Identifying High Yield Areas of Sediment and Nutrients in an Illinois CREP Watershed

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Abstract

The Conservation Reserve Enhancement Program (CREP) in Illinois is a partnership between United States Department of Agriculture's Farm Service Agency, Illinois Department of Natural Resources, and the Soil and Water Conservation Districts, providing agricultural producers with financial incentives to conserve and enhance the natural resources of the land. The Illinois CREP goal is to reduce sediment and nutrient runoffs, improve downstream water quality, and create and enhance critical habitat for fish and wildlife populations on private lands within the Illinois and Kaskaskia River watersheds. Since 1999, Hydrologic and water quality monitoring have been conducted by Illinois State Water Survey (ISWS) to assess the effects of conservation practices in the CREP watersheds. Various methods have been developed to estimate watershed sediment and nutrient contributions by different categories of sources and this includes a simple accounting of the mass balance between total watershed inputs and outputs. For example, a watershed nutrient mass balance can be calculated using total nutrient inputs (e.g., fertilizer application, manure, point sources), total outputs (e.g., nutrient removal by plant uptake, riverine nutrient loads) and their difference as total nutrient losses (e.g., due to denitrification, volatilization, soil adsorption). Such methods implicitly assume similar loss mechanisms and proportional relationships of input sources to outputs (Smith and Alexander, 2000). Quantifying the sediment and nutrient source contributions, however, requires accounting for landscape effects, degradation and deposition in the channel, and in-stream nutrient transformations that provide a more complete picture of their impact on downstream water quality. Therefore, in this study, a physically-based, semi-distributed watershed model known as the Soil and Water Assessment Tool (SWAT) was used to develop a hydrologic and water quality model for one of Illinois CREP watersheds. Detailed representation of watershed characteristics and processes in the model allows simulating more accurate relationships between watershed land use, soils, topography and climate, and its resulting watershed responses. The CREP watershed model was calibrated and validated for flow, sediment, nitrate-nitrogen, and total phosphorus simulations, and was used to identify critical source areas of sediment and nutrient yields in the watershed. In addition, eligible CREP areas were identified using the 100-year floodplain area in the watershed and this could facilitate targeting outreach programs for CREP enrollment in the watershed. The watershed model can further be used to evaluate optimal placements of best management practices in the watershed for reduction of nonpoint source pollution.

Introduction

The Conservation Reserve Enhancement Program (CREP) in Illinois is a partnership between United States Department of Agriculture's Farm Service Agency (FSA), Illinois Department of Natural Resources (IDNR), and the Soil and Water Conservation Districts, providing agricultural producers with financial incentives to conserve and enhance the natural resources of the land. The Illinois CREP goal is to reduce sediment and nutrient runoffs, improve downstream water quality, and create and enhance critical habitat for fish and wildlife populations on private lands within the Illinois and Kaskaskia River watersheds. To assess the effects of conservation practices in the watersheds, hydrologic and water quality monitoring have been conducted by Illinois State Water Survey (ISWS) since 1999.

In the Illinois River basin, there are four CREP watersheds that are being monitored since 1999 for flow, sediment and nutrients, and these watersheds are Court Creek, Haw Creek, Panther and Cox Creek. Since 2013, four more CREP watersheds in Kaskaskia River watershed were added for hydrologic and water quality monitoring because of the program's expansion. The hydrologic and water quality data collected from the CREP watersheds were used by ISWS to estimate flow, concentrations, loads and yields of sediment, different species of nitrogen and phosphorus at different time-step.

To quantify the sediment and nutrient source contributions in the study watershed, it is critical to account for landscape effects, degradation and deposition in the channel, and in-stream nutrient transformations that provide a more complete picture of their impact on downstream water quality. Various methods have been developed to estimate watershed sediment and nutrient contributions by different categories of sources. This includes a simple accounting of the mass balance between total watershed inputs and outputs. For example, a watershed nutrient mass balance can be calculated using total nutrient inputs (e.g., fertilizer application, manure, point sources), total outputs (e.g., nutrient removal by plant uptake, riverine nutrient loads) and their difference as total nutrient losses (e.g., due to denitrification, volatilization, soil adsorption). Such methods implicitly assume similar loss mechanisms and proportional relationships of input sources to outputs.

The objective of this study is to identify critical source areas of sediment and nutrient yields in the Haw Creek watershed (see Figure 1), which drains into the Spoon River. To accomplish this task, a hydrologic and water quality model of the watershed was developed using the soil and water assessment tool (SWAT), which is a physically based, semi-distributed watershed-scale model. Detailed representation of watershed characteristics and processes in the model allows simulating more accurate relationships between watershed land use, soils, topography and climate, and its resulting watershed responses. Flow, sediment, nitrate-nitrogen (N) and total phosphorus (P) data collected in the study watershed were used for model calibration and validation. Using the 100-year floodplain map, eligible CREP areas were also identified, which could facilitate targeting outreach programs for enrolling future CREP lands in the watershed. The watershed model can further be used to evaluate optimal placements of best management practices in the watershed for reduction of nonpoint source pollution.

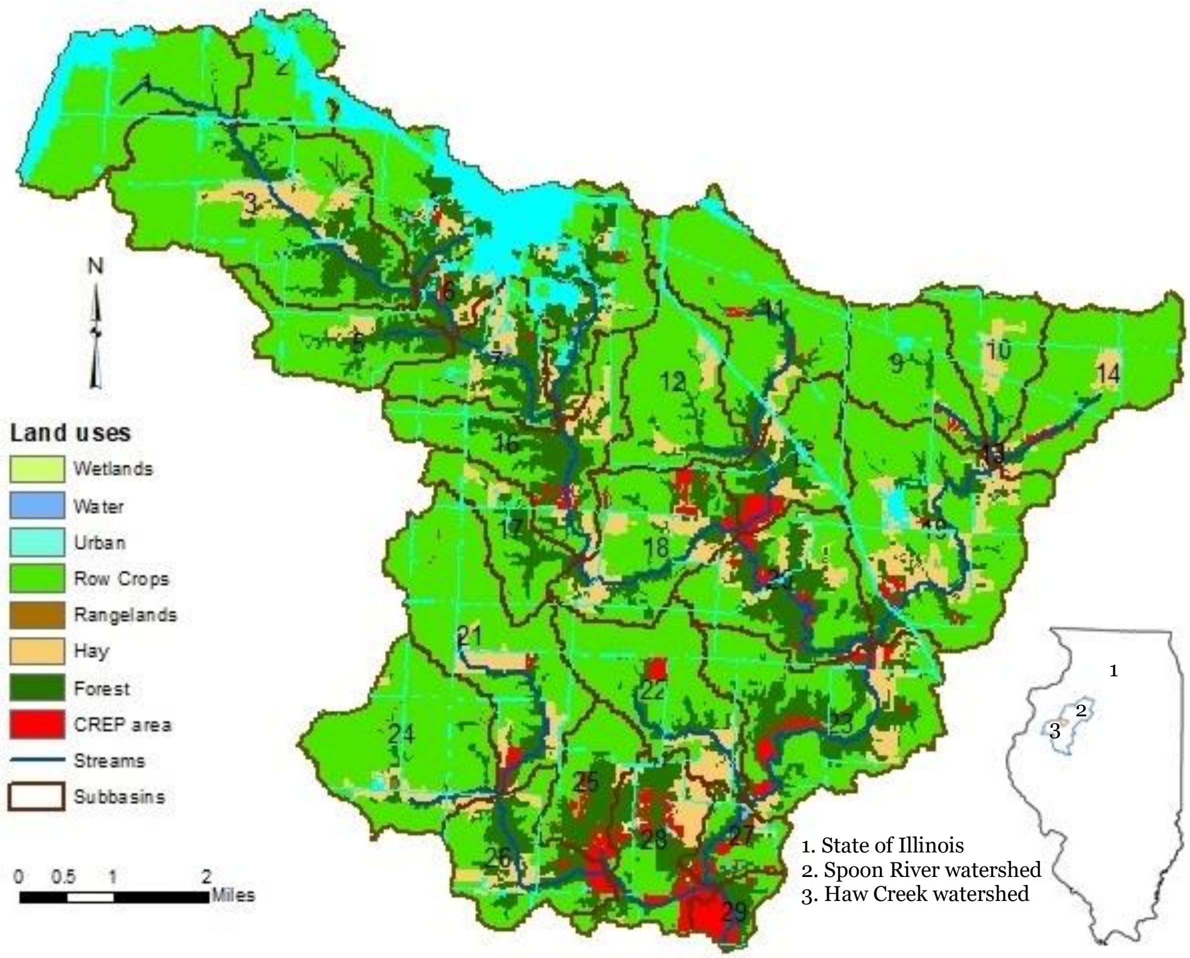

Figure 1. Haw Creek watershed, Illinois

Methods

Watershed Simulation Model

SWAT is the watershed simulation model used in this study. It is one of the most widely used, semi-distributed watershed models that was developed to predict the long-term impacts of land management practices on water, sediment, and agricultural chemical yields from complex watersheds (with varying soils, land use, and management conditions (Arnold et al., 1998; Neitsch et al., 2011). The model simulates watershed processes including surface and subsurface flows, sediment, nutrient transport and cycling, and crop growth. Modeling input data such as topography, land use, soils, land management and weather conditions are required for accurate representation of watershed characteristics and simulating watershed processes, which are predominantly available from government agencies free of charge (Neitsch et al., 2011). A watershed can be delineated into subbasins and the subbasins can further be divided into multiple hydrologic response units (HRUs), which are the smallest modeling units. HRUs are defined as patches of land areas with unique combinations of land use, soil, and slope categories. Neitsch et al. (2011) provides a detailed description of SWAT.

Input Data for Watershed Modeling

Topographic information including National Elevation Data (NED) and National Hydrographic Data (NHD) were obtained from EPA's BASINS website (available at http://www.epa.gov/-waterscience/ftp/basins/gis_data/huc/) and used for watershed delineation. The watershed elevation ranges from 128 to 292 meters, with a mean elevation of 209 meters. About 46% of the watershed area has slopes greater than 2%. Land areas with slopes less than 1%, and between 1 and 2% account for 34.1% and 19.9% of the watershed area, respectively.

The 2011 National Land Cover Dataset (NLCD) was used for general classification of watershed land uses and the data was obtained from Multi-Resolution Land Characteristics Consortium (MRLC) project (available at http://www.mrlc.gov/-nlcd2011.php). The major land uses in Haw Creek watershed include row crops (60.2%), forest (18.9%), hay (9.3%), and urban (8.7%). The remaining land uses account for less than 1%. From 1999 to 2016, the total CREP enrollment covers about 3% of the watershed area. Installed CREP practices consist of hardwood tree planting (CP3A), permanent wildlife habitat (CP4D), permanent wildlife habitat (CP4D), filter strip (CP21), riparian buffer (CP22) and wetland restoration on flood plains (CP23). It also includes additional acres of practices contiguous to the existing federal CREP land. The CREP practices are incorporated into the watershed model, thereby accounting for their impacts on simulating watershed responses. To incorporate the annual land use variations within the watersheds, crop data layers (CDLs) generated by the USDA's National Agricultural Statistics Service (available at http://nassgeodata.gmu.edu-/CropScape/) were used. The CDL data includes a more detailed classification of the cultivated crops for each year.

Soil characteristics of the watershed were derived from Soil Survey Geographic Database (SSURGO), which are county-level soil survey map units and are available at USDA's web soil survey site (http://websoilsurvey.sc.egov.usda.gov). Soil properties extracted include permeability, which influences infiltration of precipitation and thus, determines the soil's ability to generate runoff. Based on runoff potential or infiltration capacity, soils can be grouped into different hydrologic groups. More than 95% of the Haw Creek watershed area belong to hydrologic soil group B, having moderate infiltration rate and the remaining area has soils with slow infiltration rate (group C). Agricultural lands with poorly to somewhat poorly drained soils are identified as potential tile-drained areas and they are estimated to be 34.7% of the watershed area.

Daily precipitation and temperature data were obtained from Midwest Regional Climate Center (https://mrcc.purdue.edu/). Flow, sediment, and nutrient data collected at Haw Creek watershed outlet (#303) by ISWS were used for model calibration and validation.

Hydrologic and Water Quality Modeling

To delineate the Haw Creek watershed, its hydrologic and water quality monitoring station (#303) was selected as the watershed outlet and a threshold watershed area of 2% was used to define the detail of the stream network in the model, dividing the watershed into 29 subbasins with an average area of 504 hectares. Multiple HRUs were then created within each subbasin based on a 10% threshold area for land use, soil, and slope categories (i.e., <1%, 1% - 2% and > 2%). The process of HRU definition first removes all land uses below the threshold area of 10% and the areas of the removed land uses are then proportionally redistributed to the remaining land uses in that subbasin, compensating for the lost areas. However, land uses designated as agricultural row crops and CREP areas in the watersheds were exempted from the 10% threshold, keeping all their respective areas in the model. Next, for each land use in the subbasin, soils having less than 10% areal coverage were eliminated and similar redistribution of the eliminated soil areas was done. Finally, for each soil in each land use area, slope categories with less than 10% coverage were removed and redistributed. The HRU definition process resulted in 1,083 HRUs with an average area of 13 hectares.

Model Calibration and Validation

The Haw Creek watershed model was calibrated for flow, sediment, nitrate-N and total P. Automatic model calibration of the watershed responses including flow, sediment, nitrate N and total P was performed using evolutionary optimization known as NSGA-III (Deb and Jain, 2014) that was coupled with the watershed model. Four goodness-of-fit measures, which include Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), Kling-Gupta Efficiency (KGE) (Gupta et al., 2009), RMSE-observations standard deviation ratio (RSR) (Moriasi et al., 2007), and Percent Bias (PBIAS), were used to evaluate the model's performance in simulating the watershed responses.

Sediment and Nutrients Critical Source Areas

Using Haw Creek SWAT model, watershed simulation was performed to determine critical source areas of sediment and nutrient yields (i.e., total N and total P) in the watershed. The water yield of the watershed was also simulated. A data clustering method known as Jenks Natural Breaks was used to determine five yield classes from very low to very high by both minimizing and maximizing the variances within and between each class, respectively. A color-coding scheme (i.e., green (very-low yield), light green (low yield), yellow (medium yield), orange (high yield) to red (very-high yield) was adopted to illustrate the five classes for sediment and nutrient yields. The sediment, nutrient and water yields were analyzed at both subbasin and HRU levels, providing useful information for BMP targeting at different scales. Depending on availability of resources, field (HRU) or subbasin level yield results can be used for cost-effective management of agricultural watersheds. If the goal is to reduce sediment and nutrient yields from the watershed, implementation of conservation practices in subbasins with higher sediment and nutrient yields would be more effective. In contrast, if limited financial resources are available, selecting those HRUs with higher yields would be the better option.

Results and Discussion

Calibration and Validation Results

A total of 40 model parameters that influences simulations of Haw Creek watershed's flow, sediment, nitrogen and phosphorus load were calibrated. The list of parameters, their description, ranges and calibrated values are provided (Table 1). The Haw Creek watershed model was calibrated and validated for monthly flow, sediment, nitrate-nitrogen, and total phosphorus loads at the watershed outlet (#303).

Table 1. Calibrated parameters for flow, sediment, nitrogen, and phosphorus simulations

Parameter: Description	Range	Fitted value
Flow		
Cn2*: SCS runoff curve number	-20 - 20	-16.6
Alpha_Bf: Baseflow alpha factor (days)	0 - 1	0.026
Gw_Revap: Groundwater "revap" coefficient	0.02 - 0.2	0.094
Gwqmn: Threshold depth of water in the shallow aquifer for return flow to occur (mm)	0 - 5000	3288
Revapmn: Groundwater "revap" coefficient.	0 - 500	303
Gw_Delay: Groundwater delay (days)	0 - 500	435
Esco: Soil evaporation compensation factor	0 - 1	0.671
Epco: Plant uptake compensation factor	0 - 1	0.860
Sol_awc*: Available water capacity of the soil layer	-20 - 20	6.9
tlaps: Temperature lapse rate	-10 - 10	3.3
Smfmn: Min. melt rate for snow during the year	0 - 20	1.1
Smfmx: Max. melt rate for snow during the year	0 - 20	17.5
Surlag: Surface runoff lag time	0.5 - 5	0.579
Sediment		
Ch_cov1: Channel erodibility factor	-0.05 - 0.6	0.151
Ch_cov2: Channel cover factor	-0.001 - 1	0.523
Spexp: Exponent for calculating sediment reentrained in channel	1 - 1.5	1.396
Spcon: Parameter for calculating the max. amount of sediment that can be reentrained	0.001 - 0.01	0.005
Prf: Peak rate factor for sed. routing in the main channel	0 - 2	0.590
Adj_pkr: Peak rate factor for sed. routing in the subbasin	0.5 - 2	0.986
Hru_slp*: Average slope steepness	-10 - 10	-8.6
Slsubbsn*: Average slope length	-10 - 10	9.9
Usle_k*: USLE equation soil erodibility factor	-10 - 10	-3.6
Usle_p*: USLE equation support practice factor	-20 - 20	-4.5
Nitrogen		
Sol_NO3: Initial NO3 concentration in the soil layer (mg/kg)	0 - 100	95
Sol_orgn: Initial organic N concentration in the soil layer (mg/kg)	0 - 100	74
Nperco: Nitrogen percolation coefficient	0 - 1	0.298
Cmn: Rate factor for humus mineralization of active organic N	0.001 - 0.003	0.002
Cdn: Denitrification exponential rate coefficient	0 - 3	0.012
Cdnco: Denitrification threshold water content	0 - 1	0.448
N_updis: Nitrogen uptake distribution parameter	0 - 100	28.2
Rsdco: Residue decomposition coefficient	0.02 - 0.1	0.042
Biomix: Biological mixing efficiency	0 - 1	0.007
Dep_imp: Depth to impervious layer for perched water table (mm)	1100 - 3000	2634
Ddrain: Depth to subsurface drain (mm)	500 - 1100	1096
Sdrain: Distance bwtween two drain tubes or tiles (mm)	10000 - 30000	27903
Re: Effective radius of drains (mm)	10 - 40	21.5
Phosphorus		
Sol_solp: Initial soluble P concentration in the soil layer (mg/kg)	0 - 10	3.6
Sol_orgp: Initial organic P concentration in the soil layer (mg/kg)	0 - 100	36.4
Pperco: Phosphorus percolation coefficient	10 - 17.5	12
Phoskd: Phosphorus soil partitioning coefficient	100 - 200	155

** % change*

For all four simulated watershed responses, the model performance ratings including NSE, KGE, RSR and PBIAS indicate satisfactory to good monthly simulation results during both calibration (2000–2009) and validation (2010–2016) periods (Table 2). The minimum NSE and the maximum PBIAS values obtained for simulations during calibration and validation periods were 0.64 and 26.2%, respectively and they both were for nitrate N load simulations. For all remaining simulations of watershed responses, the NSE is at least 0.64 and the PBIAS is less than 14%, indicating good model performance at monthly time-step.

Table 2. Model performance ratings for simulated watershed responses

Watershed responses	Calibration (2000-2009)				Validation (2010-2016)			
	NSE	KGE	RSR	PBIAS	NSE	KGE	RSR	PBIAS
Flow (cms)	0.73	0.82	0.52	-4.8	0.8	0.82	0.45	7.8
Sediment (mtons/d)	0.65	0.61	0.59	0.4	0.69	0.61	0.55	13.4
Nitrate-N (kg/d)	0.64	0.63	0.6	13.8	0.72	0.63	0.53	26.2
Total P (kg/d)	0.68	0.74	0.57	-8.5	0.65	0.74	0.59	-1.9

Observed and simulated watershed responses at monthly time-step closely match during both calibration and validation periods (Figure 2). Average annual yields of water, sediment, nitrate-N and total P show good agreement between the observed and simulated values (Table 3). Higher water yields were exhibited during the validation period and thus, resulted in higher sediment and nutrient yields.

Table 3. Observed and simulated annual average water, sediment, nitrate N and total P yields

Average annual values	Calibration (2000-2009)		Validation (2010-2016)	
	Observed	Simulated	Observed	Simulated
Water yield (mm)	252	264	335	310
Sediment yield (mtons/ha)	1.91	1.90	2.64	2.29
Nitrate-N yield (kg/ha)	14.97	12.90	16.52	12.19
Total P yield (kg/ha)	2.01	2.18	2.54	2.59

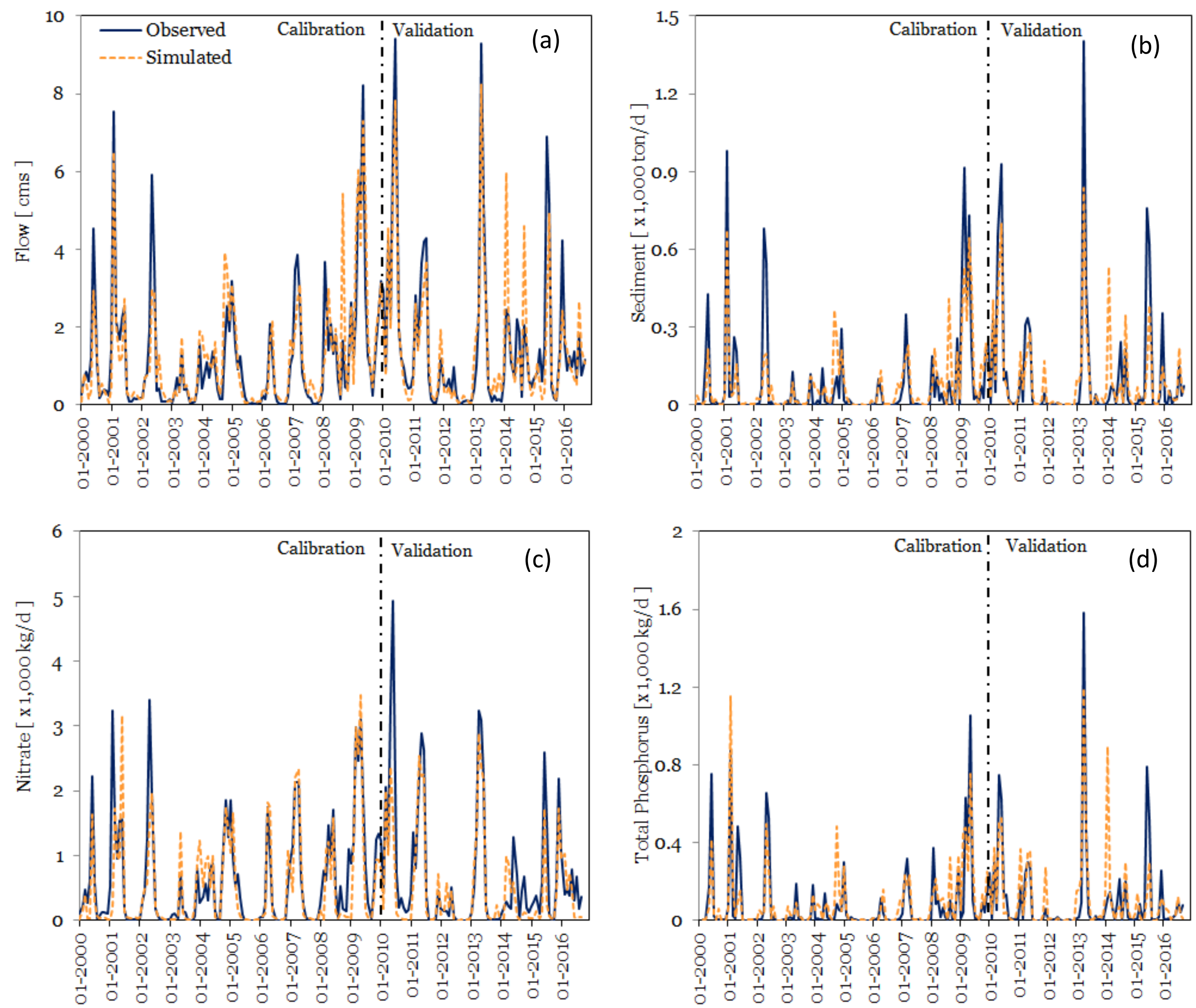

Figure 2. Observed and simulated flows (a), sediment (b), nitrate-N (c) and total P (d) loads at Haw Creek gage (#303)

Sediment, Nutrient and Water Yields

The calibrated and validated Haw Creek watershed model was used to simulate sediment, total N and total P yields from 2000 to 2016 at both HRU and subbasin scales. Five yield classes were identified to categorize sediment yields at subbasin (Figure 3a) and HRU (Figure 3b) scales. The very-high sediment yield range at subbasin level is 36.03–60.39 metric tons/hectare (mtons/ha) whereas at HRU level, it is 211.79–319.9 mtons/ha. In contrast, the average annual sediment yield of Haw Creek watershed from 2000–2016 is 19.37 mtons/ha. The subbasin and HRU sediment yields are in Figure 4, showing watershed locations with different levels of sediment yield at both subbasin (Figure 4a) and HRU (Figure 4b) levels. For example, HRUs with very-high sediment yield cover only 1.2% of the watershed area but generate 17.2% of the watershed's total sediment load. These HRUs are non-agricultural and have the highest slopes and slope length-gradient factors as compared to the remaining HRUs. The sediment yield maps provide useful information for implementing conservation measures that reduce sediment loads at both HRU and subbasin scales. The 100-year floodplain area is also shown in Figure 4b, where the HRU-level sediment yield is illustrated. Highly erodible HRUs that lie in the floodplain areas are eligible for CREP enrollments and therefore, outreach programs could target those areas.

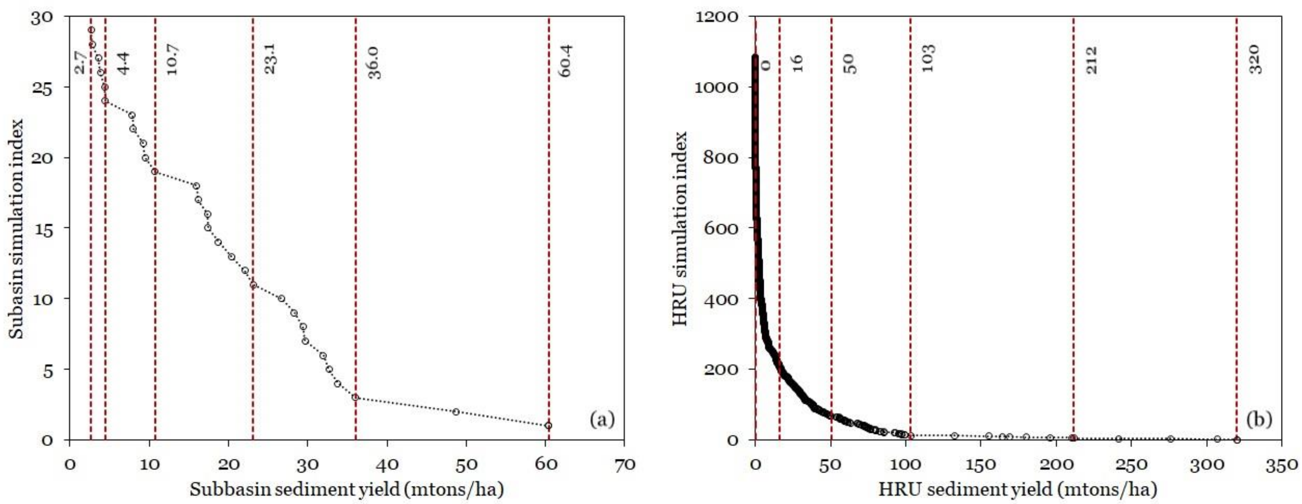

Figure 3. Sediment yield classes for Haw Creek watershed at subbasin (a) and HRU (b) levels

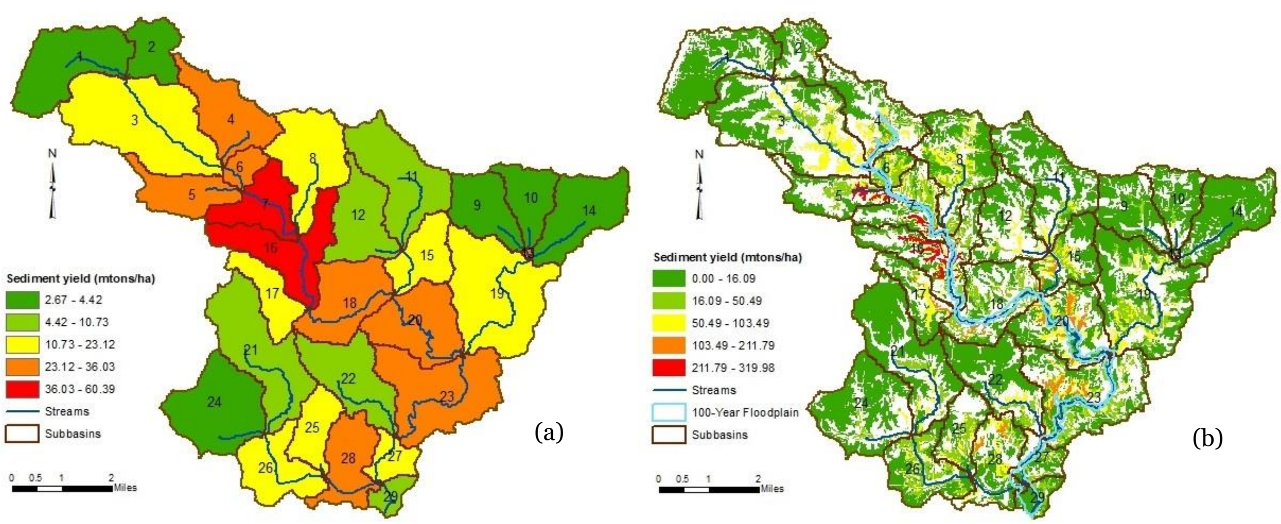

Figure 4. Haw Creek watershed sediment yields at subbasin (a) and HRU (b) levels

Similarly, the nutrient yields at subbasin and HRU levels are grouped into five classes from very-low to very high yields. The total N yields at subbasin (Figure 5a) and HRU (Figure 5b) levels are illustrated and their ranges of very-high total N yields at subbasin and HRU levels were simulated to be 17.84–23.89 kg/ha and 40.52–64.18 kg/ha, respectively. The average annual total N yield for the watershed is 13.98 kg/ha. HRUs with very-high total N yields cover 14.3% of the total watershed area but generate 55.2% of the total N load from the watershed. These HRUs are all agricultural with corn-soybean rotation and make up 41.3% of the tiled HRUs. In addition, they generate the lowest sediment yields.

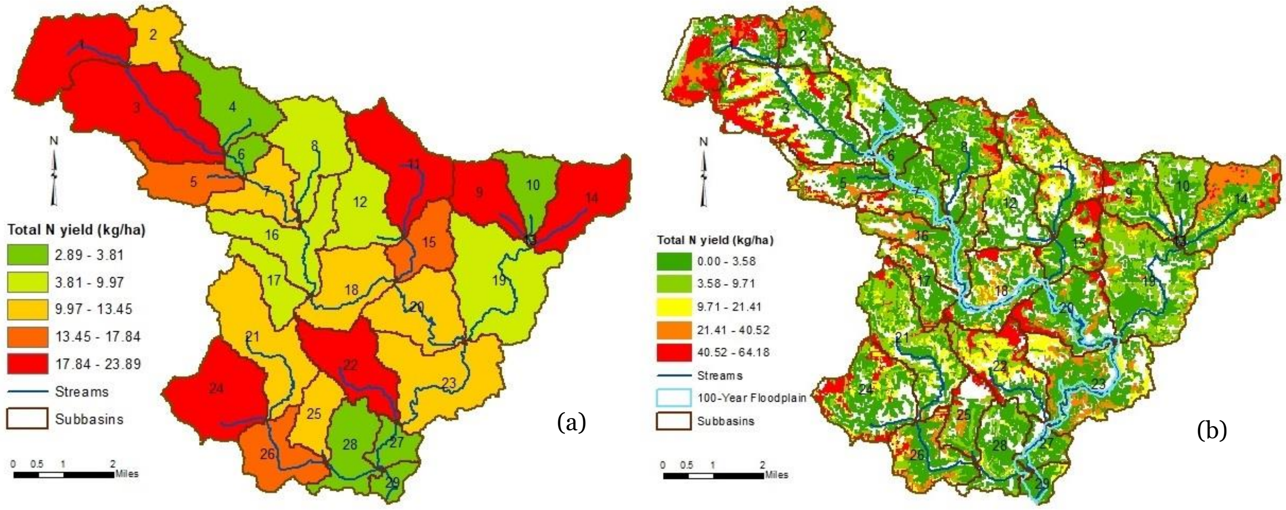

Figure 5. Haw Creek watershed total N yields at subbasin (a) and HRU (b) levels

The average annual total P yields for Haw Creek watershed were categorized into five classes from very-low to very-high yields (Figure 6). At subbasin and HRU levels, the very-high yield ranges for total P were found to be 3.60–5.43 kg/ha and 13.41–23.46 kg/ha, respectively. In contrast, the total P yield for the whole watershed is 2.44 kg/ha. Only 3.5% of the watershed area, which is in agricultural row-crop, is classified as having very-high total P yield, generating 25.5% of the total P load. The total N and sediment yields from watershed areas of very-high total P yield are high and low, respectively. The 100-year flood plain area is also shown for total N and P yields at HRU level (Figures 5 and 6), indicating eligible CREP areas for implementing nutrient load reduction strategies.

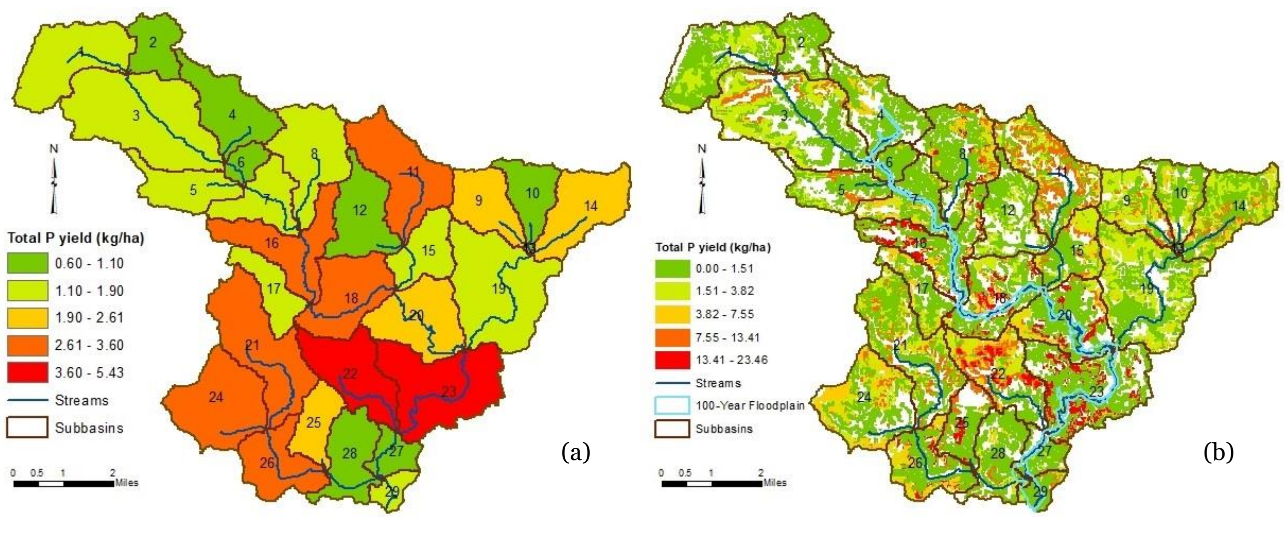

Figure 6. Haw Creek watershed total P yields at subbasin (a) and HRU (b) levels

Subbasin and HRU-level water yields are illustrated for Haw Creek watershed (Figure 7). Very-high water yield areas make up 32.2% of the watershed area and contribute 41.2% of the watershed's water yield. Watershed areas with high to very-high water yield also have high or very-high total N loads. For example, subbasins with very-high sediment and total P yields have only medium water yields.

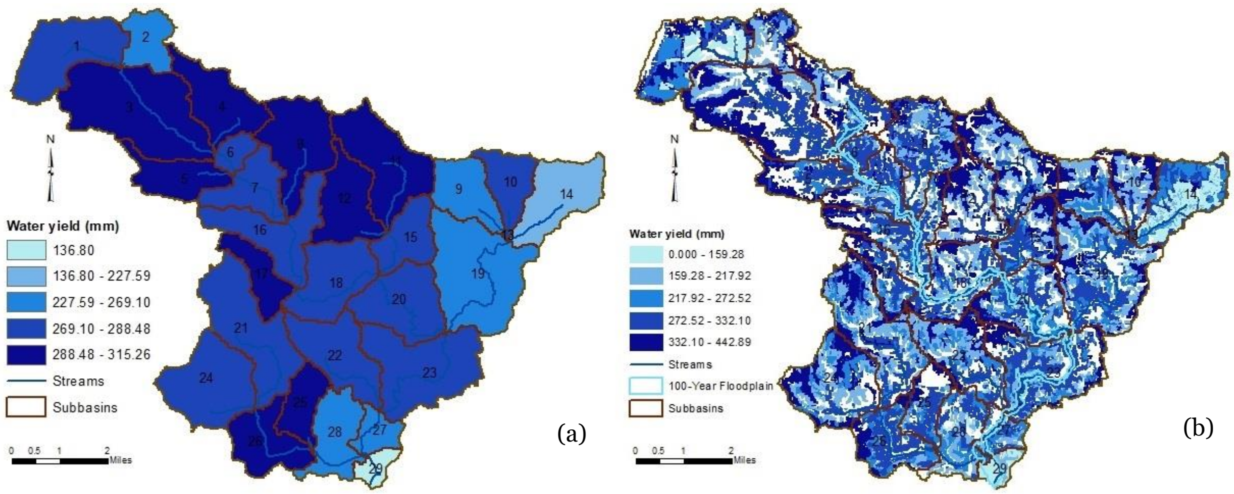

Figure 7. Haw Creek watershed water yields at subbasin (a) and HRU (b) levels

Conclusions

Haw Creek SWAT model was developed to identify critical sources areas of sediment and nutrient yields in the watershed. The model was calibrated and validated using monthly flow, sediment, nitrate-N and total P loads collected at the outlet of Haw Creek watershed from 2000 to 2016. The model performed well simulating all four watershed responses during both calibration and validation periods. Average annual water yields were simulated within -4.8 and 7.8% of the observed mean values for calibration and validation periods, respectively. In contrast, simulated sediment and nutrient yields were at least within 13.8% of their observed values except for nitrate N yields for validation period (i.e., an underestimation of 26.2%). Average annual water, sediment, total N, and total P yields (2000 to 2016) were simulated at using Haw Creek watershed model and are mapped into five levels of yield classes yields (i.e., very-low, low, medium, high, and very-high) at subbasin and HRU levels. The classification allowed to identify critical source areas of sediment and nutrient yields. Identifying areas with varying yields at subbasin and HRU scales provides useful information towards prioritizing implementation of best management practices in the watershed. Outreach programs could target high yield areas in the 100-year floodplain, which are eligible for CREP enrollments. The Haw Creek watershed model can further be used for cost-effective placements of BMPs that could result in the optimal reduction of nonpoint source pollutants including sediment and nutrients.

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