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Simulation of hydrology and erosion in a Texas watershed using SWAT

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Abstract This paper describes the application of a river basin scale hydrologic model, Soil Water Assessment Tool (SWAT) 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. The streamflow was calibrated and validated using the observed data available from two USGS streamgauge stations. Sediment calibration and validation were carried out using the sediment survey data from the Richland–Chambers Lake and a flood prevention structure within a sub-basin of RC watershed (Mill Creek watershed). The model performance was evaluated using well established statistical and visual methods and was found to explain at least 84% and 65% of the variability in the observed streamflow data for the calibration and validation periods, respectively. In addition, the model predicted the accumulated sediment load within 2% and 9% from the observed data for the RC watershed and Mill Creek watershed, respectively.

Simulación de hidrología y erosión en una cuenca hidrológica de Texas usando SWAT

Resumen Este trabajo describe la aplicación de SWAT, un modelo hidrológico a nivel de cuenca fluvial, a las cuencas de las quebradas Richland y Chambers (cuenca RC), localizadas en la parte superior de la hoya del río Trinity en Texas. Los datos de entrada al modelo fueron obtenidos de una base de datos hidrográfica y geográfica y de mapas usando un sistema de información geográfica en formato "raster". Los caudales de las quebradas fueron calibrados y validados utilizando datos observados disponibles en dos estaciones de USGS localizadas en la cuenca en mención. La calibración y validación de sedimentos fue llevada a cabo usando datos de muestreo de sedimentos del lago Richard–Chambers y de una estructura de retardo de inundación dentro de una subcuenca de la cuenca RC (Cuenca Mill Creek). El comportamiento del modelo SWAT fue evaluado utilizando métodos estadísticos y gráficos bien establecidos, y se encontró que este explica al menos el 84% y el 65% de la variabilidad presente en los datos de caudal de las quebradas, para los periodos de calibración y validación respectivamente. Además SWAT predijo la carga acumulada de sedimentos dentro del 2% y 9% de los datos observados, para las cuencas RC y Mill Creek respectivamente.

INTRODUCTION

In recent years, GIS has been playing an important role in natural resources modelling and proving to be an effective tool for non-point source (NPS) pollution models (Pelletier, 1985; Hession & Shanholtz, 1988). To analyse basin-scale hydrology, a distributed-parameter model is needed to preserve the spatial variability of the basin parameters. Manual collection of inputs for such models is 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 & Engel, 1991; Rosenthal *et al.*, 1995).

Srinivasan & Engel (1991) linked a GIS, Geographical Resource Analysis Support System (GRASS), to the Agricultural Nonpoint Source (AGNPS) model. Similarly the Areal Nonpoint Source Watershed Environmental Response System (ANSWERS) model (Beasley & Huggins, 1982) was linked to GRASS by Rewerts & Engel (1991). Both AGNPS and ANSWERS are single event distributed parameter models. A continuous time overcomes some of the limitations of single-event models (Rosenthal *et al.*, 1995). The Soil Water Assessment Tool (SWAT) (Arnold *et al.*, 1993) is a continuous time, distributed parameter model that considers a basin divided into sub-basins based on topography, soil, and land use. Thus it preserves the spatially-distributed parameters of the entire basin and homogeneous characteristics within a sub-basin. Due to the continuous nature, the model can effectively simulate flows in both perennial and seasonal streams and rivers.

The SWAT model is linked to GRASS by Srinivasan & Arnold (1994). The model link consists of input and output interfaces. The input interface interacts with the user to collect, prepare, edit, and store the basin and sub-basin information from GRASS raster/site map layers such as basin boundary map with sub-basin delineation, digital elevation map (DEM), soils map, land use/land cover map and weather generator/station location map to be formatted into SWAT input files. In addition, the reservoirs outflow and inflow, pond and lake data are collected directly from the user.

SWAT generates a variety of output files for daily, monthly or annual time intervals. The output interface consists of a generic visualization tool, developed and integrated as a part of GRASS to visualize the spatial and temporal output generated by SWAT. In addition, it can generate a model-output layer for GRASS, import other data such as measured streamflow data for further analysis, and perform linear regression analysis. Further details about the interface are given by Srinivasan & Arnold (1994).

MATERIALS AND METHODS

Description of the study area

The GIS-integrated SWAT model was applied to the RC watershed (Fig. 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 inventory sized ponds and NRCS flood prevention structures, providing an opportunity to model ponds and reservoirs. In addition to analysing the entire RC watershed, we chose to model a sub-watershed of RC watershed, Mill Creek watershed (Fig. 2), having a drainage area of 2.83×10^4 ha (109 square miles).

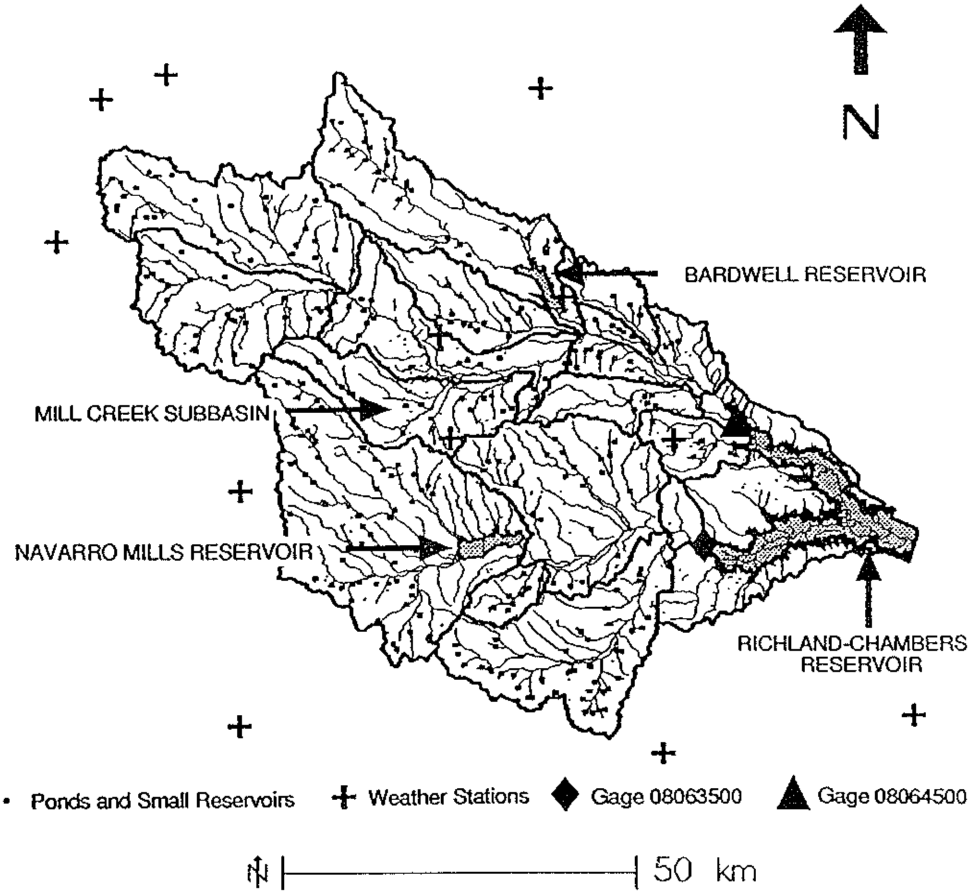

Fig. 1 Map of Richland and Chambers Creeks watershed.

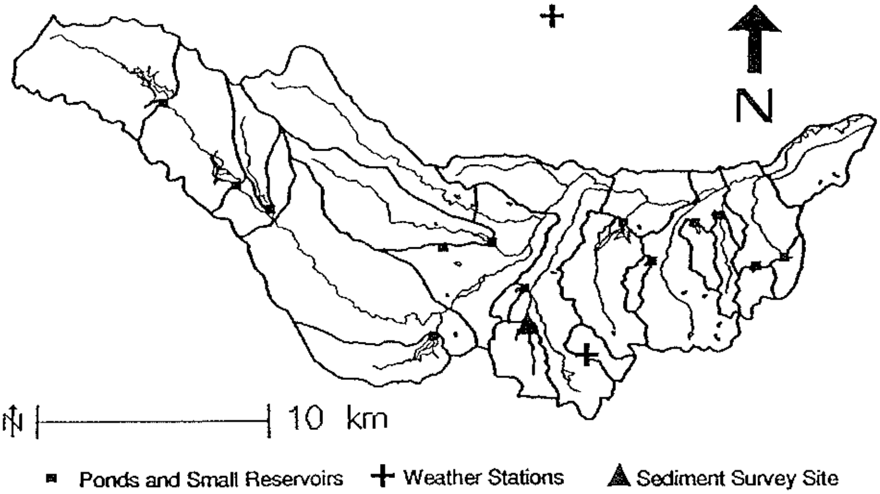

Fig. 2 Map of Mill Creek watershed.

Data sources and description

Soils and land use GIS layers were obtained from the US Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) computer-based mapping system (CBMS). The CBMS data for the study area were developed by digitizing 1:24 000 scale soil maps to create a raster layer consisting of 6.25 ha cells (250 × 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), 1:250 000 (100 × 100 m) for RC watershed and 1:24 000 (30 × 30 m) for Mill Creek, were obtained from the US Geological Survey (USGS). The watershed and sub-watershed boundaries for RC and Mill Creek watersheds were delineated using USGS 1:24 000 scale quadrangle maps. The data for ponds and reservoirs were obtained from USDA-NRCS and Texas Natural Resources Conservation Commission (TNRCC) records. Measured daily rainfall and temperatures were obtained from the USDA-NRCS climatological database. For flow calibration and validation, two USGS streamgauges, 08063500 (Station 1) and 08064500 (Station 2) were used (Fig. 1). Both weather and streamgauge data for the period 1965–1984 were used in this study. The reservoir storage and release data for the Bardwell and Navarro Mills reservoirs were obtained from US Army Corps of Engineers and USGS.

Sediment survey

Impoundment of water in RC reservoir began in 1988 and a sediment volume survey was conducted during December 1994. The sediment volume 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. We used 880 kg m^{-3} (55 lb ft^{-3}) as the specific weight of the submerged sediments in RC reservoir. This value is within the range suggested by Welborn (1967) for Trinity River submerged sediments. During the Mill Creek sediment surveys the specific weight of the submerged and aerated sediment were estimated as 1009 kg m^{-3} (63 lb ft^{-3}) and 1440 kg m^{-3} (90 lb ft^{-3}), respectively.

Model setup

Required inputs for the basin and sub-basins 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 analysed by Mamillapalli *et al.* (1996). We used the virtual basin approach to model the study area. The reservoir release volume cannot be simulated by SWAT because of its dependence on many factors other than hydrology. Therefore, the daily release rates from the Bardwell and Navarro Mills reservoirs were input directly into the model from the actual observed data.

Analysis

The flow calibration was conducted for the RC watershed for the period 1965–1969 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 1988–1994. For the MC watershed simulation the calibrated parameters from RC watershed were used. We evaluated the model prediction during the calibration and validation periods using visual and statistical techniques such as linear regression and Nash-Sutcliffe coefficient of efficiency (COE) (Nash & Sutcliffe, 1970). The COE can range from $-\infty$ to 1.0 and if the value of COE is less than zero, it is not an indication of good simulation. 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 (re-evaporation contribution from a shallow water table) coefficients were adjusted to give good correspondence with the observed data. The runoff curve number was reduced by 10% from the default value for all basins, and the revap coefficient was set to 1.0 for all the basins. Figures 3 and 4 show the time series of observed and simulated monthly streamflow at Stations 1 and 2, respectively.

Table 1 shows the statistical results of comparison of observed and simulated monthly streamflows during the calibration period. The coefficient of determination (r^2) for the linear regression between the observed and simulated streamflow 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% confidence level. The Nash-

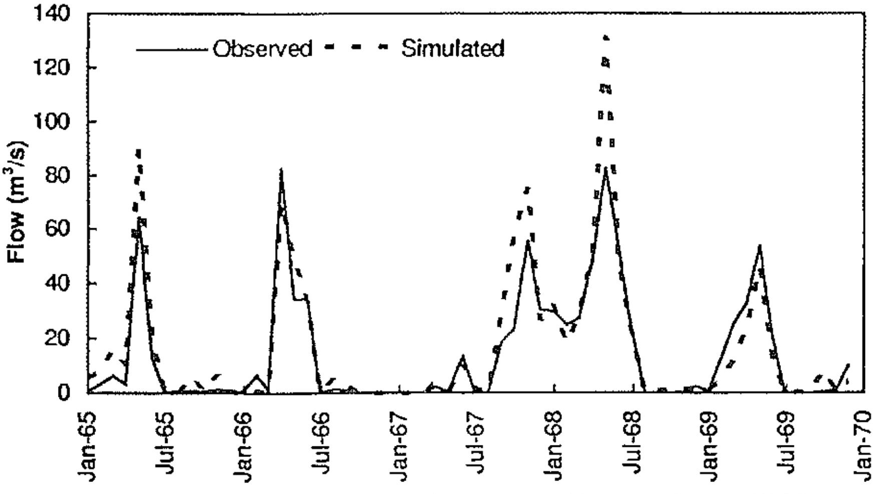

Fig. 3 Time series of observed and simulated monthly streamflow at USGS gauge 08063500 (Station 1) during the calibration period (1965–1969).

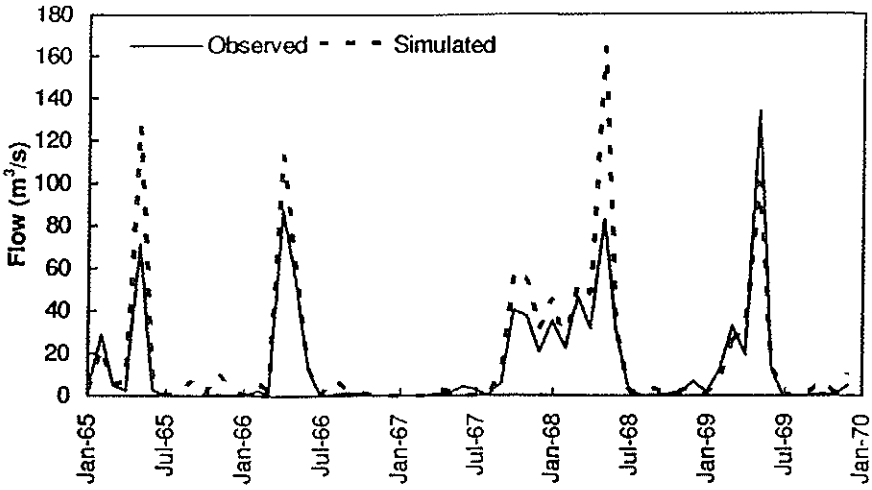

Fig. 4 Time series of observed and simulated monthly streamflow at USGS gauge 08064500 (Station 2) during the calibration period (1965–1969).

Table 1 Statistical results from comparison of observed and simulated streamflows.

Streamgauge	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)	80	0.65	2.2	0.9	2.60	–1.8	0.52
08064500 (Station 2)	80	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% (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 $|t_{\text{calc}}| \leq t_{0.975,n-1}$, accept H_0.

Sutcliffe simulation efficiency at the two streamgauge stations are 0.77 and 0.84. These results indicate that the model predicted the streamflow at these two gauges satisfactorily.

The period 1988–1994 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: (a) USLE 'P' factor = 1.0, (b) exponential factor for sediment concentration (SPC) = 0.008, (c) exponential factor for stream power equation (SPE) = 1.0, and (d) peak rate function (PRF) = 1.0. The simulated sediment delivery to the RC reservoir is 38.7 × 10^6 Mg and the measured sediment was about 37.9 × 10^6 Mg.

Validation

Flow validation was conducted using the observed streamflow data from the two USGS streamgauges for the period 1970–1984 (15 years). Figures 5 and 6 show the

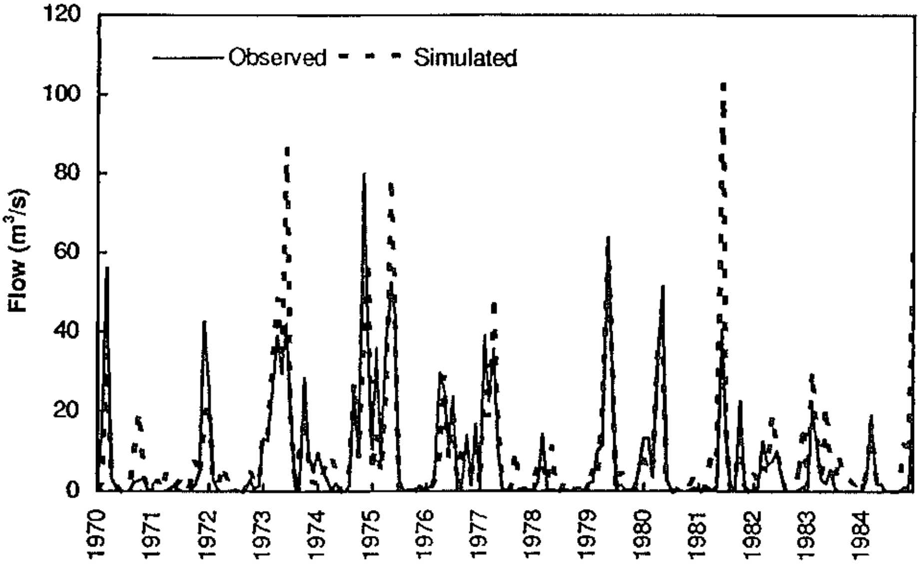

Fig. 5 Time series of observed and simulated monthly streamflow at USGS gauge 08063500 (Station 1) during the validation period (1970–1984).

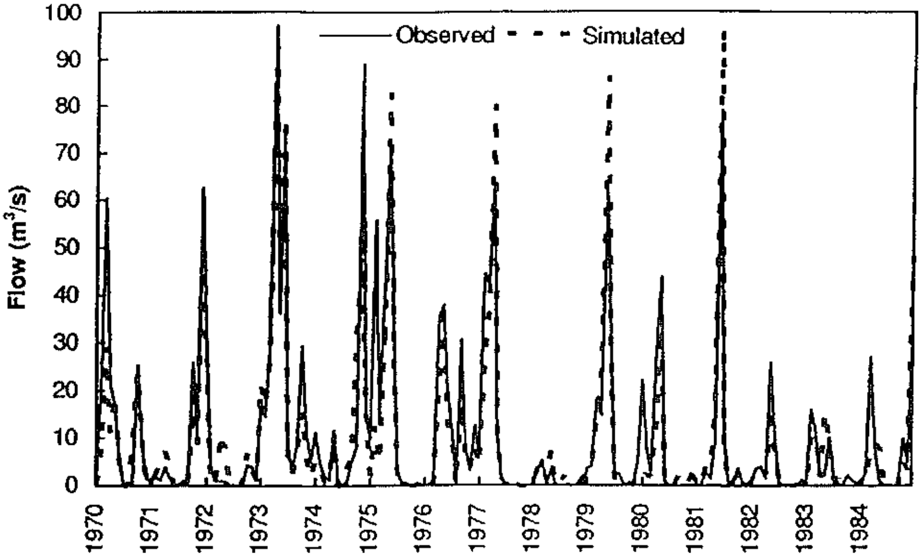

Fig. 6 Time series of observed and simulated monthly streamflow at USGS gauge 08064500 (Station 2) during the validation period (1970–1984).

time series plot of monthly observed and simulated streamflow at stations 1 and 2, respectively. On analysing the statistical results of the comparison of monthly streamflow values (Table 1), the observed values have a strong linear relationship with the predicted results. The coefficient of determination of the linear regression between observed and simulated streamflow at the two stations are 0.65 and 0.82. The Nash-Sutcliffe simulation efficiencies at the two stations are 0.52 and 0.82, respectively. The predictions at Station 2 (USGS gauge 08064500) are satisfactory, but the predictions at Station 1 (USGS gauge 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 sub-basin, but occurred over the corresponding raingauge location. Looking at Fig. 5, such events can be spotted during the spring/summer periods of 1973, 1975 and 1981.

Sediment validation was conducted by estimating sediment loading at a USDA-NRCS flood water retarding structure in Mill Creek watershed. A ten-year period (1965–1974) was chosen for validation. The calibrated erosion parameters from RC watershed were used here. Since no observed flow data was available for this watershed, 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 1965–1968 and 1968–1975 were estimated as 29 000 and 14 000 Mg, respectively. The sediment loads predicted by SWAT for the same periods are 25 000 and 14 000 Mg, respectively. 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.

SUMMARY AND CONCLUSIONS

A distributed parameter, continuous time, river basin-scale model, SWAT, was successfully calibrated and validated to simulate the hydrology, soil erosion, and sediment transport in the Richland-Chambers watershed of the Trinity river basin in Texas. The calibration conducted in this study was minimal and is justified considering the amount of input data fed into the model. The flow validation was

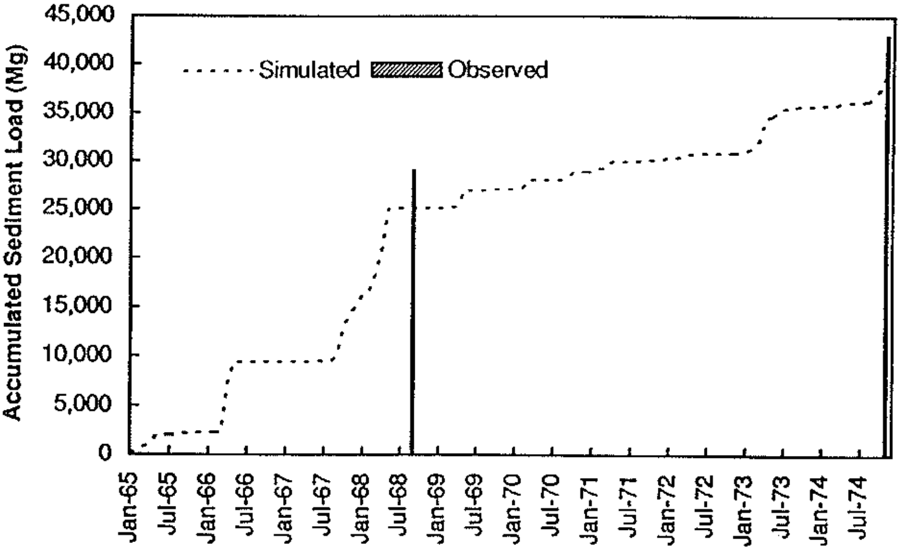

Fig. 7 Observed and simulated accumulated sediment at the flood retarding structure in Mill Creek watershed.

conducted for the period 1970–1984 using the streamflow data from two USGS streamgauges. The erosion component was validated by simulating soil erosion and sediment transport within a sub-watershed of Richland-Chambers watershed (Mill Creek) using sediment survey results at a USDA-NRCS flood water retarding structure in the sub-watershed.

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. In general the monthly streamflow rates predicted by SWAT corresponded very well with the observed values. Nevertheless, the model overestimated streamflows 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 streamflows 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 analyse future "what if" scenarios, identify critical areas in the river basin, and recommend best management practices (BMPs) to reduce soil loss.

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