EVALUATION OF SWAT AND HSPF WITHIN BASINS PROGRAM FOR THE UPPER NORTH BOSQUE RIVER WATERSHED IN CENTRAL TEXAS

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ABSTRACT. *USEPA's water program staff and their counterparts in state pollution control agencies increasingly emphasize watershed and water quality−based assessment and integrated analysis of point and nonpoint sources of pollution. BASINS 3.0 (Better Assessment Science Integrating point and Nonpoint Sources) is a system developed to meet the needs of such agencies. This study was conducted to evaluate the major watershed−scale models, SWAT (Soil and Water Assessment Tool) and HSPF (Hydrological Simulation Program − Fortran), included within the BASINS 3.0 system. SWAT and HSPF were calibrated and verified with data from the Upper North Bosque River watershed (UNBRW), an intense dairy producing region located in central Texas. The model output was calibrated for daily flow, sediment, and nutrients measured at five stream sites within the UNBRW for the period of January 1994 through June 1995 and verified (daily and monthly time−step) for the period of July 1995 to July 1999. Nash−Sutcliffe model efficiency (E) and mean error (ME) were used to evaluate the accuracy of the models. The average daily flow, sediment, and nutrient loading simulated by SWAT were closer to measured values than HSPF during both calibration and verification periods at the outlet of UNBRW. As indicated by E values, the temporal variations of daily flow (E = 0.72 and 0.70 for HSPF, while E = 0.17 and 0.62 for SWAT during the calibration and verification, respectively) and sediment (E = 0.11 and 0.23 for HSPF, while E = −2.50 and −3.51 for SWAT during the calibration and verification, respectively) were better described by HSPF during the calibration and verification periods. However, the model efficiencies of both models for monthly flow (E = 0.91 and 0.86 for HSPF, while E = 0.50 and 0.78 for SWAT during the calibration and verification, respectively) and sediment (E = 0.72 and 0.88 for HSPF, while E = 0.83 and 0.59 for SWAT during the calibration and verification, respectively) significantly improved. SWAT generally proved to be a better predictor of nutrient loading during both the calibration and verification periods.*

Keywords. *Agriculture, Dairies, Models, Nutrients, Sediment, Water quality.*

BASINS (Better Assessment Science Integrating point and Nonpoint Sources) is a watershed and water quality−based assessment system that integrates geographical information system (GIS), national watershed data, and environmental assessment and modeling tools into one package (USEPA, 2001). BASINS was originally released in September 1996 to: (1) facilitate examination of environmental information, (2) support analysis of point and nonpoint source management alternatives, and (3) provide an integrated watershed and modeling framework. BASINS currently supports the development of total maximum daily loads (TMDLs), which require a watershed−based approach that integrates both point and nonpoint sources.

The latest version of BASINS (version 3.0) includes: (1) nationally derived databases with data extraction tools; (2) assessment tools that address large− and small−scale characterization needs; (3) utilities to facilitate organizing and evaluating data; (4) watershed delineation tools; (5) utilities for classifying DEM (digital elevation models), land use, soils, and water quality observations; (6) watershed characterization reports that facilitate compilation and output of information on selected watersheds; (7) QUAL2E (version 3.2) (Brown and Barnwell, 1987), an instream water quality and eutrophication model; (8) HSPF (Hydrological Simulation Program − Fortran; Johansen et al., 1984) and SWAT (Soil and Water Assessment Tool; Arnold et al., 1998; Neitsch et al., 2002a), watershed loading and transport models; and (9) PLOAD (Pollutant Loading program), a simplified GIS−based model that estimates nonpoint loads of pollution on an annual average basis.

WinHSPF is the new interface to HSPF within BASINS 3.0. The interface to HSPF in earlier versions of BASINS was known as NPSM (Nonpoint Source Model). WinHSPF is the modified version of NPSM, which provides more accessibility to all features of HSPF by enhanced graphical displays and editing capabilities. A customized GIS environment within BASINS 3.0 integrates physiographic data, monitoring data, and associated assessment tools. The required input files are generated within the GIS environment and passed directly to the models. SWAT is a physical−based watershed−scale model that was developed to predict the impacts of land management practices over long periods of time on water, sediment, and agricultural chemical yields in large complex

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watersheds with varying soils, land uses, and management conditions (Arnold et al., 1998). The HSPF model, which has components similar to those of SWAT, also provides continuous−time simulation of both watersheds and river basins to assess NPS (nonpoint source) pollution.

A post−processor program, known as GENSCN, within BASINS 3.0 is designed to work with data in a variety of formats including watershed data management (WDM) files, SWAT output files, and observed water quality database files.

The main objective of this study was to evaluate and compare SWAT and HSPF within BASINS 3.0 using daily and monthly measured flow, sediment, and nutrient loading for the UNBRW stream system.

METHODS AND MATERIALS

DESCRIPTION OF SWAT AND HSPF MODELS

In response to the passage of the Clean Water Act in the early 1970s and the growing awareness of agricultural NPS pollution issues, the USDA Agriculture Research Service (ARS) and other agencies initiated the development of several process−based water quality models. These models were designed to provide guidance on best management practices that could help mitigate NPS pollution at the field−scale and river basin−scale.

The SWAT model was developed to provide continuous−time simulations with a high level of spatial detail by allowing the division of a watershed or river basin into hundreds or thousands of grid cells or subwatersheds. SWAT operates on a daily time−step and is designed to evaluate management effects on water quality, sediment, and agricultural chemical yield in large, ungauged basins. The model is based on a command structure for routing runoff and chemicals through a watershed. These commands allow the user to route flows through streams and reservoirs, combine flows, and input measured data (e.g., weather) and point−source loading. The major components of SWAT include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Neitsch et al., 2002a).

The hydrology component of SWAT includes surface runoff using modified SCS curve number CN2 (USDA−SCS, 1972) or the Green−Ampt (Green and Ampt, 1911) infiltration method, percolation, lateral subsurface flow, groundwater return flow, evapotranspiration, and channel transmission loss subroutines. The minimum weather inputs required by SWAT are generated or measured maximum and minimum air temperature and precipitation. Sediment yield is estimated with the modified universal soil loss equation (MUSLE) developed by Williams (1975). Daily average soil temperature is simulated as a function of the maximum and minimum annual air temperatures, surface temperature, and damping depth. SWAT also simulates several forms of nitrogen and phosphorus within soil profiles and through surface and lateral subsurface flows.

HSPF is a comprehensive, continuous, lumped parameter, watershed−scale model that simulates the movement of water, sediment, pesticides, and nutrients on pervious and impervious surfaces, in soil profiles, and within streams and well−mixed impoundments (Bicknell et al., 2000). Hydrocomp, Inc., under contract with the U.S. Environmental Protection Agency (USEPA), developed HSPF in the late 1960s. HSPF is driven by a meteorological data time series including precipitation, temperature, dewpoint, solar radiation, wind speed, and evaporation. HSPF includes routines to simulate runoff, suspended solids, nutrients, water temperature, pesticides, biochemical oxygen demand, phytoplankton, pH, and dissolved oxygen. In addition, HSPF allows the user to simulate selected water quality constituents by specifying their sources, sinks, chemical properties, and transport behavior.

WinHSPF works with the EPA−supported HSPF model (version 12.0) (Bicknell et al., 2000). WinHSPF supports a full suite of the HSPF model capabilities including estimation of nonpoint−source loading from mixed land uses and simulation of fate and transport processes in streams and one−dimensional lakes. WinHSPF is capable of simulating a single watershed or a system of multiple hydrologically connected subwatersheds. Similar to SWAT, HSPF requires land−use data, reach data, meteorological data, and information on the pollutants of concern in the watershed and its reaches. WinHSPF is designed to interact with the BASINS 3.0 utilities and data sets to facilitate the extraction of appropriate information and the preparation of model input files. The reach network is automatically developed based on the subwatershed delineation. The input files can be modified and adapted to site−specific conditions through the use of WinHSPF and supporting information provided by the BASINS 3.0 utilities and reporting functions, as well as locally derived data sources. WinHSPF is also designed to work with post−processing tools that facilitate, display, and interpret output data.

WATERSHED DESCRIPTION

The UNBRW is defined as the contributing drainage area above sampling site BO070 located on the North Bosque River at Hico, Texas (fig. 1). The UNBRW is 98% rural with the primary land uses being rangeland (43%), forage fields (23%), and dairy waste application fields (7%) (McFarland and Hauck, 1999). Dairy production is the dominant agricultural activity; other important agricultural enterprises include peanut, range−fed cattle, pecan, peach, and forage hay production. The watershed lies primarily in two major land resource areas, known as the West Cross Timbers and the Grand Prairie. The soils in the West Cross Timbers are dominated by fine sandy loams with sandy clay subsoil, while calcareous clays and clay loams are the predominant soil types in the Grand Prairie (Ward et al., 1992). The elevation in the watershed ranges from 305 to 496 m.

The city of Stephenville (population 16,000) and portions of the smaller cities of Dublin and Hico are located within the UNBRW. The Stephenville wastewater treatment plant (SWTP), with an average discharge of 6380 m^3 per day during the simulation period, is the only point source permitted to discharge into the watershed. The SWTP is located approximately 0.4 km above stream site BO040.

The average annual precipitation in the area is approximately 750 mm and the average daily temperature ranges from 6°C in winter to 28°C in summer (McFarland and Hauck, 1999). Winter and fall rainfall is induced by continental polar fronts, which produce low−intensity, long−duration storms. In the spring and summer, the majority of rainfall events are squall−line thunderstorms, which produce

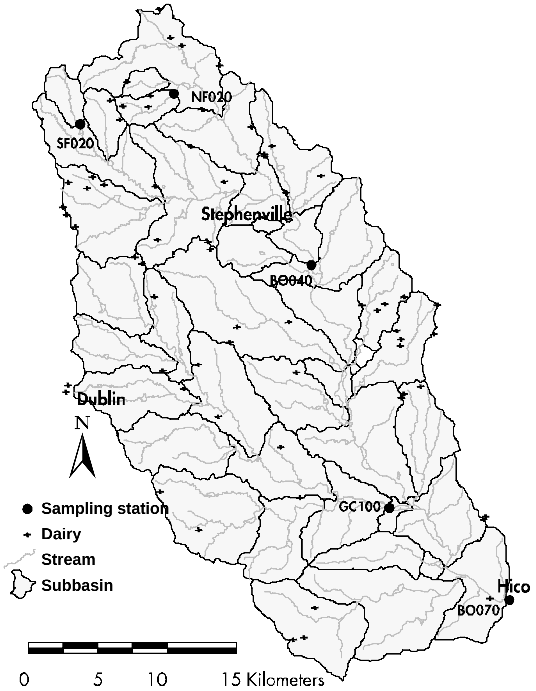


Figure 1. Location of the dairies, stream sites, and subbasins within UNBRW.

high−intensity, short−duration storms that can result in flooding in smaller subwatersheds.

A consistent period of monitoring from October 1993 through December 2000 was available for five stream sites for use in model calibration and verification (fig. 1). As figure 1 and table 1 show, the five sites are distributed throughout the watershed and represent contributing drainage areas from a few square kilometers to the entire watershed area; sites BO040, NF020, SF020, and GC100 are the most upstream stations, and BO070 is the outlet of UNBRW. Each of these sites was instrumented with an automated sampler to monitor storm events. Monthly or biweekly grab sampling was also conducted to represent base flow water quality characteristics. Routine chemical analyses of water samples using USEPA−approved analytical methods included total suspended solids (TSS), total Kjeldahl−N (TKN), ammonia−nitrogen (NH_3−N), nitrate−nitrogen (NO_3−N) plus nitrite−nitrogen (NO_2−N), total P, and soluble reactive phosphorous (PO_4−P) (USEPA, 1983). Particulate P was estimated by subtraction of PO_4−P from total P, and organic N was determined by subtraction of NH_3−N from TKN. Herein, total N is defined as the sum of organic N, NO_3−N, and NO_2−N. Water levels monitored at each stream site at 5 min intervals were combined with site−specific stage−discharge curves to develop a history of flow. Flow information and water quality data were then combined using a midpoint rectangular integration method to calculate nutrient and TSS loadings at each site. Specifics of the monitoring program and loading calculations are presented in McFarland and Hauck (1999).

MODEL INPUT DATA DESCRIPTIONS

Topographic, land use and cover, and soil data required by SWAT and HSPF for this study were generated from GIS maps using the BASINS 3.0 interface program. Topographic data were created from existing 1:24,000 scale U.S. Geological Survey (USGS) DEM and digitized USGS 7−1/2 minute quadrangle maps. A subwatershed map required for SWAT and HSPF was then generated from the topographic data with consideration of current locations of sampling sites. Based on this procedure, the UNBRW was divided into 41 subwatersheds (fig. 1).

The land use categories in the watershed were developed from the classifications of Landsat Thematic Mapper images created from an overflight taken on August 28, 1992. Ground truthing was performed to assist in the imagery classification and to verify the final results. The minimum mapping unit for land use characterization was about 0.1 ha. Land use categories included in the final land use map were rangeland, forage fields (coastal Bermuda grass and some double−cropped wheat and Sudan grass), woodland (trees and heavy brush), orchards and groves, peanuts, urban, and water. The size and location of animal waste application fields were obtained from the Texas Commission on Environmental Quality (TCEQ) dairy permits and available waste management plans (table 1). Table 1 presents general land use characteristics above each monitoring site. The land use characteristics for the entire UNBRW are represented by the percentages listed for site BO070 at Hico.

Soils data used for this study were determined using a digital soil map of the UNBRW developed by the USDA−NRCS. The major soil series in the watershed are the hydrologic group C Windthorst series (fine, mixed, thermic Udic Paleustalfs), the hydrologic group D Purves series (clayey, montmorillonitic, thermic Lithic Calciustolls), and the hydrologic group B Duffau series (fine−loamy, siliceous, thermic Udic Paleustalfs). A complete list of the soil series and their associated textures used in the simulation runs are given in table 2.

Daily rainfall data obtained from 14 gauges (including several National Weather Service and study−associated sites located throughout the watershed) were processed into the proper format for the simulation period. A similar procedure was used to convert daily temperature data available from the National Weather Service sites into the required SWAT and HSPF input data files.

NO_3−N plus NO_2−N, organic N, particulate P, and PO_4−P are common forms of nutrients simulated by SWAT and HSPF. Based on surveys of local farmers, the dairy waste application fields (WAF) were simulated in SWAT and HSPF as receiving four applications of manure, totaling an average

Table 1. Land use characteristics for drainage basins above stream sampling sites (from McFarland and Hauck, 1999).

Sampling Site	Area (km^2)	Woodland (%)	Range (%)	Forage Fields (%)	Peanuts (%)	Orchard (%)	Water (%)	Urban (%)	Barren (%)	Waste Application Field (%)
NF020	8	11.7	23.0	19.4	0.0	0.0	0.3	0.0	0.2	45.4
SF020	11	35.4	60.0	3.6	0.0	0.0	0.2	0.0	0.1	0.7
BO040	254	23.7	27.4	32.2	1.6	0.3	0.7	3.8	0.7	11.7
GC100	261	21.4	46.7	21.1	2.2	0.3	0.5	0.7	0.2	6.9
BO070	921	22.6	43.1	22.7	1.4	0.4	0.5	1.7	0.4	7.3

Table 2. Textural characteristics and percent cover of soils within the UNBRW.

Soils Series	Texture	% Area	% Clay	% Silt	% Sand	Hydrologic Group
Altoga	Silty clay	0.4	45.0	47.6	7.4	C
Blanket	Clay loam	2.3	31.0	33.6	35.5	C
Bolar	Clay loam	3.1	26.5	35.8	37.8	C
Bosque	Loam	1.9	23.5	37.2	39.3	B
Brackett	Clay loam	3.0	27.5	37.8	34.7	C
Bunyan	Sandy loam	5.0	14.0	19.9	66.1	B
Denton	Silty clay	1.9	46.0	48.3	5.7	D
Duffau	Sandy loam	5.9	11.5	26.0	62.5	B
Frio	Silty clay loam	4.5	39.5	53.3	7.2	B
Gullied land	Sandy loam	0.3	15.0	30.0	55.0	B
Hensley	Loam	0.3	22.5	37.7	39.8	D
Houston black	Clay	1.1	55.0	27.8	17.2	D
Lamar	Clay loam	1.1	27.5	45.1	27.4	B
Lindy	Clay loam	0.3	27.5	37.8	34.7	C
Maloterre	Clay loam	2.6	37.5	32.3	30.2	D
Arenosa	Sand	8.4	1.5	0.6	97.9	A
Nimrod	Sand	2.7	3.0	0.6	96.4	C
Purves	Clay	21.0	47.5	29.2	23.3	D
Selden	Loamy sand	2.3	9.0	6.5	84.5	C
Venus	Loam	0.1	24.0	37.0	39.0	B
Windthorst	Sandy loam	31.7	11.5	26.0	62.5	C

annual rate of 35.8 t/ha. The average nutrient content of manure included NO_3−N (0.17%), organic N (2.18%), particulate P (0.38%), and PO_4−P (0.66%). Other improved pasture fields, based on standard farming practice in the UNBRW, were assumed to receive four applications of N and P fertilizer at an annual rate of 336 and 49 kg/ha, respectively.

The measured daily loading of NO_3−N+NO_2−N, organic N, PO_4−P, TSS, and flow from the SWTP were added as a point source to both models. The input data regarding the SWTP were determined from average daily discharge information reported by the treatment plant and biweekly or monthly water quality samples collected and analyzed by the Texas Institute for Applied Environmental Research.

The four basic data files for HSPF simulation, including watershed (*.wds), reach (*.rch), channel geometry (*.prf), and point sources (*.psr), were created through the BASINS system using GIS map layers.

The weather data stored in a WDM file were created based on the available Texas weather data file and the measured precipitation data obtained from the 14 meteorological gauges throughout the UNBRW. Weather data were allocated to corresponding subwatersheds using the STMD (simulation time and meteorological data) function of WinHSPF. The weather data includes precipitation, potential evapotranspiration, air temperature, wind speed, dewpoint temperature, solar radiation, cloud cover, and evaporation.

The pervious land segment (PERLND) and free−flowing reach (RCHERS) were used during the simulation. The agrichemical section of HSPF, including soil temperature (PST), moisture content of soil layer (MSTL), and nitrogen and phosphorous behavior (NITR and PHOS, respectively), were selected to simulate nutrients in pervious lands.

Within SWAT, one type of land use in a subbasin could be associated with different soils, while in HSPF each land use is limited to only one soil type. Initial soil nutrient concentrations are not computed by HSPF. Therefore, procedures similar to those of SWAT were used to compute the initial NO_3−N, organic N, PO_4−P, and particulate P within soil layers for all land use categories with the exception of WAF for HSPF simulations. The concentration of PO_4−P for forest and range lands was set at 5 mg/kg, at 15 mg/kg for pastureland without WAF, and at 25 mg/kg for agricultural lands. The initial soil NO_3−N, organic N, PO_4−P, and particulate P for WAF lands were set according to actual field measurements, as reported by McFarland et al. (2000), for both SWAT and HSPF simulations.

Manure and commercial N and P were applied in HSPF at the same rate as those in SWAT, to the surface and upper soil layers using the SPEC−ACTIONS function on the rest of pasturelands. The first−order kinetics methods in NITR and PHOS sections were selected for N and P processes within plant and soil in HSPF. In−stream biological transfer was not considered for SWAT or HSPF simulations.

MODEL SIMULATIONS

SWAT and HSPF were calibrated at subwatershed and watershed levels using daily and monthly measured data from the UNBRW during January 1994 through June 1995. Field data from July 1995 through July 1999 were used for verification.

The main modeling components of HSPF are the modules that simulate water quality and quantity processes that occur on pervious land (PERLND), impervious land segments (IMPLND), and during routing through reaches (RCHRES). However, numerous parameters (e.g., over 100 parameters for the hydrologic process alone) need to be inputted (Bicknell et al., 2000). The majority of these parameters must be estimated based on judgment and knowledge of the watershed hydrology, or are used as calibrated parameters. Table 3a lists the main parameters adjusted during HSPF calibration process.

Although SWAT is capable of simulating flow by either the Green−Ampt or the CN2 method, King et al. (1999) found no significant advantage in using one method over the other when using SWAT to simulate flow for large watersheds. Therefore, in this study, SWAT simulated flow using the CN2 method.

In contrast to HSPF, only a handful of parameters within SWAT were adjusted during the calibration process of flow, sediment, and nutrients (table 3b). Similar to the HSPF calibration process, the adjusted parameters were changed within the allowable range of values described in the SWAT (Neitsch et al., 2002b) and HSPF (Bicknell et al., 2000) documentation.

MEASURE OF MODEL PERFORMANCE

The predicted and measured values were compared using standard deviation and the Nash and Sutcliffe (1970) equation as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (X_{mi} - X_{ci})^2}{\sum_{i=1}^{n} (X_{mi} - \overline{X}_m)^2} \qquad (1)$$

where

E = the efficiency of the model

X_{mi} = measured values

X_{ci} = predicted values

$\overline{X}_m$ = average measured values.

Table 3a. List of adjusted parameters for calibration of HSPF model.

Parameter (Units)	Description	Range	Calibrated Value
Hydrology			
LZSN (mm)	Lower zone nominal storage.	2.5−358	152.4
INFILT (mm h^{-1})	Soil infiltration capacity index.	0.025−25	4.064
AGWRC (day^{-1})	Groundwater recession coefficient.	0.6−0.999	0.98
UZSN (mm)	Upper zone nominal storage.	0.25−127	28.6512
KVARY (mm^{-1})	Groundwater recession parameter.	0.0−2.0	0.0
INFEXP	Infiltration equation exponent.	0.0−10.0	2.0
INFILD (mm)	Ratio between maximum and mean infiltration capacities.	1.0−2.0	2.0
INTFW	Interflow inflow parameter.	0.0−0.75	2.5
IRC (day^{-1})	Interflow recession parameter.	1×10^{-6}−0.999	0.5
LZETP	Lower zone ET parameter.	0.0−0.999	0.6
DEEPFR	Fraction of groundwater inflow lost to deep groundwater.	0.0−1.0	0.8
BASETP	Fraction of PET that can be satisfied from base flow.	0.0−1.0	0.02
AGWETP	Fraction of PET that can be satisfied from groundwater.	0.0−1.0	0.0
CEPSC (mm)	Interception storage capacity.	0.0−250.0	2.54
PLS NSUR	Manning's *n* for overland flow on impervious land segments.	0.001−1.0	0.15
Sediment			
JSER	Exponent in the detached sediment washoff equation.	0.5−2.0	1.0
KSER	Coefficient in the detached sediment washoff equation.	0.1−100	13
KGER	Coefficient in the matrix soil scour equation, simulates gully erosion, etc.	0.01−0.35	0.1
KRER	Coefficient in the soil detachment equation.	0.14−1.0	0.8
JGER	Exponent in the matrix soil scour equation.	0.9−1.1	1.0
Nutrients			
KIMP (1/day)	Phosphate immobilization factor.	0−none	2.0
KDSP (1/day)	Phosphate desorption factor.	0−none	0.1
KADP (1/day)	Phosphate adsorption factor.	0−none	1.0
KDSAM (1/day)	Ammonium desorption factor.	0−none	1.0
KIMNI (1/day)	Nitrate immobilization factor.	0−none	0.1
SLMPF	Percolation factor to adjust solutes from surface to upper layer storage.	0.001−1.0	1.0
ULPF	Percolation factor to adjust solutes from upper to lower layer storage.	1.0−10.0	10.0
UKPLP (1/day)	Factor to adjust plant phosphorus uptake from surface layer.	0−none	0.15
SKPLP (1/day)	Factor to adjust plant phosphorus uptake from surface layer.	0−none	0.2

Table 3b. List of adjusted parameters for calibration of SWAT model.

Parameter (Units)	Description	Range	Calibrated Value
SWAT			
SURLAG	Surface runoff lag coefficient.	1−12	5
ESCO	Soil evaporation compensation factor.	0.2−1.0	0.51
SPCON	Linear parameter for calculating sediment.	0.0001−0.01	0.008
CMN	Rate factor for humus mineralization of active organic nutrients (N and P).	0.0003−0.03	0.003
UBN	Uptake distribution parameter.	1−20	10
NPERCO	Nitrate percolation coefficient.	0.01−1.0	0.5
PHOSKD	Soil phosphorous partitioning coefficient.	75−175	100
CN2	Initial SCS runoff curve number to moisture condition II.	30−100	±10%

A value of E = 1.0 indicates a perfect prediction, while negative values indicate that the predictions are less reliable than if one had used the sample mean instead. In addition, the mean error (*ME*) is used. The *ME* measures bias and is computed as:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(X_{mi} - X_{ci}) \qquad (2)$$

where a negative or positive *ME* indicates under− or overprediction of simulated values, respectively.

RESULTS AND DISCUSSIONS

The average annual precipitation during the simulation period ranged from 600 mm in 1999 to 1200 mm in 1997 (fig. 2), indicating the test of SWAT and HSPF under different moisture regimes.

The SWAT model within BASINS 3.0 was more user−friendly than HSPF for the following reasons:

- Data generation for SWAT was more automated. For example, soil data files required by SWAT were generated from soil GIS map layers, while this information had to be incorporated manually for HSPF. This is time consuming and is subject to operator error.
- It was much easier to simulate and input field management practices into SWAT than HSPF. This could be because HSPF originally was not designed as an agricultural model.
- The calibration process in HSPF tends to be strenuous and long, as was also concluded by Engelmann et al. (2002). HSPF includes more input parameters to control and define the hydrologic cycle, sediment, and nutrients (table 3a).

FLOW AT THE WATERSHED OUTLET

Table 4 shows measured and simulated average, standard deviation, and *ME* of daily flow during the calibration period (January 1994 through June 1995). The average daily flows at the outlet of UNBRW (BO070) simulated by SWAT (4.26 m^3/s, *ME* = 0.33) and HSPF (4.22 m^3/s, *ME* = 0.30) are

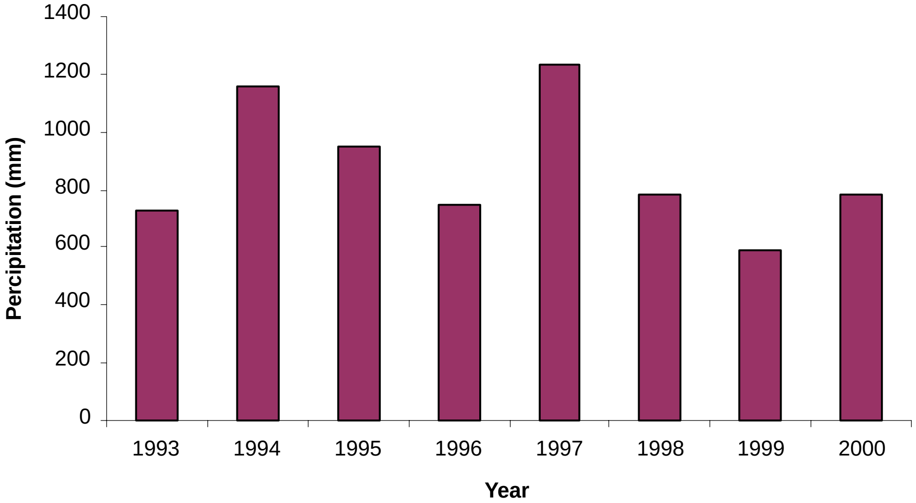


Figure 2. Average annual precipitation in UNBR watershed.

close to measured values (3.93 m^3/s) during the calibration period (table 4). However, HSPF underestimated average daily flow by about 30% (2.84 m^3/s, $ME = -1.20$) as compared to SWAT (3.85 m^3/s, $ME = -0.20$), which only underestimated flow by 6.0% during the verification period (table 5). Meanwhile, the trends of measured and predicted daily flow by HSPF (fig. 3) at site BO070 are closer ($E = 0.72$ and 0.70 for HSPF as compared to 0.17 and 0.62 for SWAT during the calibration and verification periods, respectively) than those of SWAT during calibration and verification. The model efficiencies shown in figure 3 also indicate a better description for temporal variations of average monthly flows by HSPF during the calibration and verification periods ($E =$ 0.91 and 0.86 compared to 0.50 and 0.78 for SWAT during the calibration and verification periods, respectively). The reason for lower model efficiencies for SWAT is overprediction of daily flow in the fall of 1994 during the calibration period. This indicates that HSPF is a better predictor of temporal variation of daily flow. The limitation of SWAT in predicting daily flow is probably due to use of the CN2 method. A major limitation of the CN2 method is that rainfall intensity and duration are not considered, only total rainfall volume (Rallison and Miller; 1981).

The patterns of temporal variations of measured and predicted daily and monthly flows by SWAT are closer to those of the measured values during the verification period as compared to the calibration period (fig. 3b). In addition, the model efficiencies are higher for predicted monthly flows than for daily flows, which is probably due to the elimination of some differences in measured and predicted daily flow by an averaging process within a month (fig. 3).

Flow within the Watershed

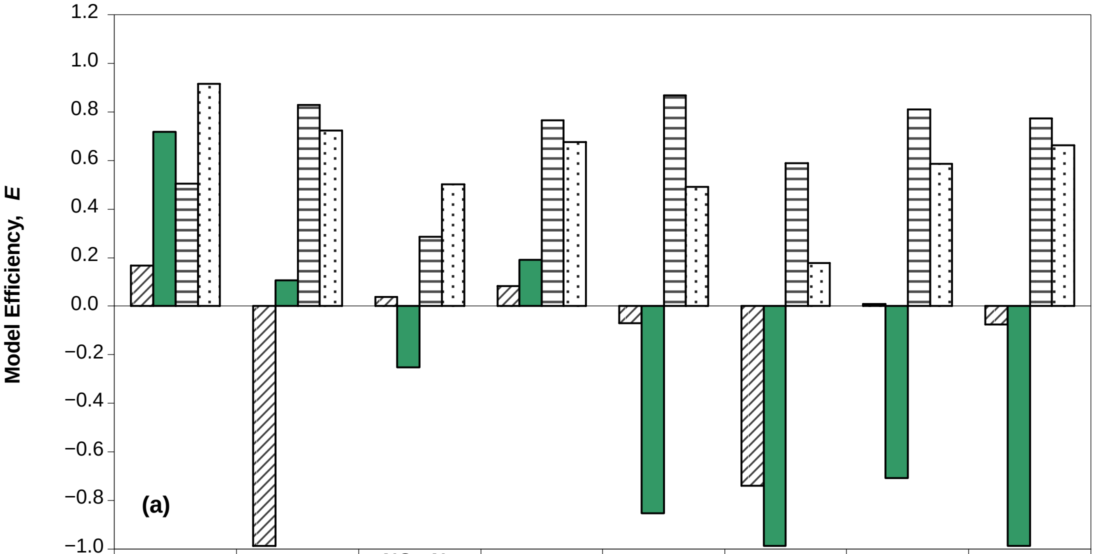
Table 4 shows the measured and simulated average daily flow at different sampling sites within UNBRW during the calibration period. The average daily flow predicted by SWAT and HSPF at different sites, with the exception of site BO040, are generally close to measured values during the calibration period (table 4). The average daily flow predicted by SWAT at site BO040 is the same as the measured value (0.79 m^3/s), while HSPF prediction is higher (1.26 m^3/s) at this site. In addition, during the verification period, average

Table 4 Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily flow and TSS loading during calibration period.

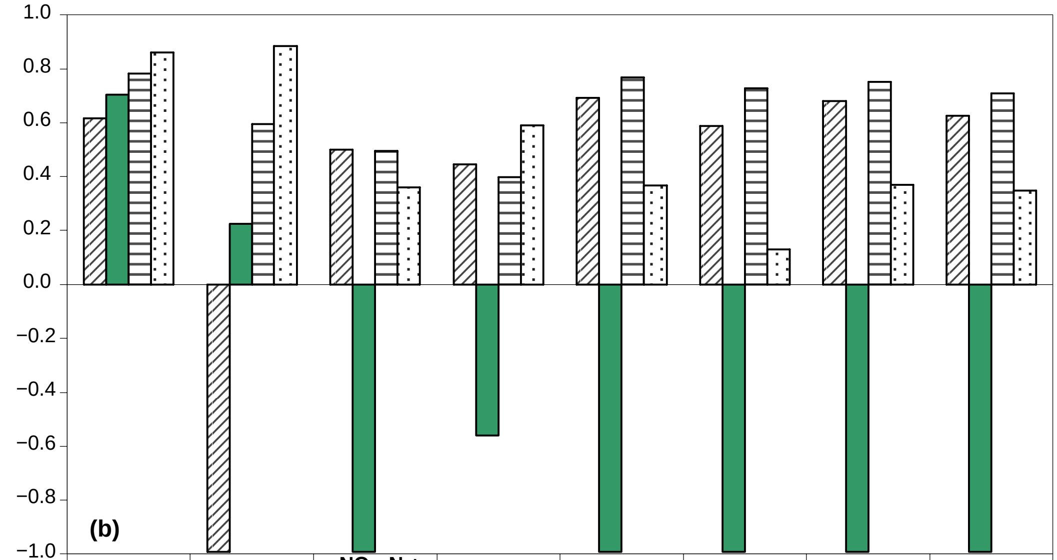
		Flow ($m^3 s^{-1}$)			Sediment (t)		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	0.03	0.14	−−	2.5	20.3	−−
	SWAT	0.02	0.10	0.00	0.6	2.4	−1.9
	HSPF	0.04	0.14	0.00	1.9	13.8	−0.6
SF020	Measured	0.03	0.17	−−	0.5	3.5	−−
	SWAT	0.02	0.05	0.00	0.6	1.4	0.1
	HSPF	0.02	0.08	−0.01	0.8	11.2	0.34
BO040	Measured	0.78	2.54	−−	26.0	188	−−
	SWAT	0.79	1.99	0.01	32.2	113.2	6.2
	HSPF	1.26	3.57	0.48	58.0	342.8	32
GC100	Measured	1.26	3.43	−−	30.4	214.5	−−
	SWAT	1.46	4.25	0.20	61.6	225.4	31.2
	HSPF	1.28	4.55	0.02	59.3	447.6	28.9
BO070	Measured	3.93	10.27	−−	142.5	963.4	−−
	SWAT	4.26	10.81	0.33	142.7	452.3	0.20
	HSPF	4.22	12.08	0.30	201.4	1123.3	58.9

Table 5. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily flow and TSS loading during verification period.

		Flow ($m^3 s^{-1}$)			Sediment (t)		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	0.03	0.24	−−	2.2	25.4	−−
	SWAT	0.02	0.15	−0.01	0.7	5.1	−1.6
	HSPF	0.03	0.14	−0.01	1.1	10.4	−1.1
SF020	Measured	0.03	0.20	−−	0.7	10.1	−−
	SWAT	0.02	0.06	−0.01	0.6	1.6	−0.1
	HSPF	0.01	0.08	−0.01	0.6	8.6	−0.2
BO040	Measured	0.91	3.16	−−	22.0	189.3	−−
	SWAT	0.77	2.58	−0.15	31.5	155.8	9.6
	HSPF	0.86	3.65	−0.05	34.2	302.6	12.3
GC100	Measured	1.03	3.98	−−	24.2	259.4	−−
	SWAT	1.02	3.52	−0.01	40.2	205.3	16.1
	HSPF	0.65	3.10	−0.37	25.4	279.4	1.3
BO070	Measured	4.09	10.90	−−	122.7	1252.1	−−
	SWAT	3.85	12.10	−0.20	122.8	472.7	0.1
	HSPF	2.84	11.50	−1.20	116.7	919.7	−6.0



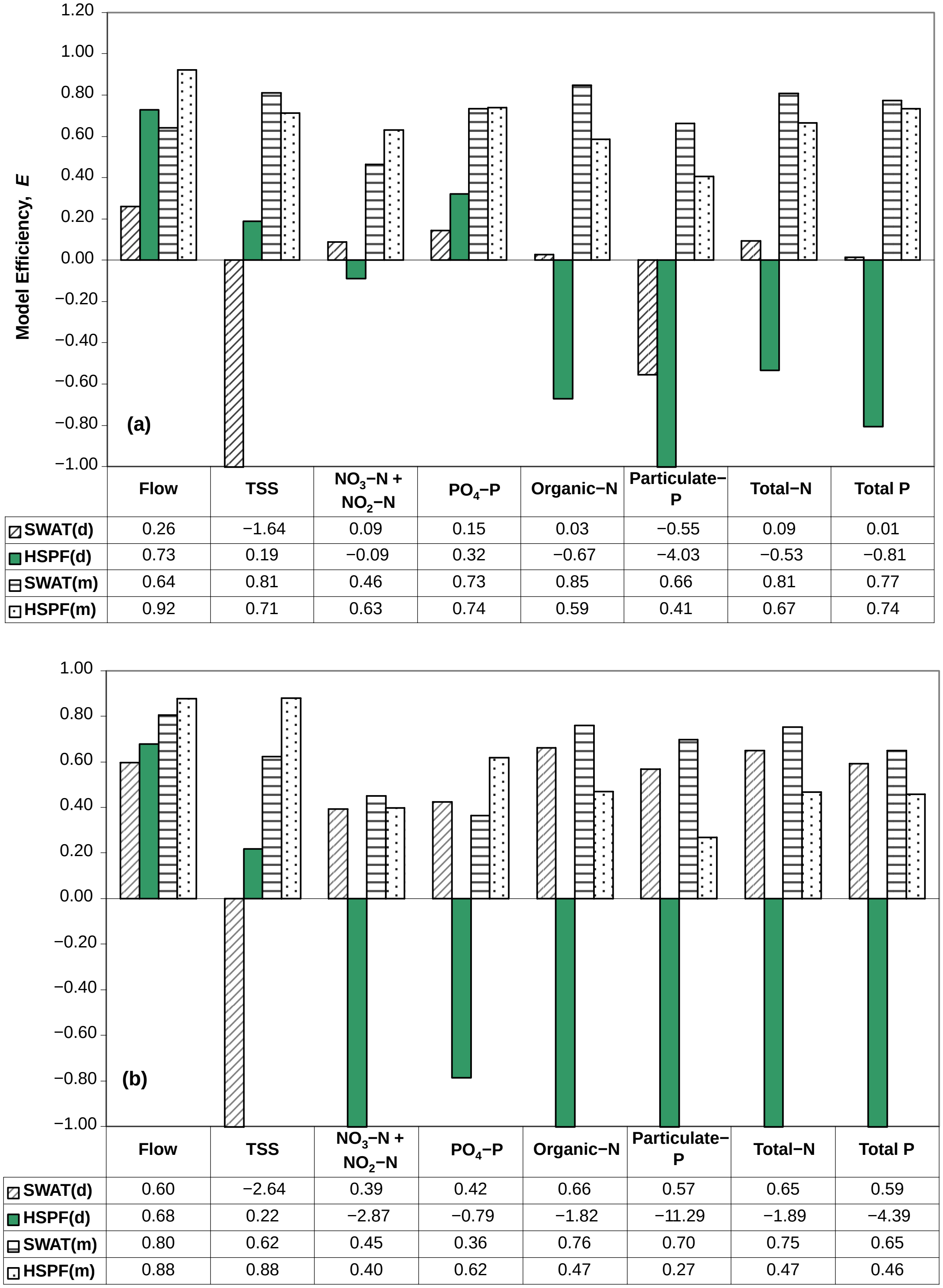
	Flow	TSS	NO_3−N + NO_2−N	PO_4−P	Organic−N	Particulate−P	Total−N	Total P
▨ **SWAT(d)**	0.17	−2.50	0.04	0.08	−0.07	−0.74	0.01	−0.08
🟩 **HSPF(d)**	0.72	0.11	−0.25	0.19	−0.85	−4.18	−0.71	−1.15
▤ **SWAT(m)**	0.50	0.83	0.29	0.76	0.87	0.59	0.81	0.77
⬚ **HSPF(m)**	0.91	0.72	0.50	0.68	0.49	0.18	0.59	0.66



	Flow	TSS	NO_3−N + NO_2−N	PO_4−P	Organic−N	Particulate−P	Total−N	Total P
▨ **SWAT(d)**	0.62	−3.51	0.50	0.45	0.69	0.59	0.68	0.63
🟩 **HSPF(d)**	0.70	0.23	−1.67	−0.56	−1.70	−10.30	−1.70	−4.26
▤ **SWAT(m)**	0.78	0.59	0.50	0.40	0.77	0.73	0.75	0.71
⬚ **HSPF(m)**	0.86	0.88	0.36	0.59	0.37	0.13	0.37	0.35

Figure 3. Model efficiency (*E*) for measured and predicted daily and monthly flow, TSS, and nutrient loading during (a) calibration and (b) verification periods at the outlet of UNBRW (BO070).

simulated daily flows by SWAT at various sites are generally closer to the measured values (table 5). However, the model efficiencies of HSPF for predicting the daily and monthly flows among all sampling sites are higher than those of SWAT during both the calibration and verification periods (fig. 4). Average model efficiencies across sampling sites for daily and monthly flows are higher for HSPF (*E* = 0.73 and 0.92 for daily and monthly flows, respectively) than for SWAT (*E* = 0.26 and 0.64 for daily and monthly flows, respectively) during the calibration period (fig. 4a). In addition, the average model efficiencies of predicted daily and monthly flows are slightly higher for HSPF (*E* = 0.68 and 0.88 for daily and monthly flow, respectively) than for SWAT (*E* = 0.60 and 0.80 for daily and monthly flow, respectively)



(a)

	Flow	TSS	NO_3−N + NO_2−N	PO_4−P	Organic−N	Particulate−P	Total−N	Total P
▨ SWAT(d)	0.26	−1.64	0.09	0.15	0.03	−0.55	0.09	0.01
🟩 HSPF(d)	0.73	0.19	−0.09	0.32	−0.67	−4.03	−0.53	−0.81
⊟ SWAT(m)	0.64	0.81	0.46	0.73	0.85	0.66	0.81	0.77
⊡ HSPF(m)	0.92	0.71	0.63	0.74	0.59	0.41	0.67	0.74

(b)

	Flow	TSS	NO_3−N + NO_2−N	PO_4−P	Organic−N	Particulate−P	Total−N	Total P
▨ SWAT(d)	0.60	−2.64	0.39	0.42	0.66	0.57	0.65	0.59
🟩 HSPF(d)	0.68	0.22	−2.87	−0.79	−1.82	−11.29	−1.89	−4.39
⊟ SWAT(m)	0.80	0.62	0.45	0.36	0.76	0.70	0.75	0.65
⊡ HSPF(m)	0.88	0.88	0.40	0.62	0.47	0.27	0.47	0.46

Figure 4. Model efficiency (*E*) for measured and predicted daily and monthly flow, TSS, and nutrient loading during (a) calibration and (b) verification periods among sampling sites within UNBRW.

among all sites (fig. 4b). Generally, the model efficiency improved from daily to monthly during both calibration and verification periods, reflecting the averaging of differences between predicted and measured daily flow.

SEDIMENT (TSS) AT THE WATERSHED OUTLET

Predicted and measured TSS loading in the UNBRW indicates a significant TSS transport from the watershed (tables 4 and 5), as expected, since a major portion of the watershed is covered by erosive soils that are susceptible to significant erosion from stream banks. The average daily TSS loading at site BO070 during calibration periods predicted by SWAT (142.7 t, *ME* = 0.2) is very close to the measured value (142.5 t), while HSPF overpredicted sediment (201.4 t, *ME* = 58.9) by 41% (table 4). Nevertheless, the model efficiency of HSPF in predicting daily TSS loading is

Table 6. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily NO_3−N+NO_2 and organic N loading during calibration period.

		NO_3−N + NO_2−N (kg)			Organic N (kg)		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	4.1	20.8	−−	8.9	48.5	−−
	SWAT	1.5	7.2	−2.6	3.9	25.6	−4.9
	HSPF	3.0	5.2	−1.1	15.3	91.5	6.4
SF020	Measured	0.4	3.6	−−	2.8	18.6	−−
	SWAT	0.7	1.7	0.3	2.8	7.4	−0.1
	HSPF	1.9	1.8	1.5	0.2	3.0	−2.6
BO040	Measured	131.9	211.7	−−	170.6	750.4	−−
	SWAT	43.7	137.2	−88.1	140.1	828.3	−30.5
	HSPF	76.7	94.9	−55.1	123.3	669.0	−47.4
GC100	Measured	59.4	172.7	−−	174.3	780.4	−−
	SWAT	58.2	193.2	−1.2	231.2	1022.1	56.8
	HSPF	72.0	96.5	12.6	77.0	513.1	−97.4
BO070	Measured	213.6	477.3	−−	591.0	2410.6	−−
	SWAT	228.6	567.9	15.0	589.9	2300.4	−1.1
	HSPF	247.5	285.2	34.0	289.2	1336.9	−301.8

higher (*E* = 0.11) than that obtained by SWAT (*E* = −2.5), indicating a better prediction of temporal variation of daily TSS by HSPF during the calibration period (fig. 3a). The lower model efficiencies for SWAT are due to the underprediction of TSS by SWAT during May of 1994. However, the model efficiency for monthly TSS predicted by SWAT is slightly higher during the calibration period (*E* = 0.83 compared to 0.72 for HSPF; fig. 3a).

A similar trend is found for measured and predicted daily TSS by SWAT and HSPF during the verification period at site BO070 (*E* = 0.23 for HSPF compared to −3.51 for SWAT; fig. 3b). The model efficiency of SWAT is higher in predicting monthly than daily TSS, but somewhat lower than that of HSPF (E = 0.88 for HSPF as compared to 0.59 for SWAT) during the verification period (fig. 3b). Similar to calibration, the average daily TSS loading at site BO070 predicted by SWAT (122.8 t, *ME* = 0.1) is closer to the measured value (122.7 t) as compared to HSPF (116.7 t, *ME* = −6.0) during the verification period (table 5), although both models are very close to the measured average.

Table 7. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily NO_3−N+NO_2 and organic N loading during verification period.

		NO_3−N + NO_2−N (kg)			Organic N (kg)		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	3.2	14.6	−−	17.7	147.4	−−
	SWAT	2.0	16.6	−1.1	13.8	190.7	−3.9
	HSPF	1.2	3.0	−2.0	10.7	94.0	−7.1
SF020	Measured	0.3	3.2	−−	2.7	20.3	−−
	SWAT	0.9	2.4	0.6	2.9	8.2	0.2
	HSPF	0.7	0.8	0.3	0.1	2.0	−2.6
BO040	Measured	120.3	281.0	−−	186.7	833.8	−−
	SWAT	46.7	187.4	−73.6	196.2	1372.6	9.5
	HSPF	33.4	62.3	−86.9	85.8	750.1	−100.9
GC100	Measured	49.7	166.1	−−	142.6	958.3	−−
	SWAT	47.1	185.0	−2.6	182.8	1009.4	40.2
	HSPF	26.3	45.3	−23.3	38.3	373.8	−104.3
BO070	Measured	175.0	397.3	−−	568.1	2760.3	−−
	SWAT	215.5	711.9	40.4	648.2	3420.9	80.1
	HSPF	101.7	174.1	−73.3	185.4	1391.6	−382.8

Table 8. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily PO_4−P and particulate P loading during calibration period.

		PO_4−P (kg)			Particulate P (kg)		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	3.1	17.9	−−	2.2	15.5	−−
	SWAT	1.0	9.2	−2.1	0.6	4.6	−1.7
	HSPF	3.2	10.1	0.0	1.9	11.6	−0.3
SF020	Measured	0.1	0.4	−−	0.5	3.6	−−
	SWAT	0.1	0.1	0.0	0.2	0.5	−0.3
	HSPF	0.4	0.4	0.4	0.0	0.2	−0.4
BO040	Measured	39.3	105.8	−−	31.6	162.7	−−
	SWAT	33.1	252.0	−6.2	25.2	184.7	−6.4
	HSPF	39.9	89.6	0.5	15.4	83.1	−16.1
GC100	Measured	18.6	76.6	−−	26.8	142.0	−−
	SWAT	21.5	154.1	2.9	27.0	148.2	0.1
	HSPF	29.6	63.8	10.9	9.1	60.3	−17.8
BO070	Measured	67.5	274.8	−−	116.8	494.2	−−
	SWAT	79.9	434.3	12.1	72.1	358.7	−44.7
	HSPF	105.8	202.5	38.2	34.4	160.0	−82.0

SEDIMENT (TSS) WITHIN THE WATERSHED

The accuracy of SWAT and HSPF in predicting average daily TSS loadings during the calibration and verification periods differs among sampling sites (tables 3 and 4). The average daily TSS loadings within the watershed predicted by SWAT and HSPF are generally close to measured values. In addition, average model efficiencies of SWAT and HSPF across all sites follow similar patterns to those found for measured and predicted daily and monthly TSS at site BO070 during the calibration and verification periods (figs. 3 and 4).

NUTRIENTS

In contrast to HSPF, the average daily nutrients predicted by SWAT, specifically at BO070, were generally closer to the measured values during both the calibration and verification periods (tables 6 through 11). Figures 3a and 4a indicate that HSPF has higher model efficiencies than SWAT in predicting daily PO_4−P during calibration at the outlet and within UNBR watershed. However, the model efficiencies of SWAT in predicting monthly PO_4−P loadings at site BO070 and

Table 9. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily PO_4−P and particulate P loading during verification period.

		PO_4−P (kg)			Particulate P (kg)		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	5.2	35.4	−−	3.7	42.7	−−
	SWAT	3.6	47.5	−1.6	3.0	44.4	−0.7
	HSPF	1.8	8.3	−3.5	1.2	10.8	−2.4
SF020	Measured	0.1	1.0	−−	0.4	4.1	−−
	SWAT	0.1	0.2	0.0	0.2	0.5	−0.2
	HSPF	0.2	0.2	0.1	0.0	0.0	−0.4
BO040	Measured	53.9	128.9	−−	32.4	190.5	−−
	SWAT	44.4	330.7	−9.5	38.8	315.5	6.4
	HSPF	22.3	80.2	−31.5	9.8	85.0	−22.6
GC100	Measured	15.6	112.6	−−	21.3	168.1	−−
	SWAT	20.7	182.7	5.1	23.4	172.9	2.0
	HSPF	12.8	38.7	−2.9	4.2	40.4	−17.1
BO070	Measured	86.4	282.0	−−	106.4	650.8	−−
	SWAT	103.7	685.7	17.3	93.8	639.9	−12.7
	HSPF	54.5	162.6	−31.9	20.5	154.5	−85.9

Table 10. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily total P and total N loading during calibration period.

		Total N			Total P		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	13.0	65.2	−−	5.3	32.1	−−
	SWAT	5.4	32.5	−7.5	1.6	13.7	−3.7
	HSPF	18.3	94.0	5.4	5.1	21.0	−0.3
SF020	Measured	3.2	22.0	−−	0.6	3.9	−−
	SWAT	3.5	9.0	0.3	0.3	0.6	−0.3
	HSPF	2.1	4.3	−1.1	0.4	0.5	−0.1
BO040	Measured	302.5	938.7	−−	70.9	256.2	−−
	SWAT	183.9	946.4	−118.6	58.3	436.2	−12.6
	HSPF	200.0	724.5	−102.5	55.3	167.0	−15.7
GC100	Measured	233.7	935.6	−−	45.4	191.2	−−
	SWAT	289.4	1209.5	55.6	48.5	301.7	3.0
	HSPF	149.0	563.7	−84.8	38.7	117.2	−6.8
BO070	Measured	804.6	2822.5	−−	184.3	733.5	−−
	SWAT	818.5	2836.7	14.0	152.0	791.8	−32.6
	HSPF	536.7	1546.0	−267.8	140.2	351.4	−43.8

across sampling sites within UNBRW are more similar to those for HSPF during the calibration and verification periods (figs. 3 and 4). The model efficiencies of SWAT in predicting daily and monthly organic N, NO_3−N+NO_2−N, and particulate P are also relatively higher than those of HSPF (figs. 3 and 4) at the outlet and at all sites within the watershed. Generally, the model efficiency improved from daily to monthly during both the calibration and verification periods, reflecting the averaging of differences between predicted and measured daily flows (figs. 3 and 4). The closer predicted average and higher model efficiencies obtained by SWAT indicate that this model is a better predictor of nutrient loading. This is probably due to ease of field management practices input in the SWAT model, including fertilizer and manure application. To overcome the differences associated with different forms of P and N between laboratory analytical procedures and those described by equations within the models, the sum of simulated monthly PO_4−P and particulate P (total P), and NO_3−N+NO_2−N and organic N (total N), were compared to the measured values. Tables 10 and 11 show a closer average and trend of total N and total P predictions from the two models to measured values than the individual nutrient comparisons. The efficiencies of both models also improved for total N and total P as compared to the individual nutrient forms (figs. 3 and 4).

Table 11. Measured and predicted mean, standard deviation (SD), and mean error (ME) of daily total P and total N loading during verification period.

		Total N			Total P		
		Mean	SD	ME	Mean	SD	ME
NF020	Measured	20.9	158.4	−−	8.9	74.2	−−
	SWAT	15.8	205.1	−5.1	6.6	91.2	−2.3
	HSPF	11.9	95.4	−9.1	3.0	18.6	−5.9
SF020	Measured	3.0	23.0	−−	0.5	4.6	−−
	SWAT	3.8	10.6	0.8	0.3	0.7	−0.3
	HSPF	0.8	2.6	−2.2	0.2	0.2	−0.3
BO040	Measured	307.0	1034.9	−−	86.3	306.6	−−
	SWAT	242.9	1535.3	−64.1	83.2	641.4	−3.1
	HSPF	119.2	781.1	−187.8	32.1	160.0	−54.1
GC100	Measured	192.3	1102.7	−−	36.9	257.3	−−
	SWAT	229.9	1186.9	37.6	44.1	354.4	7.1
	HSPF	64.6	396.3	−127.6	17.0	76.1	−20.0
BO070	Measured	743.1	3085.9	−−	192.8	894.2	−−
	SWAT	863.7	4093.0	120.5	197.5	1391.4	4.7
	HSPF	287.1	1494.6	−456.1	75.0	306.9	−117.8

SUMMARY AND CONCLUSIONS

The watershed−scale HSPF and SWAT models within the BASINS 3.0 system were evaluated by comparing the predicted and measured flows, TSS, and nutrient loadings from and within the UNBRW, a watershed that is highly impacted by dairy operations. A GIS−based BASINS 3.0 interface was used to generate much of the required data for the models. The outputs from the models were compared against measured data from five water quality and streamflow sites within the watershed.

HSPF, compared to SWAT, was less user−friendly, had numerous parameters to input and adjust, and required a long and strenuous calibration process. Both models provided reasonable predictions of average daily flow and TSS loadings during the calibration and verification periods for the five sampling sites within the UNBRW. However, HSPF was a better predictor of temporal variations of daily flow and sediment. In general, SWAT was a much better predictor of daily and monthly nutrient loadings (with the exception of PO_4−P) for the UNBRW stream system. The underprediction of nutrients by HSPF was due to the inability of this model to incorporate detailed farm management practices. The question of which model is adequate for a specific use depends on the parameters of concern and availability of data. It is important to note that the evaluation of SWAT and HSPF within BASINS 3.0 during this study was limited to the UNBRW study area. To improve this evaluation, an assessment of these models needs to be performed in other study areas.

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