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A Comparison of SWAT and HSPF Models for Simulating Hydrologic and Water Quality Responses from an Urbanizing Watershed

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Abstract. *A watershed model can be used to better understand the relationship between land use activities and hydrologic and water quality processes occurring within a watershed. Two different models, SWAT (Soil and Water Assessment Tool) and HSPF (Hydrologic Simulation Program-Fortran), were selected in this study to simulate stream flow, sediment, and nutrients loading from the Polecat Creek watershed in Virginia, which is a 12,048 ha in size. Stream flow and water quality data for the period of September 1996 to June 2000 were used for the calibrations of SWAT and HSPF. Data collected from October 1994 to December 1995 were used to validate the models. The outputs from the models were compared against monitored data at the watershed outlet and at several locations within the watershed. The results indicated that both models were generally able to simulate stream flow, sediment, and nutrients loading well during the simulation period on the Polecat Creek watershed. Considering differences in annual loads and the trend of monthly loads, HSPF simulated hydrology and water quality components more accurately than SWAT at all monitoring sites within the watershed. However, HSPF is less user-friendly than SWAT, due to numerous parameters to control and represent hydrologic cycle, sediment and nutrients transport.*

Keywords. Watershed model, HSPF, SWAT, Runoff, Sediment, Nutrient

Introduction

Nonpoint source pollution from agricultural watershed has been recognized as a significant source of surface water problems since the early 1980s (Novotny and Olem, 1994). These pollutants may be transported in solution with runoff water, suspended in water, or absorbed on eroded soil particles.

A watershed model can be used to better understand the relationship between land use activities and water quality process occurring within a watershed. There are numerous models that can continuously simulate stream flow, sediment, and nutrients loading from watersheds. Some of the most important and widely used models are AGNPS(Agricultural Nonpoint Source; Young et al., 1989), GWLF(Generalized Watershed Loading Function Model; Haith and Shoemaker, 1987), HSPF(Hydrologic Simulation Program-Fortran; Bicknell et al., 1996), and SWAT(Soil and Water Assessment Tool; Arnold et al., 1994). All models have different strengths and limitations.

The US Environmental Protection Agency (US EPA) recently commissioned the development of Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) for supporting the development of Total Daily Maximum Loads (TMDLs) (EPA, 2001). The current version of BASINS provides two watershed models for nonpoint source assessment; HSPF and SWAT models. HSPF is a lumped watershed model that simulates runoff and pollutant loadings from a watershed, integrating these with point source contributions, and performs hydrologic and water quality processes in reaches (Bicknell et al, 1996). SWAT is a physical based, watershed scaled model to predict the effects of land management on water, sediment, and agricultural chemical yields in a complex watershed (Arnold et al., 1995). SWAT was developed by the Department of Agriculture's (USDA) Agricultural Research Service (ARS). In parallel with the EPA supported HSPF, SWAT was also used to develop agricultural nonpoint source dominated TMDLs.

Two different models within the BASINS, SWAT and HSPF, were tested in this study to simulate stream flow, sediment, and nutrients loading from the Polecat Creek watershed in Virginia. Both models were calibrated and validated using flow and water quality data obtained at several sub-watershed outlets and the watershed outlet in the Polecat Creek watershed. The efficacy of the models in simulating runoff and water quality conditions was also compared.

Model Descriptions

HSPF

HSPF is a watershed model that simulates runoff and nonpoint pollutant loads leaving a watershed and performs the fate and transport processes in streams and one-dimensional lakes (Bicknell et al., 1996). HSPF is comprised of three main modules (PERLND, IMPLND, and RCHRES) and five utility modules. For simulation with HSPF, the watershed has to be represented in terms of land segments (pervious and impervious lands) and reaches. The PERLND module represents hydrology and water quality processes that occur on pervious land segment, while the IMPLND may be used for impervious surface area where little or no infiltration occurs. The RCHRES module simulates the processes that occur in a single reach of an open channel or well-mixed impoundment. HSPF is extremely data intensive and over-parameterized model that requires a large amount of site information to accurately represent hydrology and water quality processes in a watershed.

SWAT

SWAT is a physically based, continuous model. It operates on a daily time step and is designed to predict the impacts of management practices on hydrology, sediment, and water quality on an ungaged watershed. Major model components include weather generation, hydrology, sediment, crop growth, nutrient and pesticide (Arnold et al., 1994). More detailed descriptions of the model can be found in Arnold et al. (1996). The watershed is subdivided into HRUs, which is a sub-watershed unit having unique soil and land use characteristics. The water balance of each HRU in the watershed is represented by four storage volumes; snow, soil profile (0-2m), shallow aquifer (2-20m), and deep aquifer (more than 20m). Surface runoff from daily rainfall is estimated in SWAT using SCS curve number method, and sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Berndt (1977). SWAT uses a command language that defines the water movement for the different units, such as sub-basins, rivers, ponds, and reservoirs within the watershed.

Materials and Methods

The Polecat Creek watershed

The Polecat Creek watershed was selected for simulating hydrology and water quality and further comparing the ability of watershed-scale SWAT and HSPF models. It is located in Caroline County in northeastern Virginia (Figure 1). The watershed covers an area of about 12,048 ha and lies in the headwaters of Mattaponi River. The land uses in the watershed include 73% forest, 13% pasture, 2% cropland, 10% urban or developed land, and 2% water (streams, rivers and lakes).

The majority of the watershed lies in the Coastal Plain, while the upper area of the watershed is located in the Piedmont. The soils in the watershed consist of Suffolk, Rumford, Cecil and Appling soil series. Soils of Suffolk series are common in the uplands of Coastal Plain with slopes range from 0 to 50%. They are very deep and well drained soils and cover about 64% of the watershed. The Rumford series are also deep and well drained soils that were formed in the sandy and loamy marine sediment on Coastal Plain. The Cecil and Appling series are very deep, well drained moderately permeable soils on ridges and side slopes of the Piedmont upland. These soils comprise more than 30% of the watershed area.

The flow and water quality data from the Polecat Creek watershed has been measured at five monitoring stations by Chesapeake Bay Local Assistant Department (CBLAD) since 1994. The locations of the monitoring stations in the watershed are shown in Figure 1. Stream flow is measured using a continuous stage recorder at each station. Water samples are also collected at five monitoring stations and are tested for sediment and nutrients according to the standard methods (USEPA, 1979). Automatic samples are taken based on the changes in water level during storm runoff events. Weekly grab samples are also collected to evaluate baseflow condition. Rainfall data is measured at nine sites, which is located within and immediately surrounding the watershed, as shown in Figure 1. Other meteorological data such as evaporation, wind speed, air temperature, and solar radiation are also monitored at the weather station, which was installed at the middle of the watershed.

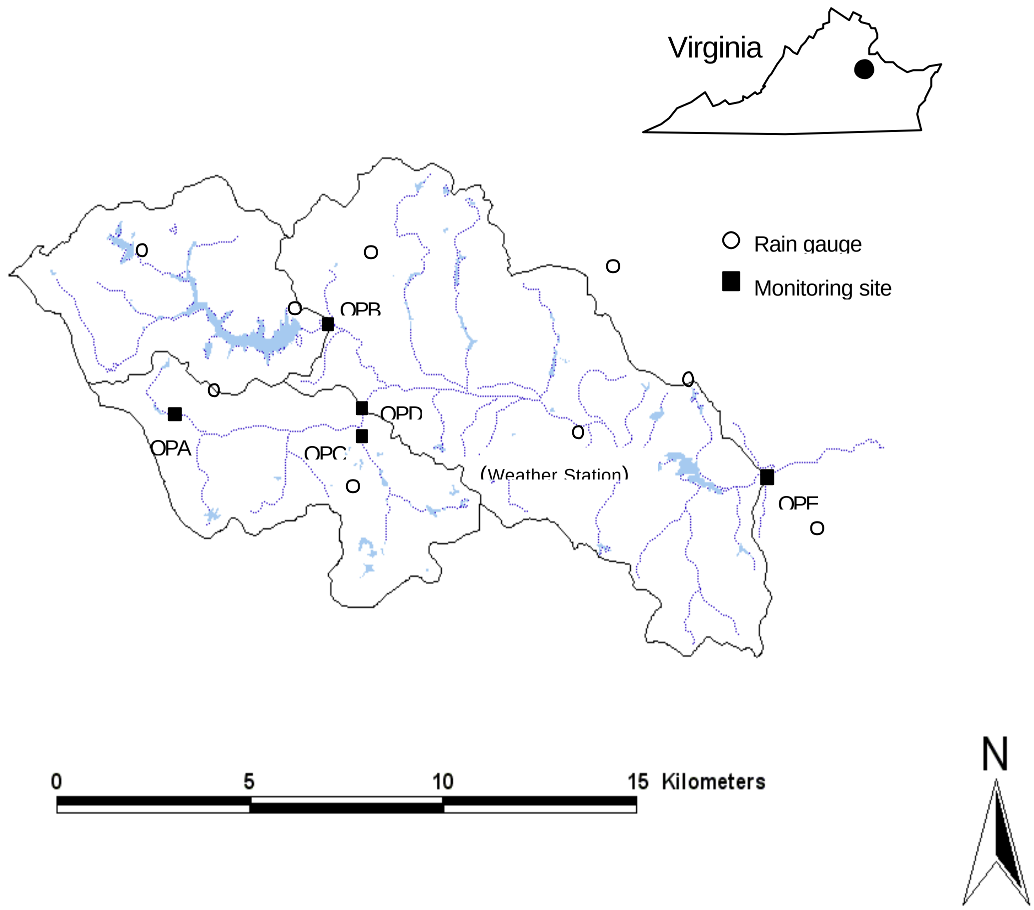

Figure 1. The Polecat Creek watershed and the monitoring stations

Based on the location of monitoring station, three sub-watersheds were delineated in the Polecat Creek watershed. The drainage areas and land use data for each sub-watershed are summarized in Table 1. Sub-watershed QPB has a drainage area of 2,658 ha and contains the most significant developed area in the watershed. Sub-watershed QPD is located in the southwestern part of the Polecat Creek watershed and is 2,605 ha in size. The outlet of the watershed, QPE has a drainage area of 12,048 ha. Land use for QPE includes 74% forest, 13% pasture, 2% cropland, and 10% urban or developed land.

Table 1. Land use data for selected sub-watersheds in the Polecat Creek Watershed

Land use	QPB	QPD	QPE
Area (ha)	2,658	2,605	12,048
Forest (%)	56.5	77.9	74.4
Cropland (%)	11.6	13.0	12.8
Pasture (%)	0.3	1.4	1.5
Commercial (%)	1.0	3.3	2.4
Residential (%)	25.4	4.4	7.8
Water (%)	5.2	0.0	1.1

Result and Discussion

Hydrology Simulation

Table 2 shows the hydrology simulation results by HSPF and SWAT in the Polecat Creek watershed. No significant differences were found in simulated runoff volumes by HSPF and SWAT during the calibration period. For the watershed outlet (QPE), the differences between observed and simulated runoff by HSPF and SWAT were 3.4%, and 2.1%, respectively. HSPF was able to best reproduce monthly runoff volume with correlation coefficients ranging from 0.87 to 0.89 during the calibration period. After hydrologic calibration by SWAT model, correlation coefficients between observed and simulated monthly runoff ranged from 0.81 to 0.84. A comparison of the observed and simulated stream flow for the validation period is also given in Table 2. The differences between observed and simulated annual runoff by HSPF ranged from 1.7% at QPB to 14.7% at QPE during the validation period. SWAT simulated stream flow with 10.7% error in annual runoff volume for QPB, 24.4% for QPD, and 13.3% for QPE.

Table 2. The results of hydrology simulation for the Polecat Creek watershed

Sub-watershed	Annual Runoff Volume (mm/yr)			Relative Error (%)		Correlation Coefficient	
	observed	HSPF	SWAT	HSPF	SWAT	HSPF	SWAT
(a) Calibration (September 1996 to June 2000)							
QPB	332	333	334	0.3	0.6	0.87	0.81
QPD	389	339	388	-12.8	-0.2	0.86	0.84
QPE	381	394	373	3.4	-2.1	0.89	0.84
(b) Validation (October 1994 to December 1995)							
QPB	178	175	197	-1.7	10.7	0.83	0.73
QPD	164	179	204	9.1	24.4	0.89	0.67
QPE	211	180	183	-14.7	-13.3	0.94	0.73

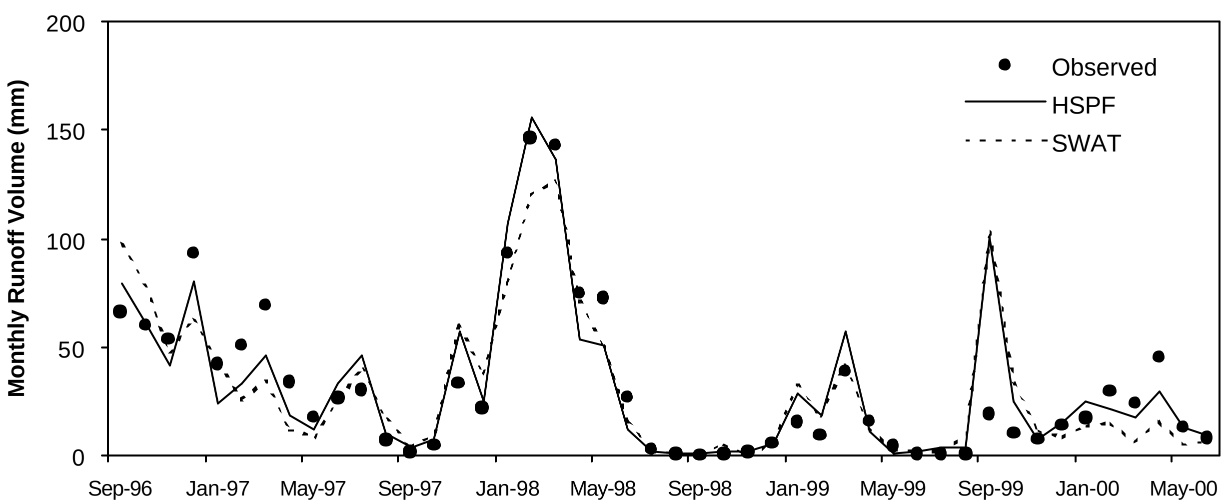

Figure 2. The observed and simulated monthly runoff volumes at QPE during the calibration period

Figure 2 presents the observed and simulated monthly runoff volumes during the calibration period. Results in Table 2 and Figure 2 indicate that the simulated runoff volumes by HSPF were close to the observed values within the Polecat Creek watershed.

Sediment Simulation

The simulated sediment yields by HSPF and SWAT were compared to the observed values collected at three monitoring sites within the Polecat Creek watershed. Table 3 shows simulated and observed sediment yields for the calibration period. The simulated sediment yields by HSPF were considered reasonable with a 8.1% error for QPB, and 0.4% for QPE. The differences between observed and simulated sediment yields by SWAT ranged from 13.9% to 82.3% during the calibration period. The correlation coefficients between observed and simulated monthly sediment yields by HSPF and SWAT during the calibration period were 0.06 and 0.32 for QPB, 0.74 and 0.81 for QPD, 0.42 and 0.39 for QPE, respectively. The calibrated sediment parameter values were validated using measured data from the period of October 1994 to December 1995. The results of sediment simulation during the validation period are also presented in Table 3. The simulated sediment yields by HSPF during the validation period was estimated to be 51.3 kg/ha/yr for QPE with 17.9% error. The correlation coefficients between observed and simulated monthly sediment loads by SWAT were 0.71, 0.64, and 0.71 for QPB, QPD, and QPE, respectively. With exception of QPD during the calibration period, simulated sediment yields by HSPF during the calibration period were generally closer to observed values than those predicted by SWAT. The resulting monthly sediment yields during the calibration period at QPE are shown in Figure 3.

Table 3. The results of sediment simulation for the Polecat Creek watershed

Sub-watershed	Annual sediment yield (kg/ha/yr)			Relative Error (%)		Correlation Coefficient	
	observed	HSPF	SWAT	HSPF	SWAT	HSPF	SWAT
(a) Calibration (September 1996 to June 2000)							
QPB	327.5	301.0	58.0	-8.1	-82.3	0.06	0.32
QPD	64.8	307.1	73.8	373.9	13.9	0.74	0.81
QPE	214.4	215.3	132.6	0.4	-38.1	0.42	0.39
(b) Validation (October 1994 to December 1995)							
QPB	56.0	72.4	27.0	29.3	-51.8	0.41	0.71
QPD	29.5	54.5	61.9	84.7	109.8	0.72	0.64
QPE	43.5	51.3	116.5	17.9	167.8	0.87	0.71

The observed sediment yields for three monitoring sites during the validation period were compared to those predicted by HSPF and SWAT and are presented in Table 3. The simulated sediment yields by HSPF were higher than observed data during the validation period. However, SWAT under-estimated sediment yields by 51.8% at QPB, and over-estimated by 109.8% and 167.8% at QPD and QPE, respectively, during the validation period. Table 3 also shows high correlation coefficients between observed and simulated monthly sediment yields by SWAT for all sub-watershed outlets. Unlike the differences in annual sediment yields, the trend of simulated monthly sediment yields by SWAT was closer to observed values at the sub-watershed outlet QPB, while similar results between HSPF and SWAT were obtained for QPD and QPE during the calibration and validation periods.

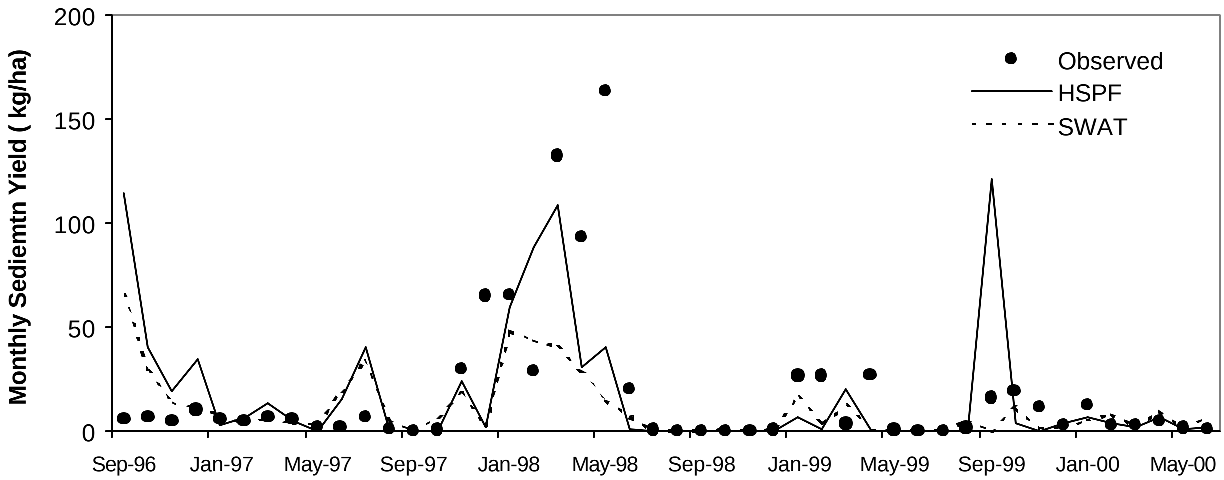

Figure 3. The observed and simulated monthly sediment yields at QPE during the calibration period

Nitrogen Simulation

The agreements between simulated and observed total Kjeldahl nitrogen (TKN) loads are presented in Table 4. The simulated annual TKN for QPE during the calibration period were 0.92 kg/ha/yr by HSPF and 0.95 kg/ha/yr by SWAT, while the measured values were 3.05 kg/ha/yr. The simulated TKN loads by HSPF were considerably lower than the measured data at three monitoring sites. SWAT, with exception of QPB, also under-estimated TKN loads for the calibration period. This is because the applied fertilizer rate used in the model does not accurately reflect the actual management practice in the Polecat Creek watershed. The simulated results by HSPF indicate that the correlation coefficients for TKN during the calibration period ranged from 0.28 to 0.63 for all sub-watersheds. During the calibration period, both SWAT and HSPF under-estimated TKN loads for QPD and QPE. However, HSPF under-estimated TKN loads by 38.2%at QPB during the calibration period, and SWAT over-estimated by 87.9%. The monthly variations of TKN loads at the outlet of the watershed (QPE) during the calibration period are represented in Figure 4.

Table 4. The results of nitrogen simulation for the Polecat Creek watershed

Sub-watershed	Annual TKN load (kg/ha/yr)			Relative Error (%)		Correlation Coefficient	
	observed	HSPF	SWAT	HSPF	SWAT	HSPF	SWAT
(a) Calibration (September 1996 to June 2000)							
QPB	1.65	1.02	3.10	*-38.2*	87.9	0.36	0.33
QPD	1.90	1.04	0.69	-45.3	-63.7	0.63	0.49
QPE	3.05	0.92	0.95	-69.8	-68.8	0.28	0.20
(b) Validation (October 1994 to December 1995)							
QPB	0.78	0.73	1.99	-6.4	155.1	0.28	0.19
QPD	1.00	0.52	0.70	-48.0	-30.0	0.71	0.18
QPE	1.35	0.60	0.74	-55.5	-45.2	0.52	0.41

The differences for annual TKN loads by HSPF and SWAT during the validation period were 6.4% and 155.1% for QPB, 48.0% and 30.0% for QPD, and 55.5% and 45.2% for QPE, respectively. The correlation coefficients of monthly TKN loads between observed and simulated values by HSPF varied from 0.28 to 0.71 during the validation period. Table 4 indicates that the TKN loads predicted by HSPF were closer to the observed values for the Polecat Creek watershed than those predicted by SWAT.

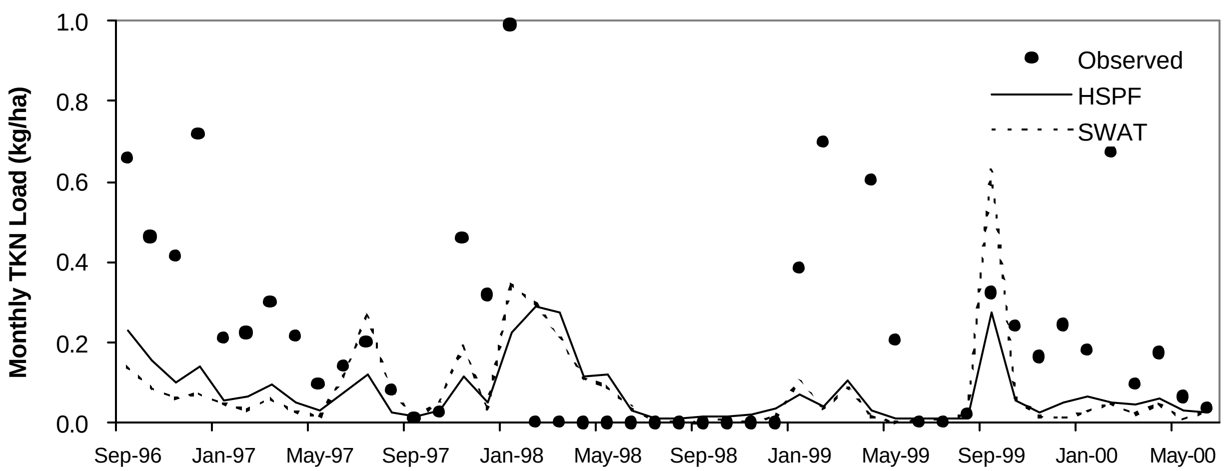

Figure 4. The observed and simulated monthly TKN loads at QPE during the calibration period

Phosphorous simulation

Table 5 shows observed and simulated total phosphorous (TP) loads by HSPF and SWAT during the calibration and validation periods. The simulated TP loads by HSPF and SWAT at the outlet of the watershed (QPE) were much lower than observed values during the calibration period. The simulated annual TP loads by HSPF for QPB and QPD were close to the observed values with a 18.7% and 11.8% errors, respectively, during the calibration period. As shown in Table 5, the trend of monthly TP loads by SWAT was closer to the observed values than HSPF during the calibration period.

Table 5. The results of phosphorous simulation for the Polecat Creek watershed

Sub-watershed	Annual sediment yield (kg/ha)			Relative Error (%)		Correlation Coefficient	
	observed	HSPF	SWAT	HSPF	SWAT	HSPF	SWAT
(a) Calibration (September 1996 to June 2000)							
QPB	0.16	0.19	0.59	18.7	268.7	0.14	0.18
QPD	0.17	0.19	0.06	11.8	-64.7	0.01	0.03
QPE	0.89	0.17	0.16	-80.9	-82.0	0.09	0.15
(b) Validation (October 1994 to December 1995)							
QPB	0.07	0.11	0.41	57.1	485.7	0.17	0.20
QPD	0.07	0.08	0.06	14.3	-14.3	0.44	0.04
QPE	0.24	0.10	0.14	-58.3	-41.7	0.65	0.36

The simulated annual TP loads by HSPF during the calibration period was close to the observed values, while the simulated monthly TP loads by SWAT represented well the trend of the observed values during the calibration period. The differences between observed and simulated annual TP loads by HSPF ranged from 14.3% to 58.3% during the validation period, while the differences in annual TP loads by SWAT varied 14.3% to 485.7%. During the validations of HSPF and SWAT with the calibrated parameters, the statistical correlations between observed and simulated monthly loads at QPE were 0.65 and 0.36, respectively. Figure 5 represents the trends of observed and simulated monthly TP loads for QPE during the calibration period.

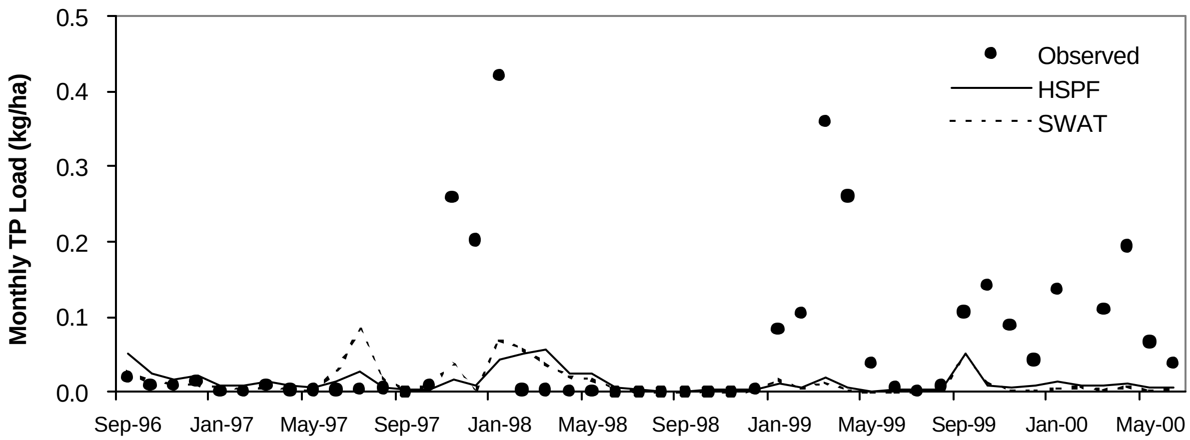

Figure 5. The observed and simulated monthly TP loads at QPE during the calibration period

Conclusion

The HSPF and SWAT models were applied to a 12,048 ha urbanizing watershed in northeastern Virginia to validate its performance in simulating hydrologic and water quality responses. The hydrology and water quality components of HSPF were calibrated against the observed data collected at the watershed outlet and at several sub-watershed outlets. Although SWAT is designed for use in ungaged watershed, the model in this study was also calibrated with available data. Model validations for two models were done for the period of October 1994 to December 1995.

Overall annual runoff volumes predicted by HSPF and SWAT agreed well with the observed data at three monitoring sites within the watershed. However, the simulated stream flows by HSPF were better than those predicted by SWAT during the calibration and validation periods. Sediment yields for the Polecat Creek watershed were adequately simulated by HSPF and SWAT. The trend of simulated monthly sediment yields by SWAT was closer to observed values at the sub-watershed outlet QPB, while similar results between HSPF and SWAT were obtained for QPD and QPE during the calibration and validation periods. With exception of simulated loads by SWAT at sub-watershed outlet (QPB), HSPF and SWAT under-estimated TKN loads at all monitoring sites during the calibration and validation periods. Results of nutrient simulation indicate that simulated TKN and TP loads by HSPF were generally closer to observed values than those predicted by SWAT.

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