J. ENVIRONMENTAL SYSTEMS, Vol. 25(4) 345-374, 1996-97

STORMWATER RUNOFF AND POLLUTANT MODELING IN A FLORIDA DRAINAGE BASIN

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ABSTRACT

A stormwater runoff and pollutant model (SRPM) was developed for catchment-scale watersheds in both urban and agricultural areas. The model was tested on a small watershed in Florida using data collected during a thirty-three-month period. The performance of the model was evaluated by comparing simulated results with outputs from a validated model, CREAMS-WT. Statistical correlations of daily, monthly, and annual values of observed and simulated runoff and phosphorus loads by SRPM and CREAMS-WT were analyzed. Statistical results indicated that the two models performed similarly in predicting daily, monthly, and annual runoff and phosphorus loads. With Pearson correlation coefficient of R^2 greater than 0.84, annual predictions from both models matched very well with observed data. A Pearson correlation coefficient grater than 0.76 indicated that both models performed well in predicting monthly runoff and phosphorus loads. Neither model performed well in predicting daily runoff or phosphorus loads, as shown by the low R^2 values (< 0.4). Key parameters of SRPM in the simulation of urban hydrology and water quality components were selected for sensitivity analyses for both a typical storm event and the whole simulation period. It was found that the phosphorus load computations for both storm events and the whole simulation period were sensitive to changes in the washoff parameters, whereas the load calculations for the whole simulation period were more sensitive to the buildup parameters than for individual storms.

doi: 10.2190/8H6X-NV3Q-LQ5Q-QLAY
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INTRODUCTION

Stormwater runoff and associated pollutant loads have gained great attention in urban planning and agricultural pollution control. Evaluation of alternative scenarios in urban development and agricultural management is needed to assess the environment impacts on existing watersheds due to changes in land use and other activities, and to design water quality and hydrologic systems [1]. A user-friendly watershed model is desired for such evaluations as a tool to predict future runoff and water quality impacts on a receiving water, and to assess urban and/or agricultural stormwater management alternatives [2]. Watershed managers and planners need such a tool to estimate relatives water quality impacts of sub-basin discharges on downstream locations, which in turn helps in selecting appropriate watershed-wide stormwater management control alternatives [3].

Modeling the quantity and quality of stormwater runoff is difficult due to variations in land use, human activities, and meteorological conditions [4]. A few existing watershed models are available to simulate stormwater runoff and its pollutant loads for different applications. The U.S. EPA defined three classes of watershed-scale models: simple, mid-range, and detailed [5]. Simple methods apply basic statistical, and/or empirical equations to simulate annual averages of runoff and pollutant loads. These models require historical monitoring data; their applications are usually limited to the areas for which the models were developed and to similar watersheds [5]. Mid-range models describe the relationship of pollutant loadings to hydrologic and erosion processes on monthly or seasonal bases. These models consider neither adsorption, degradation and transformation processes of pollutants, nor pollutant transport within and from the watershed [5]. The mid-range models can be applied for relative comparison analysis for watershed planning decisions. Both simple and mid-range models are not applicable to this study due to their limited capability in predicting surface runoff and water quality.

Detailed models simulate the physical, hydrologic, and pollutant transport and transformation processes in watershed areas at small time intervals to account for effects of storm events. Some detailed models are the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) [6], Distributed Routing Rainfall Runoff Model-Quality (DR3M-QUAL) [7], Hydrological Simulation Program-FORTRAN (HSPF) [8], Storage, Treatment, Overflow, Runoff Model (STORM) [9], Storm Water Management Model (SWMM) [10], and Simulation for Water Resources in Rural Basins (SWRRB) [11]. Among these detailed models, HSPF and SWMM were considered for this study due to their capabilities of simulating various water quality components for both long term and storm events.

HSPF simulates hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption processes to describe pollutant generation, transformation and transport from watersheds to and within receiving water bodies [8]. Three distinct categories such as pervious lands, impervious lands, and channels/streams are considered in HSPF. Drawbacks of HSPF include requirements for extensive data inputs and for highly trained personnel teams. In addition it is very difficult to develop a user-friendly interface for HSPF due to complexities of the model. SWMM was designed for application in urban areas and has been widely applied for many purposes. The SWMM model has the flexibility to simulate different land use types and user-defined water quality constituents (up to 10 constituents for each simulation run). However, it is not suitable for application in agricultural areas.

In this article, we introduce the Stormwater Runoff and Pollutant Model (SRPM), a simplified and modified version of SWMM with added phosphorus transport mechanisms applied in agricultural areas, which was designed to simulate watershed runoff and associated pollutant concentrations in catchment areas with agricultural and/or urban land uses. Most hydrologic and water quality simulation algorithms used in SRPM were adapted from SWMM. A phosphorus movement mechanism used in the Field Hydrologic and Nutrient Transport Model (FHANTM) [12] was embedded in SRPM for simulation of phosphorus transport in agricultural areas. A reservoir flow routing method [13] was used in SRPM to speed up simulation time, instead of using the Newton-Raphson technique to solve nonlinear equations for hydrologic simulation used in SWMM [14]. SRPM was designed in such way that it is easy to run and to develop a user-friendly interface for the model. The SRPM model was calibrated using data collected from a small catchment area in South Florida. Simulation results were also compared with outputs from a validated model, a field scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems-Water Table (CREAMS-WT) [15, 16].

The objectives of this study were to 1) develop a simplified hydrology and water quality model which will be applied in agricultural and/or urban areas, 2) develop a user-friendly interface for the model, 3) test the model using measured data collected from a watershed, and 4) compare simulation results with those from a validated model. SRPM was also applied and tested in another agricultural area in central Florida [17]. In that study, the model was calibrated and verified using observed data during a five-year period and simulation results were compared with FHANTM.

MODEL DESCRIPTION

SRPM is a catchment-scale hydrology and water quality model that simulates storm-related surface runoff and associated pollutant loads in a catchment or watershed. It was developed for watershed analyses in urban and agricultural areas. The model was written in FORTRAN and can be executed on both PC DOS and UNIX operating systems without any special memory or disk space requirement. SRPM is a continuous simulation model with an hourly time step. It provides results for both individual storm events and long-term simulation. It takes about two minutes to run a three-year period continuous simulation at hourly time step on a SUN SPARC 2 workstation. A user-friendly interface was developed for the model using a geographic information system (GIS). The integrated GIS tool with pre-processors and post-processors for the model enables watershed managers and planners to easily use SRPM for watershed analyses and evaluations. The model is available to the public. Model documentation and software package can be obtained from the authors.

Hydrologic Simulation

SRPM allows users to simulate up to ten sub-catchments in each application run. Each sub-catchment represents a different land-use type or percentage of pervious and impervious areas. The algorithm used in hydrologic simulation is similar to that used in the RUNOFF Block of SWMM [10]. A sub-catchment is treated as a nonlinear reservoir with consideration of the processes of precipitation, evapotranspiration (ET), infiltration, depression storage, percolation, and surface runoff:

$$\frac{ds}{dt} = P(t) - E(t) - I(t) - R(t) \tag{1}$$

where S = storage volume of water (m^3); P = precipitation rate (m^2/s); I = infiltration or percolation rate (m^3/s); R = surface runoff rate (m^3/s); and t = time (sec).

A simple hydrologic method of flow routing was presented by Chow [18] and by Linsley and Franzini [13]:

$$\frac{S_2 - S_1}{\Delta t} = \frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2} \tag{2}$$

where S_2 = storage in the reservoir at the end of routing period (m^3); S_1 = storage in the reservoir at the beginning of routing period (m^3); Δt = routing period (sec); I_1 = instantaneous inflow at the beginning of routing period (m^3/s); I_2 = instantaneous inflow at the end of routing period (m^3/s); O_1 = instantaneous outflow at the beginning of routing period (m^3/s); and O_2 = instantaneous outflow at the end of routing period (m^3/s). Precipitation is the only inflow component in SRPM while the outflow includes evapotranspiration, infiltration, percolation, and surface runoff. Equation (2) can be rewritten as the following equation after grouping the unknowns and knowns on each side of the equation [10]:

$$\frac{1}{2}O_2\,\Delta t + S_2 = \frac{1}{2}\,(I_1 + I_2)\,\Delta t + (S_1 - \frac{1}{2}O_1\,\Delta t) \tag{3}$$

The variables on the right hand side of Equation (3) are known for a given time step. The two unknowns O_2 and S_2 on the left hand side of the equation can be solved after the relationship between O_2 and S_2 is determined. In the hypothetical reservoir, the geometric dimensions of the reservoir and the outflow structure data are given. Therefore, the relation of O_2 and S_2, each of which is a function of storage depth, can be determined [10]. This reservoir routing method was applied in SRPM for speeding up the simulation of the overland flow, instead of using the Newton-Raphson technique for hydrologic simulation in the RUNOFF Block in SWMM.

Manning's equation is used for the runoff estimation in SRPM. The equation calculates overland flow velocity by using the parameters of hydraulic radius, slope, and the Manning roughness coefficient. The roughness coefficient represents the land surface condition and the land use type of a specific sub-catchment. The overland flow (i.e., surface runoff) occurs only when water depth in the hypothetical reservoir exceeds the reservoir capacity defined by the maximum depression storage [14]:

$$Q = \frac{W}{n}(d - d_p)^{5/3} S^{1/2} \tag{4}$$

where Q = runoff flow rate from a catchment (m^3/s); W = width of overland flow (m); n = Manning roughness coefficient (dimensionless); d = depth of water on the catchment (m); d_p = depth of maximum depression storage (m); and S = the slope of the catchment (m/m).

A three-parameter empirical infiltration model, the Horton Model, has been widely used to calculate the infiltration capacity into soil. The Horton model expresses that the infiltration capacity is equal to the maximum infiltration rate at the beginning of a storm event and then is reduced to a relatively low constant rate as the soil becomes saturated [19]. The potential infiltration capacity calculated by the Horton model is often less than the actual infiltration capacity because typical values for infiltration parameters are often greater than typical rainfall intensities. The integrated form of Horton's equation [10] was selected in SRPM to solve this problem:

$$F(t_p) = \int_0^{t_p} f(t)dt = f_\infty t_p + \frac{(f_0 - f_\infty)}{\alpha}(1 - e^{-\alpha t_p}) \tag{5}$$

where $F(t_p)$ = cumulative infiltration at t = t_p (m); t_p = time at the end of simulation step (sec); f(t) = infiltration capacity into soil at t = t_p (m/s); f_∞ = minimum or ultimative infiltration rate (m/s); f_o = maximum or initial infiltration rate (m/s); α = rate constant (1/sec). The regeneration or recovery of infiltration capacity during dry weather is considered for continuous simulation by applying the same approach as in SWMM. This infiltration simulation approach allows users to define the proper values of f_∞ and f_0 based on the locations of simulation. The f_∞ value in South Florida is usually higher than that observed in other areas in the U.S.A. due to the dominance of sandy soils.

Observed pan evaporation records are used in calculations of water depletion by the process of evapotranspiration in watersheds. Actual evapotranspiration is calculated from the pan evaporation values, which are multiplied by an ET coefficient. SRPM allows users to provide monthly ET coefficients to account for seasonal variations of the evapotranspiration in a watershed. The estimated evapotranspiration value is subtracted from the calculated infiltration rate to estimate percolation rate which is used to calculate the water loss into the groundwater.

Water Quality Simulation

Water quality simulation in watersheds is difficult due to various physical and chemical processes governing fate and transport of pollutants, the effects of rainfall and watershed characteristics, and the land use practices [4]. For urban land uses, a deterministic model that includes pollutant build-up and washoff components was selected for the simulation of stormwater pollutant loads in SRPM. For agricultural areas, phosphorus transport algorithm used in FHANTM was adopted. FHANTM has been identified as a valuable tool for predicting phosphorus loads in runoff from agricultural areas in South Florida [20].

Water Quality Simulation for Urban Areas

The concept of "buildup" was first introduced to describe the accumulation of dust and dirt and associated pollutants on urban street surfaces in the late 1960s [21]. Thereafter, the buildup concept (as well as washoff concept) has been included in several watershed models such as SWMM, HSPF, STORM, USGS, and SLAMM [5]. Buildup is defined as the pollutant accumulation during the dry-weather periods between storms. The buildup process is a combination of atmospheric deposition, wind erosion, street cleaning or other human activities. An exponential function was selected for SRPM similar to the one included in SWMM [5] for the simulation of the buildup of water quality constituents:

$$P_{buildup} = P_{limit}\,(1 - e^{-\alpha t}) \tag{6}$$

where $P_{buildup}$ = amount of pollutant accumulation (kg); P_{limit} = maximum value of pollutant buildup (kg); α = pollutant buildup rate (1/sec); and t = time (sec). During the continuous simulation, buildup will not occur during the wet-weather time steps unless runoff is less than 0.00127 cm/hr (0.0005 in/hr) [10].

Washoff is defined as the pollutant removal process associated with runoff during storm events. Similar to the exponential buildup equation, the exponential washoff equation describes the relationship between the initial amount and the cumulative amount washed off during storm events. By using the average power of runoff over the simulation time step, a modified washoff equation [10] was applied in SRPM:

$$P_{remain}(t + \Delta t) = P_{remain}(t)e^{-\beta\frac{1}{2}[r(t)^n + r(t+\Delta t)^n]\Delta t} \tag{7}$$

where P_{remain} = amount of pollutant remaining in a catchment (kg); β = washoff coefficient (dimensionless); Δt = simulation time step (sec); r(t) = runoff rate at time t (cm/hr); r(t+Δt) = runoff rate at time t+Δt (cm/hr); and n = washoff power factor (dimensionless). Equation (7) as well as Equation (6) was applied in SRPM to calculate pollutant loads in urban areas (up to nine user-defined water quality constituents).

Water Quality Simulation for Agricultural Areas

In order to better describe phosphorus transport mechanisms in agricultural activities, a phosphorus movement mechanism used in FHANTM was selected in phosphorus simulation with agricultural areas in SRPM [12]:

$$P_{water}(t + \Delta t) = P_{water}(t) + P_{land}(t)\,\Delta t\,(\alpha\, I_{rain} + \beta\, I_{runoff}) + CP_{rain}\,\Delta\, tI_{rain} \tag{8}$$

$$P_{land}(t + \Delta t) = P_{land}(t) - P_{land}(t)\,\Delta\, t(\alpha\, I_{rain} + \beta\, I_{runoff}) \tag{9}$$

where P_{water} = mass of phosphorus contained in surface water (kg/ha); P_{land} = mass of phosphorus contained in surface land (kg/ha); P_{rain} = phosphorus concentration contained in rainfall (mg/L); α = effectiveness of rain in removing phosphorus from P_{land} (1/cm); β = effectiveness of runoff in removing phosphorus from P_{land} (1/cm); I_{rain} = rainfall intensity (cm/hr); I_{runoff} = runoff intensity (cm/hr); C = converting factor (0.254); Δt = time step (hour); and t = time (hour).

Phosphorus deposition comes from two sources: land and air. In general, animal wastes, fertilizers, or other nutrients introduced by human activities are considered as land phosphorus deposition, whereas phosphorus in raindrops as air deposition. Equation (8) states that phosphorus mass in surface water P_{water} will cumulate with addition of phosphorus mass from raindrops P_{rain} and solubilized portion of phosphorus on surface land. Unsolubilized portion of phosphorus will remain on surface land until next rainfall or runoff occurs (Equation (9)). Daily phosphorus mass created by animal wastes or fertilizers is added to the phosphorus mass on surface land P_{land} each day [12]. Equations 8 and 9 were used for phosphorus simulation in agricultural areas. For other water quality constituents, the buildup and washoff equations were still applied for pollutant load calculations.

GIS Interface

A user-friendly interface of the SRPM model was developed using a GIS software package—ArcView [22]. The integrated GIS interface with pulldown menus consists of three major components: 1) Pre-Processors, 2) Run Model, and 3) Post-Processors. The pre-processors component was designed to obtain all input data required by SRPM and save inputs into a format for the model. The second component allows users to run SRPM without worry about input formats of the model. The post-processors component reads output files generated from SRPM and displays hourly, daily, monthly, and annual simulation results in tabular and graphical forms based on users' selection. Simulation results of two different parameters (e.g., runoff and one water quality constituent or two water quality constituents) can be viewed for comparison analyses in chart windows of the post-processors. Detailed information about the integrated GIS interface of the SRPM model was presented by Xue and Bechtel [23].

MODEL CALIBRATION AND VALIDATION

A newly-developed continuous simulation model is normally tested and validated by applying calibration and verification procedures. The number of years of observed data used for a model simulation varies from applications to applications depend on what the model is used for. Usually, three or more consecutive years of observed data are used to calibrate the model and the parameter set is then verified by using an independent series of observed data of several years or more [24]. A different approach was used here due to the limited field data collected during a thirty-three-month period, i.e., the entire data set was used to calibrate the SRPM model. The calibrated results were then compared to simulation results from CREAMS-WT with conducted by Zhang et al. [25]. Same data set was used for model calibration and to produce the results that were compared to CREAMS-WT results. The performance of SRPM was validated by means of statistical correlation analyses of daily, monthly, and annual values of measured and simulated runoff and the pollutant loads.

Watershed Description

A small catchment area located at W. F. Rucks Dairy in the Lake Okeechobee drainage basin in south central Florida was selected for this modeling study because intensive data on runoff and phosphorus transport was collected in this area from April 1989 to December 1991 [12]. The W. F. Rucks site has a drainage area of 38,850 m^2 and contains spodosol soils which are the dominant soil types for the entire region north of Lake Okeechobee [26]. The site was used to graze cattle at low densities for approximately the first half of the thirty-three month study period, but it was used for beef production for the rest of the period [12]. Average slope of the catchment area is 0.0011 m/m. A detailed description of the study area and the observed data set including precipitation, evaporation, runoff, and phosphorus loads was presented by Tremwel [12] and Zhang et al. [25].

Model Results and Analyses

Observed and simulated daily runoff and phosphorus loads from SRPM and CREAMS-WT are plotted in Figures 1 and 2. Generally, simulated results from

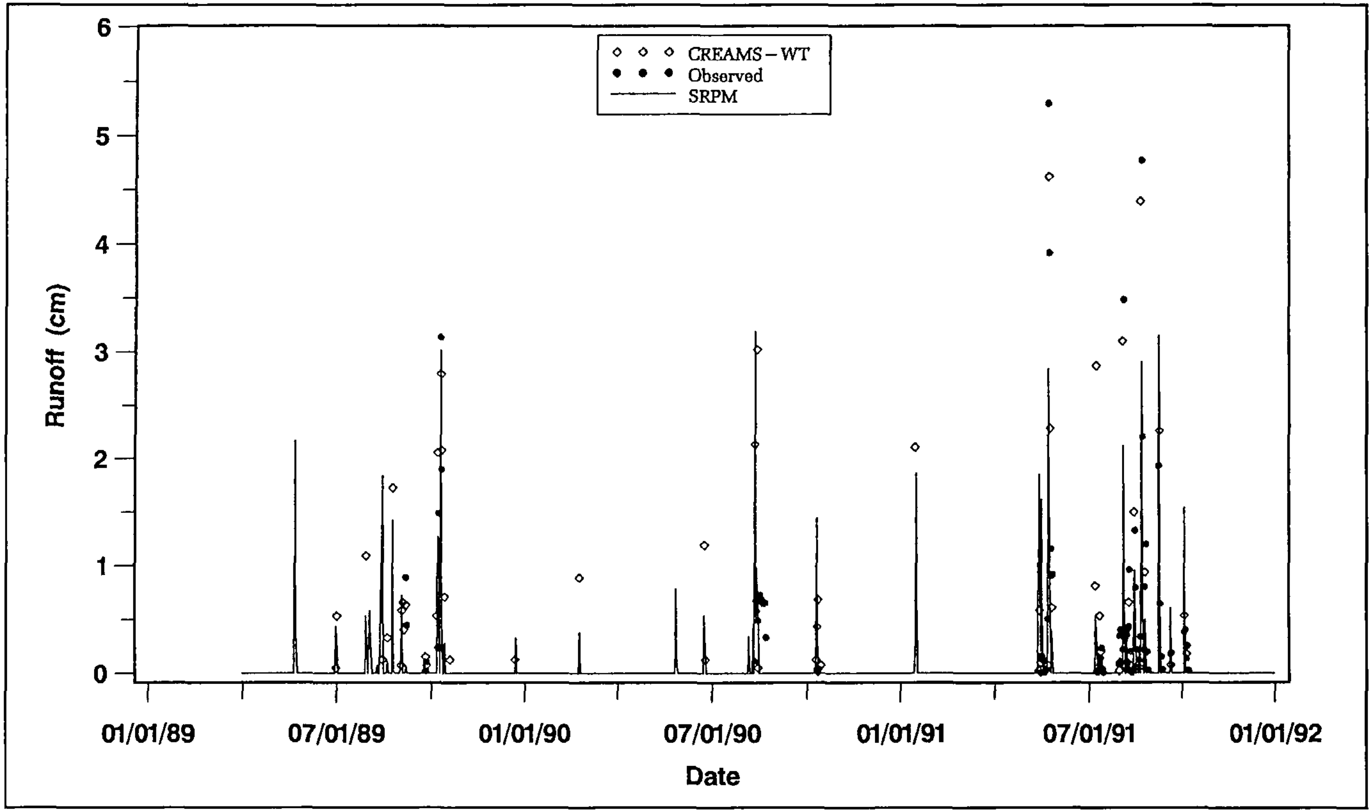

Figure 1. Observed and simulated daily runoff from CREAMS-WT and SRPM during the period from 04/01/89 to 12/31/91.

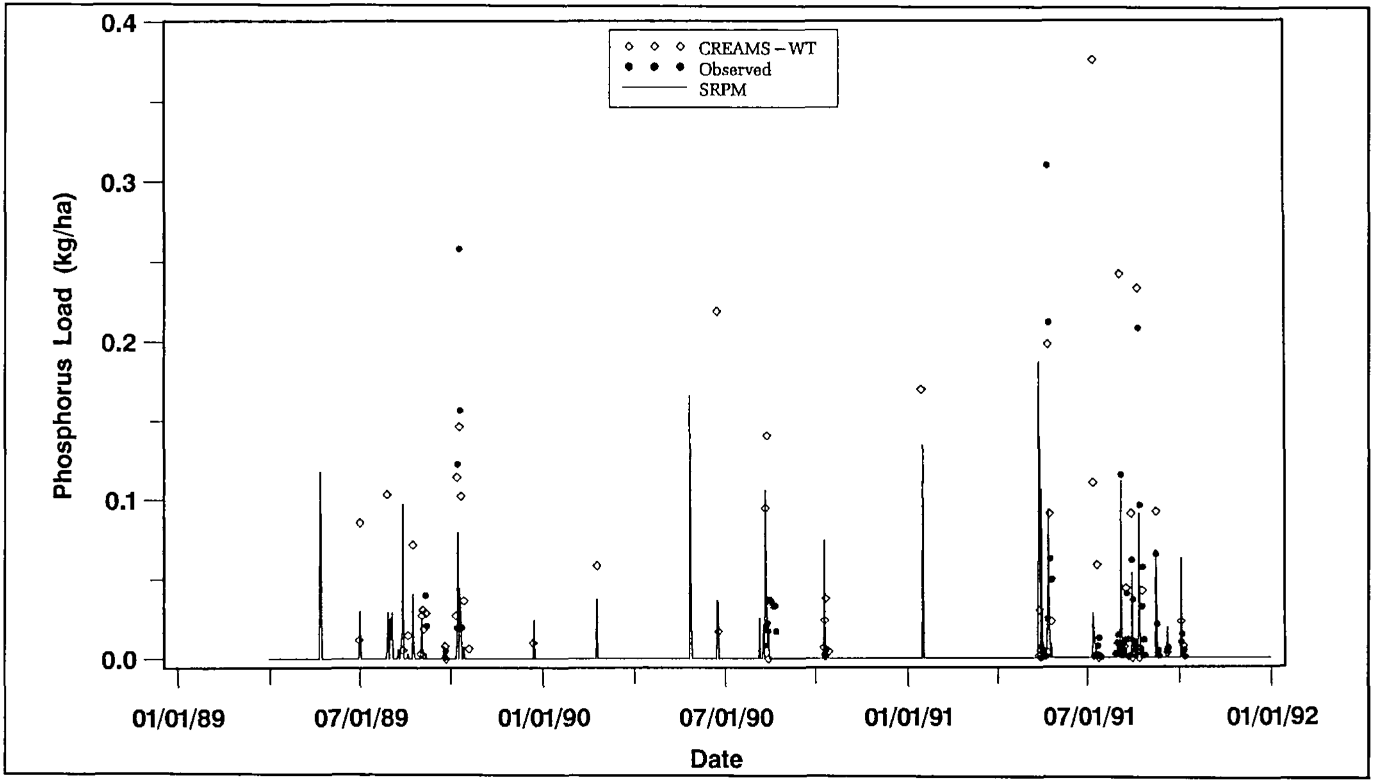

Figure 2. Observed and simulated daily phosphorus load from CREAMS-WT and SRPM during the period from 04/01/89 to 12/31/91.

SRPM compared with observed values similar to results from CREAMS-WT. The simulated daily results from both models were either underpredicted or overpredicted on certain days (Figures 1 and 2).

It can be seen that the simulated monthly runoff from SRPM and CREAMS-WT predicted the monthly runoff values fairly well except the overpredicted month of August 1989 and the underpredicted months of May and August 1991 (Figure 3). Both CREAMS-WT and SRPM performed well in simulating the monthly phosphorus loads except for the months of August and October 1989 and the months of May and August 1991 (Figure 4). Better calibrated results will be obtained if longer historic data records including a few dry and wet years are available.

Simulated annual results indicated that both models performed very closely in simulating annual runoff and phosphorus loads against observed data (Figures 5 and 6). The simulated total runoff of 54.7 cm from SRPM (percent error of 2.6) or 52.5 cm from CREAMS-WT (percent error of –1.5) in the thirty-three-month period matched well with the observed total runoff of 53.3 cm (Table 1). Similarly, the simulated total phosphorus loads of 2.55 kg/ha from SRPM (percent error of –4.1) or 3.32 kg/ha from CREAMS-WT (percent error of 24.8) were close to the observed total phosphorus loads of 2.66 kg/ha (Table 1).

Statistical Results and Analyses

Statistical correlation analyses were conducted to validate the SRPM model. The correlation analyses were performed using daily, monthly, and annual runoff and phosphorus loads simulated from both SRPM and CREAMS-WT. Tables 1 through 3 present the statistical analysis results of the observed and predicted daily, monthly, and annual runoff and phosphorus loads, respectively. Seasonal, dry-year (1988) and wet-year (1991) rainfall variations resulted in high standard deviations in simulated and observed runoff and phosphorus loads. Statistical results indicated that the two models performed similarly in predicting daily, monthly, and annual runoff and phosphorus loads. Neither model performed well in predicting daily runoff or phosphorus loads because of the low R^2 values (< 0.4) (Table 1). Pearson correlation coefficients greater than 0.88 for runoff and greater than 0.76 for phosphorus loads indicated that both models performed well in predicting monthly runoff and phosphorus loads (Table 2). With Pearson correlation coefficient or R^2 greater than 0.84 for runoff, annual runoff predictions from both models matched very well with observed data (Table 3). It can be seen from Table 3 that a strong agreement between the annual observed and simulated phosphorus loads was obtained with the Pearson correlation coefficient and R^2 1.0 for both models.

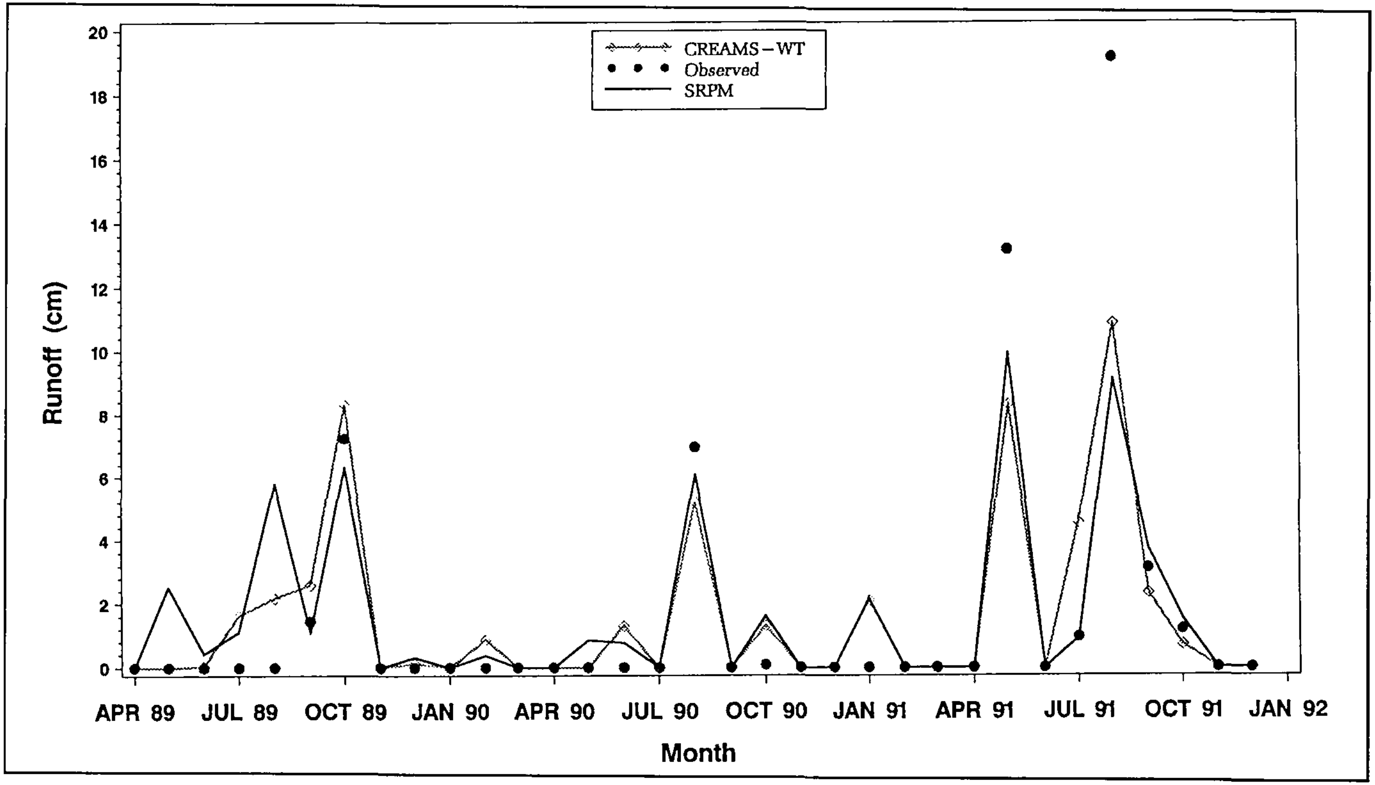

Figure 3. Observed and simulated monthly runoff from CREAMS-WT and SRPM during the period from April 1989 to December 1991.

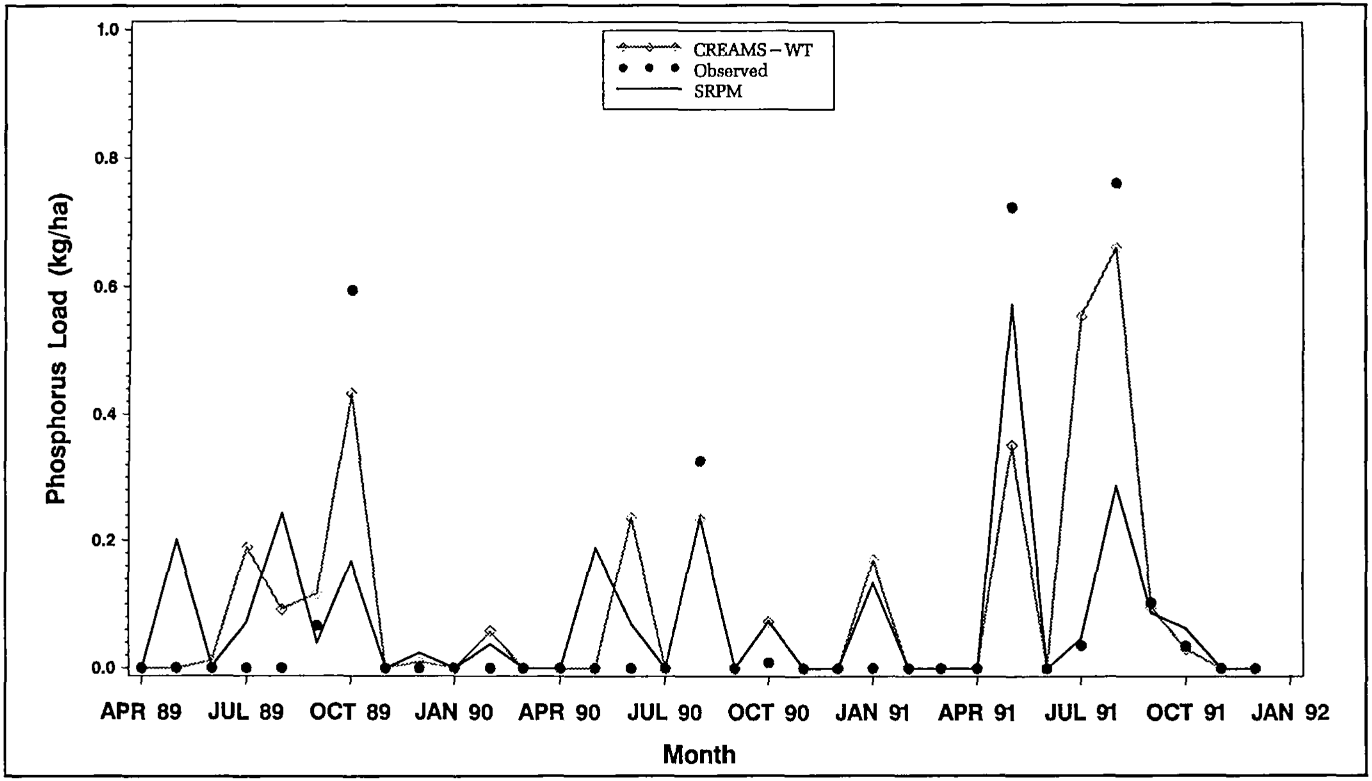

Figure 4. Observed and simulated monthly phosphorus load from CREAMS-WT and SRPM during the period from April 1989 to December 1991.

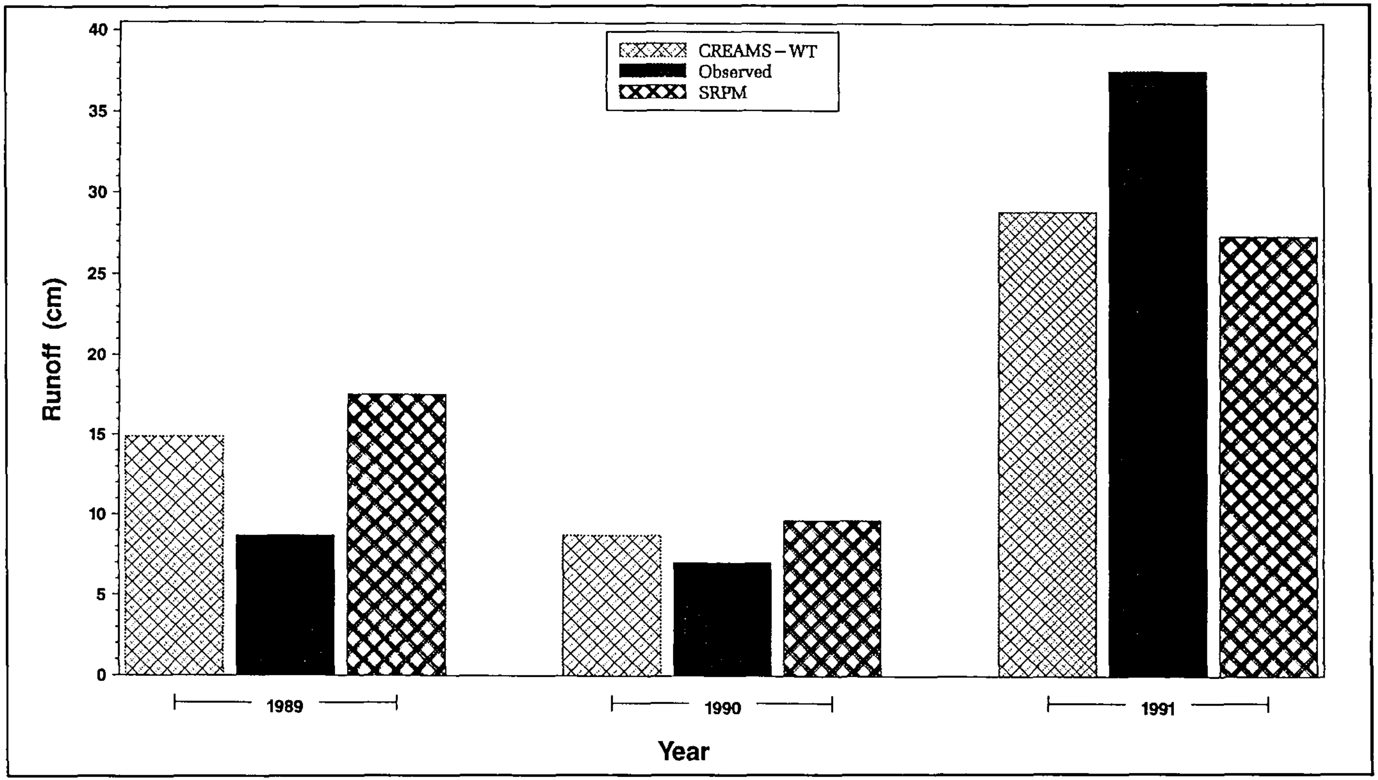

Figure 5. Observed and simulated annual runoff from CREAMS-WT and SRPM from 1989 to 1991 (note: 1989 data starts in April).

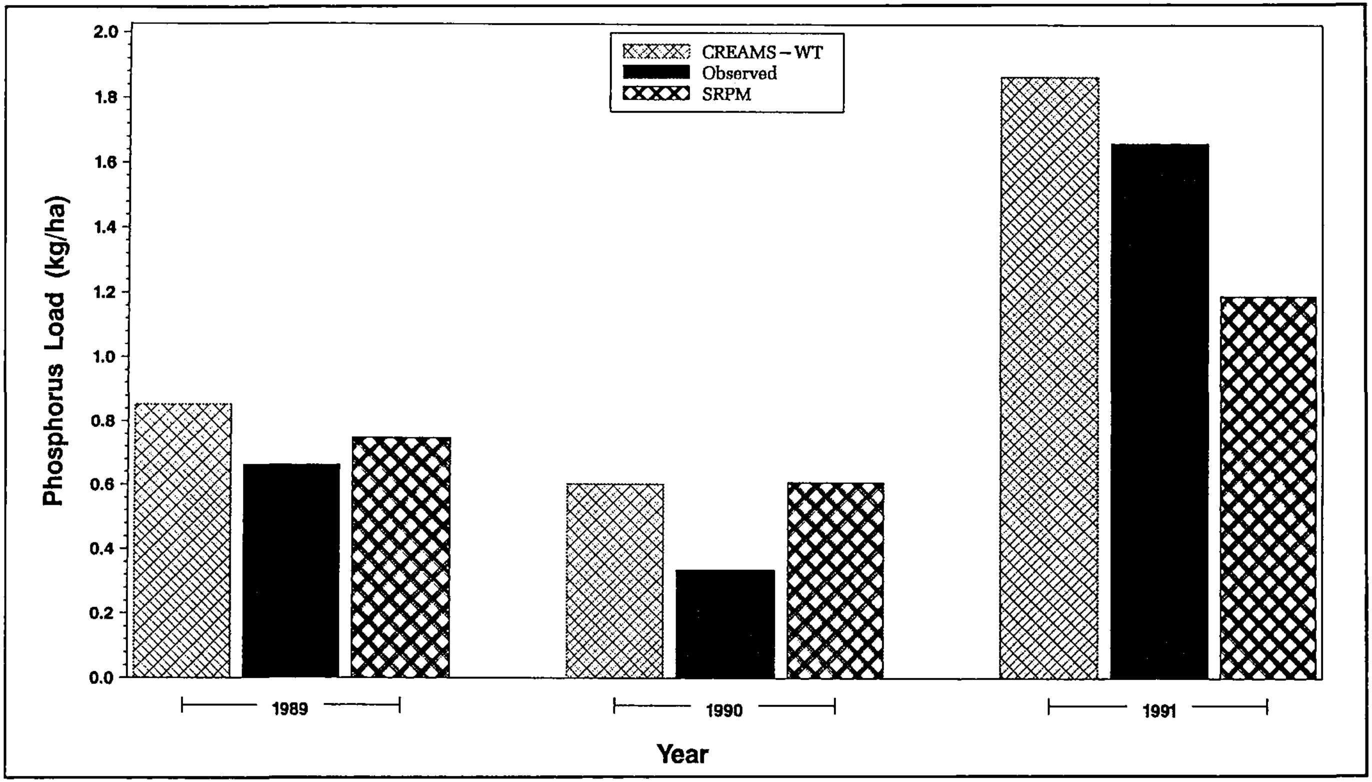

Figure 6. Observed and simulated annual phosphorus load from CREAMS-WT and SRPM from 1989 to 1991 (note: 1989 data starts in April).

Table 1. Statistics of Observed and Predicted Daily Runoff and Phosphorus Loads from CREAMS-WT and SRPM

	Runoff (cm)			Phosphorus Load (kg/ha)		
Statistics Analysis	Observed	CREAMS-WT	SRPM	Observed	CREAMS-WT	SRPM
Mean	0.053	0.052	0.054	0.003	0.003	0.003
Standard deviation	0.34	0.34	0.30	0.019	0.022	0.015
Standard error	0.0107	0.0107	0.0095	0.0006	0.0007	0.0005
Sum	53.30	52.50	54.66	2.66	3.32	2.55
Minimum	0	0	0	0	0	0
Maximum	5.30	4.62	3.19	0.310	0.376	0.187
N	1005	1005	1005	1005	1005	1005
R^2	—	0.22	0.38	—	0.12	0.13
Regression slope	—	0.47	0.53	—	0.42	0.28
Pearson correlation coefficient	—	0.47	0.59	—	0.34	0.36

Table 2. Statistics of Observed and Predicted Monthly Runoff and Phosphorus Loads from CREAMS-WT and SRPM

	Runoff (cm)			Phosphorus Load (kg/ha)		
Statistics Analysis	Observed	CREAMS-WT	SRPM	Observed	CREAMS-WT	SRPM
Mean	1.62	1.59	1.66	0.08	0.10	0.08
Standard deviation	4.22	2.79	2.72	0.21	0.17	0.12
Standard error	0.735	0.486	0.473	0.037	0.030	0.021
Sum	53.30	52.50	54.66	2.66	3.32	2.55
Minimum	0	0	0	0	0	0
Maximum	19.15	10.87	9.92	0.76	0.66	0.57
N	33	33	33	33	33	33
R^2	—	0.84	0.77	—	0.58	0.58
Regression slope	—	0.61	0.56	—	0.63	0.45
Pearson correlation coefficient	—	0.92	0.88	—	0.76	0.76

Table 3. Statistics of Observed and Predicted Annual Runoff and Phosphorus Loads from CREAMS-WT and SRPM

	Runoff (cm)			Phosphorus Load (kg/ha)		
Statistics Analysis	Observed	CREAMS-WT	SRPM	Observed	CREAMS-WT	SRPM
Mean	17.77	17.50	18.22	0.89	1.11	0.85
Standard deviation	17.19	10.32	8.87	0.69	0.67	0.30
Standard error	9.92	5.96	5.12	0.40	0.39	0.17
Sum	53.30	52.50	54.66	2.66	3.32	2.55
Minimum	7.03	8.74	9.69	0.33	0.60	0.61
Maximum	37.59	28.88	27.40	1.66	1.87	1.19
N	3	3	3	3	3	3
R^2	—	0.94	0.84	—	1.00	1.00
Regression slope	—	0.58	0.47	—	0.97	0.44
Pearson correlation coefficient	—	0.97	0.92	—	1.00	1.00

SENSITIVITY ANALYSES

Sensitivity analyses were conducted as a guide in selecting which parameters should receive the most attention in terms of calibration. Since sensitivity for FHANTM had been conducted [27], the parameters in simulating phosphorus movement in agricultural area in SRPM were not selected for sensitivity analyses in this study. The name data set used for model calibration was used for sensitivity analyses except that the general washoff-buildup pollutant movement algorithm was selected for phosphorus load calculations. In this way, the washoff and build parameters could be used for the sensitivity analyses.

Two types of sensitivity analyses were conducted by performing multiple simulations in SRPM. First, the sensitivity of the runoff hydrographs and volumes to surface characteristics was analyzed. Second, the sensitivity of the pollutographs and pollutant loads to surface characteristics and pollutant buildup and washoff coefficients was examined. The sensitivity analyses of the hydrographs and pollutographs were conducted for a typical storm event in the study area, whereas the sensitivity analyses of the total runoff volumes and total pollutant loads were conducted for the whole simulation period. Since all parameters used for the sensitivity analyses are monthly input values in SRPM, the parameter was increased by 50 percent or decreased by 50 percent only in the month when the typical storm event occurred (i.e., October) for each sensitivity analysis simulation described below.

Sensitivity of Hydrographs and Pollutographs

To examine the sensitivity of the runoff response to the surface characteristics, two key parameters (i.e., Manning roughness coefficient n and depth of maximum depression storage) in SRPM were analyzed. Figure 7 indicated that the peak of the hydrograph tended to decrease and the shape of the hydrograph changed as the n value was increased. This is very similar to the results of a sensitivity analysis on the functional relationship between the hydrograph characteristics and the roughness coefficient conducted by Greene and Cruise [2]. They observed that the hydrograph shape changed to the similar rainfall excess pattern when the Manning roughness coefficient was decreased. A delay of predicted runoff peak was observed, compared to precipitation hydrograph peak (Figure 7). This behavior also shows that the model performs as one would expect.

Similar to the previous result, the hydrograph peak was decreased when the maximum depression depth was increased (Figure 8). The runoff volume was also decreased as the depression depth was increased during the storm event. This is because that the model assumes that surface runoff occurs only when the water depth in the watershed exceeds the maximum depression depth [14]. As the maximum depression depth is increased, the water in the maximum surface storage such as ponding, surface wetting, and interception, is increased and the runoff volume is decreased. Changes in values of the evapotranspiration coefficient caused no impact on hydrographs (Figure 9). This was because no evapotranspiration was observed during storm events, especially during the heavy rainfall event which occurred on October 10, 1989.

To examine the effects of pollutant buildup and washoff coefficients on the pollutographs and total pollutant loads, four input parameters (i.e., maximum buildup value, buildup coefficient, washoff coefficient, and washoff power factor) were selected for the sensitivity analyses. Figures 10 and 11 show the same pattern when the pollutograph peak or the volume of phosphorus loads increased as the maximum buildup value or the buildup coefficient increased. However, the changes observed during the storm event are not significant because the pollutant buildup processes do not occur during storms [10].

A significant change in the pollutograph peak and the volume of phosphorus loads was observed in Figure 12 since the washoff processes occur only during storms [10]. As the washoff coefficient increased, the peak of the pollutograph and the phosphorus loads occurring in the storm event increased. However, no trend was observed in Figure 13 because the amount of pollutant washoff is a function of rainfall intensity. For values of runoff rate $r < 2.54$ cm/hr (1.0 in/hr), the pollutant loads may increase with increasing runoff rate during the middle of a storm by increasing the washoff power factor; however, a larger value of the washoff power factor generally yields lower pollutant loads [10]. Huber et al. suggested that a power factor value less than one should be used if the

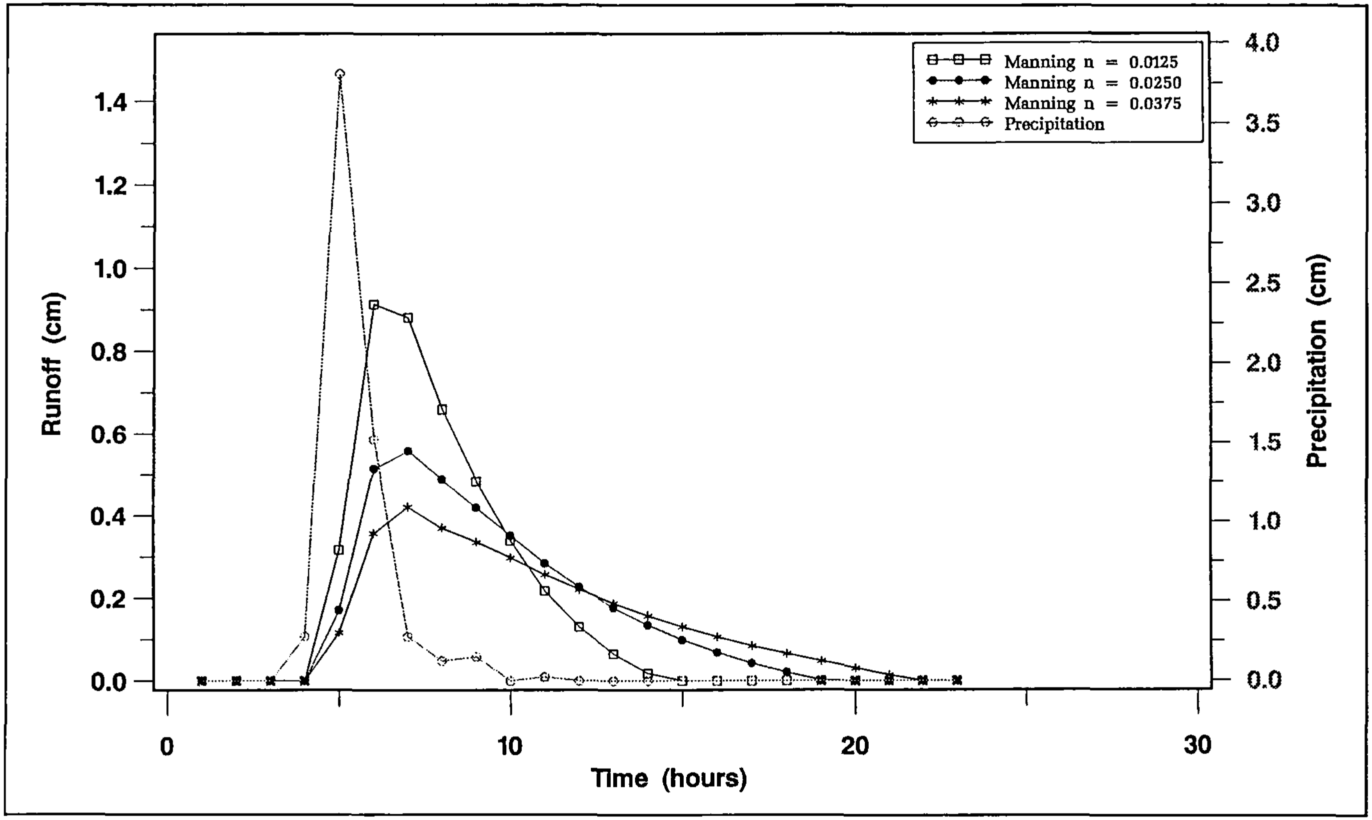

Figure 7. Sensitivity analyses results—runoff hydrographs response to changes in Manning roughness coefficient.

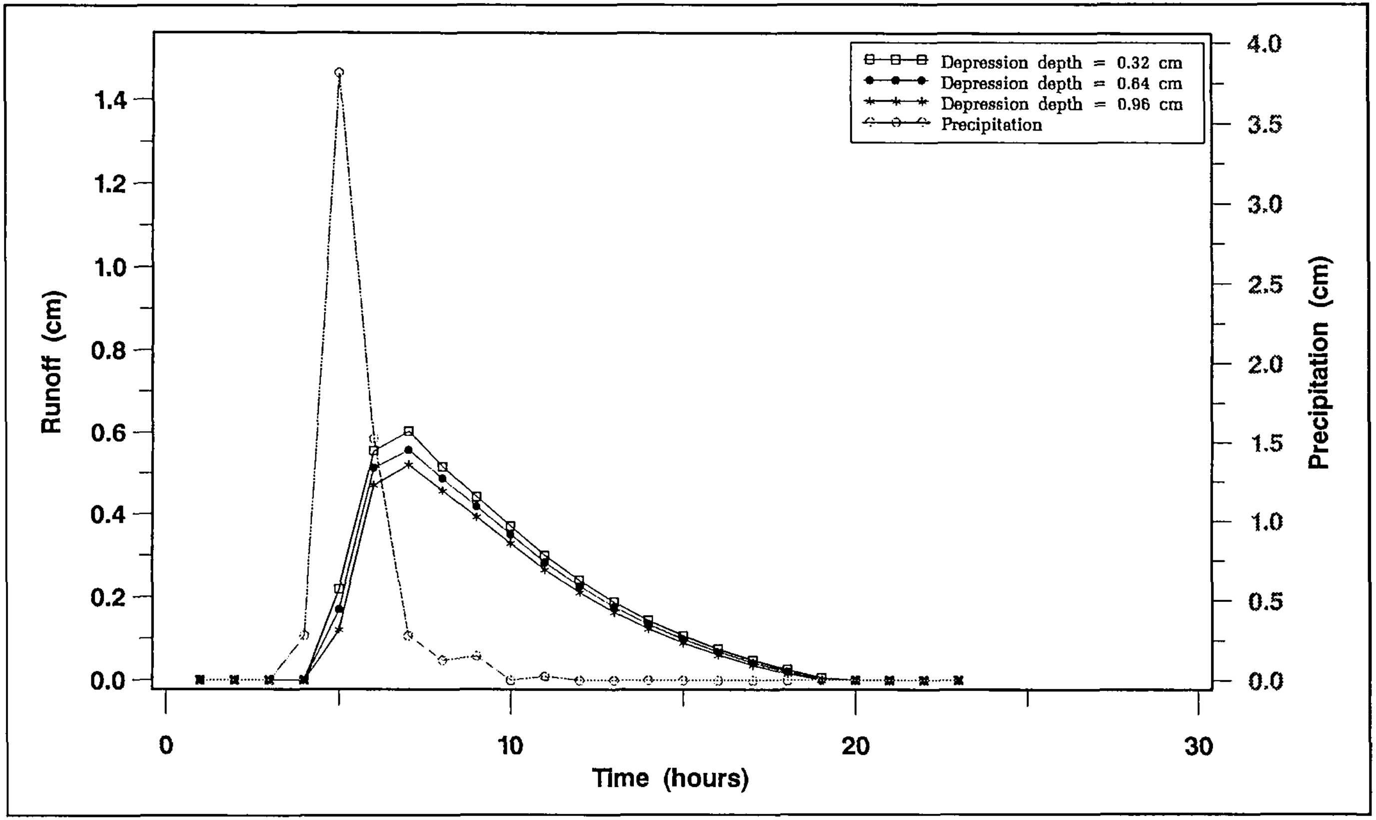

Figure 8. Sensitivity analyses results—runoff hydrographs response to changes in maximum depression depth.

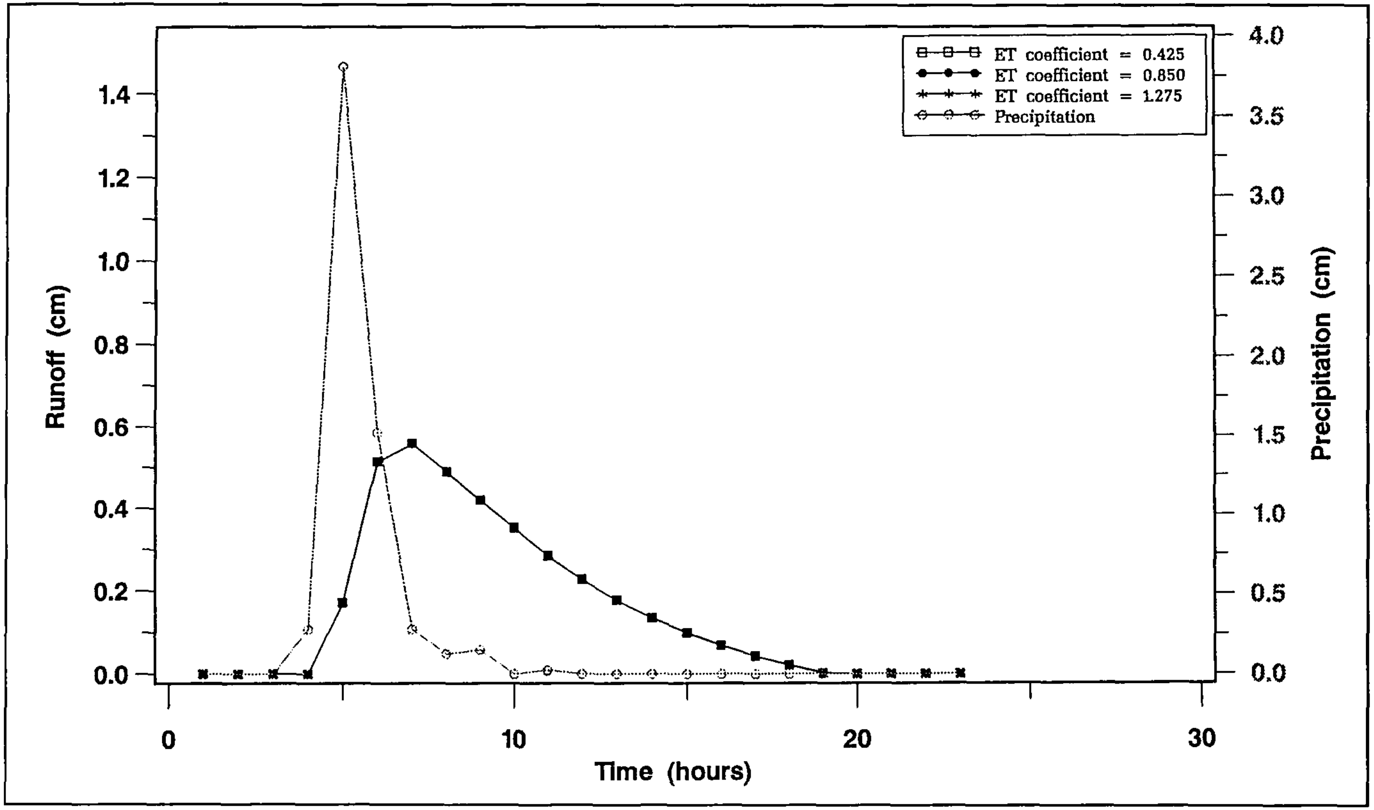

Figure 9. Sensitivity analyses results—runoff hydrographs response to changes in ET coefficient.

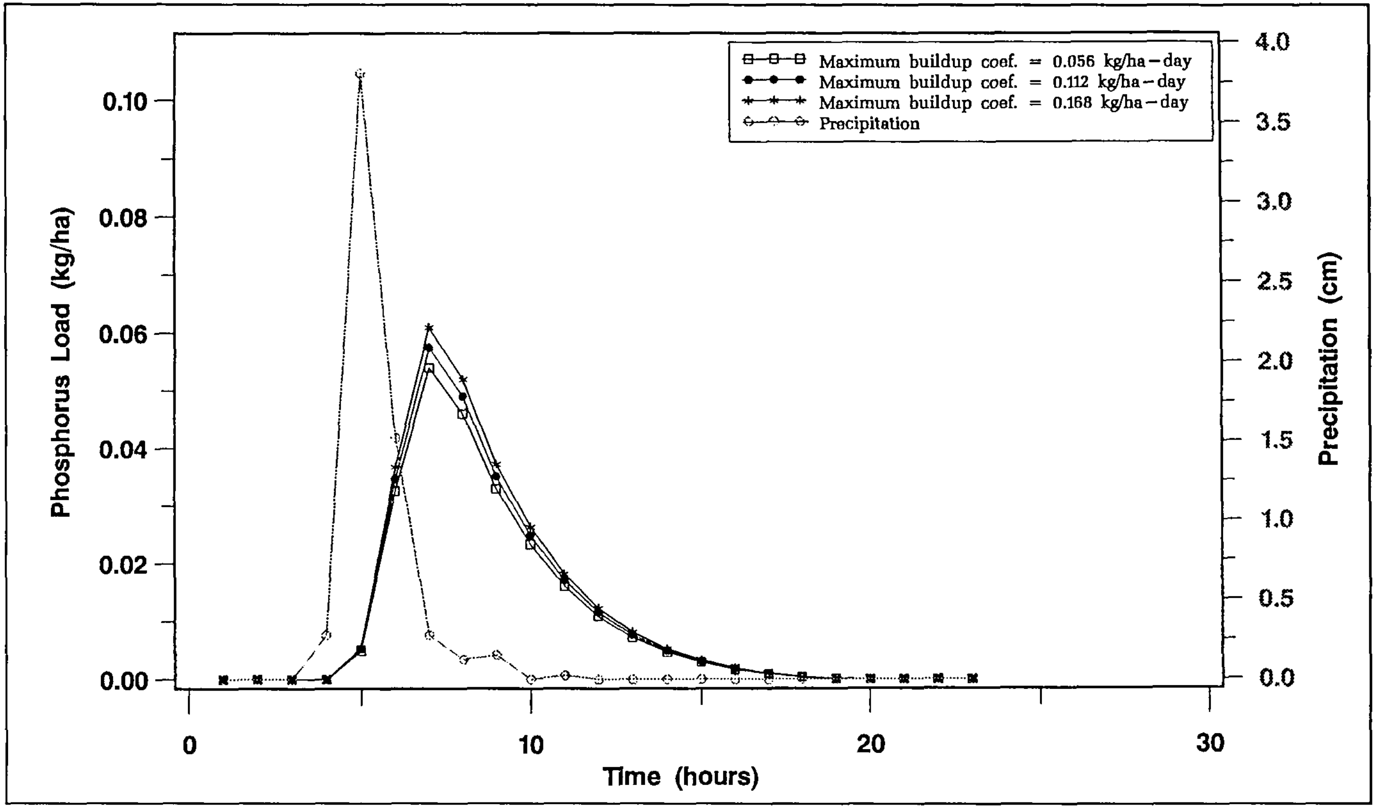

Figure 10. Sensitivity analyses results—phosphorus load pollutographs response to changes in maximum buildup value.

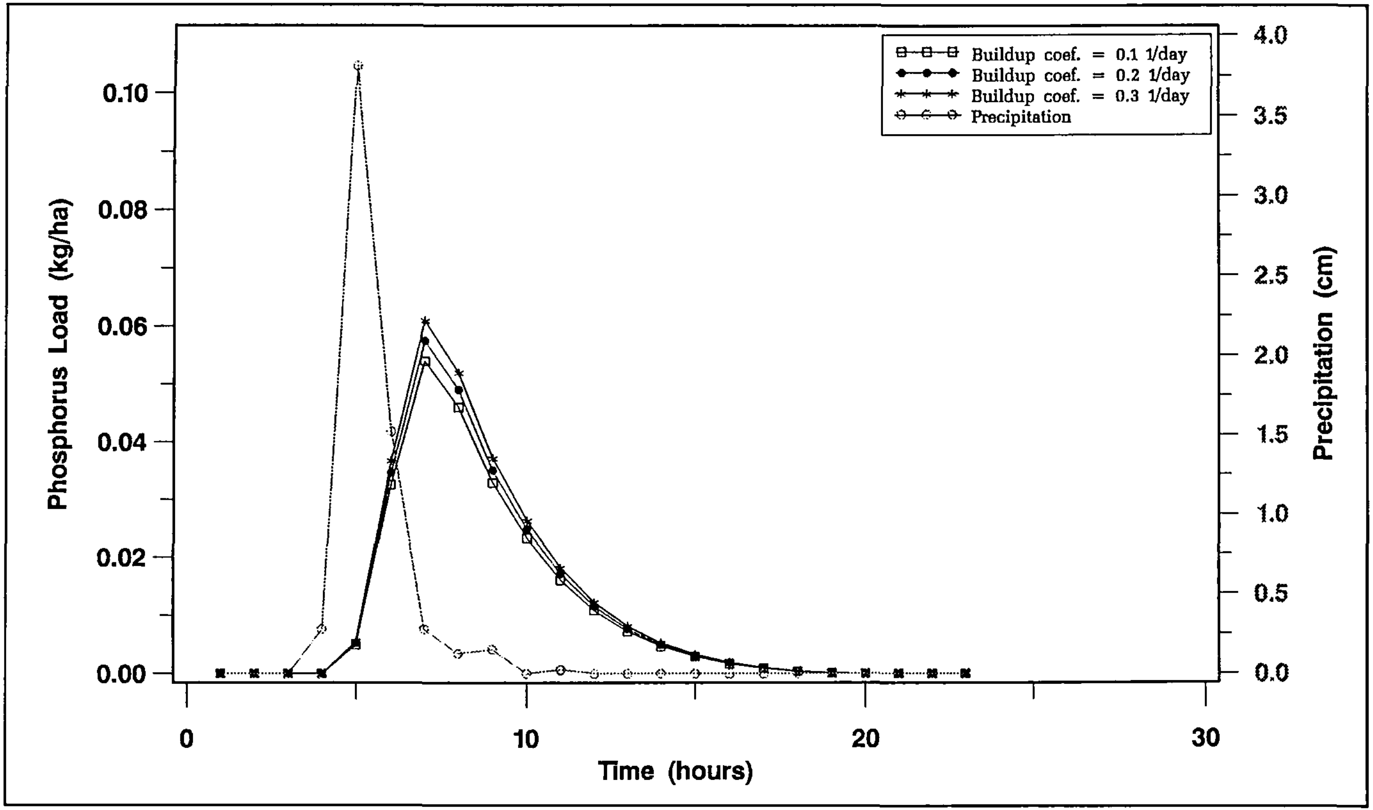

Figure 11. Sensitivity analyses results—phosphorus load pollutographs response to changes in buildup rate.

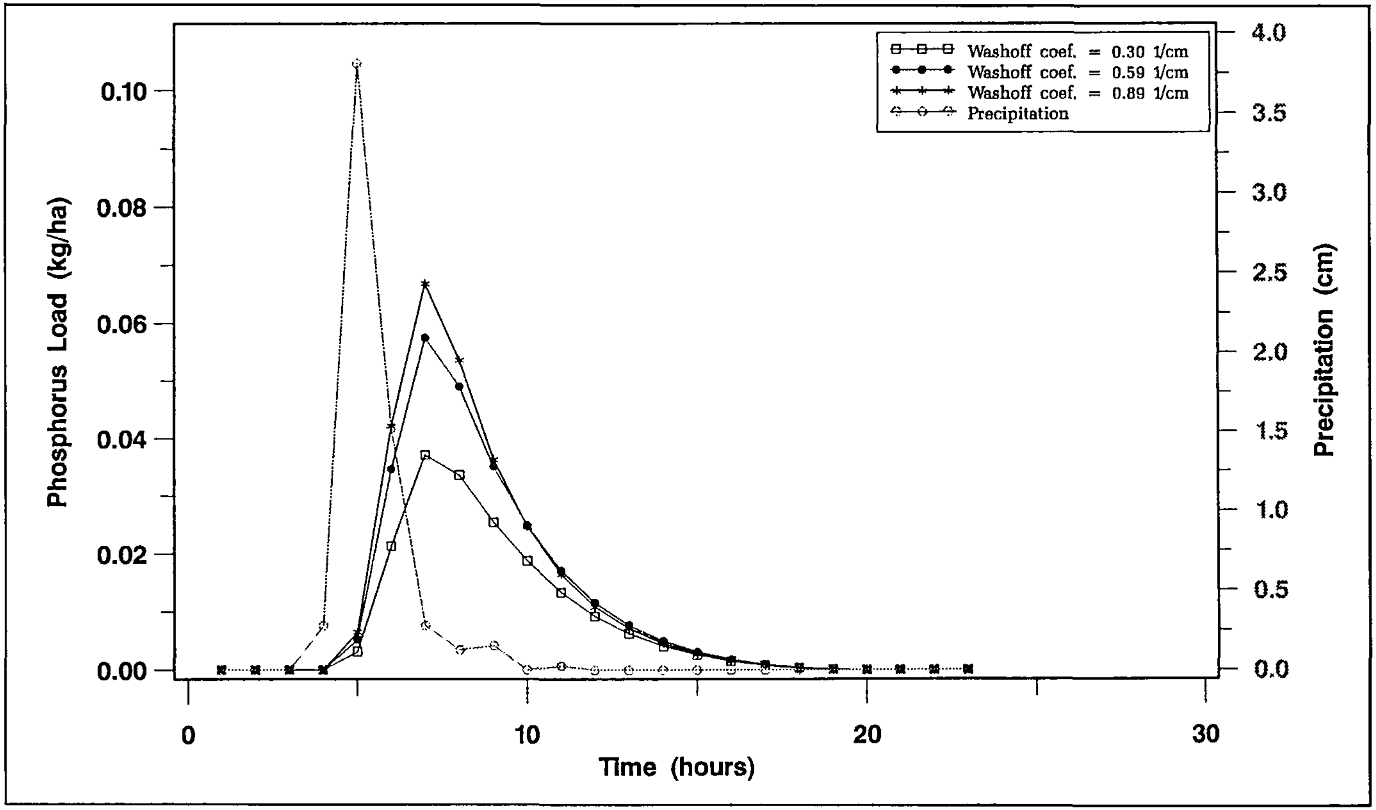

Figure 12. Sensitivity analyses results—phosphorus load pollutographs response to changes in washoff coefficient.

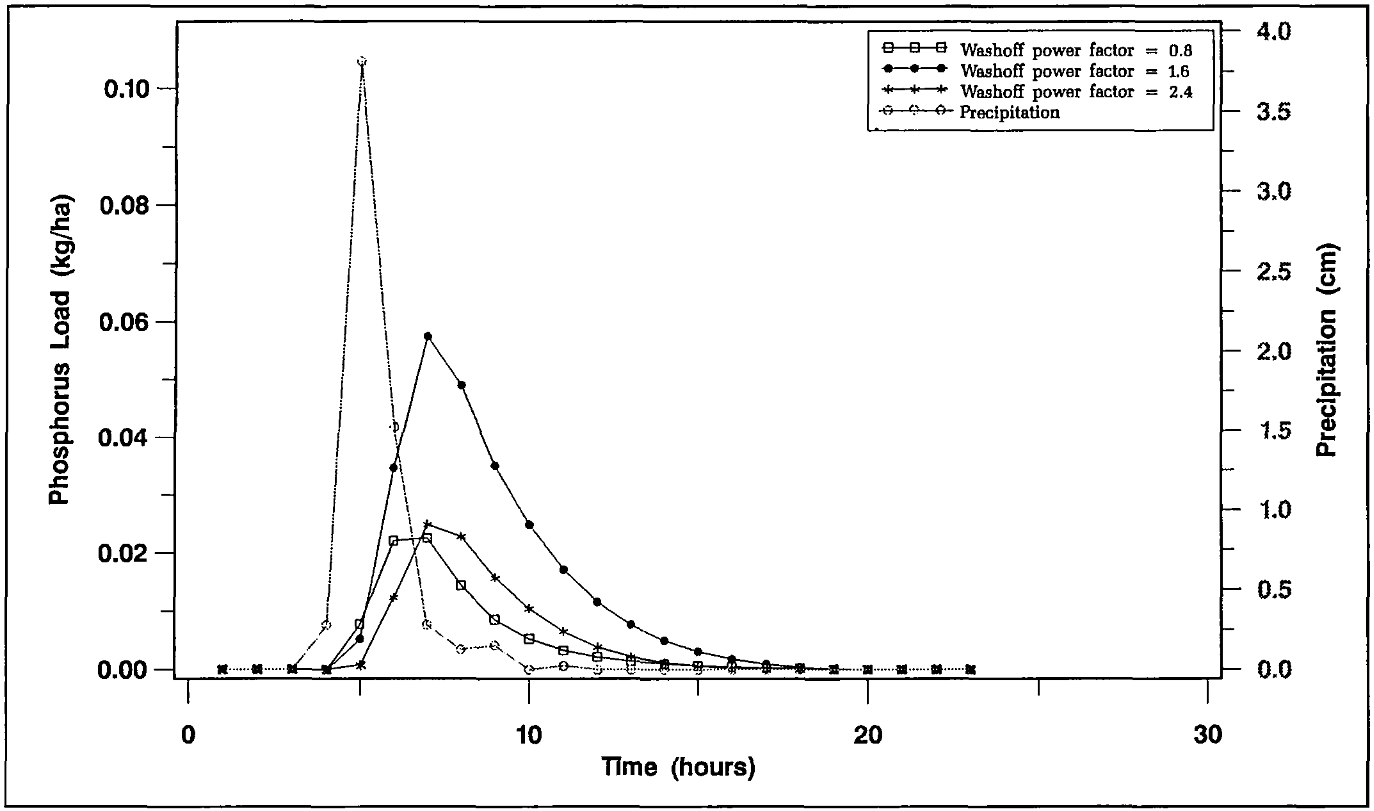

Figure 13. Sensitivity analyses results—phosphorus load pollutographs response to changes in washoff power factor.

concentration of a dissolved constituent is decreased strongly with increasing flow rate; otherwise, the power factor should be greater than one [10].

Sensitivity of Total Runoff Volume and P Loads

The sensitivity analyses of total runoff volume in the thirty-three-month simulation period to changes in the Manning roughness coefficient, maximum depression depth, and ET coefficient demonstrated that the total runoff volume was strongly decreased as the roughness coefficient or the maximum depression depth was increased (Figure 14). The increase of the ET coefficient resulted in the slightly decreased total runoff because the ET coefficient was varied only in the

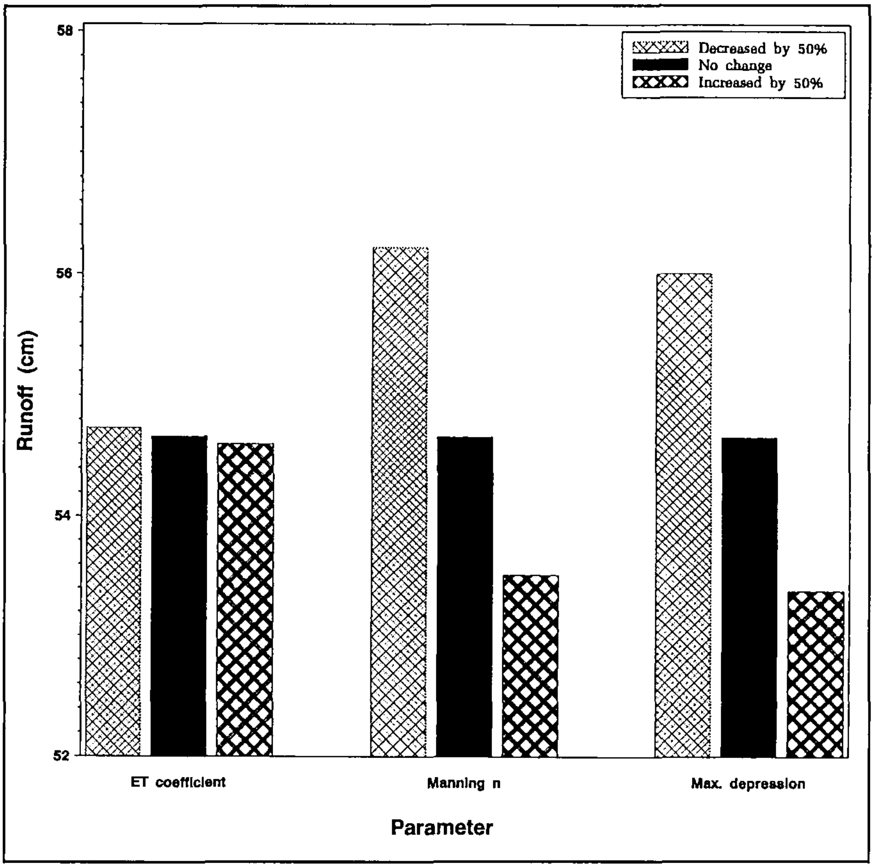

Figure 14. Sensitivity analyses results—total runoff response to key hydrology parameters.

month of October during the whole simulation run. If the ET coefficient is increased in each month, more reduction of total runoff is expected because evapotranspiration occurs mostly in summer season. A lysimeter study of evapotranspiration in South Florida indicated that ET had higher values from April to September than those from October to March [28]. Compared to the sensitivity analysis results of the depression depth to the hydrograph (Figure 8), Figure 14 indicated that cumulative surface runoff was more sensitive to maximum depression depth than storm event hydrograph.

The sensitivity analyses of total phosphorus loads response to various values of the maximum buildup value, buildup coefficient, washoff coefficient, and washoff power factor showed that the total phosphorus loads were increased as the maximum buildup value, the buildup coefficient or the washoff coefficient was increased (Figure 15). Compared with the other parameters, total phosphorus loads were less sensitive to changes in the washoff coefficient parameter and total phosphorus loads decreased as the washoff power factor increased.

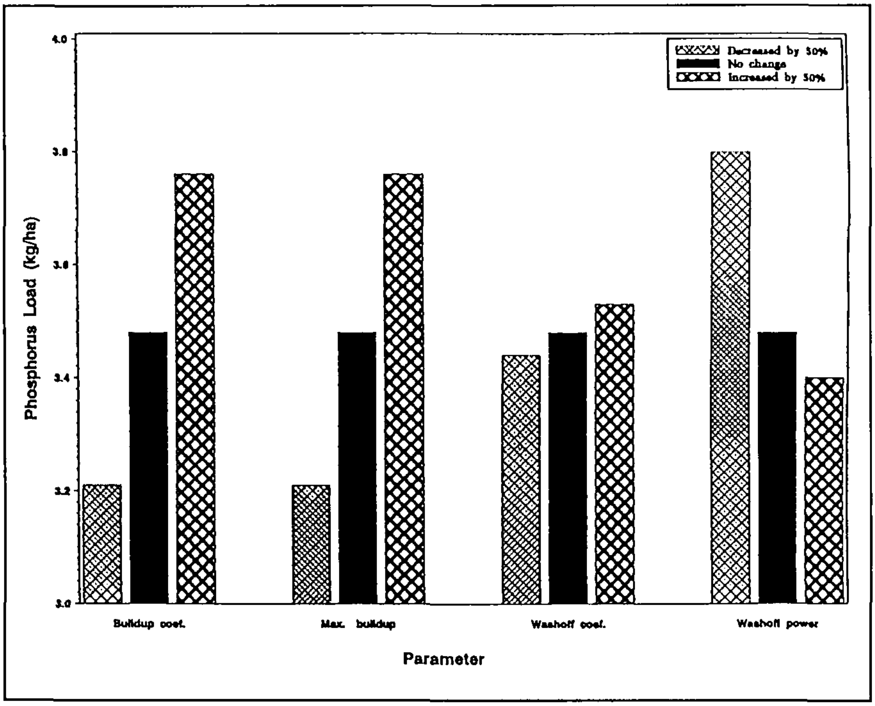

Figure 15. Sensitivity analyses results—total phosphorus loads response to key water quality parameters.

CONCLUSIONS

A stormwater runoff and pollutant model (SRPM) was developed to simulate stormwater runoff and associated pollutant loads occurring in catchments containing both urban and agricultural areas. The model operates on an hourly time step and can simulate hydrographs and pollutographs on both a storm event and a long-term basis. SRPM was written in FORTRAN and can be executed on both DOS and UNIX operating environment. A GIS-based user-friendly interface for the model was developed to allow watershed managers and planners to use SRPM for estimating impacts of urban development and agricultural activities on downstream receiving water quality and quantity.

SRPM was tested on a small catchment area north of Lake Okeechobee. Model simulation results were compared against field observations as well as CREAMS-WT predictions for a thirty-three-month period. Statistical correlation analyses indicated that both models performed well in simulating monthly and annual runoff and phosphorus loads whereas both poorly predicted poor daily runoff and loads with low R^2 values. SRPM could also provide estimates of hydrographs and pollutographs on an hourly basis demonstrated in sensitivity analyses. The model could be applied to a larger drainage basin for predicting runoff and associated pollutant loads for water resources planning and management.

Sensitivity analyses were conducted for key model parameters to examine the effects of changes of model parameters on hydrographs and pollutographs during a typical storm event, as well as on the total runoff volume and total phosphorus loads for the whole study period. The sensitivity analysis results indicated that runoff hydrographs were very sensitive to the Manning roughness coefficient. Peak reductions of hydrographs were observed as the roughness coefficient was increased from 0.0125 to 0.0375. Total runoff volume was also sensitive to the roughness coefficient and the maximum depression depth. A slight sensitivity to the maximum depression depth was observed for the hydrograph. The results of the sensitivity analyses also showed that total phosphorus loads were more sensitive to the maximum buildup value and the buildup coefficient than to the pollutograph occurred in a storm, whereas both the pollutograph and the total phosphorus loads were sensitive to the washoff coefficient or the washoff power factor.

ACKNOWLEDGMENTS

The writers gratefully acknowledge the comments of Douglas Shaw, Tim Bechtel and Garth Redfield on an earlier version of this article. Appreciation is also extended to Zhenquan Chen, Susan Gray, Steve Lin, Zaki Moustafa, and Todd Tisdale for their comments for this article. In addition, the authors would like to thank anonymous reviewers for their critical review and helpful suggestions.

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