

Article

Evaluating Impacts of Detailed Land Use and Management Inputs on the Accuracy and Resolution of SWAT Predictions in an Experimental Watershed

Junyu Qi ^{1,*}, Xiaoyu Kang ², Sheng Li ³ and Fanrui Meng ²

¹ Earth System Science Interdisciplinary Center, University of Maryland, 5825 University Research Ct, College Park, MD 20740, USA

² Faculty of Forestry and Environmental Management, University of New Brunswick, P.O. Box 4400, 28 Dineen Drive, Fredericton, NB E3B 5A3, Canada; xiaoyu.kang@unb.ca (X.K.); fmeng@unb.ca (F.M.)

³ Fredericton Research and Development Centre, Agriculture and Agri-Food Canada, P.O. Box 20280, 95 Innovation Road, Fredericton, NB E3B 4Z7, Canada; sheng.li@agr.gc.ca

* Correspondence: junyuqi@umd.edu

Abstract: Land use and management practice inputs to the Soil and Water Assessment Tool (SWAT) are critical for evaluating the impact of land use change and best management practices on soil erosion and water quality in watersheds. We developed an algorithm in this study to maximize the usage of land use and management records during the setup of SWAT for a small experimental watershed in New Brunswick, Canada. In the algorithm, hydrologic response units (HRUs) were delineated based on field boundaries and associated with long-term field records. The SWAT model was further calibrated and validated with respect to water flow and sediment and nutrient (nitrate and soluble phosphorus) loadings at the watershed outlet. As a comparison, a baseline version of SWAT was also set up using the conventional way of HRU delineation with limited information on land use and management practices. These two versions of SWAT were compared with respect to input and output resolution and prediction accuracy of monthly and annual water flow and sediment and nutrient loadings. Results show that the SWAT set up with the new method had much higher accuracies in generating annual areas of crops, fertilizer application, tillage operation, flow diversion terraces (FDT), and grassed waterways in the watershed. Compared with the SWAT set up with the conventional method, the SWAT set up with the new method improved the accuracy of predicting monthly sediment loading due to a better representation of FDT in the watershed, and it also successfully estimated the spatial impact of FDT on soil erosion across the watershed. However, there was no definite increase in simulation accuracy in monthly water flow and nutrient loadings with high spatial and temporal management inputs, though monthly nutrient loading simulations were sensitive to management configuration. The annual examination also showed comparable simulation accuracy on water flow and nutrient loadings between the two models. These results indicate that SWAT, although set up with limited land use and management information, is able to provide comparable simulations of water quantity and quality at the watershed outlet, as long as the estimated land use and management practice data can reasonably represent the average land use and management condition of the watershed over the target simulation period.

Keywords: distributed hydrological model; best management practices; hydrologic response units; water quality; soil erosion



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1. Introduction

Aside from field experiments, distributed hydrological models are important tools for assessing the impact of climate change and human interventions on hydrological processes, water resources, and non-point-source pollution [1,2]. These types of models have been used to assess the impact of land use change and best management practices

(BMPs) on soil erosion and agrochemical loadings for agricultural watersheds [3–7]. How to spatially parameterize land use and BMPs across a study watershed is addressed differently among these models [8,9]. Many distributed models discretize a watershed into hydrologic response units (HRUs) based on digital elevation models (DEMs) to account for spatial variations in watershed parameters [10,11]. Although these models are run at the HRU scale, lumped algorithms are often used to summarize input and output data at the subbasin scale [12,13]. As a result, the parameterizations of land use and BMPs are always considered at subbasins rather than individual HRUs. The advantage of this configuration is that it facilitates input data preparation and reduces computational efforts, especially for large watersheds [14]. However, it reduces the spatial resolutions of the model inputs and outputs and underuses land use and management records.

As a process-based semi-distributed hydrological model, the Soil and Water Assessment Tool (SWAT) is designed to simulate how BMPs, land use, and climate change affect water quantity and quality [15]. In particular, it is a flexible framework allowing for the assessment of the impact of a broad range of BMPs, such as fertilizer and manure applications, cover crops, filter strips, conservation tillage, irrigation management, and terraces [16,17], to solve complex watershed management problems in many regions around the world [18–25]. After discretizing a watershed into subbasins and HRUs, hydrological processes (i.e., surface and subsurface runoff, percolation and base flow, and evapotranspiration and transmission losses), crop growth, nutrient cycling, and pesticide movement are simulated. Management practices such as crop planting and harvesting, tillage operations, irrigation, fertilizer usage, and pesticide applications are associated with HRUs. The water, sediment, and nutrient generated from HRUs are summarized at the subbasin level, and the resulting loadings are routed through channels and other water bodies to the watershed outlet.

In SWAT, a reference period with negligible land use change and BMP implementation is preferred to estimate basic hydrological parameters. However, there are always changes in operational farmland, so it is difficult to find a period without the intervention of agricultural activities. SWAT is thus conventionally set up with typical crop rotation scenarios in subbasins, and BMPs are also assigned to subbasins where management practices actually take place. More specifically, since most studies have limited land use maps (sometimes only one map is available), areas of different crops during rotations are weighted and randomly assigned to different HRUs in subbasins. Areas of BMPs are also averaged over a long period and allocated proportionally across the watershed [26]. The assumption behind this conventional method is that SWAT can estimate basic hydrological parameters based on limited land use and management information during calibration. The parameters estimated can reasonably describe the general characteristics of subbasins. This conventional way of setting up SWAT has been used in most studies and proven effective, especially for large watersheds [16,27].

However, when SWAT is applied to small watersheds, the model setup is more challenging. Spatial variations in topographical features, soil characteristics, and land use for small watersheds are not as distinct as those in large watersheds. As a result, dividing a small watershed into several subbasins may not be sufficient for parameter estimation. SWAT is also not able to explicitly associate HRUs with agricultural fields where long-term land use and BMPs records are maintained because SWAT implicitly partitions a subbasin into HRUs based on combinations of land use, soils, and slopes. This configuration poses difficulties in specifying exact sources of pollutants and vulnerable areas within subbasins [12]. Long-term land use and management data are also underused [28]. Improvement in HRU delineation is thus required. The objectives of this study are to (1) develop an algorithm for field-based land use map generation and HRU delineation; (2) set up a SWAT model with long-term, detailed land use and management records for a small experimental watershed in New Brunswick, Canada; and (3) compare two versions of SWAT (one set up with the new method and another set up with the conventional method) with respect to input and output resolution and prediction accuracy.

2. Materials and Methods

2.1. Study Site and Data Collection

The Black Brook Watershed (BBW), sitting in northwest New Brunswick, Canada, is located in the Upper Saint John River Valley ecoregion in the Atlantic Maritime ecozone (Figure 1). This experimental watershed has been studied extensively for more than 20 years, evaluating the impact of agriculture on soil erosion and water quality [25,29]. The watershed covers an area of 14.5 km², with agricultural land use constituting 65% of the land base of the watershed, with the remainder either forested or used for urban and residential purposes (Figure 2a). Elevations range from 170 to 260 m above mean sea level. Slopes vary from 1% to 6% in the upper basin to 4–9% in the central area. In the lower portion, the slopes are more strongly rolling at 5–16% (Figure 2c). The climate associated with the region is moderately cool boreal with a humid to perhumid moisture regime and with ~120 frost-free days per year, an average daily temperature of 3.7 °C [26], and an annual precipitation amount of 1038 mm [30]. About one-third of the precipitation is snow, and snowmelt leads to major surface runoff and groundwater recharge events from March to May [29]. Although monthly precipitation from April to September is relatively uniformly distributed, frequent summer storm events relocate large amounts of soil within the watersheds. Six mineral soil types, i.e., Grandfalls, Holmesville, Interval, Muniac, Siegas, and Undine, and one organic soil type, St. Quentin, were identified in the BBW by soil surveys (1:10,000 scale; Figure 2b) [31].

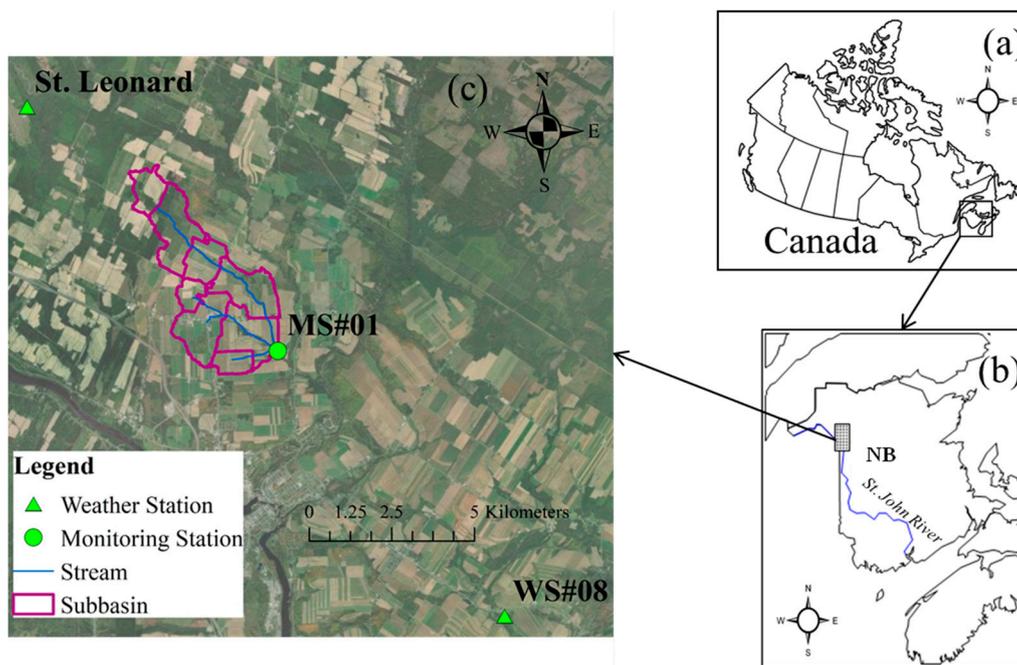


Figure 1. (a) Canada boundary, (b) New Brunswick boundary, and (c) locations of the BBW (including subbasins) and water-monitoring station #01, as well as weather station #08 and the weather station at St. Leonard.

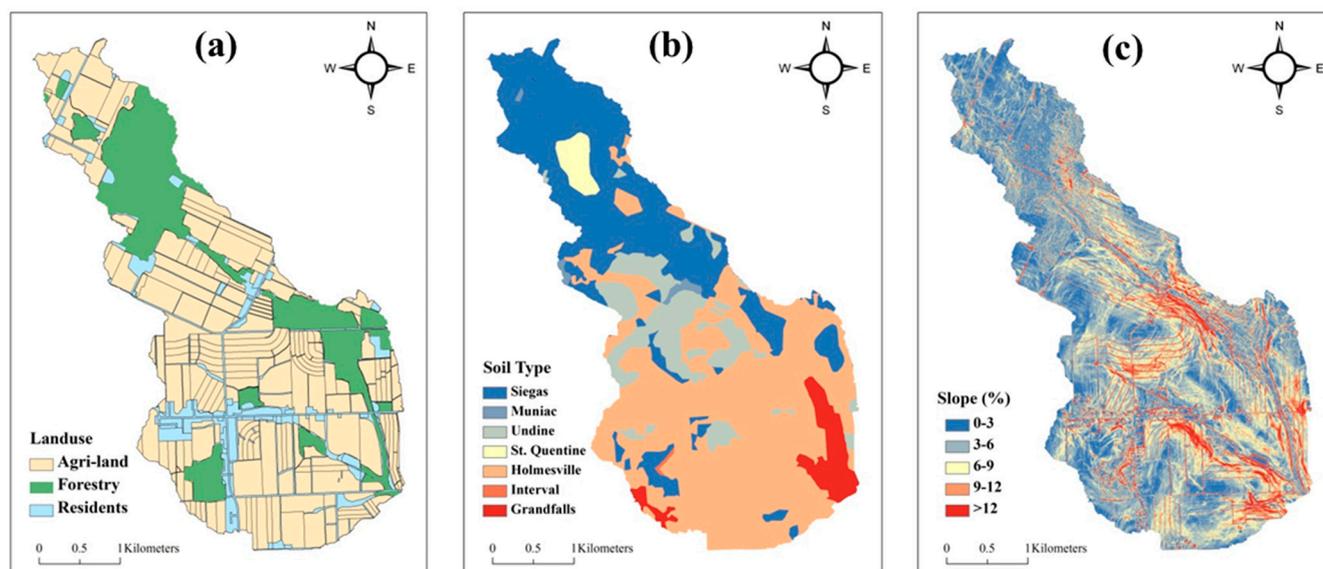


Figure 2. (a) Land use map, (b) soil map, and (c) slope classes created using a 1-m LiDAR DEM for the BBW.

At the outlet of the watershed (MS#01; Figure 1), a V-notch weir was installed in 1992, recording the stage height of water with a Campbell Scientific CR10X datalogger. Stage height values were converted to flow rates using a calibration curve function [32]. An ISCO automatic sampler was used to collect water samples (Teledyne ISCO, Lincoln, NE, USA). The sampling frequency was set at one sample every 72 h during the base flow period. During runoff events, the sampling frequency increased to one sample every 5-cm change in stage height. The samples were analyzed for concentrations of suspended solids, nitrate-nitrogen ($\text{NO}_3\text{-N}$), and soluble-phosphorus (Sol-P). All of the sample analyses were conducted in the Soil and Hydrology Laboratory in the Fredericton Research and Development Centre. In brief, after measuring the volume, each sample was first filtered through a $0.45\ \mu\text{m}$ (0.000018 in) semipermeable membrane (Millipore Corp., Billerica, MA, USA) to determine the suspended solids concentration. The remaining filtrate was measured for pH and conductivity and then was analyzed for pollutant concentrations using a Flow Injection Analyzer [32]. The monthly loadings were determined by integrating discrete loadings, which were calculated by suspended solid/nutrient concentration \times stream discharge for each sampling period.

The climate data, including daily precipitation, air temperature, relative humidity, and wind speed, were obtained from the St. Leonard Environment Canada weather station, located approximately 5 km from the BBW (Figure 1). The daily average relative humidity and wind speed were calculated based on hourly values. Since this weather station did not monitor daily solar radiation, this study used solar radiation collected from a weather station located approximately 10 km from the BBW (WS#08; Figure 1).

Since the early 1990s, a land use survey has been conducted every year in the BBW to record land use and management practices, including crop types, tillage operations, and fertilizer and pesticide applications on each farmland. During the past few decades, potato-barley crop rotation has been the dominant agricultural practice. Major BMPs are flow diversion terraces (FDT) and associated grassed waterways, protecting more than half of the agricultural area in 2011. In particular, a land use map was generated annually from 1992 to 2011 based on land use surveys, recording detailed information about field IDs, land transactions, crop rotation, and detailed management practices (e.g., names of fertilizers, composition, and application amounts and dates).

2.2. SWAT Setup

The basic input data included the DEM, land use, and soil maps for the BBW. A high-resolution light detection and ranging (LiDAR) based DEM (1-m resolution) was used to delineate the watershed and derive topographical characteristics [33,34]. The land use types in BBW are surveyed each year by Agriculture and Agri-Food Canada (AAFC) and summarized in Table 1. The soil data were obtained from an AAFC detailed soil survey map [31]. ArcSWAT 2012 was used to delineate the boundaries of the entire study area and its subbasins, along with their drainage channels. The BBW was divided into eight subbasins corresponding to surveys by AAFC. The areas of the individual subbasins ranged from 68 to 278 ha in size. Table 2 lists the characteristics of generated subbasins and stream attributes of subbasins. Slopes in the BBW were classified into five groups (Figure 2).

Table 1. Datasets used in model setup, calibration, and validation of SWAT1 and SWAT2.

Dataset	SWAT1	SWAT2	Location	Purposes
1-m resolution LiDAR DEM	2010	—	BBW	SWAT setup
Soil map	1993	—	BBW	SWAT setup
Land use maps	1992–2011	2001	BBW	SWAT setup
Precipitation, temperature, relative humidity, and wind speed	1992–2011	—	St. Leonard	SWAT setup
Solar radiation	1992–2011	—	WS#08	SWAT setup
Tillage operation (spring and fall)	1992–2011	2001	BBW	SWAT setup
Fertilizer application	1992–2011	2001	BBW	SWAT setup
Crop rotation	1992–2011	2001	BBW	SWAT setup
Terraces and grassed waterways	1992–2011	2001	BBW	SWAT setup
Discharge, sediment, NO ₃ -N, and Sol-P	1992–2011	—	MS#01	SWAT calibration & validation

Table 2. Physical characteristics of subbasins and stream attributes of the BBW.

Subbasin Number	Area (ha)	Fraction of Total Area (%)	HRUs SWAT1	HRUs SWAT2	Main Channel Width (m)	Avg. Channel Slope (m m ⁻¹)	Main Channel Length (km)	Main Channel Depth (m)
1	227	17.31	154	49	6.1	0.018	1.53	0.4
2	226	17.22	180	57	4.2	0.009	2.80	0.3
3	131	9.95	108	50	3.3	0.008	1.32	0.2
4	245	18.69	95	45	2.8	0.007	2.21	0.2
5	108	8.21	46	25	1.4	0.005	0.02	0.1
6	78	5.93	37	17	1.1	0.018	0.68	0.1
8	234	17.82	189	41	2.5	0.017	0.96	0.2
9	64	4.87	78	26	1.0	0.029	0.46	0.1

2.2.1. New Land Use Map

Two versions of the enhanced SWAT model were set up for the BBW, using detailed and coarse inputs of land use and management practices, referred to as SWAT1 and SWAT2, respectively, hereafter. The conventional way of setting up SWAT uses one land use map with the crop name as the land use ID. When HRUs are created with specified combinations of land use type, soil type, and slopes in a subbasin, one HRU can represent multiple fields. This study assigned a unique land use ID (based on farmers' names and field numbers) to each field identified in the land use map. If two fields had the same crop present, e.g., potatoes, they were assigned different land use IDs. The land use map of 2001 was chosen as the baseline map to delineate HRUs for SWAT1 and SWAT2. Figure 3a shows the land use map used for SWAT2 with 18 land use IDs. By contrast, 198 land use IDs were identified in the new land use map used for SWAT1 (Figure 3b). After combining the land use, soil, and slope maps (with area thresholds of 0, 10, and 20%, respectively) through the ArcSWAT interface, 887 and 310 HRUs were created for SWAT1 and SWAT2, respectively (Table 2).

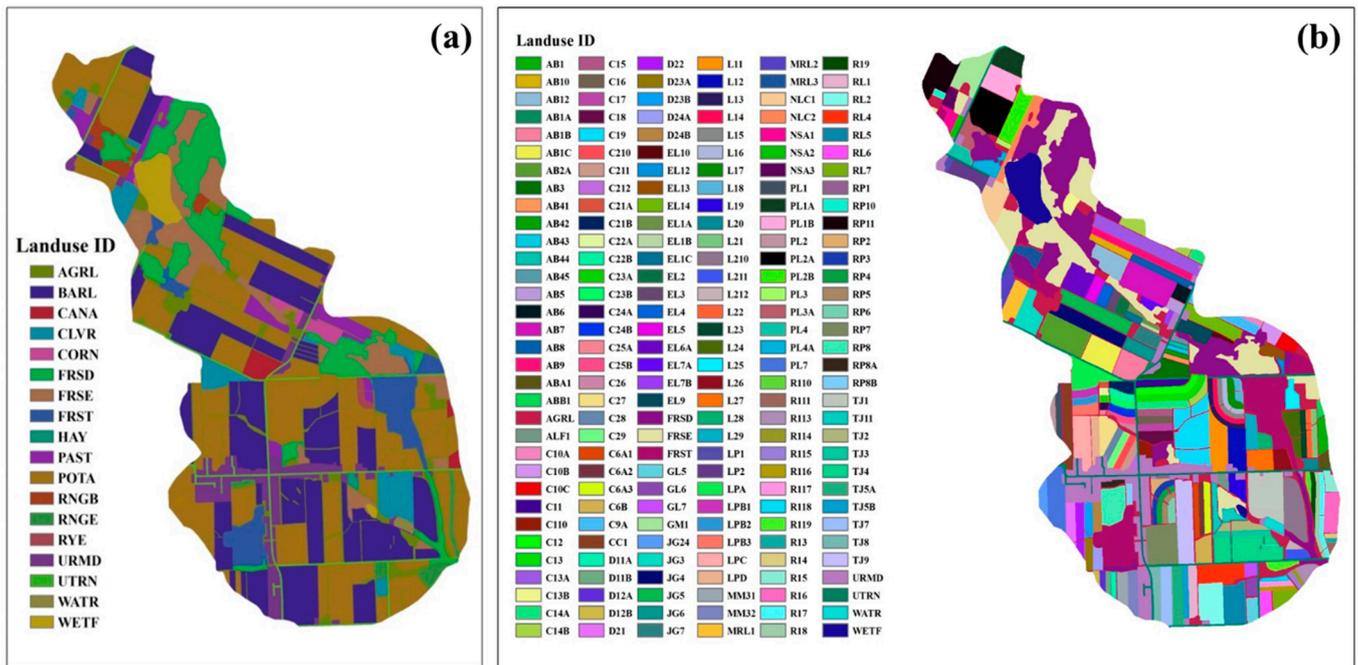


Figure 3. Land use IDs of (a) a land use map generated in 2001 and (b) in a new version of the land use map.

2.2.2. Management Data Configuration

To incorporate the recorded data into the SWAT1 management files, land use maps from 1992 to 2011 (except for 2001) were spatially joined with the new land use map based on field IDs (Figure 3b) through ArcGIS (join attributes from a table; Figure 4). As a result, the new land use map had an attribute table with 20 years of land use and management information associated with each field. The parameters of the SWAT1 management files (based on HRUs) were further modified according to field records. For example, a moldboard plow with a 150-mm mixing depth and 0.95 mixing efficiency was set for conventional tillage, and a chisel plow with a 150-mm mixing depth and 0.30 mixing efficiency was set for conservation tillage. Existing terracing and grassed waterways modules were modified corresponding to records, including the year of implementation, slope lengths of FDT, and widths of grassed waterways. The parameters of these BMPs were initially modified according to published values [35–39].

We assumed that only one land use map (2001) was available for SWAT2, and limited land use and management information was used to adjust SWAT2 management files (Table 1). As a result, the following assumptions based on the information available were made:

- (1) Potato–barley was assigned to land use ID POTA. For other land use IDs, it was assumed that no crop rotation took place;
- (2) Fertilizers were applied only to potato and barley, and fertilizer amounts and N/P ratios were averaged over the entire watershed based on 2001 survey data from the BBW;
- (3) Contour tillage was applied only to potato and barley fields, and tillage areas were proportionally assigned to potato and barley fields over the entire watershed based on 2001 survey data from the BBW; and
- (4) FDT and grassed waterways were applied only to potato and barley fields, and their areas were proportionally assigned to potato and barley fields in individual subbasins based on 2001 survey data from the BBW.

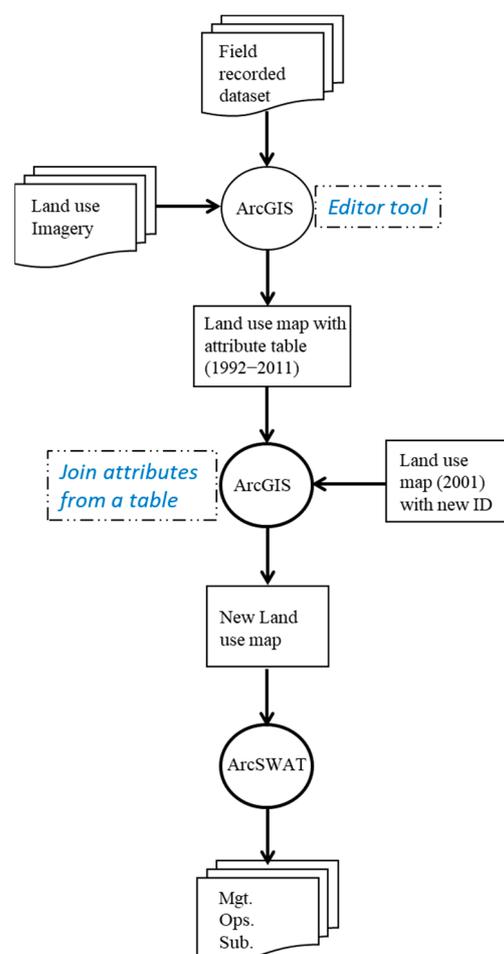


Figure 4. Flowchart of the new land use map generation and detailed land use and management information incorporated into SWAT1. “Mgt”, “Ops”, and “Sub” stand for management and operation and subbasin input files.

2.3. SWAT Calibration and Validation

The SWAT calibration uncertainty program (SWAT-CUP) was used to calibrate both models [40]. Water quantity and quality in the SWAT model were calibrated sequentially. SWAT1 was first calibrated using monthly baseflows, then the total stream discharges from 1992 to 2001. The baseflow discharge was based on previously reported values calculated using the recursive digital filter (RDF) method [41,42]. Further calibration was conducted first to monthly sediment, second to $\text{NO}_3\text{-N}$, and last to Sol-P loadings from 1992 to 2001. During calibration, we tried to avoid the equifinality problem and the best-fit of parameter sets by using thousands of simulations aided with SWAT-CUP for each water quantity and quality variable. The validation period was from 2002 to 2011. Parameters TERR_P and TERR_CN of the terracing module and USLE_P for the impact of contour tillage on sediment loading were also calibrated (Table 3). As for SWAT2, calibration parameters were set equal to those for SWAT1 with respect to water flow and sediment and nutrient loadings, as well as management practices (i.e., contour tillage, FDT, and grassed waterways). The model’s performance in simulating water quantity and quality at the watershed outlet was compared between SWAT1 and SWAT2 based on two periods, i.e., period I (1992–2001) and period II (2002–2011).

Table 3. Parameters of contour tillage, FDT, and grassed waterways adjusted for SWAT1 and SWAT2.

BMPs	Parameter	Meaning	Initial Value	Calibrated
FDT	TERR_P	USLE practice factor	0.12, slope < 3 0.10, 3 < slope < 9 0.15, 9 < slope	×(1–0.2)
	TERR_CN	Initial SCS curve number II	50	72
	TERR_SL	Average slope length (m)	25–100	50 for SWAT2
Grassed waterways	GWATN	Manning’s N value	0.35	0.35
	GWATSPCON	Sediment linear parameter	0.005	0.005
	GWATD	Depth of grassed waterway (m)	3/64 × GWATW	3/64 × GWATW
	GWATW	Mean width of grassed waterway (m)	5	5
	GWATL	Length of grassed waterway (km)	HRU length	HRU length
	GWATS	Mean slope of grassed waterways (m)	0.75 × HRU slope	0.75 × HRU slope
Contour Tillage	USLE_P	USLE practice factor	0.5	0.6

Note: “Slope” refers to the slope of HRUs (unit: %).

2.4. Statistical Evaluation

Statistical metrics used to evaluate model performance include the relative error (Re), the coefficient of determination (R^2), and the Nash–Sutcliffe (NS) coefficient [43], expressed as follows:

$$Re = \frac{(P_{avg} - O_{avg})}{O_{avg}} \cdot 100\%, \quad (1)$$

$$R^2 = \left(\frac{\sum_{i=1}^n (O_i - O_{avg}) \cdot (P_i - P_{avg})}{\left[\sum_{i=1}^n (O_i - O_{avg})^2 \cdot \sum_{i=1}^n (P_i - P_{avg})^2 \right]^{0.5}} \right)^2, \quad (2)$$

$$NS = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2}, \quad (3)$$

where O_i and P_i are the observed and predicted values, respectively, and O_{avg} and P_{avg} are the averages of the observed and predicted values, respectively.

3. Results and Discussion

3.1. Input Resolutions of Land Use and Management Practices

3.1.1. Crop Rotation, Fertilizer Application, and Contour Tillage

Percentage areas of potato and barley and annual application rates of N and P for BBW, represented with both models, were compared with records from 1992 to 2011 (Figure 5). For SWAT1, input areas for the two crops were consistent with records, with potatoes occupying 30 to 40% of the total watershed area and barley areas varying from 10 to 25%, with high percentages in the early 2000s (Figure 5a). Application rates of N for potato fields were almost constant after 1995 at $\sim 200 \text{ kg ha}^{-1}$, but decreased from $\sim 60 \text{ kg ha}^{-1}$ in the 1990s to less than 50 kg ha^{-1} in the late 2000s for barley fields (Figure 5c,d). The application rates of P for potato and barley fields were relatively constant at $\sim 70 \text{ kg ha}^{-1}$ and 5 kg ha^{-1} , respectively (Figure 5c,d). Overall, the input N and P application rates of SWAT1 agreed well with field records for both potato and barley fields. For SWAT2, input areas of potato and barley and N and P application rates did not agree well with the field records (Figure 5). The input areas of potato and barley in 2001 were consistent with records, while in other years, they varied up and down due to potato–barley rotations. Input fertilizer application rates in potato and barley fields in 2001 were consistent with records, remaining constant for other years. For the entire watershed, N and P application rates varied with potato–barley rotations (Figure 5).

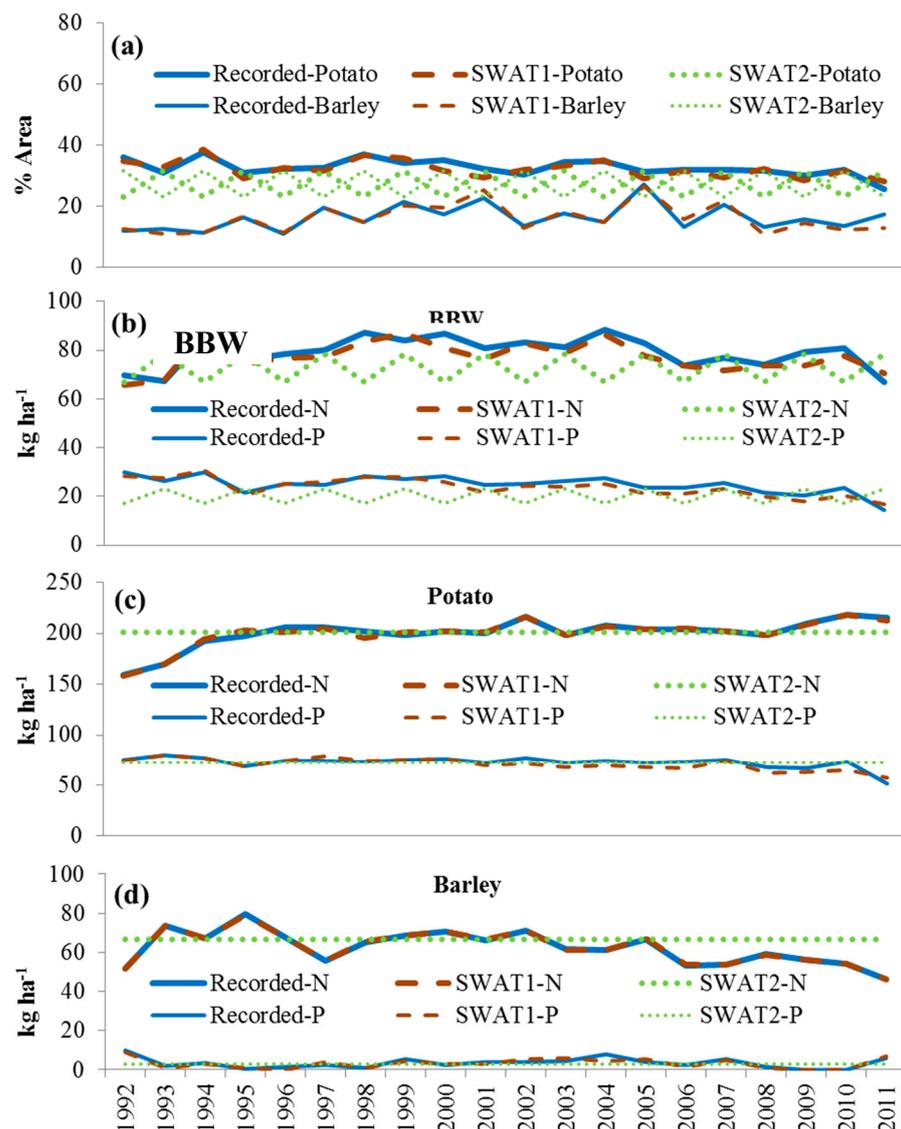


Figure 5. (a) Input percentage areas of potato and barley and annual application rates of N and P for (b) the entire watershed, and (c) potato and (d) barley fields compared with records from 1992 to 2011 in the BBW.

Figure 6 shows the input percentage areas of various tillage operations in the BBW compared with records from 1992 to 2011. For SWAT1, input areas of moldboard and chisel plow, as well as total tillage areas, were consistent with records in both spring and fall (Figure 6c–f). The chisel plow areas were slightly higher than records (about 5% higher), leading to an overestimation of the total tillage area in fall (Figure 6a,e). This was caused by the modifications we made to the contour tillage operation for several crops. Although spring tillage areas decreased and fall tillage increased from 1992 to 2011, fall tillage areas were always much greater than spring tillage areas (Figure 6a,b). In addition, fall moldboard plow areas increased in the 1990s and remained constant in the 2000s, occupying ~25% of the total watershed area (Figure 6c). Fall chisel plow areas remained under 25% of the total watershed area, with several peaks in the early 2000s (Figure 6e). Spring moldboard plow areas have decreased since the early 1990s, and spring chisel plow areas decreased to 0% after 1995 (Figure 6d,f). For SWAT2, input areas for moldboard and chisel plowing were not consistent with records (Figure 6). The percentage areas for contour tillage were equal to the records only in 2001, while in other years, they varied with potato–barley rotations.

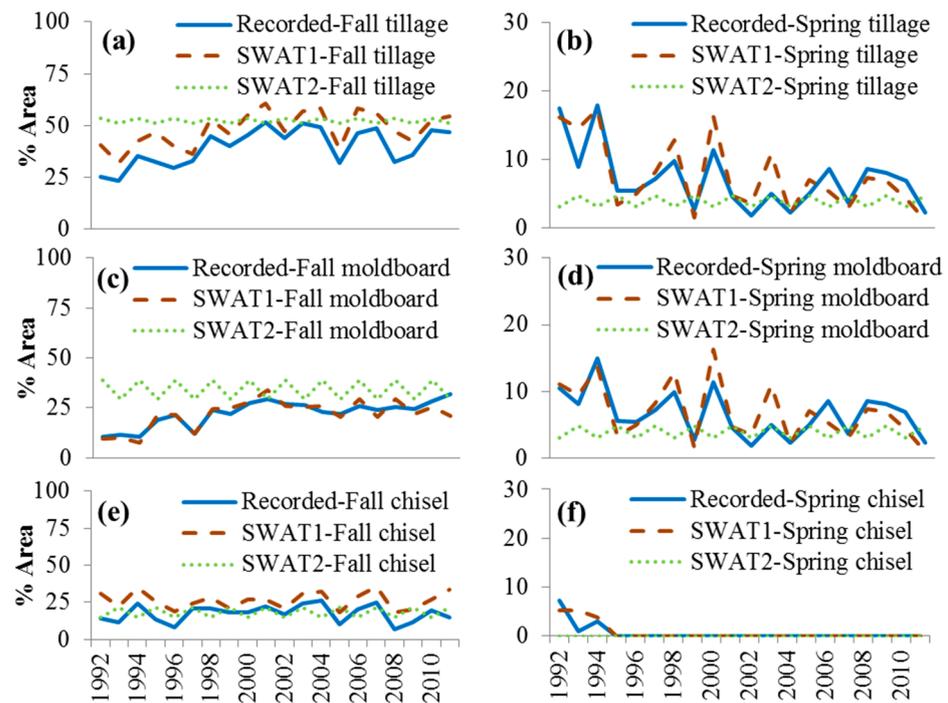


Figure 6. Input percentage areas of moldboard and chisel plowing in spring and fall and spring and fall tillage (moldboard + chisel) compared with records from 1992 to 2011 in the BBW. (a) Fall tillage, (b) spring tillage, (c) fall moldboard, (d) spring moldboard, (e) fall chisel, and (f) spring chisel.

3.1.2. Terraces and Grassed Waterways

The input percentage areas of FDT and grassed waterways were compared with records from 1992 to 2011 (Figure 7). Since most grassed waterways were constructed along with FDT, input terraces and waterways varied similarly over time. The total areas protected by FDT and grassed waterways increased from less than 10% to almost 40% from 1992 to 2011. For SWAT1, input FDT protected areas were consistent with records, and input grassed waterway protected areas were slightly greater than records, caused by missing data in several fields. Comparisons between input FDT protected areas and records in 1992, 1995, 2004, and 2011 for SWAT1 (Figure 8) show that SWAT1 successfully represented changes in FDT protected areas from 1992 to 2011. Input FDT and grassed waterway protected areas for SWAT2 were close to records only in 2001, remaining constant after 2001 (Figure 7). Although SWAT2 could generate equal areas with records for most subbasins, it could not generate the same FDT distribution pattern as SWAT1 (Figure 9).

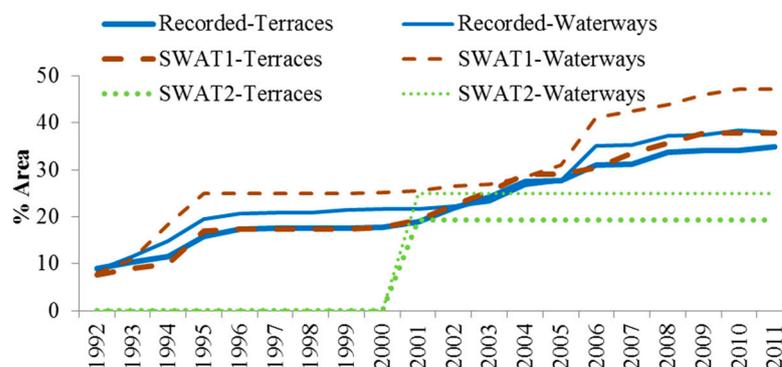


Figure 7. Input percentage areas of FDT and grassed waterways compared with records from 1992 to 2011 in the BBW.

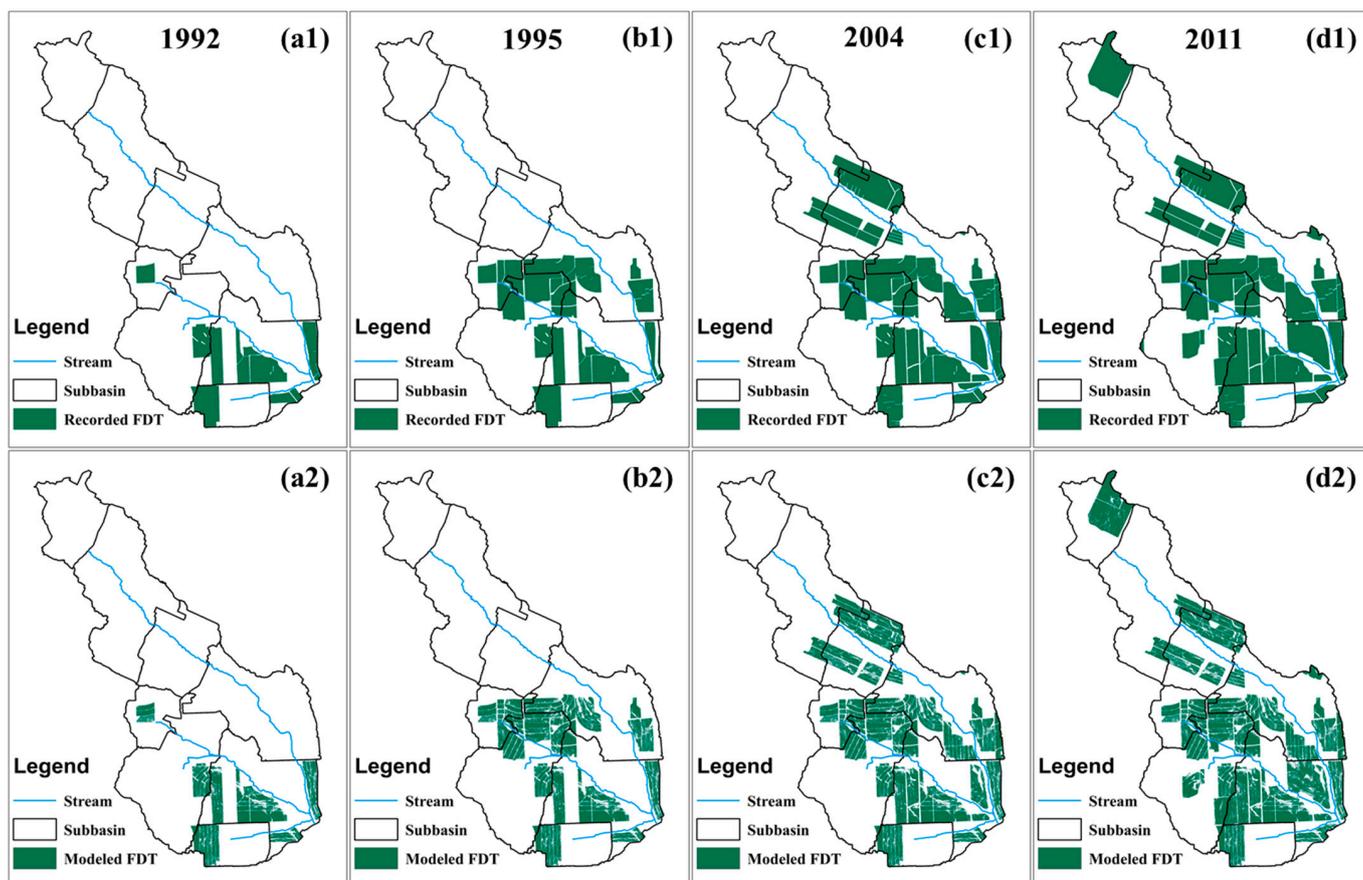


Figure 8. Recorded (top panels) and input (bottom panels) FDT protected areas in the BBW for (a1 versus a2) 1992, (b1 versus b2) 1995, (c1 versus c2) 2004, and (d1 versus d2) 2011. Results are from the SWAT1 model.

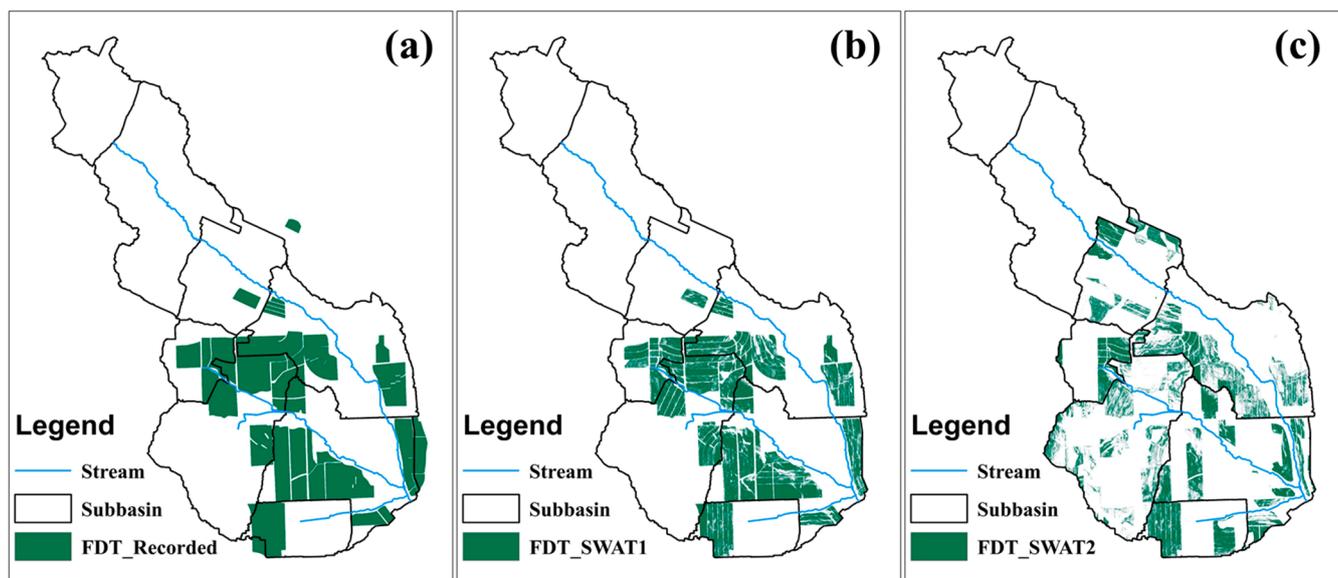


Figure 9. (a) Recorded and (b) SWAT1- and (c) SWAT2- FDT protected areas for the year 2001.

3.2. SWAT Calibration

Table 4 lists the calibrated parameters for SWAT1, where 20 parameters were adjusted. Parameter CNOP (i.e., CN_2) was initially adjusted to reflect the influences of management practices based on land use groups and hydrological properties of soils. $Alpha_{Bf}$ was

adjusted to 0.04 day^{-1} , indicating that the baseflow discharge had a slow response to recharge. The parameter *Surlag* was set to 0.075, indicating that surface runoff tended to converge quickly to the outlet. We also adjusted the relevant parameters to reflect that lateral flow increased due to unfrozen soils in winter [44]. Additionally, parameter *Anion_Excl* was reduced to improve the nitrate retention capacity of soils. Table 3 lists parameters calibrated for management practices. Support practice factor (parameter *ULSE_P*) values for contour tillage and FDT were within the range of recommended values [35,37,38]. The value of parameter *TERR_CN* (i.e., 72) was less than the mean CN_2 of croplands without FDT. Note that *TERR_SL* for SWAT2 was set to 50 m, while for SWAT1, the value varied in different HRUs, ranging from 25 to 100 m.

Table 4. Parameters adjusted during calibration of SWAT1.

Relevant Process	Parameter	Unit	Default	Used
Snowmelt	Smtmp	°C	0	0.375
	Sftmp	°C	0	0.175
	Smfmx	$\text{mm } ^\circ\text{C}^{-1}$ day^{-1}	4.5	9.725
	Smfmn	$\text{mm } ^\circ\text{C}^{-1}$ day^{-1}	4.5	3.525
	Timp	—	1	0.15
Baseflow	Alpha_Bf	day^{-1}	0.048	0.04
	Gw_Delay	day	31	1
	Revapmn	mm	1	500
	Rchrg_Dp	—	0.05	0
Surface and lateral flow	Surlag	—	4	0.075
	Esco	—	0.95	0.17
	Epc0	—	1	0.93
	Slsoil	m	default	$\times (1 - 0.5)$
$\text{NO}_3\text{-N}$	Anion_Excl	—	default	$\times (1 - 0.7)$
	CDN	—	1.4	0.15
	SDNCO	—	1.1	1
	N_Updis	—	20	100
Sol-P	Phoskd	—	175	110
	P_Updis	—	20	25
	PSP	—	0.7	0.7

3.3. Impacts on Monthly Water Flow and Sediment and Nutrient Loadings

Figures 10 and 11 show simulated and observed monthly water flows and sediment and nutrient loadings for periods I and II, respectively. Table 5 lists statistical indexes for model performances.

Table 5. Model assessments for SWAT1 and SWAT2 during two periods.

Period	Model	Index	Base Flow	Discharge	Sediment	NO ₃ -N	Sol-P
I	SWAT1	Re (%)	−5.0	−6.4	−20.3	−11.8	2.8
		R ²	0.65	0.62	0.40	0.50	0.23
		NS	0.63	0.61	0.39	0.43	0.14
	SWAT2	Re (%)	−4.8	−5.9	−16.1	−16.4	6.4
		R ²	0.67	0.58	0.39	0.51	0.16
		NS	0.65	0.58	0.39	0.46	0.09
II	SWAT1	Re (%)	−2.5	9.2	5.6	6.1	−8.7
		R ²	0.82	0.89	0.30	0.40	0.65
		NS	0.82	0.86	0.04	0.34	0.53
	SWAT2	Re (%)	−4.8	9.2	35.9	−8.2	4.3
		R ²	0.80	0.88	0.29	0.45	0.67
		NS	0.80	0.85	−0.62	0.44	0.56

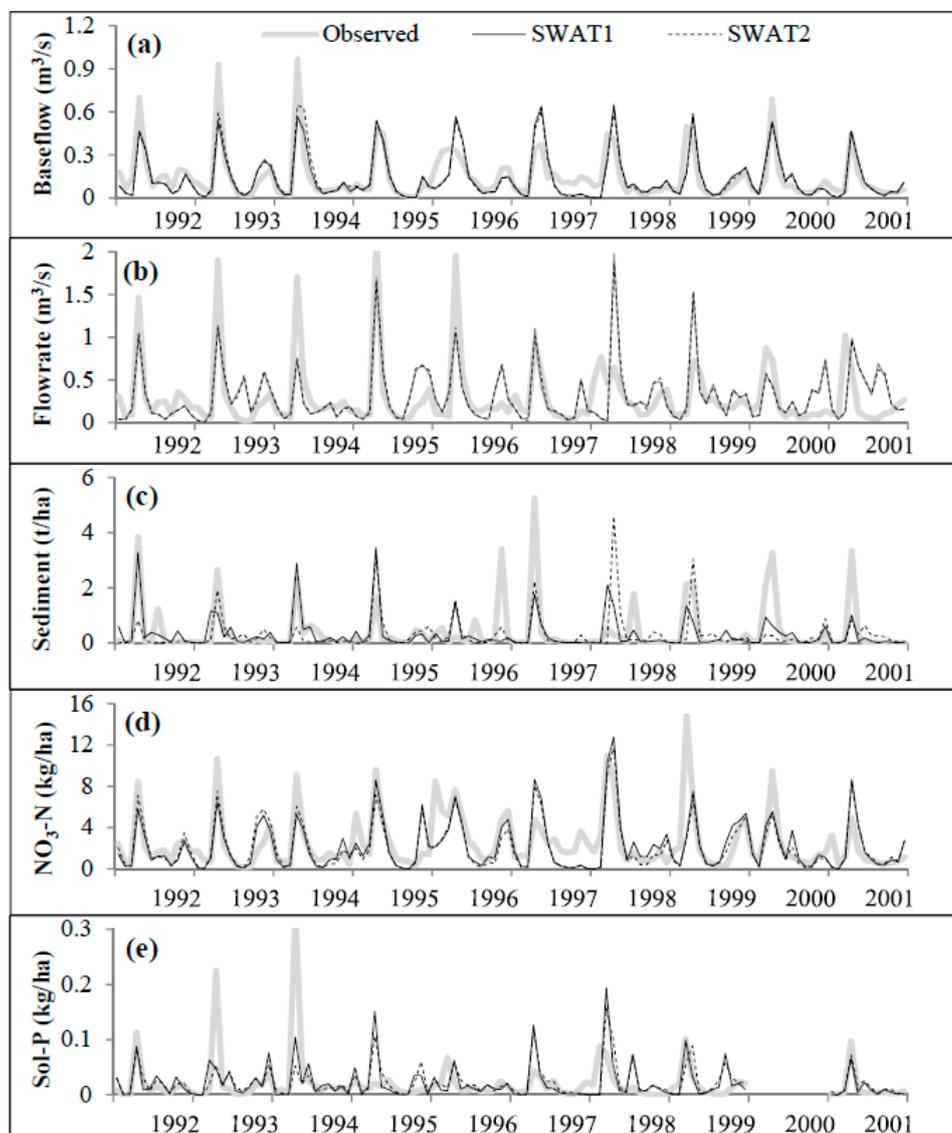


Figure 10. Comparisons of SWAT1- and SWAT2-simulated and observed monthly (a) baseflow, (b) flowrate, (c) sediment loading, (d) NO₃-N loading, and (e) Sol-P loading for period I. The “observed” values of baseflow were calculated using the RDF method.

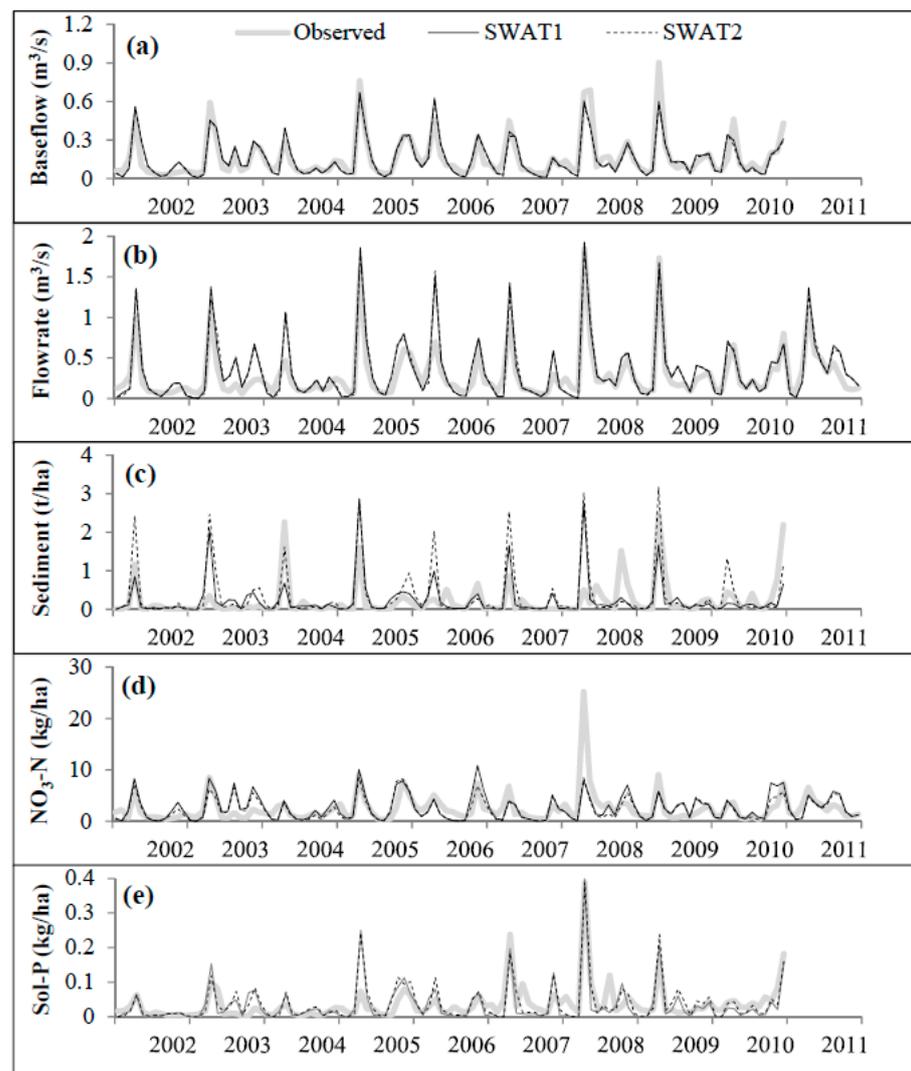


Figure 11. Comparisons of SWAT1- and SWAT2-simulated and observed monthly (a) baseflow, (b) flowrate, (c) sediment loading, (d) $\text{NO}_3\text{-N}$ loading, and (e) Sol-P loading for period II. The “observed” values of baseflow were calculated using the RDF method.

The monthly baseflow and total stream discharge simulated by both models were consistent with observations (or estimates of baseflow) in both periods (Figure 10a,b and Figure 11a,b, respectively). Both models performed satisfactorily according to guidelines established by Moriasi et al. [45]. Compared with SWAT2, SWAT1 performed slightly better in simulating monthly variations of total stream discharge for both periods and the baseflow for period II (i.e., greater R^2 and NS), while in period I, SWAT2 performed slightly better (Table 5). In both periods, the Re of SWAT1 was close to that of SWAT2 for baseflow and total stream discharge (Table 5). The results indicate that discrepancies in the management practice input between these two models had little impact on the general water balance in the BBW.

The two models performed almost equivalently in simulating the monthly variations of sediment loading in period I based on R^2 and NS (Table 5). However, visual inspection indicates that SWAT1 accurately identified several major peaks of sediment loading during the snowmelt season (e.g., 1992 and 1994), whereas SWAT2 severely underestimated them (Figure 10c). In general, both models underestimated sediment loadings in period I ($Re = -20.3$ and -16.1 for SWAT1 and SWAT2, respectively) due to a failure to capture major erosion events caused by snowmelt in humid-warm winters (e.g., 1996 to 2000; Figure 10c). In period II, SWAT1 performed better than SWAT2 (i.e., greater NS ; Table 5),

with the latter consistently overestimating peak sediment loadings during the snowmelt season ($Re = 35.9$; Figure 11). This is because SWAT1 was able to better account for gradually increasing areas of FDT after 2001 (Figures 7 and 8). However, the low NS values of both models in period II were partly due to the inability of the SWAT model's modified universal soil loss equation to address soil erosion caused by freeze–thaw cycles. The FDT module could not be calibrated to compensate for incorrect estimates of sediment loadings. An accurate soil erosion module is required for a better assessment of FDT during winter and the snowmelt season in Atlantic Canada.

SWAT2 performed slightly better than SWAT1 in simulating monthly variations of NO_3-N loading for both periods (i.e., higher R^2 and NS ; Table 5). Both models tended to underestimate monthly NO_3-N loading in period I (negative Re values), while SWAT1 overestimated NO_3-N loading in period II. Since SWAT1 can model gradually increased FDT protected areas (Figure 7), it was expected that more nitrates would be leached due to increased infiltration, which is reflected by the change of sign of Re for SWAT1 from period I to II.

For Sol-P loading, SWAT1 performed better in simulating monthly variations than SWAT2 in period I (i.e., higher R^2 and NS) while not as well in period II (i.e., lower R^2 and NS ; Table 5). Note that for both models, NS and R^2 values for Sol-P in period I were lower than those in period II, mainly due to several snowmelt peaks in the early 1990s (e.g., 1993 and 1994), which both models failed to simulate, consistent with the issue simulating stream discharge for the same periods (Figure 10b versus e). This illustrates that even though statistical indices indicate that stream discharge was reasonably simulated, the discrepancy between simulations and observations can be amplified in associated nutrients, particularly for extreme high-flow events. This is one of the SWAT limitations in simulations at daily or event scales [46]. Furthermore, changing the sign of Re from positive (overestimation) to negative (underestimation) from period I to II with SWAT1 indicates less Sol-P loadings as a response to the gradually increased area protected by FDT, leading to increased infiltration and decreased surface runoff (Table 5).

Overall, there is no definite increase in simulation accuracy in monthly variations of nutrient loadings with high spatial and temporal resolution management input data in our study, though monthly nutrient loading simulations were sensitive to management configuration.

3.4. Impacts on Annual Stream Flow and Sediment and Nutrient Loadings

Figure 12 shows observed and simulated annual baseflow and total discharge and sediment, NO_3-N and Sol-P loadings by SWAT1 and SWAT2 from 1992 to 2011. SWAT1 simulated baseflow better than SWAT2 (i.e., $R^2 = 0.63 > R^2 = 0.55$), and both models performed similarly with total discharge ($R^2 = 0.56$; Figure 12a,b), indicating again that there are discrepancies in the land use and management practice input between these two models had minimum impact on the general water balance in the BBW. Both models simulated annual sediment loadings poorly (i.e., $R^2 \leq 0.02$; Figure 12c) due to the inability of the SWAT model to address soil erosion caused by freeze–thaw cycles, which rendered difficulties in the assessment of FDT input accuracy effects on simulation. Compared with monthly evaluation (Figures 10 and 11), the annual variations in sediment loading were poorly simulated (based on R^2), demonstrating that monthly calibration would not guarantee good annual results. This is particularly evident for sediment loading, whose one or two peaks control the majority of monthly variations over a year. SWAT1 performed better than SWAT2 on simulating variations of annual loading for NO_3-N (i.e., $R^2 = 0.32 > R^2 = 0.27$) while SWAT2 was better for Sol-P based on R^2 (i.e., $R^2 = 0.40 > R^2 = 0.37$; Figure 12d,e). Similar to the monthly evaluation, there is no definite increase in simulation accuracy in annual variations of stream flow and nutrient loadings with high spatial and temporal management inputs in our study.

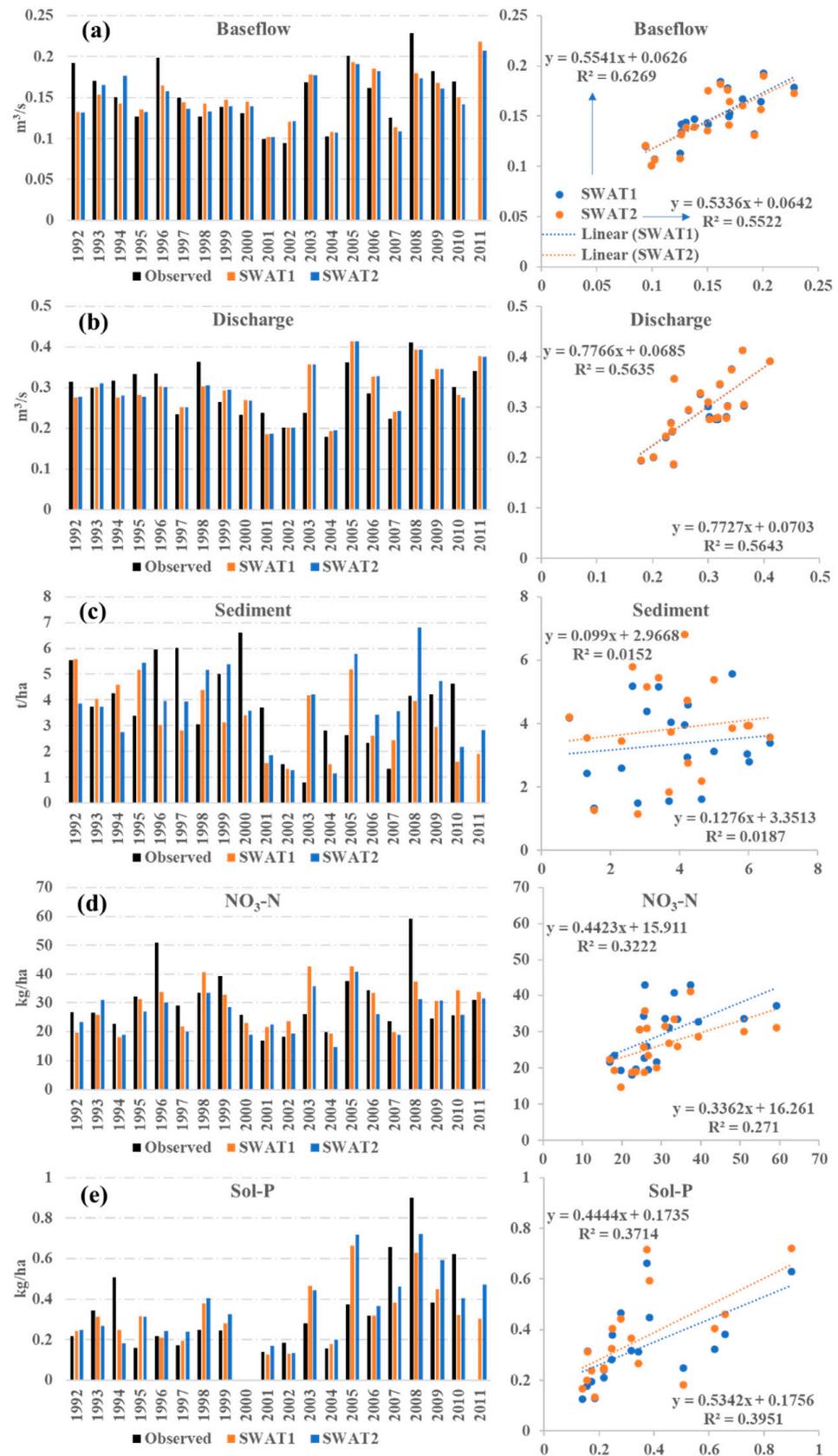


Figure 12. Observed vs. simulated annual (a) baseflow and (b) flowrate and (c) sediment, (d) NO₃-N and (e) Sol-P loadings by SWAT1 and SWAT2 from 1992 to 2011.

3.5. Spatial Impact of FDT on Soil Erosion

SWAT1- and SWAT2-simulated annual sediment loadings from HRUs were averaged over periods I and II, and erosion intensity maps were derived (Figure 13). The sediment loadings were classified into five groups according to Lobb et al. [47]. Soil loss rates greater than 11 t ha^{-1} were considered a moderate to high erosion intensity, and soil loss rates less than 11 t ha^{-1} were considered a low erosion intensity. Simulated moderate to high-intensity erosion areas decreased from period I to II for both models (Figure 13), corresponding to the increased usage of FDT in period II (Figure 7). For SWAT1, most low erosion intensity areas were associated with FDT in both periods (Figures 8 and 13), except for forested land (Figure 2). By contrast, low erosion intensity areas modeled with SWAT2 were not consistent with the actual FDT distribution in the BBW for both periods (Figures 8 and 13). SWAT2 failed to spatially represent the impact of FDT on soil erosion across the watershed. These results indicate that SWAT can provide high-resolution output, such as soil-erosion-vulnerable areas, using high-resolution management inputs through field-based HRU delineation. SWAT can thus better facilitate decision-making not only at the subbasin scale but also at the field scale.

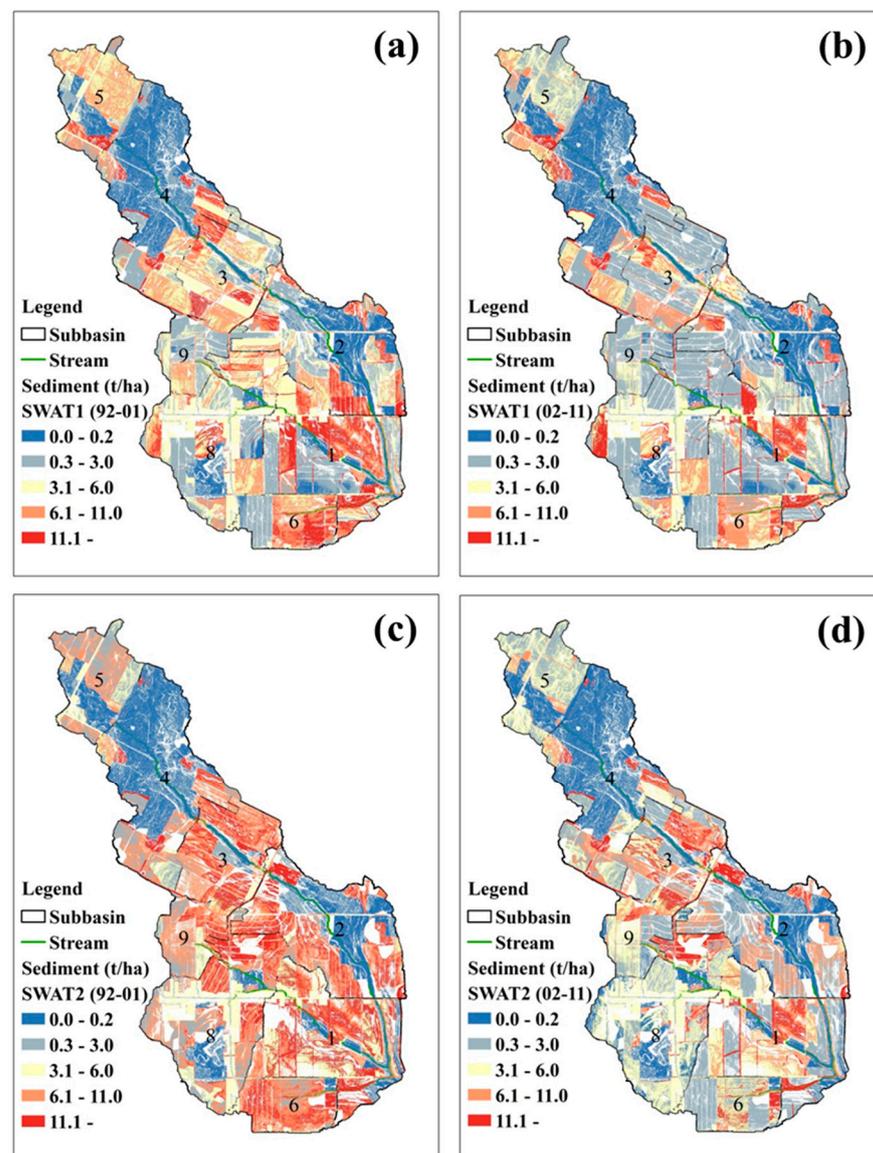


Figure 13. Comparisons of mean annual sediment loadings from HRUs in the BBW between the periods 1992–2001 (left panels) and 2002–2011 (right panels) simulated with SWAT1 [(a) versus (b)] and SWAT2 [(c) versus (d)].

4. Comparing with Other Studies

To our knowledge, there is no study for dynamic land use impacts having land use and management information for every year of the simulation period. Particularly, no study has such detailed management practice records for each simulation year as in our study. Furthermore, previous studies investigating the difference between static and dynamic land use and management practice inputs used the earliest land use map available as the static condition and baseline scenario. As a result, they found obvious effects of land use changes on the simulation of flow, and sediment, nitrogen, and phosphorus loadings [48–51] and argued that differences in the land use input conditions could affect the long-term water quantity and quality simulation so that dynamic land use input was recommended. On the contrary, we used the land use map of 2001 (in the middle of the simulation period from 1992 to 2011) and limited management information as the static land use and management practice input for SWAT2. As a result, we obtained a different conclusion that there is no definite increase in simulation accuracy in monthly and annual water flow and nutrient loadings with high spatial and temporal resolution management input data in our study. This is because land use and management information from 2001 (though we have tried to simplify inputs such as N and P application and crop rotation) could be seen as an average management condition of BBW from 1992 to 2011. In addition, the area of agricultural lands and management practices used in the BBW (except for the area of FDT) did not change too much over the simulation period. Our results indicate that SWAT, although set up with limited land use and management information, is able to provide comparable simulations of water quantity and quality at the watershed outlet, as long as the estimated land use and management practice data can reasonably represent the average land use and management condition of the watershed over the target simulation period. However, the conclusion may not be applicable to watersheds with great changes in the area of agricultural lands and management practices during the simulation period.

5. Conclusions

This study presents an algorithm that incorporates detailed land use and management inputs into the SWAT model. The method delineates HRUs based on field boundaries and associates each HRU with an individual field to facilitate incorporating detailed annual records into the SWAT management files. After model setup, the SWAT model was calibrated and validated using monthly water flow and sediment and nutrient loadings in a small experimental watershed in New Brunswick, Canada. Meanwhile, another SWAT model was set up with the original HRU-delineation method and limited information on land use and management. These two versions of SWAT were compared with respect to input and output resolution and prediction accuracy of monthly and annual water flow and sediment and nutrient ($\text{NO}_3\text{-N}$ and Sol-P) loadings. Compared with the SWAT set up with the conventional method, the SWAT set up with the new method generated accurate annual areas of crops, fertilizer application, tillage operation, flow diversion terraces (FDT), and grassed waterways in the BBW. The simulation results indicate that the SWAT set up with the new method did not evidently perform better than the SWAT set up with the conventional method in simulating monthly variations of stream discharge and $\text{NO}_3\text{-N}$ and Sol-P loadings, though monthly nutrient loading simulations were sensitive to management configuration.; however, it did improve the simulation of monthly sediment loading due to an improved representation of FDT in the watershed, and it was able to estimate the spatial impact of FDT on soil erosion across the entire watershed. Setting up SWAT with detailed land use and management information using the field-based HRU-delineation method could specify sources of pollutants and vulnerable areas in subbasins, facilitating watershed management decision-making. Furthermore, the annual examination also showed comparable simulation accuracy on water flow and nutrient loadings between the two models. We concluded that there was no definite increase in simulation accuracy in water flow and nutrient loadings with high spatial and temporal management inputs, indicating that SWAT, although set up with limited land use and management information,

is able to provide comparable simulations of water quantity and quality at the watershed outlet, as long as the estimated land use and management practice data can reasonably represent the average land use and management condition of the watershed over the target simulation period.

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