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LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART II: MODEL APPLICATION[1]

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ABSTRACT: This paper describes the application of a river basin scale hydrologic model (described in Part I) to Richland and Chambers Creeks watershed (RC watershed) in upper Trinity River basin in Texas. The inputs to the model were accumulated from hydrographic and geographic databases and maps using a raster-based GIS. Available weather data from 12 weather stations in and around the watershed and stream flow data from two USGS stream gauge station for the period 1965 to 1984 were used in the flow calibration and validation. Sediment calibration was carried out for the period 1988 through 1994 using the 1994 sediment survey data from the Richland-Chambers lake. Sediment validation was conducted on a subwatershed (Mill Creek watershed) situated on Chambers Creek of the RC watershed. The model was evaluated by well established statistical and visual methods and was found to explain at least 84 percent and 65 percent of the variability in the observed stream flow data for the calibration and validation periods, respectively. In addition, the model predicted the accumulated sediment load within 2 percent and 9 percent from the observed data for the RC watershed and Mill Creek watershed, respectively.
(KEY TERMS: simulation; GIS interface; watershed modeling; sedimentation; nonpoint source pollution.)

INTRODUCTION

The first part of this work (Arnold *et al.*, 1998), explains the formulation of a distributed parameter, continuous time, river basin-scale model called SWAT. In this part we briefly describe the GIS interface for that model that was developed to facilitate the aggregation of required input data for simulating large-scale watersheds. Using this interface, the surface hydrology, erosion and sediment transport components of the model were tested and evaluated by simulating the hydrology and soil erosion in Richland and Chambers creeks watershed (RC watershed) of the Trinity River basin in Texas. In addition to analyzing the entire watershed (5.08×10^5 ha), we also analyzed a subwatershed within it that had more detailed sediment survey data.

Geographic Information Systems (GIS) have been playing an important role in natural resources modeling and proving to be an effective tool for non-point source (NPS) pollution models (Pelletier, 1985; Hession and Shanholtz, 1988; Srinivasan and Arnold, 1994). A continuous time, distributed parameter model like SWAT overcomes some of the limitations of single-event models. SWAT considers a basin or watershed divided into subbasins based on topography, soil, and land use and thus preserves the spatially distributed parameters of the entire basin and homogeneous characteristics within a subbasin. But manual collection of inputs for such models is often difficult and tedious due to the level of aggregation and the nature of spatial distribution. For this a GIS has been proven to be an excellent tool to aggregate and organize input data for distributed parameter hydrologic/water quality models (Tim *et al.*, 1991; Rewerts and Engel, 1991; Srinivasan and Engel, 1994; Rosenthal *et al.*, 1995).

The GIS tool chosen was the Geographical Resources Analysis Support System (GRASS) developed by Environmental Division of the U.S. Army Construction Engineering Research Laboratory (U.S. Army-CERL) (Shapiro *et al.*, 1992). This is a public domain raster based GIS, that is being used by major federal agencies like the USDA-NRCS and other research communities for their work. The SWAT/GRASS interface (Srinivasan and Arnold, 1994) consists of three modules: (a) project manager, (b) input

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extractor and aggregator, and (c) input editor. The project manager interacts with the user to collect, prepare, edit, and store the basin and subbasin information to be formatted into SWAT input files. The input extractor and aggregator uses a variety of hydrologic tools (Srinivasan and Arnold, 1994) to derive SWAT input information from GRASS raster/site map layers such as basin boundary map with subbasin delineation, digital elevation map (DEM), soils map, land use/land cover map and weather generator/station location map. In addition the reservoirs, inflow, pond and lake data are collected directly from the user. The input editor is used to either view, edit or check the data collected from the previous phase, which are arranged in different data forms. Rosenthal *et al.* (1995) used this interface to aggregate SWAT input data for the Lower Colorado River basin of Texas and found that the SWAT/GRASS interface reduced the data collection and manipulation time by several folds, and allowed the user to modify and analyze various alternative management practices rather easily. Further details about the interface are given by Srinivasan and Arnold (1994).

SWAT generates a variety of output files for daily, monthly or annual time intervals (Arnold *et al.*, 1993). A generic visualization tool was developed and integrated as a part of GRASS to visualize the spatial and temporal output generated by SWAT. The capabilities of this visualization tool include bar chart, pie chart, single and double axis line graphs, scatter plot, and mixed graph (scatter, line and bar). In addition it can generate a model-output layer, import other data such as measured stream flow data for further analysis, and perform linear regression analysis.

MATERIALS AND METHODS

Description of Study Area

The GIS-integrated SWAT model was applied to the RC watershed (Figure 1). The watershed is situated in North-Central Texas and encompasses the drainage areas of Richland and Chambers creeks, tributaries of the upper Trinity River. The watershed contains two reservoirs (Bardwell and Navarro Mills) and about 300 ponds, small reservoirs and NRCS flood prevention structures, providing an opportunity to model ponds and reservoirs. In addition to analyzing the entire RC watershed, we chose to model a subwatershed of RC watershed, Mill Creek watershed (Figure 2), having a drainage area of 2.83×10^4 ha (109 sq. miles).

Data Sources and Description

Soils and land use GIS layers were obtained from the USDA-NRCS computer based mapping system (CBMS). The CBMS data for the study area was developed by digitizing 1:24,000 scale soil maps to create a raster layer consisting of 6.25 hectare cells (250 x 250 m). The NRCS 1:24,000 scale land use and land cover map was used in this study. This is the most detailed land use and land cover map available and is available in CBMS format, which is the same format as that of CBMS soil maps. The digital elevation models (DEM) of the study area were obtained from the U.S. Geological Survey. A1:250,000 (100 x 100 m) DEM was used for RC watershed and 1:24,000 (30 x 30 m) DEM was used for Mill Creek. The maps were traced, scanned and then imported into GRASS where the raster digital elevation map was created. The RC watershed and subwatershed boundaries were then delineated using the GRASS watershed command, r.watershed, creating a watershed and subwatershed map layer with 20 subwatersheds. Similarly, 23 subwatersheds were delineated for the Mill Creek watershed. The data for ponds and reservoirs were obtained from USDA-NRCS and Texas Natural Resources Conservation Commission (TNRCC) records. Measured daily rainfall and temperatures for 12 weather stations in and round the RC watershed were obtained from the USDA-NRCS climatological database. For flow calibration and validation, two USGS stream gages, 08063500 (Station 1) and 08064500 (Station 2) were used (Figure 1). Both weather and stream gage data for the period 1965 through 1984 were used in this study. The reservoir storage and release data for the Bardwell and Navarro Mills reservoirs were obtained from U. S. Army Corps of Engineers (COE) and USGS.

Sediment Survey

Impoundment of water in RC reservoir began in 1988 and a sediment survey was conducted during December 1994. The sediment surveys in Mill Creek watershed were conducted at a USDA-NRCS flood prevention structure during October 1964, September 1968, and June 1974. The RC reservoir sediment survey results were used for calibration. The sediment survey results at the Mill Creek watershed were used for validation. During the RC reservoir sediment survey, only the sediment volume was estimated. Welborn (1967) suggested that the specific weight of Trinity River submerged sediments will range from 720 kg/m^3 (45 lb/ft^3) to 1,200 kg/m^3 (75 lb/ft^3) after 50 years of submergence. In this study we used 880

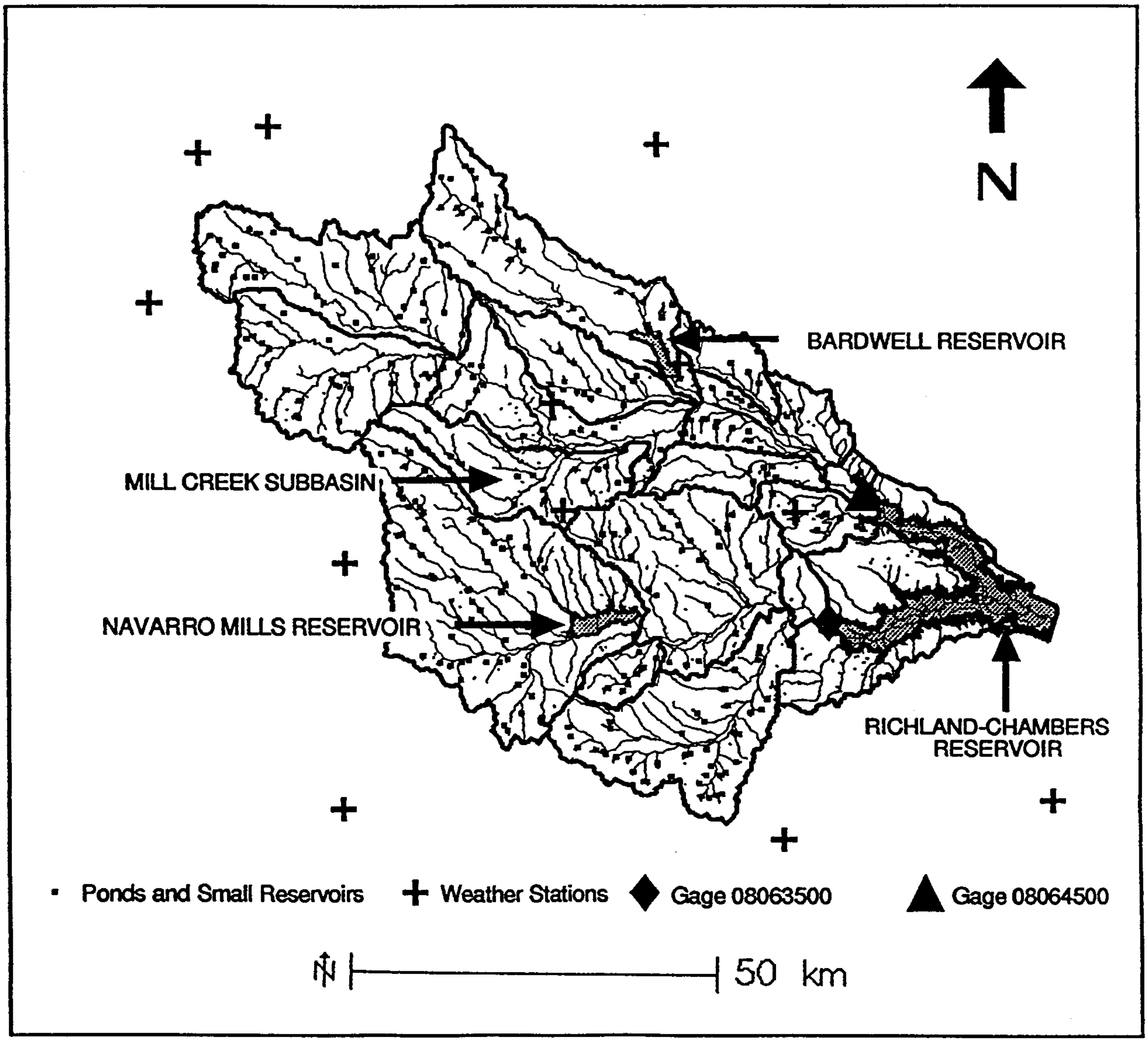

Figure 1. Map of Richland and Chambers Creeks Watershed.

kg/m³ (55 lb/ft³) as the specific weight of the submerged sediments in RC reservoir. The specific weight was multiplied by the sediment volume from the sediment survey to obtain sediment load in the reservoirs. Sediment volume and density were estimated during the sediment surveys conducted at the Mill Creek structure. The specific weight estimated for the submerged sediment at Mill Creek structure is 1009 kg/m³ (63 lb/ft³) and for aerated sediment it is 1440 kg/m³ (90 lb/ft³).

Model Setup

Required inputs for the basin and subbasins were extracted and the input files for SWAT were aggregated using the SWAT/GRASS interface. The basin configuration in SWAT can be made in two ways, namely the dominant approach and virtual basin approach. The two configurations are explained and analyzed by Mamillapalli *et al.* (1996). We used the virtual basin approach to model the study area. The input interface divided each subwatershed into a maximum of 30 subbasins, called the virtual basins. Each one of these virtual basins is assumed to have a homogeneous land use and soil. The determination of number of virtual basins was accomplished by: (1) creating a virtual basin for each land use that equaled or exceeded 5 percent of the area of the subbasin; and (2) creating a virtual basin for each soil type that equaled or exceeded 10 percent of the land uses selected in (1). The reservoir release volume cannot be simulated by SWAT because of its dependence

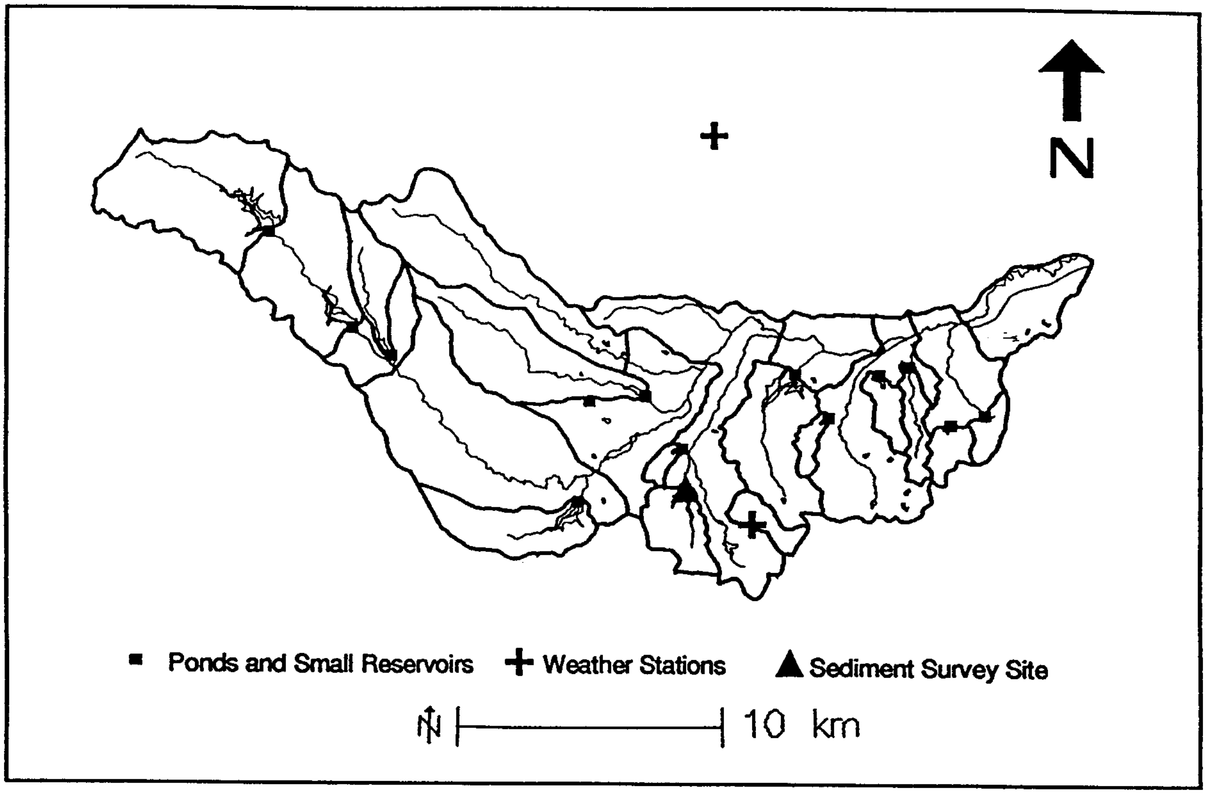

Figure 2. Map of Mill Creek Watershed.

on many factors other than hydrology. Therefore, the release rates from the Bardwell and Navarro Mills reservoirs were input directly into the model from the actual observed data. However the reservoir storage volumes were simulated by SWAT and were compared to the observed storage data.

Analysis

The flow calibration was conducted for the RC watershed for the period 1965 through 1969 and the calibrated parameters were used for the rest of the years for validation. Sediment calibration was conducted for the RC watershed for the period 1988 through 1994. For the MC watershed simulation, the calibrated parameters from RC watershed were used. For evaluating the stream flows predicted by the model during the calibration and validation periods, we used linear regression methods and also Nash-Suttcliffe simulation efficiency (Nash and Suttcliffe, 1970). Since, the observed sediment data were very sparse, statistical evaluation methods could not be used. Therefore, we used only visual methods for evaluation.

RESULTS AND DISCUSSION

Calibration

For the flow calibration, the runoff curve number and revap coefficients were adjusted to give good correspondence with the observed data. The runoff curve number was reduced by 10 percent from the default value for all basins, and the revap coefficient was set to 1.0 for all the basins. Figures 3a and 3b show the time series of observed and simulated monthly stream flow at Stations 1 and 2, respectively.

Figures 4a and 4b show the scattergram of observed and predicted monthly flow. The coefficient of determination (r^2) for the linear regression between the observed and simulated stream flow are 0.87 and 0.84, respectively for the two stations. The slopes of the regression lines are 1.14 and 1.19 and are marginally different from 1.0 at 95 percent confidence level. The Nash-Suttcliffe simulation efficiency at the two stream gage stations are 0.77 and 0.84. The statistical results of comparison of observed and simulated monthly stream flow during the calibration period can be found in Table 1. These results indicate that the model predicted the stream flow at these two gages satisfactorily.

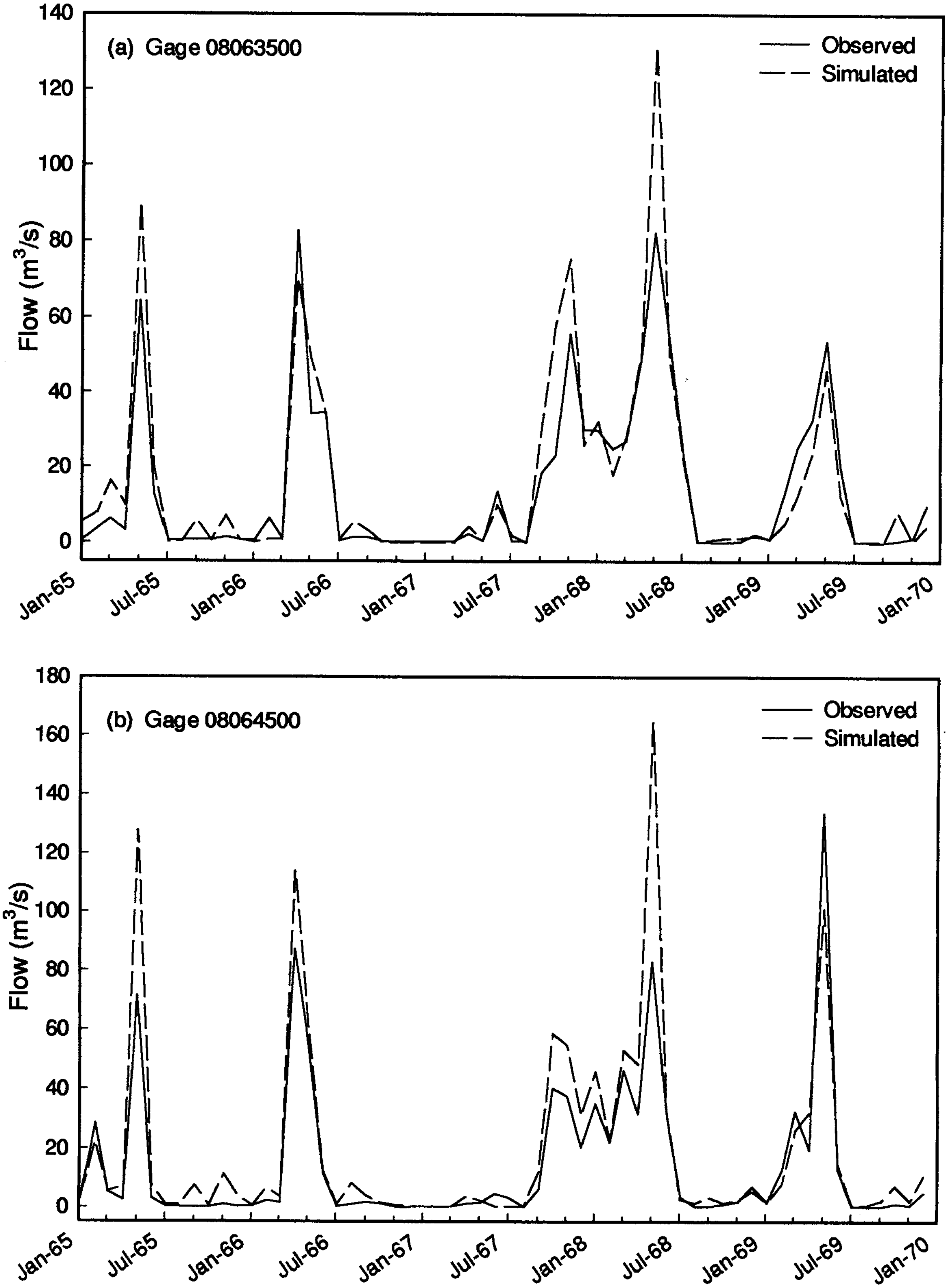

Figure 3. Time Series of Observed and Simulated Monthly Stream Flow Data During the Calibration Period (1965-1969); (a) Gage 08063500; (b) Gage 08064500.

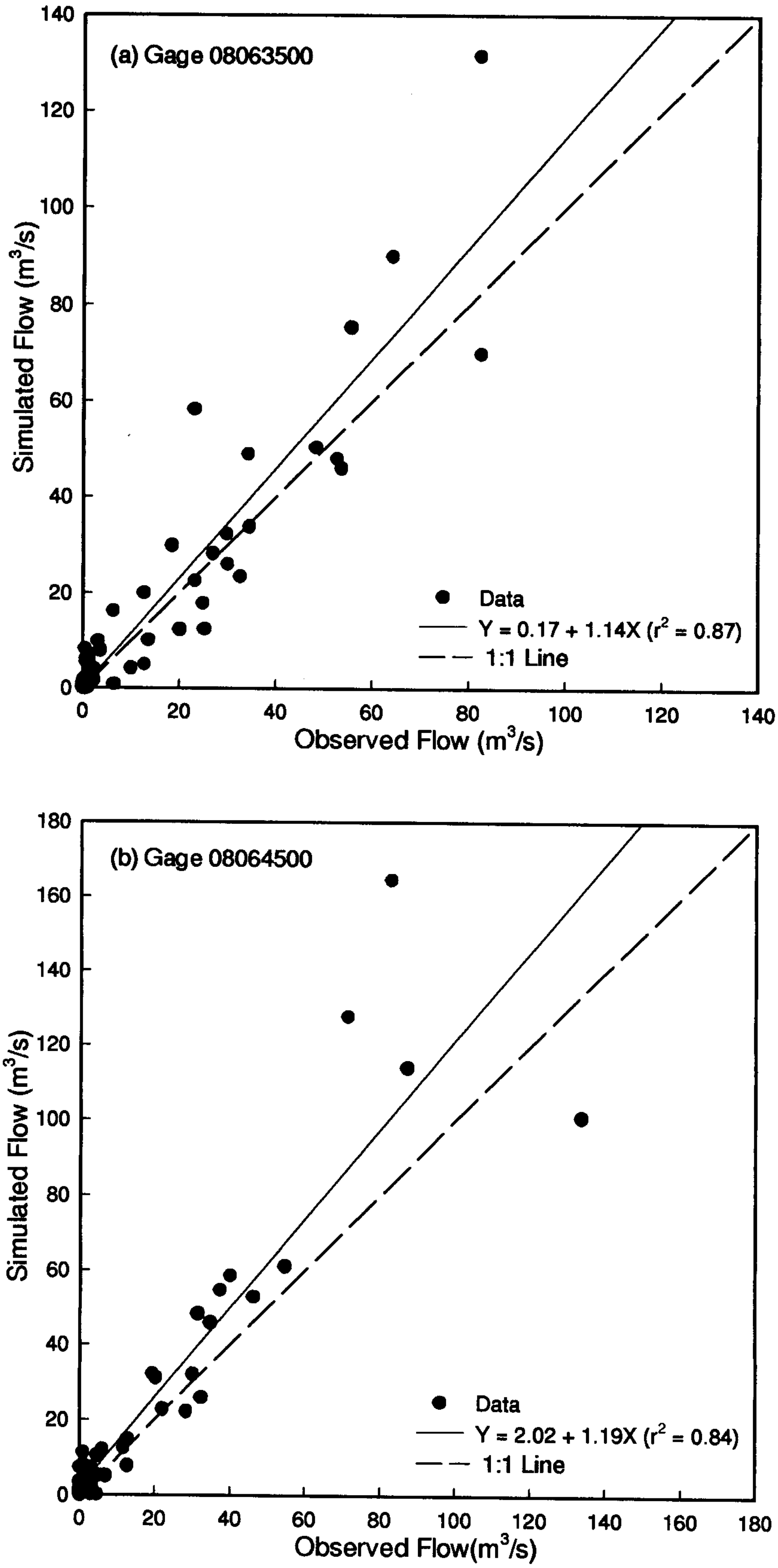

Figure 4. Scattergram of Observed and Simulated Monthly Stream Flow Data During the Calibration Period (1965-1969): (a) Gage 08063500; (b) Gage 08064500.

TABLE 1. Statistical Results from Comparison of Observed and Simulated Stream Flows.

Stream Gage	No. of Samples	r^2	a	b	t_a	t_b	COE
			Calibration Period				
08063500 (Station 1)	60	0.87	0.2	1.1	0.11	2.3	0.77
08064500 (Station 2)	60	0.84	2.0	1.2	1.00	2.7	0.84
			Validation Period				
08063500 (Station 1)	180	0.65	2.2	0.9	2.60	-1.8	0.52
08064500 (Station 2)	180	0.82	0.2	0.9	0.34	-4.3	0.82

a: Intercept of the regression.
b: Slope of the regression.
t_a: Student's 't' (t_{calc}) for H_0: a = 0.0.
t_b: t_{calc} for H_0: b = 1.0.
Confidence interval = 95 percent (therefore rejection region, $\alpha = 0.025$, -- two-tailed t-test)
$t_{0.975,59} = 2.00$ and $t_{0.975,159} = 1.97$ criteria for acceptance: if $|tcalc| \leq t_{0.975,n-1}$ accept H_0.

The period 1988 to 1994 was used for sediment calibration for the RC watershed. Parameters that had significant effect on sediment yield and delivery were adjusted until simulated sediment was nearly equal to the measured value. The resultant values for the adjusted parameters are: (1) USLE 'P' factor = 1.0, (2) exponential factor for sediment concentration (SPC) = 0.008, (3) exponential factor for stream power equation (SPE) = 1.0, and (4) peak rate function (PRF) = 1.0. The simulated sediment delivery to the RC reservoir is 38.7 x 10^6 Mg and the measured sediment was about 37.9 x 10^6 Mg.

Validation

Flow validation was conducted using the observed stream flow data from the two USGS stream gages for the period 1970 to 1984 (15 years). Figures 5a and 5b show the time series plot of monthly observed and simulated stream flow at stations 1 and 2, respectively. The figures show acceptable correspondence of simulated stream flows with the observed values. On analyzing the scattergram of observed and simulated monthly stream flow values (Figures 6a and 6b), the observed values have a strong linear relationship with the predicted results. The coefficient of determination of the linear regression between observed and simulated stream flow at the two stations are 0.65 and 0.82. The Nash-Suttcliffe simulation efficiencies at the two stations are 0.52 and 0.82. The statistical results of the stream flow comparison are summarized in Table 1.

The predictions at Station 2 (USGS gage 08064500) are satisfactory, but the predictions at Station 1 (USGS gage 08063500), though acceptable, are not as good as Station 2. The reasons for this could be localized spring/summer thunderstorms that did not occur over a major portion of a subwatershed, but occurred over the corresponding rain gage location. Looking at Figure 5a, such events can be spotted during the spring/summer periods of 1973, 1975, and 1981. This problem can be overcome by utilizing latest techniques like NEXRAD.

Sediment validation was conducted by estimating sediment loading at a USDA-NRCS flood water retarding structure in Mill Creek watershed. A ten year period (1965 to 1974) was chosen for validation. The calibrated erosion parameters from RC watershed were used here. There was no observed flow data available for MC watershed. Therefore, we compared only the sediment loads predicted by SWAT. Figure 7 shows the cumulative time series of monthly predicted sediment load and the sediment survey results for 1968 and 1975 at the NRCS structure. From the sediment survey the sediment load for the periods 1965 to 1968, and 1968 to 1975 were estimated as 29,000 and 14,000 Mg, respectively. The sediment load predicted by SWAT for the same periods are 25,000 and 14,000 Mg, respectively. It is to be noted that the sediment loading may be affected by the resolution of the DEM used. For the Richland-Chambers watershed sediment calibration we used a DEM with 100 m resolution. But due to the size of the Mill Creek watershed, we used a DEM with 30 m resolution. Considering the potential errors in measuring the volume of sediment deposited and the estimation of sediment specific weight, we conclude that the soil loss and sediment transportation simulated by SWAT for the Mill Creek watershed are acceptable and satisfactory.

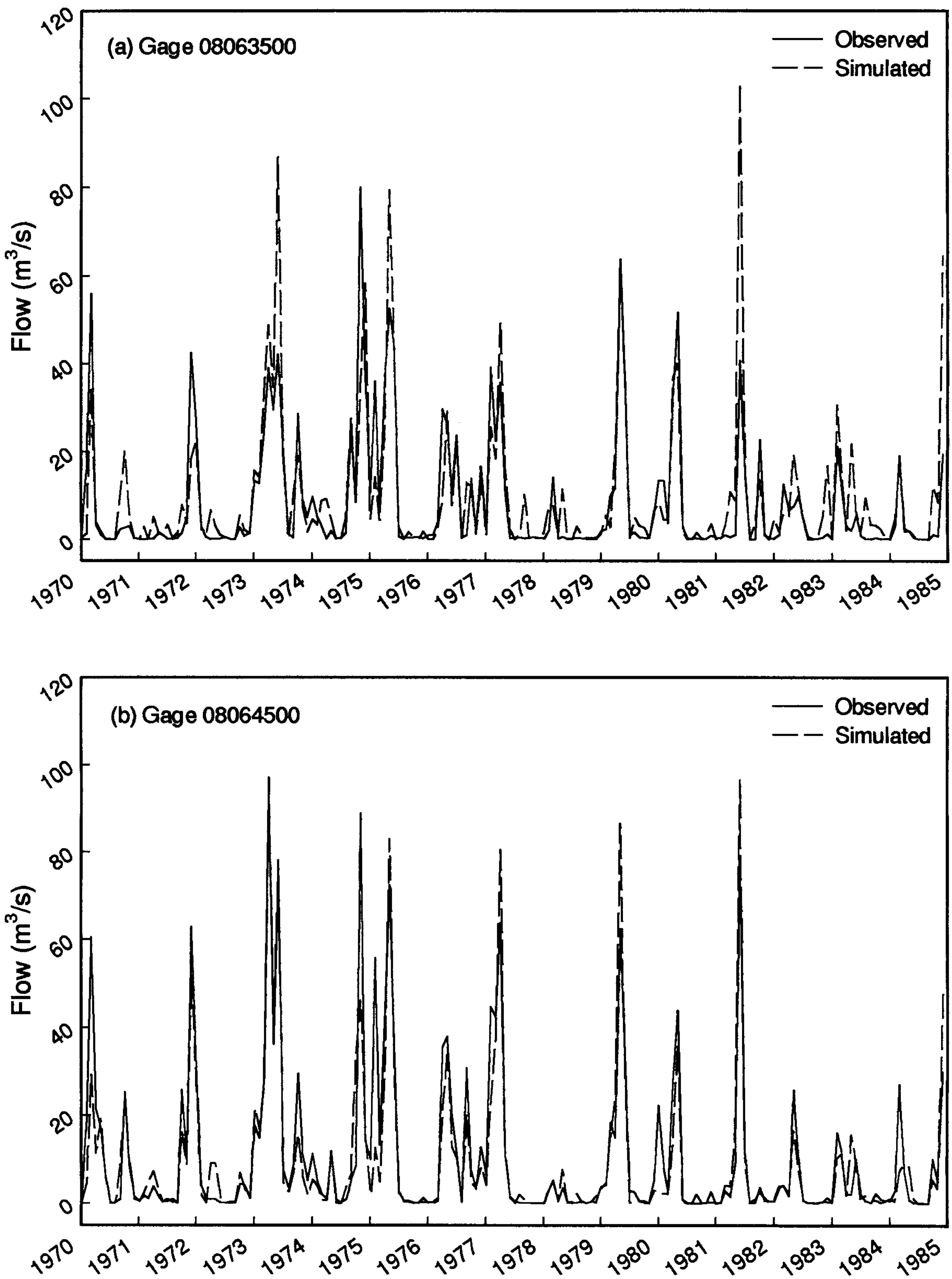

Figure 5. Time Series of Observed and Simulated Monthly Stream Flow Data During the Validation Period (1970-1984); (a) Gage 08063500; (b) Gage 08064500.

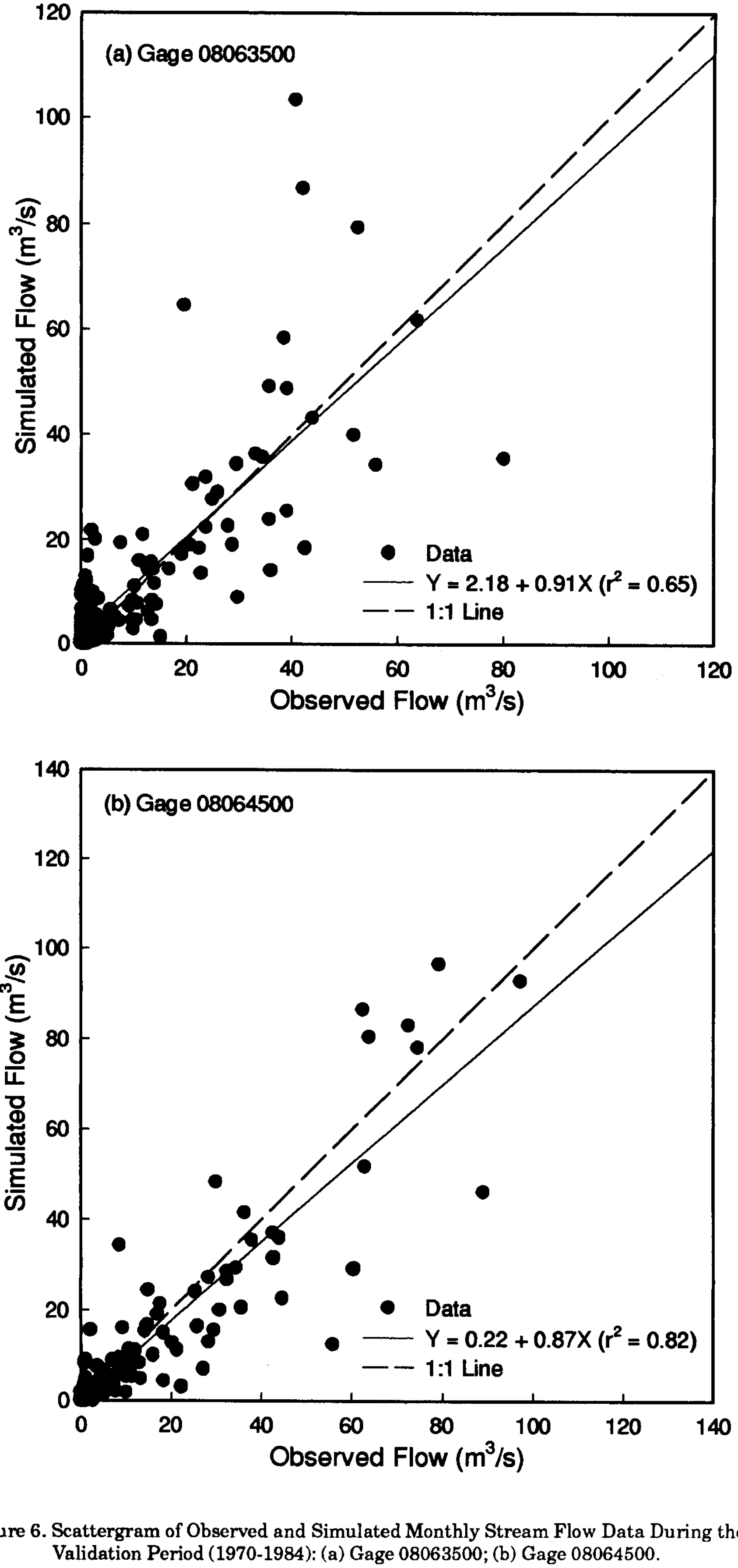

Figure 6. Scattergram of Observed and Simulated Monthly Stream Flow Data During the Validation Period (1970-1984): (a) Gage 08063500; (b) Gage 08064500.

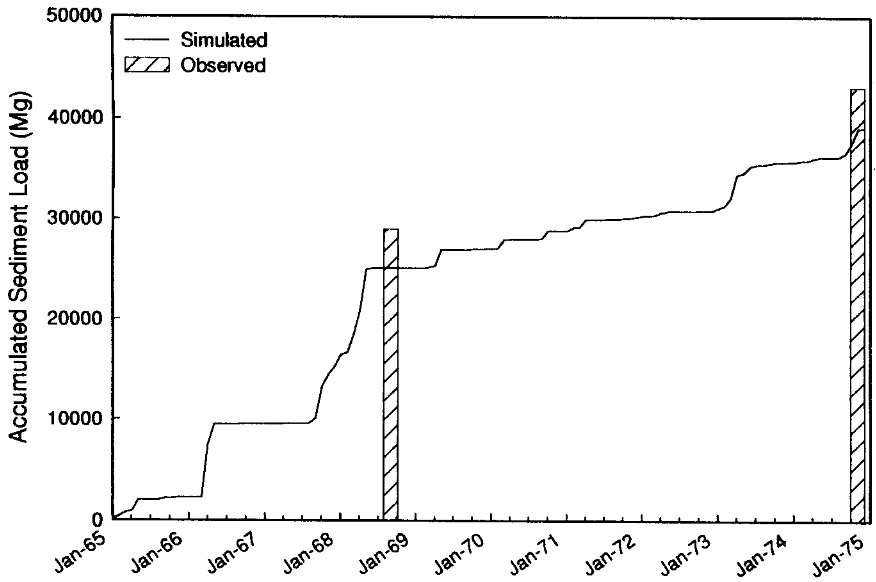

Figure 7. Observed and Simulated Accumulation of Sediment at the Flood-Retardation Structure in the Mill Creek Watershed.

SUMMARY AND CONCLUSIONS

In this second part of a two-part paper explaining a distributed parameter, continuous time, river basin-scale model, SWAT, we successfully used the model to simulate the hydrology, soil erosion, and sediment transport in the Richland-Chambers watershed of the Trinity river basin in Texas. A GIS interface was used to accumulate the necessary input data for the model. The model was calibrated for flow using five years (1965 to 1969) of stream flow data from two USGS stream gages. Sediment calibration was conducted by using the sediment survey results at the Richland-Chambers reservoir. The flow validation was conducted for the period 1970 to 1984 using the stream flow data from the two stream gages. The erosion component was validated by simulating soil erosion and sediment transport within a subwatershed of Richland-Chambers watershed (Mill Creek) using sediment survey results at a USDA-NRCS flood water retarding structure in the subwatershed.

The study demonstrates some of the major capabilities of the river-basin scale model, and also demonstrates that a GIS can be used to efficiently collect and manage input data for the SWAT model. The calibration conducted in this study was minimal and is justified considering the amount of input data fed into the model. In general, the monthly stream flow rates predicted by SWAT corresponded very well with the observed values. Nevertheless, the model overestimated stream flows in some years particularly during the spring/summer months. We conclude that the spatial variability of rainfall during the spring/summer months is the main cause for this. Efforts to incorporate the spatial variability of weather data is underway.

In addition to predicting stream flows satisfactorily, SWAT also simulated soil erosion and sediment transport within Richland-Chambers watershed satisfactorily. Using the weather generation capabilities of the model along with the calibrated parameters it can be used to analyze future 'what-if' scenarios, identify critical areas in the river basin, and recommend best management practices (BMPs) to reduce soil loss.

RECOMMENDATIONS AND FUTURE DIRECTIONS

Model Interface – The SWAT input interface is not limited to GRASS. A personal computer (PC) Windows(tm) interface has been developed in our lab. In addition, efforts are underway to develop ARC/INFO and ArcView GIS interface for SWAT.

Spatial Variability of Watershed Physical Parameters – Considering the spatial variability is one of the major strengths of the SWAT model. But the results of the model are sensitive to the level of detail of spatial scales and description of the input information. Arnold (1992) and Mamillapalli *et al.* (1996) presented some of the results of the preliminary work on the impact of lumping and optimal subbasin sizes.

Additional work is on going to develop general rules for watershed discretization and selection of spatial scales on input data.

Spatial Variability of Precipitation – One of the major limitations to large area hydrologic modeling is the spatial variability associated with precipitation. Weather generators can be used when measured data are unavailable. This is useful only if we are trying to analyze the relative hydrologic difference between different management systems. Weather generators are available for generating weather sequences at a point. However, a spatially correlated generator is required for large area hydrologic simulation. Such a generator has not been developed yet for general use. Another possibility is to utilize WSR-88D radar technology (formerly called NEXRAD – Next Generation Weather Radar) to determine aerial precipitation distribution rates needed to drive large area hydrologic models. Efforts to utilize WSR-88D data in conjunction with SWAT to predict real time flood forecasting is underway.

Stream Sediment and Chemical Routing – The limitations of the channel sediment routing routine used in this model are described in Part I. Instream pesticide and nutrient transport and transformation routines have been added to the model. Validation of these routines is needed under varying climate and land use conditions. Comprehensive data sets for different climatic and land use conditions are limited. Efforts to improve the sediment routing and to acquire data sets to validate and improve the chemical transport and transformation routines are continuing.

Refining the Ground Water Component – The ground water component currently in SWAT is one-dimensional and does not consider flow between subbasins. Work is ongoing to link SWAT to an existing three dimensional numerical ground water model.

Salinity Issues – Salinity is an important issue in some of the major river systems where water is used for irrigation (e.g., Rio Grande Basin). Work has begun to include a comprehensive salt balance model in SWAT. This will include (a) simulating salt movement in the soil profile and its impact on plant growth; (b) salt loading and routing from the subbasins to different points of water utilization; and (c) simulating salt concentration of irrigation water diverted from different sources within the basin and its impact on plant growth.

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