SWAT AND MODFLOW INTEGRATION: A PROGRESS REPORT

by

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January 31, 2000

Submitted to

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USDA, Agricultural Research Service

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Introduction

We present a report on our progress to update a linkage between SWAT and MODFLOW, originally developed for application to basins in Kansas draining the Lower Republican River (Sophocleous and Perkins [S&P], 1997; Perkins and Sophocleous [P&S], 1999) and Rattlesnake Creek (Sophocleous et al., 1999). The linkage for these models is documented in P&S (1997, 1998). The updated linkage currently being developed also incorporates code improvements made for a different linkage, that between the program POTYLDR (Koelliker, 1994) and MODFLOW for a model of Wet Walnut Creek basin in Kansas (Sophocleous et al., 1998; Koelliker et al., 1999; Ramireddygari et al., 2000). In each of these, watershed hydrology is simulated using lumped models of subbasins; spatial heterogeneity within each subbasin is represented by taking spatially weighted averages over hydrologic response units (HRUs), which are defined by combinations of the factors of spatial heterogeneity, including soil type, land use, and subsurface features. A factor for subsurface features was introduced by modifying SWAT to represent variations on the conceptual model of a soil profile entirely underlain by an aquifer with a saturated zone sufficiently deep to have negligible interaction with the root zone. These variations include (a) a soil profile that is directly underlain by bedrock so that no water percolates out of the root zone, and (b) a soil profile underlain by ground water sufficiently shallow, to interact with the root zone through evapotranspiration. Appendix A reviews the conceptual models for the linkage based on the methodology presented in Perkins (1999).

Section 1 of this report summarizes the status of tasks identified in the project proposal (S&P, 1999), and updates the task descriptions in light of recent developments. Fig. 1.1 shows the work schedule as originally proposed; Fig. 2.1 shows a revised schedule that more accurately reflects task descriptions and time frames at the time of the progress report.

Section 2 presents an overview of two preliminary versions of the SWAT-MODFLOW linkage under development. The first of these preliminary versions combines modified versions of SWAT 94.2 and MODFLOW_88. It is documented in P&S (1999b-c), and has been demonstrated for the Lower Republican River basin model (Perkins, 1999). One of its significant features is to provide a two-way coupling of the soil water balance simulated by SWAT and ground water simulated by MODFLOW. This coupling is obtained with separate execution of the two programs through the use of time-varying HRU weights and successive approximation, as discussed in Sections 2.D and A.5.

The second preliminary version is a modification of the first, replacing SWAT v.94.2 with v.99.2. In this version, the code changes made to SWAT to enable the linkage with MODFLOW have been reduced significantly. In addition, the areal components of HRUs based on soil, land use, and subsurface features can be specified by SWAT's soil (*.sol), management (*.mgt), and ground water (*.gw) input files. This may allow applying SWAT's capabilities for simulating and averaging HRUs. In the final version of the SWAT-MODFLOW linkage, MODFLOW v.88 is to be replaced by v.96.

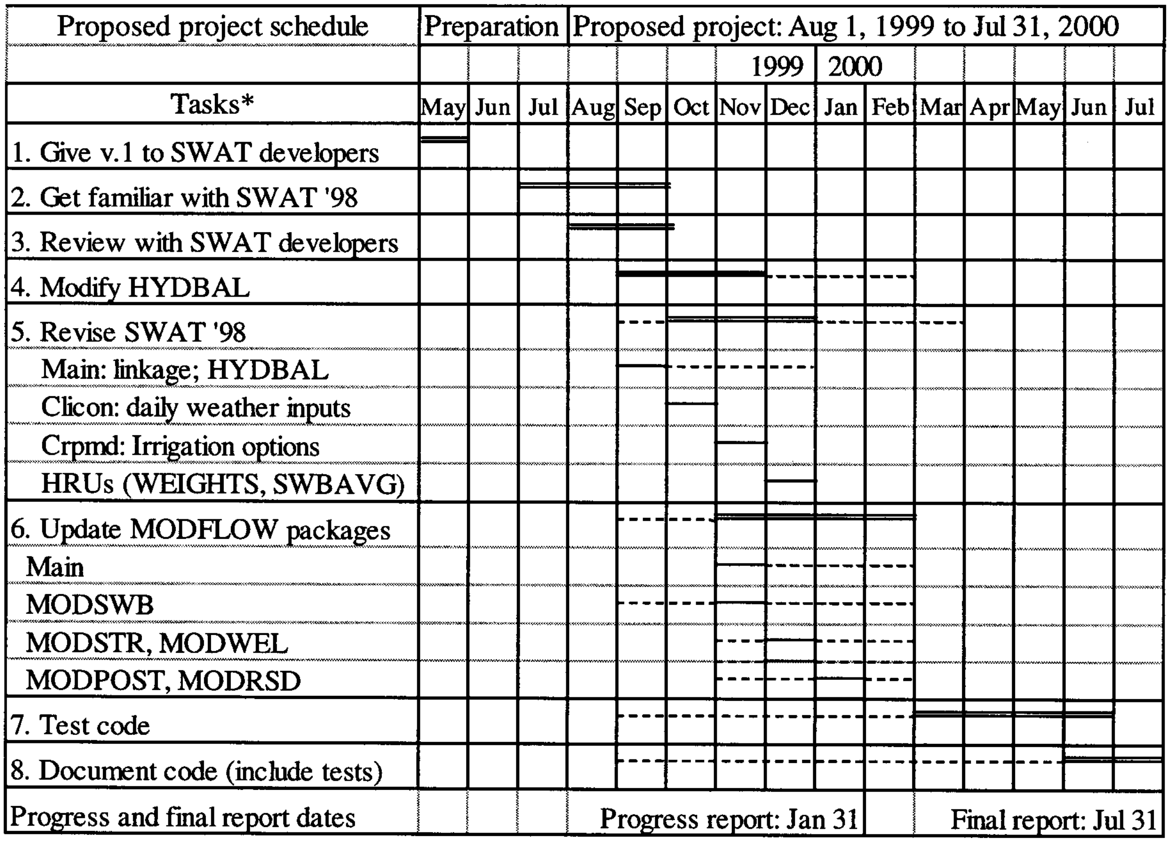

Fig. 1.1. Project schedule and deliverables as proposed in February 1999.

1. Review of tasks for SWAT-MODFLOW linkage

The objectives of tasks identified in Fig. 1.1 have been revised in light of developments since their proposal. First, the updated linkage is incorporating SWAT v.99.2, which was released in 1999. Second, a two-way coupling of the soil profile and ground water was developed and demonstrated based on separate execution of SWAT and MODFLOW for HRU scheme 3, as discussed in Section 2 and in Appendix A.5. As a result, the linked execution of SWAT and MODFLOW mentioned in Task 5, in which SWAT calls MODFLOW as a subroutine, is not being pursued.

Tasks 4-6 have been pursued somewhat simultaneously. Two preliminary versions of the SWAT-MODFLOW linkage have been developed; these are summarized in Sections 2.1 and 2.2. The first of these is an updated version of the original linkage based on SWAT 94.2 and MODFLOW.88 (S&P, 1997; P&S, 1997). This linkage is documented in P&S (1999b-c) and was used to demonstrate HRU schemes 1-3 (see Appendix A) for the Lower Republican River basin in Perkins (1999). Improvements previously made for the Walnut Creek basin model (S&P, 1998) were incorporated into the SWAT-MODFLOW linkage (Tasks 4 and 6a). The updated project schedule is shown in Fig. 2.1.

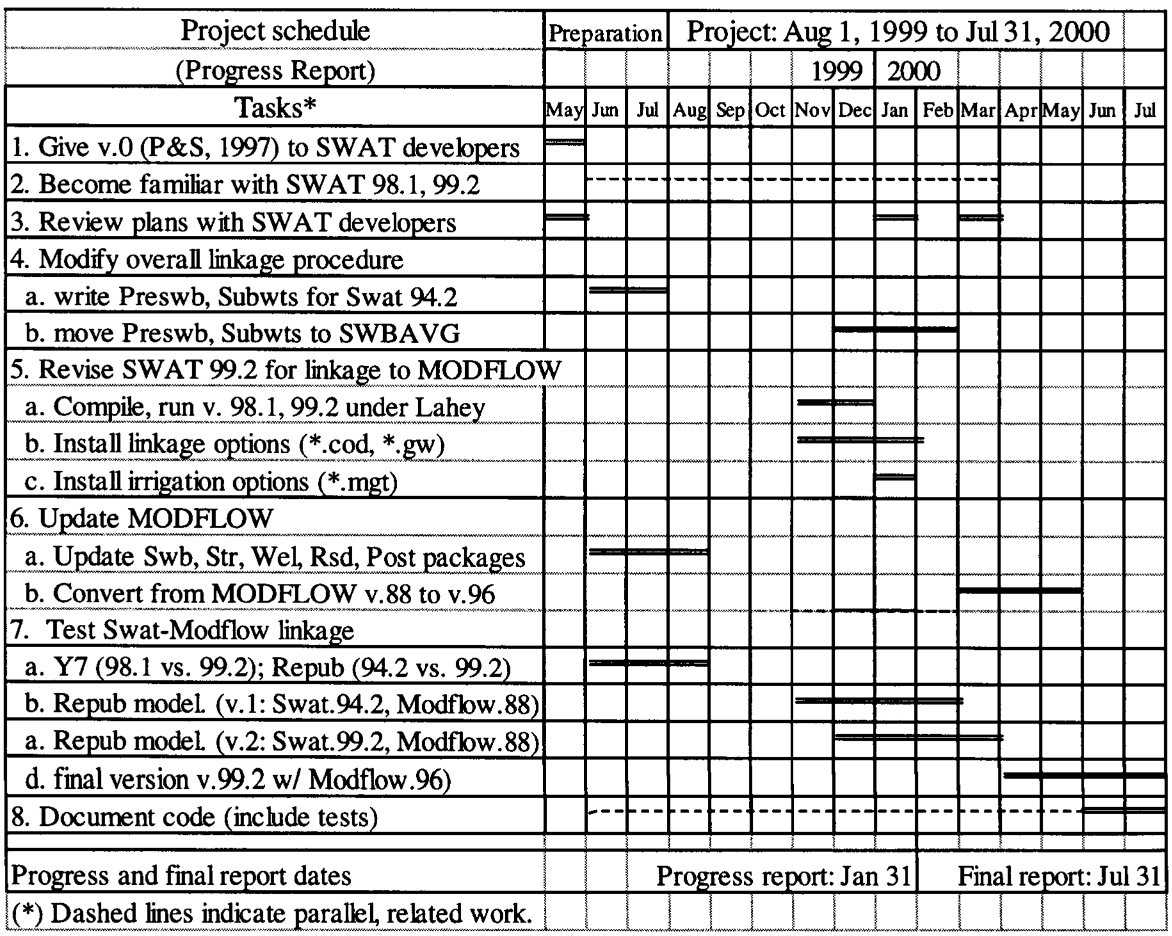

Fig. 2.1. Revised project schedule and deliverables at the time of the progress report.

HRU schemes 1-3 are composed of from 10 to 15 individual HRUs, each of which is based on subbasin areal fractions for soil types, land use, and subsurface features. For this version of the linkage, these three factors can be represented by soil (*.sol), management (*.mgt), and ground water (*.gw) input files for each subbasin. The *.gw input file format was modified to allow specifying a subsurface feature option, **ipurk**(*j*) for subbasin/HRU *j*, for alternatives to the conceptual model of a soil profile underlain by an aquifer with a saturated zone sufficiently deep that it does not interact with the root zone. Alternative conceptual models include (a) a soil profiles directly overlaying bedrock, thereby preventing percolation out of the root zone, and (b) a soil profile underlain by an aquifer with a saturated zone sufficiently shallow to interact with the root zone. The second of these alternatives depends on a two-way coupling between SWAT and MODFLOW. This is implented with separate execution of SWAT and MODFLOW based on techniques of successive approximation to obtain a two-way flow of information between the programs, and evaluation of time-varying HRU weights to reflect changes in area of shallow ground water as the hydraulic head in the aquifer responds to hydrologic conditions. This two way coupling is summarized in Section 2.3.

HRU schemes 1-3 have been run with the SWAT 99.2 version of the linkage (Section 2.2) and compared with results of the SWAT 94.2 version (Section 2.1) At this time some significant discrepancies exist between test results given by these two versions, which will hopefully be resolved soon. One option to help investigate these discrepancies is to set up a version of the SWAT-MODFLOW linkage with SWAT 98.1.

Task 1. Provide SWAT developers with the original SWAT-MODFLOW linkage.

Provide SWAT developers with executable files for our versions of SWAT (referred to here as SWAT.94) and MODFLOW; documentation, and input files for the Lower Republican River basin model base case.

This included executable files for our modified versions of SWAT (v. 94) and MODFLOW (v. 88) with documentation and input files to run the Lower Republican River basin model's base case. These were provided during our discussions in April and May 1999.

Task 2. Become familiar with SWAT 98.1

Begin working with SWAT's latest version (SWAT '98). Use SWAT_98.1 to run test cases, including demonstration of new HRU capabilities.

Since the project to link SWAT and MODFLOW was proposed, SWAT_99.2 has been released. Consequently, we have based our work linking SWAT and MODFLOW on SWAT_99.2. However, we have compiled and linked both SWAT versions 98.1 and 99.2 using the Lahey 95 Fortran 90 compiler in order to compare model results between the versions. Successful execution of both versions under the Lahey compiler required a number of minor changes, primarily to avoid references outside array bounds and references to undefined variables. See Task 7 for a summary of testing procedures.

ArcView 3.2, Spatial Analyst, and SWAT-ArcView have also been installed for eventual use during the development of the SWAT-MODFLOW linkage.

Task 3. Review plans to be implemented with SWAT developers

Review with SWAT developers the changes we made to SWAT.94 to determine whether the same changes should be made to SWAT.98. Determine how developments to SWAT since SWAT.94 affect this update; in particular, with respect to SWAT's representation of HRUs. Determine whether any modifications are needed to produce areal weights for averaging HRUs, or for simulating and averaging HRUs on a daily basis.

Changes made to SWAT 94.2 for the original linkage to SWAT were reviewed with Jeff Arnold and R. Srinivasan in our meeting of May 1999. In a teleconference between us in January 2000, the changes we have made to SWAT v.99.2 for the linkage with MODFLOW were reviewed, and the general features of our approach were found acceptable. These include separate executions of SWAT corresponding to individual HRUs, and executing SWBAVG independently from SWAT to take averages over hrus. Section 2 of this report summarizes the overall approach to the linkage, and Appendix A describes the conceptual models implemented by the linkage. Appendix B documents changes made to input files for SWAT 99.2.

Task 4. Modify SWAT to write a spreadsheet form of the balance file.

4a. In the first preliminary version of the linkage based on SWAT 94.2, SWAT's calls to HYDBAL are replaced by calls to PRESWB, which writes the balance file in a spreadsheet format. In addition, the functionality of the previously separate program, WEIGHTS, is provided by subroutine SUBWTS, which SWAT calls to evaluate HRU weights. The modified Control Codes (*.cod) input file is read both by SWAT, to specify the HRUs to be simulated and to allow calculating their weights, and by SWBAVG, to specify the HRUs to be averaged.

4b. In the second preliminary version of the linkage, SWAT 94.2 is replaced by SWAT 99.2 (see Task 5b, below). In this version, some of the functionality associated with subroutines PRESWB and SUBWTS is moved from SWAT to SWBAVG. This organizational change reduces the extent of required changes to SWAT 99.2 code and input data format for linking SWAT and MODFLOW. Changes to SWAT 99.2 input format affects the Control Codes (*.cod), Management Codes (*.mgt), and Ground Water (*.gw) input files; these are documented in Appendix B.

Task 5. Incorporate SWAT v.99.2 into the linkage with MODFLOW

5a. Preliminary work with SWAT versions 99.2 and 98.1 was summarized above as part of Task 2. Both versions were compiled and linked under Lahey 95, and were tested with comparative simulations of the Y7 watershed and the Lower Republican River basin (see Task 7).

5b. In the second of the two preliminary versions of the SWAT-MODFLOW linkage (see Section 2.2), SWAT v.94.2 is replaced by v.99.2. A key change in moving from v.94.2 to 99.2 is the transition from Fortran77 code to Fortran90 code. Effects and advantages of this transition are summarized below; see "Notes." In particular, the Module program structure was utilized for data sharing instead of subroutine argument lists and common blocks, as in the case of SWAT v.94.2. This capability eliminated the need for many of the changes made to v.94.2 for the linkage to MODFLOW.

<u>Task 6. Update MODFLOW packages</u>

6a. Incorporate the MODFLOW packages that were written or modified for the model of Walnut Creek basin (Sophocleous et al., 1998), which was simulated using POTYLDR (Koelliker, 1994) and MODFLOW. These packages include a modified version of MODFLOW's mainline, MODSWB, MODSTR, MODWEL, MODRSD, and MODPOST. These packages were incorporated into the first preliminary version of the SWAT-MODFLOW linkage reviewed in Section 2, which was demonstrated in Perkins (1999) and documented in P&S (1999b-c).

6b. Update the MODFLOW version incorporating the above packages from MODFLOW v.88 to v.96.

<u>Task 7. Test the combined SWAT-MODFLOW code.</u>

Test the combined model code as it is developed; use the Y7 Reisel watershed and Lower Republican River basin models as test cases.

Results for the test cases using the Lahey 95 executable version of SWAT_99.2 were compared both with results based on the downloaded executable file for SWAT_99.2 and results for earlier versions of SWAT. Comparisons with results based on the downloaded executable file for SWAT_99.2 provided checks on possible errors introduced either by code changes made to run under the Lahey compiler or into the data sets due to input format changes. Comparisons for the Y7 case between v.99.2 and v.98.1 for the same set of conditions showed large differences that were traced to a line of code in subr. SWU that has been commented out of the current version of SWAT 99.2 used in the preliminary linkage of SWAT and MODFLOW (see Section 2B). With this change, differences are negligible between Y7 model results for v.98.1 and v.99.2. However, differences are still large for the Lower Republican River basin model between the two preliminary versions based on SWAT v.94.2 and 99.2. See Appendix D for further discussion of test procedures and results.

Task 8. Document the combined SWAT-MODFLOW linkage

Produce a manual to document the updated model as it is developed. The manual will document how to run the model code for the Lower Republican River model's base case.

The preliminary version of the updated SWAT-MODFLOW linkage based on SWAT v.94.2 (Section 2A) was documented in two volumes corresponding to users' and programmers' manuals (P&S, 1999b-c). These volumes will serve as drafts for the final version of documentation for the linkage. Other documentation to be provided include an update of the Readme.txt file provided to SWAT developers in May 1999 with instructions on installing the original version of the SWAT-MODFLOW software and on running the program with test cases for the Y7 Reisel watershed and the Lower Republican River basin.

2. Overview of SWAT-MODFLOW linkage

An integrated watershed simulation based on the coordination of SWAT and MODFLOW is illustrated by the block diagram of Fig. 2.2 (from Perkins and Sophocleous, referred to as P&S, 1999a), which shows the hydrologic connections that couple SWAT and MODFLOW's respective solutions. Appendix A presents the conceptual models on which the linkage is based, and begins in Section A.1 with expressions of continuity for each of the partitions shown in Fig. 2.2.

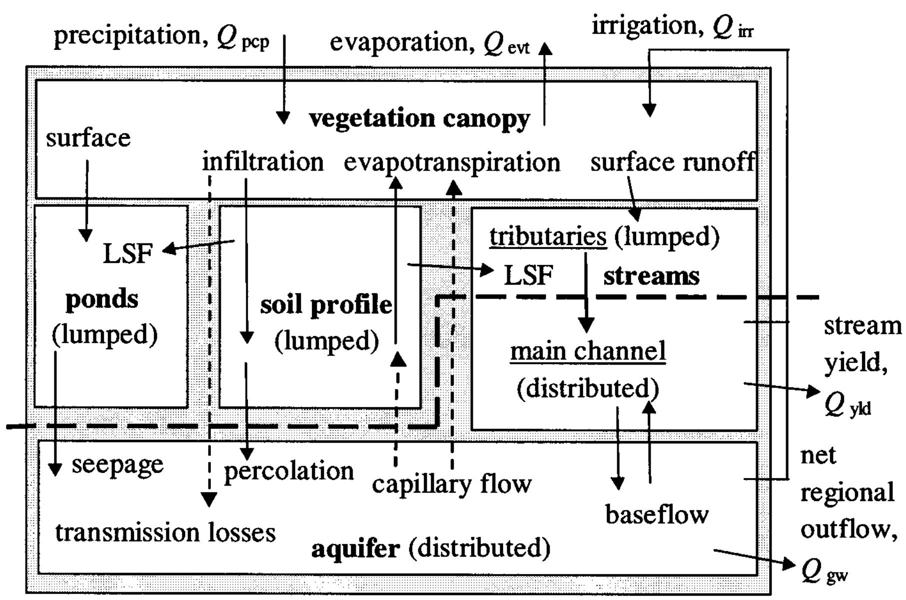

Figure 2.2. SWAT and SWBAVG simulate watershed control volume components above the dashed line (vegetation canopy, soils, and ponds), and MODFLOW those below (stream and aquifer); LSF = lateral subsurface flow. (from P&S, 1999a)

2.A. Operating procedure linking SWAT 94.2 and MODFLOW 88

A preliminary version of the updated linkage between SWAT and MODFLOW has been developed that addresses some of the key aspects of the proposal of Sophocleous and Perkins (S&P, 1999). The methodology implemented by this version was presented and demonstrated in Sam's dissertation (Perkins, 1999), and is summarized in Appendix A. The procedure for simulating the hydrology of a watershed's hydrology based on separate execution of SWAT v.94.2 and MODFLOW v.88 is illustrated in Fig. 2.3. This coordination relies on three additional components of code in addition to SWAT and MODFLOW. The essential features of these components are summarized here, and described in more detail in Perkins and Sophocleous (1999b-c).

```
1. Soil water-atmosphere simulation: SWAT (v. 94.2)
For each HRU, run SWAT as follows:
    For each day of the simulation period:
        At beginning of each aquifer solution time step, calculate (HRU scheme 3)
            Daily capillary uptake from shallow ground water (from MODFLOW)
        For each subbasin:
            Run lumped watershed model code;
            Accumulate results over each groundwater simulation time step;
        end do
        At end of each aquifer solution time step, calculate:
            Flow rates for each HRU and subbasin (subr. PRESWB);
            Spatial weights (subr. SUBWTS) to be used in average over HRUS
    end do
end do
2. Take average over HRUs: SWBAVG
For each aquifer solution time step:
    Read spatial weights written by subr. SUBWTS for each subbasin;
    For each HRU:
        Read flow rates written by subr. PRESWB for each subbasin;
        For each subbasin:
            For each hydrologic component:
                Accumulate a weighted average over all HRUs;
            end do
        end do
    end do
    Write HRU-averaged flow rates for each subbasin;
end do
3. Stream-aquifer simulation: MODFLOW (v.88)
For each aquifer solution time step:
Distribute HRU-averaged flow rates for each subbasin over grid cells to specify
    recharge, tributary flow, surface and ground water diversions, and max.
    evaporation for shallow ground water (MODSWB, MODSTR and MODWEL
    packages).
    Formulate and solve finite difference equations (FM_ and solver routines);
    Write summary of evaporation from shallow ground water (SWB2BD)
    Calculate residuals for simulated heads (MODRSD package);
    Write optional "postprocessed" results (MODPOST package);
end do
```

Figure 2.3. Procedure to coordinate separate execution of SWAT v.94.2 and MODFLOW for simulation of the Lower Republican River basin's watershed hydrology.

The first component of the SWAT-MODFLOW linkage specifies hydrologic connections between the respective control volumes simulated by SWAT and MODFLOW. These connections include tributary inflow, ground water recharge, potential evaporation, and irrigation requirements; conceptual models are presented in

Appendix A, Section A.2. At the end of each aquifer solution time step, SWAT calls subroutine PRESWB (formerly HYDBAL) to transform the hydrologic depths, or cumulative volumes per unit area simulated by SWAT, to average flow rates over the aquifer time step to represent these connections for each subbasin. These flow rates are written to a file to summarize SWAT's simulation results for MODFLOW. SWAT also calls subroutine SUBWTS (formerly WEIGHTS) to calculate HRU weights, based on soil type and land use areal fractions in each subbasin

The second component applies the HRU concept to represent the hydrologic effects of spatial heterogeneity within subbasins simulated by SWAT. Conceptual models for spatial heterogeneity are presented in Appendix A, Sections A.3 and A.5. A statistical model for spatial heterogeneity is provided by coordinating the execution of SWAT with a separate program, SWBAVG. SWAT simulates a set of representative homogeneous cases, referred to as hydrologic response units (HRUs). SWBAVG then takes an areally weighted average over the HRUs. Weight functions for the averages taken over HRUs are calculated in calls by SWAT to subroutine SUBWTS. SWAT's Control Codes input file was modified to specify the HRUs and corresponding areal weights for SWAT and SWBAVG, respectively.

The third component uses the spatially averaged results given by SWBAVG for each subbasin to specify boundary conditions over the grid of MODFLOW's spatially distributed stream-aquifer solution. Conceptual models for this component are presented in Appendix A, Section A.4. This component is provided by the package MODSWB, which was written for this purpose, in conjunction with the packages MODWEL and MODSTR, which are modified versions of MODFLOW's WELL and STREAM packages, respectively. MODSWB distributes the flow rates simulated by SWAT and SWBAVG for HRU-averaged hydrologic connections over the appropriate grid cells of the stream and aquifer domain in each time step. MODWEL and MODSTR are coordinated with MODSWB to represent irrigation requirements specified by SWAT as spatially distributed diversions from surface and ground water supplies.

Compared with the original SWAT-MODFLOW linkage used for the Lower Republican River basin study (Sophocleous et al., 1997) and documented in Perkins and Sophocleous (P&S, 1997), this version includes the following improvements:

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

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

3. Two alternatives to the original conceptual model for spatial heterogeneity (HRU scheme) have been installed as options to account for areal fractions of subbasins underlain by bedrock with no aquifer; and to further distinguish between deep and shallow areas of ground water. The two-way coupling between unsaturated and saturated

zones arising from shallow ground water is represented by one of the alternative schemes. This coupling of SWAT and MODFLOW solutions was implemented with separate execution of SWAT and MODFLOW and required relatively minor changes to the two programs. Its implementation utilizes the techniques of (a) time-varying HRU weights to reflect ground water response to weather cycles, and (b) successive approximation to pass MODFLOW's results concerning shallow ground water to SWAT. Section 4 of this report discusses options for representing this two-way coupling

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

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

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

7. The code for this version of the SWAT-MODFLOW linkage is documented in the form of Users' and Programmers' manuals (P&S, 1999b-c), which can serve as a draft of the final version of documentation (Task 8).

2.B. Revised procedure for linking SWAT v.99.2 and MODFLOW v.88

SWAT v. 99.2 has been adapted for the SWAT-MODFLOW linkage previously developed for SWAT v. 94.2 (Fig. 2.3). Revisions to this procedure, Fig. 2.4, were intended to make the SWAT-MODFLOW linkage easier to apply and to reduce the extent of changes to SWAT v.99.2 code.

Compared with the version of the linkage described above that is based on SWAT v.94.2, SWAT v.99.2 reads less data associated with the linkage, and shifts some tasks to SWBAVG. After all HRUs have been executed, SWBAVG is run, using all HRUs calculated by SWAT for input, to calculate results for input to MODFLOW. The updated version of the intermediate program, SWBAVG (step 2 in Fig. 2.4), does the following:
(a) Calculate HRU weights by calling subr. Subwts;
(b) Evaluate HRU averages as in the previous version;

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

```
For each HRU, run SWAT as follows:
    For each day of the simulation period:
            If iophru == 3 (HRU scheme 3): On first day of gw time step, calculate
                daily capillary uptake from shallow gw given by MODFLOW;
        For each subbasin:
            Run lumped watershed model code;
            Accumulate results over each groundwater simulation time step;
        end do
        At end of each aquifer solution time step, summarize results (subr. Sumstep,
            called by subroutines Writed, Writem, or Writea, depending on option
            Ipd);
    end do
end do
```

2. Take average over HRUs: SWBAVG

```
For each aquifer solution time step:
    If iophru == 3 (HRU scheme 3): Read shallow gw fraction for each subbasin
    Calculate spatial weights (subr. SUBWTS) for each subbasin;
    For each HRU:
        Read SWAT results summarized by subr. Sumstep for each subbasin;
        For each subbasin:
            For each hydrologic component:
                Accumulate a weighted average over all HRUs;
            end do
        end do
    end do
    Call Preswb to specify terms for MODFLOW (tributary inflow, recharge,
        irrigation demand) in terms of the HRU averages; and convert to flow rates;
        Write HRU-averaged flow rates for each subbasin;
end do
```

3. Stream-aquifer simulation: MODFLOW

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

Figure 2.4. Revised procedure to coordinate separate execution of SWAT (v.99.2) and MODFLOW for simulation of the Lower Republican River basin's watershed hydrology. More detailed outlines of SWAT v.99.2 and MODFLOW v.88 execution sequences to implement this procedure are shown in Appendix A, Figs. A.4 and A.5.

(c) Group hydrologic components to specify tributary inflows and ground water recharge;
(d) Convert SWAT's dimensional units of length (volumes per unit area, mm) to flow rates.

Items a, c, and d in this list were previously handled by calls to subroutines Preswb and Subwts from the modified SWAT (v. 94.2). The data describing the HRU schemes are read in SWBAVG.

An alternate version of the SWAT-MODFLOW linkage using SWAT v.94.2 has also been produced that follows the modified procedure of Fig. 2.4. This version of the linkage allows direct comparison of results from both SWAT for individual HRUs and from SWBAVG after averaging over the HRUs. This helps isolate differences between SWAT versions 94.2 (as previously modified) and 99.2; see Appendix D, "Test case results."

SWAT input data to specify the SWAT-MODFLOW linkage

See Appendix B for instructions on specifying these data for SWAT and the additional input data on the modified Control Codes input file read by SWBAVG. See Appendix C for example input data files and procedures used to apply HRU schemes 1-3 to the Lower Republican River basin model. These schemes were formulated to provide three options for conceptual models of spatial heterogeneity. The HRU approach is introduced in Appendix A, "Conceptual models for linkage," Section A.5. In this approach, each simulation by SWAT executes one HRU for each subbasin. Each HRU represents one combination of soil type, specified by the soils (*.sol) input file; land use, specified by the Management Codes (*.mgt) input file; and subsurface feature based on the option ipurk, specified by the modified ground water (*.gw) input file. Options defined for the Lower Republican River basin model are listed in the section entitled "Specifying hydrologic response unit (HRU) schemes 1-3" of Appendix C

1. Control Codes (*.Cod) input file

SWAT 99.2 reads an additional field, columns 89-92 from record 2 of the Control Codes (*.cod) input file, for the added variable **iopmod**. If positive, SWAT writes a summary of its simulation results at intervals specified by the variable ipd (0: monthly, 1: daily, 2: annual), which is read from the same record as **iopmod**. If **iopmod** > 0, a sixth record is read from the Control Code file after its five standard records have been read, to specify **cnvlen**, a conversion between SWAT and MODFLOW for units of length; and optional file names, **nambal** and **namshl**. **nambal** specifies the name of the output file for the summary of results. This file provides the basis of input to MODFLOW to specify fluxes (recharge, tributary inflows, irrigation pumping) Conversion of results for MODFLOW is organized by input to SWBAVG and is based on multiple simulations of SWAT, one for each HRU. namshl specifies the name of the input file written by MODFLOW that summarizes results for shallow ground water for each subbasin, including the area of shallow ground water, the flow rate for evapotranspiration through the soil profile based on MODFLOW's model for evapotranspiration, and the depth to ground water.

2. Ground water input data (*.gw) for each subbasin

Subroutine Readgw was modified to read option **ipurk(j)** for subbasin, j, from an unused field of the input file. **Ipurk(j)** specifies the assumed conceptual model for subsurface features as follows.

ipurk(j) = 0: the standard assumption holds for SWAT, in which the soil profile is underlain by an aquifer with deep ground water that has a negligible effect on soil water content due to evapotranspiration.

ipurk(j) = −1: the soil profile is assumed to sit on top of bedrock. This is represented in SWAT by a modification to subroutine **Purk** that holds percolation out of the root zone to zero if ipurk(j) = −1.

ipurk(j) = +1: ground water is shallow, and data are read from file **namshl** by SWAT (subroutines **Init_shl** and **Sumstep**) to specify evapotranspiration into soil profile according to MODFLOW's simulation. Evapotranspiration is converted from flow rates into daily volumes per unit area for redistribution over the soil profile using subroutine Evap_gw, called by subr. Subbasin (see Fig. 2.5). Evapotranspiration flow rates are obtained from MODFLOW using successive approximation as described in the section below,"Implementing a two-way coupling between SWAT and MODFLOW."

These options are used to represent subbasin heterogeneity for the Lower Republican River basin model due to areal fractions of each subbasin lying within an alluvial valley and having with either deep or shallow ground water, and the remaining fraction of each subbasin lying outside the alluvial valley where the soil profile sits on bedrock. See Appendix A.5 for conceptual models based on these distinctions, and Appendix C for examples of corresponding HRU schemes.

3. Management Codes (*.mgt) input file for each subbasin

SWAT was also modified to allow two additional fields of data to be read from the Management Codes (*.mgt) input file. If values are positive, these fields specify a maximum daily irrigation limit, auto_dmx, and an irrigation threshold as a fraction of available field capacity, auto_swf. The daily maximum is applied whether the irrigation threshold is given by plant stress factor or by soil water content. Soil water content threshold is indicated one of two ways. (a) A negative value in the field for plant stress factor, **auto_str**, is interpreted as a soil water content deficit below available field capacity (mm). This is a standard SWAT 99.2 option, but is not documented in the Control Codes input file. (b) If a positive value is entered in the field for available field capacity fraction, 0 < **auto_swf** < 1, a corresponding deficit is calculated and substituted for **auto_str** that is given by

$$\text{auto\_str} = \text{swcap}(\text{auto\_wsf} - 1)$$

This is interpreted by SWAT's standard code to represent the irrigation threshold, **auto_str**, as a soil water content deficit.

2.C. Flow of execution for modified versions of SWAT and MODFLOW

This section outlines the flow of execution for both SWAT and MODFLOW, and shows where their procedures have been modified to implement the linkage.

Flow of execution for modified SWAT v.99.2

A review of the procedure followed in SWAT to simulate the soil water budget components for each subbasin is outlined in Fig. A.4. Subroutines in SWAT were added or modified to coordinate with MODFLOW and to incorporate added options that are specified in the modified Control Codes (*.cod) input file for Swat unless otherwise noted below. Item numbers correspond to superscripts on subroutine names in Fig. A.4; options in **bold** type are defined as follows.

```
  Read or generate daily weather observations, Clicon;
  do for each subbasin (subr Subbasin):
     Soil temperature: calculate for each layer; Solt;
     Surface hydrology, Surface:
        Canopy interception;
        Snowmelt, Snom.
        If precip > 0:
           Excess rainfall: curve number or Green-Ampt, Volq;
           Surface storage, Surfstor; Crack volume, Crackvol;
           Transmission loss for ephemeral stream channels, Tran;
           Effective rainfall (infiltration) = precipitation – runoff

     Percolation and lateral subsurface flow, Purk^1,2.
     Redistribute uptake from shallow gw over soil profile, Evap_gw^1,3

     Evaporation:
        Potential evaporation, Etpot;
        Actual evaporation, Etact;
        Crop growth model, Crpmd;
           Supply plant evap. demand with avail. soil water, Swu^4

      Irrigation based on either plant stress factor or soil water content
           thresholds, and limited by a daily maximum (Readmgt^5, Subbasin);
  end do
end do
```

Figure 2.5. Procedure followed in the daily hydrologic simulation for each subbasin in SWAT v.99.2. Superscripts 1-5 refer to code changes or additions that are summarized in the text.

Notes on code changes or additions to SWAT v.99.2:

1. **Readgw** was modified to specify the option **ipurk**(*j*) for each subbasin, *j*. If **ipurk**(*j*) < 0, the soil profile directly overlays bedrock; subroutine **Purk** was modified to represent this conceptual model. **Ipurk**(*j*) = 0 specifies SWAT's default conceptual

model, a soil profile underlain by an aquifer with ground water sufficiently deep that its interaction with the root zone is negligible. **ipurk**(*j*) > 0 specifies that ground water in the aquifer is shallow enough to interact with the root zone. For this, subr. Subbasin calls Evap_gw to redistribute evapotranspiration from ground water, according to MODFLOW's conceptual model, over the soile profile.

2. **Purk** was modified to include an option to represent a soil profile underlain by bedrock, specified by setting option **ipurk**(*j*) = −1. In this case, percolation out of the root zone is blocked, resulting in a corresponding increase in subsurface lateral flow and soil water content. This option is used in the HRU scheme2, specified by **iophru**=2, in which a subbasin is disaggregated into components with a soil profile either sitting on bedrock or underlain by an aquifer with deep ground water with negligible effects on soil water content.
3. **Evap_gw** redistributes uptake from shallow ground water over the soil water profile, and is called by subr. Subbasin if the option **ipurk**(*j*) = +1. An HRU with shallow ground water can be associated with HRU scheme 3 (**iophru**=3), which disaggregates shallow and deep ground water components. This two-way coupling obtained using successive approximation. Evaporation from shallow ground water is given by a previous iteration of Modflow's solution for a given time step, and is redistributed over soil layers in which water content is less than available field capacity. Results from the previous iteration of Modflow's solution can be given by HRU scheme 2(see **Purk**, above). The successive approximation approach enables the coupling of Swat and Modflow solutions through shallow ground water evaporation while allowing separate execution of Swat for each HRU, SWBAVG to average the HRU results, and Modflow based on the averaged HRUs.
4. In SWAT v.94.2, **Swu** was modified to avoid references to undeclared array locations. In v.99.2, **Swu** was modified by commenting out a line of code in order to obtain consistent results from versions 98.1 and 99.2 for the Y7 test case simulated over years 1975-1977.
5. **Readmgt** was modified to specify a daily maximum irrigation, **auto_dmx**, and a soil water content threshold for irrigation, auto_swf in the management codes (*.mgt) input file for the automatic irrigation option (mgt_opt = 10). Subroutine **Subbasin** applies the daily maximum and initializes the soil water content threshold.

The following modifications to SWAT v.94.2 were not carried into v.99.2:

Clicon was modified for SWAT v.94.2, but not for v. 99.2, as follows. Option **iopwea** specifies that daily measurements of wind speed, relative humidity, and solar radiation are to be read.

Evap8 was modified to call the added subroutine **Penman**, based on the added option **ipet**=3.

Penman was added as an option to calculate potential evaporation according to the procedure recommended in Shuttleworth (1993), which accounts for the effect of long-wave radiation, i.e., black body emissions from earth; and which can make use of daily measurements, if available, of wind speed, relative humidity, and solar radiation (see option **iopwea**).

Flow of execution for modified Modflow program

MODFLOW's mainline was rewritten in the form of a subroutine to allow MODFLOW to serve dual modes of stand-alone and linked execution. Fig. 2.6 summarizes MODFLOW's mainline rewritten as a subroutine. Further details are provided in Perkins and Sophocleous (1999b-c). In linked mode (**iopswt=1**), SWAT calls MODFLOW as a subroutine (Fig. 1 of S&P, 1999). In the stand-alone mode (**iopswt=0**), a short "stub" mainline initializes arguments **iopswt** and **cnvtim.** The remaining arguments (**delt**: time step [T]; **kper, kstp, nstp**: current stress period, time step, and no. time steps) are defined within the call to Modflo(), which also reads SWAT's simulation results from the "balance" data file for each time step.

```
begin
  subroutine Modflo (main entry point)
    On the initial call to Modflo()
      call Bas1df to define grid size (rows, columns, layers), stress periods, options;
      allocate array space (AL routines);
      call Swb2al (follows Str1al) to allocate arrays for watershed-aquifer linkage;
      Read and prepare data that remain constant throughout simulation (RP routines);
      call Swb2rp (follows Bcf1rp) to associate subbasins with aquifer grid cells;
    end if;

    Do for each stress period kper=1,nper (implement loop with a counter and a go-to)
      define stress period length and divide into time steps;
      Read and prepare data that remain in effect for the stress period (RP routines);

      Do for each time step kstp=1,nstp (implement loop with a counter and a go-to)
        entry Modstp () [entry point provided for calls from Swat]
        call Swb2fm (before Bas1ad) to set up conditions based on Swat's results;
          if (iopswt = 0) read Swat's simulation results from the HRU-averaged balance
          file;otherwise, Swat calls Modstp() and passes results by reference to array Shed.
        call Bas1ad to advance time and initial hydraulic heads; calculate time step;
        Do for each iteration of approximating the solution (kiter=1,mxiter):
          formulate finite difference equations (FM routines) and solve equations;
        end iteration on solution;
        calculate budget terms for mass balance (BD routines);
        call Swb2bd to summarize Modflow results;
        call Bas1ot to optionally save and print results;
        if (iopswt > 0) return to Swat
    end time step;
  end stress period;
  entry Modend (to end Modflow execution with call from Swat)
    close files;
end.
```

Figure 2.6. Flow of execution for MODFLOW mainline rewritten as a subroutine.

MODFLOW's stand-alone mode is run as follows.

```
program modmain
  data iopswt/0/      ! set option to run modflow as stand-alone program.
  data cnvtim /1./    ! time conversion factor (to call MODFLOW from SWAT)
  call MODFLO (iopswt, cnvtim, delt, kper, nstp, kstp)
end
```

2.D. Implementing a two-way coupling between SWAT and MODFLOW

In the description of proposed tasks in S&P (1999), options to be explored for updating the SWAT-MODFLOW linkage included the alternatives of separate execution of SWAT and MODFLOW vs. linked execution, in which SWAT would call MODFLOW as a subroutine; see Section 1, Task 3, "Review plans to be implemented with SWAT authors." The first of these options is summarized in Fig. 2.3, which outlines the procedure followed in applying both the original SWAT-MODFLOW linkage (P&S, 1997) and the updated linkage (P&S, 1999b-c). An alternative procedure is outlined in Fig. 1 of S&P (1999), in which SWAT calls MODFLOW as a subroutine. As indicated in the work proposal (S&P, 1999), this linked mode of execution was assumed to be a prerequisite to simulating a two-way coupling between solutions by SWAT and MODFLOW for unsaturated and saturated zones, respectively, which would arise from shallow ground water conditions.

However, in tests of the preliminary version of the updated linkage reported in Perkins (1999), a method was demonstrated that simulates a two-way coupling of unsaturated and saturated zones based on separate execution of SWAT and MODFLOW. This method applies a form of successive approximation to the procedure outlined in Fig. 2.3 in order to supply SWAT with a summary of MODFLOW's results at the end of each time step regarding the area of shallow ground water and the flow rate from shallow ground water into the soil profile for each subbasin. These results are used by SWAT to evaluate, respectively, time-varying HRU weights and daily soil water volumes per unit area to be distributed over the soil water profile for those HRUs representing shallow ground water. This method is based on a refined conceptual model of spatial heterogeneity that is summarized in Section A.5 of Appendix A; see "Coupling SWAT and MODFLOW solutions by successive approximation." The method is presented and demonstrated in Perkins (1999), and documented in P&S (1999b-c).

This method for simulating a two-way coupling does not require the added complication of modifying SWAT to implement linked execution as outlined in Fig. 1 of the proposal (S&P, 1999). While linked execution of SWAT and MODFLOW is appealing in some respects as discussed previously, it is not necessary for implementing a two-way coupling, according to our findings. Some unexpected pitfalls might be encountered in attempting to implement a two way coupling with linked execution. One set of questions to be resolved for linked execution involve the internalized simulation of HRUs, including their specification through the *.cio and *.fig files and the spatial weights used in averaging them:

(a). Could construction of the File.cio and ~.fig files for the SWAT-based HRU approach be automated, at least in part, based on HRU descriptions given by the SWBAVG-based approach in the modified Control Codes input file (described in App. B)?
(b). Could the HRU weights calculated by SUBWTS and called by SWAT (as in the case of the preliminary version of this linkage, P&S 1999a-b) simply be substituted for the HRU weights currently read by SWAT from the general subbasin (~.sub) files?

Other questions regarding stability of the coupled solution stability and linked execution requirements for memory and file i/o should be considered. For these reasons, we suggest that the demonstrated method for representing a two-way coupling be implemented for the updated linkage of SWAT and MODFLOW, as it should not require substantial changes to SWAT. Alternatively, if the two-way coupling of SWAT and MODFLOW with time-variable HRU weights could be incorporated into SWAT's existing technique for representing HRUs, then linked execution of SWAT and MODFLOW might be considered feasible. If so, the linked execution scheme as documented for the preliminary version (P&S, 1999b-c) might be considered for possible incorporation into SWAT 99.2.

2.E. Generalizing HRU schemes for the SWAT-MODFLOW linkage

The original SWAT-MODFLOW linkage was developed for application to the Lower Republican River and Rattlesnake Creek basins. One of the goals of the present project is to make the combined code more generally applicable. One component of the linkage that may require further work in this regard is the formulation of the HRU schemes 1-3 presented in Appendix A and expressed by equations (A.15), (A.21), and (A.23), respectively. These schemes were presented and demonstrated for the Lower Republican River basin model by Perkins (1999). An important feature of these schemes to be preserved in a more generalized scheme is to allow the HRU weights to be evaluated during the simulation, rather than requiring them to be specified as input data.

We have given some thought to how the HRU schemes described in Appendix A might be generalized in a way that allows specifying the features of schemes 1-3 not only based on the specific assumptions made for the Lower Republican River basin, but for a more arbitrary watershed. One approach being explored that might serve this purpose is to evaluate the HRU weights based on a generalized form of equation (A.15b).

References

Arnold, J.G., P.M. Allen, and G. Bernhardt, 1993. A comprehensive surface-ground water flow model. J. of Hydrology 142(1–4):47–69.

Arnold, J.G., J.R. Williams, R. Srinivasan, K.W. King, and R.H. Griggs, 1994. SWAT (Soil and Water Assessment Tool) User's Manual. USDA, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, TX. For latest available SWAT version, documentation, and ArcView interface, see the SWAT website http://www.brc.tamus.edu/swat/.

DASC, Data Access and Support Center, 1999. Core Database catalog; Kansas Geographic Information Systems Initiative, Kansas Geol. Survey, Univ. of Kansas, Lawrence, KS, website at http://gisdasc.kgs.ukans.edu/dasc_net.html

Koelliker, J.K., 1994. Users manual for Potential Yield model Revised (POTYLDR). Unpublished document, Civil Engineering Dept., Kansas State University, Manhattan, KS, 41 p.

Koelliker, J.K., S.R. Ramireddygari, M.A. Sophocleous, and S.P. Perkins, 1999. Evaluation of Wet Walnut water supply availability: Final report. Kansas Water Office, Contract No. 99-122, June, 154 p.

Lane, L.J., 1982. Distributed model for small semi-arid watersheds. ASCE J. Hydr. Div. 108(HY10):1114–1131.

McDonald, M.G., and Harbaugh, A.W., 1988. A modular three-dimensional finite-differences ground-water flow model: U.S. Geol. Survey Techniques of Water-Resources Investigations Book 6, Ch. A1, 586 p.

Perkins, S.P., 1999. Integration of Watershed and Ground Water Models with Application to Lower Republican River Basin. PhD dissertation, Dept. of Civil and Environmental Engineering, Univ. of Kansas.

Perkins, S.P. and M.A. Sophocleous, 1997. Lower Republican River Stream-aquifer project, vol. 2. Development and documentation of a combined watershed/stream-aquifer modeling program. Kansas Geol. Survey Open-File Report No. 97-9, Lawrence KS.

Perkins, S.P. and M.A. Sophocleous, 1998. A computer model for water management in Rattlesnake Creek Basin, Kansas: development and documentation of SWATMOD. Open-File Report No. 98-59, Kansas Geol. Survey, Lawrence, KS, 120 p.

Perkins, S.P., and M.A. Sophocleous, 1999a. Development of a comprehensive watershed model applied to study stream yield under drought conditions. Ground Water, 37(3):418–426.

Perkins, S.P. and M.A. Sophocleous, 1999b. Documentation of a combined watershed and stream-aquifer modeling program based on SWAT and MODFLOW. Volume 1. User's manual. Open-File Report No. 99-24, Kansas Geol. Survey, Lawrence, KS, 120 p.

Perkins, S.P. and M.A. Sophocleous, 1999c. Documentation of a combined watershed and stream-aquifer modeling program based on SWAT and MODFLOW. Volume 2: Added and modified source code. Open-File Report No. 99-25, Kansas Geol. Survey, Lawrence, KS, 160 p.

Ramireddygari, S.R., M.A. Sophocleous, J.K. Koelliker, S.P. Perkins, and R.S. Govindaraju, 2000. Development and application of a comprehensive simulation model to evaluate impacts of watershed structures and irrigation water use on streamflow and ground water: the case of Wet Walnut Creek watershed, Kansas. Submitted to J. Hydrology August 1999.

Redwine, C., 1994. Upgrading to Fortran 90. Springer, New York, 501 p.

Seaber, P.R., F.P. Kapinos, and G.L. Knapp, 1987. Hydrologic Unit Maps, U.S. Geol. Survey Water Supply Paper 2294.

Shuttleworth, W.J., 1993. Handbook of Hydrology, D.R. Maidment, Ed., McGraw-Hill. Ch. 4, Evaporation.

Sophocleous, M.A., J.K. Koelliker, R.S. Govindaraju, T. Birdie, S.R. Ramireddygari, and S.P. Perkins, 1999. Integrated numerical modeling for basin-wide water management: the case of the Rattlesnake Creek basin in south-central Kansas. J. of Hydrology, 214:179–196.

Sophocleous, M.A. and S.P. Perkins, 1999. SWAT-MODFLOW Integration Proposal. Kansas Geological Survey, Lawrence KS, 20 p.

Sophocleous, M.A., S.P. Perkins, N.G. Stadnyk, and R.S. Kaushal, 1997. Lower Republican Stream Aquifer Project, Vol. 1. Combined watershed/stream-aquifer model conceptualization and application. Open-File Report No. 97–8, Kansas Geol. Survey, Lawrence, KS, 243 p.

Sophocleous, M.A., S.P. Perkins, Koelliker, J.K., and S.R. Ramireddygari, 1998. Evaluation of Wet Walnut water supply availability: development and application of an integrated watershed model; a year-end progress report. Open-File Report No. 98–60, Kansas Geol. Survey, Lawrence, KS.

Stoertz, M.W., and K.R. Bradbury, 1989. Mapping recharge areas using a ground-water flow model. Ground Water 27(2):220–228.

U.S. Department of Agriculture (USDA), Soil Conservation Service, 1972. National Engineering Handbook, Hydrology Section 4, Chapters 4–10. Washington, D.C.

Appendix A. Conceptual models for linkage

Section 2, "Overview of SWAT-MODFLOW linkage," introduced the three main components of the linkage in procedural form as outlined by Fig. 2.3. The conceptual models and methodology of all three components are presented in Perkins (1999). This Appendix summarizes the conceptual models for hydrologic connections between SWAT and MODFLOW, and the conceptual models for spatial heterogeneity simulated by SWAT and SWBAVG. These are the conceptual models associated with the code that is being upgraded to SWAT's latest version (99.2). The third component of the procedure shown in Fig. 2.3 involves distribution of results from SWAT and SWBAVG over the stream-aquifer domain simulated by MODFLOW for each subbasin, and is executed by MODFLOW. It will be examined in more detail for the conversion to MODFLOW-96 after conversion to SWAT v.99.2.

A.1. Hydrologic balances and governing equations

A watershed's overall hydrologic balance is given by

$$dS/dt = Q_{pcp} - Q_{evt} - Q_{yld} + Q_{gw} \quad \text{(A.1)}$$

The rate of change in storage, dS/dt, includes components in the watershed's streams, aquifer, soil profile, vegetation, and ponds. Terms on the right-hand side include net inflows for precipitation, Q_{pcp}, and net regional ground water inflow, Q_{gw}; and net outflows for evaporation, Q_{evt}, and stream yield, Q_{yld}. Irrigation is an internal transfer within the watershed from surface and ground water sources to the land surface, and so is not included with precipitation. Evaporation from water bodies and the land surface is driven by atmospheric conditions and, over land, is supplied by upward flow from the soil profile and plant transpiration. Stream yield consists of the net lateral contributions to streamflow. Net regional ground water inflow, Q_{gw}, is zero if surface water and ground water divides coincide (Freeze and Cherry, 1979), which is not the case in our study area.

The watershed control volume is partitioned conceptually into interacting components for the vegetation canopy, soil profile, ponds, streams, and aquifer. SWAT and MODFLOW are coordinated to simulate different components of the watershed as illustrated in Figure A.1. Above the dashed line, the vegetation canopy, soil profile, and pond storage are represented for each subbasin by SWAT and the HRU averaging technique. Below the dashed line, the Republican River and alluvial aquifer are represented by MODFLOW. Flow paths across the dashed line represent connections made in MODSWB that use results from SWAT to specify conditions for MODFLOW's solution in each time step, including ground water recharge, evapotranspiration from shallow ground water, withdrawals by both surface and ground water rights, and runoff to streams represented by MODFLOW.

Stream yield is based on a mass balance for a stream reach given by

$$(dS/dt)_{str} = Q_{in} - Q_{out} + Q_{trib} - Q_{sdiv} - Q_{evs} + Q_{base} \quad \text{(A.2)}$$

which equates the rate of change in storage on the left to the sum of net inflows. Defining stream yield as the net channel outflow ($Q_{out} - Q_{in}$) under steady flow conditions, $(dS/dt)_{str} = 0$, stream yield includes terms for tributary inflow, Q_{trib}, diversions for irrigation and other uses, Q_{sdiv}, evaporation from the stream surface, Q_{evs}, and baseflow, Q_{base}:

$$Q_{yld} = Q_{trib} - Q_{sdiv} - Q_{evs} + Q_{base} \tag{A.3}$$

A mass balance for ground water flow is given by

$$(dS/dt)_{gw} = Q_{gw} + Q_{rech} - Q_{gdiv} - Q_{et\text{-}gw} - Q_{base} \tag{A.4}$$

On the left is the rate of change in aquifer storage, $(dS/dt)_{gw}$. On the right, Q_{gw} = net lateral ground water inflow, Q_{rech} = recharge, Q_{gdiv} = ground water diversions (primarily irrigation pumping), and $Q_{et\text{-}gw}$ = evapotranspiration from shallow ground water.

Streambed leakage, which couples the control volumes for ground water and channel flow, is given by Darcy's law,

$$Q_{base} = -K_s A_s \frac{dh}{dl}, \tag{A.5}$$

where K_s is the streambed hydraulic conductivity; A_s is the streambed area, the product of wetted perimeter P and reach length L; and dh/dl is the hydraulic gradient across the streambed. Equation (A.5) is evaluated as part of MODFLOW's simultaneous solution for stream stage and aquifer head. Streambed leakage is bidirectional, but is commonly referred to as baseflow, a term that implies unidirectional contribution to streamflow from ground water. Streambed leakage will flow from the stream into the aquifer in response to either a rise in stream stage due to a flood wave or a water table depression due to irrigation pumping.

Combining continuity in differential form with Darcy's law gives the governing equation for saturated flow in a porous medium,

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{dh}{dt} - R(\mathbf{x}), \tag{A.6}$$

where S_s is specific storage, $R(\mathbf{x})$ represents the spatially distributed sum of net inflows to ground water, in particular recharge, evaporation from shallow ground water, and pumping from wells. Coordinates $\mathbf{x} = (x,y,z)$ are assumed to be oriented to lie along the principal components $\mathbf{K} = (K_x, K_y, K_z)$ of hydraulic conductivity (Anderson and Woessner, 1992). MODFLOW applies a finite differences solution to equation (A.6). Unconfined flow is linearized by successive approximation of saturated thickness based on the latest solution for hydraulic heads $h(\mathbf{x})$.

MODFLOW's STREAM package (Prudic, 1989) provides an approximation for a simultaneous solution of streamflow and streambed leakage. Its routing procedure is given by expressing equation (A.3) in terms of outflow from a given reach by

$$Q_{out} = Q_{in} + Q_{trib} - Q_{sdiv} - Q_{evs} + Q_{base} \tag{A.7}$$

and proceeding downstream from the top reach of each segment. The routing procedure assumes steady flow and ignores momentum, so that both change in storage and time of travel of a flood wave are neglected. This is reasonable when time steps for the aquifer solution are much larger than the time of travel of a flood wave through the solution domain.

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

$$d_{sw}(t) - d_{sw}(0) = \sum_{i=1}^{t} \left(d_{pcp} - d_{ro} - d_{xm} - d_{perc} - d_{et} \right) \qquad (A.8)$$

On the left-hand side is the change in soil water content after t days; on the right are terms integrated over time for precipitation, d_{pcp}, which includes snowmelt and applied irrigation; runoff, d_{ro}; transmission losses, d_{xm}; percolation from the soil profile, d_{perc}; and evapotranspiration, d_{et}. Fig. A.1 is a block diagram showing the hydrologic connections to be represented by the SWAT-MODFLOW linkage.

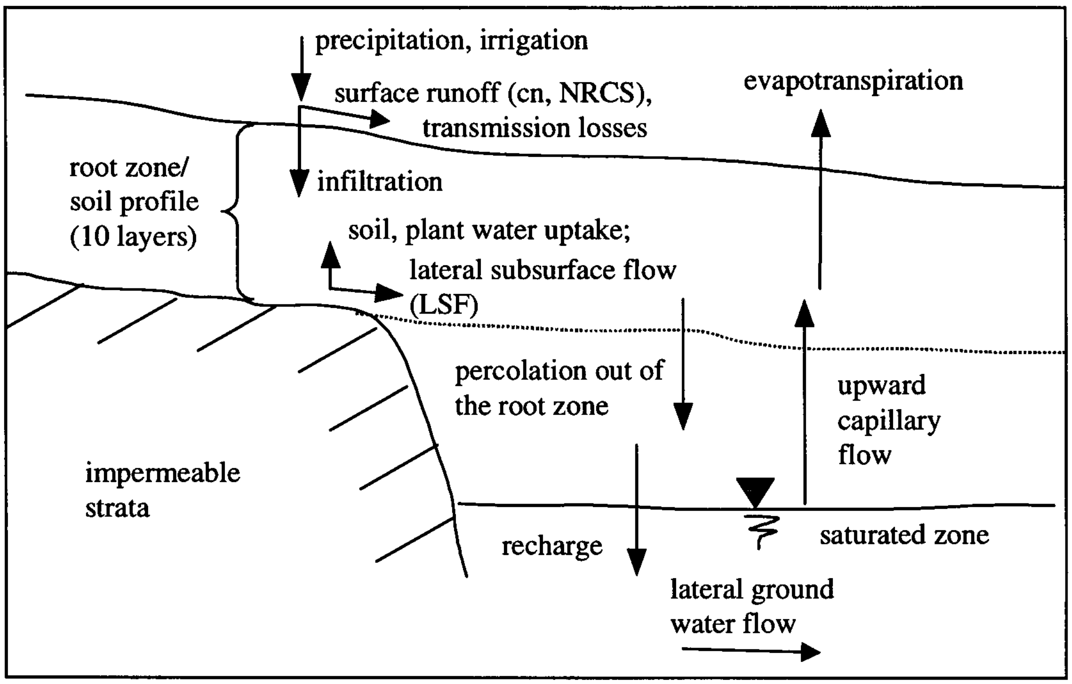

Figure A.1. Conceptual model for soil water hydrology simulated by SWAT.

Equation (A.8) expresses each of these components as a depth, d, based on a geometrical interpretation of volume given by $V = dfA$, where f is the areal fraction of watershed area, A, to which the hydrologic component applies. This volume is also given by integrating flow rate over time. For average flow rate, Q, and time step, Δt, $V = Q\Delta t$. Combining these relates the hydrologic flow rates, Q, and depths, d, by

$$cQ\Delta t = dfA, \qquad (A.9)$$

where c is a length conversion factor.

Surface runoff, d_{ro}; is based on the NRCS curve number method (USDA, 1972), and reflects variations in watershed slope and soil water content. Runoff is reduced by channel transmission losses, d_{xm}, which infiltrate to an underlying aquifer along ephemeral streambeds. Each subbasin is divided into a contributing fraction, f_{con}, in which surface and subsurface runoff flow to the subbasin's outlet; and a noncontributing fraction, $(1-f_{con})$, in which runoff flows to ponds within the subbasin. SWAT calculates a separate water budget for pond storage given by

$$(dS/dt)_{pond} = Q_{in} - Q_{out} + Q_{dir} - Q_{evap} - Q_{seep}, \qquad \text{(A.10)}$$

where $(dS/dt)_{pond}$ is the rate of change in pond storage, Q_{in} is inflow due to runoff, Q_{out} is pond overflow, Q_{dir} is direct precipitation, Q_{evap} is evaporation, and Q_{seep} is pond seepage.

A.2. Lumped models for hydrologic connections: SWAT and PRESWB

SWAT calls subroutine PRESWB to calculate flow rates from each subbasin representing contributions for a single HRU to tributary inflows to the Republican River, aquifer recharge, surface and ground water diversions, and evapotranspiration from shallow ground water. Calculation of these flow rates involves combining terms simulated by SWAT, reviewed below, and conversion from hydrologic depths (cumulative volumes per unit area of the watershed) into flow rates according to equation (A.9).

Irrigation water use, recharge, tributary flow, and evaporation

Irrigation demand is simulated as summarized above for SWAT's soil water balance simulation. This is converted to a flow rate according to equation (A.9) by

$$Q_{irr} = d_{irr} f_{irr} A/c\Delta t. \qquad \text{(A.11)}$$

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

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

$$Q_{rech} = (d_{perc} + d_{xm} + d_{psep})A/c\Delta t. \qquad \text{(A.12)}$$

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

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

$$Q_{trib} = (d_{sro} + d_{lat}) f_{con} A/c\Delta t + Q_{po} + Q_{rbed} \qquad \text{(A.13)}$$

Overall, the watershed fraction contributing runoff directly to streams is estimated to be 0.98, based on USGS streamflow data reports. The remaining noncontributing component of the watershed drains to ponds, from which water may overflow with a flow rate Q_{po}, or seep to streams. The last term in equation (A.13), Q_{rbed}, is related to equation (A.12) as follows.

SWAT simulates percolation, transmission losses, and pond seepage, the terms included for recharge by equation (A.12), based on the assumption that the full areal extent of a subbasin's soil profile is underlain by an alluvial aquifer. To represent a subbasin only partially underlain by an aquifer, several alternatives are available. A somewhat simplistic method is to partition recharge according to equation (A.12) into two components,

$$Q_{rech} = Q_{raqf} + Q_{rbed} \tag{A.14a}$$

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

$$Q_{raqf} = Q_{rech} f_{aqf} \tag{A.14b}$$

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

$$Q_{rbed} = Q_{rech}(1 - f_{aqf}) \tag{A.14c}$$

This term is added into tributary flow as shown in equation (A.13).

These ad hoc schemes are based on the partitioning of equation (A.12) to satisfy continuity, but equation (A.14a) is inconsistent with the hydrologic model simulated by Swat, in which the full extent of the subbasin is assumed to be underlain by an aquifer. More hydrologically consistent alternatives are provided by refined conceptual models of spatial heterogeneity, which are presented in Section A.5.

Potential evaporation simulated by SWAT is passed to MODFLOW to represent a maximum rate of evapotranspiration from shallow ground water. This coupling is described in Section A.4, "Distributed model of hydrologic connections," the third component of the SWAT-MODFLOW linkage as outlined in Fig. 2.1. The coupling of the soil water profile to shallow ground water incorporates changes to Swat's hydrologic model simulation, and is based on the conceptual model for spatial heterogeneity given by HRU scheme 3 (Section A.5). In contrast to hydrologic connections for irrigation, recharge, and tributary flow, this coupling requires that information flow from MODFLOW to SWAT. This is accomplished with only minor changes to SWAT and MODFLOW by the use of successive approximation (Section A.5).

A.3. Basic model of heterogeneity (HRU scheme 1)

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

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

HRU scheme 1 accounts for variability of soil type and land use, and has been applied to models of the Lower Republican River, Rattlesnake Creek, and Wet Walnut Creek watersheds. Two additional schemes have been incorporated into the SWAT-MODFLOW linkage to disaggregate each subbasin into components that have a soil profile underlain by either bedrock or an aquifer. The third HRU scheme further disaggregates the component underlain by an aquifer into deep and shallow components, and provides the means of representing a two-way coupling between unsaturated and saturated components. The methodology for the basic HRU scheme 1 is presented here; schemes 2 and 3 are presented in Section A.5.

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

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

$$d_i = \sum_{k=1}^{n_h} d_{ik} w_k \qquad \text{(A.15a)}$$

$$w_k = s_m c_n \qquad \text{(A.15b)}$$

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

$$c_{1j} = f_{cj} - f_{\text{irr},j} \quad \text{(non-irrigated cropland);} \qquad \text{(A.15c)}$$

$$c_{2j} = f_{\text{irr},j} \quad \text{(irrigated cropland);} \qquad \text{(A. 15d)}$$

$$c_{3j} = 1 - f_{cj} \quad \text{(grassland);} \qquad \text{(A.15e)}$$

The areal fraction of cropland is denoted by f_{cj} for each subbasin, j, in equation (A.15c). The non-irrigated areal fraction is given by subtracting from cropland the irrigated areal fraction, $f_{\text{irr},j}$ (A.15d). In this scheme, grassland represents areal fraction of the subbasin not under cultivation (A.15e). Table A.1 summarizes the values required for the soil type and land use areal fractions. The irrigated areal fraction for the basin, f_{irr}, is derived from data obtained from the Kansas Division of Water Resources (DWR) and varies slightly with time over a range of 3-4 percent.

Table A.1. Land resource, use, and soil areal fractions for Lower Republican River Basin.

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

[1]Subbasin areal fraction of study area (2569.6 km^2). [2]Areal fraction of subbasin draining to ponds. [3]Areal fraction of subbasin underlain by alluvial aquifer. [4]From 1990 LANDSAT Thematic-Mapper (T-M) data analysis. [5]Derived from analysis of STATSGO Soils data base obtained from DASC (1999).

For the basic HRU scheme, areal fractions for soil type and land use are specified by input to the modified version of SWAT's *.COD input file. At the end of each aquifer solution time step, SWAT calls subroutine SUBWTS to calculate the weights, w_k, for each HRU and subbasin (Fig. 2.1). After all HRUs have been simulated by independent executions of SWAT, program SWBAVG takes the weighted average according to equation (A.15a) over the HRUs. The areally weighted average hydrologic fluxes from SWAT and SWBAVG are used as input to MODFLOW's MODSWB package.

A.4. Distributed model of hydrologic connections

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

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

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

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

where z_s = surface elevation and $z_{ext} = z_s - d_{ext}$, elevation at extinction depth. The maximum value, q_{max}, is provided by SWAT as the potential evaporation rate. The evaporation rate given by equation (A.16) is head-dependent, and is treated implicitly in MODFLOW's solution. The relative significance of the coupling due to uptake from shallow ground water varies both with the area of shallow ground water and the depth to water. Subroutine SWB2BD in the MODSWB package writes a summary of shallow ground water, including its area, mean depth, and evaporation rate for each subbasin. These results can be used as input to a subsequent execution of the linked SWAT-MODFLOW procedure outlined in Fig. 2.1, thereby coupling SWAT and MODFLOW's solution by the method of successive approximation. This approach is applied in an alternate HRU scheme that disaggregates shallow and deep ground water, and is described below.

Associating watershed subbasins with stream-aquifer grid

To initialize an association between MODFLOW's stream-aquifer grid with the subbasins simulated by SWAT, MODSWB reads an input file, illustrated at the end of Appendix B, that provides the following two items:

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

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

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

In each time step, MODSWB reads tributary inflows, ground water recharge, irrigation demand, and potential evaporation for each subbasin as HRU-averaged flow rates from a data file written by SWBAVG. In addition, "actual" evaporation and rates of change in storage for soil water and ponds are passed, allowing evaluation of an overall water balance according to equation (A.1) based on these and MODFLOW's results. Pumping rates from surface and ground water diversions are specified to meet the irrigation demand simulated by SWAT, but are constrained to stay within operating limits imposed on individual water rights, and within supply limits imposed by available streamflow and aquifer saturated thickness. The modified packages MODSTR and MODWEL are both involved in satisfying these constraints.

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

Meeting irrigation demand with surface and ground water diversions

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

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

$$Q_{app} = \Sigma q_{gk} + \Sigma q_{sk} \qquad (A.17)$$

The first summation on the right is taken over the appropriations for n_g individual ground water rights, and the second for n_s individual surface water rights. For a given time period of interest, if water use is known for the individual water rights, total water use can be similarly expressed. Otherwise, the irrigation demand simulated by SWAT and given as a flow rate, Q_{irr}, by equation (A.11) can be distributed over water rights appropriated for irrigation. This is done by defining the factor, $s = Q_{irr}/Q_{app}$, which is used to scale the annual appropriations of the individual diversions, expressed as pumping rates. Multiplying equation (A.17) by s gives

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

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

In the case of the Lower Republican River basin model, irrigation demand was simulated in SWAT on a daily basis, summarized for monthly time steps Δt, and averaged over the eighteen HRUs for each subbasin by equation (A.15) to give the average depth $d_{irr}f_{irr}$. The average irrigated area fraction of the basin was $f_{irr} \approx 0.04$ for years 1977-1994. The flow rate corresponding to this monthly demand is given by equation (A.11). The total annual appropriations for ground and surface water rights meet this demand by distributing the scaling factor, s, which is zero except during the growing season, over the individual water rights according to equation (A.18). Data from DWR were used to develop estimates of irrigation water use. Predictive models of irrigation water use were also developed thad depend on total precipitation during the growing season.

Operational and supply limits on surface and ground water diversions

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

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

$$q'_{gk} = \min(s, s_g)\, q_{gk}, \qquad \text{(A.19)}$$

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

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

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

This technique provides a realistic means of preventing grid cells from going "dry" as a result of excessive pumping from wells. But equation (A.20) makes the affected pumping rates head-dependent components of the forcing function $R(\mathbf{x})$ in equation (A.6), which can adversely affect solution convergence if not handled properly.

A.5. Spatial heterogeneity of an underlying aquifer (HRU schemes 1-3)

A preceding discussion of the conceptual model for ground water recharge (equation A.12) notes that SWAT's model for the soil profile presumes the existence of a vadose zone and underlying aquifer, the destination of water that percolates below the root zone. But approximately 87 percent of the study area lies outside the alluvial valley, where the soil profile is underlain by bedrock. A conceptual model for these features and their hydrologic effects are illustrated by Figs. A.2 and A.3. Figure A.2 shows a hypothetical watershed, part of which is underlain by an alluvial aquifer with a corridor of shallow ground water along the stream. Irrigated cropland is signified by the green circles. Figure A.3 shows the vertical profile for watershed transect A-A'. Along this transect, the segment b-b' spans the alluvial valley, and the segment c-c' spans the corridor of shallow ground water near the stream. Three HRU-based approaches to modeling the hydrologic effects of this spatial heterogeneity are presented here.

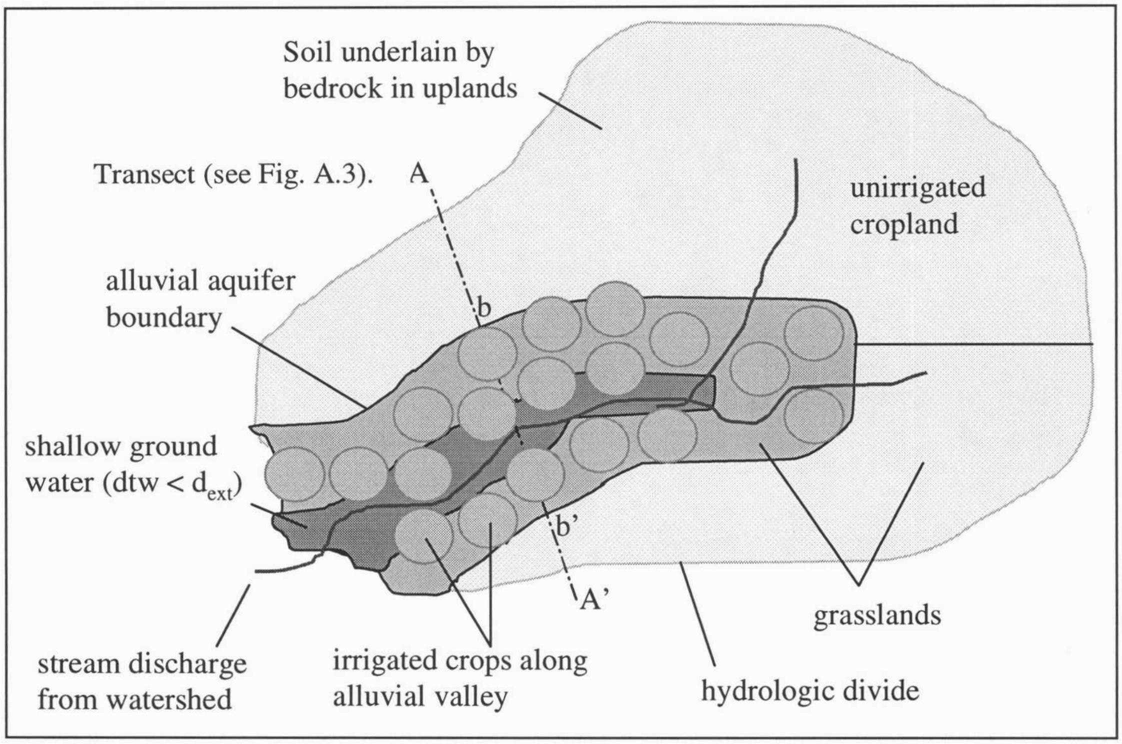

Fig. A.2. Conceptual model for spatial heterogeneity with respect to a subbasin's geomorphology. HRU schemes 2 and 3 disaggregate the alluvial aquifer from the uplands, and deep from shallow ground water (scheme 3).

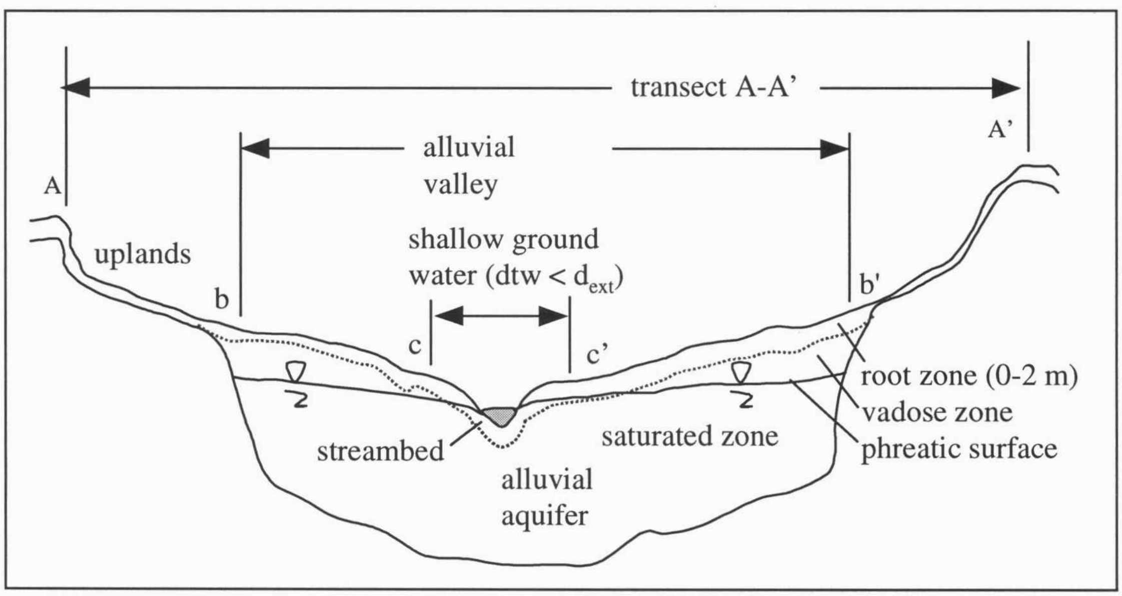

Fig. A.3. Profile of subbasin shown in Fig. A.2 along an arbitrary transect A-A'.

HRU scheme 1 for a subbasin partially underlain by an alluvial aquifer

HRU scheme 1 represents the hydrologic effects of a watershed partially underlain by an aquifer as follows. First, HRUs are simulated on a daily basis by SWAT assuming that the soil profile is underlain by an aquifer. Irrigation, recharge, tributary flow, and potential evaporation are based on equations (A.11-A.14). Ground water recharge includes percolation, transmission losses, and pond seepage for the areal fraction of the watershed underlain by an aquifer, f_{aqf} (equation A.14b). For the remainder of the watershed outside the alluvial valley, these components are assumed to contribute to streamflow (equation A.13). This scheme is intended to preserve continuity, but is inconsistent with assumption of an underlying aquifer in SWAT's simulation. Effects of this inconsistency were examined in Perkins (1999) by comparison with alternative HRU schemes 2 and 3, described below.

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

HRU schemes 2 and 3 provide a more hydrologically consistent approach in which the soil profile for a given HRU is underlain completely by either an aquifer or bedrock, according to an option specified by SWAT's modified Control Codes input file (*.cod). For the subbasin component outside the alluvial valley, percolation out of the root zone is held to zero, producing increases in lateral subsurface flow, soil moisture, and evaporation. These alternate flow paths are illustrated in Fig. A.1. SWAT's subroutine Purk18, which simulates percolation through the soil layers, was modified to implement this option. The hydrologic connections for ground water recharge and tributary inflow (equations A.12-A.14) still apply, taking $f_{aqf} = 1$ for HRUs with an underlying aquifer, and $f_{aqf} = 0$ with underlying bedrock. Then for a soil profile underlain by bedrock, components that would otherwise contribute to ground water recharge are treated as components of tributary flow.

Land use heterogeneity for HRU scheme 2

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

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

1. Non-irrigated crop rotations outside the alluvial valley (no aquifer);

2. Irrigated cropland within the alluvial valley (with aquifer);
3. Grassland within the alluvial valley (with aquifer);
4. Grassland outside the alluvial valley (no aquifer).

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

$$c_{1j} = f_{cj} - f_{\mathrm{irr},j} \quad \text{(non - irrigated cropland, soil over bedrock);} \quad \text{(A.21a)}$$

$$c_{2j} = f_{\mathrm{irr},j} \quad \text{(irrigated cropland, alluvial aquifer);} \quad \text{(A.21b)}$$

$$c_{3j} = f_{\mathrm{aqf},j} - c_{2j} \quad \text{(grassland, alluvial aquifer);} \quad \text{(A.21c)}$$

$$c_{4j} = 1 - f_{\mathrm{aqf},j} - c_{1j} \quad \text{(grassland, soil over bedrock).} \quad \text{(A.21d)}$$

This scheme builds on the one given by equations (A.15a-c) for HRU scheme 1. The areal fraction of cropland within each subbasin, *j*, is denoted by f_{cj}, which is divided into non-irrigated and irrigated components of cropland corresponding to equations (A.21a-b). In Equations (A.21c-d), c_{3j} and c_{4j} are the alluvial and upland components of the subbasin not under cultivation, respectively, and are represented as grassland.

The alluvial valley's areal fraction of the basin, 0.125, exceeds that of irrigated cropland, 0.04; but the alluvial valley's areal fraction within each subbasin varies widely, from 0.01 to 0.25 pct (Table A.1). To keep the irrigated cropland within the alluvial valley for HRU schemes 2 and 3, the basin's irrigated area was distributed over the subbasins using the approximation $A_{\mathrm{irr},j} \approx A_{\mathrm{irr}}\left(A_{\mathrm{aqf},j} / A_{\mathrm{aqf}}\right)$. Dividing this by the subbasin area, $A_{\mathrm{sub},j}$, multiplying and dividing the right-hand side by basin area, A_{bas}, and rearranging, the irrigated areal fraction for each subbasin is approximated by $f_{\mathrm{irr},j} = \dfrac{f_{\mathrm{irr}}}{f_{\mathrm{aqf}}} \dfrac{A_{\mathrm{aqf},j}}{A_{\mathrm{sub},j}}$. Note that this would likely have been a better approximation than the basin-wide areal fraction, f_{irr}, that was used for HRU scheme 1

The land use scheme given by equations (A.21a-d) is justified mathematically by showing that the coefficients for a given subbasin add to 1. Similarly, the areal fractions for the six soil types add to 1 for a given subbasin. If the soils and land uses are assumed to be independent as in the case of the basic HRU scheme 1, their combinations yield 24 HRUs to be simulated and averaged according to equations (A.15a-b). But by recognizing dependencies between soil types and land classes, spatial heterogeneity within each subbasin can be more accurately represented, and the required number of HRUs can be reduced significantly as follows.

The two alluvial land use schemes given by equations (A.21b-c) are associated only with Carr and Muir soils; their combinations are represented by four HRUs. Combinations of the remaining two land uses and four soil types can be represented by eight HRUs, for a total of 12 HRUs. The number of required simulations can be further reduced to 10. Noting that two of the soils outside the alluvial valley, Hastings and

Hedville, do not occur together within subbasins (Table A.1), execution of their HRUs can be combined.

HRU scheme 3: disaggregating areas with shallow ground water

HRU scheme 3 further distinguishes deep and shallow aquifer components as illustrated in Fig. A.2. For HRUs representing areas with shallow ground water, SWAT and MODFLOW solutions are coupled by uptake of shallow ground water into the soil profile. These schemes are implemented by modifications to SWAT's simulation of the component HRUs and to the SWAT-MODFLOW linkage (Fig. 2.1).

Here shallow ground water is considered to be at a depth $z < z_{ext}$, where z_{ext} is the extinction depth as defined for MODFLOW's Evaporation package. MODFLOW approximates evaporation from shallow ground water as a linearly varying function of depth to water given by equation (A.16), where the maximum rate can be specified by potential evaporation calculated by SWAT.

SWAT simulates components of a soil water balance using the SCS curve number procedure (USDA, 1972) to determine excess rainfall, and storage routing techniques (Arnold et al., 1994) to determine infiltration, percolation,subsurface lateral flow, upward capillary flow, and plant water uptake. In addition, SWAT defines "revap" as flow from shallow ground water to the soil profile, but treats revap as water that evaporates directly from ground water to the atmosphere, bypassing the soil water balance. Note that equation (A.8) neglects upward movement of water into the soil profile, while accounting for downward movement out of the soil profile by percolation. Revap is given simply by the product of the "actual" evaporation rate and a constant (Arnold et al., 1994).

HRU scheme 3 provides a means for coupling the soil water balance in SWAT to upward flow from shallow ground water simulated by MODFLOW. The soil water balance (equation A.8) can be rewritten to include a term for capillary uptake from shallow ground water, denoted here as d_{cap}:

$$d_{sw}(t) - d_{sw}(0) = \sum_{i=1}^{t} \left(d_{pcp} - d_{ro} - d_{xm} - d_{perc} - d_{et} + d_{cap} \right) \qquad \text{(A.22)}$$

For an HRU-averaged soil water balance, capillary uptake into the soil profile, d_{cap}, is expressed in equation (A.22) as a daily volume per unit area of subbasin. This depends on simulation results from MODFLOW for "evaporation from shallow ground water," expressed as a flow rate, and the area of shallow ground water. This area is also used to calculate weights for HRUs with shallow ground water in each solution time step.

The dependence of the term d_{cap} in equation (A.22) on MODFLOW's results implies that a simultaneous solution is needed for SWAT and MODFLOW. This was originally assumed to require linked execution of SWAT and MODFLOW as outlined by Fig. 1 of S&P (1999). HRU scheme 3 provides an alternate means of coupling these solutions based on separate execution of SWAT and MODFLOW using successive approximation, a technique that is discussed below.

In each aquifer solution time step and for each subbasin, MODFLOW's MODSWB package summarizes evaporation from shallow ground water as a flow rate and the corresponding area of shallow ground water within the active grid domain. These results are summarized by subroutine SWB2BD for each corresponding time step to a file that can be read in a subsequent execution of SWAT. They are used to calculate (a) time-varying spatial weight functions (subroutine SUBWTS) for the HRU scheme 3 that distinguishes deep and shallow ground water components, and (b) daily capillary uptake into the soil profile from shallow ground water, converting flow rates given by MODFLOW into volumes per unit area according to equation (A.9) in subroutine PRESWB. SWAT's subroutine Subbasin was modified to distribute the daily uptake over the soil profile, beginning with the bottom layer, limited by each layer's available water capacity. This incorporates capillary uptake from shallow ground water, d_{cap}, into the soil water balance (equation A.22). The routing approach taken to this redistribution in subroutine Subbasin is ad hoc but appropriate to the essentially ad hoc models implemented in MODFLOW for evaporation from shallow ground water and in SWAT for soil water movement.

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

$$c_{1j} = f_{cj} - f_{\mathrm{irr},j} \qquad \text{(non - irrigated cropland, no aquifer)} \qquad \text{(A.23a)}$$

$$c_{2j} = f_{\mathrm{irr},j}\left(1\text{-}f_{\mathrm{shl},j}\right) \qquad \text{(irrigated cropland, deep alluvial aquifer)} \qquad \text{(A.23b)}$$

$$c_{3j} = \left(f_{\mathrm{aqf},j} - c_{2j}\right)\left(1\text{-}f_{\mathrm{shl},j}\right) \qquad \text{(grassland, deep alluvial aquifer)} \qquad \text{(A.23c)}$$

$$c_{4j} = 1 - f_{\mathrm{aqf},j} - c_{1j} \qquad \text{(grassland, no aquifer)} \qquad \text{(A.23d)}$$

$$c_{5j} = f_{\mathrm{irr},j} f_{\mathrm{shl},j} \qquad \text{(irrigated cropland, shallow alluvial aquifer)} \qquad \text{(A.23e)}$$

$$c_{6j} = \left(f_{\mathrm{aqf},j} - c_{2j}\right) f_{\mathrm{shl},j} \qquad \text{(grassland, shallow alluvial aquifer)} \qquad \text{(A.23f)}$$

In this land use/resource scheme, $f_{\mathrm{shl},j}$ represents the shallow aquifer's areal fraction of the gridded aquifer area within subbasin j. Land use components representing the alluvial valley for HRU scheme 2 (equations A.21b-c) have simply been divided into two components each, corresponding to deep aquifer components (equations A.23b-c) and shallow aquifer components (equations A.23e-f). Outside the alluvial valley, land uses and soil types are represented by six HRUs as before. Within the alluvial valley, the four land use components and two associated soil types are represented by eight HRUs, requiring a total of 14 HRUs. This is still fewer that the number required for the basic HRU scheme 1, which can be reduced to 15 if HRUs associated with Hastings and Hedville soils (Table A.1) are combined as described for HRU schemes 2 and 3.

HRU weights, w_k, for this scheme are given by the products of soil type and land use (equation A.15b), and are calculated by subroutine SUBWTS in each aquifer solution time step. This accounts for time-varying changes in the area of shallow ground water in response to drought-flood cycles. As illustrated by Figs. A.2-A.3, the rise and fall of the water table with wet and dry seasons and with irrigation pumping affects not only the direction of flow across the streambed into or out of the stream channel, but also the width of the aquifer extent with a depth less than the extinction depth, d_{ext}. This is taken to be the lower limit for shallow ground water based on MODFLOW's conceptual model for evapotranspiration, which is assumed to contribute to upward capillary flow through the soil profile and to plants. The temporal variation of the spatial extent of shallow ground water results in time-varying HRU weights, which are consequently evaluated for each time step.

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

$$d_{i,j} = cQ_{i,j}\Delta t / f_{s,j}A \qquad \text{(A.24)}$$

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

$$f_{s,j} = f_{\text{sub},j} f_{\text{aqf},j} f_{\text{shl},j} \qquad \text{(A.25)}$$

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

Coupling SWAT and MODFLOW solutions by successive approximation

Results from MODFLOW's simulation of evaporation from shallow ground water and the associated area are passed to SWAT in each time step using the technique of successive approximation. This is used routinely for numerical solutions that depend on a converging sequence of approximations, such as MODFLOW's solution for aquifer heads. Here, HRU scheme 2 provides an initial solution for the coupled SWAT-MODFLOW simulation, following the procedure outlined by Fig. 2.1 and with $d_{\text{cap}} = 0$ in the soil water balance (equation A.22). A summary of results for evaporation from shallow ground water for each time step of this simulation can be used in a subsequent pass through the procedure of Fig. 2.1 based on HRU scheme 3, with $d_{\text{cap}} \neq 0$ for HRUs with shallow ground water. Results for HRU schemes 2 and 3 corresponding to the first two passes through the simulation procedure (Fig. 2.1) are presented in Perkins (1999).

Appendix B. Specifying the SWAT-MODFLOW linkage

A description of the SWAT-MODFLOW linkage as a user's manual will appear in volume 1 of documentation for this project as a sequel to KGS Open-File Report 99-24 (P&K, 1999).

SWAT

The SWAT-MODFLOW linkage is specified in SWAT by additional data that are read from the Control Codes input file that control the writing and reading of data files that provide either one-way or two-way couplings between SWAT and MODFLOW simulations. In addition to the Control Codes input file, two additional fields of data are proposed for the automatic irrigation operation (mgt_op = 10) in the Management Codes input file in order to specify a maximum daily irrigation limit and to allow specifying a soil water content threshold as a fraction of available field capacity.

The proposed changes to the Control Codes and Management Codes input files do not appear to interfere with the existing SWAT capabilities nor with their specification in these data files. The only restriction on data sets used for input to the original SWAT v.99.2 is that the data fields used for the added capabilities contain blanks or a value of zero. The relevant fields include the following:

Control Codes input file: **iopmod** (columns 89-92 on record 2), to indicate that an additional record (6) is to be read specifying the SWAT-MODFLOW linkage;

Management Codes input file, for automatic irrigation initialization (**mgt_op** = 10):

i. **auto_swf** (columns 49-56), automatic irrigation threshold based on soil water content as a fraction of available field capacity,

ii. auto_dmx (columns 61-66), maximum daily irrigation limit on automatic irrigation that applies to both plant stress factor and soil water content threshold options.

SWBAVG

As in the case of the unmodified SWAT v.99.2 code, spatial heterogeneity is represented by spatially weighted averages of hydrologic response unit (HRU) simulations. In addition to the unmodified version's capability for representing HRUs, the SWAT-MODFLOW linkage includes the capability for calculating HRU weights and averages external to SWAT using the program SWBAVG. This capability is useful for modeling watersheds requiring a large number of HRUs to represent each subbasin, represented by the combinations of soil types and land use/land form classes. It is also useful for calculating HRU weights that vary over time. This latter case can occur if subbasins are to be partitioned into HRU components with either deep or shallow ground water, since both the land area with shallow ground water and the associated upward flow rate due to capillary, evaporative, or seepage processes will vary with depth to ground water in response to meteorological conditions.

MODFLOW

SWAT simulation results, summarized over each aquifer time step and averaged over HRUs by SWBAVG, are used as input to MODFLOW. The package MODSWB was written for MODFLOW to read these data as flow rates and convert them for each subbbasin into flow rates for individual cells of the stream and aquifer grids to specify flow conditions for MODFLOW's solution in each time step. MODSWB also summarizes MODFLOW's solution for each subbasin in a form that can be input to SWAT and SWBAVG in subsequent executions. This capability is applied to represent a two-way coupling between SWAT and MODFLOW based on successive approximation (see Methodology). Here we describe input data to SWAT v.99.2 and SWBAVG for a linkage to the version of MODFLOW that is documented in KGS Open-File Reports 99-24 and 99-25 (Perkins and Sophocleous)

<u>HRU-related input to SWAT and SWBAVG</u>

The following HRU-related items are all specified as part of the modified Control Codes (*.cod) input file, but only **iaqufr** is read by SWAT; the remaining items are read only by SWBAVG, which calculates HRU weights and HRU-weighted averages. The modified Control Codes (~.cod) input file provides these data for the linkage as required to both SWAT and SWBAVG as described below under "Instructions for modified Control Codes (*.cod) input data file."

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

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

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

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

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

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

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

1. Control codes file (~.cod) format for input to SWAT (items 1 to 6)

The following data records are read by SWAT subroutine READCOD from the Control Codes (*.cod) input file. Only input variables affected by SWAT-MODFLOW linkage are defined; for definitions of standard input, see SWAT v.99.2 documentation.

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

title: input description line.

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

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


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

Added item for SWAT-MODFLOW coordination:
if (**iopmod** > 0) read item 6:

```
Data (FREE) cnvlen, cnvlbl, nambal, namshl    !(f8.4,3a)              (6
```

Example Control codes input file hru_deep.cod

```
Control File ! hru_deep.cod (aquifr=1, swminf=0.65)                  (1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
                                                                     (3
                                                                     (4
                                                                     (5
   1 ' '  ' '                   ! '(i4,2a)': iaqufr nambal namshl    (6
```

Definitions for Control Codes input file (~.cod) record items 1-6

ipd (cols. 13-16): print code for standard output file (0: monthly, 1: daily, 2: annually). NOTE: if **iopmod** > 0 (see below), **ipd** also specifies ground water simulation time steps over which SWAT results are to be summarized for linkage to MODFLOW's stream-aquifer simulation. In addition, if **iaqufr** = 2 (specified on record 6; see below), which specifies a two-way coupling between SWAT and MODFLOW, then SWAT also reads a summary of results describing shallow ground water in the corresponding time steps; the name of this file is specified by the variable **namshl** (also on record 6).

ipet (cols. 77-80): choice of method for calculating potential evaporation; see manual for explanation of original options 0-2:

0: Priestley-Taylor;
1: Penman-Monteith;
2: Hargreaves;
3: no available option for SWAT v.99.2. (In SWAT v.94.2, this invoked use of subr. Penman, which applied the Penman method as recommended by W.J. Shuttleworth in Chapter 5 of the Handbook of Hydrology, Maidment, ed., 1993. This option was incorporated into SWAT v.94.2 in order to include the effects of long-wave radiation emission; see P&S, 1999b-c).

iopmod (cols. 89-92): This input code is now read from record 2 of the Control Codes input file (*.cod). A positive value indicates that a summary file for the SWAT-MODFLOW linkage is to be written. An additional record of data is also read following the standard records; see record item 6 (below).

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

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

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

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

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

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

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

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

2. Control codes file (~.cod) format for input to SWBAVG (record items 7 to 14)

In addition to records 1-6 that are read by SWAT (above), SWBAVG reads data records 7-14 as labeled in the example shown below (file hru1.cod). These data are used by SWBAVG to take spatially weighted averages over HRUs simulated by SWAT to represent spatial heterogeneity with respect to soil type and land use within subbasins.

Record items 7-14 specify the HRU scheme, individual HRUs, and their properties as they pertain to the calculation of HRU weights, spatial averaging of HRUs simulated by SWAT for each hydrologic component, combination of hydrologic components to specify ground water recharge and tributary inflow; and conversion of HRU-averaged results simulated by SWAT from hydrologic depths (volumes per unit area) to flow rates for input to MODFLOW.

```
Data (FREE) iophru numhru nsubs                                    (7
format (3i4)
```

<u>Subbasin areal fractions for aquifer, crops, and soils for each defined type</u>

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

Read for each subbasin i:

```
    Data (FREE) idx,aqffrc(i),crpfrc(i),(soilwt(i,j),j=1,nsoils)   (9

Data (FREE) (pctirr(k), k=1,nyrs)                                  (10

Data (FREE) numuse, (crpnam(i),i=1,numuse)                         (11
```

<u>Table of properties associated with each HRU</u>

```
Data (text) header                                                 (12
```

Read for each HRU *i* =1 to numhru (see item 3, above):

```
    Data (FREE) idx,idxsol(i),idxuse(i),idxaqf(i), namhru(i)       (13


Data (FREE)  casavg                                                (14
```

<u>Example Control codes input file hru1.cod</u>

This input file specifies HRU scheme 1.

```
hru1.cod (15 HRUs, iophru=1; swminf=0.65,ipet=0(Priestley-Taylor) iaqufr=1     (1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1
0                                                                              (2
                                                                               (3
                                                                               (4
                                                                               (5
  0.3048  'm/ft'  ' '   ' '     ! '(f8.4,3a)': cnvlen cnvlbl nambal namshl     (6
   1  15   9                    ! '(3i4)':     iophru numhru nsubs cnvlen cnvlbl  (7
5,     'aqffrc' 'crpfrc' 'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir'           (8
   1     0.0733  0.5962   0.092   0.471   0.099     0.338     0               (9
   2     0.2053  0.5463   0.191   0.064   0.402     0.342     0
   3     0.2368  0.6281   0.098   0.637   0.132     0.052   0.081
   4     0.0924  0.5737   0.126   0.543   0.054     0.274   0.004
   5     0.2106  0.7164   0.043   0.745       0     0.086   0.126
   6     0.0122  0.6113       0   0.741   0.176     0.059   0.024
   7     0.0829  0.6753       0   0.869   0.022         0   0.108
   8     0.0257  0.5316       0   0.697   0.279         0   0.024
   9     0.2504  0.4991       0   0.630   0.021         0   0.348
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28  4.21  4.31  4.52  4.42
4.77  4.70                                                                     (10
3,'nonirrig','irrig','noncrop'    !numuse, (crpnam(j),j=1,numuse)              (11
  hru soil  use aquifr namhru                                                  (12
```

```
   1    1    1    1  'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.)                    (13
   2    1    2    1  'carr-irm'          (irrigated corn)
   3    1    3    1  'carr-pam'          (grass: range and pasture)
   4    2    1    1  'cret-wsm'   soil 2
   5    2    2    1  'cret-irm'
   6    2    3    1  'cret-pam'
   7    3    1    1  'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
   8    3    2    1  'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
   9    3    3    1  'hshd-pam'
  10    4    1    1  'kips-wsm'   soil 4
  11    4    2    1  'kips-irm'
  12    4    3    1  'kips-pam'
  13    5    1    1  'muir-wsm'   soil 5
  14    5    2    1  'muir-irm'
  15    5    3    1  'muir-pam'
'hru1', namcas (this line is read by Swbavg, not Swat)                                 (14
```

Definitions for record items 7-14

Record item 7:

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

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

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

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

b) 10-HRU scheme taking into account soil and land use dependencies. Alluvial land uses (irrigated corn and grasslands) are associated only with alluvial soils (1:Carr and 2:Muir); upland land uses (dryland crop rotation and grassland) are associated only with non-alluvial soils 3:Crete, 4:Kips, and 5:(Hastings and Hedville). Hastings and Hedville are combined into one HRU soil factor with Hastings soils only in subbasins 1-4 and Hedville soils in subbasins 6-9.

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

numhru: no. HRUs (hydrologic response units) that must be run and then averaged for a complete simulation of this case. The case numhru = 1 indicates that the HRU averaging, if any, was handled by SWAT. In this case, only input and output file name prefixes, namhru(1) and casavg on record item 8a need to be read; items 8b-14 are read only if **numhru** > 1.

nsubs: no. subbasins.

if numhru = 1 (read only record item 8a):

Record item 8a (for the case numhru = 1):

namhru(1) name of HRU, up to 8 characters; compared with case name for match to determine which HRU is represented by the simulation.

casavg: suffix for balance file to be written by Swbavg.

If numhru > 1 (read items 8b-14, the data needed to take averages over HRUs):

Record item 8b:

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

aqflbl, crplbl: Column labels for areal fractions of aquifer and cropland within each subbasin.

soilnm(i): Column labels for areal fractions of each soil type, i=1 to nsoils.

Record item 9:

idx = index to subbasin (should be the same as counter i).

aqffrc(i) area of aquifer underlying soil as a fraction of subbasin *i*

crpfrc(i) cropland as fraction of subbasin *i*

soilwt(i,j) fraction of subbasin *i* covered by each soil type *j*

Record item 10:

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

Record item 11:

numuse = no. land use classes defined for this HRU scheme (iophru, line 7)

crpnam(i) = name of land use class i from 1 to numuse.

Land use class labels for each of three defined HRU schemes (1-3):

iophru	numuse	labels for land use schemes (crpnam(j),j=1,numuse)
1	3	'nonirrig','irrig','noncrop' !numuse,
2	4	'wsf-upld','irr-aqfr','grs-aqfr','grs-upld'
3	6	'wsf-upld','irr-aqdp','grs-aqdp','grs-upld','irr-aqsh','grs-aqsh'

Description of land use classes for each HRU scheme (1-3)

```
if (iophru.le.1) then    !HRU model option 1: 3 land uses
  crpnam(1) = 'nonirrig'  !no irrig. e.g. wheat,sorghum,fallow rotation
  crpnam(2) = 'irrig'     !irrigated crops
  crpnam(3) = 'noncrop'   !range, pasture, and other noncrop land uses
else if (iophru.eq.2) then !option 2 distinguishes subbasin with aquifer
  crpnam(1) = 'wsf-upld'  !non-irrigated crops in upland, no aquifer
  crpnam(2) = 'irr-aqfr'  !irrigated cropland over alluvial aquifer
  crpnam(3) = 'grs-aqfr'  !grasslands over alluvial aquifer
```

```
  crpnam(4) = 'grs-upld'  !grass in upland, no aquifer
else  !option 3 distinguishes aquifer with shallow & deep components
  crpnam(1) = 'wsf-upld'  !non-irrigated crops in upland, no aquifer
  crpnam(2) = 'irr-aqdp'  !irrigated cropland, deep alluvial aquifer
  crpnam(3) = 'grs-aqdp'  !grasslands, deep alluvial aquifer
  crpnam(4) = 'grs-upld'  !grass in upland, no aquifer
  crpnam(5) = 'irr-aqsh'  !irrigated cropland, shallow alluvial aquifer
  crpnam(6) = 'grs-aqsh'  !grasslands, shallow alluvial aquifer
end if
```

Record item 12:
header = heading for the following table (item 13).

Record item 13:
idx index to identify HRU (should be the same as counter i)
idxsol(i) soil type associated with HRU i
idxuse(i) land use associated with HRU i
idxaqf(i) aquifer status associated with HRU i. Definitions:
= −1: soil is underlain by bedrock. Option is passed to subroutine Purk to indicate that percolation out of the root zone is blocked by bedrock, resulting in alternate routes (increased lateral subsurface flow, soil water content, and evaporation).
= 0: soil is underlain by an aquifer that is deep enough that soil and plant water uptake from ground water is negligible.
= 1: soil is underlain by a shallow aquifer. This case is associated with HRU option 3 and input file **namshl** (above), which specifies areal fraction of shallow aquifer and evaporation from shallow ground water in each time step for each subbasin according to Modflow's solution.
namhru(i) name of HRU, up to 8 characters; compared with case name for match to determine which HRU is represented by the simulation.

Record item 14:
casavg: suffix for balance file containing average over all HRUs, and written by Swbavg.

Instructions for modified ground water (*.gw) input data file

Format for this file was modified to specify conceptual models for a soil profile sitting on bedrock (ipurk(j) = -1) and for shallow ground water (ipurk(j) = 1) The case of deep ground water is considered the default conceptual model for MODFLOW.

Modified format of record 3:

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

ipurk(j) = 0: soil profile is underlain by an aquifer with ground water that is deep enough that uptake from ground water by capillary or evaporative processes into the soil profile can be neglected. This is the default case represented by SWAT.
ipurk(j) = −1: soil profile is underlain by bedrock (no aquifer). In this case, no water percolates out of the root zone. This conceptual model is implemented in subr. Purk by setting the variable **sep** to zero after percolation out of the root zone has been calculated.
ipurk(j) = 1: soil profile is underlain by an aquifer with ground water that is shallow enough that uptake into the soil profile is signficant. Subroutine Subbasin was modified to implement this conceptual model by calling subr. Evap_gw to distribute this uptake over the soil profile. This uptake is specified by MODFLOW using a form of successive approximation in which the SWAT-MODFLOW linkage is first applied with the initial assumption of deep ground water in SWAT, and MODFLOW revises this initial assumption by summarizing the area of shallow ground water within each subbasin and the corresponding flow rate into the soil profile based on MODFLOW's evapotranspiration model. This revised estimate of uptake from shallow ground water can be used in a second application of the SWAT-MODFLOW linkage. MODFLOW's results from the second application of the linkage can be used in a third pass and so on in order to examine convergence properties of the solution.

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

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

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

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

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

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

deficit (mm) = swtrig – sol_sumfc(j)

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

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

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

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

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

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

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

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

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

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

Appendix C. Example procedures (HRU schemes 1-3)

Specifying hydrologic response unit (HRU) schemes 1-3

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

Land use/land form schemes for each of three HRU schemes (1-3)

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

HRU Scheme 1:

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

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

In HRU schemes 2 and 3, the conceptual models of a soil profile with underlying bedrock or ground water are consistent between SWAT and SWBAVG. HRUs simulated by SWAT are distinguished by a soil profile either underlain by bedrock (iaqufr = 0) or by ground water (iaqufr > 0). The case of bedrock is represented by a modification to subroutine purk() in which percolation out of the soil profile is set to zero. This is compensated by increased soil water content, lateral subsurface flow, and evaporation.

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

Scheme 1. treat soil type and land use as independent factors

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

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

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

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

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

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

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

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

nsoils=6 (hru1.cod): six soils are specified; specifying Hasting and Hedville separately results in distinct HRUs; in schemes shown below these are combined, since Hasting and Hedville soils are disaggregated by subbasins (Hasting in subbasins 1-4, Hedville in subbasins 6-9, neglecting the small component in subbasin 3).

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

```
rem simulate hrus with deep aquifer: set ipurk(j) = 0 for each subbasin
copy /y hru_deep.gw h2.gw

copy /y   hru1.cod hru.cod

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

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

time
```

File Hru1.cod, input to Swat and Swbavg for HRU scheme 1

```
hru1.cod (15 HRUs, iophru=1; swminf=0.65,ipet=0(Priestley-Taylor) iaqufr=1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
1   0


  0.3048 'm/ft' ' '  ' '  ! '(f8.4,3a)': cnvlen cnvlbl nambal namshl (last line read by
SWAT in subr Readcod)
   1  15    9   ! '(3i4)': iophru numhru nsubs  (read by SWBAVG)
5,     'aqffrc' 'crpfrc' 'Carr' 'Crete' 'HastHedv' ' Kipson' 'Muir' !nsoils,...;
aqfbas=0.1261
   1     0.0733  0.5962   0.092   0.471    0.099     0.338       0
   2     0.2053  0.5463   0.191   0.064    0.402     0.342       0
   3     0.2368  0.6281   0.098   0.637    0.132     0.052   0.081
   4     0.0924  0.5737   0.126   0.543    0.054     0.274   0.004
```

```
  5     0.2106  0.7164   0.043    0.745        0      0.086   0.126
  6     0.0122  0.6113       0    0.741    0.176      0.059   0.024
  7     0.0829  0.6753       0    0.869    0.022          0   0.108
  8     0.0257  0.5316       0    0.697    0.279          0   0.024
  9     0.2504  0.4991       0    0.630    0.021          0   0.348
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28  4.21  4.31  4.52
4.42  4.77  4.70
3,'nonirrig','irrig','noncrop'    !numuse, (crpnam(j),j=1,numuse)
  hru Soil  Mgt Ipurk(gw) namhru   HRU description
   1    1    1     0  'carr-wsm'   soil 1 (wheat/sorghum/fallow rot.) (case, file name)
   2    1    2     0  'carr-irm'          (irrigated corn)
   3    1    3     0  'carr-pam'          (grass: range and pasture)
   4    2    1     0  'cret-wsm'   soil 2
   5    2    2     0  'cret-irm'
   6    2    3     0  'cret-pam'
   7    3    1     0  'hshd-wsm'   soil 3:Hastings(subs 1-5), Hedville(subs 6-9)
   8    3    2     0  'hshd-irm'  (collapses 6 hrus for the two soils into 3 hrus)
   9    3    3     0  'hshd-pam'
  10    4    1     0  'kips-wsm'   soil 4
  11    4    2     0  'kips-irm'
  12    4    3     0  'kips-pam'
  13    5    1     0  'muir-wsm'   soil 5
  14    5    2     0  'muir-irm'
  15    5    3     0  'muir-pam'
'hru1', namcas (this line is read by Swbavg, not Swat)
```

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

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


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

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

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

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

Execution of MODFLOW given results on file Hru1.bal:

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

Response file Hru1.rsp contents:

```
    hru1                                       case name (~.log, ~.prn, ~.rsp)
    ..\inbase\bcase_t4.bas                    .bas unit   1 Monthly Basic package
    ..\inbase\kbase20b.bcf                    .bcf unit  61 Block-centered flow
    ..\inbase\wrrepub.wel                     .wel unit  62 Well: groundwater use
    ..\inbase\repsurf.evt                     .evt unit  65
    ..\inbase\rptest.swb                      .swb unit  66 Soil water balance
    ..\inbase\matrix1.rch                     .rch unit  67 Recharge
```

```
..\inbase\model1bs.pcg                        .pcg unit  68 precond. conj. grad.
..\inbase\rpbase.oc                           .oc  unit  69 Output control
..\inbase\rptest.str                          .str unit  70 monthly Streamflow
..\inbase\basecase.pos                        .pos unit  64 Postprocessor: budgets
..\inbase\gwuadmnu.obs                        .obs unit  72 gw level observations
```

Scheme 2. disaggregate alluvial valley and upland

Table C.1 shows the land use areal fractions given by equations 4.21a-d.

Table C.1. HRU scheme 2 land use fractions

sub-basin	upland, dry crop c1	alluv, irrig c2	alluv, grass c3	upland, grass c4	=sum
1	0.566024	0.030176	0.043124	0.360676	1
2	0.461782	0.084518	0.120782	0.332918	1
3	0.530614	0.097486	0.139314	0.232586	1
4	0.535661	0.038039	0.054361	0.371939	1
5	0.629700	0.086700	0.123900	0.159700	1
6	0.606277	0.005023	0.007177	0.381523	1
7	0.641172	0.034128	0.048772	0.275928	1
8	0.521020	0.010580	0.015120	0.453280	1
9	0.396015	0.103085	0.147315	0.353585	1

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

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

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

```
rem simulate hrus with deep aquifer: set ipurk(j) = 0 for each subbasin
copy /y hru_deep.gw h2.gw

rem note: indiv. cio files refer to hru_deep.cod.
rem copy /y   hru_deep.cod hru.cod

copy /y   carr-ird.cio file.cio
..\swt99opt >hru2.jnl
copy /y   carr-pad.cio file.cio
..\swt99opt >>hru2.jnl

copy /y   muir-ird.cio file.cio
..\swt99opt >>hru2.jnl
copy /y   muir-pad.cio file.cio
..\swt99opt >>hru2.jnl

rem simulate hrus with bedrock under soil profile: set ipurk(j) = -1
copy /y hru_bedr.gw h2.gw

rem note: indiv. cio files refer to hru_bedr.cod instead of generic
hru.cod.
rem copy /y   hru_bedr.cod hru.cod
```

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

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

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

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

File Hru2.cod, input to SWAT and SWBAVG

```
hru2.cod (10 HRUs, iophru=2; swminf=0.65,ipet=0(Priestley-Taylor) iaqufr=1
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0


  0.3048 'm/ft' ' '  ' '  ! '(f8.4,3a)': cnvlen cnvlbl nambal namshl
   2  10   9   ! '(3i4)': iophru numhru nsubs  (read by SWBAVG)
5,     'aqffrc' 'crpfrc' 'Carr' 'Muir'  'Crete' 'Kipson' 'HastHedv' !nsoils,...;
  1     0.0733    0.5962         1         0  0.518722  0.372247  0.109031
  2     0.2053    0.5463         1         0  0.079208  0.423267  0.497525
  3     0.2368    0.6281  0.547486  0.452514  0.775883  0.063337  0.160780
  4     0.0924    0.5737  0.969231  0.030769  0.623421  0.314581  0.061998
  5     0.2106    0.7164  0.254438  0.745562  0.896510  0.103490         0
  6     0.0122    0.6113         0         1  0.759221  0.060451  0.180328
  7     0.0829    0.6753         0         1  0.975309         0  0.024691
  8     0.0257    0.5316         0         1  0.714139         0  0.285861
  9     0.2504    0.4991         0         1  0.967742         0  0.032258
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28  4.21  4.31  4.52  4.42  4.77
4.70
4,'wsf-upld','irr-aqfr','grs-aqfr','grs-upld' !numuse, (crpnam(j),j=1,numuse)
  hru Soil  Mgt Ipurk(gw) namhru
    2    1    2    0  'carr-ird' soil 1 deep alluvial: irrigated corn
    4    1    3    0  'carr-pad'        deep alluv.:  grass (range and pasture)
    6    2    2    0  'muir-ird' soil 2 deep alluvial: irrigated corn
    8    2    3    0  'muir-pad'        deep alluv.: grass (range and pasture)
    9    3    1   -1  'cret-wsb' soil 3 upland: wheat/sorghum/fallow rotation
   10    3    4   -1  'cret-pab'                grass (range and pasture)
   11    4    1   -1  'kips-wsb' soil 4 upland: wheat/sorghum/fallow rotation
   12    4    4   -1  'kips-pab'                grass (range and pasture)
   13    5    1   -1  'hshd-wsb' soil 5 upland (Hasting 1-4, Hedville 6-9)
   14    5    4   -1  'hshd-pab'                grass (range and pasture)
'hru2', namcas (this line is read by Swbavg, not Swat)


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

File Hru_deep.gw, input to SWAT for HRUs with deep ground water

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

File Hru_bedr.gw, input to SWAT for HRUs with bedrock underlying soil profile

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

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

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

Response file Hru2.rsp contents:

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

Scheme 3. further disaggregate deep and shallow alluvial ground water

Table C.2, below, shows the areal fractions of shallow ground water that can be used with the land use fractions shown in Table C.1 for HRU scheme 2 to obtain those required for HRU scheme 3 according to equations (4.23a-f). Coupling of Swat and Modflow is based on shallow ground water evaporation and area given on file Hru2.shl resulting from the uncoupled HRU scheme 2 (case Hru2, above).

Table C.2. Beginning subbasin areal fractions of shallow ground water

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

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

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

Batch file Hru3.bat to run SWAT and SWBAVG for HRU scheme 3:

```
rem simulate hrus with shallow aquifer: set iaqufr = 2
rem
rem note 1: Run this batch file only after case hru3 has been run.
rem note 2: indiv. cio files refer to hru_shal.cod instead of generic hru.cod.

rem simulate hrus with shallow aquifer: set ipurk(j) = 0 for each subbasin
copy /y hru_shal.gw h2.gw

rem copy /y   hru_shal.cod hru.cod
```

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


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

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

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

File Hru3.cod, input to Swat and Swbavg for HRU scheme 3

```
hru3.cod (14 HRUs, iophru=3; swminf=0.65,ipet=0(Priestley-Taylor)
  181977   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   1   0



  0.3048 'm/ft' ' '  'hru2.shl'  ! '(f8.4,3a)': cnvlen cnvlbl nambal namshl
   3  14   9   ! '(3i4)': iophru numhru nsubs  (read by SWBAVG)
5,     'aqffrc' 'crpfrc' 'Carr' 'Muir'  'Crete' 'Kipson' 'HastHedv' !nsoils,...; aqfbas=0.1261
  1     0.0733    0.5962         1          0  0.518722  0.372247  0.109031
  2     0.2053    0.5463         1          0  0.079208  0.423267  0.497525
  3     0.2368    0.6281  0.547486  0.452514  0.775883  0.063337  0.160780
  4     0.0924    0.5737  0.969231  0.030769  0.623421  0.314581  0.061998
  5     0.2106    0.7164  0.254438  0.745562  0.896510  0.103490         0
  6     0.0122    0.6113         0          1  0.759221  0.060451  0.180328
  7     0.0829    0.6753         0          1  0.975309         0  0.024691
  8     0.0257    0.5316         0          1  0.714139         0  0.285861
  9     0.2504    0.4991         0          1  0.967742         0  0.032258
3.13  3.32  3.42  4.18  4.06  3.54  3.61  3.66  3.51  3.55  3.76  4.28  4.21  4.31  4.52  4.42  4.77
4.70
6,'wsf-upld','irr-aqdp','grs-aqdp','grs-upld','irr-aqsh','grs-aqsh' !numuse, (crpnam(j),j=1,numuse)
  hru Soil  Mgt Ipurk(gw) namhru
    1    1    5    1  'carr-irs' soil 1 shallow alluvial: irrigated corn
    2    1    2    0  'carr-ird'        deep alluvial: irrigated corn
    3    1    6    1  'carr-pas'        shallow alluv.:  grass (range and pasture)
    4    1    3    0  'carr-pad'        deep alluv.:  grass (range and pasture)
    5    2    5    1  'muir-irs' soil 2 shallow alluvial: irrigated corn
    6    2    2    0  'muir-ird'        deep alluvial: irrigated corn
    7    2    6    1  'muir-pas'        shallow alluv.: grass (range and pasture)
    8    2    3    0  'muir-pad'        deep alluv.: grass (range and pasture)
    9    3    1   -1  'cret-wsb' soil 3 upland: wheat/sorghum/fallow rotation
   10    3    4   -1  'cret-pab'                grass (range and pasture)
   11    4    1   -1  'kips-wsb' soil 4 upland: wheat/sorghum/fallow rotation
   12    4    4   -1  'kips-pab'                grass (range and pasture)
   13    5    1   -1  'hshd-wsb' soil 5 upland (Hasting 1-4, Hedville 6-9)
   14    5    4   -1  'hshd-pab'                grass (range and pasture)
'hru3', namcas (this line is read by Swbavg, not Swat)
```

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

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

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

Response file Hru3.rsp contents:

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

rptest.shl: summary of evaporation from shallow ground water

This file is written in Modflow by subroutine Swb2bd, part of the Modswb package. In Swat, it is opened and data for the first time step are read in the mainline (included file Swatmod3.h). At the end of each time step, data for the next time step are read in subroutine Preswb after results for the current time step have been summarized. In the following listing, only data for the first time step, January 1977, are shown.

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

Input file to MODSWB package

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

```
9,    nwshed   (balance file: use case name); file c:\gh\test\inbase\rptest.swb
' ',     1     3     1     1 0.00     1     0 0.0    nambal,irropt,ievopt,ioprch,rchmpy,
                                                    evapir,welmpy,iadcod,frseep
  sub   act   row col sbnxt       tributary
    1     1     4   16    1       Salt Cr
    2     1     6   14    2       Oak Cr
    3     1     6   21    3       Elm Cr
    4     1     5   24    4       Elk Cr
    5     1     7   30    5       Scribner Cr
    6     1     7   30    6       Parsons Cr
    7     1    11   32    7       Peats Cr
    8     1    21   36    8       Five Cr
    9     1    21   37    9       Huntress Cr (Spring & Dry Cr's)
       66             1 (39i2)                            2       iwshed.mod
 0 1 1 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 4 5 5 5 6 6 6 6 6 6 7 7 7 7 7 7
 0 1 1 1 1 0 0 0 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 4 5 5 5 6 6 6 6 6 6 7 7 7 7 7 7
 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 5 5 5 5 6 6 6 6 7 7 7 7 7 7 7
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4 4 4 4 4 5 5 5 5 6 6 6 6 7 7 7 7 7 7 7
 1 1 1 1 1 2 1 1 1 2 2 2 2 1 1 3 3 3 3 3 4 4 4 4 5 5 5 5 6 6 6 7 7 7 7 7 7 7 7
 0 0 2 2 2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 3 3 3 3 5 5 5 5 5 6 6 7 7 7 7 7 7 7 7
```

0	0	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	5	5	5	5	6	6	7	7	7	7	7	9	9	0
0	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	5	5	5	3	7	7	7	7	7	7	9	9	9
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	7	7	7	7	7	9	9	9	9
2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	7	7	7	7	9	9	9	9	9
0	0	0	0	0	0	0	0	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	7	7	7	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	7	7	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	3	8	8	3	3	3	3	3	7	7	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3	8	8	8	8	8	8	3	3	3	3	7	9	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	3	8	8	8	8	8	8	8	8	8	3	3	3	9	9	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	3	8	8	8	8	8	8	8	8	8	3	3	9	9	9	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	3	3	9	9	9	9	9	9	9	9
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	3	3	9	9	9	9	9	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	3	3	3	9	9	9	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	3	9	9	9	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	9	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	0	0	0	0

Appendix D. Test case results

Y7 test case

Comparison of y7 results for 98.1 and 99.2 versions of SWAT

The 99.2 version of SWAT was compiled and linked under Lahey 95. The comparison is for average results for 1975-1977 based on observed Reisel precipitation data. It shows that potential et increases only slightly in moving from the 98.1 version to the 99.2 version (~24 mm), but that actual et is reduced considerably (~-266 mm). There is what appears to be a related increase in surface runoff (~206 mm). There's also an increase of ~51 mm in xm loss; which might also be related to the et reduction.

Summary of results for Y7 test case 1975-1977

version:	98.1	99.2	notes
Precipitation	867.9	867.9	(using observations for both, file riesel.pcp, reformatted for v.99.2)
Surface runoff	350.86	555.95	
Percolation	0.76	0.49	
potential et	2195.4	2219	
et	608.6	342	
h2o yield	346.81	500	
xm loss	4.81	56.4	(shows as zero for 99.2 executable version as downloaded)

Y7 test case results for 1975 using SWAT v. 99.2 can be obtained that are very similar to those for SWAT v. 98.1 for actual (supplied) evaporation if the following three lines are commented out of subroutine swu(), listed in Appendix A, which were added since version 98.1:

```
if (sol_st(k,j) > sol_fc(k,j)) then
   wuse(k) = 0.
end if
```

The insertion of these three lines appears to affect actual (supplied) evaporation drastically for the y7 case. This modified version of Swat 99.2, with the above lines commented out of swu(), will next be used for the Lower Republican case.

Overall water balance for a watershed

Continuity is expressed for a watershed by

dS/dt = net inflow,

where

dS/dt = rate of change in total storage (soil, ponds, ground water, streams);

net inflow = Q_precip +Q_gwlat – Q_evap – Q_yield

Net inflow to the watershed is given by the sum of terms on the right-hand side, which are flow rates for precipitation, net lateral ground water inflow, evaporation, and stream yield. One objective in applying the SWAT-MODFLOW linkage to a watershed model is to obtain an overall water balance for the watershed, in which the equality above for continuity holds; this is expressed by

balance = net inflow – change in storage

Soil water balance for SWAT versions 94.2 and 99.2

As an intermediate check on mass balance, a soil water balance is evaluated for the results written by SWAT that are used to specify fluxes for MODFLOW of recharge and tributary inflows. The soil water balance is intended to be consistent with SWAT's definitions and assumptions. This balance is calculated at the end of each aquifer time step in SWAT by subr. Sumstep in terms of volumes per unit basin area (mm), and is applied to basin-wide fluxes as follows:

```
         basin-wide soil water balance:

c          input = precip + irrigation:
         flxinp = basflx(1) +basflx(2)

c          output = et + (surq+xmloss) +latq + perc:
         flxout = basflx(3)+basflx(4)+basflx(6)+basflx(7)
         flxnet = flxinp - flxout       ! basin-wide soil water net inflow

c          soil water balance = net inflow - chg in storage, dsol_sw:
         flxbal = flxnet - basflx(15)
```

Runoff is accumulated into ssub(4,*) before xmloss has been subtracted from runoff, so basflx(4) includes both. The above balance is also calculated in Swbavg for the HRU-averaged version of the soil water balance.

Runoff and transmission losses

One source of confusion on the soil water mass balance was traced to the accumulator for surface runoff in subbasin j, ssub(4,j), which includes both surface runoff and transmission loss. This appears to be the case for both versions 94.2 and 99.2. What happens is the following. In version 94.2, subroutine Subbasin calls subr. Volq11 to compute runoff, qd, which is then accumulated into ssub(4,j). Subr. Subbasin then calls subr. Tran12 to compute transmission losses, qtl, on the basis of runoff, qd. Transmission losses are accumulated into ssub(13,j) and are subtracted from the scalar qd but not from the accumulator ssub(4,j). Version 99.2 proceeds similarly, with subroutine Subbasin calling subr. Surface, which does the above by making calls to subroutines Volq and Tran. Prior to accumulating runoff, qd, into ssub(4,j), qd is modified by models for crack flow and effective rainfall. After accumulating qd into ssub(4,j), qd is reduced by transmission losses as above.

SWAT evaluates a running basin-wide soil water balance in subroutine swbl20 in v.94.2, and in subr. swbl in v. 99.2. The balance is evaluated by subr. swbl for v.99.2 as follows:

```
      subroutine swbl(p,q,et,ssfl,ol,sxx,tranl,tir)
      use parm
c     name      name       definition (units all mm)
c    (dummy) (actual)      basin-wide areally averaged values (mm)
c                                                ~ ~ ~ INCOMING VARIABLES
c     p         sm(1)      precipitation
c     q         sm(3)      runoff
c     et        sm(7)      evapotranspiration
c     ssfl      sm(4)      subsurface flow
c     ol        sm(5)      percolation out of soil profile
c     sxx       ssb(35)    soil water content
c     tranl     sm(38)     channel transmission losses
c     tir       tir        irrigation
c                                                ~ ~ ~ OUTGOING VARIABLES
c     wshd_sw (passed in module Parm)  area weighted soil water

      wshd_sw = wshd_sw + p - q - ssfl - et - ol - sxx + tranl + tir

      return
      end
```

Subroutine swbl20 in v.94.2 applies the same calculation as above.

Soil water balance: Y7 (v.99.2) and Repub. R. basin (94.2 and 99.2)

The above balance calculation for Swat v.99.2 shows negligible error for case Y7 (Fig. D.1). For the Republican River test case, HRU scheme 1, cumulative mass balance error calculated by SWBAVG varies about zero (Fig. D.2).

For the Republican R. test case under Swat v.94.2, the cumulative mass balance error calculated by SWBAVG is the negative of the cumulative transmission loss (Fig. D.3). Adding transmission loss back into net inflow reduces the cumulative mass balance error to a small but increasing value (Fig. D.4).

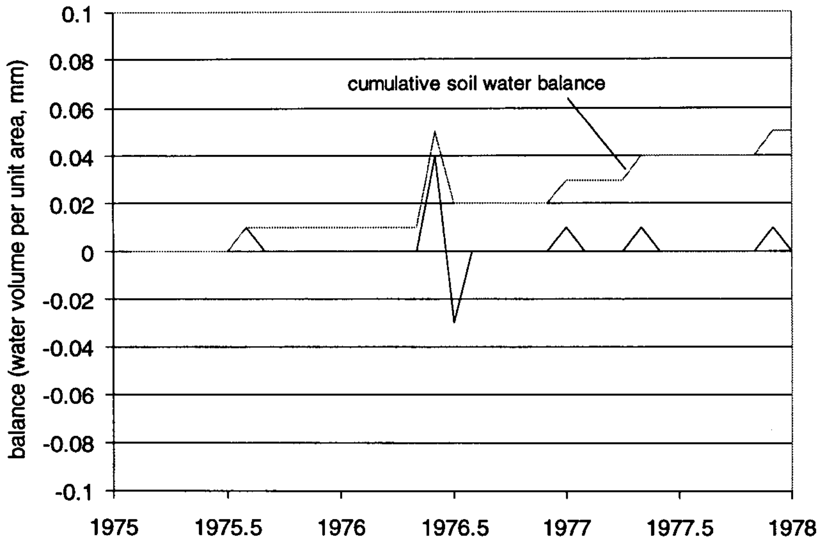

Fig. D.1. Soil water balance and cumulative balance for case Y7 under SWAT v. 99.2.

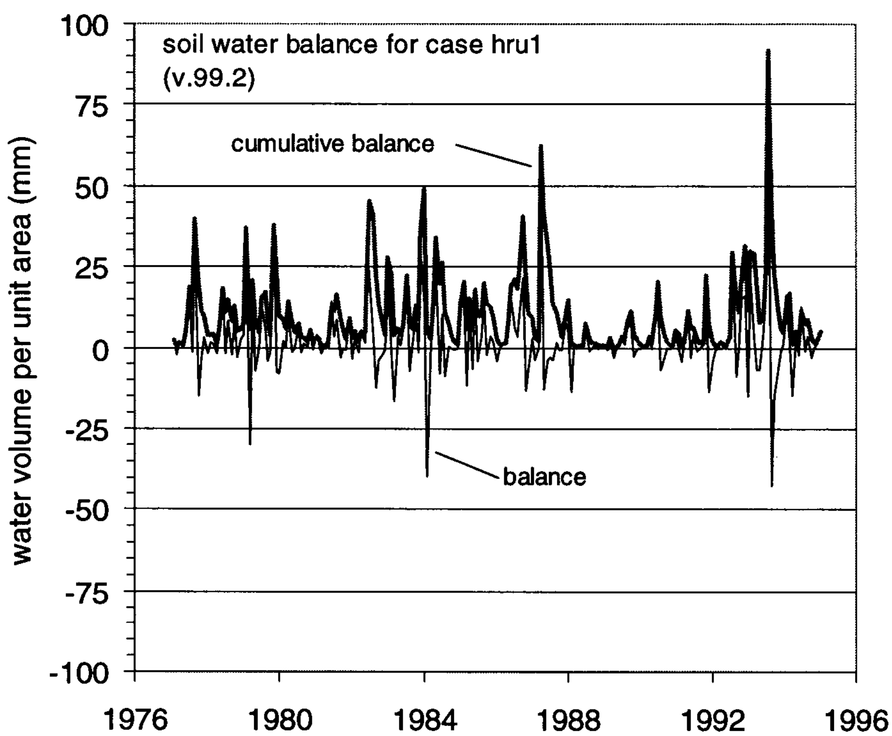

Fig. D.2. Soil water balance and cumulative balance for the Lower Republican River basin case, HRU scheme 1. Balance is based on HRU-averaged results calculated by SWBAVG, based on component HRUs that were run under SWAT v. 99.2.

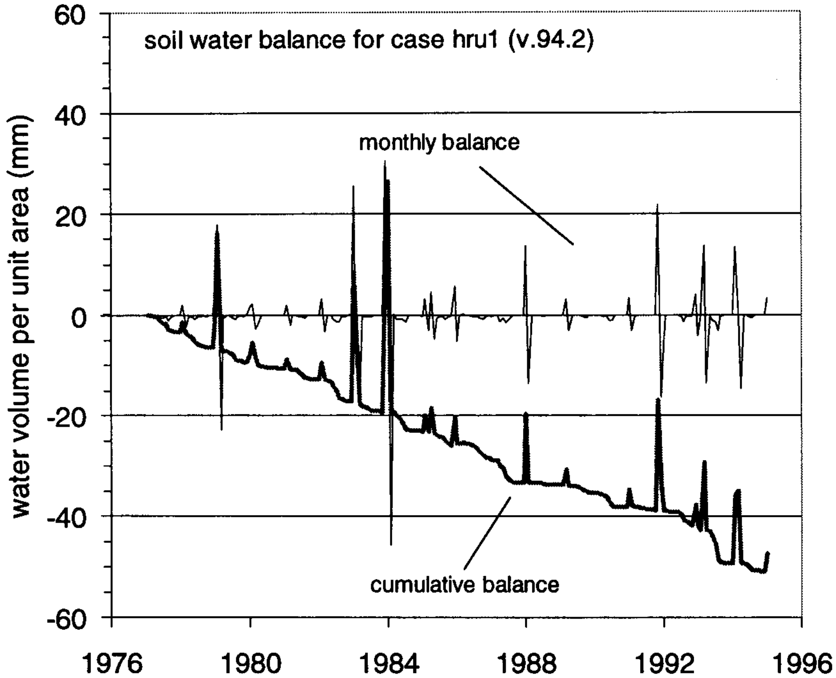

Fig. D.3. Soil water balance and cumulative balance for the Lower Republican River basin case, HRU scheme 1. Balance is based on HRU-averaged results calculated by SWBAVG, as above, but based on component HRUs that were run under SWAT v. 94.2.

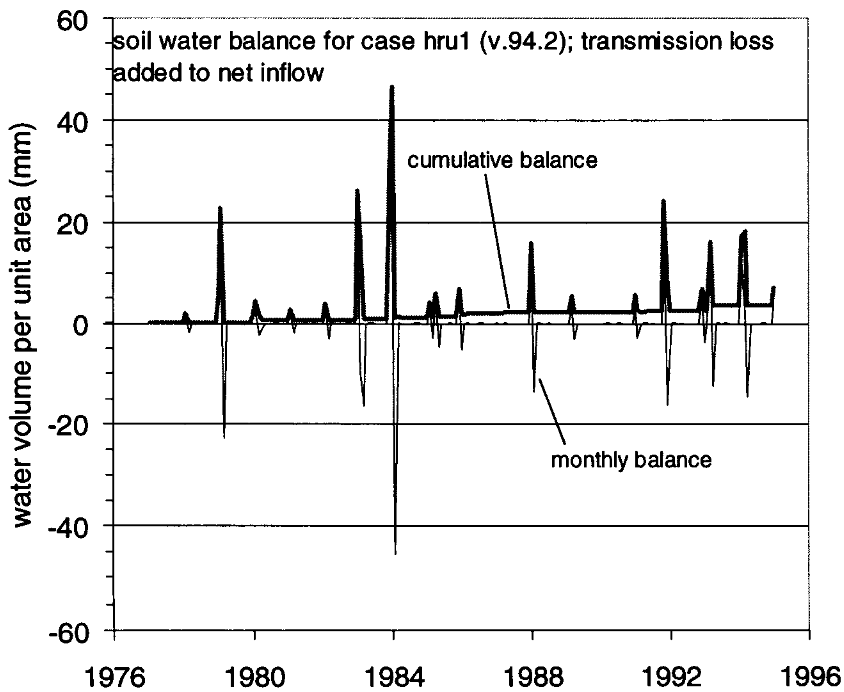

Fig. D.4. Same soil water balance and cumulative balance shown in Fig. D.3, but with transmission losses added into net inflow (or, equivalently, subtracted from runoff).

Repub. R. test case HRU scheme 1 under Swat v. 94.2 with Modflow

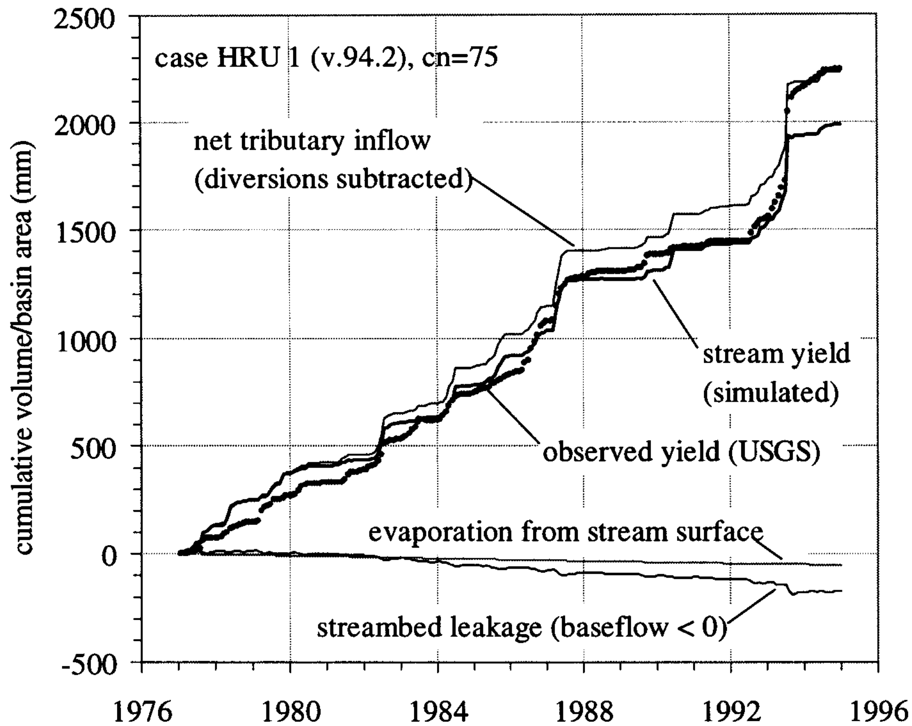

Fig. D.5. Stream yield components (case HRU1 under Swat v.94.2).

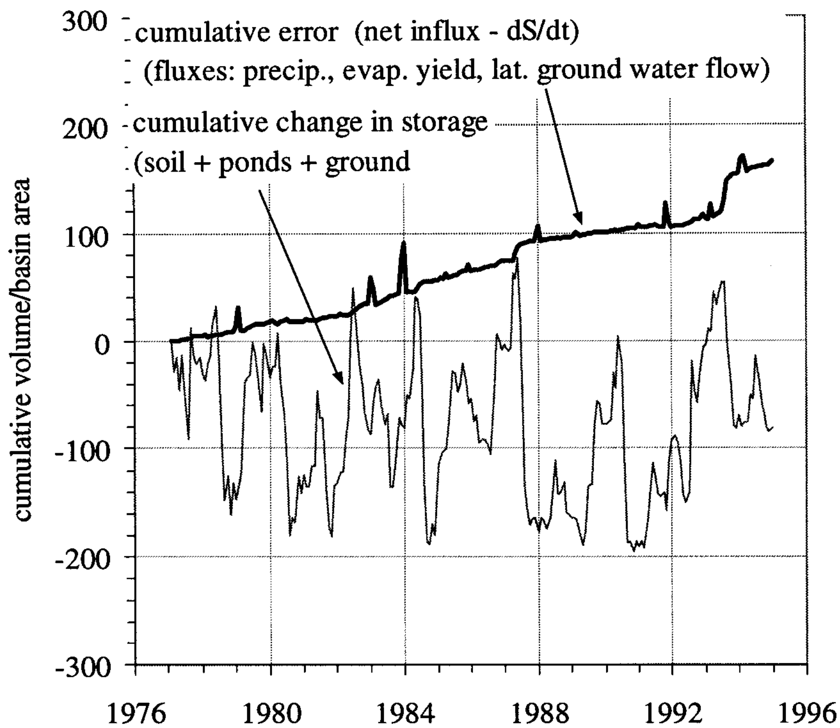

Fig. D.6. Overall watershed balance error and net inflow (case HRU1 under Swat v.94.2).

<u>Repub. R. test case HRU scheme 1 under Swat v. 99.2 with Modflow</u>

The main intended difference for this test case from the corresponding case run under Swat v. 94.2 is that the soil water threshold for irrigation has not implemented for the v.99.2, so that the plant stress factor threshold is applied; sensitivity cases are shown that demonstrate the strong sensitivity to this factor. Comparison with results obtained using a soil water threshold under v.94.2 suggests that the soil water threshold allows irrigation to be calibrated more easily for the Republican River basin model.

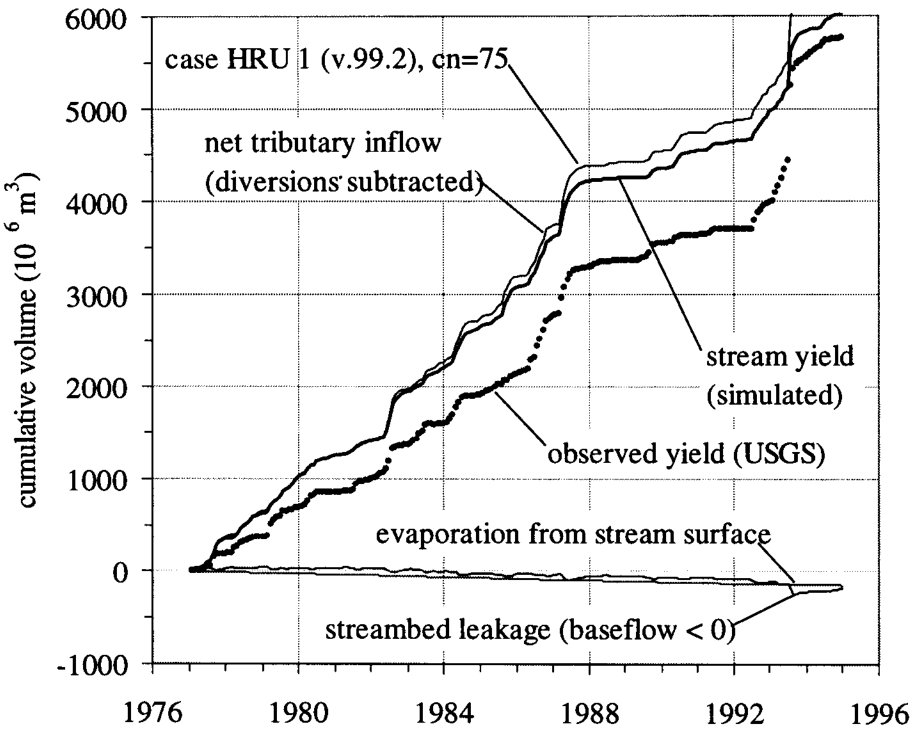

Fig. D.7. Stream yield components (case HRU1 under Swat v.99.2).

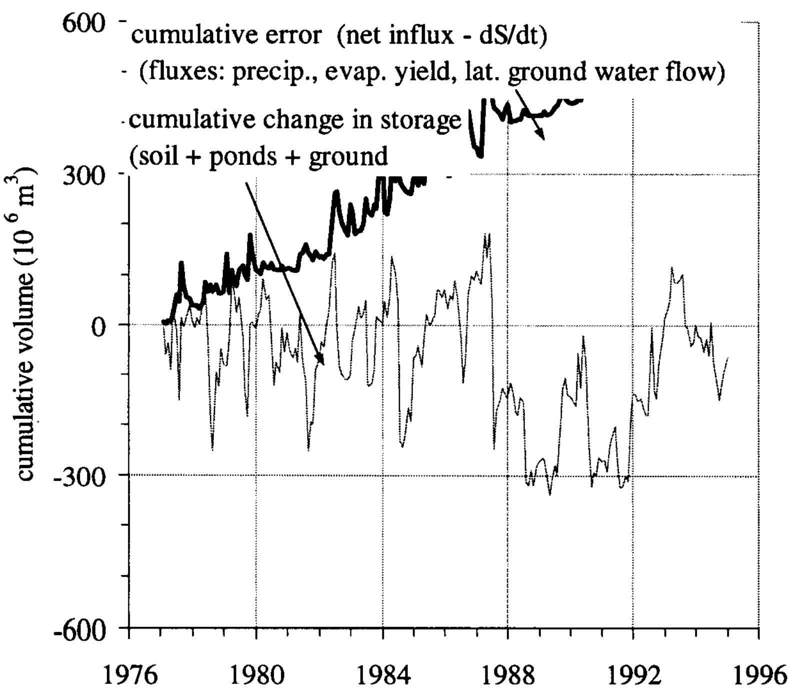

Fig. D.8. Overall watershed balance error and net inflow (case HRU1 under Swat v.99.2).

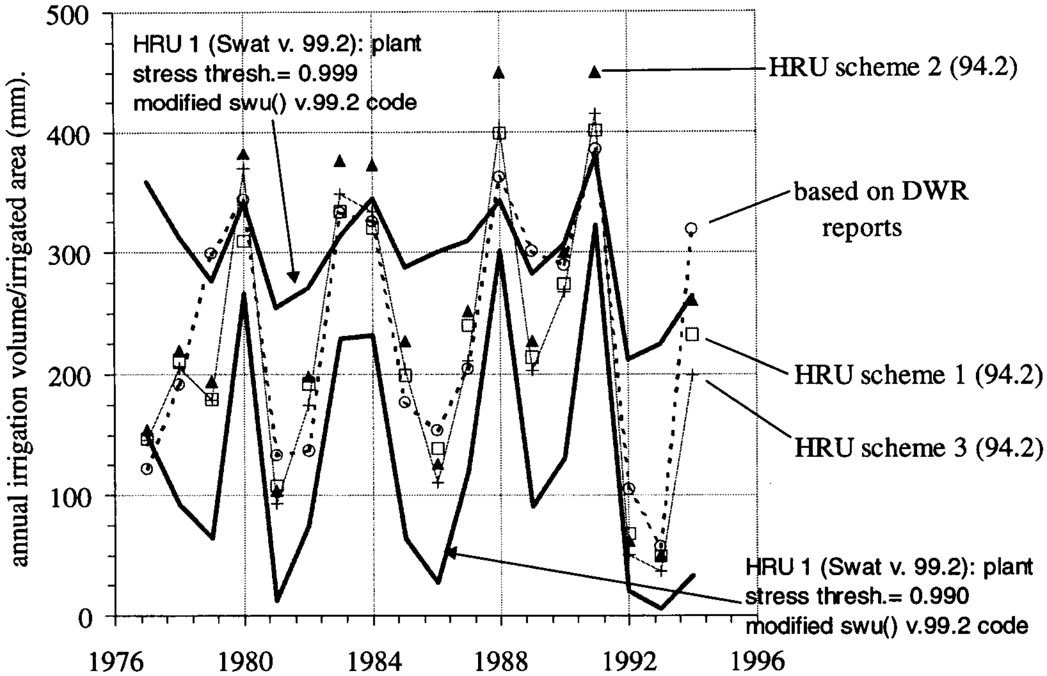

Fig. D.9. Simulated irrigation demand based on soil water threshold (v. 94.2) is compared with irrgation based on plant stress factor (v.99.2) for stress factor threshold values of 0.990 and 0.999.

Appendix E. Compiling and linking under Lahey 95

Listings of modified and added code will appear in volume 2 of documentation for this project as a sequel to KGS Open-File Report 99-25. They are currently listed in Appendix B, "Code Listings" under "SWAT v.98.1 modified code" in the document entitled "Progress Report Draft," Word file d:\gh\Ars\swt99chg.doc. The following is a listing of contents in Appendix B of this document.

<u>Modules or subroutines added to SWAT</u>

<u>Modified SWAT subroutines</u>

Transition from Fortran77 to Fortran90 code

This transition appeared to result in some minor idiosyncracies, but also some advantages. In particular, the "Module" program structure was utilized to declare, initialize, and share data (scalars, arrays, and strings) between SWAT mainline and subroutines. Use of the module in this way avoided the more complicated means for sharing data provided by argument lists and common blocks. This was implemented as follows. For the SWAT-MODFLOW linkage. File swtmod99.h was "included" for compilation just above the mainline on its source file. The module swtmod99 was then invoked by the "Use" statement in each routine where needed. In addition, dynamic memory allocation was used (subroutine Alloc_Swtmod). An apparent idiosyncracy worth mentioning is that precipitation and temperature input data had to be prepared in spreadsheets using a fixed numeric field format instead of the "general" numeric format as defined in Excel (Microsoft Office). Numeric values shown in the resulting file as integers in the general format were treated as zeroes by the Fortran90 version of SWAT.

Compiling and linking SWAT v.99.2.

With the Lahey 95 compiler for Fortran 90, debugging and optimized versions of executable versions of SWAT 99.2 can differ drastically in both executable file size and in runtime. Optimized executable file size is comparable to that of the "Microsoft" compiler, about 1.2 Mb, whereas a debugging version of the executable file can be 18 Mb. For a year's execution of the Lower Republican test case on a 90MHz pc, the "Microsoft" version of the executable file takes about 15 sec. By comparison, the debugging version of the Lahey executable file takes 2:05 min, and the optimized version takes about 8 sec. The downside of the optimized version is that it does not provide a trace to execution errors.

Lahey expects the source file extension ".for" for fixed format, so all source files except the included files modparm.f and common.f were changed to have the extension ".for". To compile under Lahey, the only problem encountered was the$debug statement, which was commented out of the following files:
Main, Operatn, Readbsn, Simulate, Subbasin, Virtual.

Initial compilation and linkage used array bounds checking and tracing options in "automake" configuration file:

```
QUITONERROR

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

LINK=@lf95 @%rf -g -fullwarn -exe %ex
TARGET=Swat99Lh.exe
```

This produces a very large executable file (~17 Mb) and is very slow. Optimizing compiler was found to produce an executable file about 1.2 Mb in size that is very fast, but at the loss of the error tracing capability. An executable file slightly reduced in size (~15 Mb) was produced using the following configuration file (automake.fig):

```
QUITONERROR

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

LINK=@lf95 @%rf -exe %ex
TARGET=swat99Lh.exe
```

The above configuration file is essentially that used for the optimized version, except that the "-trace" option was added in order to obtain a traceback from runtime errors. Adding that one feature appears to increase executable file size from about 1.2 Mb to 15 Mb, and increase runtime for a year of the Lower Republican River test case from about 8 sec to about two minutes.

Compiling and linking SWAT v.98.1 under Lahey 95

This was begun and completed on Dec 23 1999 in order to compare results for the Y7 test case under versions 98.1 and 99.2. After successful compiling and linking of v. 98.1, results for the Y7 test case were compared for version 98.1 based on the downloaded executable version and the executable version obtained under Lahey 95. These results were shown to be virtually identical. Once this was accomplished, the comparison with results based on v.99.2 was made. Changes made to v.99.2 for linkage to MODFLOW were not made to v.98.1.

In order to indicate fixed-format source code for Lahey 95, source files were all first renamed to have the extension ".for" instead of ".f" except for the files common.f and modparm.f, which are included in other source files.

Execution testing of v.98.1 was done with the Y7 case. All fatal errors were due to encounters with undefined variables. These were handled by initializing the relevant variables and arrays in subroutine Initial() as shown in the listing of the code. These will appear in volume 2 of documentation for this project as a sequel to KGS Open-File Report 99-25. They are currently listed in Appendix B, "Code Listings" under "SWAT v.98.1 modified code" in the document entitled "Progress Report Draft," Word file d:\gh\Ars\swt99chg.doc.