

# Methodology and application of combined watershed and ground-water models in Kansas

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## Abstract

Increased irrigation in Kansas and other regions during the last several decades has caused serious water depletion, making the development of comprehensive strategies and tools to resolve such problems increasingly important. This paper makes the case for an intermediate complexity, quasi-distributed, comprehensive, large-watershed model, which falls between the fully distributed, physically based hydrological modeling system of the type of the SHE model and the lumped, conceptual rainfall-runoff modeling system of the type of the Stanford watershed model. This is achieved by integrating the quasi-distributed watershed model SWAT with the fully-distributed ground-water model MODFLOW. The advantage of this approach is the appreciably smaller input data requirements and the use of readily available data (compared to the fully distributed, physically based models), the statistical handling of watershed heterogeneities by employing the hydrologic-response-unit concept, and the significantly increased flexibility in handling stream–aquifer interactions, distributed well withdrawals, and multiple land uses. The mechanics of integrating the component watershed and ground-water models are outlined, and three real-world management applications of the integrated model from Kansas are briefly presented. Three different aspects of the integrated model are emphasized: (1) management applications of a Decision Support System for the integrated model (Rattlesnake Creek subbasin); (2) alternative conceptual models of spatial heterogeneity related to the presence or absence of an underlying aquifer with shallow or deep water table (Lower Republican River basin); and (3) the general nature of the integrated model linkage by employing a watershed simulator other than SWAT (Wet Walnut Creek basin). These applications demonstrate the practicality and versatility of this relatively simple and conceptually clear approach, making public acceptance of the integrated watershed modeling system much easier. This approach also enhances model calibration and thus the reliability of model results. © 2000 Elsevier Science B.V. All rights reserved.

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## 1. Statement of the problem

Many regions of Kansas, besides the well-known High Plains (Ogallala) aquifer in semiarid western

Kansas, have experienced significant ground-water and streamflow declines, especially during the last three decades (Sophocleous, 1981, 1998, 2000; Sophocleous and McAllister, 1987, 1990; Sophocleous et al., 1999; Perkins and Sophocleous, 1999a; Koelliker et al., 1999; Ramireddygarri et al., 2000). One such region is the Rattlesnake Creek basin in south-central Kansas (Fig. 1). Streamflow and

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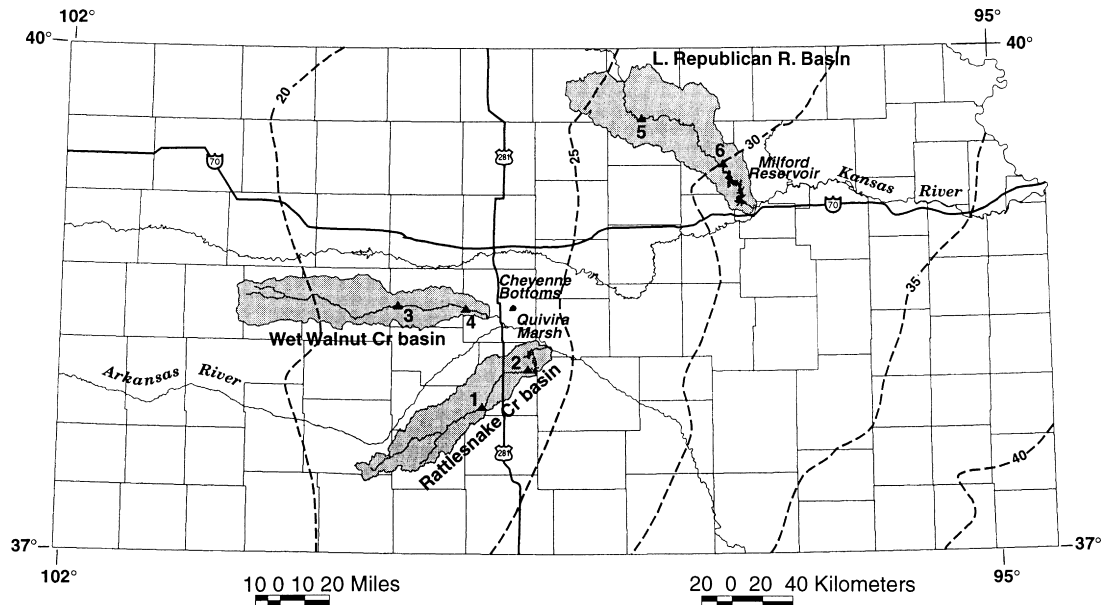


Fig. 1. Location of watershed case studies in Kansas. Dashed lines indicate normal annual precipitation in inches (multiply by 25.4 to convert to mm.) Numbered triangles indicate US Geological Survey streamgaging stations: (1) Macksville; (2) Zenith; (3) Nekoma; (4) Albert; (5) Concordia; and (6) Clay Center.

ground-water levels have been declining since the 1970s, though precipitation patterns and amounts apparently have remained unchanged. During that same time, however, the number and amounts of ground-water rights for irrigation increased dramatically. In addition, the quality of both ground and surface water in the area is deteriorating in some locations, mainly because of the increased saltwater intrusion from underlying geologic formations — a result of the declines in the overlying freshwater aquifer. In north-central Kansas, in the Lower Republican River basin, the monthly average streamflows occasionally fell below minimum desirable streamflow standards during the drought years of 1988–1991 (Fig. 1). These declines raised concerns about the river's capacity to supply Milford Reservoir, one of the state's largest, and also raised the question of the impact of crop irrigation along the Republican River alluvial valley on these declines. Diminished streamflows have also been observed in west-central Kansas in the Wet Walnut Creek basin (Fig. 1). This has had an impact on the water supply to Cheyenne Bottoms, the largest and most important wetland in Kansas. Increased use of ground water for crop irrigation

and the construction of numerous watershed structures (relatively small earth dams) in the basin have raised serious concerns about apparent links to the declines in streamflow and ground-water levels.

Because similar problems exist throughout the Great Plains of the US and many regions of the world (Sophocleous, 2000), the development of comprehensive, long-term strategies to resolve such water problems becomes increasingly important. The first step is to quantify the impact of irrigation and major land-use changes on both surface- and ground-water resources. This needs to be done on a basin-wide basis, from the standpoint of anticipating and minimizing potential environmental impacts (ASCE, 1985). To accomplish this task, numerical simulation models must be developed that are comprehensive, basin-wide, and continuous in time, as well as practical and conceptually clear. Given the proliferation and widespread availability of numerical models during the recent years, and the broad recognition of the need for integrated surface and ground-water resources management, there is still a surprising scarcity of operational, integrated models, applicable to real-world problems. Especially lacking is two-way

coupling of watershed and ground-water models, which not only account for inputs to the ground-water system but also for the impact of the ground-water system on the overlying unsaturated zone and, in particular, the root zone. Such two-way interactions are common in areas of shallow water table often encountered near streams and marsh areas. Also lacking are flexible linkages of watershed and ground-water models that allow relatively easy replacement of one surface water or watershed model with another in particular implementations of the integrated model.

This paper provides a comprehensive outline of the development, implementation, and calibration of an integrated and flexible modeling system that can serve as a long-term management tool in an agriculturally dominated environment such as that of the US Great Plains. Particular emphasis is placed on the conceptualization of hydrologic coupling of a shallow water table and the overlying root zone. The paper also provides a brief overview of three real-world applications from Kansas that demonstrate the utility of the integrated modeling system. Each application will highlight a different aspect of the integrated model. The management aspects of the implementation of our model will be outlined in more detail for the case of the Rattlesnake Creek basin in south-central Kansas; the two-way coupling in a shallow water table conceptualization will be demonstrated for the case of the Lower Republican River basin in north-eastern Kansas, whereas the flexible linkage aspect of our integrated model will be demonstrated for the case of Wet Walnut Creek basin in west-central Kansas.

## **2. Traditional approaches and present needs**

Traditionally, watershed models have been applied to problems of surface-water management without treating ground water in much detail (El-Kadi, 1989). For example, many surface-water models assume that percolation from the soil profile is lost from the system and thus ignore it. Ground-water-based irrigation is treated as having no impact on the source aquifers and streamflows. Because of their complexity, most watershed models employed in real-world applications are of the lumped, conceptual type.

Similarly, ground-water models have been applied to aquifer-management problems without treating surface water in any detail. For example, precipitation-dominated recharge, evapotranspiration, tributary flows, and diversions from surface and ground-water rights for irrigation and other uses are not treated in terms of the hydrologic processes involved, but are specified as known inputs or parameters to be determined by calibration, thus having no impact on surface-water management. Most ground-water models employed in real-world applications today are distributed and physically based.

It is essential to quantify the impacts of irrigated agriculture (by far the largest user of freshwater supplies in Kansas and many other regions) and of major land-use changes on water resources in order to anticipate and minimize potential adverse environmental impacts. Our scientific and popular understandings have recently advanced to the point that ground-water management is no longer thought to be separate from management of surface waters (Sophocleous, 1998). The ability to adapt to new knowledge and the resulting new ways of thinking about resources is the hallmark of successful management, and it is a necessary condition for water management as we move from an era of rapid exploitation to one of sustainable use. Integrated, holistic approaches constitute the distinguishing characteristic of present-day water management. Therefore, integrated watershed and ground-water models that attempt to represent all the relevant processes in the hydrological system are needed to provide decision support for large-area water resources management.

In fact, integrated watershed modeling is fundamental to integrated management. The power of numerical models to shape long-term environmental policy is clearly evidenced by the unfolding debates about climate change and acid rain (Wilby, 1997). One of the most well-known, complete representations of the physical hydrological cycle is the distributed model known as SHE (Système Hydrologique Européen), developed over a 20-year period by cooperation between research institutions in France, Denmark, and the United Kingdom (Abbott et al., 1986a,b). The complexity of the SHE model means that it requires a great amount of input data and powerful computers. Although powerful computers are relatively easy to come by, field data are available

only for some of the needed quantities, or are too sparse, making realistic interpolation impossible. The scale of measurements is often too small to enable integration of the variability. There is an element of unknowability of the system resulting from heterogeneity (Beven, 1987). Therefore, the usefulness of such models for management purposes will remain limited.

What is needed are practical, operational models that not only represent all of the relevant processes in the hydrologic system in a physically meaningful way, but are also simple enough to allow large-scale basin-wide applications. These models need to take into account readily available, distributed data on soil, vegetation, topography, climate, streamflow, land use, water use, water level (both surface and ground water), etc. Hydrologic modelers must also remember that public understanding and acceptance of models are necessary for effective water-resources management. Some of the simpler approaches that consider only the factors most important to the response of interest may be more appropriate for the level of available data in the majority of management decisions (Grayson et al., 1992). Before these simpler models are used for predictive and management purposes, they must undergo extensive testing to ensure that they accurately produce outputs for certain specified conditions.

The rationale and modeling requirements for basin-wide water-resources management were outlined in Sophocleous et al. (1999) as applied to the Rattlesnake Creek basin in south-central Kansas, and are summarized here. For stream-aquifer systems, it is critical that the model adequately handles the hydraulic interaction between the surface and ground-water systems. Equally important is the detailed representation of irrigation pumping and its areal distribution, since irrigated agriculture is the predominant water user. In addition, the effects of land-use, crop rotations, irrigation demand, evapotranspiration, surface runoff, and climate need to be simulated in sufficient detail and accuracy using readily available data. All key hydrologic processes within a basin need to be simulated on a continuous basis for long periods of time, and in a computationally efficient manner on readily available PC platforms. Finally, model credibility and general acceptance and use are important considerations in management applications. Such practical considerations led us to link two well-established,

tested, and widely known models — the semi-distributed agricultural watershed model SWAT (Arnold et al., 1993, 1994; see Appendix A for a short description of this model) and the well-known, distributed ground-water model MODFLOW (McDonald and Harbaugh, 1988) — into an integrated, physically based watershed model. The SWAT-MODFLOW interface was designed to maintain MODFLOW's modularity, allowing other watershed model codes to be used in place of SWAT in the linkage. Integrating these models with different spatial and temporal scales and accounting for heterogeneities was not an easy task, as will be outlined in the next section. Continued feedback from water managers was instrumental in adopting modeling features and procedures for the integrated watershed model.

### **3. Integrating watershed and ground-water models: temporal and spatial scales, and heterogeneity**

A major source of difficulty in efficiently coupling and numerically solving surface-water (streamflow) and ground-water equations is the intrinsic difference in time scales between the two systems. Precipitation and streamflow have much shorter residence times than those of the slow-moving ground water. Most network climatic and streamflow data are available on a daily basis. Because soil-profile-bottom fluxes (deep percolation) and recharge are much smaller quantities than precipitation and evapotranspiration, relatively large time-lumping in a soil-water hydrologic budgeting analysis may mask short periods of recharge by the averaging effect of larger time-interval data (Howard and Lloyd, 1979; Sophocleous, 1992). In addition, because of the importance of antecedent moisture conditions on deep percolation and runoff, and of their transient nature, relatively large time-lumping of soil moisture will significantly affect the hydrologic balance components. Therefore, to adequately represent watershed processes on a continuous basis, a relatively short time-step is needed, and a daily-time step is a practical and adequate time-scale for field, large-area, multi-year applications.

In contrast, most network measurements of ground-water levels are done annually, quarterly or, at most,

monthly because of the sluggishness of the ground-water system. However, large disparities in time-steps between surface and ground water often lead to numerical instabilities in solving for stream seepage (Perkins and Koussis, 1996). Ideally, streamflow and ground-water movement should be calculated with the same time-step because of their interactions, thus avoiding possible numerical instability problems. To overcome these problems (at least partially) and given data availability, a monthly time-step is considered adequate to represent ground-water processes for field, large-area, multi-year applications.

Most ground-water models are physically based and spatially distributed, with the system states described by partial differential equations. Their numerical solutions are based on a regular or irregular grid, the mesh size of which depends on the system geometry, data availability, and numerical-solution convergence requirements. Although data are practically never available at every grid node or cell of the model domain, ignoring for the moment the issues of scale of measurements (Beven, 1989), the fine numerical grid is still maintained for better system-geometry approximation and numerical-solution convergence. Zoning the model domain into regions of relatively uniform physical properties usually makes up for the lack of sufficient data.

Most watershed models, on the other hand, are conceptual and physically based, but use lumped parameters. To overcome this problem, such models have recently been evolving towards “lumped-distributed” models by dividing the basin into several topographically based subbasins, each with different physical characteristics. In effect, both subbasins and grid cells are lumped elements in all physically based models. Although such an approach may represent some weather-related characteristics adequately, other characteristics, such as soil and land use, cannot be adequately addressed without refining downwards to at least the scale of individual crop fields. Thus, even a relatively fine subdivision of the watershed rarely approaches the fine-mesh, distributed-model discretization, posing problems in linking watershed and ground-water models together.

Heterogeneities exist within subbasins with respect to soil, vegetation, land use and other factors. Reducing the size of subbasins to resolve these heterogeneities is generally not a practical approach. A practical

alternative is to represent the effects of these heterogeneities statistically by use of the hydrologic response unit (HRU) concept (Leavesley et al., 1983). These HRUs are statistically defined soil-vegetation/land use spatial complexes (within a specified climatic regime) with a distinct hydrologic response. Thus, each subbasin is discretized into virtual areas (Mamillapalli et al., 1996), each having a unique soil and land use combination without reference to their spatial positioning within the subbasin. The subbasin’s mean hydrologic response is then given by the mean of each hydrologic component taken over each of these virtual areas and weighted by their respective areas for all hydrologic components (i.e. runoff, percolation, evapotranspiration, irrigation, etc.). This approach allows a subbasin to be further subdivided using differences in soil, land use, and management, while retaining the topographically defined inputs of the subbasin. The approach can provide considerable spatial detail on large basins without simulating each individual field. This is the approach we took in developing the integrated model we describe next.

## 4. Integration of SWAT and MODFLOW

### 4.1. Overview of SWAT–MODFLOW linkage

Combining SWAT and MODFLOW into an integrated watershed model not only has disadvantages associated with increased complexity of the model domain, computer code, data requirements, and operation, but also has advantages. Linkage allows an overall water balance for the watershed to be determined that can serve as a check on continuity and a constraint on model parameters.

A watershed’s overall hydrologic balance is given by

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

where  $dS/dt$  is the rate of change in storage, including components from the watershed’s streams, aquifer, soil profile, vegetation, and ponds;  $Q_{pcp}$  the net precipitation inflows;  $Q_{evt}$  the net outflows by evaporation;  $Q_{yld}$  the stream yield, consisting of the net lateral contributions to streamflow; and  $Q_{gw}$  net regional ground-water inflows. Irrigation is an internal transfer within the watershed from surface- and ground-water

**1. Soil water-atmosphere simulation: SWAT**

For each HRU, run SWAT as follows:

For each day of the simulation period:

At beginning of each aquifer solution time step, calculate daily capillary uptake from shallow ground water (from MODFLOW)

For each subbasin:

Run lumped watershed model code;

Accumulate results over each ground-water simulation time step;

end do

At end of each aquifer solution time step, calculate:

Flow rates for each HRU and subbasin (subroutine PRESWB);

Spatial weights (subroutine SUBWTS) to be used in average over HRUs

end do

end do

**2. Take average over HRUs: SWBAVG**

For each aquifer solution time step:

Read spatial weights written by subroutine SUBWTS for each subbasin;

For each HRU:

Read flow rates written by subroutine PRESWB for each subbasin;

For each subbasin:

For each hydrologic component:

Accumulate a weighted average over all HRUs;

end do

end do

end do

Write HRU-averaged flow rates for each subbasin;

end do

**3. Stream-aquifer simulation: MODFLOW**

For each aquifer solution time step:

Distribute HRU-averaged flow rates for each subbasin over grid cells to specify recharge, tributary flow, surface and ground water diversions, and maximum evaporation for shallow ground water (MODSWB, MODSTR and MODWEL packages).

Formulate and solve finite difference equations (FM\_ and solver routines);

Write summary of evaporation from shallow ground water (subroutine SWB2BD);

Calculate residuals for simulated heads (MODRSD package);

Write optional "post-processed" results (MODPOST package);

end do

Fig. 2. Procedure to coordinate separate execution of SWAT and MODFLOW for simulation of a basin's watershed hydrology. (Subroutines and model packages identified were developed as parts of the integrated watershed model).

sources to the land surface, and so is not included with precipitation. Net regional ground-water inflow,  $Q_{gw}$ , is zero if surface water and ground-water divides coincide.

The SWAT–MODFLOW linkage also provides a forward model for hydrologic fluxes. Specifically, SWAT provides MODFLOW with a forward model for ground-water recharge, tributary inflows to the stream network, irrigation requirements, and evaporation from shallow ground water, all of which must be specified as boundary conditions for MODFLOW's solution.

An integrated watershed simulation that is based on the coordination of SWAT and MODFLOW as separate executable programs is illustrated in Fig. 2. This coordination relies on three components of code that form the functional parts of the linkage between SWAT and MODFLOW.

The first component, illustrated in Fig. 2, specifies hydrologic connections between the respective control volumes simulated by SWAT and MODFLOW. At the end of each aquifer solution time step, SWAT calls subroutine PRESWB (an updated version of HYDBAL, referred to in Sophocleous et al., 1999, and documented in Perkins and Sophocleous, 1999b,c) to transform hydrologic depths, or cumulative volumes per unit area simulated by SWAT (such as tributary inflows to the main stream, aquifer recharge, surface and ground-water diversions, and evapotranspiration from shallow ground water) into average flow rates over the aquifer time step. These flow rates are written to a file to summarize SWAT's simulation results for MODFLOW. Calculation of these flow rates involves combining terms simulated by SWAT (Perkins and Sophocleous, 1999a) and conversion from hydrologic

depths,  $d$ , into flow rates,  $Q$ , according to the following equation:

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

where  $f$  is the areal fraction of watershed area,  $A$ , to which the hydrologic component applies,  $\Delta t$  is the time step, and  $c$  is a length conversion factor. For example, aquifer recharge passed to MODFLOW includes contributions from percolation through the soil profile, transmission losses along ephemeral streams, and pond seepage.

The second component (Fig. 2) applies the HRU concept to represent the hydrologic effects of spatial heterogeneity within subbasins simulated by SWAT. A statistical model for spatial heterogeneity is provided by coordinating the execution of SWAT with a separate program, SWBAVG (Perkins and Sophocleous, 1999b,c). SWAT simulates a set of representative homogeneous cases, referred to as HRUs. SWBAVG then takes an areally weighed average over the HRU simulation results. The hydrologic fluxes simulated by SWAT for a given HRU contribute a fractional weight,  $w_k$ , to the average of hydrologic fluxes taken over all HRUs,  $k$  (from 1 to  $n$ ). For each subbasin, the HRU-averaged value for a given hydrologic component,  $d_i$  is given by

$$d_i = \sum_{k=1}^n d_{ik}w_k \quad (3a)$$

$$w_k = s_l c_m \quad (3b)$$

The HRU weight,  $w_k$ , is given by the product of subbasin areal fractions,  $s_l$  and  $c_m$ , corresponding to soil type,  $l$ , and land use,  $m$ . For each aquifer solution time step, SWAT calls subroutine SUBWTS (Perkins and Sophocleous, 1999b,c) to calculate the weights,  $w_k$ , for each HRU and subbasin (Fig. 2). After all HRUs have been simulated by independent executions of SWAT, program SWBAVG takes the weighted average according to Eq. (3a) over the HRUs. This approach allows the time-varying nature of land uses to be represented over the period of simulation.

The third component (Fig. 2) uses the spatially averaged results given by SWBAVG for each subbasin to specify boundary conditions over the grid of MODFLOW's spatially distributed stream-aquifer

solution. This component is provided by the package MODSWB, which was written for this purpose, in conjunction with the packages MODWEL and MODSTR, which are modified versions of MODFLOW's Well and Stream packages, respectively (Perkins and Sophocleous, 1999b,c; see also Appendix B). MODSWB distributes the flow rates simulated by SWAT and SWBAVG for HRU-averaged hydrologic connections over the appropriate grid cells of the stream and aquifer domain in each time step. Thus, 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 for irrigation involve the packages MODSTR and MODWEL, respectively, which provide features necessary for the SWAT–MODFLOW linkage, as further explained in Appendix B.

The strength of coupling due to shallow ground-water evapotranspiration varies both with the area of shallow ground water and the depth to water table. Subroutine SWB2BD (Perkins and Sophocleous, 1999b,c) in the MODSWB package writes a summary of shallow ground water, including its area, mean depth, and evaporation rate for each subbasin. These results can be used as input to a subsequent execution of the linked SWAT–MODFLOW procedure outlined in Fig. 2, thereby coupling SWAT and MODFLOW's solution by the method of successive approximation. This approach is applied in an HRU scheme (see Table 1, HRU3) that disaggregates shallow and deep ground water and is described next.

#### 4.2. Hydrologic coupling of SWAT and MODFLOW via shallow ground-water processes

Three conceptual models of spatial heterogeneity of increasing complexity were adopted in the case where the aquifer and watershed boundaries do not coincide (Table 1). The basic conceptual model (HRU1) assumes that the watershed is completely underlain by an aquifer, and that soil type and land use factors are independent. The second conceptualization

Table 1  
Conceptualizations of hydrologic coupling of SWAT and MODFLOW

HRU1	Watershed completely underlain by an aquifer; water table below root zone (deep water table); no interaction of water table with overlying sediments
HRU2	Watershed may be partly underlain by an aquifer; water table below root zone: (deep water table); no interaction of water table with overlying sediments
HRU3	Watershed may be partly underlain by an aquifer; water table is within the root zone (shallow water table), thus interacts with overlying sediments

(HRU2) disaggregates areas with and without an underlying aquifer, but without the aquifer interacting with the overlying sediments. The third conceptualization (HRU3) further disaggregates the watershed areas underlain by a non-coinciding aquifer into shallow and deep aquifer components, but with the shallow aquifer interacting with the overlying soil. This latter conceptualization demonstrates a method for coupling separately executed simulations of SWAT and MODFLOW using successive approximation. Shallow ground water is considered to be at a depth,  $z < z_{\text{ext}}$ , the extinction depth as defined for MODFLOW's Evapotranspiration package. MODFLOW approximates evapotranspiration from shallow ground water as a linearly varying function of depth to water, where the maximum rate can be specified by potential evapotranspiration calculated by SWAT.

SWAT uses routing procedures to simulate soil-water movement for infiltration and subsurface lateral flow during storm periods and for evapotranspiration by way of both soil and plant water uptake, but without coupling water content in the soil profile to evaporation from shallow ground water. This coupling would require passing MODFLOW's results for evaporative flow rates from shallow ground water to SWAT, and simulating the uptake of such flow rates into the soil profile in each aquifer time step.

For each subbasin and aquifer solution time step, MODFLOW's MODSWB package summarizes both evapotranspiration rate from shallow ground water and the corresponding area of the grid domain with shallow ground water from where evapotranspiration takes place. These are written for each corresponding time-step to a summary file that can be read in a

subsequent execution of SWAT. They are used to calculate: (1) time-varying spatial weight functions for HRU3 (Table 1) mentioned previously; and (2) daily capillary uptake into the soil profile from shallow ground water, converting flow rates given by MODFLOW into depths (volumes per unit area) according to Eq. (2). SWAT was modified to distribute the daily uptake over the soil profile, beginning with the bottom layer, limited by each layer's available water capacity. This routing approach is an ad hoc scheme to represent uptake from shallow ground water, but is appropriate as a connection between MODFLOW's model for evapotranspiration from shallow ground water and SWAT's routing procedures for representing soil water movement.

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 (e.g. MODFLOW's solution for aquifer heads). In this case, we used HRU2 (Table 1) as an initial solution for the coupled SWAT–MODFLOW simulation following the procedure outlined in Fig. 2. Results for evapotranspiration from shallow water for each time-step from this simulation can be used in a subsequent pass through the procedure of Fig. 2 based on HRU3 (Table 1), in which uptake from shallow ground water couples SWAT and MODFLOW solutions. This conceptualization was implemented as a pilot test case in the context of the Lower Republican River basin to be summarized in Section 6.

## 5. Summary background on how the integrated models were applied and calibrated

### 5.1. GIS coverages and other model input data

The modeling effort was supported in the three case studies shown in Fig. 1 by data organized in Geographical Information System (GIS) databases. The GIS used in this study were Arc/Info and ArcView (ESRI, 1997, 1999), and they were employed to georeference, analyze, and map spatial data for use as input to the computer models. GIS data were gathered for most of the spatial parameters of the watershed

and ground-water models. These data provide spatial distribution of climate, channel morphology, ground-water table, and basin conditions such as basin topography, land use, soils, hydrography, and geology. Other necessary data include township and range, and other administrative boundaries.

The model inputs and parameters were extracted through various GIS procedures, depending upon the nature of the parameters. In this study, length and areal measurements were frequently needed, such as stream lengths and areas of subbasins, various land-uses, and soil polygons, as well as distances of ground- and surface-water rights from major streams. These values were calculated automatically and stored as part of attributes when GIS coverage was created. GIS overlay functions were used to obtain composite parameters as needed, such as soil properties in a subbasin, where soil coverage was overlaid with basin-boundary coverage. With appropriate areal weights calculated by GIS procedures, spatial averages of soil parameters were estimated for each subbasin and used as input for the hydrologic model. Using relational database functions, attributes from different data sources were linked and manipulated to derive required parameters for the model. For spatial data that were only available at point locations, spatial interpolation was used to extend point data to grid cells through a number of Arc-Info commands. Model results were also converted into coverages and displayed on the GIS system.

US Geological Survey datasets incorporated into GIS coverages included basin topography, hydrologic unit code (HUC) basin divides, stream channel delineation, and gaging station locations. Existing digital elevation models (DEM) for the study areas were too coarse for delineating drainage areas (the existing DEM corresponded to a scale of 1:250,000). However we had available digital line graph (DLG) GIS coverages of the study areas, with elevation contours corresponding to 1:100,000 scale or larger (i.e. more detailed), and we made use of these coverages. Hydrologic data associated with the gaging stations include channel flow characteristics and daily streamflow measurements, obtained from the US Geological Survey's ADAPS database. Soils data (STATSGO database) were obtained from the Natural Resources Conservation Service (NRCS), including hydraulic properties and areal extents as soil polygon coverages.

Land use classifications were based on Landsat Thematic Mapper data (DASC, 1999), and also on NRCS reports and Kansas Farm Facts statistics for each county.

Climatological data stations and daily measurements of precipitation and temperature were obtained from the National Weather Service (NWS). The precipitation point measurements represent relatively large areas, on the order of 300 km<sup>2</sup> each, and lie approximately 30 km apart. Rainfall measurements can show strong spatial variability between stations separated by this distance. One approach to representing precipitation over each subbasin is to take a weighed average of measurements from neighboring stations, weighted by the areas of the Thiessen polygons. For convective storms covering a small area relative to the Thiessen polygon area, this approach could tend to artificially increase the number of storms and decrease daily rainfall volumes, which may distort the simulated hydrologic response. To avoid this type of distortion, a single neighboring station was chosen to represent each subbasin.

Data describing water rights and water use were obtained from the Kansas Division of Water Resources (DWR) of the Kansas Department of Agriculture. These were characterized by location of diversion source (surface or ground water), type of use, annual volumetric appropriation, maximum allowed pumping rate, land area associated with irrigation water use, date of initial appropriation, and other data. DWR also provided reports of annual water use that are considered reliable only for more recent years (since 1980s), including reported depth to water table for many of the irrigation wells. Data from individual reports were compiled to determine annual irrigation water use,  $Q_{\text{irr}}\Delta t$ , and area irrigated,  $A_{\text{irr}}$ , for both surface and ground-water rights in each of these years. Annual irrigation depth,  $d_{\text{irr}}$ , was estimated from these by using Eq. (2), where  $f = A_{\text{irr}}/A$ . In order to account for the early years in the simulations during which reported water use data were not available, a statistical relationship between annual irrigation depth and irrigation-season precipitation was developed (Sophocleous et al., 1997a,b, 1998) and employed to fill in the missing irrigation data.

Elevations for water table and bedrock were obtained from previous studies or ongoing field programs during the duration of the projects reported

here. The same holds true for aquifer hydrogeologic properties.

### 5.2. Model calibration and verification

The models were calibrated using iterative, trial-and-error, multi-target approaches to reduce model error with respect to mean and standard deviation of residuals, and also, in the case of the Rattlesnake Creek basin, employing automated parameter estimation approaches using PEST (Doherty et al., 1994) for the MODFLOW portion of the combined model. Calibration targets included streamflow measurements at more than one streamgaging station, ground-water levels measured at different times during the calibration period, and annual reported irrigation water use. A split-sample calibration/verification approach was employed, designating measurements from the earlier years for calibration, and those from the later years for verification or corroboration of the calibrated results. Extensive sensitivity analyses were carried out to identify and assess sensitive parameters and uncertainty ranges.

During calibration, greater emphasis was placed on trying to replicate low flows during dry weather conditions, when efficient management of limited water resources is required, and less on replicating flood events because water availability then becomes less of a problem. A general observation from sensitivity analysis is that watershed-related parameters such as the NRCS runoff curve number, soil properties (particularly available water capacity), crop type, and land use characteristics (particularly irrigated area and water use) were more sensitive parameters affecting stream yield and ground-water recharge (and thus ground-water levels) than aquifer and stream hydrogeologic properties, such as aquifer hydraulic conductivity and storativity, and streambed hydraulic conductivity. Of the hydrogeologic parameters, aquifer hydraulic conductivity and storativity were more sensitive parameters than streambed hydraulic properties.

As a result of the sensitivity analysis, the following strategies were followed during calibration. Watershed-related parameters that were identified as sensitive by trial-and-error (mainly runoff curve number and secondarily plant stress factor or soil moisture threshold value to trigger irrigation) were

adjusted so that the resulting surface runoff and aquifer recharge (deep percolation) produced relatively low errors in streamflows and ground-water levels. The aquifer hydraulic conductivity was then adjusted within expected limits either through parameter estimation procedures (such as PEST) or through trial-and-error for that particular distribution of surface runoff and aquifer recharge by minimizing the ground-water-level residuals for predevelopment (steady-state) conditions. The aquifer storativity was then optimized by trial-and-error for transient conditions. This iterative procedure was repeated until further refinement in surface runoff and aquifer recharge yielded negligible improvements in results. For details on the calibration and verification procedures, the reader is referred to the referenced individual reports and papers for each of the three cases presented next.

## 6. Real-world case applications of the integrated modeling approach in Kansas

### 6.1. Rattlesnake creek basin, south-central Kansas (Fig. 1)

In 1993, the Division of Water Resources (DWR) of the Kansas Department of Agriculture initiated a special program known as the Subbasin Water Resources Management Program. The program's goal was to develop a comprehensive, long-term management strategy to solve water problems on a proactive basis and enforce water-rights conditions to make the best possible use of the available water resources. Issues such as ground-water declines, surface-water depletions, and water-quality deterioration were to be addressed in conjunction with other local, state, and federal agencies with a significant opportunity for public input. The program uses the hydrologic basin approach to water-resources administration and management; it consists of five phases, one of which is the development of an appropriate hydrologic model capable of handling the subbasin surface water, ground water, and streamflow-aquifer interaction, and evaluating various management strategies. This is where our integrated watershed model comes into play.

Because of the pilot-project nature of this case, and

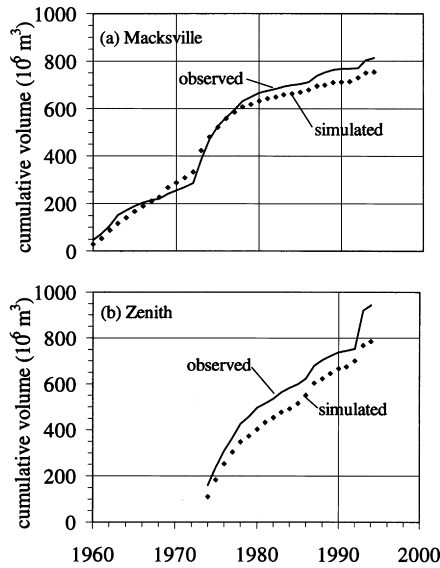


Fig. 3. Simulated and observed cumulative streamflow for Rattlesnake Creek at US Geological Survey's: (a) Macksville; and (b) Zenith gaging stations.

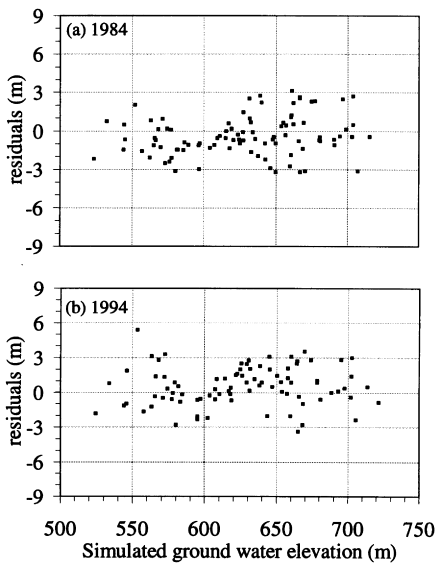


Fig. 4. Variation of ground-water-level residuals (simulated-observed values, *m*) with simulated water table elevation for the Rattlesnake Creek alluvial aquifer: (a) 1984 calibration period; and (b) 1994, verification period.

the importance of resolving the water problems in that region as an example for other areas placed by state and local agencies, this case will be presented in somewhat greater detail than the other cases. The residents of the Rattlesnake Creek subbasin area and government agencies formed the Rattlesnake Creek/Quivira Partnership (hereafter referred to as the Partnership) to co-operatively develop and implement solutions to water problems within the subbasin. An essential element of establishing such a management program is the development and calibration of an integrated watershed model for the region.

The results of our integrated watershed model show that the regional trends were reproduced fairly well (Sophocleous et al., 1999). The cumulative streamflows at Macksville and Zenith gaging stations (Fig. 1) for the entire calibration and verification periods are shown in Fig. 3, which show satisfactory agreement between observed and simulated flows, although flood years (such as 1973 and 1993) were underestimated. Fig. 4 shows a typical distribution of ground-water level residuals against simulated ground-water levels for a typical year from the calibration and verification periods, respectively. The nearly horizontal banding of residuals around the zero line indicates a satisfactory fit.

A Decision Support System (DSS) coupled with a graphical user interface for this integrated model was also developed to assist water managers to interact with the model in order to evaluate and display the hydrologic effects of various water management scenarios in a user-friendly manner (Sophocleous et al., 1999; Ramireddygarri et al., 1998). This aspect of technology transfer to water managers and members of the Partnership proved very effective. As a result, numerous management alternatives were thus tested, displayed on the color screen, and evaluated, (see Sophocleous et al., 1997a, 1999 for a selection of alternatives tested) and problem areas with the most significant ground-water and streamflow declines were identified and outlined.

Four specific issues were identified for the Rattlesnake Creek Subbasin Management Program: (1) streamflow declines; (2) streamflows into Quivira National Wildlife Refuge (at the downstream portion of the basin, Fig. 1), including timing of those flows; (3) ground-water declines; and (4) mineral (saltwater) intrusion. The first three issues were addressed with

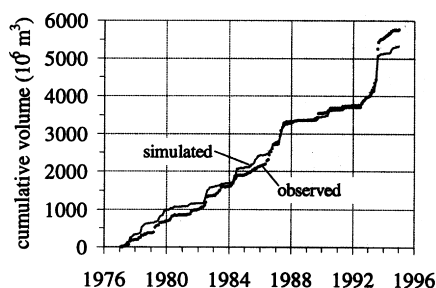


Fig. 5. Simulated and observed cumulative stream yield for the Republican River from Concordia to Clay Center, Kansas.

our integrated watershed model (Sophocleous et al., 1999), whereas the mineral intrusion issue was addressed by parallel studies (Ma et al., 1997; Sophocleous and Ma, 1998; Ma et al., 1999, among others). Based on these studies, the results of the integrated modeling, and other analyses by the Partnership, three target areas were tentatively identified in the draft Rattlesnake Creek Subbasin Management Program (I. Brascum, DWR, 1999, written communication). These areas were: (1) a 6.44-km (4-m)-wide corridor along most of the length of the Rattlesnake Creek, 3.22 km (2 m) on each side of the creek; (2) a ground-water area with severe decline trends north and west of the Rattlesnake Creek, in the north/central portion of the subbasin; and (3) a mineral-intrusion problem area in the lower segment of the basin, basically the basin area east of US Highway 281 (Fig. 1). Despite some inherent limitations, the integrated watershed model and the mineral intrusion studies [(Sophocleous et al., 1999 (for items 1–3 above); Sophocleous and Ma, 1998 (for item 4 above)] were indispensable for such integrated basinwide management and decision support, especially in evaluating the efficacy of a number of considered water-management scenarios (Sophocleous et al., 1997a, 1999).

In the stream-corridor target area, the goal is to stabilize streamflow declines in the short term, and increase streamflow in the future. To do this, average ground-water use within the Rattlesnake Creek corridor would need to be reduced in order to attain a 10-year average January target streamflow at the Zenith streamgaging station of 708 l/s (25 cfs). Integrated modeling and other analyses indicated that at least a 12% reduction in the 10-year (1987–1996) average

annual water use was needed to reach the set streamflow target.

The goal for the ground-water management area in the north/central portion of the basin is to stabilize ground-water declines, and over the long term improve ground-water level trends. Therefore, the objective was set to reduce average annual water use in that area over a period of 12 years. Integrated modeling and other hydrologic analyses indicated a 16% reduction in the 10-year (1987–1996) average water use was needed to reach that goal. Similar goals were set for the mineral intrusion area as well. Incentive-based alternatives within each of the above-mentioned target areas and within the basin in general are now being implemented.

#### 6.2. Lower Republican River basin, north-central Kansas (Fig. 1)

A key management concern in this area was to understand how significantly irrigation water-use affects streamflow and ground-water levels, particularly during drought periods. During droughts in the years 1988 to 1991, monthly average streamflows in the Lower Republican River basin fell below established minimum desirable streamflow standards, raising concerns regarding the Republican River's capacity to adequately supply Milford Reservoir, a major Kansas reservoir. The alluvial aquifer, characterized by a relatively shallow water table, represents only a small fraction (approximately 1/8) of the Lower Republican River basin. Our integrated watershed model (Perkins and Sophocleous, 1999a) was indispensable in understanding the hydrology of the Lower Republican River basin system and in evaluating management options. A sampling of the calibration/verification results for the Lower Republican River case is shown in Fig. 5, where a comparison of simulated and observed stream yield based on streamflow measurements at Concordia and Clay Center (Fig. 1) shows satisfactory results. These results are based on an improved conceptual model of the basin (HRU3 in Table 1) from the one presented in Perkins and Sophocleous (1999a). The corresponding ground-water level residuals, shown in Fig. 6, also demonstrate a satisfactory match. By applying the model, we found that tributary inflows were the dominant component of Lower Republican River yield, and

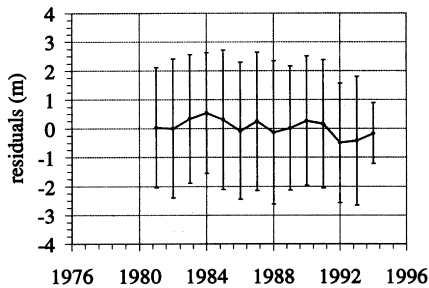


Fig. 6. Time series of ground-water-level residual annual means for Republican River alluvial aquifer; error bars are  $\pm 1$  standard deviation.

that baseflow was relatively insignificant. As a result, the study showed that management alternatives to reduce predominantly ground-water-based irrigation water use are unlikely to increase stream yield enough to restore minimum desirable streamflows.

### 6.3. Wet Walnut Creek basin, west-central Kansas (Fig. 1)

Wet Walnut Creek basin is a major source of water to Cheyenne Bottoms, an internationally recognized wetland that provides essential stopover sites for migratory shore birds of the Central North American

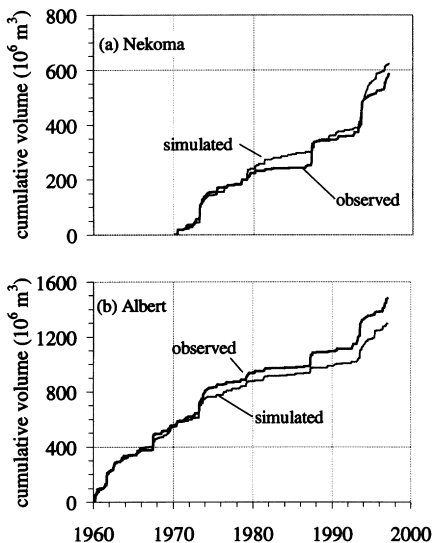


Fig. 7. Simulated and observed cumulative streamflow for Wet Walnut Creek at US Geological Survey's: (a) Nekoma; and (b) Albert gaging stations.

flyway. A diversion canal downstream of the Wet Walnut Creek basin is connected to Cheyenne Bottoms diversion works. In recent years, streamflow from Wet Walnut Creek watershed has been reduced in both quantity and duration. In addition to more than 40 watershed structures (relatively small earth dams) added to the basin, other significant developments over the past several decades include withdrawals of ground and surface water from the alluvial aquifer and stream, changes in agricultural land use, and adoption of conservation tillage and terrace systems. Changes in streamflow amount and distribution, and excess withdrawals from ground water resulted in the implementation of an “intensive ground-water use control area” in 1992 by the DWR to limit ground-water withdrawals. However, not enough information on the impact of watershed structures on stream yield and how to manage their operation was available. This led to our development and application of the integrated watershed modeling approach to estimate the effects of watershed dams on available water resources in the basin (Koelliker et al., 1999; Ramireddygarri et al., 2000).

This case presented us with an opportunity to generalize and test the flexibility of our watershed ground-water model linkage procedures. Instead of SWAT as the watershed simulator, we used POTYLDR (Koelliker, 1994), a roughly equivalent but simpler code, which we linked to MODFLOW with little additional effort using the existing SWAT–MODFLOW linkage structure. The linkages we employed in our integrated model are independent of the conceptual models used to calculate the various hydrologic fluxes in the individual watershed models; only the resulting watershed hydrologic fluxes were passed on to MODFLOW. The POTYLDR–MODFLOW model linkage and its calibration and corroboration are summarized in Sophocleous et al. (1998), Koelliker et al. (1999) and Ramireddygarri et al. (2000). A sampling of the calibration/verification results for the Wet Walnut River basin case is shown in Figs. 7 and 8. Fig. 7 shows the observed and simulated cumulative streamflows at Nekoma and Albert gaging stations (Fig. 1), whereas Fig. 8 shows the mean and standard deviation of the ground-water level residuals for the entire simulated period. These results are generally satisfactory. The use of this integrated watershed model clarified the effects of

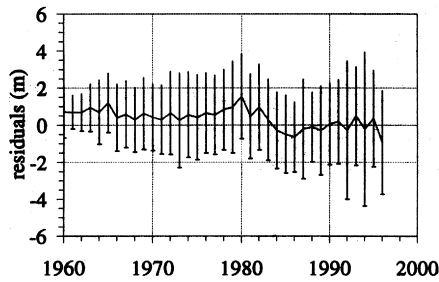


Fig. 8. Time series of ground-water-level residual annual means for Wet Walnut Creek alluvial aquifer; error bars are  $\pm 1$  standard deviation.

watershed structures and irrigation water-use on stream yield. The results showed that the impact of watershed structures on stream yield was relatively small (Koelliker et al., 1999; Ramireddygarri et al., 2000). Even if all structures were to be removed from the basin, the resulting increase in stream yield was estimated to be less than 10% of simulated streamflow near the downstream end of the basin. However, our integrated modeling indicated that water use for irrigation has a much greater impact on streamflow than watershed structures and also has a substantial effect on divertable flows to Cheyenne Bottoms.

For additional information on individual case studies and the variant of the integrated modeling system employed in each case, the reader is referred to the cited individual case references.

## 7. Concluding comments

The integrated watershed and ground-water models allow a complete analysis of the land-based hydrologic cycle, thus providing the means for evaluating the impacts of land use, irrigation development, and climate change on both surface- and ground-water resources. Such models allow predictions of the impact of management changes on total water supplies. Evaluation of such impacts is at the core of present-day debates on the sustainability of water resources. The seasonal variation of water-table levels and recharge can be more accurately predicted by the soil-moisture accounting system employed in the integrated model than by using only the ground-water model. This increased flexibility, however,

comes at the expense of increased complexity and expertise needed to effectively use integrated watershed modeling. In addition, this proposed modeling might not be the most appropriate tool for all cases.

It is worth emphasizing that relatively simple, conceptually clear, physically based, quasi-distributed models, which address all major components of the land-based hydrologic cycle and use readily-available input data, are what is needed in most cases for real-world, basinwide management applications. These simpler models will also enhance public understanding and acceptance of modeling in water resource management. The component models selected (SWAT and MODFLOW) for the integration into a comprehensive watershed/ground-water model are compatible with this prescription. Feedback from water-managers was indispensable in selecting and designing the features of the integrated model. Although not discussed here, model integration was improved further with each model application. The two-way coupling conceptualization was implemented and successfully demonstrated for the Lower Republican River basin; additional work is proceeding to generalize our two-way coupling procedures. It is hoped that the complexity of integrated modeling was reduced in the applications we reported on by our choice of the component models, which are widely supported and enhanced with user-friendly interfaces and GIS-compatibility, and with our continued refinement of the component model linkages. The substitution of the POTYLDR watershed code for SWAT in the Wet Walnut case study indicates the flexibility of our linkage procedures, which allow connecting alternative watershed codes to the standard MODFLOW code.

An additional advantage of integrated modeling, over either watershed or ground-water models alone, is improved model calibration. With the integrated models, the calibration targets increase, resulting in more reliable results than otherwise would be possible. For example, in the three case studies discussed, we calibrated against three readily available, simultaneous calibration targets: (1) ground-water levels; (2) streamflows (at more than one streamgaging stations, where available); and (3) reported irrigation water-use time-series (irrigation water-use reports are required each year from all water-rights holders in Kansas and

are compiled by DWR). Additional calibration targets could be added, if available. Although integrated models require extensive data, such integrated modeling constrains the adjustment of model parameters because overall water budgets must be observed. Whereas traditional methods used to calibrate ground-water models may include adjustments to water-table elevations or recharge rates, in an integrated model, recharge is completely constrained by an overall water budget for the surface-water system. In addition, stream–aquifer interactions are constrained by the generated amount of surface runoff to streams that in turn, impacts the stream stage and thus the driving forces for stream–aquifer interaction.

### Acknowledgements

The financial assistance of the Kansas Water Office and the Division of Water Resources of the Kansas Department of Agriculture, as well as the useful feedback of their staff during the development and application of this modeling approach to different basins in Kansas is gratefully acknowledged. The collaboration of Drs James K. Koelliker and Sreepathi R. Ramiredygar of Kansas State University (KSU) and Dr Rao S. Govindaraju, formerly of KSU and presently with Purdue University, was instrumental in the development and application of the Rattlesnake Creek and Wet Walnut Creek basin cases. Dr David Wolock of the US Geological Survey provided a useful review of the original version of this paper. Journal reviewers' comments helped improve the manuscript.

### Appendix A

#### *A brief introduction to SWAT*

This introduction is based on the SWAT web site (<http://www.brc.tamus.edu/swat/>). SWAT (Soil and Water Assessment Tool) is a river basin or watershed scale model developed by the US Department of Agriculture, Agricultural Research Service. SWAT was developed to predict the impact of land-management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The model is physically based, uses

readily available inputs, is computationally efficient, and enables users to study long-term impacts. SWAT is a continuous time model using daily time steps. The model is not designed to simulate detailed, single-event flood routing. For modeling purposes, a watershed may be partitioned into a number of subwatersheds or subbasins. Input information for each subbasin is grouped into the following categories: weather or climate; unique areas of land cover, soil, and management within the subbasin (HRUs); ponds/reservoirs; ground water; and the main channel or reach draining each subbasin. The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a better physical description of the water balance. For further details, the reader is referred to the SWAT web site mentioned above.

### Appendix B

This appendix provides some details on how our integrated model distributes HRU-averaged flow rates over a stream–aquifer grid and how it satisfies irrigation demands with surface- and ground-water diversions.

In each time step, our MODSWB package reads HRU-averaged flow rates from SWAT and SWBAVG, and the overall water balance, according to Eq. (1), is evaluated by combining the SWAT 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 appropriations, and within supply limits imposed by available streamflow and aquifer saturated thickness. The modified packages MODSTR and MODWEL are both involved in satisfying these constraints.

MODSTR uses a modified routing procedure to account for net lateral surface inflows in each reach that represent 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* (Perkins

and Sophocleous, 1999b,c), is a feature added to look up a stream reach that is to be associated with grid coordinates specified for subbasin outflows and surface water diversions.

Channel-flow characteristics (depth, width, wetted perimeter, and others) can be represented not only for rectangular channels, but also for trapezoidal and natural channels. Streambed conductance may be calculated on the basis of streambed hydraulic conductivity and stream width. Hydraulic conductivity may be resolved into components corresponding to bottom and side walls; and streambed leakage due to flooding outside the main channel is characterized as recharge due to percolation instead of coupled stream–aquifer interaction.

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

The supply for surface-water diversions is limited by the sum of channel and lateral surface inflows to its associated stream reach. This limit is applied as part of the modified stream routing procedure in MODSTR. The supply for ground-water diversions is limited by the aquifer's saturated thickness. Above an upper limit,  $d_u$ , 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 technique, employed in the MODWEL package, provides a realistic means of preventing grid cells from going dry as a result of excessive pumping from wells. For additional details refer to Perkins and Sophocleous (1999a,b,c).

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