농촌계획
Vol. 9, No. 4, 2003 (59-64)

Predicting Runoff and Sediment Yield on a Forest Dominated Watershed using HSPF and SWAT Models

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HSPF와 SWAT 모형을 이용한 산림유역의 유출 및 유사량 추정

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ABSTRACT : U.S. EPA의 BASINS (Better Assessment Science Integrating Point and Nonpoint Sources)에 통합되어 있는 HSPF (Hydrologic Simulation Program-Fortran)와 SWAT (Soil and Water Assessment Tool) 모형을 이용하여 Polecat Creek 유역의 유출과 유사량을 모의하였다. 모형의 보정을 위하여 1996년 9월부터 2000년 6월까지의 하천 유량 및 유사 농도 자료를 이용하였으며, 1994년 10월부터 1995년 12월까지의 관측자료를 이용하여 모형의 검정을 실시하였다. HSPF 모형에 의해 추정된 연 평균 유출량의 상대오차는 보정 및 검정기간에 각각 0.8%, 0.5%이었으며, SWAT 모형에 의해 추정된 연 평균 유출량은 실측치와 각각 2.1%, 16.1%의 오차를 보였다. 연 평균 유사량을 비교하면, HSPF 모형이 보정 및 검정기간에 각각 8.8%와 7.2%의 오차를 보인 반면에 SWAT 모형은 각각 40.0%, 188.4%의 차이를 보였다. HSPF 모형에 의해 추정된 월 평균 유출량 및 유사량의 상관계수는 보정기간에 대하여 0.94와 0.52이었으며, SWAT 모형에 의한 결과는 상관계수가 각각 0.84와 0.39이었다. 이상의 연구 결과에 의하면, HSPF 모형이 SWAT 모형보다 유출과 유사량을 관측치와 유사하게 모의함을 알 수 있었다. 하지만 입력 자료의 구축 및 모형의 적용에는 SWAT 모형보다 많은 시간과 노력을 필요로 하였다.

Key words : HSPF, Hydrology, Nutrient, Performance comparison, Sediment, SWAT

I. 서 론

Vegetation type and land use practices are known to influence runoff and sediment yield in a forested watershed. These potential impacts can be assessed in terms of runoff-generating capacity and soil erosion rate. The most direct and accurate method for assessing the watershed behaviors is to monitor runoff and water quality concentration at the location of interest. The monitoring procedure, however, is expensive, and data monitored are often misinterpreted, due to the lack of understanding of hydrologic and erosion processes occur within the watershed. For these reasons, a properly calibrated watershed model can be used in predicting runoff and sediment yield in a watershed, and evaluating the impacts of different land use practices and sources.

Although many watershed models are available, the selection of the model should ultimately depend on the objectives of the study, the available resources and data. In recent years an increasing number of watershed models can be used to simulate hydrology and water quality responses from a small watershed. 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

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Assessment Tool, Neitsch et al., 2001). All models have different strengths and limitations.

Therefore, the comparison of model performance of various watershed models regarding their capacity of simulating hydrology and water quality is needed for evaluating the advantages and disadvantages of these models. Perrin et al.(2001) performed the comparative studies of 19 daily lumped models on 429 catchments. Johnson et al.(2003) applied HSPF and SMR (Soil Moisture Routing) models to a 102 km^2 watershed and evaluated different runoff mechanisms by comparing simulated streamflow against observed value. Baird et al.(1996) used SWAT and HSPF models in a comparison of each model's effectiveness for predicting streamflow on the Oso Creek watershed. These comparative studies were made to assess the applicability of watershed models, but the studies to date have tended to focus either on rainfall-runoff models, or model capability on hydrology.

The U.S. Environmental Protection Agency (USEPA) recently commissioned the development of Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) for supporting the development of Total Daily Maximum Loads (TMDLs) (USEPA, 2001). Both HSPF and SWAT can be incorporated into USEPA's BASINS, which allows integration of watershed models and in-stream process models within a geographic information system (GIS) framework. In this study, two different models within the BASINS, HSPF and SWAT, were tested to simulate streamflow and sediment yield from the Polecat Creek watershed in Virginia. Both models were evaluated for the period of 1994 to 2000, using rainfall data from nine rain gauges in the watershed, and streamflow and water quality data obtained at the watershed outlet in the Polecat Creek watershed.

II. OVERVIEW OF HSPF AND SWAT MODELS

1. HSPF Model

HSPF is a lumped deterministic 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). It is also incorporated as a part of BASINS system used by USEPA for assessing the effects of point and non-point sources on in-stream water quality. The model uses information such as meteorological data, watershed characteristics, and various model parameters. The simulation result are the time series of the runoff, sediment yield, and nutrient and pesticide concentrations at any point in a watershed. HSPF also simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical.

HSPF consists of different sub-modules for simulating hydrologic and water quality processes in pervious lands, impervious lands, and streams. The watershed has to be represented in terms of two land segments (PERLND and IMPLND) and reach segment (RCHRES). In HSPF, the various hydrologic processes are represented mathematically as flows and storages. Outflow is calculated as a function of the current storage amount and the physical characteristics of the subsystem. Water movement in a pervious land (PERLND) modeled along three paths: overland flow, interflow, and groundwater flow. Each of these three paths experiences differences in time delay and differences in interaction between water and its various dissolved constituents. A variety of storage zones are used to represent the storage processes that occur on the land surface and in the soil horizons. Processes that occur in an impervious land segment (IMPLND) are also simulated. A separate module is used for urban areas where no or little infiltration occurs. Simple constituent concentration in overland flow relys on simple relationship between sediment and water and the assumptions of complete-mixing. Flow through a RCHRES segment is assumed to be unidirectional, and routed by the kinematic wave equation. The migration of each sediment fraction between suspension in water and the bed is modeled by balancing deposition and scour computations.

2. SWAT Model

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 (Neitsch et al., 2001). The watershed is subdivided into hydrologic response units (HRUs), having unique soil and land use characteristics. More detailed descriptions of the model can be found in Neitsch et al.(2001).

The hydrologic model is based on the water balance equation :

$$SW_t = SW_o + \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \qquad (1)$$

where SW_t is the final soil water content, SW_o is the initial soil water content on day i, t is time in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, runoff, evapotranspiration, percolation, and return flow, respectively. All units are in mm.

SWAT uses the SCS curve number method to compute surface runoff from daily rainfall amount. A modified rational method and SCS TR-55 method are used to compute the peak runoff rate. Three available methods, Penman-Monteith, Hargreaves, and Priestley-Taylor methods are also used for estimating the evapotranspiration within SWAT.

Sediment yield is computed for each HRU with the Modified Universal Soil Loss Equation (MUSLE).

$$SED = 11.8(Q \cdot q_p \cdot A)^{0.56}(K)(C)(P)(LS)(CFRG) \qquad (2)$$

where SED is the sediment yield on a given day (metric tons), Q is the surface runoff column (mm), q_p is the peak flow rate (m^3/s), A is the area of HRU (ha), K is the soil erodibility factor, C is the crop management factor, P is the erosion control practice factor, and LS is the topographic factor. $CFRG$ is the coarse fragment factor.

III. MATERIALS AND METHODS

1. Site Description

The Polecat Creek watershed was selected for simulating hydrology and water quality and further comparing the ability of HSPF and SWAT models. It is located in Caroline County in northeastern Virginia as referred to by Im et al.(2003). 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.

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.

Stream flow is measured using a continuous stage recorder at the outlet of the watershed. Discharges were generated from measured stages (water depth) and the stage-discharge relations. Water samples were also collected at monitoring station and are tested for sediment and nutrients according to the standard methods (USEPA, 1979). Composite samples are taken based on the changes in water level during storm runoff events. Weekly grab samples are also collected to evaluate baseflow condition. Monthly sediment yield was calculated based on measured concentration for both storm flow and ambient flow periods. For the purpose of selecting storm flow period, time series of rainfall and stream flow were used to define the starting and ending time of each storm event. The sediment loads for each of the storm events were calculated as the concentrations of each composite sample multiplied by the flow volume during collection of that sample. Monthly sediment yield during ambient flow periods were estimated as the product of the runoff volume for a given month and an average sediment concentration, which was calculated as the median value of grab sampling data for that particular year.

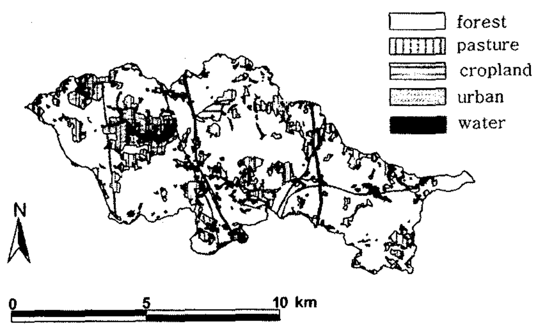


Figure 1. The Polecat Creek watershed

2. Model Evaluation

Measured streamflow and water quality data were used for model calibration in terms of hydrology, sediment, nitrogen, and phosphorous from September 1996 to June 2000. Validation for both models was performed for the period of September 1994 to December 1995. In order to determine appropriate initial conditions for the corresponding time of year, a one-year warm-up period was inserted at the beginning of each simulation period. Model results for the parameter initialization period were ignored in the computation of model performance. HSPF and SWAT models' results were evaluated on a daily time step for hydrology simulation. Hourly HSPF results were aggregated to a daily time step prior to the comparison. Sediment calibration was performed to establish a long-term and monthly sediment balance for observed and simulated sediment yields.

IV. RESULTS AND DISCUSSION

1. Long-term balance analysis

The long-term balances in runoff and sediment yield were first evaluated by comparing simulated average annual values against observed values for the calibration and validation periods. The relative error, expressed in percent, of average annual value was used in this study for one of the model performance estimator. A comparison of average annual values in runoff and sediment yield is presented in Table 1.

The average annual runoff of the Polecat Creek watershed predicted by HSPF and SWAT was close to the observed value for the simulation period. The differences between observed and simulated average annual runoff volumes by HSPF and SWAT were 0.8% and 2.1% for the calibration period, and the differences for the validation period were 0.5% and 16.1%, respectively. Average annual runoff predicted by HSPF was closer to observed value than SWAT for the calibration and validation period.

Average annual sediment yields simulated by HSPF were estimated to be 201.5 kg/ha/yr, and 40.4 kg/ha/yr, respectively, for the calibration and validation periods. These resulted in 8.8% and 7.2% relative errors for the simulation period. Table 1 shows that SWAT under-predicted

Table 1. Observed and Simulated average annual values of runoff and sediment yield

Average annual value	Calibration			Validation		
	Observed	HSPF	SWAT	Observed	HSPF	SWAT
Runoff (mm/yr)	381	384 (0.8)	373 (2.1)	218	217 (0.5)	183 (16.1)
Sediment (kg/ha/yr)	220.9	201.5 (8.8)	132.6 (40.0)	40.4	43.3 (7.2)	116.5 (188.4)

*( ): Percent relative error of average annual value (%)

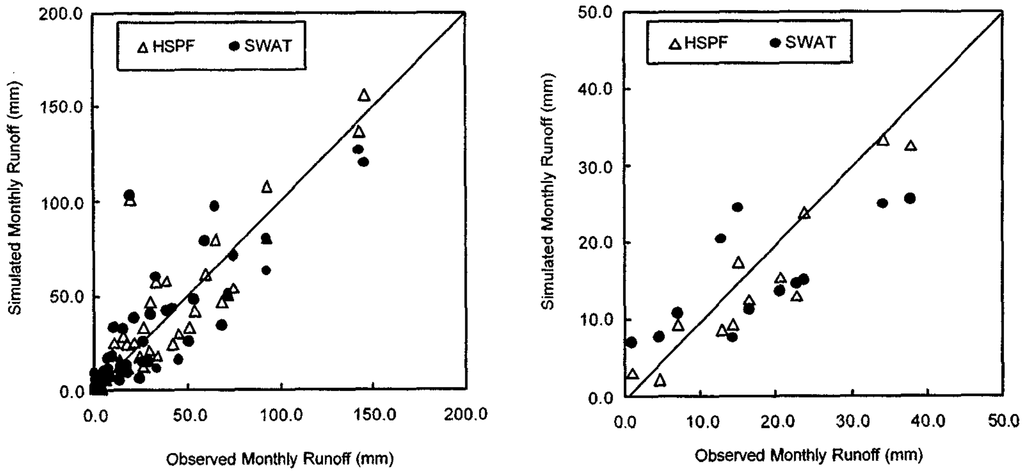
sediment yield by 40.0% for the calibration period, while SWAT over-predicted by 188.4% for the validation period. For the simulation period, simulated sediment yield by HSPF was generally closer to observed values than that predicted by SWAT.

2. Seasonal Variation

The trend of simulated monthly value was compared to that of observed value. Correlation coefficients between observed and simulated monthly values by HSPF and SWAT were compared for evaluating the performance of HSPF and SWAT models. Table 2 shows the correlation coefficients between observed and simulated monthly runoff and sediment yield by HSPF and SWAT models.

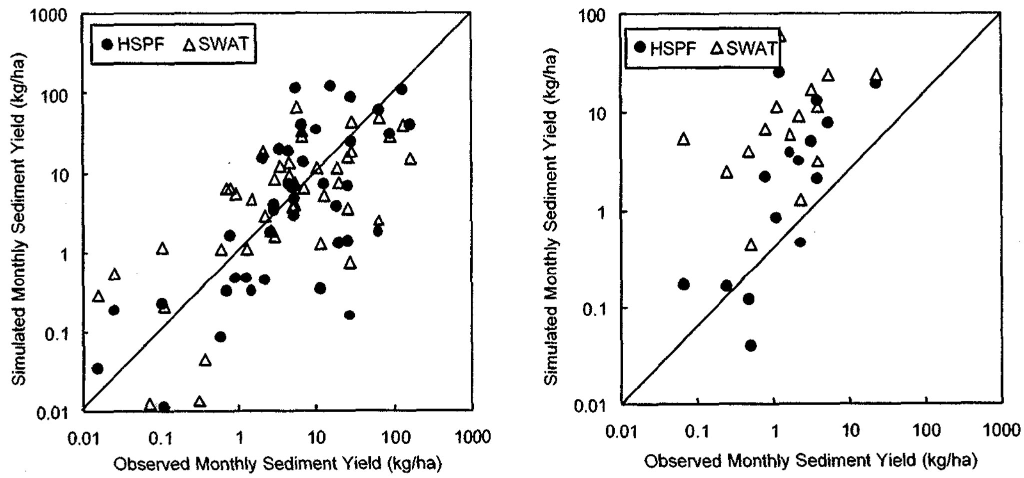
HSPF was able to best reproduce the trend of monthly runoff with higher correlation coefficient during the calibration period. After hydrologic calibration by HSPF and SWAT models, correlation coefficients between observed and simulated monthly runoff were 0.74 and 0.73, respectively, for the validation period. Simulated monthly runoff volumes by HSPF and SWAT were close to the measured values during calibration, while HSPF presented a better average monthly flow for the validation period. A comparison of observed and simulated monthly runoff for the calibration and validation periods is presented in Figure 2.

The correlation coefficients between observed and simulated monthly sediment yields by HSPF and SWAT during the calibration period were 0.52 and 0.39, respectively, while correlation coefficients for the validation period were 0.81 and 0.71, respectively. For the validation period both models have the better prediction of sediment yield from the Polecat Creek watershed. However, the overall trend of simulated monthly sediment yield by HSPF was closer to observed value on the Polecat Creek watershed. Figure 3 shows the scatter plot of monthly sediment yield for the calibration and validation periods.



(a) Calibration (b) Validation

Figure 2. Observed and simulated monthly runoff volumes of the Polecat Creek watersh



(a) Calibration (b) Validation

Figure 3. Observed and simulated monthly sediment yields of the Polecat Creek watershed.

Table 2. Correlation coefficients of monthly runoff and sediment yield

Correlation coefficient*	Calibration		Validation	
	HSPF	SWAT	HSPF	SWAT
Runoff volume	0.94	0.84	0.74	0.73
Sediment Yield	0.52	0.39	0.81	0.71

* Correlation coefficient between observed and simulated monthly values

V. CONCLUSION

The HSPF and SWAT models were applied to a 12,048 ha forest dominated watershed in northeastern Virginia to validate its performance in simulating hydrologic and water quality responses. The hydrology and sediment components of HSPF were calibrated against the observed data collected at the watershed outlet. Although SWAT is designed for use in the ungaged watershed, the model in this study was also calibrated with available data. Data collected from September 1996 to June 2000 were used for the calibrations of HSPF and SWAT. 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 the Polecat Creek watershed. However, the simulated stream flows by HSPF were better than those predicted by SWAT during the calibration and validation periods. Average annual sediment yields for the Polecat Creek watershed were adequately simulated by HSPF. However, SWAT under-predicted sediment yield for the calibration period, and over-predicted for the validation period.

Considering differences in annual totals and the trends of monthly values, HSPF simulated hydrology and sediment more accurately than SWAT on the Polecat Creek watershed. However, HSPF is less user-friendly than SWAT. HSPF includes numerous parameters to represent the hydrologic cycle, and erosion loss and transport. The calibration of these parameters in HSPF is strenuous and time consuming process. In SWAT, most of the parameters are automatically generated from GIS data or other information and relatively easy to adjust with proper instruction.

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