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## COMBINING SWAT AND MODFLOW INTO AN INTEGRATED WATERSHED MODEL

by

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# Combining SWAT and MODFLOW Into an Integrated Watershed Model

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# 1. Introduction

## 1.1. SWAT and MODFLOW

We present an update of a linkage between SWAT v.99.2 and MODFLOW-96 (v.3.3). Its purpose is to enable a coordinated approach to simulating watershed hydrology, stream-aquifer interaction, and groundwater movement. SWAT v.94.2 (Arnold et al., 1994) and MODFLOW-88 (McDonald and Harbaugh, 1988) were originally combined for application to the Lower Republican River Basin in north central Kansas (Perkins and Sophocleous [P&S], 1999a), and Rattlesnake Creek watershed in south central Kansas (Sophocleous et al., 1999). The codes for these models are documented in P&S (1997 and 1998). The MODFLOW component of these codes was subsequently combined with another watershed model code, POTYLDR (Koelliker, 1994) for application to Wet Walnut Creek watershed in Kansas (Sophocleous et al., 1998) to study the effect of flood control structures on recharge of the alluvial aquifer (Ramireddigari et al., 2000). In each of these three studies, MODFLOW has been combined with a watershed model code, and calibrated models of the watersheds have been developed for application to watershed management problems. Sophocleous and Perkins [S&P] (2000) present an overview of these studies. The immediate predecessor to the updated version of the code presented here was based on SWAT v.94.2 and MODFLOW-88, and is documented in P&S (1999b-c).

SWAT and MODFLOW represent two general classes of models that are commonly applied independently to problems that are naturally coupled, namely watershed hydrology and ground water hydraulics. The methods and procedures followed to coordinate execution of SWAT and MODFLOW is presented in Chapter 2.

MODFLOW is a distributed ground water model code that is well-accepted, flexible, and general. As such, MODFLOW is an attractive alternative to SWAT's lumped and more specialized analytical ground water model. On the other hand, SWAT and other watershed simulators can be used to specify fluxes for the stream-aquifer system simulated by MODFLOW. These fluxes include ground water recharge, irrigation pumping and other water uses, potential evaporation rates from shallow ground water, and tributary inflows. SWAT has capabilities that are desirable for developing a calibrated model of a watershed or river basin, and for using the model to examine how these stream-aquifer fluxes are affected by various changes in land use and climate.

In the present version of the linkage, code changes made to SWAT and MODFLOW have been reduced considerably. The modified versions of SWAT and MODFLOW may be applied to conventional data sets for the respective programs. The linkage between the two can be optionally activated in SWAT by extensions to SWAT's Control Codes (*.cod) input file, and in MODFLOW by invoking the SWBX package, which provides an interface to simulation results produced by SWAT or, alternatively, one of the HRU-averaging programs, SWBAVG and HRUAVG (see Ch. 6 and 7). Modified SWAT data sets include the Control Codes (*.cod), management (*.mgt), and ground water (*.gw) input files. The User's Manual provides instructions for these data sets. The Control Codes input file was expanded to specify one of three HRU schemes to represent spatial heterogeneity. Input data instructions and examples are provided in the User's Manual for modified and added components of SWAT v.99.2 and MODFLOW-96.

### 1.2. SWAT's model of spatial variability

SWAT applies a two-tiered approach to representing the effects of spatial heterogeneity on watershed hydrology. First, a watershed is divided into geographically defined subbasins. Secondly, each subbasin is further subdivided into "virtual subbasins" that are not defined geographically, but represent spatially weighted combinations of the significant factors contributing to the watershed's spatial heterogeneity. The hydrologic response of each such virtual subbasin is simulated separately, after which a spatially weighted mean hydrologic response is calculated. The virtual subbasins are commonly referred to as hydrologic response units (HRUs), and the modeling method is referred to as the HRU approach. This is described in terms of virtual subbasins by Mamillapalli et al. (1996) as follows:

> Instead of assuming the dominant soil and landuse to be the soil or landuse of the subbasin, each subbasin is discretized into virtual areas (referred to as virtual basins), each having a unique soil and landuse combination without reference to their spatial positioning within the subbasin...The hydrologic response is generated within each of these virtual areas and then the weighted average (by area) of the response from these virtual subbasins is taken to be the output of the subbasin.

SWAT simulates watershed hydrology on a daily basis by applying a separate soil water balance for each subbasin. Spatial variability within each subbasin is represented by SWAT with "virtual subbasins," also referred to as hydrologic response units (HRUs). Each virtual subbasin is defined in terms of a particular combination of subbasin attributes, including soil type and land use. For each day, the virtual subbasins are simulated separately. Each geographically defined subbasin is represented by a spatially weighted mean taken over its corresponding virtual subbasins. The spatial weight for each virtual subbasin is given by the product of the areal fractions of its defining soil type and land use.

SWAT associates each virtual subbasin with a routing sequence in the Configuration (*.fig) input file, and with a set of data files to specify its characteristics in the File Control (*.cio) input file. The spatial weight of each HRU is given as a constant value by the Subbasin (*.Sub) input file. The input files for SWAT can be manually constructed through use of a text editor, or automatically generated under the control of the ArcView extension, AvSwat. Under AvSwat, the spatial weight for each HRU is calculated in terms of the areal fractions of the soil types and land uses that define the HRU. The spatial weight is used to specify the area of a corresponding virtual subbasin that is to be simulated by SWAT. The procedure for using AvSwat is documented in Neitsch et al. (1999), which includes a tutorial for an example data set (Lakefork). We extend this example by showing how to modify the procedure of Neitsch et al. to obtain results from SWAT that could be used as input to MODFLOW. Although the

MODFLOW side of the linkage is not illustrated by this example, the MODFLOW linkage is demonstrated for the Lower Republican River basin model.

## 1.3. Extending SWAT's model of spatial variability

The extended HRU approach that we have implemented in SWAT includes the following capabilities:

1. Represent spatial variability within subbasins that is due not only to soil type and land use but also to subsurface features, or geomorphology. In particular, virtual subbasins may be distinguished on the basis of whether the soil profile is underlain by bedrock, deep groundwater, or shallow groundwater.

2. Represent temporal variations in spatial variability due to changes in soil, land use, and subsurface characteristics, including groundwater response to storm-interstorm cycles, climate change, and groundwater pumping.

3. Represent spatial dependence among HRU factors. This is useful, for example, to avoid pairing land uses and soil types that occur only along an alluvial valley with factors occurring only outside the valley.

Extensions to SWAT's model of spatial variability were first implemented by a separate, intermediate program, SWBAVG, which took spatially weighted averages over HRUs that were simulated individually by SWAT. As part of the update to SWAT 99.2 and MODFLOW-96, the intermediate program HRUAVG was developed to replace SWBAVG and thereby generalize this approach for application to other basins.

More recently, SWAT was modified to incorporate the capabilities of the program HRUAVG to calculate HRU weights and areas corresponding to virtual subbasins. If the option is chosen to calculate HRU weights (Iopwts > 0, Control Codes input file), the virtual subbasin areas, which are read from the subbasin (*.sub) input file, are replaced by the calculated values. This change allows the three HRU schemes as they were applied to the Lower Republican River Basin to be specified relatively easily, and executed with a less elaborate procedure than that required with the HRU-averaging programs, SWBAVG and HRUAVG.

For the standard version of SWAT, HRU weights are specified by input to SWAT after calculation on the basis of subbasin areal fractions corresponding to soils and land uses within the subbasin. These weights may be automated through the ArcView extension, AvSwat. The first of the three HRU schemes presented in this report is also based on combinations of soil and land use factors. HRU schemes 2 and 3 take into account a third factor to represent subsurface features, including a soil profile underlain by bedrock, deep groundwater, or shallow groundwater.

Automating the calculation of HRU weights as summarized above allows SWAT to simulate these schemes relatively easily. Areal fractions of each subbasin are specified for soils, land uses, and subsurface features through an extended version of the Control

Codes (*.cod) input file. This file also defines combinations of these factors that can be used to calculate HRU weights. An additional numeric field is read from the configuration (*.fig) file to allow associating these combinations with HRUs. If a specified combination has been defined in the Control Codes input file, the initial HRU weight is calculated. This option has been tested successfully for the Lower Republican River basin model under HRU schemes 1-3, which are explained in Chapter 2. The automation of SWAT's calculation of virtual subbasin areas is summarized in Section 3.1.

## 1.4. Coupling SWAT and MODFLOW

Options have been incorporated into SWAT to represent the hydrologic effects of a soil profile underlain by bedrock, and the effect of shallow groundwater on the soil profile. As part of these options, a two-way coupling with MODFLOW has been implemented so that areal extent and depth of shallow groundwater simulated by MODFLOW is summarized for input to SWAT. Three alternative conceptual models for representing spatial variability with respect to geomorphology were implemented originally as part of the SWAT-MODFLOW linkage based on SWAT v.94.2 and MODFLOW-88. These conceptual models, referred to here as HRU schemes 1-3, are presented in Chapter 2. They were previously presented in Perkins (1999).

SWAT implements the HRU approach using spatial weights that are specified as input and which remain constant over the study period. We present a modified approach to account for the effects of spatial heterogeneity in which spatial weights, corresponding to combinations of the significant land uses and soil types, are allowed to vary over time in response to changing land use factors. SWAT simulates the HRU associated with each combination of soil type and land use factor separately. At the end of each groundwater time step, SWAT can optionally calculate spatial weights corresponding to the HRUs in each subbasin, and then call SUMHRUs to calculate a spatially weighted mean over the HRUs for each term of its simulated soil water budget. SWAT calls SUMSTEP to convert these terms from volumes per unit area to flow rates, and combine the terms to represent specified fluxes for input to MODFLOW, including recharge, irrigation demand, and tributary inflows.

Refined HRU schemes based on the updated SWAT-MODFLOW linkage have also been developed to model additional features, including (a) spatial heterogeneity with respect to an underlying aquifer, such as in a basin with an alluvial river valley; (b) spatial dependencies among HRU factors within subbasins, particularly associations of soil types and land uses with basin features; and (c) a two-way coupling of the soil water profile simulated by SWAT to evaporation from shallow ground water simulated by MODFLOW. The two-way coupling involves temporally varying HRU weights in response to wet-dry cycles and the associated changes in areal extent of shallow ground water. Successive approximation is also used; the two-way coupling is initialized by a simulation with SWAT in which ground water is assumed to be sufficiently deep that it has negligible effect on soil water content in the root zone. The HRU schemes associated with these model features were developed specifically for application to the Lower Republican River. They were originally presented in Perkins (1999), and documented in P&S (1999a-b).

In order to generalize these schemes for application to other basins, the program HRUAVG was written to replace SWBAVG. Conceptually, the difference between these two programs lies in the definition of the factors that are combined into HRUs. SWBAVG combines only soil type and land use factors to specify HRUs, although the definitions of land use factors was extended to incorporate subsurface features for alternate HRU schemes described in Ch. 2. In contrast, HRUAVG is used to specify HRUs as products of three independent factors, including soil type, land use, and subsurface features. Additionally, each of these three factors may be specified as either spatially independent or dependent with respect to regions within the subbasins. The more general HRUAVG has performed satisfactorily by producing sets of weights with only minor differences from those calculated by the program SWBAVG in simulations of the Lower Republican River basin model.

## 1.5. Program version compatibility and the SWAT-MODFLOW linkage

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

SWAT 2000 has been released and will likely replace SWAT 99.2, on which the linkage presented here is based. Some revisions, especially input to SWAT, will be required if the linkage is to incorporate SWAT 2000.

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

Please refer to Section 1.2 of the User's Manual for some further points concerning program and compiler-related compatibility issues.

# 2. Methodology

## 2.1. Components of the integrated SWAT-MODFLOW model code

SWAT: a daily soil water balance simulation of watershed hydrology

SWAT simulates watershed hydrology in a continuous mode with daily time steps. It is quasi-distributed: a basin model can be partitioned into an arbitrary number of subbasins, each of which is represented by a single set of characteristics without spatial variation. A lumped hydrologic model based on a soil water balance is applied separately to simulate each subbasin. The soil water balance has the form

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

Terms of eqn. (2.1) are in units of length (mm) representing water volume per unit area, where water volume is given by integrating flow rate over time; that is, $d = Q\Delta t / A$. On the left-hand side is the change in soil water content after $t$ days; on the right are terms integrated over time for precipitation, $d_{pcp}$, including snowmelt; $d_{irr}$, applied irrigation; surface runoff, $d_{ro}$; lateral subsurface flow, $d_{lat}$; percolation from the soil profile, $d_{perc}$; and evapotranspiration, $d_{et}$. Channel transmission losses, $d_{xm}$, are treated as a component of surface runoff that contribute to ground water and not to soil water.

The procedure followed in SWAT to simulate the components of the soil water balance (2.1) is summarized in Fig. 2.1. This summary identifies model-related changes to SWAT's simulation. The methodology behind these changes is presented in this chapter; the associated input data and code modification or additions are presented in Chapter 3.

SWAT provides options to apply either the SCS curve number (SCS, 1972) or Green and Ampt (1915) methods for paritioning rainfall into infiltration and runoff. A method by Lane (1983) is applied to represent transmission loss as a component of runoff. SWAT has options to calculate potential evaporation according to methods of Penman-Monteith (Monteith, 1965), Priestley-Taylor (1972), and Hargreaves and Samani (1985). SWAT simulates actual evaporation based with a method similar to that of Ritchie (1972) based on ground cover and leaf area. Vertical movement of water through soil layers is represented by storage routing procedures. Irrigation can be triggered by pecifying a threshold for either plant stress factor or soil water content. Most of these methods and their coordination by SWAT are presented in Arnold (1993), while some have been added to more recent versions of SWAT, such as the Green-Ampt model for infiltration and the soil water content threshold for automatic irrigation; see also the SWAT website, referenced under Arnold et al. (1994).

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 (**Readgw**[1], **Purk**[2]);
    Redistribute uptake from shallow gw over soil profile, **Evapgw**[1,3]

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

    Irrigation based on either plant stress factor or soil water content
            thresholds, and limited by a daily maximum (**Readmgt**[4], **Subbasin**[5]);
end do
end do

[1]**Readgw** : modified to specify the option **ipurk**(*j*) for each subbasin, *j*, in *.gw.
[2]**Purk**: modified to represent a soil profile underlain by bedrock (**ipurk**(*j*) = −1)
[3]**Evapgw**: added to distribute shallow gw evap. in soil profile (**ipurk**(*j*) = +1)
[4]**Readmgt**: modified to specify a daily max. irrigation limit, **auto_dmx**, and a soil water content threshold for irrigation, **auto_swf**, in *.mgt.
[5]**Subbasin**: modified to apply daily maximum irrigation limit and optionally observe both plant stress factor and soil water thresholds.

Fig. 2.1. Procedure followed in the daily hydrologic simulation for each subbasin in SWAT v.99.2 (subroutine Subbasin).

MODFLOW: ground water hydraulics simulation

MODFLOW applies a spatially distributed model to simulate saturated flow in a porous medium. The flow rate per unit cross sectional area is governed by Darcy's law, $q = -K\, dh/dl$, where $K$ = hydraulic conductivity, and $dh/dl$ is the hydraulic gradient driving the flow. Darcy's law is combined with the continuity equation in differential form to give

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{dh}{dt}-R(\mathbf{x}), \quad (2.2)$$

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 expresses equation (2.2) as a system of finite difference equations that can be represented by the linear system

$$\mathbf{Ah} = \mathbf{b}\,, \quad (2.3)$$

which is to be solved for aquifer heads $\mathbf{h}$, where $\mathbf{A}$ = the head coefficient matrix, and $\mathbf{b}$ = vector of head-independent terms. The coefficent matrix $\mathbf{A}$ includes conductances between nodes and coefficients for head-dependent components of external storage and source terms. Head-dependent fluxes, such as evaporation from shallow ground water and baseflow, are typically expressed in the form $q(h) = C(h - h_1)$. MODFLOW decomposes this form into separate terms, $q(h) = Ch - Ch_1$, which are incorporated into the left- and right-hand sides of (2.3), respectively, as head-dependent and head-independent components of the flux, $q(h)$. For further explanation, see the section "Incorporating Head-dependent fluxes" in this report. See also the manual for MODFLOW-88 (McDonald and Harbaugh, 1988), which provides a detailed explanation of how the system of equations (2.3) is formulated, and optional methods of its solution.

Fig. 2.2 outlines the modified mainline of MODFLOW and identifies where calls are made to subroutines of the nonstandard package SWBX, added to provide an interface to SWAT's simulation. SWBX and other nonstandard packages associated with the SWAT-MODFLOW linkage that are optionally callable from the mainline but not identified in Fig. 2.2 are introduced below; see "Operating procedure linking SWAT-99.2 and MODFLOW-96". For information on using MODFLOW-96, see Harbaugh and McDonald (1996).

After MODFLOW's solution of (2.2) has converged, a ground water budget is evaluated in each time step based on continuity expressed in integral form,

$$(dS/dt)_{gw} = Q_{gw} + Q_{rech} - Q_{gdiv} - Q_{et\text{-}gw} - Q_{base} \quad (2.4)$$

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

**Modflow** (mainline)

**Bas5df**: define grid size (rows, columns, layers), stress periods, options;
call *AL subroutines to allocate array space;
**Swb2al** (after **Bcf5al**) to allocate arrays for watershed-aquifer linkage;
call *RP routines to read and prepare data that remain constant throughout simulation;
**Swb2rp** (after **Bcf5rp**) to associate subbasins with aquifer grid cells;

Do for each stress period kper=1,nper:
**Bas5st**: read stress period timing information;
call *RP routines to read and prepare data that remain in effect for the stress period;
**Evtval** (after Evt5rp): initialize arrays for depth to gw (dtw) and shallow gw evap rate;
**Swb2str** (after Chd1rp): initialize areal fraction of basin drained by each stream reach

Do for each time step kstp=1,nstp:
**Swb2fm**: read flow rates from **SWAT** summary to specify fluxes;
Bas5ad: advance time and initial hydraulic heads; calculate time step;
Do for each iteration of approximating the solution (kiter=1,mxiter):
call *FM routines to formulate and solve finite difference equations;
end iteration on solution;
call *BD routines to calculate budget terms for mass balance;
**Evtval** (after **Evt5BD**): update dtw and evap arrays;
**Sbas2t** (after **Ibs1ot**): repeat calculations of **Sbas5t** for use in **Swb2bd** (below);
**Swb2bd**: summarize Modflow results for each subbasin; write a summary of shallow gw for input to **SWAT**;
call Bas1ot to optionally save and print results;
end time step;
end stress period;
close files;
end.

Fig. 2.2. Flow of execution for the modified MODFLOW-96 mainline. Calls to subroutines in the SWBX package, shown in bold, were added to provide an interface to SWAT's simulation.

Surface water modeling in MODFLOW: streamflow

Using MODFLOW's STREAM package (Prudic, 1990), a stream network can be specified as a quasi-distributed hydrologic model. The STREAM package applies a routing procedure that satisfies continuity while ignoring the streamflow's momentum equation, which is based on Newton's Second Law, $F = ma$ (Henderson, 1966). A volumetric balance for streamflow is given by

$$(dS/dt)_{str} = Q_{in} - Q_{out} + Q_{trib} - Q_{sdiv} - Q_{evs} + Q_{base} \quad (2.5)$$

which equates the rate of change in storage on the left to the sum of net inflows. Stream yield is defined 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 streambed leakage, or baseflow, $Q_{base}$:

$$Q_{yld} = Q_{trib} - Q_{sdiv} - Q_{evs} + Q_{base} \tag{2.6}$$

Streambed leakage, $Q_{base}$, couples ground water and streamflow as shown by the continuity equations (2.4) and (2.6). The STREAM package applies Darcy's law to represent streambed leakage in terms of the hydraulic gradient across the streambed, which may point in either direction. Baseflow is the negative of streambed leakage for the commonly assumed case that the the hydraulic gradient drives flow into the stream channel. The application of Darcy's law and the coupling of streamflow and ground water solutions are discussed in greater detail below; see "Incorporating head-dependent fluxes."

## 2.2. The SWAT-MODFLOW linkage

The hydrologic connections to be represented by the SWAT-MODFLOW linkage are illustrated in Fig. 2.3. This linkage provides a means of coordinating the simulations of SWAT and MODFLOW to provide an overall hydrologic balance for a watershed given by

$$dS/dt = Q_{pcp} - Q_{evt} - Q_{yld} + Q_{gw} \tag{2.7}$$

The rate of change in storage, $dS/dt$, lumps together components given by the left-hand sides of equations for soil water (2.1), ground water (2.4), and streamflow (2.5). 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, $Q_{yld}$.

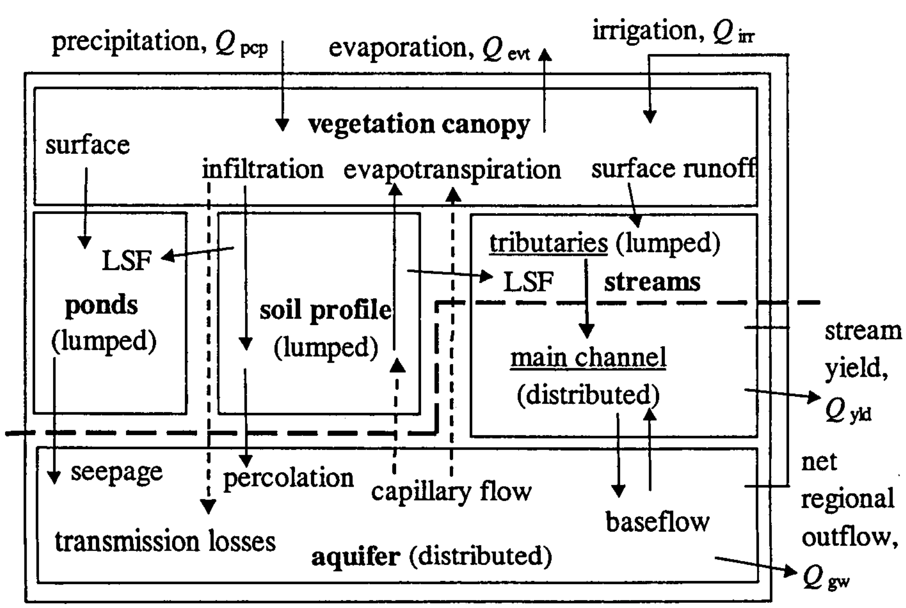


Fig. 2.3. Conceptual model for SWAT-MODFLOW linkage (from P&S, 1999a). Hydrologic components above the heavy dashed line are simulated by SWAT; those below the line are simulated by MODFLOW.

Other hydrologic components identified in the separate hydrologic balances above are internal transfers between elements of the watershed. For example, 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).

Operating procedure linking SWAT 99.2 and MODFLOW 96

The procedure linking SWAT v.99.2 and MODFLOW-96 is outlined in Fig. 2.4. Steps 1a-1d have been recently incorporated into SWAT; in previous versions of this linkage, these steps were carried out by SWBAVG or, more recently, by HRUAVG. These steps are summarized as follows.

Hydrologic terms shown in SWAT's soil water balance (2.1) are accumulated over each groundwater time step. Depending on Control Code Ipd, subroutine Writed, Writem, or Writea summarizes each daily, monthly, or annual gw time step of the simulation by calling first Sumhru and then Sumstep. Sumhru takes a spatially weighted average over all HRUs (virtual subbasins) within each geographically defined subbasin, for each hydrologic term of the soil water balance (2.1). Then Sumstep performs the following steps (a-d):

a) Combine hydrologic terms simulated by SWAT for each subbasin to specify fluxes for MODFLOW's solution in each time step, including irrigation demand, ground water recharge, tributary inflow, and potential evaporation from shallow ground water; see equations (2.11–2.16) below.

b) Transform the terms simulated by SWAT from cumulative volumes per unit area [L] to flow rates [$L^3/T$] in the system of units specified for MODFLOW's simulation. The terms in (2.1) have the units of depth corresponding to a volume given by $V = dfA$, where $f$ is the areal fraction of watershed area, $A$, to which the hydrologic term applies. This volume is given by integrating flow rate over time. For average flow rate, $Q$, and time step, $\Delta t$, $V = Q\Delta t$. Combining these relates the flow rates, $Q$, to depths, $d$, by

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

where $c$ is a length conversion factor.

c) Write simulation summary to a file for input to MODFLOW.

d) If Iopshl > 0, prepare for next gw time step by reading Modflow summary of shallow gw and evaporation. If Iopwts > 0, update HRU weights (subr Rte_Update).

2. In each time step of MODFLOW's simulation, the added package SWBX reads the HRU-averaged results produced by SWAT (or, optionally, by SWBAVG or HRUAVG) as flow rates for each subbasin to specify inflows to the stream network, groundwater recharge, irrigation demand, and potential evaporation.

```
1. Soil water-atmosphere simulation: SWAT (v.99.2)
  Initialize Swat-Modflow linkage:
    Read Swat-Modflow linkage option Iopmod from modified *.Cod (Readcod);
    Read optional HRU identifiers from *.Fig input file (Readfig);
    If Iopmod > 0:
      Read extended *.Cod input file and HRU def's. (Readwts);
      If Iopwts > 0: evaluate spatial weights for HRUs (Readwts, RteInit);
      Read add'l groundwater and management options (Readgw, Readmgt);
      Initialize output to Modflow for each gw time step (Init_bal);
        if Iopshl > 0: initialize shallow gw input from Modflow (Init_shl)
    End if;
  For each day, simulate hydrologic processes for each HRU (subr Simulate);
      If Iopmod > 0, summarize simulation at the end of each gw time step (day,
                month, or year, depending on Ipd; subr's Writed, Writem, Writea):
        Take spatial average over HRUs for each subbasin (subr. Sumhrus);
        Summarize results for each subbasin as follows (subr. Sumstep):
          Evaluate tributary inflow and gw recharge for input to Modflow;
          Convert volumes per unit area (mm) to flow rates;
          If Iopshl > 0:
             Read shallow gw input from Modflow for next gw time step;
             If Iopwts > 0: update spatial weights for HRUs to represent shallow gw
                  response to conditions (subr's. Regfact, Calcwts, and Rte_Update);
      End if
  Next day

2. Stream-aquifer simulation: MODFLOW-96 (v.3.3)
For each aquifer solution time step:
    Distribute HRU-averaged flow rates for each subbasin over grid to specify
        recharge, tributary flow, surface and ground water diversions, and max.
        evaporation for shallow gw (SWBX, STRX and WELX packages).
    Formulate and solve finite difference equations (FM_ and solver routines);
    Write summary of evaporation from shallow ground water to be read by SWAT
        on a subsequent run (subr. SWB2BD);
Next time step
```

Fig. 2.4. Procedure to coordinate SWAT (v.99.2) and MODFLOW for simulating watershed hydrology. Alternative procedures to take spatial averages over HRUs external to SWAT are presented for programs SWBAVG and HRUAVG.

SWBX distributes the flow rates over the corresponding stream reaches and aquifer grid cells. WELX and STRX are nonstandard versions of MODFLOW's STREAM and WELL packages, respectively, which are coordinated with SWBX to distribute irrigation demand over spatially distributed diversions from surface and ground water supplies.

Steps (1a-1d) in Fig. 2.4 are based on SWAT's representation of HRUs as virtual subbasins. Performing these operations within SWAT should enable an improved integration of the procedure into a GIS-based model. Alternatively, these intermediate steps may be applied externally by using SWAT in combination with program SWBAVG or HRUAVG. These programs and corresponding procedures are covered in Chapter 6 of the User's Manual for the SWAT-MODFLOW linkage.

<u>HRU scheme 1: a basic model of spatial heterogeneity in the watershed</u>

This scheme rests on the following model assumptions: (a) the basin's soil profile is underlain by a "deep" aquifer, that is, one that does not interact with the soil profile; and (b) soil type and land use factors are spatially independent. In the case of the Lower Republican River basin, six soil types and three land uses correspond to $n_h = 18$ combinations. 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, for $k = 1$ to $n_h$. For each subbasin, $j$, the HRU-averaged value for a given hydrologic component, $d_i$, is given by

$$d_{ij} = \sum_{k=1}^{n_h} d_{ijk} w_{jk} \tag{2.9a}$$

$$w_{jk} = s_{lj} u_{mj} \tag{2.9b}$$

The HRU weight, $w_{jk}$, is given by the product of subbasin areal fractions, $s_{lj}$ and $u_{mj}$, corresponding to soil type, $l$, and land use, $m$. Areal fractions for the land use classes in each subbasin, $u_{mj}$, are expressed as follows:

$$u_{1j} = f_{cj} - f_{\text{irr},j} \qquad \text{(non-irrigated cropland);} \tag{2.10a}$$

$$u_{2j} = f_{\text{irr},j} \qquad \text{(irrigated cropland);} \tag{2. 10b}$$

$$u_{3j} = 1 - f_{cj} \qquad \text{(grassland);} \tag{2.10c}$$

The areal fraction of cropland is denoted by $f_{cj}$ for each subbasin, $j$, and was derived from GIS-based analysis of satellite imagery. Irrigated cropland as an areal fraction of the subbasin, $f_{\text{irr},j}$, is given by (2.10b); see below. The remaining unirrigated cropland is given by (2.10a), and the uncultivated fraction of the subbasin by (2.10c).

The irrigated areal fraction, $f_{\text{irr},j}$, of each subbasin, $j$, is given by

$$f_{\text{srr},j} = f_{\text{ird},j} f_{\text{irb}} / f_{\text{sub},j} \,. \tag{2.10d}$$

Factors on the right-hand side are $f_{\text{irb},j}$, irrigated area in subbasin $j$ as a fraction of total irrigated area in the basin; $f_{\text{ird}}$, irrigated areal fraction of basin for each year; and $f_{\text{sub},j}$, subbasin area as a fraction of the watershed. The first two of these were derived from water use reports. The above equation is based on the assumption that the spatial distribution of irrigated area over the basin, represented by $f_{\text{irb},j}$, does not change significantly over the time period of simulation. To show that (2.10d) is valid, substitute the corresponding ratios of areas:

$$f_{\mathrm{srr},j} = \frac{A_{\mathrm{irr},j}}{A_{\mathrm{irr}}}\frac{A_{\mathrm{irr}}}{A_{\mathrm{bas}}}\frac{A_{\mathrm{bas}}}{A_{\mathrm{sub},j}}$$

After cancelling factors, this gives the irrigated areal fraction of subbasin $j$ as defined,

$$f_{\mathrm{srr},j} = \frac{A_{\mathrm{irr},j}}{A_{\mathrm{sub},j}}$$

In addition to allowing temporal variation of HRU weights in the basic scheme, the external HRU approach using SWBAVG has been applied to refined HRU schemes that incorporate a third HRU factor, namely spatial heterogeneity of subsurface features. In addition to the SWAT model assumption of deep ground water, two additional cases of subsurface features have been incorporated into the SWAT model to represent alternative cases of a soil profile directly underlain by bedrock and of shallow ground water. These cases are discussed below; see "HRU schemes 2 and 3."

Using SWAT's simulation results to specify fluxes for MODFLOW's solution

This section describes items 3 and 4 in the summary of operations for the SWAT-MODFLOW linkage. The hydrologic terms simulated by SWAT that flow into the stream-aquifer system are expressed in terms of the fluxes to be specified for MODFLOW's solution in each time step. These conceptual models combine operations 3 and 4 of the SWAT-MODFLOW linkage as follows.

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

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

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

Recharge to ground water includes contributions from percolation through the soil profile, $d_{\mathrm{perc}}$, channel transmission losses, $d_{\mathrm{xm}}$, and pond seepage, $d_{\mathrm{psep}}$. 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

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

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

Tributary flow, $Q_{\mathrm{trib}}$, 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, $d_{\mathrm{sro}}$, and lateral (subsurface) flow, $d_{\mathrm{lat}}$, calculated by SWAT for each subbasin's contributing areal fraction, $f_{\mathrm{con}}$. Tributary flow is expressed as

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

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.

A variation on HRU scheme 1 to represent aquifer spatial heterogeneity

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

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

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

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

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

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

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

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

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

## 2.3. Spatial distribution of fluxes over MODFLOW's stream-aquifer grid

This section describes item 5 in the summary of operations for the SWAT-MODFLOW linkage. The SWBX package was written to provide a means of specifying conditions for MODFLOW's stream-aquifer solution in terms of results from a watershed simulator. SWAT and SWBAVG provide HRU-averaged, lumped quantities as flow rates from each subbasin to simulate these conditions for each solution time step. Simulated recharge and potential evaporation for each subbasin are distributed over the corresponding grid cells of arrays for MODFLOW's Recharge and Evapotranspiration packages. Simulated tributary inflows from each subbasin are associated with corresponding stream reaches, and irrigation demand is distributed over surface and ground water points of diversion. The associations of tributary inflows and diversions involve nonstandard versions of MODFLOW's STREAM and WELL packages, referred to as STRX and WELX, respectively, which provide features necessary for the SWAT-MODFLOW linkage.

Associating watershed subbasins with stream-aquifer grid with SWBX

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

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

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

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

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

In each time step, SWBX reads tributary inflows, ground water recharge, irrigation demand, and potential evaporation for each subbasin as HRU-averaged flow rates from a data file written by SWBAVG. In addition, "actual" evaporation and rates of change in storage for soil water and ponds are passed, allowing evaluation of an overall water balance according to equation (2.7) based on these and MODFLOW's results. Pumping rates from surface and ground water diversions are specified to meet the irrigation demand simulated by SWAT, but are constrained to stay within operating limits imposed on individual water rights, and within supply limits imposed by available streamflow and aquifer saturated thickness. The nonstandard MODFLOW packages STRX and WELX are both involved in satisfying these constraints.

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

Spatial distribution of recharge

This section has been added since submission of the Final Report (P&S, 2000a) to reflect an update of the SWBX package for distributing recharge. The following terms are defined:

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

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

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

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

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

At the beginning of each stress period, the Recharge package subroutine Rch5rp reads the recharge array RECH as a flux, $R_{in}$(ic,ir) [L/T], for each column, ic, and row, ir, of the model grid. Rch5rp converts this flux to a flow rate, $R$ [$L^3$/T] by multiplying the flux specified for each grid cell by the grid cell's area,

$$R(\text{ic},\text{ir},t) = R_{\text{in}}(\text{ic},\text{ir})A(\text{ic},\text{ir}), \tag{2.17}$$

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

For the default option Ioprch = 0, recharge specified by (2.16b) is applied for each time step of the stress period by the Recharge package subroutine Rch5fm. If Ioprch > 0, the initial recharge array $R$(ic,ir,$t_0$) is used by subroutine Swb2rch to specify the spatial distribution of recharge, $f_r$(ic,ir). This is given by

$$f_r(\text{ic},\text{ir}) = R(\text{ic},\text{ir},t_0)/Q_r(\text{isub},t_0), \tag{2.18a}$$

where

$$Q_r(\text{isub},t_0) = \sum R(\text{ic},\text{ir},t_0), \tag{2.18b}$$

which is the sum of recharge flow rate taken over grid cells within the corresponding subbasin, isub. The operation in (2.18a) normalizes the distribution $f_r$(ic,ir) so that

$\sum f_r(\mathrm{ic,ir}) = 1$ for each sum taken over grid cells (ic,ir) of the corresponding subbasin, isub. Then in each time step, the recharge flow rate specified by SWAT for each subbasin, $Q_r(\mathrm{isub},t)$, is distributed over the grid cells of the subbasin according to

$$R(\mathrm{ic,ir},t) = f_r(\mathrm{ic,ir})Q_r(\mathrm{isub},t). \qquad (2.19)$$

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

If input to the Recharge package for the initial recharge array, RECH, is specified to be uniform (or uniform with respect to the grid cells within each subbasin), then recharge will be distributed uniformly over the grid cells within each subbasin. On the other hand, the spatial distribution specified by the initial recharge array is preserved in the operation given by (2.19) only with respect to the grid cells within each subbasin, and not with respect to the entire basin, unless the recharge flux specified in each time step, $Q_r(\mathrm{isub},t)/A(\mathrm{isub})$, is uniform over all subbasins. If the basin-wide spatial distribution indicated by the initial recharge array RECH is to be preserved in each time step, then it must be applied to a basin-wide recharge flux simulated by SWAT.

Subroutine Swb2rch, which specifies the initial recharge distribution array, $f_r(\mathrm{ic,ir})$, is patterned after the Recharge package subroutine Rch5fm to ensure that the correct grid cells are included in the sums given by (2.18b) for all options specified by the code NRCHOP, which is read by the Recharge package.

The initial distribution of recharge over the grid cells according to (2.19) does not take into account the possible occurrence of "dry cells," in which case initially active grid cells become inactive, or "no-flow" cells, as indicated by the Ibound array (defined in MODFLOW's Basic package). If necessary, this problem might be remedied by additional calls to subroutine Swb2rch to update the recharge distribution array for each time step in which dry cells occur.

Meeting irrigation demand with surface and ground water diversions

WELX, the modified version of the WELL package, represents diversions from both ground and surface water, which are distinguished by a source indicator. Locations of both types of sources are given by grid coordinates. The indexing array, Idxstr, defined in STRX, is used to look up corresponding reaches of a stream network that is specified by input to STRX. 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,

$$Q_{\text{app}} = \Sigma q_{\text{gk}} + \Sigma q_{\text{sk}} \tag{2.20}$$

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, $Q_{\text{irr}}$, by equation (2.11) can be distributed over water rights appropriated for irrigation. This is done by defining the factor, $s = Q_{\text{irr}}/Q_{\text{app}}$, which is used to scale the annual appropriations of the individual diversions, expressed as pumping rates. Multiplying equation (2.20) by $s$ gives

$$Q_{\text{irr}} = sQ_{\text{app}} = s(\Sigma q_{\text{gk}} + \Sigma q_{\text{sk}}) = \Sigma s q_{\text{gk}} + \Sigma s q_{\text{sk}} \tag{2.21}$$

Here, the normalized spatial distribution of appropriations is given by dividing equation (2.20) by $Q_{\text{app}}$, 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 $\Delta t$, and averaged over the eighteen HRUs for each subbasin by equation (2.9) to give the average depth $d_{\text{irr}}f_{\text{irr}}$. The flow rate corresponding to this monthly demand is given by equation (2.11). The total annual appropriations for ground and surface water rights meet this demand by distributing the scaling factor, $s$, which is zero except during the growing season, over the individual water rights according to equation (2.21).

Operational and supply limits on surface and ground water diversions

Pumping limits may be specified for WELX in terms of both operating and supply limits. Operating limits with respect to pumping capacity are specified as maximum scaling factors for ground and surface water diversions, $s_g$ and $s_s$, as a variation on equation (2.21) given by

$$\begin{aligned} Q'_{\text{irr}} &= \sum_{k=1,n_s} q'_{sk} + \sum_{k=1,n_g} q'_{gk}, \\ q'_{gk} &= \min(s, s_g)\, q_{gk}, \\ q'_{sk} &= \min(s, s_s)\, q_{sk}. \end{aligned} \tag{2.22}$$

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

$$q''_{gk}(h) = \begin{cases} q'_{gk} & h > z_u, \\ q'_{gk}\left(\dfrac{h - z_l}{z_u - z_l}\right) & z_u > h > z_l, \\ 0 & h < z_l \end{cases} \tag{2.23}$$

Incorporating head-dependent fluxes

The above technique to limit pumping provides a realistic means of preventing grid cells from going "dry" as a result of excessive pumping from wells. But equation (2.20) makes the affected pumping rates head-dependent components of the forcing function $R(\mathbf{x})$ in equation (2.2), which can adversely affect solution convergence if not handled properly. These head-dependent fluxes are incorporated into the solution in the same way that other head-dependent fluxes are represented, including evaporation from shallow ground water and streambed leakage. For each grid cell, the flux in (2.23) is separated into head-dependent and head-independent components,

$$q''_{gk}(h) = \frac{q'_{gk}h}{z_u - z_l} - \frac{q'_{gk}z_l}{z_u - z_l}, \qquad z_l < h < z_u \tag{2.24}$$

These are accumulated, respectively, into the left-hand and right-hand sides of (2.3), the system of equations to be solved for aquifer heads. For node $i$ of this system, the coefficient of the first term on the left-hand side is accumulated into the diagonal element $a_{ii}$ of the coefficient matrix, $\mathbf{A}$, and the head-independent second term is accumulated into the corresponding element of the vector $\mathbf{b}$ in (2.3).

$$\left.\begin{aligned} a_{ii} &= a_{ii} + \frac{q'_{gk}}{z_u - z_l} \\ b_i &= b_i - \frac{q'_{gk}z_l}{z_u - z_l} \end{aligned}\right\} \quad z_l < h_i < z_u$$

$$b_i = b_i + q''_{gk}, \qquad h_i \geq z_u \tag{2.25}$$

The above assignments are incorporated into WELX, the modified version of MODFLOW's WELL package. This method of incorporating head-dependent pumping rates into the solution for hydraulic heads is the standard approach used in MODFLOW.

The expression for ground water pumping as a head-dependent flux given by (2.23) has an analog in evapotranspiration from shallow ground water. Above a user-specified extinction depth, evapotranspiration from ground water, $q_{ET}(d)$, varies linearly with depth up to a maximum, $q_{ET}(0) = q_{max}$, which represents ground water at the land surface. For a given grid cell, this is expressed as a function of hydraulic head, $h$, by

$$q_{ET}(h) = \begin{cases} q_{max} & h > z_s, \\ q_{max}\left(\dfrac{h - z_{ext}}{z_s - z_{ext}}\right) & z_s > h > z_s - d_{ext}, \\ 0 & h < z_s - d_{ext} \end{cases} \quad (2.26)$$

where $z_s$ = surface elevation and $z_{ext} = z_s - d_{ext}$, elevation at extinction depth. Note that this is the same form as equation (2.23) for head-dependent pumping rates from wells limited by saturated thickness. Evaporation from shallow ground water is incorporated into MODFLOW's solution by the EVT package using the approach shown above for head-dependent pumping (2.25).

Streambed leakage is also incorporated as a head-dependent flux in MODFLOW's STREAM package (Prudic, 1990) if the hydraulic head in the aquifer exceeds the bottom elevation of the streambed. Streambed leakage couples the equations for groundwater movement and streamflow, and is evaluated according to Darcy's law,

$$Q_l = -K_s P \Delta x (dh/dl) \quad (2.27)$$

Streambed leakage, $Q_l \equiv q_l \Delta x$, represents a flow rate per unit stream length, $q_l$, integrated over a stream reach of length $\Delta x$. On the right-hand side of (2.27), $K_s$ = hydraulic conductivity, $P$ = wetted perimeter, and $dh/dl$ = hydraulic gradient across the streambed. Streambed conductance, $C$, represents the product of the coefficients in (2.24), that is, $C = K_s P \Delta x / dl$. In the standard version of the STREAM package, streambed conductance is constant and is specified by input data as a separate value for each stream reach. Streambed leakage in the corresponding grid cell is given by

$$Q_l = \begin{cases} C(h_s - h), & h > z_b \\ C(h_s - z_b), & h \le z_b \end{cases} \quad (2.28)$$

This is separated into head-dependent and independent components which are accumulated into the left- and right-hand sides of (2.3) as in the cases above; that is,

$$\left.\begin{aligned} a_{ii} &= a_{ii} - C \\ b_i &= b_i - C h_s \end{aligned}\right\} \quad h_i > z_b$$
$$b_i = b_i - Q_l, \quad h_i \le z_b \quad (2.29)$$

The modified version of the package, STRX, allows streambed conductance to be evaluated as a function of hydraulic conductivity, reach length, and wetted perimeter in each time step. STRX also provides options for trapezoidal and natural channel geometry in which the wetted perimeter is allowed to vary with stream stage, which is coupled to the aquifer head by the streambed leakage given by (2.28). This can introduce a nonlinear head dependency of the streambed conductance, which is added into the coefficient matrix, **A**. Spurious oscillations between coupled and decoupled states can arise when the hydraulic head, $h$, is close to the elevation of the streambed bottom elevation, $z_b$. These oscillations, which can adversely affect solution convergence, are avoided by fixing the state given by the second iteration of the solution (in subroutine Strlkg of the STRX package).

## 2.4. Spatial heterogeneity of an underlying aquifer

A preceding discussion of the conceptual model for ground water recharge (equation 2.12) notes that SWAT's model for the soil profile presumes the existence of a vadose zone and an underlying aquifer. In the case of the Lower Republican River basin, however, 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. 2.6 and 2.7. Fig. 2.6 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 represented by the green-filled circles. Fig. 2.7 illustrates the vertical profile for the transect A-A' shown in Fig. 2.6. 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.

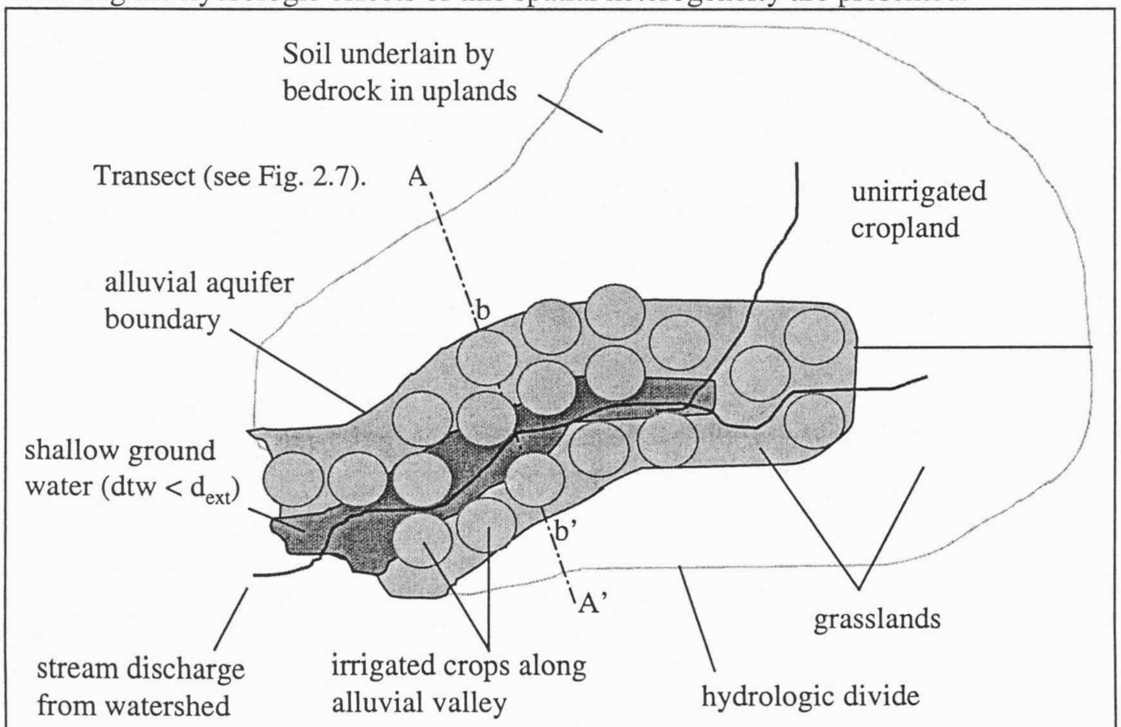


Fig. 2.6. Conceptual model for spatial heterogeneity with respect to a subbasin's geomorphology. HRU schemes 2 and 3 disaggregate the alluvial aquifer from the uplands, and deep from shallow ground water (scheme 3). (From Perkins, 1999)

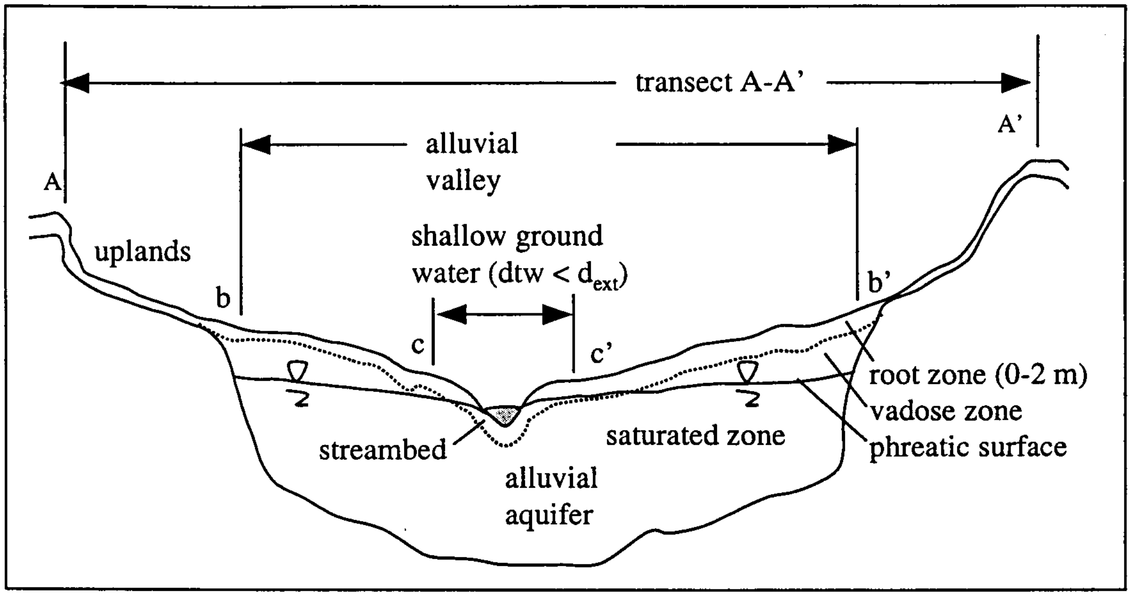


Fig. 2.7. Profile of subbasin shown in Fig. 2.6 along an arbitrary transect A-A'. (From Perkins, 1999)

Representing subbasins partially underlain by an aquifer with HRU scheme 1

SWAT's simulation is based on the assumption that the soil profile is underlain by an aquifer over the entire extent of each subbasin. Irrigation, recharge, and tributary flow are based on equations (2.11-2.13). To account for cases such as the Lower Republican River basin in which this assumption is unreasonable, HRU scheme 1, presented in Section 2.2, provides an ad hoc means of adjusting tributary inflows and recharge as follows.

For the areal fraction of the watershed underlain by an aquifer, $f_{aqf}$, percolation, transmission losses, and pond seepage contribute to ground water recharge (equation 2.15a). For the remainder of the watershed outside the alluvial valley, these components are assumed to contribute to streamflow (eq. 2.15b). Two weaknesses of this scheme are the following. First, the hydrologic processes associated with the aquifer's spatial heterogeneity are not simulated in SWAT, but are instead represented by the partitioning of equations (2.15a-2.15b). Second, spatial dependencies among HRU factors are ignored; soil types and land uses within each subbasin are assumed to be independent, so that unrealistic combinations such as upland soils and alluvial land uses are included (equations 2.9a-2.9b).

Representing variations on a deep aquifer with SWAT: HRU schemes 2 and 3

The shortcomings of first assuming a subbasin fully underlain by a deep aquifer in SWAT and then making an ad hoc adjustment of tributary inflows and recharge to account for a subbasin only partially underlain by an aquifer were addressed by HRU schemes 2 and 3, which are presented here. They were designed for application to the

Lower Republican River basin (Perkins, 1999), but have been generalized for application to other watersheds. Their development has also provided a means of simulating a two-way coupling between the solution domains of SWAT and MODFLOW.

**HRU scheme 2**

HRU scheme 2 invokes a modification of SWAT's subroutine Purk. To optionally represent a soil profile that sits on bedrock, percolation out of the root zone is held to zero; this is offset by increases in subsurface lateral flow and soil water content. This case allows a more physically based model of subbasins such as those of the Lower Republican River basin model that have both alluvial valley and upland components which can then be represented by distinct HRUs. A modified set of four land uses was constructed for this HRU scheme that incorporates the presence or absence of an underlying aquifer as follows for each subbasin, $j$:

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

$$u_{1j} = f_{cj} - f_{\mathrm{irr},j} \tag{2.30a}$$

2. Irrigated cropland within the alluvial valley (with aquifer);

$$u_{2j} = f_{\mathrm{irr},j} \tag{2.30b}$$

3. Grassland within the alluvial valley (with aquifer);

$$u_{3j} = f_{\mathrm{aqf},j} - f_{\mathrm{irr},j} \tag{2.30c}$$

4. Grassland outside the alluvial valley (no aquifer).

$$u_{4j} = 1 - f_{\mathrm{aqf},j} - \left(f_{cj} - f_{\mathrm{irr},j}\right) \tag{2.30d}$$

The above scheme combines land use classes of HRU scheme 1 with subsurface features represented by the areal fraction of each subbasin underlain by an aquifer, $f_{\mathrm{aqf},j}$. The areal fraction of cropland within each subbasin is denoted by $f_{cj}$, which is divided into non-irrigated and irrigated components of cropland corresponding to equations (2.30a-b). In Equations (2.30c-d), $u_{3j}$ and $u_{4j}$ are the alluvial and upland components of the subbasin not under cultivation, respectively, and are represented as grassland. HRU averages are evaluated by (2.9a-b) as for HRU scheme 1, but land use fractions are given by (2.30a-d).

**HRU scheme 3**

HRU scheme 3 invokes a second modification of SWAT that is coordinated with programs SWBAVG and MODFLOW to disaggregate deep and shallow ground water. HRS may be specified to represent shallow ground water, the uptake of shallow ground water into the soil water profile, and the variation of its areal extent over time in response to drought-flood cycles as follows.

The definition of shallow ground water according to MODFLOW's Evapotranspiration package was accepted: the depth to water is less than a user-specified extinction depth, above which evapotranspiration from ground water, $q_{\mathrm{ET}}(d)$, varies linearly with depth up to a maximum for ground water at the land surface, $q_{\mathrm{ET}}(0) = q_{\max}$; see equation (2.26). The maximum value, $q_{\max}$, is provided by SWAT as the potential evaporation rate. The evaporation rate given by equation (2.26) 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 SWBX 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. 2.3, thereby coupling SWAT and MODFLOW's solution by the method of successive approximation as discussed below.

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. 2.6, 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:

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

$$u_{1j} = f_{cj} - f_{\mathrm{irr},j} \tag{2.31a}$$

2. Irrigated cropland within the alluvial valley (deep ground water);

$$u_{2j} = f_{\mathrm{irr},j}\left(1 - f_{\mathrm{shl},j}\right) \tag{2.31b}$$

3. Grassland within the alluvial valley (deep ground water);

$$u_{3j} = \left(f_{\mathrm{aqf},j} - f_{\mathrm{irr},j}\right)\left(1 - f_{\mathrm{shl},j}\right) \tag{2.31c}$$

4. Grassland outside the alluvial valley (no aquifer).

$$u_{4j} = 1 - f_{\mathrm{aqf},j} - \left(f_{cj} - f_{\mathrm{irr},j}\right) \tag{2.31d}$$

5. Irrigated cropland within the alluvial valley (shallow ground water);

$$u_{5j} = f_{\mathrm{irr},j} f_{\mathrm{shl},j} \tag{2.31e}$$

6. Grassland within the alluvial valley (shallow ground water);

$$u_{6j} = \left(f_{\mathrm{aqf},j} - f_{\mathrm{irr},j}\right) f_{\mathrm{shl},j} \tag{2.31f}$$

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 2.30b-c) have simply been divided into two components each, corresponding to deep aquifer components (equations 2.31b-c) and shallow aquifer components (equations 2.28e-f). HRU averages are evaluated by (2.9a-b) as for HRU schemes 1 and 2, but land use fractions are given by (2.31a-f).

The soil water balance (equation 2.1) can be rewritten to include a term for evaporation from shallow ground water, denoted here as $d_{\mathrm{shl}}$:

$$d_{\mathrm{sw}}(t) - d_{\mathrm{sw}}(0) = \sum_{i=1}^{t}\left(d_{\mathrm{pcp}} - d_{\mathrm{ro}} - d_{\mathrm{lat}} - d_{\mathrm{perc}} - d_{\mathrm{et}} + d_{\mathrm{shl}}\right) \tag{2.32}$$

For an HRU-averaged soil water balance, incorporating the evaporation from shallow ground water into the soil profile, $d_{shl}$, is expressed in equation (2.32) 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. These are summarized by subroutine SWB2BD of the SWBX package. Under HRU scheme 3, this summary is read in SWAT at the beginning of each aquifer time step; this is performed by subroutine Init_shl for the first time step and by subroutine Sumstep for succeeding time steps. Shallow ground water, denoted by $Q_{i,j}$ and corresponding to hydrologic component $i$ and subbasin $j$, is converted in these subroutines to a daily volume per unit area of shallow ground water, $d_{shl}$ (mm). Rearranging (2.8) to integrate the flow rate over a day's time step and divide by the shallow aquifer area, this depth is given by

$$d_{\text{shl}} = cQ_{i,j}\Delta t / f_{s,j}A \tag{2.33}$$

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

$$f_{s,j} = f_{\text{sub},j} f_{\text{aqf},j} f_{\text{shl},j} \tag{2.34}$$

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. The daily volume per unit area of evapotranspiration from shallow ground water given by (2.33) is distributed over the soil profile by a routing procedure, beginning with the bottom soil layer, up to the available water capacity specified for the soil. This is performed by subroutine Evapgw, which is called by the modified subroutine Subbasin.

The intermediate program SWBAVG also reads the summary of evapotranspiration from shallow ground water, which is used in evaluating HRU weights, $w_k$. These are given by the products of soil type and land use (equation 2.9b), and are calculated by subroutine SUBWTS in each aquifer solution time step. This accounts for time-varying changes in the areal extent of shallow ground water in response to drought-flood cycles and irrigation water use.

<u>Coupling SWAT and MODFLOW solutions by successive approximation</u>

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 in Fig. 2.3 and with $d_{shl} = 0$ in the soil water balance (equation 2.32). 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. 2.3 based on HRU scheme 3, with $d_{shl} \neq 0$ for HRUs with shallow ground water. Results for HRU schemes 2 and 3 corresponding to the first two passes through the simulation procedure are presented in Perkins (1999).

This multi-pass procedure is expected to converge quickly; second and third pass should produce very similar results. However, conditions of strong coupling between the systems simulated by SWAT and MODFLOW might introduce unintended behavior such as oscillations. A dynamic analysis of such coupled systems was reported by Brandes et al. (1998). In a previous study of a similar coupling between streamflow and saturated ground water flow, simulations have shown significant oscillations and solution error under conditions of strong coupling when different time steps are used for streamflow and aquifer solutions (Koussis et al., 1994; Perkins and Koussis, 1996).

Spatial dependence among HRU factors

The land use class definitions for HRU schemes 2 and 3 account for spatial dependencies between the original land use classes of HRU scheme 1 (eqs. 2.10a-c) and two physiographic regions, which are the Republican River's alluvial valley and the uplands. Each subbasin contains areas of these regions, each of which has distinguishing features with respect to not only land uses but also soil types and subsurface characteristics as shown in Table 2.1.

Table 2.1. Regional characteristics within each subbasin

| Region | Uplands | Alluvial valley |
|---|---|---|
| basin areal fract. | 0.875 | 0.125 |
| land uses | unirrigated crops, grasses | irrigated crops, grasses |
| soil types | Crete, Hasting, Hedville, Kipson | Carr, Muir |
| subsurface | bedrock | alluvial aquifer |

The soils and the subsurface underlying soils are both closely associated with the physiography of the two regions. The alluvial valley is characterized by Carr and Muir soils and by an underlying aquifer, while the uplands are characterized by Crete, Hastings, Hedville, and Kipson soils, and by a soil profile underlain by bedrock. Land uses are also regionally dependent; irrigated cropland lies along the alluvial valley, and unirrigated cropland lies in the uplands. The remainder of the basin is represented as grassland, which lies in both regions.

Implementing HRU schemes 2 and 3 for the Lower Republican R. basin model

For the Lower Republican River basin model, the land use and subsurface features were combined into equivalent sets of land classes, given by eqs. (2.30a-d) for HRU scheme 2 and (2.31a-f) for HRU scheme 3. These land classes account for the regional dependencies shown in Table 2.1 between land use and subsurface features, and unrealistic combinations of these factors are excluded. Similarly, Table 2.1 shows a regional dependence for soil types.

The method used to calculate weights for HRU schemes 2 and 3 takes into account these spatial dependencies, and is expressed by a modified version of eq. (2.9) as follows. Each HRU represents the features of only one region within a subbasin. The land use classes given by eqs. (2.30a-d) or (2.31a-f) and soil types associated with a given region are assumed to be independent within the region. For a given HRU, $k$, its spatial weight, $w_{jk}$, is given for region, $i$, within subbasin, $j$, by

$$w_{jk} = \frac{s_r(l,i,j)}{r_{ij}} \frac{u_r(m,i,j)}{r_{ij}} r_{ij} . \tag{2.35}$$

where $r_{ij}$ = region, $i$, areal fraction of subbasin, $j$; $s_r(l,i,j)$ = soil type, $l$, areal fraction of subbasin within region, $i$; and $u_r(m,i,j)$ = land use, $m$, areal fraction of subbasin within region, $i$. In eq. (2.35), the regionalized land use fractions, $u_r$, are given by eqs. (2.30a-d) for HRU scheme 2 and by eqs. (2.31a-f) for HRU scheme 3. The HRU-averaged hydrologic components are evaluated as before by eq. (2.9a). To illustrate equation (2.35), consider a region containing only one soil type, $s_r = r_{ij}$, and one land use, $u_r = r_{ij}$. In this case, a single HRU would represent the region, and its spatial weight according to (2.35) reduces to $w_{jk} = r_{ij}$. Another example illustrates a typical case. If a subbasin contains only one region, then $r_{ij} = 1$, and (2.35) reduces to (2.9b).

The HRU weights given by eq. (2.35) are evaluated in program SWBAVG. The input to SWBAVG, an extended version of the Control Codes (*.cod) input file for SWAT, associates each soil type with a region. SWBAVG evaluates the weights according to an equivalent but less apparent version of (2.35) given by

$$w_{jk} = \frac{s_r(l,i,j) u_r(m,i,j)}{r_{ij}} . \tag{2.36}$$

SWBAVG was designed to implement this regionalized HRU approach for a particular basin, that of the Lower Republican River. Its implementation of HRU schemes 2 and 3 restricts the model to the case that all soil types can be associated with one region or another, as shown in Table 2.1. Because the soil weights, $s_r$, and the regional fractions, $r_{ij}$, are constant, they are combined into a single coefficient in SWBAVG, and (2.36) is evaluated in subroutine SUBWTS by

$$w_{jk} = s_r'(l,i,j) u_r(m,i,j) , \tag{2.37}$$

where $s_r'(l,i,j) = s_r(l,i,j)/r_{ij}$ . A more general version of this approach has been developed that allows a mix of region-dependent and region-independent factors to be specified. This approach has been implemented as program HRUAVG, and is presented below.

In HRU scheme 2, the alluvial valley with an underlying aquifer included only two soil types and two land uses (eqs. 2.30b-c), and were represented by four HRUs. The uplands with bedrock under the soil profile included the remaining four soil types and two land uses (eqs. 2.30a and 2.30d), and were represented by eight HRUs, so that the basin could be represented by a total of 12 HRUs instead of 36 by taking into account these spatial dependencies. In addition, the HRUs for Hastings and Hedville soils were run as single simulations of SWAT, since these soils occur in disjoint sets of subbasins, so that only ten separate simulations of SWAT were required.

In HRU scheme 3, HRUs in the upland region are the same as for HRU scheme 2. Eight HRUs were simulated to represent the alluvial region based on two soil types and four land use classes, including eqs. (2.31b-c) for deep ground water and (2.31e-f) for shallow ground water. A total of 16 HRUs were simulated for this case, which required only 14 runs of SWAT, since Hastings and Hedville soils were combined as they were for HRU scheme 2 (above).

## 2.5. A more general model of spatial dependency

HRU schemes 1-3 as presented in Section 2.4 provide alternative models of spatial heterogeneity in the Lower Republican River basin, but lack the generality required for more general application. A generalized version of these schemes presented here was implemented first with the program HRUAVG, which performs the function of SWBAVG in the SWAT-MODFLOW linkage. In comparisons of HRU schemes 1-3 for the Lower Republican River basin model, the program HRUAVG produced weight functions with small differences from those calculated by SWBAVG for the basin-specific schemes.

More recently, the functionality of HRUAVG has been incorporated into SWAT, allowing for a greatly simplified procedure for orchestrating SWAT and MODFLOW. The original procedures based on SWBAVG and HRUAVG are still available as options, and are presented in Chapter 6 of the User's Manual. Whether the HRU averaging is applied in SWAT, SWBAVG, or HRUAVG, the SWAT-MODFLOW linkage provides the capability for HRU weights to be evaluated during the simulation, rather than requiring them to be specified as input data. Consequently, the HRU weights can represent changing areal extents of the component factors, particularly those of land use and shallow ground water.

The generalized scheme for representing spatial heterogeneity accounts for land use, soil type, and subsurface features as three separate but not necessarily independent factors, which often exhibit spatial dependencies associated with physiographic regions. These dependencies were ignored in formulating soil type-land use combinations for HRU scheme 1 as applied to the Lower Republican River basin, so that many of the combinations included in its simulation did not actually occur in the basin. Spatial dependencies of land use, soil type, and subsurface features are identified with respect to two distinct physiographic regions in the Lower Republican River basin, namely the alluvial valley and the remaining upland region outside the valley. Spatial dependencies associated with these three factors significantly reduce the number of combinations required to represent spatial heterogeneity in the basin. These dependencies include the following:

1. Subsurface features are associated closely with these physiographic regions. Along the alluvial valley, the soil profile is generally underlain by an alluvial aquifer, part of which may have a shallow depth to water and contribute significantly to evapotranspiration. On the other hand, the soil profile in the uplands is underlain by bedrock that directs percolation out of the soil profile to flow laterally, and alters related hydrologic components, particularly soil water content and evaporation from the soil profile.

2. The Carr and Muir soil types in the Lower Republican River basin occur only within the alluvial valley, and generally have greater thickness and higher soil water capacity than the remaining soils (Crete, Hastings, Hedville, and Kipson), which occur only outside the alluvial valley.

3. Irrigated cropland is assumed to occur exclusively along the alluvial valley, and dryland cropping only outside the alluvial valley. The remaining grasslands occur in both.

Method for generalized HRU schemes

Areal fractions of each subbasin are specified for each physiographic region and for the three factors to be considered (subsurface features, soil types, and land uses). Factors are either associated with a particular region or with no region, in which case they are treated as spatially independent. The spatially dependent factors reduce the area over which the spatially independent factors can occur in the basin.

A hydrologic response unit (HRU) is represented by the characteristics of a subbasin associated with a particular combination of factors. The HRU-averaged value for a given hydrologic component, $d_i$, in subbasin $j$ is given by (2.9a), reproduced here,

$$d_{ij} = \sum_{k=1}^{n_k} d_{ijk} w_{jk} \text{ ,} \qquad (2.9a)$$

where the number of HRUs, $n_k$, depends on the particular scheme, as in the cases of HRU schemes 1-3, which varied from 10 to 15 HRUs for the Lower Republican River basin. Each HRU weight, $w_k$, is evaluated in terms of the areal fractions corresponding to the three factors representing hydrogeologic feature, $g_j$, land use, $c_j$, and soil type, $s_m$. Each of these may be restricted to a particular physiographic region, $r_i$, and are expressed as conditional probabilities that are explained below. Table A.1 shows areal fractions within each subbasin for soil types, land underlain by an alluvial aquifer, and cropland.

Areal fractions, $r_{ij}$, for physiographic regions, $i$, in each subbasin, $j$, for the Lower Republican River basin are given by:

$$r_{1j} = 1 - f_{\mathrm{aqf}j} \qquad \text{uplands: bedrock underlies soil profile;} \qquad (2.38a)$$

$$r_{2j} = f_{\mathrm{aqf}j} \qquad \text{alluvial valley: ground water underlies soil profile.} \qquad (2.38b)$$

Here, $f_{\mathrm{aqf}j}$ = areal fraction of subbasin with an aquifer underlying the soil profile. Areal fractions, $g_{ij}$, for hydrogeologic features, $i$, of subbasins, $j$, are given by:

$$g_{1j} = 1 - f_{\mathrm{aqf}j} \qquad \text{uplands: bedrock underlies soil profile;} \qquad (2.39a)$$

$$g_{2j} = f_{\mathrm{aqf}j}\left(1 - f_{\mathrm{shl}j}\right) \qquad \text{alluvial valley, deep ground water component;} \qquad (2.39b)$$

$$g_{2j} = f_{\mathrm{aqf}j} f_{\mathrm{shl}j} \qquad \text{alluvial valley, shallow ground water component;} \qquad (2.39c)$$

where $f_{\text{shl}j}$ = areal fraction of aquifer in subbasin with shallow ground water, based on a criterion that is specified as extinction depth in MODFLOW (McDonald and Harbaugh, 1988). Clearly, these hydrogeologic features are closely tied to the basin's physiographic regions.

Areal fractions, $u_{i,j}$, for each land use classes, $i$, in subbasin, $j$, are given by extending equations (2.10a-2.10c) to include a class for urban land use, (2.40d), as a more general case:

$$u_{1j} = f_{cj} - f_{\text{irr},j} \quad \text{(non-irrigated cropland);} \quad (2.40a)$$

$$u_{2j} = f_{\text{irr},j} \quad \text{(irrigated cropland);} \quad (2.40b)$$

$$u_{3j} = 1 - \left(f_{cj} + f_{\text{urb}j}\right) \quad \text{(grassland or undeveloped land);} \quad (2.40c)$$

$$u_{4j} = f_{\text{urb}j} \quad \text{(urban land uses).} \quad (2.40d)$$

The areal fraction of cropland is denoted by $f_{cj}$ for each subbasin, $j$, in equations (2.40a) and (2.40c). The non-irrigated areal fraction is given by subtracting from the irrigated areal fraction, $f_{\text{irr},j}$, from cropland (2.40a). In this scheme, grassland (2.40c) represents the areal fraction of the subbasin not under cultivation or in urban areas (2.40d).

Regional dependencies among HRU factors

Each HRU is defined to represent a combination of factors with respect to only one physiographic region within a subbasin. Consequently, we need to estimate the areal fraction within each such region for each component of a given factor, e.g., for each soil type, land use, and subsurface type. Subroutine Regwts was written to calculate these areal fractions, taking into account the specified spatial dependencies for each component of a given factor, e.g. land use types. Consider, for example, land uses along the Lower Republican River alluvial valley, which includes irrigated crops and grasslands. The first of these land uses occurs only in the alluvial valley, whereas the grasslands are spread over both the alluvial valley and the uplands of the basin. The assumed restriction of the irrigated cropland to the alluvial valley reduces the available land area, or probability space, of the basin over which the spatially independent land use for grasslands may be distributed. More generally, spatially independent factors are distributed over the regions within the subbasin in proportion to the areal fraction of each region that remains after subtracting the areal fraction associated with spatially dependent factors. This procedure is applied by subroutine Regwts separately for the following three factors in each region, $i$, and subbasin, $j$: $s_r(l,i,j)$ = areal fraction of soil type, $l$, $u_r(m,i,j)$ = areal fraction of land use, $m$, and $g_r(n,i,j)$ = areal fraction of subsurface type, $n$.

Subroutine Regwts is called once to evaluate the regional soil fractions, $s_r(l,i,j)$, which are constant; but Regwts is called in each time step to evaluate the regional land use fractions, $u_r(m,i,j)$, and subsurface type areal fractions, $g_r(n,i,j)$. In the case of land use fractions, $u_r$, the irrigated areal fraction of the basin, $f_{\text{irr}}$, varies over time from year to year, based on changing appropriations for irrigation water rights. The subsurface type areal fractions, $g_r$, vary on the time scale of storm periods, reflecting the response of ground water levels and the corresponding areas of shallow ground water.

Separation of the above three factors allows the probability, or spatial weight, of each combination to be represented by their product. This constrasts with the original formulation of HRU schemes 2-3, in which the land use and subsurface features were combined into one factor. Based on the three independent factors (soil, land use, and subsurface features) within a given physiographic region, $i$, and subbasin, $j$, the spatial weight, $w_{jk}$, for each HRU, $k$, is given by

$$w_{jk} = \frac{s_r(l,i,j)}{r_{ij}} \frac{u_r(m,i,j)}{r_{ij}} \frac{g_r(n,i,j)}{r_{ij}} r_{ij} . \tag{2.41}$$

where $r_{ij}$ = the areal fraction of region, $i$, with respect to subbasin, $j$. This is a generalized form of equation (2.35), which was based on the land use classes given by eqs. (2.30a-d) and (2.31a-f) that were devised for HRU schemes 2 and 3 specifically for the Lower Republican River basin. In contrast, eq. (2.41) should be more generally applicable to other basins.

Regwts is called by either SWAT or by HRUAVG, depending on the procedure chosen by the user for linking SWAT and MODFLOW simulations.

## 2.6. Transmission losses and the soil water balance

The option added to SWAT to represent the hydrologic effects of a soil profile underlain by bedrock (**Ipurk**(j) = −1) and applied in HRU schemes 2 and 3 includes a change to the SWAT subroutine Purk. For this added option, percolation out of the soil profile is held to zero, which is compensated by increased subsurface lateral flow and soil water content. An aspect of a conceptual for a soil profile underlain by bedrock that was ignored concerns transmission losses, which are treated in SWAT as a component of runoff that flows through ephemeral channel beds to an aquifer. The partitioning by SWAT of excess rainfall into surface runoff and transmission loss components is presumed to be independent of the soil water balance. But this appears inconsistent with the added option to represent a soil profile underlain by bedrock (**Ipurk**(j) = −1). For this conceptual model, there is no aquifer to receive transmission losses, and the soil water balance would likely be affected. Instead, transmission losses for this case are lumped into runoff. An alternative model for transmission losses affecting the soil profile that was implemented for another watershed simulation program is described in Ramireddygari et al. (2000).

# 3. Implementing the SWAT-MODFLOW linkage

Code changes and additions are summarized for SWAT in Section 3.1, and for MODFLOW-96 in Section 3.2. Procedures for compiling, linking, and running SWAT, MODFLOW, and related programs are summarized in Section 3.3. the documentation file \gh\docs\swt99chg.doc. Execution of SWAT was tested on the Y7 watershed model (Arnold et al., 1994), the Lakefork example included with the AvSwat extension, and sample cases from the Lower Republican River basin model.

The original SWAT-MODFLOW linkage was based on SWAT v.94.2 and MODFLOW-88, and was applied to models of the Lower Republican River basin and Rattlesnake Creek watershed in Kansas for use in water resource studies of these watersheds. A second set of changes, documented in S&P (1999), was made to implement and compare HRU schemes 1-3 for the Lower Republican River basin (Perkins, 1999). In contrast, the update presented here is intended to make the SWAT-MODFLOW linkage available for application to other watersheds. As a consequence of this change in focus, some of the options incorporated into the earlier linkage are not included in the update, primarily to avoid changing the code and input format of the program for purposes that may be irrelevant to other applications. Some options for the original SWAT-MODFLOW linkage were eliminated by making use of existing options in SWAT.

## 3.1. Automating the calculation of virtual subbasin areas

The task of specifying virtual subbasin areas was automated, which allowed for a much simpler procedure for combining SWAT and MODFLOW. The more complex, three-step procedure it replaced involved multiple runs of SWAT to simulate individual HRUs, an intermediate program such as SWBAVG or HRUAVG to average the HRUs and convert HRU-averaged results to flow rates for input to MODFLOW, and subsequent execution of MODFLOW; see Ch. 6 of the User's Manual for further specifics. Automating calculation of the virtual subbasin areas allowed a practical means of encapsulating in SWAT the steps involving HRU simulation, HRU-averaging, and conversion to flow rates. This resulted in a simple two-step procedure of running SWAT to obtain results for input to MODFLOW, and then running MODFLOW.

The option to calculate these areas was specified by setting Iopwts > 0 in the *.cod input file. Combinations of HRU factors (soils, land uses, and subsurface types) were defined in the same file. HRU schemes 1-3 were defined in terms of 15, 10, and 14 combinations, respectively, as shown in listings of the *.cod files, below. For each HRU scheme, an added field for the configuration file (*.fig) allowed associating each virtual subbasin with a combination of HRU factors. For each virtual subbasin, if the *.fig input file specified such a combination that was defined in the *.cod input file, and the option Iopwts > 0, then the virtual subbasin area is calculated, replacing the value specified in the virtual subbasin (*.sub) input file. Further, the virtual subbasin areas are updated in each time step in the case of HRU scheme 3 in order to model the changing area of shallow groundwater in response to storm-interstorm cycles. Virtual subbasin areas could be similarly updated to represent changing land uses over the time period of a simulation, although this has not yet been implemented. For the case of the Lower Republican River basin model, the land use changes of interest did not appear to be very significant. Based on water use and water rights reports from Kansas Division of Water Resources (DWR), the irrigated areal fraction of the basin appeared to vary over a narrow range of about 3-5 percent.

By automating the calculation of the virtual subbasin areas for each groundwater time step, the model can simulate temporal variation of HRU factors and, consequently, a two-way coupling of SWAT's daily watershed soil water balance and MODFLOW's stream-aquifer hydraulics solution.

### Recent SWAT-MODFLOW linkage developments since Final Report

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

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

An option to calculate HRU weights for virtual subbasins has been incorporated into Swat. HRU weights are based on spatial variability factors for soils, land use, and subsurface features. Areal fractions of each subbasin are specified for these factors in an extended version of the Control Codes (*.cod) input file. This file also defines combinations of these factors that can be used to calculate HRU weights. An additional numeric field is read from the configuration (*.fig) file to allow associating these combinations with HRUs. If the option Iopwts > 0 has been set in the Control Codes input file, and if the combination specified in the Configuration file has been defined in the Control Codes input file, then the initial HRU weight and the corresponding virtual subbasin area are calculated, thereby replacing the value specified in the Subbasin (*.sub) file. Similarly, HRU weights and the corresponding virtual subbasin areas can be updated for each groundwater model time step to reflect changing areas of shallow groundwater in response to storm-interstorm cycles. These code changes have allowed the Lower Republican River basin model to be run with only a single execution of SWAT under HRU schemes 1-3. Related code changes include the following.

a. (Modflow, SWAT): Evaporation from shallow groundwater is summarized for each subbasin (in subr. Swb2bd, Swbx package) as a fraction of potential ET, which varies linearly with depth to water according to Modflow's ET model. This summary is read in SWAT by subroutines Init_shl (called by Init_bal) and Sumstep. For each HRU, j, with shallow groundwater (specified by Ipurk = 1 in the *.gw input file), the configuration routing array Inum3s(j) associates the HRU with the corresponding subbasin, isub, and the gw ET as a fraction of potential ET, given by frcpot(isub) for the duration of the groundwater time step. This is multiplied by daily potential ET for the HRU in each day of the time step in subroutine Subbasin to give the daily uptake into the soil profile, which is distributed over the soil profile by subr. Evap_gw.

b. (Swbavg, Hruavg): The shallow gw evaporation summary written by Modflow also gives the shallow gw areal fraction of the subbasin, total gw areal fraction of the subbasin, depth to water within the shallow gw extent of the subbasin, and avg depth to water in the subbasin. The shallow gw areal fraction is used in the intermediate program Swbavg (or Hruavg) to calculate HRU weights in each time step. This capability to represent time-varying spatial weights of HRUs is provided by simulating HRUs with separate executions of SWAT and averaging the HRUs external to SWAT using Swbavg or Hruavg.

c. (Swat): Subr. Sumhrus was written to take a spatially weighted average over HRUs within each subbasin. Sumhrus is called at the end of each gw time step, just prior to the call to subr. Sumstep. The subroutine Sumhrus is required for the general case that each subbasin is represented by one or more HRUs. Subroutine Sumhrus was not required for the special case of one HRU per subbasin, which was sufficient for the purposes of the models we developed using Swat and Modflow.

d. Subroutine Sumstep, which was previously added to SWAT to summarize simulation results for MODFLOW, was modified to be independent of the order in which simulated hydrologic components are stored in SWAT's array, ssub. This makes the subroutine more easily adapted for use in linking Modflow with other watershed hydrology simulators other than Swat. One of the sections of this document summarizes the data that are to be passed between SWAT and MODFLOW, and corresponding array locations. The indexing array Idxsub, defined in Swtmod99.h, is used to select data from SWAT's monthly summary array, ssub, or annual summary array, Sysub, just prior to calling Sumstep in subroutines Writem, Writea, and Writed.

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

MODFLOW's system of units. After SWAT has simulated all subbasins, Swbmerge can combine them into a basin summary file for input to MODFLOW.

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

SWAT 98.1 was also adapted for coordination with MODFLOW, incorporating the changes and additions made to SWAT 99.2. This was done to allow testing the linkage to MODFLOW for the case where separate models of a basin using SWAT 98.1 and MODFLOW were available. Instructions for coordinating SWAT and MODFLOW were intended to apply to both versions of SWAT. However, recent developments to simplify use of SWAT v.99.2 with Modflow have not yet been applied and tested for SWAT v.98.1.

Two additional postprocessing packages, Rsdx and Postx, are included with the updated Modflow-96 code, and the subroutiness associated with these two packages are called by the modified mainline, modflx96.for. These postprocessors were developed for internal use on groundwater modeling studies at Kansas Geological Survey, and are documented separately in KGS Open_File Report No. 2000-x4.

### 3.3. SWAT v.99.2 source code changes and additions

Changes to subroutines called by SWAT's Main

Readcod was modified to read Iopmod from the Control Codes (*.cod) input file, an option to activate the Swat-Modflow linkage.

Readfig was modified to read IdComb, an optional HRU identifier which, if positive, is associated with a unique combination of factors defined in Readwts, allowing the HRU weight to be calculated.

Readwts (added; called by Main if Iopmod > 0): read areal fractions for soil, land use, and groundwater in each subbasin from the extended Control Codes (*.cod) input file. Define combinations of these factors and calculate sp_wts, the HRU weight as an areal fraction of subbasins.

Rteinit (called by Readinpt): added option to calculate HRU spatial weights, hru_fr(), replacing the value read from the subbasin (*.sub) input file. Define:

subfrc() = the corresponding subbasin's areal fraction of the basin;

sp_wts() is calculated in Readwts using methods described for HRUAVG (Ch. 3).

If, for each HRU, the following conditions are true:

Iopwts > 0 (modified *.cod file sets option to calculate HRU weights);

IDComb > 0 (HRU identifer, read from the modified configuration (*.fig) file);

IDComb = Idxhru, an index to a defined combination of HRU factors given by the modified Control Codes (*.cod) input file.

Then evaluate the HRU weight given by

hru_fr() = sp_wts()*subfrc().

Init_bal (called by Simulate if Iopmod > 0): Initialize output files to summarize SWAT simulation for input to MODFLOW.

Init_shl (called by Init_bal if Iopshl > 0): Initialize input from MODFLOW to give areal fraction of shallow groundwater and evaporation from shallow gw in each subbasin.

<u>Subroutines called in each groundwater time step</u>

Rte_Update (called by Init_shl and Sumstep if Iopwts > 0): Update spatial weight of HRU in each gw time step to reflect changing areal fraction of shallow groundwater given by Modflow; compare with modified subroutine Rteinit (above).

Hydrologic terms shown in SWAT's soil water balance (2.1) are accumulated over each groundwater time step. Based on Control Code Ipd, call Writed, Writem, or Writea to summarize each daily, monthly, or annual gw time step as follows.

For each gw time step of simulation period:
Call Sumhru: for each hydrologic term of the soil water balance (2.1), take a spatially weighted average over HRUs within each subbasin.

Call Sumstep to do the following:

a) Combine hydrologic terms simulated by SWAT for each subbasin to specify fluxes for MODFLOW's solution in each time step, including irrigation demand, ground water recharge, tributary inflow, and potential evaporation from shallow ground water; see equations (2.11–2.16) below.

b) Transform the terms simulated by SWAT from cumulative volumes per unit area [L] to flow rates [$L^3/T$] in the system of units specified for MODFLOW's simulation. The terms in (2.1) have the units of depth corresponding to a volume given by $V = dfA$, where $f$ is the areal fraction of watershed area, $A$, to which the hydrologic term applies. This volume is given by integrating flow rate over time. For average flow rate, $Q$, and time step, $\Delta t$, $V = Q\Delta t$. Combining these relates the flow rates, $Q$, to depths, $d$, by

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

where *c* is a length conversion factor.

c) Write simulation summary to a file for input to MODFLOW.

d) If Iopshl > 0, prepare for next gw time step as follows:
Read Modflow summary of shallow gw and evaporation;
If Iopwts > 0, update HRU weights (subr Rte_Update).

Steps (1a-1d) are based on SWAT's representation of HRUs as virtual subbasins. Performing these operations within SWAT should allow an improved integration of the procedure into a GIS-based model. Alternatively, these intermediate steps may be applied externally by using SWAT in combination with program SWBAVG or HRUAVG. For information on this option, see Chapter 3 on programs SWBAVG and HRUAVG.

Use of the "Module" program structure in Fortran 90

The "Module" program structure, a capability of Fortran 90 not available in Fortran 77, 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 of 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 in its source file, which is listed as follows (Listing 3.1):

Listing 3.1. Swat's main program (file main.for)

```
c file main.for            code for modules parm and Swtmod99
c$debug                    !compiler statement (not used by Lahey compiler)
      include 'modparm.f'  !Module parm:     data for Swat-99.2 (unmodified)
      include 'swtmod99.h' !Module Swtmod99: data for Swat-Modflow linkage--spp
      program main         !begin program mainline
      use parm             !use original module to share Swat data f90-style
      use swtmod99         !use added Swat-Modflow module--spp
c                           read Control Codes (*.cod) and call subroutines
c     ~ ~ ~ COMMON BLOCKS
      include 'common.f'
c     ~ ~ ~ INCOMING VARIABLES ~ ~ ~
c      name        units          definition
c     ch_l(2,j)     |(km)          |channel length
c     nres          |
c     resvo(j)
c     ~ ~ ~ SUBROUTINES/FUNCTIONS CALLED ~ ~ ~
c     openfile, readcod, readfig, gcycl, readbsn, readwwq, readpts, readfile
c     readinpt, ttcoef, readres, openwth, simulate, finalbal, writeaa, pestw
c     statcomp, randn
c     ~ ~ ~ ~ ~ ~ END SPECIFICATIONS ~ ~ ~ ~ ~ ~
      character*80 titldum
      prog = "SWAT  Oct.'99 SUNSPARC VERSION99.2"
      write (*,2231)
2231  format(1x,'                  SWAT 99.2                       ',/,
     *          '        Soil and Water Assessment Tool            ',/,
     *          '        PC Version with Modflow option            ',/,
     *          ' Program reading from file.cio ... executing     ',/)
      call getallo
      call allocate_parms
      call alloc_swtmod (mnr,ma,mhru,mbb,mhyd) !allocate arrays for swtmod99.h
```

```
      call openfile (stdout)
      call date_and_time (date, time, zone, values)
      call readcod
      call readfig                  !modified to optionally read idcmb !spp
      if (iopmod > 0) call readwts (nbyr,iyr,Lubtot,mhyd,mhru,
     1                              icodes,inum1s,inum3s,hru_fr)        !spp
      call gcycl
      call initial
      call readbsn
      call std1
      call readwwq
      call readfile
      call readinpt
      call std2
      cn = cn1
      call openwth
      call headout
      call simulate
      call finalbal(j)
      call writeaa
      call pestw
c     call statcomp
      do 90 i = 1, 9
        close (i)
   90 continue
      stop
      end
```

The module swtmod99 is invoked by the "Use" statement in each routine where needed. In addition, dynamic memory allocation is applied by subroutine Alloc_Swtmod, which is analogous to Swat's subroutine Allocate_Parms. The "use swtmod99" statement is inserted just below the "use parm" statement for those subroutines in SWAT that use the Modparm module, and most of them do. Some of the source code files that were added to implement the SWAT-MODFLOW linkage and related changes do not use the Modparm module. The inclusion of SWAT's common blocks (file common.f) and the usage of the two modules Modparm and Swtmod99 in the added and modified subroutines are shown in Table 3.1 (below). Additions or changes to SWAT indicated in Table 3.1 are summarized as follows.

**Main.for**: include Swtmod99.h immediately after inclusion of modparm.f and prior to beginning of mainline. Note: the code added for the Swat-Modflow linkage uses i/o device numbers 100-109.

**Main**: added **stdout**, declared in module Swtmod99, to argument list for subr. Openfile; added call to Alloc_swtmod to allocate additional arrays defined for the SWAT-MODFLOW linkage.

**Alloc_swtmod**: allocate memory for added arrays, which are shared via the "use swtmod99" command that is inserted into routines as shown in the above table.

**Openfile**: declared stdout as dummy argument to pass back to Main so that the standard output file name prefix could be used to name files associated with the SWAT-MODFLOW linkage; this is done in subr. Init_bal. For Main, file name stdout is declared in module Swtmod99.

Table 3.1. Modified or added SWAT routines for SWAT-MODFLOW linkage

| subroutine or module name[1] | added subr's. | existing subr's. | include common.f | use parm | use swtmod99 |
|---|---|---|---|---|---|
| Swtmod99[2] | | | | | |
| Main | | x | x | x | x |
| Alloc_swtmod | x | | | | x |
| Openfile | | x | x | x | |
| Simulate | | x | x | x | x |
| Init_bal | x | | x | x | x |
| Init_shl[3] | x | | x | x | x |
| Echoinpt | x | | x | x | |
| Readinpt | | x | x | x | |
| Readcod | | x | x | x | x |
| Readfig | | x | | | |
| Readwts | x | | | | |
| Readmgt | | x | x | x | x |
| Readgw | | x | x | x | x |
| Subbasin | | x | x | x | x |
| Purk | | x | x | x | x |
| Evapgw | x | | | | |
| Swu | | x | x | x | |
| Writem | | x | x | x | x |
| Writea | | x | x | x | x |
| Writed | | x | x | x | x |
| Sumhru | x | | | | |
| Sumstep | x | | | | x |

Notes (T. 3.1): [1]File names are given by subroutine names with the extension ".for" to denote fixed format of Fortran-90 code for Lahey compiler. File name exceptions: [2]Module Swtmod99 is on file swtmod99.h, which is inserted into the source file Main.for with an Include statement just above the start of Main. [3]Subroutine Init_shl is on file Init_bal.for.

**Readcod**: Read additional data from the *.cod input file. Theo added option iopmod > 0 specifies an addition line of data to be read to specify options for the SWAT-MODFLOW linkage. Other added input data are read by modified subroutines **Readgw** and **Readmgt**.

**Readwts**: If Iopmod > 0 (as specified in the Control Codes input file), read the additional data from the modified Control Code input file. Then if Iopwts > 0), these data allow SWAT's HRU weights and corresponding virtual subbasin areas to be calculated.

**Simulate**: modified to do the following:

a) optionally initialize input and output files associated with SWAT-MODFLOW linkage: call Init_bal if **Iopmod** > 0 (added input, read in Readcod); and call Init_shl if **Iopshl** > 0 (read in subr. Readcod);

b) Initialize and accumulate the counter **ndstep**, no. days in each aquifer time step;
c) Initialize **cn_basn**, a basinwide average of SCS curve number, which is calculated in subroutine Subbasin and is written in subroutine Sumstep.

**Subbasin**: modified to do the following:
accumulate cn_sub(j), the SCS cn for subbasin j time-averaged over aquifer time step. [Define cn_sub(j) in Swtmod99.h; initialize in subr. Simulate, accumulate in subr. Subbasin, cn_sub(j) = cn_sub(j) + cn. Divide by ndstep and write to files ~.bal and ~.dep in subr Sumstep.]

**Init_bal**: Name and initialize files associated with the SWAT-MODFLOW linkage, including file *.bal, which is written in subr. Sumstep to summarize SWAT simulation results for each HRU, and file *.shl, which is written by MODFLOW to summarize evaporation from shallow ground water and is read in subr. Sumstep.

**Init_shl**: call from subr. Simulate to initialize and read for an initial time step an input file, written by a prior execution of Modflow that summarizes evaporation from shallow ground water. Init_shl is called if Iopshl > 0 (read in subr. Readcod).

**Writem**: add call to Sumstep for SWAT-MODFLOW option (**iopmod** >0) to summarize SWAT results to be used as input to SWBAVG or MODFLOW for monthly aquifer time steps.

**Writea**: changes similar to Writem but for annual aquifer solution time steps.
**Writed**: changes similar to Writem but for daily aquifer solution time steps.

**Sumhru**: called by subr. Writem, Writea, or Writed just prior to calling Sumstep (below). Sumhru evaluates a spatially weighted average of each hydrologic term simulated by SWAT over the virtual subbasins within each geographically defined, or actual, basin. These results are passed to Sumstep.

**Sumstep**: called by subroutine Writem, Writea, or Writed to summarize SWAT results listed in Table 2.2 for each aquifer time step. SWBAVG reads these results for all HRUs, takes a spatially weighted average over the HRUs, and converts the HRU-averaged hydrologic components simulated by SWAT into flow rates that can be used as input to MODFLOW to specify fluxes its solution, including recharge, surface and ground water pumping for irrigation, and tributary inflows.

<u>Additional modifications to SWAT required for implementing HRU schemes 2 and 3:</u>
**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 soil profile. This option input from Modflow summarizing evaporation from shallow ground water.

**Readmgt** was modified to specify a daily maximum for irrigation, **auto_dmx** (mm), and a soil water content threshold for irrigation, **auto_swf** (fraction of available capacity) 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.

**Subbasin**: modified to do the following (see also the outline of the modified subroutine in Fig. 2.3) in addition to item (a), above:

b) if **Ipurk** > 0, (read from modified *.gw), call Evapgw to redistribute upward flow from shallow ground water over soil profile;
c) if **divmax** > 0 (read from modified *.mgt), set a daily max. limit on irrigation, divmax;
d) if **wsfmax** > 0 (read from modified *.mgt), apply automatic irrigation subject to **wsfmax**, a soil water threshold as fraction of available field capacity. In addition, if plant stress factor threshold is also positive, automatic irrigation is applied to maintain both soil water content and plant stress factor above these thresholds. These options are designed to enhance but not interfere with the existing options to apply one or the other thresholds exclusively, depending on the sign of the specified plant water stress factor threshold.

**Purk** was modified 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.

**Evap_gw** was added to SWAT, and is called by subroutine Subbasin to redistribute uptake from shallow ground water over the soil water profile for the option **ipurk**(*j*) = +1. HRUs with shallow ground water can be associated with HRU scheme 3 (**iophru**=3), which disaggregates shallow and deep ground water components. Evaporation from shallow ground water is given by a previous iteration of Modflow's solution for a given time step, and is redistributed by subr. **Evap_gw** over soil layers in which water content is less than available field capacity. This two-way coupling is obtained using successive approximation that is initialized by simulation of HRU scheme 1 or 2 in which all ground water is assumed to be deep. MODFLOW's solution for evaporation from shallow ground water can be summarized for one of these schemes by the SWBX package (subr. SWB2BD). The resulting summary is read by SWAT in a subsequent simulation of HRU scheme 3.

An idiosyncracy apparently related to the conversion from Fortran77 to Fortran90 under the Lahey compilers is that numeric input data values specified as integers but read into real variables were assigned as zeroes. in the Fortran 90 version, whereas the integers had been converted properly to reals under Fortran 77. Consequently, input data that had been prepared in spreadsheets under the "general" numeric format as defined in Excel (Microsoft Office) required a second preparation using a fixed numeric field format that explicitly included a decimal point. This was the only unexpected difference encountered between versions, but posed a potential for undetected errors.

Other changes made to subroutines to eliminate eompiler or runtime errors are detailed in the documentation file \gh\docs\Swtchg99.doc.

The following code was included in an early version of Swat 99.2 but not carried into the latest version:

**EchoInpt**: added to be called by Main to provide a procedure to check for input data errors, Echoinpt was added to SWAT to echo input read by SWAT; based on code from previous SWAT version 98.1. If **Iprn** ≤ 0, **EchoInpt** is called from the mainline. In addition, if **Iprn** < 0, execution is halted after calling EchoInpt. These variations on the standard meanings of Control Code Iprn (*cod) were found useful for locating input data errors.

Several changes were made to SWAT v.94.2 for specific application to models of either the Lower Republican River basin or Rattlesnake Creek watershed, but were not carried into v.99.2 to avoid unnecessary changes for the general case, or because equivalent options were available in the more recent versions of SWAT. These changes include the following:

**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 **Clicon** and the option **iopwea**, above).

### 3.4. MODFLOW-96 source code changes and additions

The update of the SWAT-MODFLOW linkage to run with MODFLOW-96 has resulted in a version in which coding changes are restricted to the mainline (file modflx96.for) and some nonstandard packages that were linked with Modflow's standard source files. The resulting modified program, compiled and linked as executable file modflx96, allows data sets prepared for standard Modflow to run as expected. This has been demonstrated for two sets of test cases that include seven examples from USGS and twenty examples from EPA. The modified mainline and the added nonstandard packages are summarized in Table 3.2.

Table 3.2. MODFLOW-96 additions or changes for SWAT-MODFLOW linkage

| package file name | added subr's. | modified subr's. | required for linkage | can be used outside linkage |
|---|---|---|---|---|
| Modflx96 | | x | x | x |
| Swbx | x | | x | |
| Strx | x | | x | x |
| Welx | x | | x | |

The added and modified components of MODFLOW-96 are the following:

modflx96.for: modified mainline, which replaces modflw96.for, and includes calls to modified or added subroutines, which follow. The first three of these are coordinated to provide the linkage with a watershed simulation provided by SWAT but not restricted to SWAT:
Swbx.for: added package to provide interface to watershed simulation;
Welx.for: modified version of the Well package;
Strx.for: modified version of the Stream package;

The package SWBX provides an interface between watershed simulation results produced by SWAT and SWBAVG for each subbasin and the corresponding grid cells of MODFLOW's stream-aquifer model. Variations on MODFLOW's Stream and Well packages were also written, STRX and WELX, that are coordinated with the added package SWBX. In the STRX package, the routing procedure of the Stream package was modified to include components for tributary inflow, surface water diversions, and evaporation for each stream reach. The WELX package allows specifying both surface and ground water rights to supply irrigation demand simulated by SWAT. Surface water rights are associated with a reach of the stream network specified for the STRX package. The WELX package also allows regulating pumping rates to limit ground water drawdown to a minimum saturated thickness. This introduces a coupling due to head-dependent pumping rates that is incorporated into MODFLOW's solution in the same way that head-dependent fluxes are incorporated in standard packages, including evaporation from shallow ground water and flow across a streambed given that the aquifer hydraulic head exceeds the streambed bottom elevation. These couplings are presented in the chapter on methodology.

The nonstandard STRX and WELX packages can also be used in place of the corresponding standard packages independent of whether the SWBX package is used. In addition, the SWBX package can provide a connection to watershed simulators other than SWAT, as in the case of an earlier version mentioned above that was applied to Wet

Walnut Creek in Kansas. This allows for a wide range of choices for modeling hydrologic processes in the watershed.

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

SWAT v.99.2 and documentation was downloaded from the website http://www.brc.tamus.edu/swat/. Modflow-96 code and documentation was downloaded from the USGS Water Resources Applications Software website, ground water page, at http://water.usgs.gov/software/ground_water.html, as recently as May 2000, when v.3.3 became available. These versions of SWAT and MODFLOW were incorporated into the updated SWAT-MODFLOW linkage. The reader is referred to Section 3.5 in the User's Manual for details on compiling and linking SWAT and MODFLOW in their modified form for the SWAT-MODFLOW linkage.

# 4. Lakefork and Lower Republican R. test cases

## 4.1. Lakefork example from AvSwat

Procedure for obtaining a Lakefork model summary for input to MODFLOW

The procedure outlined in N&D (1999) for the Lakefork example using AvSwat is adapted to produce a summary data file for input to MODFLOW. The following is assumed: (a) The SWAT data set runs under SWAT v.99.2, which may be executed through the AvSwat extension for ArcView; and (b) the MODFLOW data set runs under MODFLOW-96. The specific procedure follows; file listings are shown below.

Watershed simulation using modified SWAT v.99.2 within AvSwat

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

SWAT Control Codes input file basi.cod

This file was generated by AvSwat for the Lakefork model. It has been modified to specify that an output file (below) is to be written that can be read by Modflow.

```
20000815 Simulation in Basin Watershed:  .COD control file ArcView-SWAT interface      MDL
   21977   0   0   1   1   0   0   0   0   0   0   0   0   1 365   0   1   0   2   0   1   2


   0   1   1, ' ', ' ' !  (3i4,2a):iopshl itmuni Lenuni nambal namshl                   6
   1   0   0               (3i4):  iophru iopwts iprwts                                  7
```

File basi.bal: Lakefork model summary written by SWAT for input to Modflow

```
2    2  0.5885921E+10 0.0000000    1    20 basi
  sub sub fract noncontrb aqf_fr(j)    swfrac sol_sw,mm     pnd_vol,m^3
    1 0.0259135 0.0000000 1.0000000 0.5265466     120.77  0.0000000E+00
    2 0.0219451 0.0000000 1.0000000 0.5265466     120.77  0.0000000E+00
    3 0.0746681 0.0000000 1.0000000 0.4664558     106.99  0.0000000E+00
    4 0.0514795 0.0000000 1.0000000 0.5265466     120.77  0.0000000E+00
```

```
     5 0.0258220 0.0000000 1.0000000 0.5265467    116.22  0.0000000E+00
     6 0.0493032 0.0000000 1.0000000 0.5265467    116.22  0.0000000E+00
     7 0.0485717 0.0000000 1.0000000 0.4664558    106.99  0.0000000E+00
     8 0.0339966 0.0000000 1.0000000 0.4664558    102.96  0.0000000E+00
     9 0.0599283 0.0000000 1.0000000 0.4664558    106.99  0.0000000E+00
    10 0.0757653 0.0000000 1.0000000 0.4664558    106.99  0.0000000E+00
    11 0.0345818 0.0000000 1.0000000 0.4664558    102.96  0.0000000E+00
    12 0.0494313 0.0000000 1.0000000 0.4664558    102.96  0.0000000E+00
    13 0.0928276 0.0000000 1.0000000 0.4664558    102.96  0.0000000E+00
    14 0.0348012 0.0000000 1.0000000 0.4664558    158.64  0.0000000E+00
    15 0.0302110 0.0000000 1.0000000 0.5265466    104.85  0.0000000E+00
    16 0.0352767 0.0000000 1.0000000 0.5265466    104.85  0.0000000E+00
    17 0.1184302 0.0000000 1.0000000 0.4664558    106.99  0.0000000E+00
    18 0.0442010 0.0000000 1.0000000 0.4664558    106.99  0.0000000E+00
    19 0.0365385 0.0000000 1.0000000 0.5265466    120.77  0.0000000E+00
    20 0.0563074 0.0000000 1.0000000 0.5265466    120.77  0.0000000E+00
  Year  mon days     delt (sec)  sub    precip     irrig      ETact     runoff     XMloss
QLAT       PERC   recharg      et-gw   baseflo   pondsep      ETpot   tribflo     dSW/dt
dPND/dt et-gw(un) cn_av       c*A/dt
 1977     1   31        2678400.   1      3.33      0.00       2.87      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00       9.44      0.00       0.45
0.00       0.00  77.6      0.1868315
 1977     1   31        2678400.   2      2.82      0.00       2.43      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00       7.99      0.00       0.39
0.00       0.00  77.6      0.1582201
 1977     1   31        2678400.   3      9.58      0.00       7.81      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00      28.08      0.00       1.76
0.00       0.00  77.4      0.5383431
 1977     1   31        2678400.   4      6.61      0.00       5.70      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00      18.74      0.00       0.90
0.00       0.00  77.6      0.3711576
 1977     1   31        2678400.   5      3.31      0.00       2.81      0.05       0.01
0.00       0.00      0.01      0.00     0.00      0.00       9.40      0.04       0.45
0.00       0.00  78.2      0.1861718
 1977     1   31        2678400.   6      6.33      0.00       5.37      0.09       0.01
0.00       0.00      0.01      0.00     0.00      0.00      17.95      0.08       0.86
0.00       0.00  78.2      0.3554669
 1977     1   31        2678400.   7     10.23      0.00       6.44      0.00       0.00
0.01       0.00      0.00      0.00     0.00      0.00      18.04      0.01       3.77
0.00       0.00  77.7      0.3501929
 1977     1   31        2678400.   8      7.16      0.00       4.27      0.12       0.01
0.00       0.00      0.01      0.00     0.00      0.00      12.63      0.11       2.77
0.00       0.00  79.3      0.2451092
 1977     1   31        2678400.   9     12.62      0.00       7.95      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00      22.26      0.00       4.65
0.00       0.00  77.7      0.4320719
 1977     1   31        2678400.  10     15.95      0.00      10.05      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00      28.14      0.00       5.89
0.00       0.00  77.7      0.5462537
 1977     1   31        2678400.  11      7.28      0.00       4.34      0.12       0.02
0.00       0.00      0.02      0.00     0.00      0.00      12.85      0.10       2.82
0.00       0.00  79.3      0.2493283
 1977     1   31        2678400.  12     10.41      0.00       6.20      0.17       0.02
0.00       0.00      0.02      0.00     0.00      0.00      18.36      0.15       4.03
0.00       0.00  79.3      0.3563905
 1977     1   31        2678400.  13     19.54      0.00      11.65      0.32       0.04
0.01       0.00      0.04      0.00     0.00      0.00      34.48      0.28       7.57
0.00       0.00  79.3      0.6692697
 1977     1   31        2678400.  14      7.33      0.00      11.60      0.00       0.00
0.00       0.00      0.00      0.00     0.00      0.00      16.57      0.00       0.00
0.00       0.00   0.0      0.2509102
 1977     1   31        2678400.  15      3.88      0.00       3.02      0.00       0.00
0.01       0.00      0.00      0.00     0.00      0.00      11.00      0.01       0.84
0.00       0.00  75.8      0.2178157
 1977     1   31        2678400.  16      4.53      0.00       3.53      0.00       0.00
0.01       0.00      0.00      0.00     0.00      0.00      12.84      0.01       0.98
0.00       0.00  75.8      0.2543384
 1977     1   31        2678400.  17     24.93      0.00      16.52      0.00       0.00
0.01       0.00      0.00      0.00     0.00      0.00      43.16      0.01       8.39
0.00       0.00  77.9      0.8538597
```

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1977 | 1 31 | 2678400. | 18 | 9.31 | 0.00 | 5.86 | 0.00 | 0.00 | |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 16.42 | 0.00 | 3.43 | |
| 0.00 | 0.00 77.7 | 0.3186810 | | | | | | | |
| 1977 | 1 31 | 2678400. | 19 | 4.69 | 0.00 | 4.04 | 0.00 | 0.00 | |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 13.30 | 0.00 | 0.64 | |
| 0.00 | 0.00 77.8 | 0.2634358 | | | | | | | |
| 1977 | 1 31 | 2678400. | 20 | 7.23 | 0.00 | 6.23 | 0.00 | 0.00 | |
| 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 20.50 | 0.00 | 0.99 | |
| 0.00 | 0.00 77.8 | 0.4059659 | | | | | | | |

## 4.2. Applying the SWAT-MODFLOW linkage to a Kansas river basin

A model of the Republican River basin in Kansas was developed based on the SWAT-MODFLOW linkage. The model was used to help investigate the effect of groundwater pumping for irrigation along an alluvial valley on streamflow in the river. This required consideration of the soil water balance for the watershed simulated by SWAT, a stream-aquifer model simulated by MODFLOW, and a means of representing hydrologic connections between surface water and groundwater.

The following Tables and Figures are shown below to summarize data and model results.

Figures
4.1. Republican River monthly streamflow and desired minimum
4.2. Water rights and estimated water use
4.3. Annual irrigation as a function of precipitation May through August.
4.4-3.6. Model results: figures comparing simulated and measured values for stream yield, irrigation, and groundwater levels under HRU schemes 1-3.

Tables
4.1. Subbasins and areas represented by weather stations
4.2. Soils: types, textures, storage capacity, and alluvial associations
4.3. Summary of land resources, land use, and soils for each subbasin

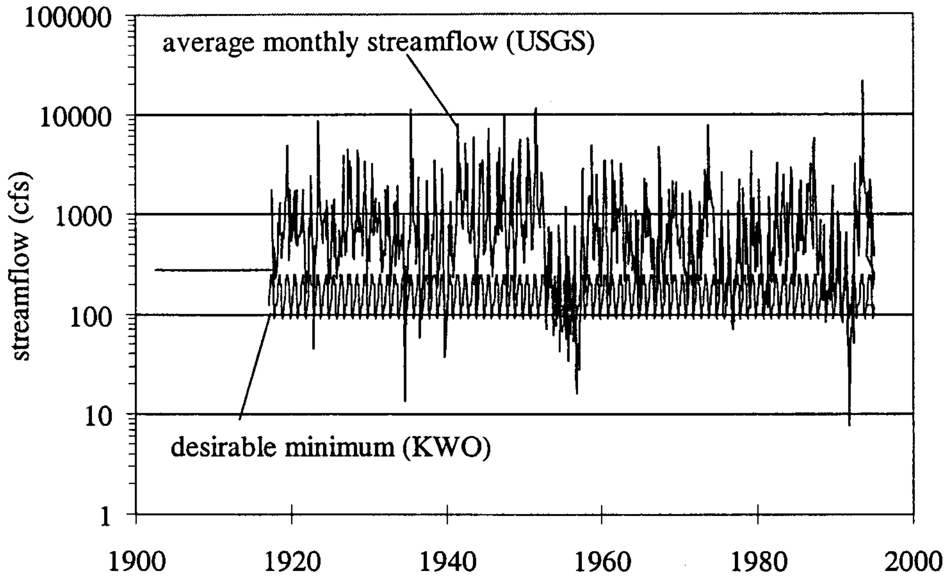


Figure 4.1. Republican River monthly streamflow and desired minimum at Clay Center for the period 1917-1994.

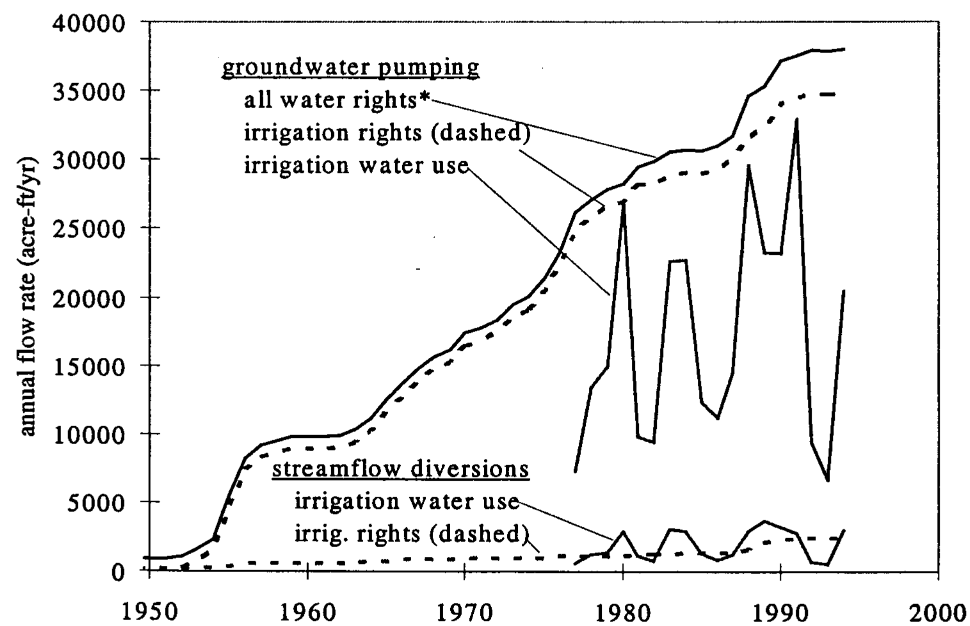


Fig. 4.2. Water rights and estimated water use based data from Division of Water Resources. (*): Domestic water use is excluded.

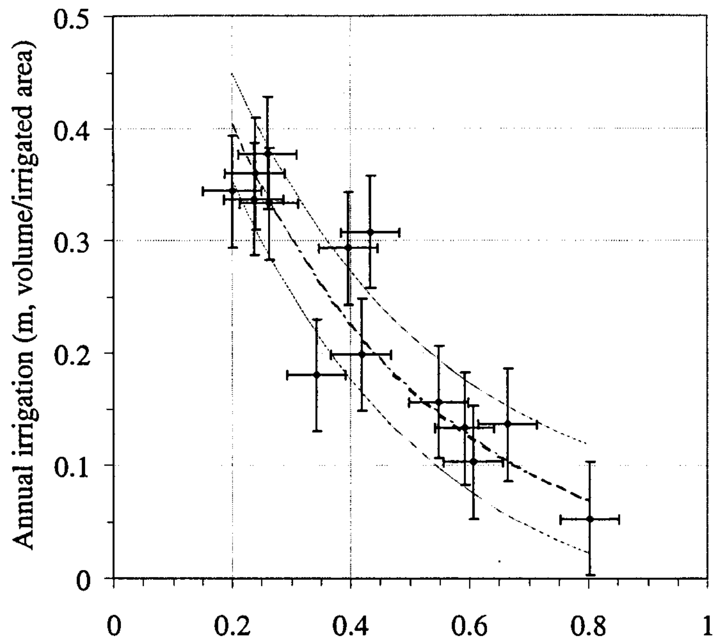


Fig. 4.3. Annual irrigation as a function of precipitation May through August.

## Weather data: precipitation and temperature

Table 4.1. Subbasins and areas represented by weather stations

| subbasins | area ($km^2$) | fraction | precipitation station | temperature (min,max) station |
|---|---|---|---|---|
| 1 | 565.7 | 0.220 | Belleville | Belleville |
| 2,3,4 | 875.5 | 0.341 | Concordia | Concordia |
| 5,6,7 | 628.9 | 0.245 | Washington | Washington |
| 8,9 | 499.5 | 0.194 | Fact | Clay Center |
| total | 2569.6 | 1.000 | | |

## Summary of soil types, land uses, and subsurface (gw, bedrock)

Table 4.2. Soils: types, textures, storage capacity, and alluvial associations

| soil | depth (mm) | awc[1] (mm) | soil texture | soil associations[2] | alluvial | extent |
|---|---|---|---|---|---|---|
| Carr | 1524 | 207 | fine sandy loam | 374 | yes | Concordia-Clifton |
| Crete | 1524 | 292 | silty clay loam | 301, 307, 327 | no | |
| Hasting | 1524 | 256 | silty clay loam | 345 | no | |
| Hedville | 406 | 71 | stony loam | 302 | no | |
| Kipson | 483 | 89 | silty loam | 304, 314 | no | |
| Muir | 1524 | 322 | silty loam | 372 | yes | Clifton-Clay Center |

[1]awc = available water capacity (mm), given by sum over soil layers of (effective porosity times layer depth). [2]STATSGO designations for Kansas, obtained from DASC (1999).

Table 4.3. Summary of land resources, land use, and soils for each subbasin

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

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

<u>HRU schemes 1-3 for the Lower Republican River basin model</u>

As in the case of Ch. 4, this section was written prior to the incorporation of the functions of HRUAVG into SWAT. Where the programs HRUAVG or SWBAVG are referred to, the execution of SWAT under options Iopmod = 2 and Iopwts = 1 can be assumed, which specify that SWAT converts its summary of results to units of flow rate for input to MODFLOW, and that HRU weights and corresponding virtual subbasin areas may be calculated in SWAT.

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

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

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

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

**<u>HRU Scheme 1 combinations</u>**

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

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

**<u>HRU Scheme 2 combinations</u>**

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

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

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

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

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

**HRU Scheme 3 combinations**

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

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

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

HRU scheme 1 conditions. treat soil types and land uses as spatially independent

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

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

ipd=0 (hru1virt.cod): monthly time steps for stream-aquifer solution

numhru=15 (hru1virt.cod): number of HRUs to be simulated by SWAT and averaged by SWBAVG

iophru=1 (hru1virt.cod): basic HRU scheme (soils and land uses assumed independent; alluvial/upland heterogeneity is ignored.

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

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

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

nsoils=5 (hru1virt.cod): six soils are defined for SWAT, but for SWBAVG, Hasting and Hedville soils are combined, since they occur in separate subbasins (Hasting in subbasins 1-4, Hedville in subbasins 6-9, neglecting the small component in subbasin 3). By combining these two soils for SWBAVG, the number of required simulations is reduced from 18 to 15 (five soils, three land uses; see below).

numuse=3

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

Procedure for running HRU schemes 1-3

Each of the three schemes summarized above is simulated by a single pair of Swat-Modflow executions. For each scheme, Swat's execution is directed by a File Control file (*.cio), and Modflow's by a Name file (*.nam); these are identified as follows.

| HRU scheme | File Control file for Swat | Name file for Modflow |
|---|---|---|
| 1 (hru1virt) | hru1virt.cio | hru1virt.nam |
| 2 (hru2virt) | hru2virt.cio | hru2virt.nam |
| 3 (hru3virt) | hru3virt.cio | hru3virt.nam |

Procedure for each of these is the following:
1. Copy the File Control file to File.cio;
2. Run Swat;
3. Run Modflow, which prompts for the Name file

The two model identifying files for HRU scheme 1, hru1virt.cio for Swat and hru1virt.nam for Modflow, are listed in Section 7.3 of the User's Manual.

For each of these schemes, Swat's File Control file specifies associated Control Codes (*.cod) and Configuration (*.fig) files, which are named similarly (e.g., hru1virt.cod and hru1virt.fig for scheme 1). Key output files, also named similarly, are the standard output (*.std) and balance (*.bal) files. If Iopmod = 2 is specified in the extended Control Codes (*.cod) input file, then the balance file is written in terms of flow rates for input to Modflow.

The Name file that specifies the files associated with a particular model. For the SWAT-MODFLOW linkage, the Name file invokes the SWBX package and specifies the following associated files:
Input:
1. File rptest96.swb associates the subbasins simulated by SWAT with the stream-aquifer grid simulated by MODFLOW, and is the same for all three HRU schemes.
2. The balance file written by SWAT (e.g. hru1virt.bal for scheme 1).
Output:
3. A summary of shallow groundwater (e.g. hru1virt.shl), written by SWBX, which can be read by SWAT on a subsequent run, enabling a two-way coupling based on successive approximation.
4. A summary of hydrologic components based on SWAT and MODFLOW (e.g. hru1virt.swm). For example, it shows not only irrigation demand simulated by SWAT,

but also the irrigation supplied by surface and groundwater sources according to MODFLOW, taking into account operation and supply constraints, particularly stream inflows and groundwater saturated thickness.

Key data files associated with these schemes are listed in Section 7.3 of the User's Manual, which also provides definitions and formats for the input data files.

Example results: comparison of HRU schemes 1-3

A comparison of calibration results for HRU schemes 1-3 are shown in Figs. 4.4-4.6 that were obtained using the previous version of the SWAT-MODFLOW linkage, based on Swat 94.2 and Modflow-88 and documented in P&S (1999). These results are shown to illustrate a calibrated version of the model, and for comparison of the three HRU schemes. The same cases have been run using the most recent versions of SWAT and MODFLOW and according to the simplified procedure presented above in Ch. 4.

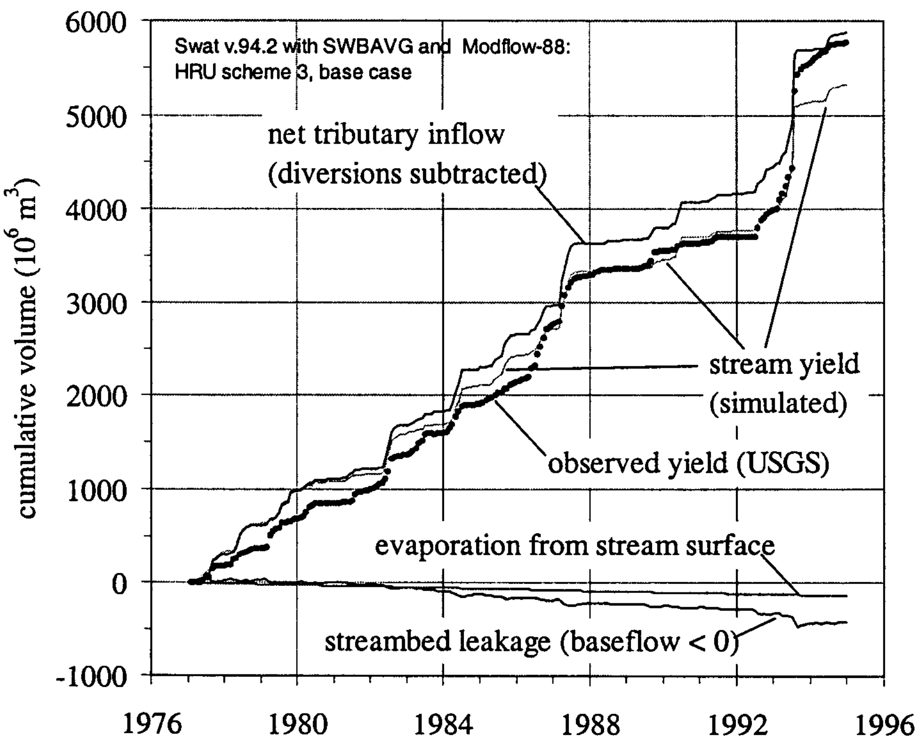


Fig. 4.4. Comparison of simulated stream yield HRU schemes 1-3 with difference in USGS stream gage measurements at Clay Center and Concordia; HRU schemes are presented in Ch. 2 (From Perkins, 1999).

Results from the most recent versions are similar to those shown below; differences are likely due to model differences between versions, and might be eliminated by minor adjustments in parameters. In particular, stream yield is slightly higher than what is shown in Fig. 4.4, the difference might be eliminated by a reduction in the initial SCS curve number of about 1. The simulated irrigation demand for the latest version is consistently lower than that shown for the previous version in Fig. 4.5. Residuals for computed heads are slightly higher than those shown in Fig. 4.6. Because comparisons of the revised SWAT 99.2 code have been made for the Y7 test case and for the Lakefork example included with the AvSwat extension for ArcView, the differences for the Lower Republican R. basin model appear attributable to model differences between versions and to possible errors that were made in converting data sets due to input format changes between versions.

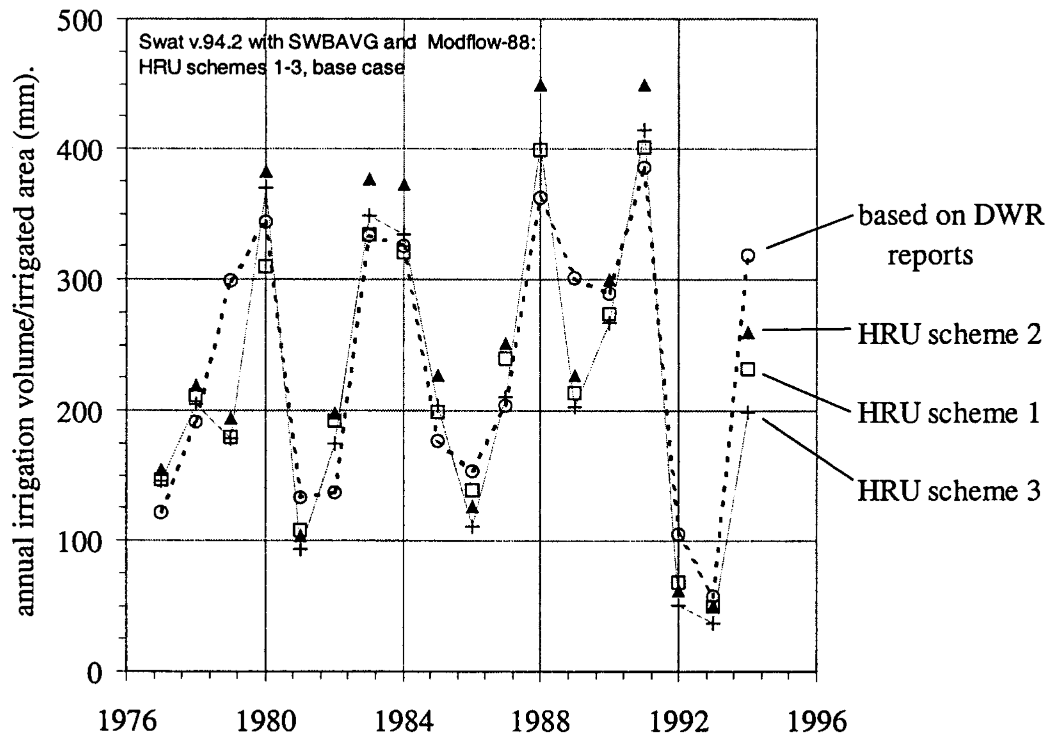


Fig. 4.5. Comparison of simulated annual irrigation demand for HRU schemes 1-3 with estimates based on KS Div. of Water Resources reports (From Perkins, 1999).

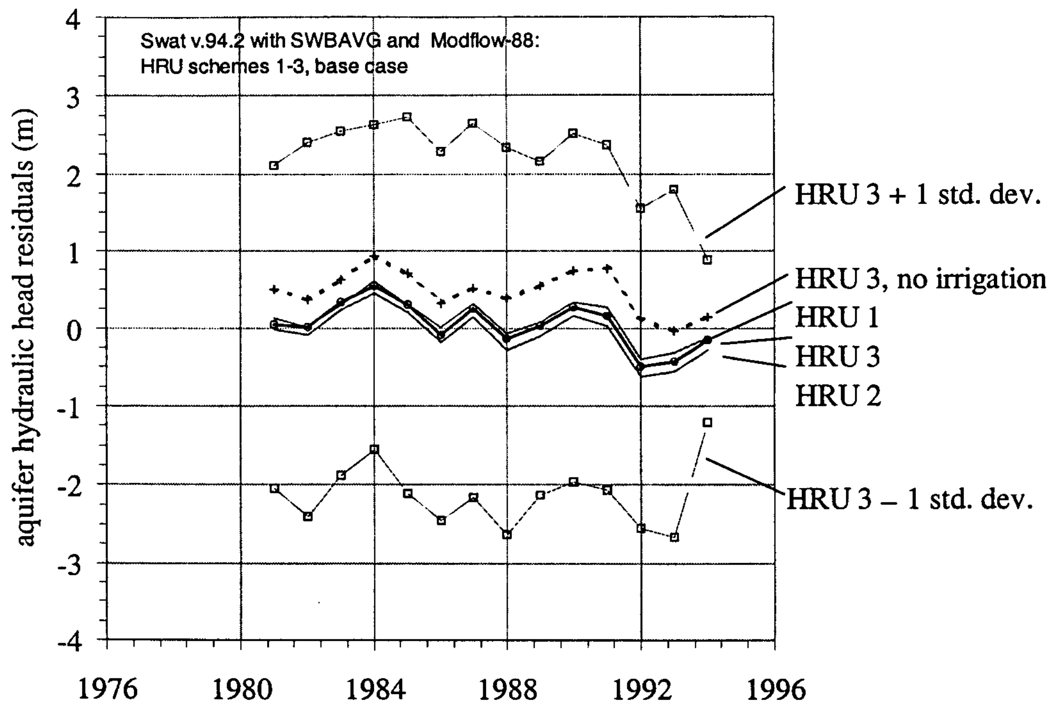


Fig. 4.6. Ground water level residuals for HRU schemes 1-3, presented in Ch. 2 (from Perkins, 1999).

# 5. Summary

Tests of the updated version of the SWAT-MODFLOW linkage based on SWAT v.99.2 and MODFLOW-96 indicate that the efforts of the project were largely successful. A comparison of SWAT versions 98.1 and 99.2 on the basis of the Y7 test case showed only slight differences for a three-year summary of results. Comparison of SWAT versions 94.2 and 99.2 for the Lower Republican River basin show some differences that might be attributed to model differences between the versions. Thse differences might be reduced by further calibration of parameters, including the SCS curve number, aquifer characteristics, and soil water content threshold for irrigation. Results for the stream-aquifer system simulated by MODFLOW appear to be relatively sensitive to the differences between versions of SWAT's simulated results. This suggests that the conceptual models for tributary inflow and recharge given by equations (2.12-2.16) represent an important part the the linkage and warrant closer examination for possible improvement, particularly for application of the SWAT-MODFLOW linkage to other watersheds.

A related and important role in the SWAT-MODFLOW linkage is played by the model of spatial variability. Alternatives to the static model of spatial contributions implemented by the virtual subbasin approach in SWAT have been developed and presented in Chapter 2 as HRU schemes 1-3. These provide the capability to represent time-varying spatial contributions of HRUs. In addition, schemes 2 and 3 represent hydrologic effects of hydrogeologic heterogeneities and regional dependencies within subbasins. Scheme 3 also provides a means of representing a two-way coupling between SWAT and MODFLOW. The spatial weights for HRUs in this scheme reflect the time-varying area of shallow ground water in response to climatic patterns. Although these schemes have been developed and demonstrated only for the Lower Republican River basin test case, a more general approach has been developed and implemented as program HRUAVG, which has been tested by comparison with the more basin-specific program SWBAVG. This approach, presented in Chapter 2, was intended to provide an additional tool for incorporating hydrologic effects of spatial heterogeneity into models of other watersheds.

The most recent development of the model code has been to incorporate into SWAT the procedure implemented by the program HRUAVG. This is viewed as a significant improvement by providing the capability of HRUAVG but eliminating excessive complexity in the operating procedure required to run a combined SWAT-MODFLOW simulation. A follow-up effort might be to consider implementing this approach using GIS techniques.

SWAT's "virtual subbasin" approach to representing spatial heterogeneity was reviewed in Chapter 2, and a method of coordinating this approach with MODFLOW was presented at the end of Chapter 2. Examples of this coordination for HRU scheme 1 are presented in "A Guide to Coordinating SWAT and MODFLOW," Perkins and Sophocleous, Kansas Geological Survey Open-File Report 2000-38. Capabilities of SWAT's virtual subbasin approach are limited to specifying HRU weights as constants that are input for each HRU (*.Sub files). Recent developments incorporate the capability of program Hruavg into Swat, which are specified through extensions to Swat input files (configuration, *.Fig; and control codes, *.Cod). These developments provide, as part of Swat, options to automate the calculation of HRU weights in terms of areal fractions for soils, land uses, and subsurface features; to update these weights during a simulation to represent variation with time; and to represent spatial dependencies among HRU factors. The added capabilities eliminate the need for applying Swbavg or Hruavg as external, intermediate programs between Swat and Modflow. The capabilities of Hruavg, now encapsulated as part of Swat, include calculating HRU weights, averaging HRUs, combining hydrologic terms simulated by Swat, converting the combined hydrologic terms from volumes of water per unit area to flow rates for input to Modflow, and converting Modflow's summary of shallow groundwater depth, area, and shallow groundwater for use in Swat to evaluate HRU weights and uptake into the soil water profile. The components of this added capability are summarized in the Preface to the revised Final Report.

HRU schemes 1-3 were introduced to provide alternative methods for representing spatial variability within subbasins related to subsurface features. Schemes 2 and 3 involve specifying modifications to SWAT's simulation procedure to represent the hydrologic effects of a soil profile underlain by bedrock and of shallow ground water. All three of these schemes have been tested successfully for Lower Republican River basin test cases using the updated SWAT-MODFLOW code according to the procedure developed for the previous version of the linkage (P&S, 1999). Some differences are apparent between cases run under Swat v.94.2 and v.99.2 that are likely due to simulation model differences, and which can likely be resolved by minor recalibration of model parameters.

Additionally, the three HRU schemes have been tested successfully for Lower Republican River basin test cases using the recently installed capabilities of Swat that incorporate functions of the intermediate program Hruavg. Operationally, the differences are that all of the HRUs are specified as virtual subbasins in Swat's file control (*.Cio) and configuration (*.fig) input files, and the necessity to write, store, and coordinate large intermediate files for HRUs and to preprocess them for input to Modflow are eliminated. Using this capability, a single execution of Swat simulates all of the HRUs for the basin. Examples of time-varying HRU factors that are represented for the Lower Republican River basin cases include areas of irrigated cropping, urban land uses, and shallow groundwater area, particularly along surface water bodies, in response to storm-interstorm cycles.

# References

**SWAT references**

For the latest available version, documentation, and ArcView interface for SWAT, see http://www.brc.tamus.edu/swat/.

For an explanation of the HRU approach as implemented in SWAT, see http://www.brc.tamus.edu/swat/usermanual/watermanagement.html

SWAT software downloads: http://www.brc.tamus.edu/swat/swatmod.html

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.

Hargreaves, G.H. and Z.A. Samani, 1985. Reference crop evapotranspiration from temperature. Applied Engr. Agric. 1:96-99.

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

Neitsch, S.L., J.G. Arnold, and J.R. Williams, 1999. Soil and Water Assessment Tool User's Manual, Version 99.2. Grassland, Soil and Water Research Laboratory and Blackland Research Center, Agricultural Research Service. 808 East Blackland Rd., Temple, TX 76502.

Priestley, C.H.B. and R.J. Taylor, 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

USDA, Soil Conservation Service (SCS), 1972 (Natural Resources Conservation Service). National Engineering Handbook, Hydrology Section 4, Ch. 19.

USDA, Soil Conservation Service (SCS), 1983 (Natural Resources Conservation Service). National Engineering Handbook, Hydrology Section 4, Ch. 4-10.

**MODFLOW references**

MODFLOW-96 can be downloaded complete with documentation, executable, source, and test data files from the USGS Water Resources Applications Software website, ground water page, at http://water.usgs.gov/software/ground_water.html.

Harbaugh, A.W. and M.G. McDonald, 1996a. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. USGS Open-File Report 96-485.

Harbaugh, A.W. and M.G. McDonald, 1996b. Programmer's documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. USGS Open-File Report 96-486.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model: User guide to modularization concepts and the ground-water flow process. USGS Open-File Report 00-92, Reston VA.

Hill, M.C., E.R. Banta, A.W. Harbaugh, and E.R. Anderman, 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model: User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs. USGS Open-File Report 00-184, Denver, CO.

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.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

Note: An informative summary of MODFLOW with useful links, such as to a website with EPA's own manual and example problems, is currently available through the University of Kassel in Germany at the following website:
http://dino.wiz.uni-kassel.de/model_db/mdb/modflow.html
See also the summary of tests in Ch.4 and the "Readme" document.

**General references**

Brandes, D., C.J. Duffy, and J.P. Cusumano, 1998. Stability and damping in a dynamical model of hillslope hydrology. Water Resourc. Res., 34(12):3303–3313.

Cuencas, R., 2000. Part 2, Scientific Basis for CASES (see Pflaum, 2000). Part 2.2.B, Hydrologic Models (contact: Richard Cuenca, Dept. Bioresource Engineering, Oregon State Univ., Corvallis, OR 97331-3906, cuencarh@pandora.bre.orst.edu. The following description of the HRU approach is given on this website:

"The hydrologic response unit (HRU) concept has been used to scale segments of a watershed with similar soil texture, topography, land use, vegetation and geological features (e.g. soil depth). The use of a GIS framework is particularly useful in delineating watershed and HRU boundaries. Physically-based hydrologic process models are applied to each HRU to simulate the response of the land surface to precipitation and atmospheric forcing through evaporation and transpiration (Leavesley et al., 1983)."

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.

Koussis, A.D., M.A. Sophocleous, L. Bian, S. Zou, 1994. Lower Republican River Basin: stream-aquifer study. First year report to Kansas Water Office, 142 pp.

Koussis, A.D., M.A. Sophocleous, J.L. Martin, and S.P. Perkins, 1994. Evaluation of the role of stream-aquifer hydraulics in the administration of water rights and minimum streamflow standards, Final report. Contribution No. 311, Kansas Water Resources Research Institute, Kansas State University, Manhattan KS 66506.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-Runoff Modeling System: User's Manual: U.S. Geological Survey Water-Resources Investigations 83-4238, 207 p.

Mamillapalli, S., R. Srinivasan, J.G. Arnold, B.A. Engel, 1996. Effect of spatial variability on basin scale modeling. In: Proc. of the third Internationial Conference Integrating GIS and Environmental Modeling, Santa Fe, New Mexico, 10 p. Available at http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/mamillapali_sudhakar/my_paper.html

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. Kansas Geological Survey Open-File Report

Perkins, S.P., and A.D. Koussis, 1996. Stream-aquifer interaction model with diffusive wave routing. J. Hydraul. Engrg., ASCE, 122(4):210–218.

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.

Perkins and Sophocleous, 2000a. Combining SWAT and MODFLOW into an Integrated Watershed Model. Open-File Report 2000-67, Kansas Geological Survey, 1930 Constant Ave., Univ. of Kansas, Lawrence KS 66047. December 2000.

Perkins and Sophocleous, 2000b. User's manual for a combined watershed and stream-aquifer modeling program based on Swat-99.2 and Modflow-96. Open-File Report 2000-68, Kansas Geological Survey, 1930 Constant Ave., Univ. of Kansas, Lawrence KS 66047. December 2000.

Pflaum, J.C., 2000. Overview and Implementation of CASES (Cooperative Atmosphere-Surface Exchange Study). National Center for Atmospheric Research (NCAR). Website: http://www.joss.ucar.edu/cases/overview.html#Overview

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 groundwater: the case of Wet Walnut Creek Watershed, Kansas, USA. J. Hydrology 236:223–246.

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

Sophocleous, M. and S.P. Perkins, 2000. Methodology and application of combined watershed and ground-water models in Kansas. J. Hydrology 236:185–201.

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.

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.

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.

Viger, R., 2000. The GIS Weasel: An Interface for The Treatment of Spatial Information in Modeling. USGS Website: http://wwwbrr.cr.usgs.gov/weasel/ From "New Weasel Features": "There has been a minor shift in terminology. Hydrologic Response Units (HRUs) have been supplanted by Modeling Response Units (MRUs) in the interest of not scaring away physical process modelers who do not focus on things hydrologic."

Viger, R.J., Markstrom, S.L., and Leavesley, G.H., The GIS Weasel - An Interface for the Treatment of Spatial Information Used in Watershed Modeling and Water Resource Management in Proceedings of the First Federal Interagency Hydrologic Modeling Conference, April 19-23, 1998, Las Vegas, Nevada, Vol II, Chapter 7, pp. 73-80. Website: see Viger (2000).