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Simulation of Agricultural Management Alternatives for Watershed Protection

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Abstract The Bosque River Watershed in Texas is facing a suite of water quality issues including excess sediment, nutrient, and bacteria. The sources of the pollutants are improperly managed cropland and grazing land, dairy manure application, and effluent discharge from wastewater treatment facilities. Several best management practices (BMPs) have been proposed for pollution reduction and watershed protection. The overall objectives of this study were to demonstrate a modeling approach using Soil and Water Assessment Tool (SWAT) model to simulate various BMPs and assess their long-term impacts on sediment and nutrient loads at different spatial levels. The SWAT model was calibrated and validated for long-term annual and monthly flows at Valley Mills and for monthly sediment, total nitrogen (TN) and total phosphorus (TP) at Hico and Valley Mills monitoring locations. The BMPs including streambank stabilization, gully plugs, recharge structures, conservation tillage, terraces, contour farming, manure incorporation, filter strips, and PL-566 reservoirs were simulated in the watershed areas that met the respective practice's specific criteria for implementation. These BMPs were represented in the pre- and post-conditions by modifying one or more channel parameters (channel cover, erodibility, Manning's n), curve number (CN), support practice factor (P-factor), filter strip width, and tillage parameters (mixing efficiency, mixing depth). The BMPs were simulated individually and the resulting Hydrologic Response Units (HRUs), subwatershed, and watershed level impacts were quantified for each BMP. Sensitivity of model output values to input parameters used to represent the BMPs was also evaluated. Implementing individual BMPs reduced sediment loads from 3%

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to 37% and TN loads from 1% to 24% at the watershed outlet; however, the changes in TP loads ranged from 3% increase to 30% decrease. Higher reductions were simulated at the subwatershed and HRU levels. Among the parameters analyzed for sensitivity, P-factor and CN were most sensitive followed by Manning's n. The TN and TP outputs were not sensitive to channel cover. This study showed that the SWAT modeling approach could be used to simulate and assess the effectiveness of agricultural best management practices.

Keywords SWAT · Watershed modeling · Best Management Practice (BMP) · Streambank stabilization · Gully plugs · Recharge structures · Terrace · Filter strips

1 Introduction

Nonpoint source pollution is the most significant source of water quality impairment in the United States, with sediment and nutrients (nitrogen (N) and phosphorus (P)) being key pollutants of concern (USEPA 2005). As of December 2007, there were 39,910 impaired water bodies reported in USEPA 303(d) list nationwide (USEPA 2008). The best management practices (BMPs) attempt to alleviate pollutant generation and transport potential, depending on the type of practice and location of implementation. It is important to estimate the pollution reduction efficiency of these BMPs in order to help policy makers make decision on future resource allocations. Published literature values exist; however, site characteristics can alter their worth. A comprehensive watershed modeling tool can more effectively capture site-specific characteristics (i.e. climate, topography, and soil) and multiple scenarios limiting labor, time, and financial expenses associated with intensive field studies (Koch and Grünewald 2009). Thus, models through the "what-if" scenario analysis can provide scientific information on the impacts of various alternative management options and can assist stakeholders and policy-makers with decisions for ensuring effective integrated water resources management and protection of their watersheds. Application of simulation models in integrated water resources management is reviewed in Yang and Wang (2009), Silva-Hidalgo et al. (2009), and Gaddis and Voinov (2009).

A few studies quantified the effects of BMPs on water quality at multiple spatial scales using a modeling approach. Vache et al. (2002) quantified the impacts of no-till, strip intercropping, rotational grazing, riparian buffers, engineered wetlands, and filter strips over 51.3 km^2 Walnut Creek and 88.2 km^2 Buck Creek Watersheds in central Iowa. Generally, these BMPs resulted in a 15% to 60% decrease in median sediment loading and a 57% to 70% decrease in median nitrate loading. Bracmort et al. (2006) evaluated long-term water quality impacts of structural BMPs (grassed waterways, grade stabilization structures (GSSs), field borders, and parallel terraces) in two subwatersheds (6.2 km^2 and 7.3 km^2) of the Black Creek Watershed in northeastern Indiana. Their study concluded that the BMPs reduced average annual sediment yield by 16% to 32% and average annual P yield by 10% to 24%. Secchi et al. (2007) analyzed land set-asides, terraces, grassed waterways, contouring, conservation tillage, and nutrient reduction strategy in 13 watersheds (ranging in size from 2,051 km^2 to 37,496 km^2) in Iowa. When compared to baseline conditions, implementing these practices resulted in a 6% to 65% reduction in predicted sediment losses, a 28% to 59% reduction in total phosphorus (TP) losses, and a 6% to 20% reduction in nitrate losses at the watershed outlet. From Gitau et al. (2005)'s summary on the published information on BMP effectiveness for P pollution control, conservation tillage and filter strips reduced TP by a maximum of 95% and 93%, respectively. A study by Dalzell et al. (2004) over 650 km^2 Sand Creek Watershed in southcentral Minnesota found that 40%, 50%, 75%, and 100% conversion of cropland from conventional tillage to conservation tillage resulted in reduction in sediment losses by 20%, 26%, 33%, and 40%, respectively and 2%, 6%, 7%, and 10% reduction in P losses, respectively. Santhi et al. (2006) evaluated the impacts of BMPs (including nutrient management, waste utilization, forage harvest management, brush management, pasture planting, range seeding, critical area planting, and GSSs on sediment and nutrient loadings in 4,554-km^2 West Fork Watershed in Trinity River Basin in Texas. The model predicted that critical area planting and GSSs resulted in the highest percentage reduction in sediment and nutrients at farm level. Predictions of the average annual reductions at farm level across the subbasins for all BMPs modeled in the study ranged from 5% to 99% for sediment, 5% to 90% for TN, and 3% to 78% for TP. Gassman et al. (2006) evaluated the effectiveness of terraces, no-till farming, contouring, in-field contour buffers, and grassed waterways in 162-km^2 upper Maquoketa River Watershed in northeastern Iowa in reducing flow, sediment, and organic and soluble N and P. They reported that terraces reduced sediment by more than 60% and organic N and organic P by more than 70%. In-field contour buffers resulted in 44%, 47%, 48% reduction in sediment, organic N, and organic P, respectively. Similar reductions were observed from grassed waterways. Manure incorporation resulted in an increase in sediment and nutrient losses. Nitrates increased in several scenarios including no-till, incorporation and injection, terraces, contouring, in-field contour buffers and this was attributed to the fact that these practices results in increased leaching of N in response to increased infiltration. Inamdar et al. (2001) reported that no-till, filter strips, and nutrient management implemented in a 14.63-km^2 Nomini Creek Watershed reduced average annual loads and flow-weighted concentrations of N by 26% and 41%, respectively and TP by 4% and 24%, respectively. They noticed increase in nitrate-N, dissolved P (ortho-P and dissolved organic P) after BMP implementation. Narasimhan et al. (2007) reported that an in-stream BMP, such as streambank stabilization, can reduce sediment load by 15% at the outlet of Cedar Creek Watershed in northcentral Texas.

So far, no hydrologic modeling study has been published that evaluated the impacts of BMPs such as gully plugs, recharge structures, and manure incorporation on a large watershed using the SWAT model. In the above studies, the BMPs simulated were different or in different agricultural settings such as tiled-drained, cropland dominated (corn/soybeans) watersheds (Vache et al. 2002; Gassman et al. 2006) or the studies used different approaches in terms of parameters and their values used to represent the BMPs in the model (Secchi et al. 2007; Bracmort et al. 2006; Narasimhan et al. 2007; Santhi et al. 2006). Furthermore, none of the above studies have validated predicted BMP effectiveness using observed water quality data (which is also the case in the present study) and therefore no definite guidelines are available to evaluate various BMPs using the hydrologic/water quality models. Hence, published information available pertaining to BMP effectiveness is inadequate. This study adds to the body of literature available related to simulation of BMPs and their effectiveness. The overall objectives of this study were to demonstrate a modeling approach using the SWAT model to simulate various BMPs including streambank stabilization, gully plugs, recharge structures, conservation tillage, terrace, contour, manure incorporation, and filter strips and assess their long-term impacts on sediment and nutrient loads at different spatial levels. In addition, the purpose of the BMPs simulated, methodology of their representation in the model in pre- and post-BMP conditions, and simple sensitivity analysis of the model parameters used to represent the BMPs are described in the later sections below.

2 Materials and Methods

2.1 The Soil and Water Assessment Tool (SWAT) Model

The SWAT model is a nonproprietary hydrologic/water quality tool developed by the United States Department of Agriculture-Agriculture Research Service (USDA-ARS) (Arnold et al. 1998; Neitsch et al. 2005a; http://www.brc.tamus.edu/swat/). The SWAT model is also available within the United States Environmental Protection Agency's Better Assessment Science for Integrated Point and Nonpoint Sources (USEPA's BASINS) as one of the models that the USEPA supports and recommends for state and federal agencies to use to address point and nonpoint source pollution control. The SWAT model is a distributed parameter, continuous scale model that operates on a daily time-step. It has the capability to simulate a variety of land management practices. The SWAT model divides the watershed into a number of subwatersheds based on topography and user defined threshold drainage area (minimum area required to begin a stream). Each subwatershed is further divided into Hydrologic Response Units (HRUs), which are a unique combination of soil, land use, and land management. The HRU is the smallest landscape component of SWAT used for computing the hydrologic processes. The hydrological processes are divided into two phases: the land phase where the model determines the upland loadings of flow, sediment, nutrients, and pesticides from each HRU and then the loading are area-weighted to subwatershed level; and the channel/floodplain phase, where the model routes the upland loadings from each subwatershed through the channel/stream network.

Within each HRU, the major hydrological processes simulated by SWAT include canopy interception of precipitation, infiltration, surface runoff, evapotranspiration, lateral flow or subsurface flow, shallow ground water flow (or baseflow or return flow), soil moisture redistribution, and percolation to deep aquifer (Fig. 1). The incoming precipitation, snow melt, and irrigation water is partitioned between surface runoff and infiltration. Infiltrated water can be stored in soil profile, percolate deeper to reach shallow and/or deep aquifer, lost via evapotranspiration, or move laterally to feed back to the stream. Weather inputs required in SWAT include precipitation, minimum and maximum temperature, solar radiation, relative humidity, and wind speed depending on the evapotranspiration method selected. Precipitation data could be daily if curve number (CN) method (USDA-SCS 1972) is used or sub-daily if Green-Ampt (Green and Ampt 1911) infiltration method is used to estimate surface runoff (Lacewell et al. 2010). In the CN method, surface runoff is estimated as a function of daily CN adjusted for the moisture content of the soil on that day. The

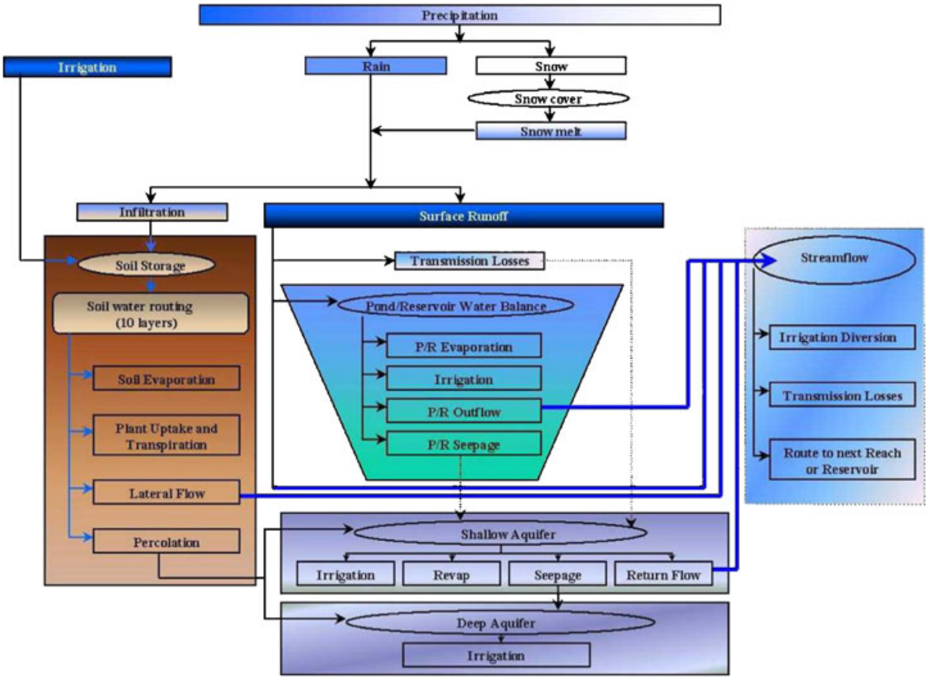

Fig. 1 Schematics of water movement pathways in SWAT (source: Neitsch et al. 2005a; http://swatmodel.tamu.edu/documentation)

CN method is widely used due to simplicity, predictability, and its responsiveness to soil type, land use and land condition, and antecedent soil moisture. Some of the disadvantages are that the method has no explicit provision for spatial scale effects and is sensitive to low CNs and low rainfall depths (Ponce and Hawkins 1996). Also, this method only considers total rainfall volume and not rainfall intensity and duration. However, break point rainfall input and streamflow routing at sub-daily time step used by Green-Ampt infiltration method not necessarily result in significant improvement in the model prediction for large basins (King et al. 1999). Further, Van Liew et al. (2003) report that Philip infiltration equation used in HSPF model may provide accurate simulation of hydrologic processes provided site-specific data are available. SWAT allows defining upto 10 soil layers within the routing depth (soil profile) of 2 m. A storage routing technique is used to calculate redistribution of water between layers in the soil profile. Water infiltrated into the soil layer is allowed to percolate into the next deeper soil layer if the water content exceeds the field capacity water content of that layer. Lateral flow (subsurface flow) is estimated using kinematic storage model. Recharge below the soil profile is partitioned between shallow and deep aquifers. The shallow aquifer contributes to baseflow (or return flow) to the main channel (or reach) when the amount of water stored in the aquifer exceeds user specified threshold value. Water in shallow aquifer is also allowed to move up into the soil profile in response to the water deficiency in order to meet the evapotranspiration demands. Also, SWAT allows deep-routed plants uptake water directly from the shallow aquifer. That portion of the water that recharges the deep aquifer is assumed lost from the system. SWAT estimates crop yields and/or biomass output for a wide range of crop rotations, grassland/pasture systems, and trees. Planting, harvesting, tillage passes, and nutrient and pesticide applications can be simulated for each cropping system with specific dates or with a heat unit scheduling approach. Residue and biological mixing are simulated in response to each tillage operation. Nitrogen and phosphorus inputs can be in the form of inorganic fertilizer and/or manure inputs. An alternative automatic fertilizer routine can be used to simulate fertilizer applications, as a function of user-specified nitrogen stress. Biomass removal and manure deposition can be simulated for grazing operations. The type, rate, timing, application efficiency, and percentage application to foliage versus soil can be accounted for simulations of pesticide applications. Simulation of irrigation water on cropland can be based on five alternative sources: stream reach, reservoir, shallow aquifer, deep aquifer, or a water body source external to the watershed. The irrigation applications can be simulated for specific dates or with an autoirrigation routine, which triggers irrigation events based on user-specified water stress threshold (Lacewell et al. 2010).

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975) to estimate sediment yield at HRU level. The model simulates transformation of nitrogen (N) and phosphorus (P) between organic and inorganic pools in the nutrient cycle (Fig. 2). The loss of both N and P from the soil system of each HRU is accounted for by plant uptake, their transport via surface runoff, eroded sediment, lateral flow and percolation below the soil profile, and by volatilization to the atmosphere (Lacewell et al. 2010).

Flow, sediment, nutrients, pesticide and bacteria from all HRUs are summed to the subwatershed level and then routed through the channels, ponds, reservoirs, and wetlands to the watershed outlet. Flow is routed using either variable-rate storage method (Williams 1969) or Muskinghum method (Overton 1966). Sediment

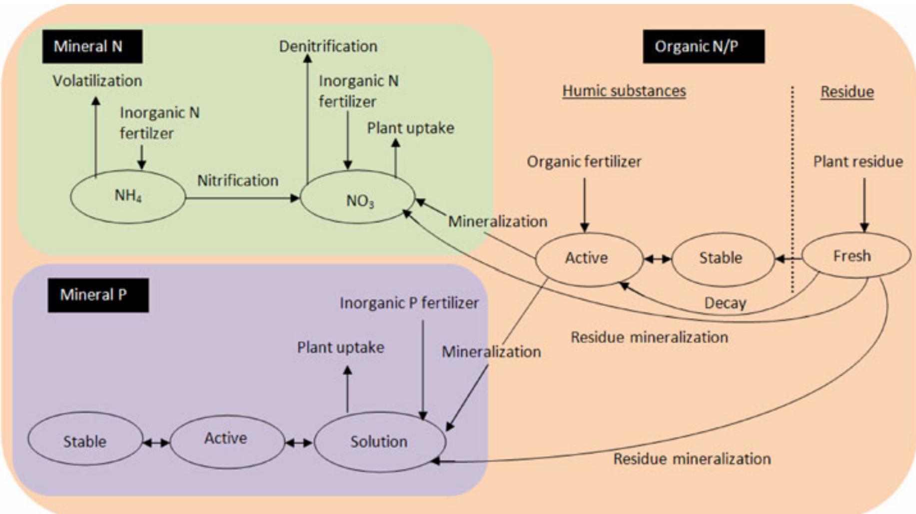

Fig. 2 Nitrogen and phosphorus transformation simulated in SWAT (source: Neitsch et al. 2005a; http://swatmodel.tamu.edu/documentation)

transport is simulated, using modified Bagnold's equation (Bagnold 1977), as a function of peak channel velocity. Sediment is either deposited or re-entrained through channel erosion depending on the sediment load entering the channel. The QUAL2E model (Brown and Barnwell 1987) has been incorporated into SWAT to process in-stream nutrient dynamics (Lacewell et al. 2010). Complete theoretical and input/output documentations for SWAT 2005 can be found in Neitsch et al. (2005a, b); downloadable for free from <http://swatmodel.tamu.edu/documentation>. The SWAT model has been extensively applied for issues ranging from hydrology, climate change, pollutant load assessment, and BMP evaluation at various spatial and temporal scales.

The SWAT model streamflow predictions were generally insensitive to subwatershed or HRU delineations (Bingner et al. 1997; FitzHugh and Mackay 2000; Chen and Mackay 2004; Tripathi et al. 2006). Sediment and nitrate predictions were sensitive to variations in subwatersheds and HRUs (Bingner et al. 1997; Jha et al. 2004). Arabi et al. (2006) found that the effects of BMPs on SWAT predicted sediment and nutrients were sensitive to subwatershed delineation and that average subwatershed area equal to about 4% of the total watershed area could adequately account for the impact of BMPs. Cotter et al. (2003) and DiLuzio et al. (2005) report that DEM is the most critical input to the SWAT model. Arabi et al. (2007) showed that the uncertainty associated with estimated BMP effectiveness is substantially smaller than the uncertainty associated with the absolute prediction. Additional insights on SWAT application related to uncertainty analysis are provided by Eckhardt et al. (2003), Muleta and Nicklow (2005), and Shirmohammadi et al. (2006). A comprehensive review of SWAT including historic developments and applications can be found in Gassman et al. (2007).

The present study used SWAT2005 version and ArcView Geographic Information System interface (AVSWAT-X), an upgrade of AVSWAT (Di Luzio et al. 2004a) with added SEA (SSURGO Extension for AVSWAT) (Di Luzio et al. 2004b) to process and manage the SSURGO (soil survey geographic; USDA 1995) dataset to derive the required soil inputs.

2.2 Watershed Description and Model Inputs

The Bosque River Watershed (BRW) is located in the Brazos River Basin in central Texas and encompasses an area of 4,282 km^2 (Fig. 3). The Bosque River drains into Lake Waco, which is the primary drinking water supply for more than 200,000 people in the greater Waco area. In 2000, the North Bosque River was listed in the 303(d) list for concerns of increased levels of nutrients entering this portion of the watershed from tributary watersheds. Upper North Bosque listed in the 303(d) list had elevated levels of sediments, N, and P. Previous studies have attempted to understand and analyze the sources of pollution and to evaluate potential landscape implementations to improve water quality in the BRW. Fields receiving dairy manure (referred to as Waste Application Fields (WAFs) hereafter) and row crop production resulted in high loadings of P and TN in the North BRW, respectively (McFarland and Hauck 1999). Santhi et al. (2001a, b), applied SWAT model to evaluate water quality impacts of dairy BMPs including hauling solid manure out of the watershed, applying liquid manure to meet the P needs of the crops, and reducing the P content in cattle feed. McFarland et al. (2000) demonstrated the effects of amount and timing

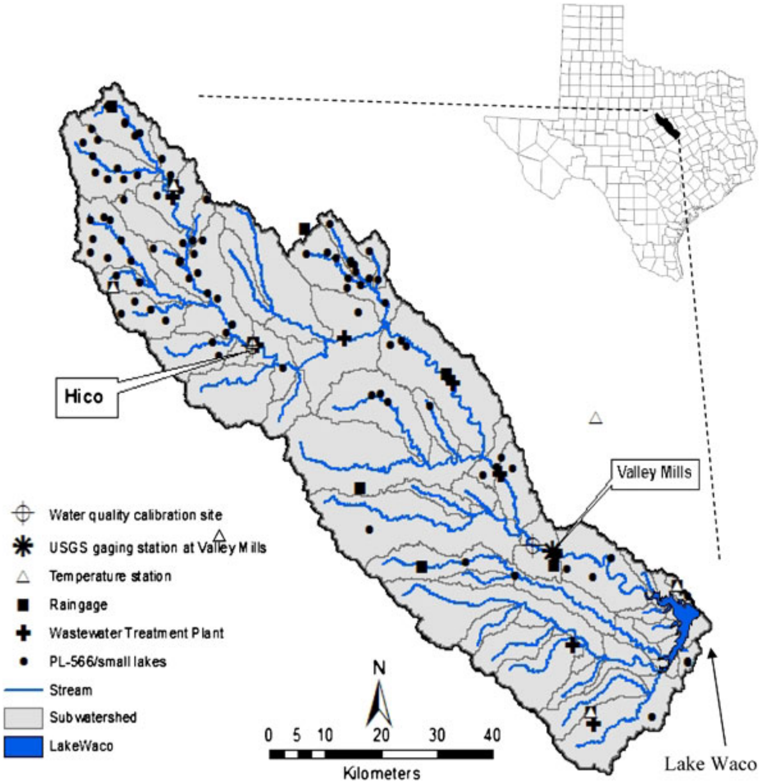

Fig. 3 SWAT model set up for Bosque River Watershed: monitoring stations and reservoirs

of fertilizer application on P loading in the North BRW using APEX model. Growing turf grass as an alternative to maximize nutrient removal from the watershed was evaluated by Stewart et al. (2006) and Hanzlik et al. (2004).

The watershed is comprised mostly of rangeland, pastureland and cropland. Elevation in the watershed ranges from 129 m to 495 m. The major soil series include Eckrant (clayey-skeletal), Brackett (loam), Purves (clayey), Aledo (loamy-skeletal), Windthrost (fine), Slidell (fine), Cranfill (fine-loamy), Crawford (fine), Frio (fine), Maloterre (loamy), Denton (fine-silty), and Bolar (fine-loamy). The sources of different dataset used in the model set up are listed in Table 1. The BRW was divided into 48 subwatersheds (Fig. 3) and a total of 2,680 HRUs.

Daily effluent discharge volume, total suspended sediment, and organic and mineral N and P data from the eight wastewater treatment plants (WWTPs) were incorporated into the model as point sources. Also, 88 PL-566 reservoirs (inclusive of Lake Waco) were incorporated into the simulation (Fig. 3). The pertinent reservoir data (i.e., surface area and storage at principal and emergency spillways) was lumped within a subwatershed because there were more than one PL-566 reservoir in a subwatershed. The WAFs map was overlaid on the landuse map to identify areas with dairy manure applications. For the WAFs, total manure generated by all dairies within a subwatershed was applied on the WAFs within that subwatershed. Mineral

Table 1 Model input information for Bosque River Watershed

Data	Scale/no.	Source
Topography/DEM	1:24,000 (30 m resolution)	USGS
Landuse/landcover	1:24,000	USGS NLCD1992
Soils	1:24,000	SSURGO
PL566	88 no.	USDA-NRCS
Wastewater treatment plants	8 plants	TIAER
Waste application fields	1:24,000	TIAER
Precipitation and temperature	11 precipitation and 7 temperature stations	National Weather Service-National Climatic Data Center (NWS-NCDC)
Wind speed, solar radiation, and relative humidity		SWAT model in-built weather data simulator
Land management information on WAF, cropland, and pastureland		TIAER/Santhi et al. (2001a, b)/expert opinion

fertilizer was applied for all other applicable areas. Pastureland was simulated as improved pasture with typical nutrient application rates for the area, allowing four cuttings per year. Corn, winter wheat, and grain sorghum were the major crops in the watershed. Tillage operations, fertilizer application dates and rates were adopted from Santhi et al. (2001a, b).

2.3 Model Calibration and Validation

The SWAT model was manually calibrated for long-term annual and monthly streamflow (the term 'flow' used elsewhere in this paper refers to streamflow unless specified otherwise) using the streamflow records from USGS gaging station at Valley Mills (VM; # 08065200; Fig. 3) for the period from 1980 through 2005. The model was validated for flow at the same location for the period from 1960 through 1979. During calibration, care was also given to match the proportions of surface flow and baseflow contribution to streamflow. Baseflow contribution to streamflow was analyzed using baseflow filter program (Arnold and Allen 1999; Arnold et al. 1995; Nathan and McMahon 1990). The SWAT model was calibrated for sediment, TN, and TP at two monitoring stations, Hico and VM using the monthly measured data obtained from TIAER (McFarland and Hauck 1997) for the period January 1993 through July 1997 at Hico and January 1996 through July 1997 at VM. The model was also validated at both these locations for the period August 1997 through July 1998. Hico covers 22% (942 km^2) of the northern BRW and has intensive dairy facilities. The drainage area at VM is 70% (3,014 km^2) of the upstream BRW. The type, a brief description, range, and the actual value of the variable used for calibration

Table 2 Model parameters, range, and actual values used for calibration

Variable	Model component	Description	Range	Actual value used in this study
CN2	Flow	Initial SCS runoff curve number for moisture condition II	−5 − +5 from the initial values	−3
ESCO	Flow	Soil evaporation compensation factor; lower the ESCO value, the model extracts more water from the lower soil layers to meet the evaporative demand	0.01–1.00	0.6
EPCO	Flow	Plant uptake compensation factor; higher the EPCO value, the model lets more of the water uptake demand to be met by lower soil layers	0.01–1.00	1.0
GW_REVAP	Flow	Groundwater revap coefficient; as GW_REVAP increases, the rate of water moving from the shallow aquifer to the root zone increases and is equal to the rate of PET when the value of GW_REVAP is equal to 1	0.02–0.20	0.08
GWQMN	Flow	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O); Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than GWQMN	0.0–300.0	50
C-factor	Sediment	Minimum value of USLE C factor for water erosion applicable to the land cover/plant	0.003 to 0.45	Corn: 0.08 Sorghum: 0.08 Range grass: 0.006 Pasture: 0.006
SPEXP	Sediment	Exponent parameter for estimating maximum amount of sediment that can be reentrained during channel sediment routing	1.0–2.0	1.0
SPCON	Sediment	Linear parameter for estimating maximum amount of sediment that can be reentrained during channel sediment routing	0.0001–0.01	0.003
CH_COV	Sediment	Channel cover factor	0.0–1.0	0.4
CH_EROD	Sediment	Channel erodibility factor	0.0–1.0	0.008–0.049
CH_N(2)	Sediment	Channel Manning's roughness coefficient	0.014	0.014–0.03
CDN	N	Denitrification exponential rate coefficient	0.0–3.0	3.0

Table 2 (continued)

Variable	Model component	Description	Range	Actual value used in this study
CMN	N	Rate factor for humus mineralization of active organic nutrients (N and P)	0.0001–0.0003	0.0001
NPERCO	Mineral N	Nitrate percolation coefficient	0.01–1.0	0.01
PPERCO	Mineral P	Phosphorus percolation coefficient	10.0–17.5	10
PHOSKD	Mineral P	Phosphorus soil partitioning coefficient, m^3/Mg	100–175	100
RSDCO	Sediment and nutrients	Residue decomposition coefficient	0.01–0.05	0.01
BC2	N in reach	Rate constant for biological oxidation of NO2 to NO3 in the reach at 20°C (day^{-1})	0.2–2.0	0.2
BC4	P in reach	Rate constant for mineralization of organic P to dissolved P in the reach at 20°C (day^{-1})	0.01–0.70	0.01
RS5	P in reach	Organic phosphorus settling rate in the reach at 20°C (day^{-1})	0.001–0.1	0.1
AI1	N in reach	Fraction of algal biomass that is nitrogen	0.07–0.09	0.09
AI2	P in reach	Fraction of algal biomass that is phosphorus	0.01–0.02	0.02
MUMAX	N and P in reach	Maximum specific algal growth rate (day^{-1})	1.0–3.0	2.0
SDNCO	N	Denitrification threshold water content (fraction of field capacity water content above which denitrification takes place		0.975

along with the component(s) that the variable influences are listed in Table 2. Mean, standard deviation, coefficient of determination (R^2), and Nash-Sutcliffe modeling efficiency (NSE) (Nash and Sutcliffe 1970) were used to evaluate model predictions during calibration and validation. A value greater than 0.75 for monthly NSE can be considered very good; between 0.65 and 0.75 can be considered good while its value between 0.5 and 0.65 is considered satisfactory (Moriasi et al. 2007).

2.4 BMPs Simulated

The simulated BMPs included streambank stabilization, gully plugs, recharge structures, conservation tillage, terrace, contour farming, manure incorporation, edge-of-field filter strips, and PL-566 reservoirs. A brief description of each BMP and its representation in the model before (pre-BMP) and after (post-BMP) condition is given below. The Natural Resources Conservation Service (NRCS) standard practice code (USDA-NRCS 2008) is given next to the heading of the BMP whenever applicable. The model parameters and their values altered in pre- and post-BMP conditions are presented in Table 3. Considering the hydrologic/water quality processes simulated

Table 3 Model parameters used to represent pre-BMP and post-BMP conditions

BMP	Purpose	Selection criteria	Variable name	Pre-BMP (from calibration)	Post-BMP	Reference
Streambank stabilization	Reduce sediment load in streams	Main stream (3rd, 4th order and above)	CH_COV	0.4	0.25	Narasimhan et al. (2007)
			CH_EROD	0.008–0.05	Reduced by 50%	
	Maintain channel capacity		CH_N(2)	0.014	0.03	Chow (1959)
Porous gully plugs	Reduce ephemeral gully erosion	Tributary channels in subbasins with slope >5%	CH_N(1)	0.014	0.05	Chow (1959)
	Reduce velocity of flow					Srinivasan (2008)
	Trap sediment					
Recharge structures	Increase ground water recharge	Tributary channels in subbasins with soils of hydrologic group A and B	CH_K(1), mm/h	0.5	25	Lane (1983)
	Facilitate sediment settling		CH_N(1)	0.014	0.08	Chow (1959)
Conservation tillage	Reduce velocity of flow	All cropland	EFFMIX	0.70–0.75	0.25	Neitsch et al. (2005a, b)
	Reduce erosion		DEPTIL, mm	75–100	100	
			CN2	Varies	CN2 reduced by 2 from the calibration values	
Terrace	Reduce overland flow and conduct runoff to a safe outlet	All cropland	CN2	Varies	CN2 reduced by 5 from the calibration values	SCS Engineering Division (1986)
	Reduce sheet erosion		P-factor	1.0	0.10, if slope = 1 to 2% 0.12, if slope = 3 to 8%	Schwab et al. (1995)

Contour farming	Reduce sheet erosion	All cropland	CN2	Varies	CN2 reduced by 3 from the calibration values	
			P-factor	1.0	0.5, if slope = 1 to 2% 0.6, if slope = 3 to 8%	Schwab et al. (1995)
Manure incorporation	Reduce nutrients loading in runoff	All waste application fields	FRT_SURFACE	1.0	0.0[a]	Neitsch et al. (2005a, b)
Filter strip	Reduce sediment, dissolved contaminants, and sediment adsorbed organics in runoff	All cropland and WAF	FILTERW	0.0	6.0 m	USDA-NRCS (2008)

CN2 initial SCS runoff curve number for moisture condition II, *CH_COV* channel cover factor, *CH_EROD* channel erodibility factor, *CH_N(1)* Manning's "n" value for the tributary channel, *CH_N(2)* Manning's "n" value for the main channel, *CH_K(1)* effective hydraulic conductivity in tributary channel alluvium (mm/h), *DEPTIL* depth of mixing caused by the tillage operation (mm), *EFFMIX* mixing efficiency of tillage operation, *FRT_SURFACE* fraction of fertilizer applied to top 10 mm of soil, *FILTERW* width of edge-of-field filter strip (m), *HI* harvest index, *P-factor* conservation support practice factor

[a]When the FRT_SURFACE is set to zero, the model applies 20% of the fertilizer to the top 10 mm and the remainder to the first soil layer

by SWAT and watershed subdivision pertaining to this study, these parameters and their values selected were based on published literature and expert opinion.

2.4.1 Streambank Stabilization (NRCS Practice Code 580)

Streambank stabilization uses vegetation or structural techniques to stabilize and protect banks of streams or constructed channels against scour and erosion. This practice increases channel cover and roughness and decreases channel erodibility. To mimic these functions, streambank stabilization BMP was represented using channel erodibility (CH_EROD), channel cover factor (CH_COV), and channel Manning's roughness coefficient (Manning's n) (CH_N(2)) for the main channels (Table 3). Some of the previous studies have used similar approach to model streambank stabilization (Narasimhan et al. 2007). The SWAT model default Manning's n of 0.014 used in the pre-BMP simulation was increased to 0.03 in the post-BMP simulation assuming excavated or dredged channel with earthen bottom and rubble sides (Chow 1959).

2.4.2 Porous Gully Plugs

Plugging the gullies using rocks or logs can reduce the velocity of concentrated flow thereby reducing the erosive power of flowing water and facilitating sediment settling. Porous gully plugs are generally installed on the ephemeral gullies and therefore gully plugs were simulated by modifying Manning's n parameter for the tributary channel instead of main channel as in case of streambank stabilization. The selected subbasins had a total tributary channel length of 959 km. The SWAT model default Manning's n of 0.014 used for simulating pre-BMP condition was increased to 0.05 in the post-BMP simulation assuming minor natural streams with more stones (Chow 1959).

2.4.3 Recharge Structures

Recharge structures are small dams designed to retain a portion of water moving through a channel and to let the water infiltrate and percolate to reach the shallow ground water. Also, recharge structures decrease energy of the stream and in turn reduce its sediment carrying capacity. To simulate these characteristics, recharge structures were represented by effective hydraulic conductivity (CH_K(N1)) and Manning's n of the tributary channels in the subwatersheds. All 48 subwatersheds were selected for implementing recharge structures (Srinivasan 2008). The CH_K(N1) controls the infiltration of surface runoff within that subwatershed which in turn takes care of the recharge function of the practice. Manning's n parameter, which represents the channel roughness, controls the energy of the stream. Increasing the channel roughness will reduce the peak runoff rate and in turn reduce sediment transport by increasing sediment settling. The SWAT model default Manning's n of 0.014 used in the pre-BMP simulation was increased to 0.08 in the post-BMP simulation assuming sluggish reaches with deep pools (Chow 1959).

2.4.4 Conservation Tillage (NRCS Practice Code 328)

Conservation cropping practice involves less tillage. Thus, it increases the amount of residue on the surface after harvest of the crop and through planting of the next crop. Conservation cropping was simulated by using appropriate SCS CN values and by maintaining residue on the surface. An intensive tillage operation before planting such as tandem disk plow in the pre-BMP condition was replaced with generic conservation tillage in the post-BMP condition. In SWAT, these tillage operations differ in terms of mixing efficiency (EFFMIX) which specifies the fraction of materials (residue, nutrient, and pesticides) on the soil surface that are mixed uniformly throughout the soil depth specified by DEPTIL (depth of mixing caused by tillage operation). The EFFMIX values for tandem disk and conservation tillage are 0.75 and 0.25, respectively.

2.4.5 Terrace (NRCS Practice Code 600)

Terraces are broad earthen embankments or channels constructed across the slope to intercept runoff water and control erosion. Terraces serve for both erosion control and water management. Terraces decrease hill slope length, prevent formation of gullies, and intercept, retain, and conduct runoff to a safe outlet thereby reducing sediment content in runoff water. By retaining runoff, terraces increase the amount of water available for recharging the shallow aquifers (Schwab et al. 1995). In this study, terraces were represented by conservation support practice factor (P-factor) and CN. Also, it was assumed that terraces were in conjunction with waterways or graded channel outlets (Table 4).

2.4.6 Contour Farming (NRCS Practice Code 330)

Contour farming consists of performing field operations along the contour. These operations include plowing, planting, cultivating, and harvesting. Contour practices intercept runoff and reduce development of rills. In this study, the representation of contour farming was very similar to that of a terrace.

2.4.7 Manure Incorporation

Manure incorporation is a management practice where instead of applying the solid/liquid manure to the surface, it is incorporated into the soil by knifing.

Table 4 Conservation practice factor P for the Modified Universal Soil Loss Equation (MUSLE)

Farming up and down slope P = 1.0					
For contour farming					
(a) Land slope	Maximum slope length, feet (m)		(d) Maximum	P factors	
(percent)	(b) Contouring	(c) Strip cropping	strip width, feet (m)	(e) Contour	(f) Strip crop
1 to 2	400 (121.92)	800 (243.84)	130 (39.62)	0.6	0.3
3 to 5	300 (91.44)	600 (182.88)	100 (30.48)	0.5	0.25
6 to 8	200 (60.96)	400 (121.92)	100 (30.48)	0.5	0.25
9 to 12	120 (36.58)	240 (73.15)	80 (24.38)	0.6	0.3
13 to 16	80 (24.38)	160 (48.77)	80 (24.38)	0.7	0.35
17 to 22	60 (18.29)	120 (36.58)	60 (18.29)	0.8	0.4
21 to 25	50 (15.24)	100 (30.48)	50 (15.24)	Too steep	0.45

For terraces, use revised LS factor, loss from crop, same P as contouring factor; loss from terrace with graded channel outlet, contour P factor ×0.2, loss from terrace with underground outlet, contour P factor ×0.1. Source: Schwab et al. (1995), originally based on Wischmeier and Smith (1978)

2.4.8 Edge-of-Field Filter Strip (NRCS Practice Code 393)

Filter strips are a length of herbaceous vegetation between cropland, grazing land, or any disturbed land and environmentally sensitive area. Filter strips can trap sediment, which reduces the sediment and sediment-bound pollutants in runoff.

2.4.9 PL-566 Structures

In 1954, the Watershed Protection and Flood Prevention Act (PL 83-566), authorized USDA-NRCS to cooperate with other federal, state, and local agencies in making investigations and surveys of river basins as a basis for the development of coordinated water resource programs, and floodplain management and flood insurance studies. The USDA-NRCS assists public sponsors to develop watershed plans to mitigate flood damages; conservation, development, utilization and disposal of water; and conservation and proper utilization of land (USDA-NRCS 2007). As a result of the PL-83 566 efforts, a number of small upstream dams were built in the late 50s, 60s, and early 70s, which provided flood protection and served as a water source for municipal water supplies, wildlife habitat, and livestock and recreation. There were 88 such small reservoirs with drainage areas ranging from 0.5 km^2 to 76.0 km^2 in the BRW (Fig. 3). In the present study, these PL-566 reservoirs were simulated as existing in the pre-BMP condition because of their existence during the period considered for model calibration. Except Lake Waco, all PL-566 reservoirs were modeled as ponds in the SWAT model. Reservoir data including the locations and dimensions were obtained from the US Army Corps of Engineers National Inventory of Dams (NID) dataset (USACE 1982). The impact of these PL-566 structures on sediment, TN, and TP were evaluated by running the SWAT simulation without these structures (i.e., in their absence) and quantifying the increase in sediment, TN, and TP loads.

2.5 BMP Evaluation

The effects of BMP implementation on water quality are presented as percent reductions in average annual sediment, TN, and TP loadings at the HRU, subwatershed, and watershed levels. The HRU and subwatershed level percent reductions represent overland load reductions due to BMP implementation. Watershed level reductions include cumulative load reductions considering overland transport and routing through the stream network. Also, load reduction summaries on the HRU level consider only areas with BMPs, whereas load reductions summarized at the subwatershed level consider both areas with and without BMPs. The calibrated model (without BMPs except PL-566s) was run for 32 years (1974–2005, including first 2 years of warm-up for parameter initialization) to establish baseline condition against which to evaluate BMP effects. The BMPs were simulated individually, and all inputs except the parameters used to represent a BMP were held constant. The percent reduction was calculated as:

$$reduction, \% = \frac{100\,(preBMP - postBMP)}{preBMP} \tag{1}$$

A paired t-test ($\alpha = 0.05$) (Ott and Longnecker 2001) was conducted on the simulated time series of sediment, TN, and TP values at the watershed outlet before and after BMP realization to test for significance in percent change.

2.6 Sensitivity Analysis of BMP Parameters

This study attempts to relate BMP parameter value sensitivity to the uncertainty of BMP effectiveness at the watershed outlet. While traditional sensitivity analysis in models is performed by ranking the parameters in order of their amount of relative change in output to input, this paper uses existing knowledge of the most sensitive parameters (CN, P-factor) to focus on the relative change in output for the limited parameter's range that can be applied to BMPs. For example, the SCS CN can range from 35 to 98 and represents the watershed's physicality; whereas in this study, CN is reduced by up to 10 from the calibrated value to solely reflect the BMPs physicality for only those HRUs that represents contour farming or terraces in order to reflect the reduction in runoff due to these practices. By establishing the impact of parameter value ranges on the BMPs modeled, users can ensure that the BMPs are more realistically being modeled. Utilizing this approach results in a more efficient and realistic BMP simulation and assessment of their implementation. This study uses a sensitivity index (SI) (Eq. 2) based on a nominal range sensitivity analysis to analyze various BMP parameter value sensitivity. The nominal range sensitivity analysis evaluates the effect on model outputs exerted by individually varying only one of the parameters across its specified range, while holding all other parameters at their nominal or baseline values (Cullen and Frey 1999).

$$SI = \frac{(y_{2-}y_1)}{y_{preBMP}} \tag{2}$$

Where y_2 and y_1 are the model output values corresponding to the minimum and maximum values in the range of BMP parameters. A positive SI value indicates that an increase of the parameter value leads to an increase of the model output value and a decrease of the parameter value leads to a decrease of the model output value. A negative SI value indicates that an increase in the parameter value leads to a decrease in the output value and a decrease in the parameter value leads to an increase in the output value.

3 Results and Discussion

3.1 Model Calibration and Validation

Long-term calibration (1980–2005) and validation (1960–1979) results for measured and simulated annual and monthly flow data for VM stations are presented in Table 5. Measured and predicted baseflow contribution to streamflow had close match during both calibration and validation periods (Table 5). The absolute percent difference between measured and simulated flows at annual and monthly time steps were 3% and 4%, respectively. The model performance was considered good with both R^2 and NSE being ≥ 0.73 based on the rating of Moriasi et al. (2007). The model performance was satisfactory during the validation period (0.64 and 0.60,

Table 5 Flow calibration and validation results at Valley Mills

Flow (m^3/s)	Mean		Std. dev.		R^2	NSE
	Measured	Predicted	Measured	Predicted		
Calibration (1980 to 2005)						
Annual	9.07	9.36	8.12	6.15	0.74	0.73
Monthly	9.10	9.47	20.56	14.38	0.77	0.74
Validation (1960 to 1979)						
Annual	6.81	7.26	5.07	4.53	0.65	0.64
Monthly	6.81	7.27	12.65	10.09	0.60	0.60
Baseflow fraction						
Calibration	0.37	0.40				
Validation	0.35	0.37				

respectively). The absolute percent difference between measured and simulated flows for the validation period, both at annual and monthly time steps were 7% and 7%, respectively. The monthly means, during both the calibration and validation periods, at Hico monitoring station had the greatest difference with TN followed by sediment, and TP (Table 6). At VM, the difference in measured and predicted means for sediment and TN during calibration was 18%, each and 12% for TP (Table 7). The R^2 and NSE values for monthly TN and TP at Valley Mills were very good for both calibration and validation periods (Tables 6 and 7) while sediment qualified as satisfactory or better than satisfactory. The disparity between measured and predicted values may be due to the limited amount of water quality data available for calibration and validation, which may include inherent environmental variability.

3.2 BMP Evaluation

The length of stream or area of the watershed in each practice is presented in Table 8. Streambank stabilization BMP reduced 213 Mg, 60 kg, and 22 kg of sediment, TN,

Table 6 Monthly calibration (January 1993 to July 1997) and validation (August 1997 to July 1998) at Hico

Component (unit)	Mean		Std. dev.		R^2	NSE
	Measured	Predicted	Measured	Predicted		
Calibration						
Flow (m^3/s)	4.41	3.99	5.20	4.59	0.65	0.62
Sediment (t/ha)	0.05	0.04	0.09	0.09	0.72	0.70
TN (kg/ha)	0.32	0.20	0.43	0.39	0.68	0.59
TP (kg/ha)	0.07	0.08	0.10	0.17	0.75	0.01
Validation						
Flow (m^3/s)	2.52	2.26	4.98	3.45	0.91	0.68
Sediment (t/ha)	0.04	0.03	0.11	0.07	0.98	0.80
TN (kg/ha)	0.26	0.19	0.38	0.48	0.95	0.84
TP (kg/ha)	0.07	0.07	0.11	0.19	0.96	0.35

Table 7 Monthly calibration (January 1996 to July 1997) and validation (August 1997 to July 1998) at Valley Mills

Component (unit)	Mean		Std. dev.		R^2	NSE
	Measured	Predicted	Measured	Predicted		
Calibration						
Flow (m^3/s)	21.23	17.12	31.41	16.86	0.81	0.66
Sediment (t/ha)	0.11	0.13	0.24	0.21	0.91	0.89
TN (kg/ha)	0.39	0.32	0.70	0.48	0.97	0.88
TP (kg/ha)	0.08	0.09	0.16	0.17	0.95	0.92
Validation						
Flow (m^3/s)	11.19	7.55	22.93	10.90	0.87	0.63
Sediment (t/ha)	0.13	0.08	0.38	0.17	0.88	0.62
TN (kg/ha)	0.31	0.24	0.80	0.45	0.93	0.76
TP (kg/ha)	0.06	0.08	0.16	0.18	0.96	0.93

and TP, respectively, per km length of stream stabilized. Simulating streambank stabilization in the main channels resulted in average reduction of 34%, 4%, and 4% in sediment, TN, and TP, respectively (Fig. 4a, b, and c). Percent reduction was highest in the most downstream reach that received contribution from over 70% of the upstream BRW. Streambank stabilization achieved substantial reductions in sediment at the watershed outlet (Table 9). Increasing channel roughness reduce peak flow rate. Reduced channel flow rate in turn reduces the maximum amount of sediment that can be transported by water. Also, increased channel cover and decreased channel erodibility reduce channel degradation and thereby reduce the amount of sediment reentraining in the reach. Therefore streambank stabilization simulated in SWAT model results in substantial sediment reduction. On the other hand, this practice showed non-significant to slight reduction in TN and TP (Table 9)

Table 8 Long-term (30 years) annual average percent reductions at the subwatershed level

Type of BMP	Sediment	TN	TP	Total length, km or area, km^2 of BMP implementation (% of total stream length or watershed area)
Streambank stabilization[a]	–	–	–	245 km* (25)
Gully plug	12.9	7.8	6.8	959 km** (74)
Recharge structures	46.7	36.8	31.7	1,302 km** (100)
Conservation tillage	4.6	3.6	1.4	432 km^2 (10)
Terrace	24.6	21.3	20.5	432 km^2 (10)
Contour	15.9	11.9	11.5	432 km^2 (10)
Manure incorporation	0.0	2.8	9.7	88 km^2 (2)
Filter strip	16.8	17.6	20.1	499 km^2 (12)
PL-566s	25.4	16.6	18.8	975 km^2 (23)

[a]No subwatershed level (corresponds to the overland processes including tributary channel processes) reduction was estimated because this was simulated as in-stream process in the main routing channel
*Length of the main channel in the subbasins considered
**Length of the tributary channels in the subbasins considered

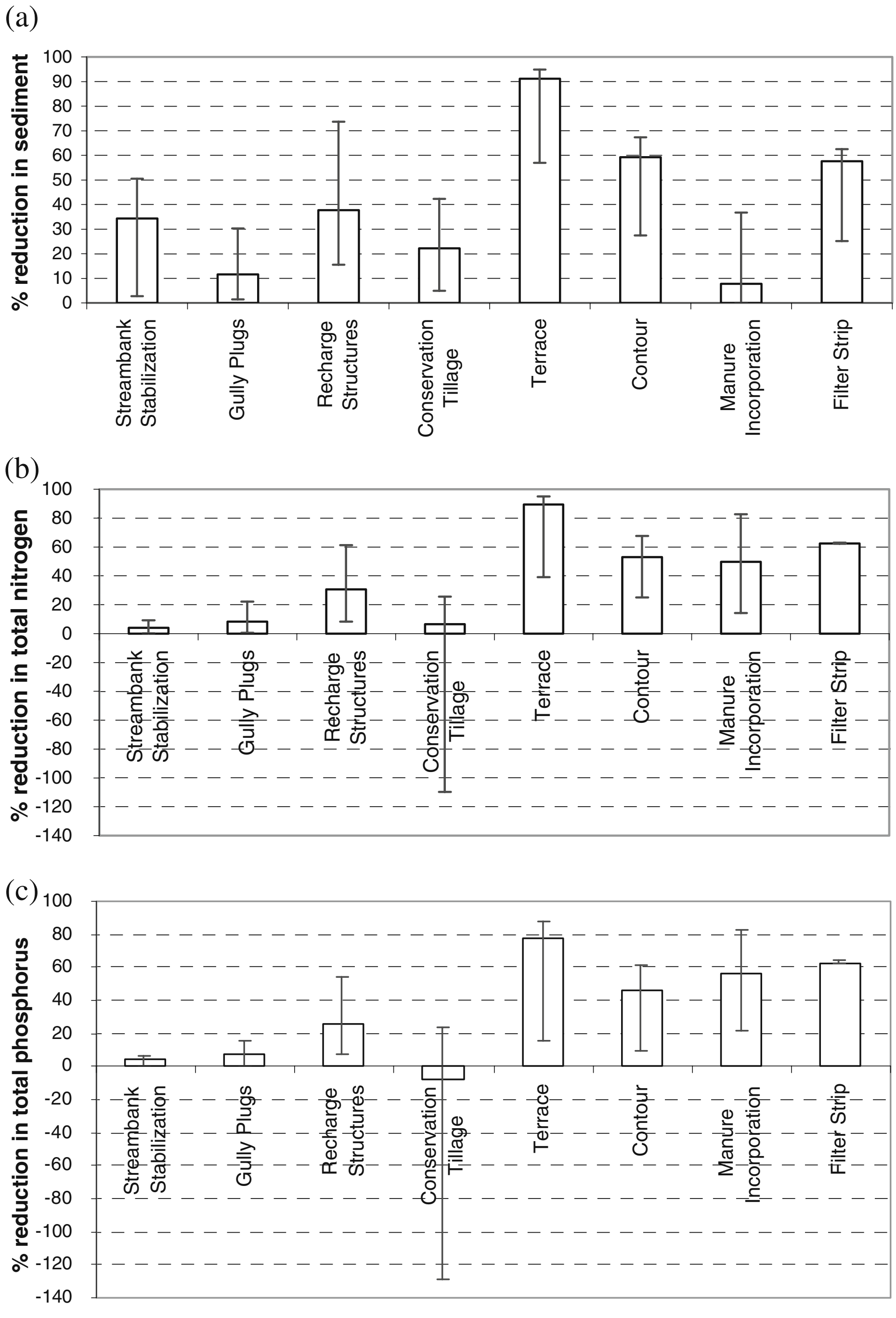

Fig. 4 Long-term (30 years) HRU average (*bars*) and range (minimum and maximum represented by the *line through the bars*) of % reduction in **a** sediment, **b** total nitrogen, and **c** total phosphorus for various BMPs

Table 9 Long-term (30 years) annual average percent reduction at the watershed outlet (load into Lake Waco)

Type of BMP	Sediment	TN	TP
Streambank stabilization	34.6	0.9[a]	4.0
Gully plug	5.3	4.8	4.9
Recharge structures	37.2	24.4	29.6
Conservation tillage	3.0	3.1	–3.3
Terrace	17.2	18.5	28.0
Contour	10.0	10.2	15.6
Grazing management	7.4	5.3	4.0
Manure incorporation	0.0	1.7	20.9
Filter strip	9.4	15.5	25.7
PL-566s	9.5	15.2	16.9

[a]Not significantly different from baseline as determined by a paired *t* test ($\alpha = 0.05$)

because only peak flow rates influence nitrogen and phosphorus transport as simulated by QUAL2E (Brown and Barnwell 1987) in-stream algorithms in SWAT. Also, QUAL2E do not consider channel cover and erodibility in their in-stream nitrogen and phosphorus transformation equations. Narasimhan et al. (2007) estimated a reduction in sediment load of upto 15% at the outlet of Cedar Creek Watershed in northcentral Texas due to streambank stabilization simulated for varying stream lengths. They concluded that the reduced effectiveness of the practice in their study was due to the addition of sediment loadings from the downstream-untreated stream segments.

The total length of the tributary channels for gully plug BMP was 959 km. Gully plugs yielded sediment, TN, and TP reductions of 7.5 Mg/km, 7.4 kg/km, and 0.9 kg/km of the tributary channel, respectively. Benefits resulting from implementing gully plugs ranged from 1.4% to 30.3% for sediment, 0.6% to 22% for TN, and 0.5% to 16% for TP (Fig. 4a, b, and c). Gully plugs were not as effective as streambank stabilization in reducing the sediment load at the watershed outlet (Table 9). However, because these were simulated in the tributary channels within the subbasins by increasing Manning's n, they reduced the amount of nutrient loads entering the main streams. Comparing gullied and gully treated watersheds (3.8 and 5.7 ha), Sharpley et al. (1996) noticed that gully treatment reduced sediment, N, and P by 82%, 56%, and 61%, respectively. These watersheds are field-sized watersheds whereas subwatershed sizes where gully plugs were simulated in the present study ranged from 7 km^2 to 292 km^2.

Recharge structures resulted in reductions of 14 Mg/km in sediment, 18 kg and 2 kg, respectively, in TN and TP per km of tributary channel length. Quantitative effectiveness of the recharge structures (as represented in this study) in reducing sediment load was similar to that of streambank stabilization at the watershed level. Recharge structures reduced surface runoff by 23%. The reductions in sediment in individual subwatersheds ranged from 15.5% to 73.7% while reductions in TN and TP ranged from 8.2% to 61.3% and 7.2% to 54.6%, respectively (Fig. 4a, b, and c). Recharge structures reduced TN and TP by 24% and 30%, at the watershed outlet, respectively compared to 1% and 4% by streambank stabilization. This relates to the representation of these two practices in the SWAT model. The recharge structures are simulated to have influence in the tributary channels within subwatersheds while streambank stabilization was simulated to have influence in the main routing channels. In SWAT, the pollutant load estimated from the subwatershed is added to the channel to be routed through it. Increase in channel roughness reduces peak runoff rate which in turn reduces sediment (simulated using MUSLE equation in SWAT) and sediment bound nutrients. As simulated by the SWAT model in this study, recharge structures curtail the pollutant load generated in the source and therefore in general results in higher reduction in TN and TP compared to that obtained by streambank stabilization. Increased effective hydraulic conductivity and higher Manning's n value compared to gully plugs increased the pollutant reduction potential of recharge structures compared to gully plugs.

At HRU level, conservation tillage resulted in sediment reductions of 5% to 42% (Fig. 4a) and average TN reduction of 6%. Total phosphorus increased on an average by 8%. Similar to other studies (Sharpley and Smith 1994; Gitau et al. 2005), dissolved P and N increased due to the implementation of the conservation tillage practice (indicated by negative % reduction in TN and TP in Fig. 4b and c) as compared to baseline conventional tillage. This increase is most likely attributed to the possible increase of residue and the build up of easily available soluble N and P at the surface due to lack of soil inversion and mixing. Reduction in sediment, TN, and TP at the subwatershed level due to conservation tillage was only 1.4% to 4.6% (Table 8). A reduction in sediment and TN of 3% at the watershed outlet could possibly be due to only 10% of the watershed area in conservation tillage (Table 8). From a field study, Soileau et al. (1994) found a reduction of 56% in sediment from conservation tillage compared to conventional tillage in a 0.038-km^2 watershed in northwestern Alabama. Dalzell et al. (2004) predicted, using ADAPT model, a 20% reduction in sediment and 2% reduction in phosphorus at the outlet of 650 km^2 Sandy Creek Watershed in southcentral Minnesota due to conservation tillage implemented on 40% of the cropland area.

Terraced areas reduced sediment at the HRU level by 57% to 95%; TN by 39% to 95%; and TP by 16% to 88% (Fig. 4a, b, and c). Terraces were applied to the same land area as conservation tillage and resulted in 25% sediment, 21% TN, and 21% TP reductions at the subwatershed level (Table 8). Comparing the BMPs evaluated in this study, terraces were most effective in reducing the pollutant loss at the HRU level (Fig. 4). A SWAT model application study by Santhi et al. (2006) estimated a HRU level reduction in sediment, TN, and TP of 84–86%, 56–59%, and 60–65%, respectively, due to contour terrace farming. Baird (1964) reported that a contour tillage system with terraces reduced erosion by 88% compared to traditional farming methods in the Texas Blackland Prairie.

Contour farming BMP was very similar to terraces in terms of representation in the model and trend in pollution reduction. Contour farming BMP reduced sediment by 28% to 67%, TN by 25% to 68%, and TP by 10% to 62% at the HRU level (Fig. 4a, b, and c). The subwatershed and watershed level reductions are presented in Tables 8 and 9.

Maximum sediment reduction brought about by incorporating manure was 37%, reduction in TN ranged from 14% to 83%, and TP ranged from 22% to 83% at the HRU level (Fig. 4a, b, and c). Incorporating the manure in the subsoil prevents its vulnerability to being carried downstream by runoff and sediment. This effect is more pronounced for phosphorus in the BRW because dairy manure is rich in P compared to N. Manure incorporation had no effect on sediment at subwatershed and watershed levels. Though the area within the watershed where manure was incorporated was only 2%, it reduced TN by 2% and TP by 21% at the watershed outlet (Table 9).

Edge-of-field filter strips were simulated for all cropland and WAFs, amounting to 12% of the watershed area (Table 8). The effectiveness of filter strips at the HRU level ranged from 25% to 63% in reducing sediment, 62% to 64% in reducing TN and TP (Fig. 4a, b, and c). Effectiveness of the filter strips at subwatershed and watershed levels is presented in Tables 8 and 9. Parajuli et al. (2008) predicted that a 15 m filter strip applied based on targeted approach for 10% of the watershed area reduced sediment by 46% at the subwatershed level whereas the reduction was 12% at the outlet of 950 km^2 Upper Wakarusa Watershed in Kansas.

Though originally designed for flood control, PL-566 structures play an important role in improving watershed water quality. PL-566s significantly reduced sediment, TN, and TP loading at the subwatershed and watershed levels (Tables 8 and 9).

With the lack of empirical equations or process descriptions to adequately model the BMPs, some of the existing model parameters were adjusted in this study to mimic the hydrologic/environmental effects of the BMPs. For instance, the SWAT model does not simulate bank failure directly but only simulates fluvial erosion, which is removal of sediment from bank, bed or toe due to the erosive power of the stream (Narasimhan et al. 2007). Stream bank stabilization projects are usually implemented on fairly limited stream reaches. The SWAT model has no direct way of representing a section of the stream within a subwatershed.

3.3 Sensitivity Analysis of BMP Parameters

Among the parameters analyzed for sensitivity, P-factor and CN were most sensitive followed by Manning's n and channel cover for sediment (Table 10; Figs. 5, 6 and 7). The TN and TP were sensitive to the parameters such as P-factor, CN, and filter width that influence the overland processes and relatively less sensitive to Manning's n. The SWAT in-stream water quality algorithms that incorporate QUAL2E (Brown and Barnwell 1987) do not consider channel cover in their nitrogen and phosphorus transformation equations. Therefore in this study, varying channel cover had no effect on SWAT predicted TN and TP loads at the watershed outlet.

Based on the sensitivity index in Table 10, it is obvious that the uncertainty of determining the BMP parameter values may have implications on BMP effectiveness. For example, if we choose a P-factor of 0.5 to represent a "BMP" (say, contour farming), then the reduction of TP is 11.6%, but if we choose P-factor of 0.4 to represent the same BMP, then the reduction of TP is increased to 14.1%.

Table 10 Sensitivity of model output to input parameters

Parameter	Sensitivity index		
	Sediment	TN	TP
P-factor	0.14	0.18	0.25
Curve number	0.11	0.10	0.17
Filter width	−0.06	−0.08	−0.13
Manning's n	−0.09	−0.01	−0.02
Channel cover	0.08	0.00	0.00

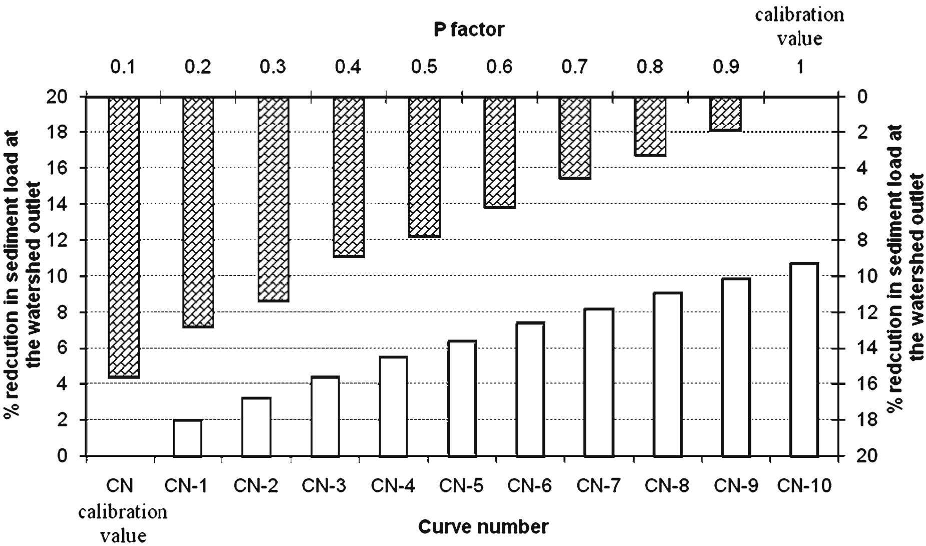

Fig. 5 Variations in percent reduction in sediment load at the watershed outlet with respect to varying CN and P factor. Primary axis: % reduction in sediment load at the watershed outlet on primary *y*-axis (*left*) corresponds to the curve number (*CN*) on primary *x*-axis (*bottom*). *CN-1* denotes CN reduced by one from the calibrated value and *CN-2* denotes CN reduced by two from the calibrated value and so on. Secondary axis: % reduction in sediment load at the watershed outlet on secondary *y*-axis (*right*) corresponds to the P factor values on secondary *x*-axis (*top*)

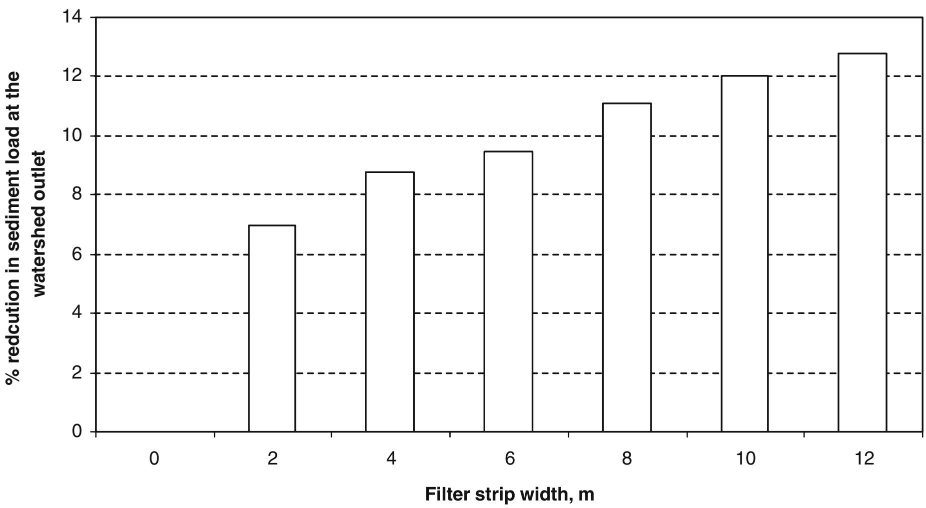

Fig. 6 Variations in % reduction in sediment load at the watershed outlet with respect to varying filter strip width

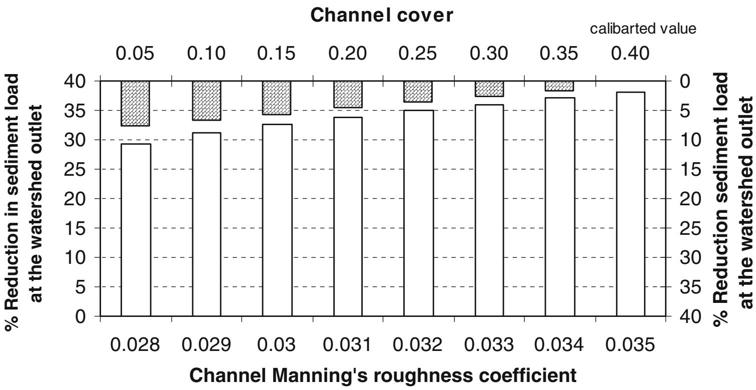

Fig. 7 Variations in percent reduction in sediment load at the watershed outlet with respect to varying channel Manning's roughness coefficient and channel cover. Primary axis: % reduction in sediment load at the watershed outlet on primary *y*-axis (*left*) corresponds to the channel Manning's roughness coefficient on primary *x*-axis (*bottom*). Secondary axis: % reduction in sediment load at the watershed outlet on secondary *y*-axis (*right*) corresponds to the channel cover values on secondary *x*-axis (*top*). Note the inverse relationship of the channel cover value. In SWAT, the channel cover value range from 0.0 to1.0; a value of 0.0 indicates that the channel is completely protected from degradation by vegetal cover and a value of 1.0 indicates that the channel has no vegetative cover

4 Conclusions

This study demonstrated application of SWAT model to predict the effectiveness of several management practices at HRU, subwatershed, and watershed levels. The SWAT model was used to simulate the hydrologic and water quality processes in the Bosque River Watershed as affected by a variety of agricultural BMPs. The BMPs simulated included streambank stabilization, gully plugs, recharge structures, conservation tillage, terrace, contour farming, manure incorporation, edge-of-field filter strips, and PL-566 reservoirs. In general, the BMPs achieved significant reductions at the HRU, subwatershed, and watershed levels, compared with a baseline scenario. Implementing these BMPs individually resulted in sediment reduction ranging from 3% to 37% and TN reduction ranging from 1% to 24%. The TP increased by 3% due to conservation tillage. The BMP reductions simulated in this study could vary from other such studies due to variability in weather, soils, topography, extent of BMP implementation, and any other unknown variability.

Sensitivity of parameters used to represent the BMPs varied among the constituents. The P-factor, CN, Manning's n, channel cover, and filter width were sensitive for sediment output, in that order. The TN and TP were sensitive to the parameters such as P-factor, CN, and filter width that influence the overland processes and relatively less sensitive to Manning's n and not sensitive to channel cover.

Nevertheless, the possible scenarios evaluated through modeling allow decision makers to identify potential long-term BMP effectiveness on sediment and nutrient load reduction at different levels in the watershed. This approach could be expanded to model additional BMPs as well as BMPs in a variety of watersheds. Although the approach used to represent certain BMPs has limitations, it is preferable due to simplicity and availability of no other explicit approach. Incorporating more explicit methods of modeling various BMPs would expand the capabilities of the model in such application studies. Evaluation of BMP effectiveness through monitoring would provide in-field data to validate the method. Further testing of the method presented here at different geographic settings and subwatershed discretization levels is highly encouraged. The sensitivity of BMP parameter values to represent the BMPs should be thoroughly investigated in order to quantify the uncertainty in modeled effectiveness of different BMPs.

List of Acronyms

AI1	Fraction of algal biomass that is nitrogen
AI2	Fraction of algal biomass that is phosphorus
ARS	Agriculture Research Service
BASINS	Better Assessment Science for Integrated Point and Nonpoint Sources
BC2	Rate constant for biological oxidation of NO2 to NO3 in the reach at 20°C (day^{-1})
BC4	Rate constant for mineralization of organic P to dissolved P in the reach at 20°C (day^{-1})
BMP	Best Management Practice
CDN	Denitrification exponential rate coefficient
C-factor	Land surface cover factor
CH_COV	Channel cover factor
CH_EROD	Channel erodibility factor
CH_K(1)	Effective hydraulic conductivity in tributary channel alluvium (mm/hr)
CH_N(1)	Manning's "n" value for the tributary channel
CH_N(2)	Manning's "n" value for the main channel
CMN	Rate factor for humus mineralization of active organic nutrients (N and P)
CN	Curve Number (Soil Conservation Service)
CN2	Initial SCS runoff curve number for moisture condition II
DEM	Digital Elevation Model
DEPTIL	Depth of Mixing caused by tillage operation
EFFMIX	Mixing Efficiency
EPCO	Plant uptake compensation factor
ESCO	Soil evaporation compensation factor
FILTERW	Width of edge-of-field filter strip (m).
FRT_SURFACE	Fraction of fertilizer applied to top 10 mm of soil
GW_REVAP	Groundwater revap coefficient
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur
HI	Harvest Index
HRU	Hydrologic Response Unit
HUC	Hydrologic Unit Code
MUMAX	Maximum specific algal growth rate (day^{-1})

N	Nitrogen
NCDC	National Climatic Data Center
NID	National Inventory of Dams
NLCD	National Land Cover Dataset
NPERCO	Nitrate percolation coefficient
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
NWS	National Weather Service
P-factor	Conservation support practice factor
P	Phosphorous
PHOSKD	Phosphorus soil partitioning coefficient
PL566	Public Law – 566
PPERCO	Phosphorus percolation coefficient
R^2	Coefficient of Determination
RS5	Organic phosphorus settling rate in the reach at 20°C (day^{-1})
RSDCO	Residue decomposition coefficient
SCS	Soil Conservation Service
SDNCO	Denitrification threshold water content (fraction of field capacity water content above which denitrification takes place
SPCON	Linear parameter for estimating maximum amount of sediment that can be reentrained during channel sediment routing
SPEXP	Exponent parameter for estimating maximum amount of sediment that can be reentrained during channel sediment routing
SSURGO	Soil Survey Geographic
SWAT	Soil and Water Assessment Tool
TIAER	Texas Institute for Applied Environmental Research
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Nitrogen
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
WAF	Waste Application Field
WWTP	Wastewater Treatment Plant

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