Exhibit 5

Development of a Comprehensive Watershed Model Applied to Study Stream Yield under Drought Conditions

by Samuel P. Perkins[a] and Marios Sophocleous[b]

Abstract

We developed a model code to simulate a watershed's hydrology and the hydraulic response of an interconnected stream-aquifer system, and applied the model code to the Lower Republican River Basin in Kansas. The model code links two well-known computer programs: MODFLOW (modular 3-D flow model), which simulates ground water flow and stream-aquifer interaction; and SWAT (soil water assessment tool), a soil water budget simulator for an agricultural watershed. SWAT represents a basin as a collection of subbasins in terms of soil, land use, and weather data, and simulates each subbasin on a daily basis to determine runoff, percolation, evaporation, irrigation, pond seepage, and crop growth. Because SWAT applies a lumped hydrologic model to each subbasin, spatial heterogeneities with respect to factors sucb as soil type and land use are not resolved geographically, but can instead be represented statistically. For the Republican River Basin model, each combination of six soil types and three land uses, referred to as a hydrologic response unit (HRU), was simulated with a separate execution of SWAT. A spatially weighted average was then taken over these results for each hydrologic flux and time step by a separate program, SWBAVG. We wrote a package for MODFLOW to associate each subbasin with a subset of aquifer grid cells and stream reaches, and to distribute the hydrologic fluxes given for each subbasin by SWAT and SWBAVG over MODFLOW's stream-aquifer grid to represent tributary flow, surface and ground water diversions, ground water recharge, and evapotranspiration from ground water. The Lower Republican River Basin model was calibrated with respect to measured ground water levels, streamflow, and reported irrigation water use. The model was used to examine the relative contributions of stream yield components and the impact on stream yield and base flow of administrative measures to restrict irrigation water use during droughts. Model results indicate that tributary flow is the dominant component of stream yield and that reduction of irrigation water use produces a corresponding increase in base flow and stream yield. However, the increase in stream yield resulting from reduced water use does not appear to be of sufficient magnitude to restore minimum desirable streamflows.

Introduction

Water resource managers are charged with the task of maintaining water supplies and quality standards in the face of increasing demand, changing land use, weather variability, and long-term climate changes. The effects of these factors and management actions can be difficult to assess because of the complex and interrelated nature of a watershed's hydrology. A computer model that can simulate possible scenarios and their effects on a watershed can be a useful management tool to investigate the watershed's sensitivity to change with respect to a variety of factors. Here we report on the development of a watershed simulation model and its application to the Lower Republican River Basin in north-central Kansas between Concordia and Clay Center (Figure 1).

A key management concern is to understand how significantly irrigation water use affects streamflow and ground water levels, particularly during drought periods. Irrigation water use diminishes streamflow directly, in the case of surface water diversions, and indirectly by ground water pumping, through its effect on the water table and the resulting net contribution to streamflow from ground water (i.e., base flow). In the case of the Republican River during droughts in the years 1988 through 1991, monthly average streamflows between Concordia and Clay Center occasionally fell below minimum desirable streamflow standards established by the Kansas Water Office. These low flows raised concerns regarding the Republican River's capacity to adequately supply Milford Reservoir below Clay Center, and whether crop irrigation along the alluvial valley was a significant factor. For the period 1950 through 1994, appropriations for irrigation increased by nearly a factor of 200 for ground water, from approximately 7 to 1360 L/s, and almost tenfold for surface water, from approximately 10 to 96 L/s.

We chose to develop a model that is physically based to the extent practical. The model was required to represent tributary flow in terms of runoff; surface water diversions and ground water pumping in terms of irrigation; ground water recharge in terms of percolation from the soil profile and stream channels; and base flow in terms of stream-aquifer hydraulics. The model was to be calibrated by adjusting key parameters to minimize model error with respect to one set of measurements, and validated by comparison with another. Available data for calibration and verification included measurements of streamflow, ground water levels, and reported annual water use for irrigation. Because no measurement record exists for inflows to the Republican River between Concordia and Clay Center from more than 20 tributaries, a model of the watershed cannot be calibrated or verified with respect to base flow. This is an important weakness of this model and others, where simulated effects of water use on stream yield depend on correct base flow calculations.

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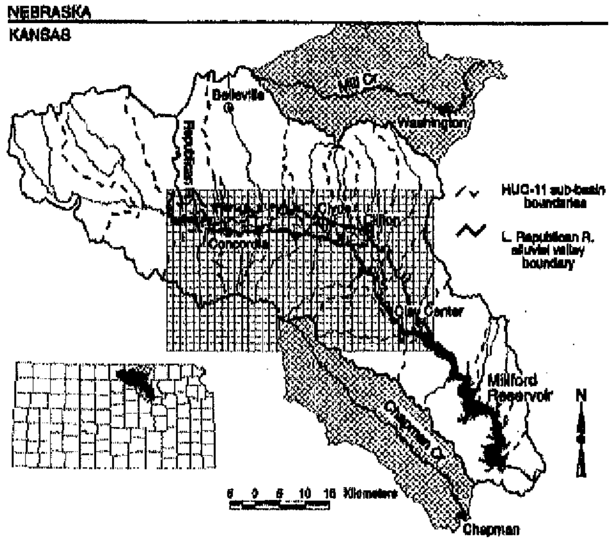

Figure 1. The study area, drained by the Republican River between gauging stations at Concordia and Clay Center, and within the Lower Republican River Basin. It is divided into nine subbasins (dashed lines) that are simulated using SWAT. The Republican River and its alluvial aquifer are simulated using MODFLOW on a grid of township sections. Adjacent watersheds for Mill Creek and Chapman Creek have gauging stations at Washington and Chapman.

Study Area in the Lower Republican River Basin

Our scope of interest is a watershed covering 2569 km^2 in north-central Kansas comprising approximately one-half of the Lower Republican River Basin (Seaber et al. 1987). The watershed is drained by the Republican River, which travels approximately 100 km between gauging stations at Concordia and Clay Center, below which it discharges into Milford Reservoir (Figure 1). The river valley is about 5 km wide and covers approximately 13% of the watershed; the remainder is characterized by upland hills. The river valley contains soils associated with Quaternary alluvium and terrace deposits and a highly productive aquifer that is predominantly sand and gravel. Outside the alluvial valley, soils are composed primarily of silt loam derived from loess, with underlying shale, sandstone, and limestone formations of Cretaceous and Permian periods forming the base of the aquifer.

The basin has a subhumid climate with an average annual temperature of 13°C and an average annual precipitation that increases from west to east, from 69 cm at Concordia to 79 cm at Clay Center. Average annual lake evaporation ranges from 124 to 140 cm (Koelliker 1984). Approximately 75% of annual precipitation occurs from April to September, the growing season. Average annual streamflow is about 19 m^3/s at Concordia and 27 m^3/s at Clay Center, a gain of 8 m^3/s, or 10 cm/yr from the watershed.

The watershed of interest within the Lower Republican Basin between Concordia and Clay Center was partitioned into nine subbasins identified by 11-digit hydrologic unit codes (HUC-11) in the U.S. Geological Survey (USGS) river basin system (Seaber et al. 1987). A geographic information system (GIS) was used to construct maps and to help produce geographical data to be used as input to simulations of the watershed's hydrology, such as determining the areal fractions of predominant soil types and land uses within each subbasin (Sophocleous et al. 1997a).

The next section describes the conceptual models used to simulate the watershed's hydrology and their implementation as a computer code. The third section discusses model calibration and verification. The fourth section gives model results for stream yield composition and compares model results for tributary flow against measurements for neighboring watersheds. The fifth section presents sensitivity analysis, including the effect of water use on stream yield. The sixth section presents conclusions and recommendations.

Model Development

The watershed simulation code is based on MODFLOW (McDonald and Harbaugh 1988), which solves the equations of flow for ground water (Freeze and Cherry 1979) and its interaction with streamflow (Prudic 1989). MODFLOW's solution depends on specified conditions for tributary flow, recharge, evapotranspiration, and diversions from surface and ground water rights for irrigation and other water uses. MODFLOW lacks a means of specifying these conditions in terms of hydrologic processes at the watershed's surface and in the soil profile. One approach is to treat specified conditions as parameters to be determined by calibration. However, a variety of models exist to simulate these processes. Our approach has been to apply one of these to simulate the soil water budget profile and pond storage in the basin, and to write additional MODFLOW packages to apply these simulations to specify conditions for MODFLOW's solution.

For this purpose we used SWAT (Arnold et al. 1993, 1994) to simulate an agricultural watershed's hydrologic processes. SWAT represents a watershed as a collection of subbasins and simulates water budgets for the soil profile and pond storage in each subbasin with a daily time step. Lumped models of hydrologic processes are applied to each subbasin. SWAT itself is a comprehensive watershed model code that includes features to represent ground water and base flow. SWAT applies lumped, analytical models to represent ground water elevation specific to an agricultural field with regularly spaced drains, and base flow by percolation out of the root zone that returns to a stream with a time delay (Arnold et al. 1994). These analytical models are of limited use in representing the hydraulics of stream-aquifer interaction and distributed ground water pumping, which can be represented in a generalized manner with MODFLOW.

We wrote additional code to provide an interface between the different temporal and spatial scales represented in SWAT and MODFLOW, and to meet some specific modeling requirements. We modified SWAT to accumulate its daily simulation results over each aquifer time step of a month or a year to be used in specifying conditions for MODFLOW's solution in each time step, and to add options related to the simulation of irrigation and evaporation.

The interface between the spatial scales of SWAT and MODFLOW has two sides. On MODFLOW's side, we wrote the MODSWB package, which provides a mapping similar to MODFLOW's IBOUND array to associate the domain of each subbasin with aquifer grid cells, and to associate the outflow of each subbasin with a stream reach and corresponding grid cell location. In each time step, MODSWB uses SWAT's simulation results to specify conditions for MODFLOW's solution, including tributary inflows, both surface and ground water diversions to meet irrigation demand, a maximum evaporation rate from shallow ground water, and recharge.

For SWAT's side, we wrote additional code to implement a statistical technique that enables SWAT's lumped model to represent a heterogeneous subbasin. SWAT is first run to simulate the watershed for each combination of factors, notably soil type and land use, that give rise to heterogeneity within subbasins. Each such simulation of SWAT is referred to as an HRU. A spatially weighted average is then taken over the HRUs. For a given subbasin, the weight applied to each HRU is the product of the areal fractions of the HRU factors such as soil type and land use. The resulting average over the HRUs is used by the MODSWB package to specify conditions for MODFLOW's solution. We have applied the model code to watersheds in Kansas, including the Lower Republican River Basin (Sophocleous et al. 1997a) and the Rattlesnake Creek Basin (Sophocleous et al. 1997b, 1999). The watershed model code as it was applied to the Lower Republican River Basin is documented in Perkins and Sophocleous (1997).

Overview of the Watershed Control Volume

A useful check on a simulation that combines results for separate control volumes is provided by a hydrologic balance on the net flows for the watershed,

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

The rate of change in storage, dS/dt, has components in the watershed's streams, aquifer, soil profile, vegetation, and ponds. Net flows on the right include precipitation, stream yield, evaporation, and regional ground water flow, respectively. Precipitation is a net inflow, whereas irrigation is regarded as an internal transfer within the watershed to the land surface from both surface water and ground water sources. Evaporation from water bodies and the land surface, Q_{evt}, is driven by atmospheric conditions and, over land, is supplied by upward flow from the soil profile and plant transpiration. Stream yield, Q_{yld}, is the net outflow from streams. Net regional ground water inflow, Q_{gw}, is zero if surface water and ground water divides coincide (Freeze and Cherry 1979), which is not the case in our study area.

The watershed control volume is partitioned conceptually into interacting components for the vegetation canopy, soil profile, ponds, streams, and aquifer. SWAT and MODFLOW are coordinated to simulate different components of the watershed as illustrated in Figure 2. Above the dashed line, the vegetation canopy, soil profile, and pond storage are represented for each subbasin by SWAT and the HRU averaging technique. Below the dashed line, the Republican River and alluvial aquifer are represented by MODFLOW. Flowpaths across the dashed line represent connections made in MODSWB that use results from SWAT to specify conditions for MODFLOW's solution in each time step, including ground water recharge, evapotranspiration from shallow ground water, withdrawals by both surface and ground water rights, and runoff to streams represented by MODFLOW.

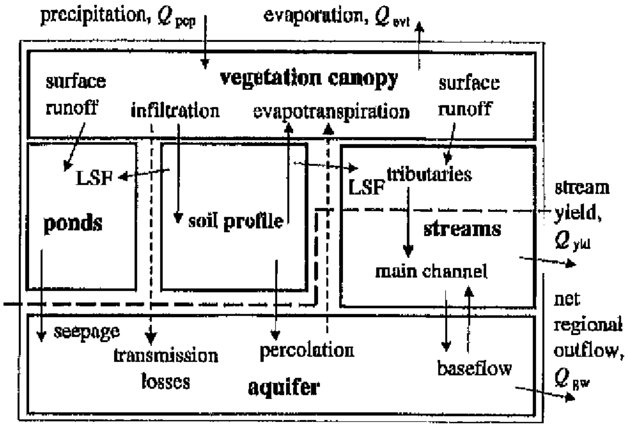

Figure 2. Watershed control volume, partitioned conceptually into components for the vegetation canopy, soils, ponds, streams, and the aquifer. Components above the dashed line are simulated by SWAT, and those below by MODFLOW. LSF = lateral subsurface flow.

Stream and Aquifer Control Volumes: Stream Yield and Base Flow

To investigate base flow connections such as the effect of irrigation water use on streamflow, we begin with our conceptual model for base flow, the net flow from ground water to the stream, and by examining mass balances for streamflow in the Republican River and for ground water in the adjacent alluvium. The governing equation for our conceptual model of base flow is Darcy's law,

$$Q_{base} = -K_s A_s \frac{dh}{dl} \qquad (2)$$

where K_s is the streambed hydraulic conductivity; A_s is the streambed area, the product of wetted perimeter P and reach length L; and dh/dl is the hydraulic gradient across the streambed. Base flow according to Equation 2 is bidirectional, and will flow from the stream into the aquifer in response to either a rise in stream stage due to a flood wave or a water table depression due to irrigation pumping. Equation 2 is evaluated by MODFLOW as part of its simultaneous solution for stream stage and aquifer head.

Stream yield can be expressed in terms of a mass balance applied to a stream reach,

$$(dS/dt)_{str} = Q_{in} - Q_{out} + Q_{trib} - Q_{sdiv} + Q_{base} \qquad (3)$$

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

A mass balance for ground water flow is given by

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

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

The term for regional flow, Q_{gw}, in Equation 4 represents the net outflow of ground water resulting from specified boundary conditions. For the Republican River Basin model, we make the approximation that the alluvial aquifer is underlain by impermeable bedrock; no-flow conditions are specified along the valley walls; and hydraulic heads are specified along the upstream and downstream boundaries transverse to the direction of streamflow.

Surface Water and Soil Water Control Volumes

SWAT simulates each subbasin separately according to the soil water budget equation

$$d_{sw}(t) - d_{sw}(0) = \sum_{i=1}^{t} (d_{pcp} - d_{ro} - d_{xm} - d_{perc} - d_{et}) \qquad (5)$$

On the left-hand side is the change in soil water content after t days; on the right are terms for precipitation, d_{pcp}, which includes snowmelt and applied irrigation; runoff, d_{ro}; transmission losses, d_{xm}; percolation from the soil profile, d_{perc}; and evapotranspiration, det. Equation 5 is given in terms of depths, d_i, which are related to flow rates, Q_i, time step, Δt, and area, f_iA, by

$$cQ_i\Delta t = d_i f_i A \tag{6}$$

where c is a length conversion factor, and f_i is a fraction of watershed area, A. Simulation of the soil water budget by SWAT is documented by Arnold et al. (1994) and summarized as follows.

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

$$(dS/dt)_{pond} = Q_{in} - Q_{out} + Q_{dir} - Q_{evap} - Q_{seep} \tag{7}$$

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

Excess precipitation that remains after runoff and transmission losses are removed infiltrates into the soil profile. SWAT applies a multilayer storage routing technique to partition drainable soil water content for each layer into components for lateral subsurface flow and percolation into the layer below. A kinematic storage routing technique is used to calculate lateral subsurface flow as a function of soil slope, hillslope length, drainable porosity, and excess soil water. Total lateral flow for all soil layers is denoted by d_{lat}, and percolation from the lowest soil layer is denoted by d_{perc}.

Plant growth characteristics, including leaf area and root depth, are simulated. Evaporation of soil water and transpiration by plants in each layer are evaluated as functions of potential evaporation and plant leaf area as described by Ritchie (1972). To simulate potential evaporation, the Penman equation for a reference crop according to Shuttleworth (1993) was implemented to make use of available measurements of daily precipitation and temperature measurements. Other meteorological data were generated on the basis of monthly data and statistical distributions.

SWAT's irrigation model was modified to allow specification of a daily maximum irrigation depth, and to allow irrigation to be triggered by a threshold on soil water content as an alternative to SWAT's plant stress factor. Soil water content was preferred over plant conditions as an indicator for irrigation, particularly for corn, based on experimental results at the Scandia, Kansas, irrigation field in the alluvial valley just northwest of the study area (Rogers 1994).

Spatial Heterogeneity of Soils and Land Uses within Subbasins

SWAT represents each subbasin with a single, homogeneous set of characteristics and a lumped model of its water budget. This will likely be adequate for some characteristics, such as precipitation and temperature, but not for factors such as soil type and land use. Resolving the spatial heterogeneity of these factors within each subbasin might require subdivision of the watershed down to individual crop fields. Instead, we apply a statistical approach to represent heterogeneous soil types and land uses.

Soils of the watershed were categorized roughly into six predominant types; each is characterized in terms of its bulk density, saturated hydraulic conductivity, and silt, sand, clay, and organic carbon content by data from Natural Resources Conservation Service (NRCS). By applying GIS operations to computer-based soil and subbasin maps, the areal fraction of each soil type within each subbasin was determined (Sophocleous et al. 1997a). Areal fractions of crops were determined similarly for each subbasin, based on LANDSAT thematic maps. Approximately 60% of the land is covered by crops; the remainder is covered by grasses and woods, based on LANDSAT data. Predominant land uses were represented approximately by three components: a nonirrigated rotation of wheat, sorghum, and fallow (56% of land area); range and pasture (40%); and irrigated corn cultivated along the alluvial valley (4%), based on farm facts reports (Kansas Department of Agriculture) and water use reports from the Kansas Division of Water Resources (DWR).

SWAT simulates the watershed for each of the 18 combinations of the six major soil types and three land-use management schemes, holding other conditions constant. Each of these cases is referred to as an HRU. For each time step and subbasin, a weighted average of each hydrologic component, i, is taken over the HRUs, k, from 1 to 18, by

$$d_i = \sum_k d_{ik} W_k \tag{8}$$

Each subbasin is associated with a distinct weight function, w_k, given by the product of the subbasin's areal fractions for soil type and land use associated with the HRU. This approach to representing spatial heterogeneity within subbasins was coded as program SWBAVG.

Conceptual Models for Specifying Conditions for MODFLOW's Solution

We wrote the MODSWB (soil water balance) package for MODFLOW to use results simulated by SWAT and combined by SWBAVG to specify conditions for the stream-aquifer solution in each time step. These conditions include tributary flow to the Republican River, aquifer recharge, surface and ground water diversions, and evapotranspiration from shallow ground water. For each subbasin, the watershed simulation results are converted from depths to flow rates that are to be distributed over the gridded aquifer domain according to Equation 6 for aquifer time step Δt and land surface area, f_iA.

Tributary Flow, Recharge, and Evaporation

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

$$Q_{trib} = (d_{sro} + d_{lat}) f_{con} A / c\Delta t \tag{9}$$

Overall, the watershed fraction contributing runoff directly to streams is estimated to be 0.98, based on USGS streamflow data reports. The remaining noncontributing component of the watershed drains to ponds, from which water may overflow or seep to streams.

Percolation from the soil profile, d_{perc}, and transmission losses along a subbasin's ephemeral flowpaths, d_{xm}, both contribute to recharge for the fraction of the subbasin underlain by an aquifer, f_{aqf}. Pond seepage, d_{psep}, is assumed to flow to the aquifer from the noncontributing fraction, $(1-f_{con})$, of each subbasin. This conceptual model for recharge is expressed as

$$Q_{rech} = [(d_{perc} + d_{xm})\, f_{aqf} + d_{psep}\, (1 - f_{con})]\, A/c\Delta t \qquad (10)$$

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

Evaporation, d_{et}, shown in the soil water balance Equation 5, is supplied in part by shallow ground water, denoted $d_{et\text{-}gw}$. MODFLOW represents evapotranspiration from shallow ground water as a linear function of depth to ground water, with a maximum corresponding to ground water at the land surface and a minimum of zero corresponding to a specified extinction depth. The maximum is represented by potential evaporation, which is converted to a flow rate over the area of each active grid cell for MODFLOW's evaporation package.

Irrigation Water Use

Annual appropriations are specified as flow rates for each ground water right, q_{gk}, by MODFLOW's WELL package, and for each surface water diversion, q_{sk}, by an analogous package, MODSRF, which we wrote to represent appropriations for streamflow diversions. Total annual appropriations for irrigation are denoted by the sum over both appropriation sources,

$$Q_{app} = \Sigma q_{gk} + \Sigma q_{sk} \qquad (11)$$

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. On the other hand, if only a total water use estimate, Q_{irr}, is given, water use by individual points of diversion can be approximated by multiplying all appropriations by a common scaling factor, given by $s = Q_{irr}/Q_{app}$. That is, multiplying Equation 11 by s gives

$$Q_{irr} = sQ_{app} = s(\Sigma q_{gk} + \Sigma q_{sk}) = \Sigma s q_{gk} + \Sigma s q_{sk} \qquad (12)$$

In Equation 12, the normalized spatial distribution of appropriations is used to approximate the one for water use in the absence of complete information regarding water use by individual water rights.

Irrigation demand was simulated in SWAT on a daily basis, summarized for monthly time steps Δt, and averaged over the 18 HRUs for each subbasin by Equation 8 to give the average depth $d_{irr}f_{irr}$. The average irrigated area fraction of the basin was $f_{irr} \approx 0.04$ for the years 1977 through 1994. The flow rate corresponding to this monthly demand is $Q_{irr} = d_{irr}f_{irr}A/c\Delta t$ from Equation 6. 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 12.

Water Use and Precipitation

National Weather Service (NWS) observations were available for daily precipitation at nine locations within or nearby the watershed, and for minimum and maximum daily temperature at four locations, including a primary station at Concordia. We chose to associate each subbasin with precipitation and temperature data for a neighboring NWS station rather than with a spatial average taken over measurements from neighboring stations. Observations from neighboring stations often have noncoincident daily temporal sequences of precipitation, particularly from localized convective storms that occur during the growing season. Averages of such sequences may artificially decrease rainfall rates and increase frequency, which may decrease simulated runoff and increase simulated infiltration (Koelliker 1997).

DWR provided data describing individual water rights from 1945 to the present for both ground and surface water sources, including date of appropriation, annual appropriated quantity (volume of water), pumping rate, type of use, and irrigated area. DWR also provided reports of annual water use for 1980 through 1993, which included reported depth to water for many of the irrigation wells. Data from individual reports were compiled to determine annual irrigation water use, $Q_{irr}\Delta t$, and area irrigated, A_{irr}, for both surface and ground water rights in each of these years. Annual irrigation depth was estimated from these by $d_{irr} = Q_{irr}\Delta t/A_{irr}$. These depths were compared with NWS precipitation for the months of May through August, when most irrigation is applied. Depth of irrigation, d_{irr} (m), from both surface and ground water sources was represented satisfactorily by

$$d_{irr} = a \exp(bp) \qquad (13)$$

where p = May through August precipitation (m). For the station at Concordia, coefficients are a = 0.72 and b = −2.91 ($r^2 = 0.86$, d.f. = 13, s.e. = 0.046 m). This relationship was examined for sensitivity to both irrigation source and precipitation station. Irrigation depths for surface and ground water sources showed small differences for 1980 through 1993 (mean difference = 0.01 m, standard deviation = 0.046 m). Comparing precipitation data sources, coefficients for Equation 13 based on NWS data from Clifton and Clay Center differed only slightly from those for Concordia (Figure 1). The small sensitivity to these factors showed that Equation 13 could satisfactorily represent both ground and surface water sources over the entire study area. Equation 13 was useful for estimating irrigation water use in years when individual use reports were not available.

Model Calibration and Verification

Our objective was to calibrate the watershed model for exploratory investigation of water management of drought conditions with greater attention paid to simulating dry periods and less to flood conditions. For this purpose we used reconnaissance-grade calibration instead of more rigorous optimization techniques.

Calibration targets for the model include measured stream yield from USGS gauging stations and alluvial ground water levels and water use from DWR reports. We used a split-sample approach: measurements from the years 1977 through 1990 were designated for calibration, and those from 1991 through 1994 for verification. Parameters were adjusted by trial and error to reduce mean and standard deviations of residuals, i.e., the differences between simulated and measured values. We used available data for stream yield measurements from USGS gauging stations, and data from DWR for ground water elevations and water use in the alluvial valley. The resulting simulation model for the period 1977 through 1994 is referred to as the base case.

Stream Yield and Calibration of Runoff

Runoff is simulated by SWAT on a daily basis using the NRCS curve number procedure. Cumulative stream yield, based on USGS streamflow measurements at Concordia and Clay Center for 1977 through 1990, was used as a calibration target to determine an initial value for the NRCS curve number, cn = 78. Figure 3 compares simulated monthly streamflow for the years 1977 through 1994 at Clay Center, denoted Q_b, with measured streamflow, Q, on logarithmic axes. The results were fitted to the equation $Q_b = Q^{0.98}$, with $r^2 = 0.85$, the coefficent of determination. The residual mean is e = –2.8 m^3/s with little deviation in trend; and standard deviation s = 13.8 m^3/s. Figure 4 compares simulated and measured yield for drought years 1988 through 1991, and shows that low flows, our target of interest, are matched satisfactorily. For this drought period, monthly average streamflow at Clay Center was less than the minimum desired streamflow (MDS) for 17 of the 48 months. Simulated streamflow for the base case was below the MDS for 16 of the months; of these, 13 were coincident with measured flows below the MDS.

Ground Water Levels and Calibration of Aquifer Parameters

Many of the water use reports to DWR included depth to water (dtw) measurements taken predominantly during the months of December through March in years 1981 through 1993. We also measured water levels of 80 wells in November 1994. Total measurement error components, in decreasing order of estimated magnitude, included: land surface elevation taken from USGS 7.5 min maps based on approximate well locations, casing height, which was not known for measurements from DWR reports, and depth to water.

In a previous study, Fader (1968) conducted step drawdown pump tests in the alluvial valley along the Republican River reach from the Nebraska-Kansas border to Concordia; 18 were in Cloud County, which includes Concordia at the upstream end of our study area. Using the Theis equation (1935), Fader determined aquifer parameters corresponding to a specific yield $S_y = 0.2$ and a mean hydraulic conductivity K = 129 m/day (standard deviation s = 61 m/day, n = 18). These values for K and S_y were used as initial estimates in calibration runs under both steady-state conditions, for which the transient term $S_y dh/dt$ vanishes, and transient conditions. Measured ground water levels for 1980 through 1990 from DWR were used as calibration targets. Because we found little improvement in water level residuals by varying K and S_y, the values from Fader's study were accepted for our model. Figure 5 shows the mean and standard deviation of residual error and the corresponding number of observations for the years 1980 through 1994, which includes verification data for the years 1991 through 1994. The low standard deviation in 1994 is attributed to smaller errors in our field measurements, which, unlike the DWR reports, considered casing height.

Figure 6 compares simulated heads at grid cell (9,30) with a series of monthly water level measurements taken from the 1991–1994 period at a well within 800 m from the river and approximately 2 km south of Clifton, Kansas (Taddiken 1994). Total measurement error (indicated by error bars in Figure 6) was estimated to be on the order of ±1 m, due primarily to uncertainty in

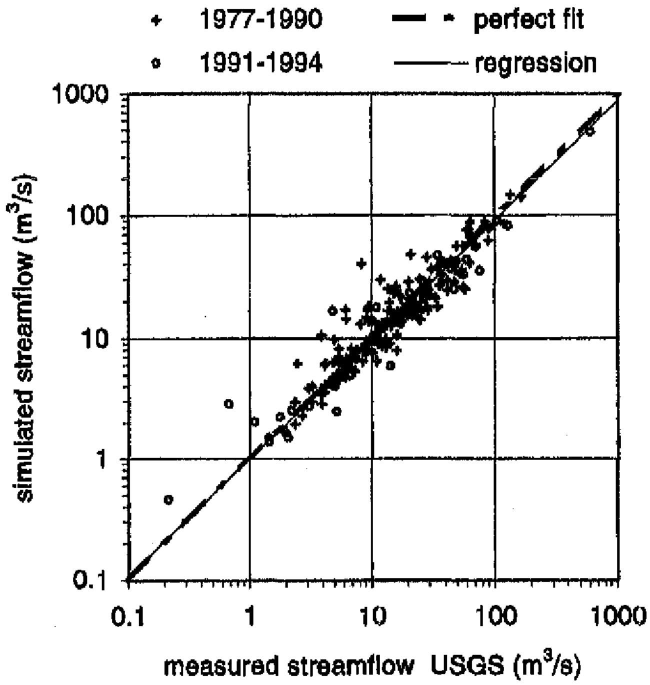

Figure 3. Comparison of simulated and measured monthly streamflow at Clay Center for both calibration period (1977–1990) and verification period (1991–1994).

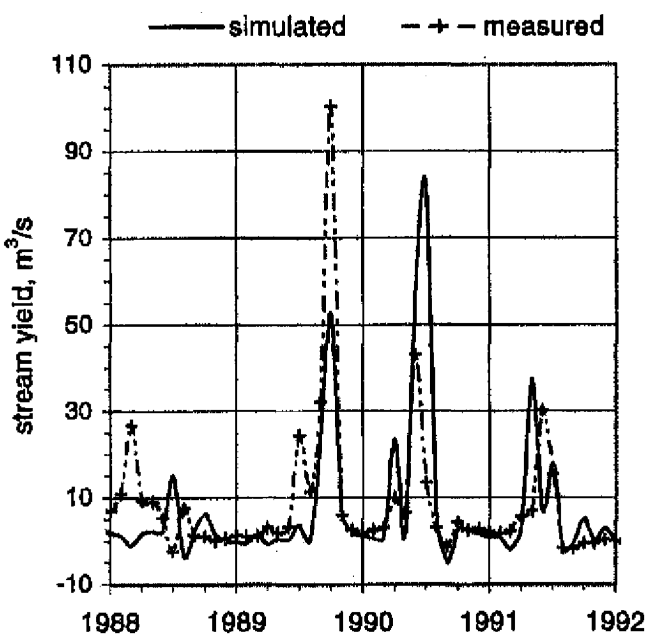

Figure 4. Simulated and measured stream yield for drought period 1988–1991.

land surface elevation. Taddiken's measurements spanned drought and flood conditions, and show that the response to the 1993 flood is simulated satisfactorily.

Water Use and Calibration of Irrigation Parameters

Annual irrigation depth based on water use data from DWR was used as a calibration target to determine parameters for a modified version of SWAT's daily irrigation model. Key parameters for this

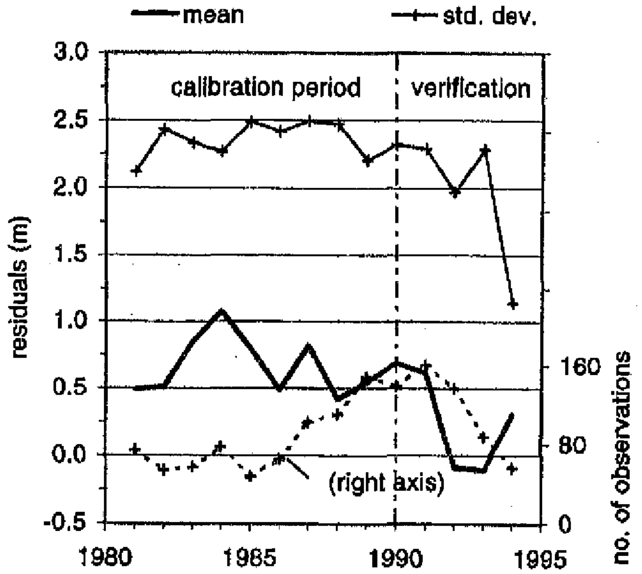

Figure 5. Errors in simulated water levels for base case, 1981–1994, showing number of residuals, their means and standard deviations (m) in each year.

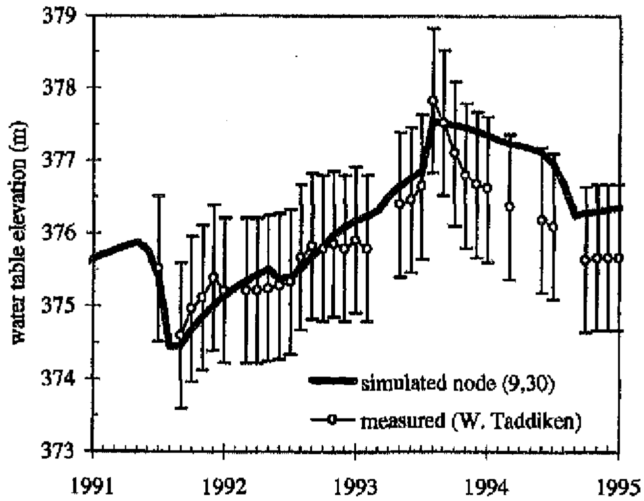

Figure 6. Simulated water table elevation for the base case at grid cell (9,30) is compared with water levels measured monthly for years 1991–1994 at a well (Taddiken) located within the grid cell, shown with estimated error s = ± 1 m.

model included a threshold to trigger irrigation based on soil water content as a fraction of field capacity (0.70) and maximum daily applied irrigation depth (12.7 mm). Sophocleous et al. (1997a) present details of this calibration.

Irrigation simulated by SWAT controls monthly pumping rates of surface and ground water diversions in MODFLOW using Equations 6 and 12 . For the base case, simulated annual water use, Q_u, is compared with annual use based on DWR data, Q_d, for the years 1980 through 1993 by the linear regression $Q_u = 0.94Q_d$, with $r^2 = 0.99$.

Results: Stream Yield Components and Comparison with Adjacent Watersheds

Stream yield components for the base case, expressed as averages over the simulation period 1977 through 1994, are tributary inflow (7.51 m^3/s), surface water diversions (0.075 m^3/s), and base flow (–0.044 m^3/s). For comparison, flow rates for aquifer components are recharge (0.528 m^3/s) and ground water pumping (0.733 m^3/s). Compared to tributary flow, the base flow component is relatively insignificant and slightly negative. Stream yield and its base flow component are shown in Figure 7, which compares the base case with sensitivity cases discussed later.

Because the effect of water use on base flow is one of the key interests in this model's application, one of its main weaknesses is the lack of supporting data such as tributary flow measurements to calibrate and verify the base flow contribution to stream yield. Lacking this, we look for indirect support of the model's results. First, the calibrated value for the NRCS curve number of 78 is reasonable (Koelliker 1997). Second, adjacent watersheds for Mill and Chapman Creeks (Figure 1) are both gauged; streamflow from these watersheds can be reasonably expected to contain only runoff with negligible base flow components, since no significant aquifer exists there, and to have runoff characteristics similar to those of the Republican River watershed to the extent that the watersheds are similar with respect to climate, land use, soils, and physiography.

Based on these assumptions, we compared simulated tributary flow to the Republican River with runoff from Mill Creek, denoted V_M, and Chapman Creek, V_C, scaled with watershed area. For Mill Creek, scaled runoff is given by $V_{MS} = c(A_R/A_M)^bV_M$; and for Chapman Creek, by $V_{CS} = c(A_R/A_C)^bV_C$. Area for the Republican River watershed is $A_R = 2569$ km^2; for Mill Creek, $A_M = 891$ km^2; and for Chapman Creek, $A_C = 777$ km^2, based on USGS streamflow data reports. Assuming linear scaling (b = 1), the coefficient, c, was adjusted to a value of 0.8 to approximately match Mill and Chapman Creek cumulative streamflows to the cumulative tributary flow simulated for the Republican River. The difference (1–c) represents discrepancies in the aforementioned assumptions, streamflow measurements, and model error. Alternatively, we obtain about the same match with coefficient c = 1 and exponent b = 0.8, which is shown in Figure 8. As a point of interest, Goodrich et al. (1997) found, for a semiarid watershed, that mean annual runoff scaled linearly with watershed area up to about 10^6 m^2, above which runoff scaled with an exponent b = 0.82. This nonlinearity in watershed response was attributed to partial storm area coverage and ephemeral channel transmission losses.

Figure 8 shows that only during the flood events of 1987 and 1993 do the cumulative scaled streamflows for Mill and Chapman Creeks diverge significantly from the cumulative yield for the Republican River. This comparison is consistent with results for the base case shown in Figure 7, indicating that tributary flow constitutes all but a small fraction of stream yield in the Republican River watershed between Concordia and Clay Center.

Sensitivity Analysis of Model Parameters and Water Use

Stream yield is sensitive to certain key parameters through their effects on tributary flow or base flow. Figure 7 shows cumulative stream yield and base flow for the base case over the simulation period and compares the base case with sensitivity cases in which only one parameter is varied, holding all other conditions of the sim-

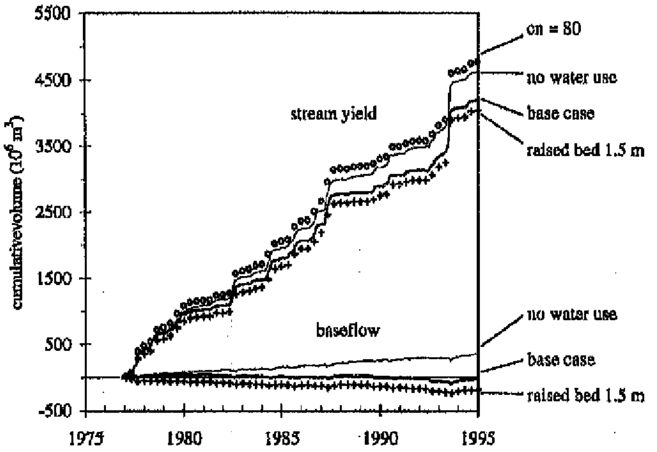

Figure 7. Cumulative base flow and stream yield for base case, with comparison to sensitivity cases for elimination of all water use, increase in runoff curve number from 78 to 80, and increase in streambed elevation by 1.5 m.

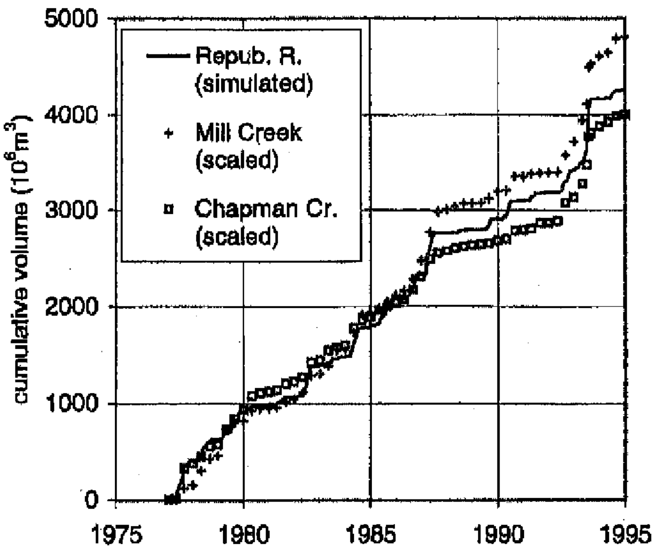

Figure 8. Comparison of simulated tributary inflow to the Republican River between Concordia and Clay Center with streamflows from the adjacent Mill and Chapman Creek watersheds (shown in Figure 1) scaled from their respective areas to that of the Lower Republican River Basin.

ulation constant. Effects of sensitivity cases are discussed in terms of average flow rates for the simulation period.

Base flow is presumed to be sensitive to the hydraulic gradient across the streambed (Equation 2). Streambed elevations were read with an estimated error of 1.5 m from USGS 7.5 min maps with 3 m contours. Raising the streambed elevation uniformly by 1.5 m affects stream yield through base flow, which is reduced by 0.28 m^3/s; lowering the streambed elevation 1.5 m increases base flow by the same rate. This indicates that model error in streambed elevation is unlikely to change the relative magnitudes of base flow and tributary flow significantly.

Water use reduces stream yield through surface water diversions and base flow. The elimination of ground water pumping, $dQ_g = -0.733$ m^3/s, produces an increase in base flow, $dQ_b = 0.679$ m^3/s. Their ratio, $dQ_b/dQ_g = -0.926$, shows a strong sensitivity of base flow to ground water pumping (i.e., almost all water pumped from the aquifer is balanced by a reduction in base flow, and consequently in stream yield). With no pumping, simulated base flow represents 7.8% of stream yield.

The strong effect of ground water pumping on base flow is attributed to the impact of pumping on the hydraulic gradient across the streambed (Equation 2). This is supported by the significant increase in simulated ground water elevation due to elimination of ground water pumping. Compared with the base case in Figure 5, the mean residual errors in simulated ground water levels for this case are higher by more than 0.5 m for all years and up to 0.9 m in drought years.

Stream yield was calibrated by adjusting runoff through the NRCS curve number's initial value. By increasing this initial value from cn = 78 to 80, tributary flow is increased by 1.04 m^3/s. The increased runoff reduces ground water recharge and consequently base flow by 0.046 m^3/s; and stream yield is increased by 1 m^3/s. Comparison of the sensitivity cases in Figure 7 shows that increasing the NRCS curve number's initial value by two points has a greater effect on stream yield than the complete elimination of all water use. This highlights the hazards of errors in a parameter-rich model such as this.

Overall, simulation results for stream yield components showed relatively strong sensitivity to watershed parameters, including the NRCS curve number for runoff, soil properties, especially available water capacity, and land-use characteristics, particularly irrigated area and water use. Results showed relatively weak sensitivity to aquifer parameters of hydraulic conductivity and specific yield, and to stream parameters such as streambed hydraulic conductivity. An exception was the relatively high sensitivity of base flow to streambed elevation. Details of the sensitivity analysis are given in Sophocleous et al. (1997a).

Effect of Water Use Reduction on Stream Yield During Droughts

Various alternatives for administrative management of water use were constructed that depend on criteria such as seniority of water rights (i.e., year of appropriation), distance from the river to points of diversion, and streamflow conditions. Alternatives include, for example, the option to curtail all irrigation water use appropriated after 1984 whose points of diversion lie within 800 m of the Republican River. Management scenarios were simulated and compared to a baseline scenario, which differed from our base case in the assumption that appropriations for ground and surface water rights were fixed at their 1994 values. Management alternatives were implemented as a component of the MODSWB package. Details of the implementation of these scenarios and their effects on irrigation water use and stream yield are given in Sophocleous et al. (1997a).

An upper bound on the simulated effects of restrictions on water use are shown in the preceding sensitivity case that completely eliminates water use. Even this drastic measure does not satisfy MDS at Clay Center. For drought years 1988 through 1991, the number of months that simulated streamflow falls below the MDS is reduced from 16 for the base case to 13; the number of coincident months (those that measurements and simulations agree that streamflow was below the MDS) is reduced from 13 to 10. It follows from this sensitivity case that less drastic, but more realistic, management alternatives for reducing irrigation water use are unlikely to increase stream yield sufficiently to meet MDS standards.

Conclusions and Recommendations

We developed a watershed model code that incorporates modified versions of two widely used programs, SWAT and MODFLOW. We combined these with additional code to represent the effects of spatial heterogeneity on a watershed's hydrology, provide an interface between the different temporal and spatial scales represented by SWAT and MODFLOW, and specify conditions for solution of ground water movement and stream-aquifer interaction by MODFLOW in terms of watershed hydrology simulated by SWAT. The combined watershed model presented here can better represent the watershed's physical processes than either SWAT or MODFLOW by itself.

The model code was used to construct calibrated models of basins in Kansas along the Republican River, reported here, and Rattlesnake Creek (Sophocleous et al. 1999), and to help examine interrelated watershed issues regarding streamflow, ground water, and water use for irrigation. Eighteen-year simulations of the Lower Republican River Basin were run primarily to examine the effects on stream yield of administrative restrictions on water use during droughts (Sophocleous et al. 1997a). These simulations show that average tributary flow over this time period between Concordia and Clay Center is a strongly dominant component of stream yield, and base flow is relatively insignificant. Only during drought periods is base flow a relatively significant component of stream yield, although it is also typically small compared with minimum desirable streamflow standards for the Republican River. Sensitivity analysis has shown base flow to be strongly sensitive to ground water pumping. Although management alternatives to reduce irrigation water use have shown a corresponding increase in base flow, the resulting increase in stream yield has not been sufficient to restore minimum desirable streamflows. These appear unlikely to be met solely by restricting irrigation water use, according to our model results.

Further efforts to improve the model's predictive capability might be directed toward both the forward and inverse models, and the data base. The forward model could be improved by refining the conceptual models used to simulate hydrologic processes in the watershed and stream-aquifer system, and to represent spatial heterogeneity in the watershed. The inverse model could be improved by a more systematic and thorough calibration of model parameters and verification of model results, such as the work applied to the Rattlesnake Creek model (Sophocleous et al. 1999). For the model's application to the Republican River watershed, however, its predictive capability is limited by the lack of data to calibrate and verify its simulation of tributary flow. These data could be provided by daily streamflow measurements of the significant tributaries to the Republican River between Concordia and Clay Center.

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