub\wurep90.prn |        |      |
| 1991 | 39     | 28     | 0      | 0.290  | 0.533  | 1.168  | 1.168  | 0.308  | c:\sp\repub\wurep91.prn |        |      |
| 1992 | 40     | 31     | 0      | 0.514  | 0.425  | 0.290  | 0.290  | 0.084  | c:\sp\repub\wurep92.prn |        |      |
| 1993 | 40     | 32     | 0      | 0.850  | 0.059  | 0.212  | 0.212  | 0.032  | c:\sp\repub\wurep93.prn |        |      |
| 1994 | 40     | 0      | 0      | 0.390  | 0.000  | 1.216  | 1.216  | 0.240  | c:\sp\repub\wurep93.prn |        |      |

No. report records= 18029

## Linking programs

```
c:\sp\repubhyd\dtwdata\surfelev.for spp Feb 28 95 read water well levels
*
c:\sp\for\leo211\
* file tstgrd.for spp Mar 2 95 legal to (lat;long) (deg) conversion
* (and vice versa)
to link: Lnkgrd
file Lnkgrd.bat:
386link tstgrd,lgl2geo,splcnv,leocvt,trgrid3 -symbol -stub runb -exe tstgrd.exe

Program TSTGRD
*
c:\sp\for\leo211\
* file wurepub.for dec 10 96 sam perkins kgs geohydrology
program WUREPUB
c
c to link: LWUREPUB

c file Lwurepub.bat:
386link wurepub,wyear,lgl2geo,splcnv,leocvt,indexx,trgrid3

c to run: wurepub <gwutest.rsp >gwutest.jou
c
c example keyboard input (redirected from file gwutest.rsp):
c -----
c g optsrc: source=ground water (G) or surface water (S).
```

```

c y      op7780: set use fraction to 0.63 ('80-'93 avg) for yrs before 1980
c n      opt94:  set use fraction for 1994? (y/n)
c y      optgrd: select by grid? (y/n; if y, read ibound file next)
c ibrepub.      ibound array name
c gwutest       case name
c 1977, 1994    range of years to estimate water use
c greptest.rc   water rights file (from wrrepub)
c -----
c data files opened for the case specified by the response file shown above:
c 11 in  c:\sp\repub\wurepNN.prn, for NN=80-93:
c      water use reports for years 1980-1993;
c 13 out gwutest.WEL well file to be read by MODFLOW;
c 14 out gwutest.SUM use summary file;
c 15 in  ibrepub.      ibound array file defining active nodes, boundary conditions;
c 16 out gwutest.DTW DTW measurement time series for each reporting well;
c 17 in  greptest.rc   water rights input file, written by program wrrepub.
c -----

```

```

c:\sp\for\leo211:
* wrrepub.for
  program WRREPUB
  .
c to link: Lwrrepub
c file Lwrrepub.bat:
386link wrrepub,wryear,lg12geo,splcnv,leocvt,indexx,trgrid3

```

```

c to run: wrrepub <greptest.rsp >greptest.jou

```

```

c example keyboard input (redirected from file greptest.rsp):

```

```

c -----
c g      surface or groundwater
c greptest case name
c c:\sp\repub\klrpd.prn water rights input file name
c rpann.str stream input file name
c ibrepub. ibound matrix file name
c y      select active nodes only?
c repsurf.elv surface elevation matrix file name
c -----

```

```

c data files opened in wrrepub:
c 15 in  dist_geo.prn shortest distance from each of 349 wells to Republican River.
c 15 in  elevwr.prn ground surface elevation at each of 349 wells.
c 11 in  c:\sp\repub\klrpd.prn: description of both surface and ground water
c      rights within the Lower Republican River basin.
c 14 out CASENAME.sum use summary file;
c 16 out CASENAME.rc water rights summary file, to be read by program wurepub.
c 21 out CASENAME.grd summary of each water right in order read from input file
c 15 in  ibrepub.      ibound array file defining active nodes and boundary
c      conditions; array ibound is also read by Modflow's Basic
c      package.
c 15 in  rpann.str     stream input file representing Republican R.; also read by
c      Modflow's Stream package, and produced by program STRMDATA.
c 15 in  repsurf.elv  array srfelev: ground surface elevations at active nodes
c      of the aquifer grid. The grid cells are superimposed on
c      the township sections, and the elevations correspond to
c      the center of the sections, taken from USGS 1:24000 maps;
c      this array is also read by Modflow's Evaporation package.
c -----

```

```

c field def. of water rights input record (see format 620 and equivalence, below)

```

| field char | fmt,var | numeric | fmt,var               | field description          |
|------------|---------|---------|-----------------------|----------------------------|
| c 1:9      | a9      | fileid  |                       |                            |
| c 10:17    | a8      | legloc  | (see breakdown below) |                            |
| c 18:19    | a2      | chdwr   |                       |                            |
| c 20:27    | a8      | subsec  |                       |                            |
| c 30:32    | a3      | chbas   | i3                    | ibasin basin               |
| c 44:46    | a3      | chcty   | i3                    | icnty county               |
| c 47:48    | a2      | qrec    |                       | Qrecord Qrecord            |
| c 47       |         |         | i1                    | ngrec Qrecord              |
| c 54       | a1      | pd      | i1                    | numpd no. pts of diversion |
| c 59:63    |         |         | f5.0                  | taeres                     |
| c 73:82    |         |         | f10.0                 | qnet                       |
| c 83:92    |         |         | f10.0                 | qnu qnew                   |
| c 107      | a1      | src     |                       |                            |
| c 108      | a1      | chuse   |                       |                            |
| c 125:129  | a4      | chrata  | f4.0                  | qrata pumping rate (gpm)   |
| c 151:154  |         |         | f4.0                  | atw depth to water         |

```

c 155:158          f4.0   dtb   depth to bottom of well
c-----
c breakdown of legal location legloc:
c  1:2   i2      tship
c    3   a1      ns
c  4:5   i2      range
c    6   a1      ew
c  7:8   i2      sect
c-----

```

## 10. POSTPROCESSING PROGRAMS FOR MODFLOW

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

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 1/12/56 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]heads
DRAWn [D]rawdowns
Enter choice: [H]: H
Input 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

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 nstream= 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 |

## 11. SWAT INPUT DATA FORMAT

This section was written as 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.

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.

## 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, p. 135) includes options relevant to our revision of SWAT and its linkage with MODFLOW. The general basin file (~.bsn, p. 145) was changed to correct a problem in v. 2's initialization of soil moisture profiles. Formats for the soils data files (~.sol, p. 155) and weather data files (rf and tmp, p. 141) 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 ffc 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 ffc, 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. p. 162). However, in

the original source code for SWAT (v. 94.2), ffc was not passed from Read to Readinpt, and Readinpt did not handle ffc 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 ( $r(8)=\text{sum of smy, above}$ ), to be overridden by fraction ffc 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 ffc in Read(), but ffc 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  $\text{sand} = 100 - (\text{silt} + \text{clay})$ .

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, p. 155.

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.

5. subr swu19: accounting for plant water use in soil profile is described in the SWAT manual by eqn (222), in which soil water use is reduced if soil moisture in a layer is less than 1/4 times field capacity. SWAT subr swu19 substitutes porosity for field capacity. This is interpreted as a coding error, and has been changed to be consistent with eqn (222) in a rewritten version of the subroutine on file swu19sp.for.

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.

Equation (200), for maximum damping depth (mm) soil for calculating soil temperature as a function of depth, has a term of 100; the corresponding term in the code (subr solt22) has a term of 1000.

## 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 (p. 135). 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.

### File names: read file named "file.cio" on (2) from Open, Main, and Open2

Read from Open (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)
```

Read from Main (swatmain.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)
```

Read from 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, pondat, 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,mgt-dat); (18,mcodat); (19,gwdat); (20,wgendat)  
end do
```

Example: base case component carr-irc.cio (Carr soil, irrigated corn)

This file is renamed as "file.cio" for execution of SWAT.

```

Republican R. Basin, KS carr-irc irrig95.mco (irr=3,swtrig=0.8,wsf=.95) (1)
Weather: Concordia carr-irc.cod (w/et; annual limit on irrig, ->carr-irc.bal),ponds
carr-irc.std      out10.sbs      out10.rch      out10.rsv      out10.lqo      out10.pso      (2)
  out10.eve      crop.dat      till.dat      pest.dat      carr-irc.cod      in10.bsn      (3)
  in10.lwq      in10.fig      in10.sta      in10.bsb      (4)
  9      4      (5)
bell7794.pcp      clay7794.pcp      cliff7794.pcp      conc7794.pcp      fact7794.pcp      hadd7794.pcp      (6)
milt7794.pcp      scan7794.pcp      wash7794.pcp
bell7794.tmp      clay7794.tmp      conc7794.tmp      wash7794.tmp      (7)

in10.res (8)
1 0 0 0 0 slp101.sub in101.rte in1.pnd in101.chm carr.sol (9)
  corn.mgt irrig95.mco h2.gw in10.wgn 1 1 (10)
2 0 0 0 0 slp102.sub in102.rte in2.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 4 3
3 0 0 0 0 slp103.sub in103.rte in3.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 7 3
4 0 0 0 0 slp104.sub in104.rte in4.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 3 3
5 0 0 0 0 slp105.sub in105.rte in5.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 3 4
6 0 0 0 0 slp106.sub in106.rte in6.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 3 4
7 0 0 0 0 slp107.sub in107.rte in7.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 3 4
8 0 0 0 0 slp108.sub in108.rte in8.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 2 2
9 0 0 0 0 slp109.sub in109.rte in9.pnd in101.chm carr.sol
  corn.mgt irrig95.mco h2.gw in10.wgn 2 2

```

!



3. Swat-Modflow coordination options

```
read (10, '(2014)') i1og, iopmod, iopswt, ibgndv, ienddv, iopsol,      (3)
1      iopwfl, ithpcp, ithtmp, ioplim, iopqtl, iopcmp,
1      iopyrf, iopyrl, iopet, iopwea, ioprev, itrace, jkkopt
```

- 1 **i1og**: an original SWAT option; see SWAT manual, 3.2, p. 8.
2. **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.
3. **iopswt**: option to either (0) run Swat and Modflow independently or (1) call MODFLOW from SWAT at the end of each aquifer time step. If iopswt=1, Swat calls MODFLOW at the end of each time step specified by iopmod (above).
4. **ibgndv**: beginning day of year to print daily results for rain days.
5. **ienddv**: ending day of year for printing daily results for rain days.
- 6 **iopsol**: option to show initial and final states of soil on hydrologic balance file after average 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 file.cio (above) 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 Thiessen weights to calculate spatial averages of daily precipitation reported at weather stations. Thiessen polygon weights are read from file namths specified on record 4.
- 9 **ithtmp**: option (y=1,n=0) to use Thiessen weights to calculate spatial averages of daily temperature at weather stations. Thiessen 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/day, below) 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 (**iopswt**=0) and **ioplim**>0, annual irrigation limits are read from record 9 (below). If SWAT calls MODFLOW (**iopswt**>0) and **ioplim**>0, SWAT calls subr PASSFLX at the beginning of each year (stress period) to obtain annual maximum pumping flux rates (mm/yr) for each subbasin, based on Modflow's ~.WEL input file and summarized by MODSWB subroutine SWB1RP.  
Note: MODFLOW also has the option (applied in SWB1FM) to either assign pumping rates specified by the ~.WEL input file (**irropt**=0), or scale 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 **qtl** with infiltration as input to soil profile; subr **purk18**.
- 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, p. **Error! Bookmark not defined.**) 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.

Penman calculations are based on wind speed at 2 m above land surface (ALS), which is estimated as follows, using eq. 4.4.9 in Handbook of Hydrology, D.R. Maidment, ed., 1993, McGraw-Hill. Wind speed measured at 10 m (see daily weather input data, below) is reduced by a factor f given by  $f = 34.9648/(f_h \cdot f_w)$ , where  $f_h = \ln[(z_h - 0.08)/0.001476]$ ,  $f_w = \ln[(z_w - 0.08)/0.01476]$ ; and  $z_h$  and  $z_w$  are heights (ALS) of humidity and wind speed measurements, respectively. For  $z_h = 2$  m and  $z_w = 10$  m, wind speed measured at 10 m is reduced by a factor  $f = 0.749$ .

- 16 iopwea: 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.
- 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 (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  $c = 1 - \text{pond fraction}(8)$ , these definitions are as follows.

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

$$\begin{aligned} \text{Recharge (25)} &= \text{xmloss}(14) + \text{perc}(16) + \text{pond seepage}(20), & \text{(default)} \\ &= \text{xmloss}(14) + c \cdot \text{latq}(15) + \text{perc}(16) + \text{pond seepage}(20), & \text{jkkopt} > 0 \end{aligned}$$

#### 4. File names: balance, weights, radiation

read (10, '(3a13)') nambal, namths, namrad

(4

- 1. nambal: output file name for hydrologic balance to be passed to Modflow

2. **namths**: input file name for Thiessen weight functions for averaging rainfall or temperature based on options **ithpcp** and **ithtmp**, above. Format for this input file is described below.
3. **namrad**: input file name for measured daily radiation (ly/d), relative humidity (pct) and wind speed (m/s) 2 m above land surface (ALS).

Weather input data formats, up to 30 chars each (may be 'FREE'):

```
read (10,'(a)') fnttmp      ! temperature data format      (5)
read (10,'(a)') fntpcp     ! rainfall data format      (6)
read (10,'(a)') fmtrad     ! radiation, rel. humidity & wind speed (7)
```

Data in free format, defined below:

```
read (10,*) wsfdmx, swminf, pmpeff, phideg, rlamdg      (8)
```

**wsfdmx**: Daily irrigation pumping limit (mm).

**swminf**: Available water capacity threshold, below which irrigation is applied during the growing season, but only if irrigation option **irr(j) = 3** as read from the **~.mco** file (subr **readinpt**). If **irr(j) = 1**, then the plant stress factor controls irrigation according to Swat's original version, but subject to added daily and annual constraints.

**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, nyrB)      (9)
```

## Data base input files

### Crop data base: read file **crop.dat** (15) from **Readinpt**

Excerpt from file **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  | 5.00   | .50    |
|   | 4.75  | 2.00  | 0.40  | 0.20  | 47.60  | 1.0000 |       |        |        |        |

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), cpmn(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), cpmn(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)

```

## Tillage data base: read file till.dat (16) from Readingpt

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

```

## Pesticide data base: read file pest.dat (17) from Readingpt

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   | 0.75 | 500000.0 |
| 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

```

## Daily weather input data

Input file names for daily rainfall and temperature measurements are given on the input control file.cio (p. 132), 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 (p. 134); 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 (options input file ~.cod,above) allows all rainfall data to be contained on 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 standard SWAT, daily radiation, relative humidity, wind speed and [CO2] are only simulated (subr CLGEN4); however, see option iopwea on the ~.cod file (above), which allows the first three of these to 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` (p. 135) specifies (`iopwfl>0`) that precipitation and temperature data are to be consolidated into one file each for `pcp` and `tmp`; and (`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)
```

Source code (subr `Clicon`, file `cliconsp.for`) to read precipitation, temperature, radiation, relative humidity and wind speed data

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. 129).

### Daily temperature (deg C): read file `~.tmp (27+k)` for station `k` from subr `Clicon`

```
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,fmtmp) 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,fmtmp) (txmeas(kfld),tnmeas(kfld),
1      kfld=1,ntgage)
  end if
end if
```

Example 1: Excerpt from Concordia NWS temperature file `conc7794.tmp`: first ten days of 1977.

Format: Free (Julian day, year, Tmax (C), Tmin (C))

```
1 1977 -8.3 -16.7
2 1977 -5.0 -10.0
3 1977 -2.8 -6.1
4 1977 -3.9 -8.9
5 1977 -6.7 -14.4
6 1977 -3.9 -14.4
7 1977 -0.6 -13.9
8 1977 -3.3 -18.3
9 1977 -13.3 -22.2
10 1977 -13.3 -22.2
```

Example 2: Excerpt from temperature input file all.tmp for Rattlesnake Basin study.  
 In this case, temperature data for all six stations are read from the same file.

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

```

**Daily precipitation (mm): read file ~.pcp (9+k) for station k from  
 subr Clicon**

```

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 1: Excerpt (first ten days) from Concordia NWS precipitation conc7794.pcp:

Format: Free

```

1 1977 0.5
2 1977 2.3
3 1977 0.0
4 1977 4.8
5 1977 0.3
6 1977 1.5
7 1977 0.0
8 1977 0.3
9 1977 0.0
10 1977 0.0

```

Example 2: Excerpt from precipitation input data rs6093.pcp with format (i4,8f6.1)  
 (Format is specified by ffmtpcp 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   |

## Daily radiation (ly/d), relative humidity (%) and wind speed (m/s)

This is read depending on added option `iopwea`; see option codes file, p. 135.  
 Previously, SWAT only generated these data as described in the SWAT manual.

Whether these data are read or generated, wind speed measurements are assumed to be taken 10 m above land surface (ALS). The measurement at 10 m is used in SWAT as `u10(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 as described above; see Option Code `iopet`.

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,fmttrad) 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

```

Excerpt from radiation, rel. humidity and wind speed file sand6092.rad (Rattlesnake):

|   |    |      |    |      |     |      |      |       |      |
|---|----|------|----|------|-----|------|------|-------|------|
| 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   |

## Basin input files

### General basin input data file ~.bsn (11): read from subr Read

See also note on input variable ffc b data bug and its fix (p. 129).

#### Example: file snake.bsn

```

Watershed: Republican River Basin File ! in10.bsn      1
          2569.6  1.00   1.00  240.0   1.00   0   0   0      2
da          p2(1)  bif    brt    ffc b  (npno(k),k=1,10)
f10.3      f6.3   f8.3   f8.3   f8.3   1014

```

#### 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), bif, brt, ffc b, (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

```

## Lake water quality input data file ~.lwq (8): read from 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)
```

## Watershed configuration input data file ~.fig (9): read from Main

Example input file in10.fig:

```

subbasin 1 1 1 1
subbasin 1 2 2 2
subbasin 1 3 3 3
subbasin 1 4 4 4
subbasin 1 5 5 5
subbasin 1 6 6 6
subbasin 1 7 7 7
subbasin 1 8 8 8
subbasin 1 9 9 9
route 2 10 4 1
add 5 11 4 10
route 2 12 5 11
add 5 13 5 12
route 2 14 6 13
add 5 15 6 14
route 2 16 7 15
add 5 17 7 16
route 2 18 9 17
route 2 19 3 2
add 5 20 3 19
route 2 21 8 20
add 5 22 8 21
route 2 23 9 18
add 5 24 22 23
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(ihours(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

```

**Measured streamflow and sediment yield at gaged station: read file ~.sta (9) from Main**

```
open (9,file=stain)
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)
```

## 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 slp101.sub in101.rte in1.pnd in101.chm carr.sol (9
corn.mgt irrig95.mco h2.gw in10.wgn 1 1 (10
```

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

### General subbasin input data file ~.sub (10)

Example: file slp101.sub

```
Subbasin Data File ! 1/9 sub(10):slp101.sub 1
0.22015 73.000 0.125 0.000 52.710 0.0017 3.050 33.020 0.050 2
0.100 440. 0.000 500. 0.500 405.250 .0022 0.0 3
0 0 0 0 0 0 rfinc(i,mo),mo=1,6 (6f8.3) 4
0 0 0 0 0 0 " ,mo=7,12 5
0 0 0 0 0 0 radinc(i,mo),mo=1,6 6
0 0 0 0 0 0 " ,mo=7,12 7
0 0 0 0 0 0 huminc(i,mo),mo=1,6 8
0 0 0 0 0 0 " ,mo=7,12 9
0 0 0 0 0 0 co2inc(i,mo),mo=1,6 10
0 0 0 0 0 0 " ,mo=7,12 11
```

```
title 1
flu cn2 co2 sno chl chS chW chK chn (f9.7,8f8.3) 2
ovn elev rt css ecp sL stp rsdin (8f8.3) 3
```

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 1
```

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), 2
* 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), (3
    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) 4
        read (10,10300) (rfinc(i,mo),mo=7,12) 5
        read (10,10300) (radinc(i,mo),mo=1,6) 6
        read (10,10300) (radinc(i,mo),mo=7,12) 7
        read (10,10300) (huminc(i,mo),mo=1,6) 8
        read (10,10300) (huminc(i,mo),mo=7,12) 9
        read (10,10300) (co2inc(i,mo),mo=1,6) 10
        read (10,10300) (co2inc(i,mo),mo=7,12) 11

```

## Subbasin routing input data file ~.rte (11)

Example: file rat01.rte

```
Subbasin Routing Data ! 1/9 rte(11): in101.rte
 6.100  0.240 0.00073 88.866  0.050  33.02  0.280  1.000
   chw   chd   chss   chl   chnn   chk   chxk   chc
```

```
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
```

## Pond/reservoir input data file ~.pnd (12)

Example:

```
Pond Data File in1.pnd, pnd(12)
 0.0343  61.08 10.000 62.000 31.488 20.000  0.  .001  .001  1.  1
 1 12 10
 0 0 0 0 0 0 0 0 0 0 0 0 4
```

data fields for each record (ref. Swat manual section 3):

```
title record
  fp sax vmx sae vme v sepp cs cfp hc (10f8.3)
iflod1, iflod2, ndtarg (3i4)
 fw saxw vmxw saew vmew vw sepw csw cfw hcw
formats:
1 (a)
2 (10f8.3)
3 (3i4)
4 (10f8.3)
```

Note: the 4th record, wetlands data, has been added for the Swat94.2 version.

```
sax units in ha
vmx in mm
sae=sax since there is no reservoir in subbasin
vmx=vme since there is no reservoir in subbasin
```

```
dC*****READ POND/RESERVOIR DATA
C      FP = FRACTION OF SUBBASIN THAT FLOWS INTO PONDS
C      SAX = TOTAL SURFACE AREA OF ALL PONDS IN SUBBASIN TO
C      PRINCIPAL SPILLWAY(HA)
C      VMX = RUNOFF VOLUME FROM POND CATCHMENT AREA REQUIRED TO
C      FILL EMPTY PONDS AT PRINCIPAL 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 (12,9901) titldum
      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      VMKW = RUNOFF VOLUME FROM WETLANDS CATCHMENT AREA REQUIRED TO
C      FILL EMPTY PONDS AT PRINCIPAL SPILLWAY(MM).
C      SAEW = TOTAL SURFACE AREA OF ALL WETLANDS IN SUBBASIN AT
C      EMERGENCY SPILLWAY(HA)
C      VMKW = 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), vmkw(i), saew(i), vme(i),
*      vw(i), sepw(i), csw(i), cfw(i), hcw(i)
10300  format(10f8.3)

```

## Top ten pesticides input data file ~.chm (13)

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

Example: file chemical.chm

```

dummy chemical data file
.000 .000 .000 (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), exp(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

```

# Soil input data file ~.sol (14) (format from '93 version of SWAT is used)

## Example: carr.sol

```

Subbasin Soil Data File! 1/17 (add top layer of 10mm)
 4  0.240  41.0  CARR                                no. layers, K factor, %silt, soil name      1
 10.    304.8 1270.0 1524.0                          depth(mm)                                    2
 1.63   1.63  1.63   1.4                            bulk density(g/cc)                           3
 0.17   0.17  0.14   0.08                          available water content (4th layer?)          4
101.6   101.6 101.6  330.2                          sat. conductivity (mm/hr)                   5
 10.    10.0  10.0   5.0                            clay content(%)                              6
0.222   0.222 0.222  0.222                          organic carbon content(%)                   7
 10.    10.0  5.0    5.0                            initial NO3 (g/t)                            8
 0.     0.0   0.0    0.0                            particle size distribution                    9
1524.                                       max. rooting depth(mm)                      10

```

Note: sand content(%) is not read but calculated as sand = 100 - clay - silt

```

(*) detached sediment particle size distribution as fractions
for the following 5 classes:
1 0.20 mm sand
2 0.01 mm silt
3 0.002 mm clay
4 0.03 mm small aggregates
5 0.50 mm large aggregates

```

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(1,i)-xx)
    if (cbn(l,i).eq.0.) cbn(l,i) = cbn(l-1,i) * exp(-.001*dg)
    xx = z(1,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
  end if
160 continue

```

### Example 2: soil data file Houston.s93

#### 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   |
|------------------------------------------------------------------------|---|---|--------|---------|---|-----|---|-----|
| 1234567890123456789012345678901234567890123456789012345678901234567890 |   |   |        |         |   |     |   |     |
| 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    |   |     |   |     |

## Management input data file ~.mgt (17) (crop rotation schedules)

### Example 1: file 3-wsf.mgt (no irrigation)

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

```

Rattlesnake Creek Watershed - Crop Data for Wheat-Fallow: 2-wf.mgx

```

1 1 0
6 25 5 1650.00 4 60.00 .00 0 0 0
9 20 1 1650.00 4 60.00 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   pant = 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, pant, 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.

```

## Management codes input data file ~.mco (18).(automatic irrigation option)

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

Example: file90.mco

```

Management Code File ! 1/9 mco(18): irrig95.mco: irr=3, swtrig=0.8, wsf=0.95
3 0.95 0.8 0 0 0 0 0 0 0 0 wures(mo,i) 1-6 1
0.0 0.0 0.0 0 0 0 0 0 0 0 wures(mo,i) 7-12 2
0 0 0 0 0 0 0 0 0 0 wurch(mo,i) 1-6 3
0 0 0 0 0 0 0 0 0 0 wurch(mo,i) 7-12 4
0 0 0 0 0 0 0 0 0 0 wushal(mo,i) 1-6 5
0 0 0 0 0 0 0 0 0 0 wushal(mo,i) 7-12 6
0 0 0 0 0 0 0 0 0 0 wushal(mo,i) 7-12 7
0 0 0 0 0 0 0 0 0 0 wushal(mo,i) 7-12 8
0 0 0 0 0 0 0 0 0 0 wushal(mo,i) 7-12 9

```

```

0      0      0      0      0      0      0 wudeep(mo,i) 1-6 10
0      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 option
c   = 3 (added): irrigate during growing season if available soil
      water as fraction of available field capacity < swmin,
      specified by input to the Option Codes input file (~.cod).
c   = 1 irrigate during growing season if water stress factor < wsf;
c   =-1 read schedule (irrigation date and amount)
c   = 0 no irrigation
c   = 3: automatic by soil water content (see below)
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)

```

Added option to irrigate on the basis of soil water content during the crop growing season (irr(i)=3):

irr; a previously existing irrigation control option, read from the management code file (~.mco) corresponding to subbasin j. Options, originally 0, -1, or 1, are now as follows; see also p. 158.

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 swj falls below a threshold, swtrig, which is specified in terms of available capacity by swminf (read from the ~.cod file).

subr crpmd for subbasin j:

After soil and plant evaporative demand have been met (or decreased to correspond to available supply), irrigation is handled. The following options, coordinated in subr CRPMD, apply:

- \* ioplim = option (y=1,n=0) to limit irrigation by annual appropriation (~.cod);
- \* pmpeff = groundwater pumping efficiency (per unit) (~.cod);
- \* pmpmax = annual groundwater appropriation (flux; mm) (~.cod);
- \* wsfdmx = daily max. added water (mm/operation) for automatic irrigation (~.cod);
- \* swminf = min. soil water as fraction of available water capacity below which irrigation will take place during growing season (~.cod);
- \* swtrig = soil water trigger: minimum soil moisture (total in profile, mm) below which irrigation will be applied if option irr(j)=3 (~.mco file; see above); swtrig is calculated as follows:

```

ccc if (igro(j).eq.1.and.g(j).gt.0.1 .and.g(j).lt.1.) then
ccc   swtrig = FLOAT(igro(j))*sumfc(j)*swminf
ccc else
ccc   swtrig = 0.
ccc end if

```

## Groundwater input data file ~.gw (19) (read but not used for SWATMOD)

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 in10.gw

```

Groundwater Data File in10.gw! 1/9
      2.0      0.1      0.4      .10      100.0      10.00      0.30      100.0
      0.0

```

record 1: (8f10.4)

gwht gwq abf syld delay revapc rchrgc revapmn

record 2: (f10.4)

deepst

rchrgc: deep aquifer percolation coef [0,1]  
revapmn: revap storage (mm); shallow aquifer storage must exceed revapmn before groundwater flow can begin.

```

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      RCHRG = 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
C      read (19,'(a)') title
C      read (19,5301) gwht(i), gwq(i), abf(i), syld(i), delay(i),
*      revapc(i), rchrg(i), revapmn(i)
C      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)

```

# Weather generation input data file ~.wgn (20) (monthly weather statistics)

Example: file rat.wgn

```

Weather Generation Data from Station Concordia WSO AP KS: file in10.wgn
68.33 132.08 22.0 39.55 tp5, tp6, tp24, ylt 1
1.3 5.2 11.6 18.3 23.4 29.2 32.8 31.4 26.1 20.3 11.1 4.1 obmx=Tmx, c 2
-9.8 -6.9 -1.4 5.2 10.6 16.2 19.6 18.4 13.1 6.7 -.7 -6.7 obmn=Tmn, c, c 3
.55 .43 .30 .19 .14 .10 .09 .09 .14 .18 .26 .41 cvt(1) 4
210. 279. 370. 455. 528. 578. 579. 530. 430. 320. 234. 181. obsl=Ra, ly 5
5.08 5.33 9.65 32.26 31.75 29.72 31.75 29.46 46.48 22.10 15.75 7.11 wi=R5mx 6
.140 .120 .170 .250 .250 .240 .240 .230 .200 .140 .130 .120 prd 7
.360 .320 .460 .450 .490 .440 .430 .410 .450 .420 .400 .320 prw 8
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 wlv 9
2.54 4.06 6.35 6.10 9.65 12.70 11.18 10.16 9.14 8.64 6.10 4.06 rmn 10
3.30 5.59 8.89 7.62 13.97 17.27 16.51 14.73 11.94 13.72 8.89 5.08 rst 11
1.26 1.59 1.60 .75 2.69 2.16 2.02 1.89 1.09 3.46 1.64 1.09 rsk 12
-6.34 -3.88 -2.01 4.20 11.20 15.77 17.58 16.47 12.12 6.56 -.20 -4.31 dewpt:Rsnake 13
5.57 5.65 5.47 6.27 5.65 5.91 5.11 4.94 5.32 5.47 5.46 5.46 uavm: Rsnake 14
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)) (wv1(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)
```

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