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A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas

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Abstract

Several best management practices (BMPs) have been implemented through Water Quality Management Plans (WQMPs) in the West Fork Watershed of Trinity River Basin in Texas, USA, where nonpoint source pollution is a serious concern. Major sources of pollution are sediment erosion and nutrients. The objective of this study was to evaluate the long-term impact of implementation of WQMPs on nonpoint source pollution at the farm level and watershed level using a modeling approach. The Soil and Water Assessment Tool watershed model was applied to quantify the impacts of implementing WQMPs on sediment and nutrients. A pre-BMP scenario representing conditions of the watershed prior to the implementation of WQMPs, and a post-BMP scenario representing the conditions of the watershed after implementation of WQMPs were simulated to estimate the reductions in nonpoint source pollution due to WQMP implementation. The results are presented as percentage reductions in sediment and nutrient loadings, at the farm level and at two locations within the watershed. The results revealed that (a) the benefits of the WQMPs were greater (up to 99%) at the farm level and (b) the benefits due to WQMPs were 1–2% at the watershed level. Watershed level benefits are tangible as the WQMP implementation area is very small compared to the watershed area. An additional scenario was evaluated to show the possible impacts of expanding the current BMP effort on load reductions. This study showed that a modeling approach can be used to estimate the impacts of water quality management programs in large watersheds.

Keywords: SWAT; Watershed modeling; Nonpoint source pollution; Best management practices

Software availability

Name of the software: Soil and Water Assessment Tool (SWAT)
Developer and contact address: Dr. Jeffrey G. Arnold, United States Department of Agriculture-Agriculture Research Service, 808 E. Blackland Road, Temple, TX 76502, USA, email: jgarnold@spa.ars.usda.gov
Available at: http://www.brc.tamus.edu/swat
Available since: 1994
Hardware required: PC with 128 MB RAM or Unix workstation
Software required: Arc View 3.2 for the AVSWAT GIS interface
Programming language: FORTRAN 90
Program size: 50,000 lines and 250 subroutines
Cost: Free

1. Introduction

Water quality is becoming an increasing concern in the United States and other parts of the world. To improve the quality of polluted water bodies, the United States

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Environmental Protection Agency (USEPA) mandates individual States to implement the Total Maximum Daily Load (TMDL) process through section 303(d) of the Clean Water Act (USEPA, 2002). A TMDL is a written, quantitative assessment of water quality problems and contributing pollutant sources. It specifies the amount of a pollutant or other stressor that needs to be reduced to meet water quality standards, allocates pollution control responsibilities among pollution sources in a watershed, and provides a basis for taking actions needed to restore a water body (http://endeavor.des.ucdavis.edu/geowbs/www/tmdl.htm). The United States Department of Agriculture–National Resources Conservation Service (USDA-NRCS) is also implementing several conservation practices to improve water quality in cooperation with state agencies and farmers.

In the State of Texas, the Texas Commission on Environmental Quality (TCEQ) (formerly known as Texas Natural Resources Conservation Commission – TNRCC) has identified impairments in many water bodies. The TCEQ and the Texas State Soil and Water Conservation Board (TSSWCB) are involved in the TMDL programs to restore water quality. Stream segments 0810 and 0812 of the West Fork Watershed (Fig. 1) of the Trinity River Basin in Northcentral Texas were classified in the 1999 Clean Water Act (CWA) 303(d) list for nonpoint source pollution concerns (TNRCC, 1999). Segments 0810 and 0812 are continued to be classified for water quality concern under the "Category 5" in the Draft 2004 CWA 303(d) list prepared by TCEQ. Category 5 indicates that the water body is not meeting water quality standards and prioritized for TMDL and additional data and information will be collected before scheduling the TMDL. It is also reported that the bacteria concentrations were exceeding the standards specified for normal recreational use in segments 0810 and 0812. Sources of contamination were point and nonpoint pollution sources (TCEQ, 2002). In addition, total dissolved solid is high and dissolved oxygen level is low in segment 0812.

The TSSWCB is implementing several best management practices (BMPs) through the 319(h) project to reduce nonpoint source pollution loadings from agriculture. Usually, the TSSWCB implements these 319(h) project BMPs in watersheds prioritized for TMDL process. TSSWCB provides technical and financial assistance to landowners through local Soil and Water Conservation Districts (SWCDs) for implementation of Water Quality Management Plans (WQMPs). A WQMP is a site-specific plan with a list of required BMPs. The BMPs may be a combination of land treatment practices, production practices, and technologies.

In the United States, the USDA-NRCS is implementing several conservation practices such as filter strips, nutrient management practices, manure management practices, grade stabilization structures, critical area

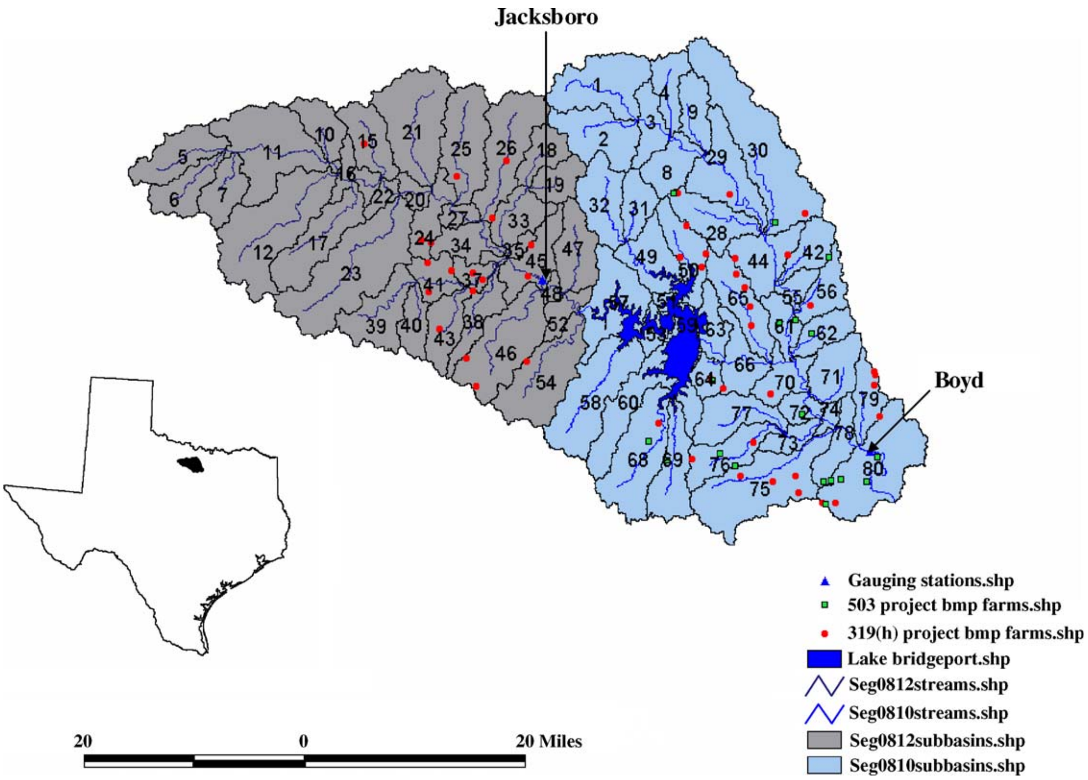

Fig. 1. Locations of the BMP farms in the West Fork Watershed, Texas.

planting and other practices (USDA-NRCS, 2003). However, there is no adequate information available to show the benefits of these programs at the watershed scale. Several field scale studies focused on assessing the impacts of some of these practices such as vegetative filter strips (Dillaha et al., 1989; Schmitt et al., 1999), nutrient management practices (NCAES, 1982; Osei et al., 2000) and riparian forest buffers (Sheridan et al., 1999) have been reported. Similarly, basin-scale studies on effectiveness of pre- and post-implementation of BMPs have been reported through field observations and monitoring studies. Walker and Graczyk (1993) monitored two small basins in Wisconsin and evaluated BMPs such as contour strip cropping, minimum tillage, changing crop rotation and barnyard treatment. The authors reported that the BMPs reduced the mass of suspended sediment and NH3-N in one basin, and significant reductions were not detected due to insufficient data set in the other basin. Park et al. (1994) monitored the Nomini Creek Watershed (14.6 km^2) in Virginia where the main focus was on row crop production. The authors estimated the benefits of BMPs by comparing selected parameters related to runoff, erosion and nutrients such as curve number, concentrations of total suspended solids, and discharge-nitrogen and phosphorus concentration relationships before, during, and after implementation of BMPs. They concluded that extensive monitoring data with intensive observations of BMPs over a larger portion of watershed are required to identify BMP effectiveness. In continuation of this study, Inamdar et al. (2001) reported the effectiveness of BMPs for this watershed by comparing more than 10 years of monitoring data. Brannan et al. (2000) reported the benefits of animal waste BMPs on stream water quality in Owl Run Watershed in Virginia based on an analysis of water quality data collected over a 10-year period.

Conducting field experiments or collection of long-term data is very expensive and time consuming. There are uncertainties/errors associated with the measured data and also difficulty in repeating the monitoring process without additional resources and time when corrections are warranted. With nonpoint source pollution emerging from a large watershed with mixed land uses and soil, it is quite difficult to associate water quality improvements to specific BMPs using the monitoring data, unless extensive sampling points are available. In this context, an application of a watershed simulation model becomes useful. Because the climate, land use, soil, topography and geological conditions vary within a watershed, a watershed based modeling approach (with spatial or geographic information system capability) allows for the consideration of these variations, and quantifying the impacts of BMPs at different locations. Hence, the objective of this article is to demonstrate the utility of a modeling approach to quantify the long-term impacts of best management practices implemented in reducing the nonpoint source pollution (sediment and nutrients) at the farm level and watershed level. Several authors have applied modeling approach to study the impacts of BMPs in different perspective. Turpin et al. (2005) have used a modeling framework to evaluate the impacts of BMPs in terms of hydrological effectiveness, costs for the farmers and society, and their acceptability in several European watersheds. Zhang and Jørgensen (2005) have used a modeling approach to evaluate the BMP scenarios related to reducing the point and nonpoint source pollution in Denmark.

2. Methodology

2.1. Model description

The watershed loading/water quality model, Soil Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2002; http://www.brc.tamus.edu/swat), developed by the United States Department of Agriculture-Agriculture Research Service (USDA-ARS), was used in this study. The USEPA supports and recommends that state and federal agencies use a set of models available within a framework called Better Assessment Science Integrating Point and Nonpoint Sources (BASINS). BASINS framework also has the various databases required for the models (http://www.epa.gov/waterscience/basins/basinsv3.htm). SWAT is available within BASINS framework (Di Luzio et al., 2002).

SWAT was selected for this study because of its ability to simulate land management processes in larger watersheds. SWAT is a physically based simulation model developed to simulate continuous-time landscape processes and streamflow with a high level of spatial detail by allowing the river/watershed to be divided into subbasins or subwatersheds. Each subbasin is divided into several land use and soil combinations called Hydrologic Response Units (HRUs) based on threshold percentages used to select the land use and soil (Arnold et al., 1998). HRUs within each subbasin are defined by first selecting land uses whose percentages (based on area) are greater than the user-defined land use threshold percentage and within those selected land uses, by selecting the soils whose percentages are greater than user-defined soil threshold percentage (Neitsch et al., 2002). SWAT model operates on a daily time step and is designed to evaluate the impacts of different management conditions (point and nonpoint sources) on water quality in large ungauged basins. Major components of the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural management. A complete description of all components can be found in Arnold et al. (1998) and Neitsch et al. (2002).

A brief description on flow, sediment and nutrients is provided here.

The local hydrologic water balance in the hydrologic response unit is provided by four storage volumes: snow (stored volume until it melts), soil profile (0–2 m), shallow aquifer (typically 2–20 m), and deep aquifer (>20 m). The soil profile can be subdivided into multiple layers. Soil water processes include infiltration, runoff, evaporation, plant uptake, lateral flow, and percolation to lower layers. Percolation from the bottom of the soil profile recharges the shallow aquifer (groundwater recharge). SWAT simulates the total groundwater recharge as: (a) water that passes past the bottom of the soil profile, (b) channel transmission losses and (c) seepage from ponds and reservoirs. Surface runoff from daily rainfall is estimated with a modification of Soil Conservation Service (SCS) curve number method (USDA-SCS, 1972). In the curve number method, the daily rainfall is partitioned between surface runoff and infiltration as a function of antecedent soil moisture condition. Green & Ampt infiltration method is also available within SWAT to simulate surface runoff and infiltration (Green and Ampt, 1911; Mein and Larson, 1973). Curve number method was used for this study. SWAT has options to estimate the potential evapo-transpiration (PET) by different methods such as Modified Penman Montieth, Hargreaves, and Priestley-Taylor. Modified Penman Montieth is used in this study.

Erosion and sediment yield are estimated for each subbasin with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The channel sediment routing equation uses a modification of Bagnold's sediment transport equation (Bagnold, 1977) that estimates the transport concentration capacity as a function of flow velocity. The model either deposits excess sediment or re-entrains sediment through channel erosion depending on the sediment load entering the channel.

The nitrogen (N) processes and soil pools simulated by SWAT are described in Neitsch et al. (2002). Plant use of nitrogen is estimated using the supply and demand approach (Williams et al., 1984). Daily plant demand is a function of plant biomass and biomass N concentration. Available nitrogen in the soil (root depth) is supplied to the plant. When demand exceeds supply, there is a nutrient stress. Amounts of NO_3-N transported with runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate (NO_3-N) in the soil layer. Organic N transport with sediment is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events. The loading function estimates daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and an enrichment ratio. Enrichment ratio is the ratio of organic N in sediment to organic N in soil. It is calculated by SWAT and typically ranges from 2 to 4.

The phosphorus (P) processes modeled by SWAT and the various pools of phosphorus in the soil are described in Neitsch et al. (2002). Plant use of phosphorus is estimated using the supply and demand approach similar to nitrogen. The loss of dissolved phosphorus in surface runoff is estimated based on the concept of partitioning phosphorus into solution and sediment phases as described by Leonard and Wauchope (1980) for pesticides. The amount of soluble P removed in runoff is predicted using labile P concentration in the top 10 mm of the soil, the runoff volume and a phosphorus soil-partitioning factor, that is, the ratio of P attached to sediment to P dissolved in soil water. The phosphorus soil-partitioning factor is a model input parameter and typical values range from 100 to 175 depending on the soil. Sediment transport of P is simulated with a loading function as described for the organic N transport.

Instream nutrient dynamics have been incorporated into SWAT (Ramanarayanan et al., 1996; Neitsch et al., 2002) using the kinetic routines from the in-stream water quality model, QUAL2E (Brown and Barnwell, 1987).

Arnold et al. (1999) has reported several studies in the Unites States that used SWAT for flow and sediment predictions. Alexander et al. (2000) applied SWAT and SPARROW models (Smith et al., 1997) for regional estimations of nitrogen flux in the United States. Santhi et al. (2001a) applied the SWAT model to quantify the effects of BMPs related to dairy manure management and municipal wastewater treatment plant effluent in the Bosque River Watershed for a TMDL project. Kirsch et al. (2002) applied SWAT to predict sediment and phosphorus loads in the Rock River Basin for a TMDL project. SWAT was applied for modeling the WQMPs mostly related to poultry manure management and estimating the nonpoint source reductions in the Big Cypress Creek Watershed in Texas (Santhi et al., 2003). SWAT has been applied for numerous other hydrologic and/or nonpoint source pollution studies (http://www.brc.tamus.edu/swat/swat-peer-reviewed.pdf). European Union (EU) has initiated several water quality improvement efforts in Europe through EU water framework directive (Chave, 2001). SWAT model has been widely applied in Europe including the current efforts of EU water framework (Arnold and Fohrer, 2005).

2.2. Study area

In the West Fork Watershed, river segment 0812 and river segment 0810 (Fig. 1) have a total drainage area of 4554 km^2 inclusive of Lake Bridgeport. Lake Bridgeport is classified as segment 0811. The various land uses in this watershed are range (48.0%), pasture (17.0%), cropland (5.0%), forest (17.0%), water (2.0%) and others such as urban, barren and wooded wetland (11.0%). Pasture is a managed land used for grazing or other grass planting and range is an unmanaged land used for grazing or it can be considered as an unmanaged pasture. Most of the soils are fine sandy loam and stony fine sandy loam.

In mid-1990s, Texas State Legislature passed the Senate Bill 503 for controlling water pollution from agricultural and silvicultural nonpoint sources, and authorized TSSWCB to assist landowners in this project. TSSWCB provided incentives to landowners for installation of BMPs to control nonpoint pollution sources and protect water quality (TSSWCB, 2001). As part of the 503 project, BMPs such as nutrient management, waste utilization, brush management, pasture planting, critical area planting and grade stabilization structures were implemented mostly in the watershed area of segment 0810. Descriptions of these practices can be found in the later section and also in the USDA-NRCS's handbook on conservation practices (USDA-NRCS, 2003). In later 1990s, in compliance with section 319(h) of the Clean Water Act, the USEPA provided funding to TSSWCB to implement water quality management measures to abate nonpoint source pollution in Texas. Starting in the year 2000, BMPs were installed through the 319(h) project in this watershed. These BMPs were related to: (1) nutrient management such as waste utilization practice, nutrient management practice and forage harvest management, (2) erosion control such as grade stabilization structure, critical area planting, residue management and range seeding, and (3) other practices such as brush management and contour terracing. These BMPs were implemented on 48 farms located across both the segments in the watershed (Fig. 1). Area of the BMPs installed in both projects is less than 1% of the watershed area.

2.3. Model inputs

The Arc View-Geographic Information System interface of the SWAT2000 version (Di Luzio et al., 2004) was used to develop the SWAT input files. Recently available GIS maps with 30 m resolution for topography, land use, and soils were used (Table 1). The interface delineates the watershed into subbasins or subwatersheds based on topography. A map of the BMP farms was overlaid on the subbasins to identify the BMP area and non-BMP area in each subbasin. The watershed conditions were simulated from 1982 through 2001 using daily historical weather information. Each individual farm was represented as an HRU in SWAT. BMPs implemented on the same piece of land in each farm were identified and grouped for modeling. For BMP farms, the management practices were adapted as described in the BMP scenario section. For non-BMP area, typical management practices such as crops grown, fertilizer application and tillage operations for different land uses were gathered from project personnel and county agents.

Table 1
Model input data sources for the West Fork Watershed

Data type	Scale	Source	Data description/ properties
Topography	1:24,000	USGS	Elevation, overland and channel slopes, lengths
Soils ((Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) Databases)	1:24,000	USDA-NRCS	Soil physical properties such as bulk density, texture, saturated conductivity, etc.
Land use	1:24,000	USGS	Land use classifications
BMP farms	–	TSSWCB	Location, area of farms and pre- and post-management information
Weather	7 stations	National Weather Service (NWS)	Daily precipitation and temperature
Land management information	–	TSSWCB	Fertilizer application rates and timing, planting and harvesting information

2.4. Model calibration

The SWAT model is built with state-of-the-art components with an attempt to simulate the processes physically and realistically as possible. Most of the model inputs are physically based (that is, based on readily available information). It is important to note that SWAT is not a 'parametric model' with a formal optimization procedure (as part of the calibration process) to fit any data. Instead, a few important variables that are not well defined physically such as runoff curve number and Universal Soil Loss Equation's (USLE) cover and management factor (C factor) may be adjusted to provide a better fit. SWAT has been widely used in the United States and other countries (Arnold et al., 1999; Borah and Bera, 2004; Arnold and Fohrer, 2005). Borah and Bera (2004) have extensively reviewed the various nonpoint source pollution models and their applications and indicated that SWAT is found to be sound and suitable for long-term continuous simulations in agricultural watersheds.

2.4.1. Flow

Flow calibration was performed for the period from 1982 through 2001. Calibration was performed for annual and monthly-simulated flows using observed flows from the USGS gauging stations at Jacksboro (Station 8042800 near the outlet of subbasin 45) and at Boyd, Texas (Station 8044500 near the outlet of subbasin 80) (Fig. 1). The calibration process consisted of ensuring (a) the simulated flow match the observed flow at Jacksboro and Boyd and (b) proper split (proportioning) of the simulated flow between surface runoff and base flow. An automated digital filter technique (Nathan and McMahon, 1990; Arnold et al., 1995; Arnold and Allen, 1999) was used separately for the observed daily flow and simulated daily flow at Boyd, for base flow separation and estimating the proportion of the base flow.

Several statistics including the mean, standard deviation, coefficient of determination (R^2), Nash-Suttcliffe prediction efficiency (E_{NS}) and prediction efficiency (P_{E}) were used to evaluate the model predictions against the observed values. The R^2 value is an indicator of strength of relationship between the observed and simulated values. The Nash-Suttcliffe simulation efficiency (Nash and Suttcliffe, 1970) indicates how well the plot of observed versus simulated value fits the 1:1 line. The prediction efficiency indicates the model's ability to describe the probability distribution of the observed results. If the R^2, E_{NS} and P_{E} values are less than or very close to 0.0, the model prediction is considered 'unacceptable or poor'. If the values are 1.0, then the model prediction is 'perfect'. A value greater than 0.5 for these variables was considered acceptable, which was the criteria used by Santhi et al. (2001b).

Surface runoff and base flow were calibrated simultaneously. Calibration parameters adjusted for surface runoff was mainly curve number. The parameters adjusted for base flow proportioning were groundwater revap coefficient, plant uptake compensation factor, soil evaporation compensation factor and threshold depth of water in shallow aquifer. These parameters were adjusted within the reported ranges (Table 2). Surface runoff was calibrated until average observed and simulated surface runoff was within 15% and R^2, E_{NS} and $P_{\mathrm{E}} > 0.5$, as possible. Similarly, base flow was calibrated until the simulated base flow is within 15% of the observed base flow and surface runoff was continually verified as the base flow calibration variables also effect surface runoff. Detailed calibration procedures for SWAT model and the definitions of various calibration parameters are described by Neitsch et al. (2002) and Santhi et al. (2001b).

Measured and simulated annual flows at Jacksboro and Boyd matched well (Fig. 2 and Table 3). The simulated annual flows were slightly higher for the years 1989 and 2001 (Fig. 2) and these were due to the over predictions of flows during a few months in those years (Figs. 3 and 4). Monthly simulated and observed at these two locations matched well except for a few months at Jacksboro, where the model over predicted the flow (Fig. 3). Means, standard deviations, R^2, E_{NS} and P_{E} values indicate the good agreement between simulated and observed values except for the monthly calibration at Jacksboro (Table 3). The model over predicted the flow during a few months in 1989, 1990 and 2001 at Jacksboro. Hence the mean of the simulated flow was slightly higher than the mean of the observed flow (about 30% difference) and resulted in lower E_{NS} value at this location. The estimated proportion of base flow from the observed flow at Boyd was 34% and it was 38% for the same location for SWAT simulated flow. Proportions of the base flow estimated for nearby watersheds in Texas were verified. Base flow proportions ranged from 30% to 34% in the Bosque Watershed (Santhi et al., 2001b) and 33% for the Richland Chambers Creek Watershed. These proportions for surface runoff and base flow estimated for the West Fork Watershed reveal that hydrologic processes and flow regimes in SWAT are modeled reasonably well.

2.4.2. Sediment and nutrients

Continuous records of monitoring data for sediment and nutrients were not available for calibration for this watershed. However, grab sample data were available from 1980 through 2001 (usually 2–5 samples per year, with a few years missing) for a monitoring station near Boyd in segment 0810 from the Texas Commission on Environmental Quality (TCEQ, 2003). Some of the sampling days were low flow days. Rigorous calibration of sediment and nutrients could not be performed due to limited sampling data. However, careful considerations were given to verify the key processes related to sediment and nutrients. The model parameters related to sediment and nutrients (Table 2) were set based on expertise and experience from previous studies (Santhi et al., 2001b; Neitsch et al., 2002). Model parameters verified for sediment (for upland processes) calibration were the Universal Soil Loss Equation's C factor, erodibility factor (K) and slope length factor. Parameters verified for channel sediment routing processes were coefficients of the Bagnold equation (Bagnold, 1977). Parameters verified for nutrients (nitrogen and phosphorus) were initial concentrations in the soil, nitrogen and phosphorus percolation coefficients, biological mixing efficiency, residue decomposition coefficient, and phosphorus-partitioning coefficient. Similarly, parameters related to in-stream kinetics (QUAL2E) occurring in the stream channel such as algae growth and decay factors, and fraction of algae biomass as nitrogen and phosphorus were adjusted (Neitsch et al., 2002; Brown and Barnwell, 1987).

Mean simulated daily flow and sediment and nutrient loadings were compared with the mean daily observed

Table 2
Model inputs used in SWAT

Variable name	Model processes	Description[a]	Normal range	Actual value used
CN2	Flow	Curve number	−5 to +5	−3 to +3
ESCO	Flow	Soil evaporation compensation factor	0.00–1.00	0.80
EPCO	Flow	Plant uptake compensation factor	0.00–1.00	0.00
GW_REVAP	Flow	Groundwater revap coefficient	0.02–0.40	0.4
GWQMN	Flow	Threshold depth of water in shallow aquifer for percolation to occur	0.0–300.0	200.0
RCHRG_DP	Flow	Deep aquifer percolation fraction	0.0–1.0	0.6
C FACTOR	Sediment	Cover or management factor	0.003–0.2	Pasture: 0.003, range: 0.003, cropland: 0.20
SPCON	Sediment	Linear factor for channel sediment routing	0.0001–0.01	0.001
SPEXP	Sediment	Exponential factor for channel sediment routing	1.0–1.5	1.00
SOL_ORGN	Organic nitrogen	Initial organic nitrogen concentration in the upper soil layer for a particular land use		Manure area: 2000 ppm, pasture/range: 800 ppm, cropland: 800 ppm
SOL_ORGP	Organic phosphorus	Initial organic phosphorus concentration in the upper soil layer for a particular land use		Manure area: 250 ppm, pasture/range: 100 ppm, cropland: 100 ppm
NPERCO	Mineral nitrogen	Nitrogen percolation coefficient	0.2–0.6	0.2
SOL_MINP	Mineral phosphorus	Initial mineral phosphorus concentration in the upper soil layer for a particular land use		BMP area 3–351 ppm, pasture/range: 5 ppm, cropland: 20 ppm
PPERCO	Mineral phosphorus	Phosphorous percolation coefficient	10.0–17.5	10
PHOSKD	Mineral phosphorus	Phosphorous soil-partitioning coefficient	100–175	175
BIOMIX	Sediment, organic and mineral nutrients	Biological mixing efficiency	0.2–0.5	0.2
RSDCO	Sediment, organic and mineral nutrients	Residue decomposition coefficient	0.01–0.05	0.05
AI1	Nitrogen in channel	Fraction of algae that is nitrogen	0.02–0.09	0.09
AI2	Phosphorus in channel reach	Fraction of algae that is phosphorus	0.01–0.02	0.02
MUMAX	Nitrogen and phosphorus in reach	Algae growth rate	1.0–3.0	3.0
RS5	Phosphorus in reach	Organic phosphorus settling rate in the reach	0.001–0.1	0.1
BC2	Nitrogen in reach	Rate constant for biological oxidation of NO_2 to NO_3	0.2–2.0	0.3
BC4	Phosphorus in reach	Rate constant for mineralization of organic phosphorus to dissolved phosphorus	0.01–0.7	0.05

[a] Detailed descriptions are available at http://www.brc.tamus.edu/swat/swatdoc.html (Neitsch et al., 2002).

data considering the sampling days alone (Table 4). Average and total simulated loadings for sediment and mineral N were higher than observed values. This was due to the over predictions of sediment and nitrogen loadings by the model during a few (sampling) days in 1993 and 1994. Mean and total simulated mineral P loadings were closer to the observed values and simulated total P loading was slightly lower. It should be noted that some of the sampling days were low flow days. Given the facts that there were only a few sampling days per year to calibrate the model, and matching the daily simulated values to those days alone is tedious, the results obtained seemed to be reasonable (Table 4). Nevertheless, continued collections of monitoring data are necessary for adequate validation of the model, but data are still scarce, especially sediment and nutrient data. Efforts must continue to collect these data.

2.5. BMP scenarios

In order to estimate the reductions in nonpoint source pollution due to implementation of WQMPs through 319(h) project, a pre-BMP scenario representing conditions of the watershed prior to the implementation of WQMPs, and a post-BMP scenario representing the conditions of the watershed after implementation of WQMPs were studied. Both of these scenarios included the BMPs implemented through the 503 cost-sharing project, because they were implemented in the watershed prior to the implementation of 319(h) project. Changes in sediment and nutrient loadings between these two

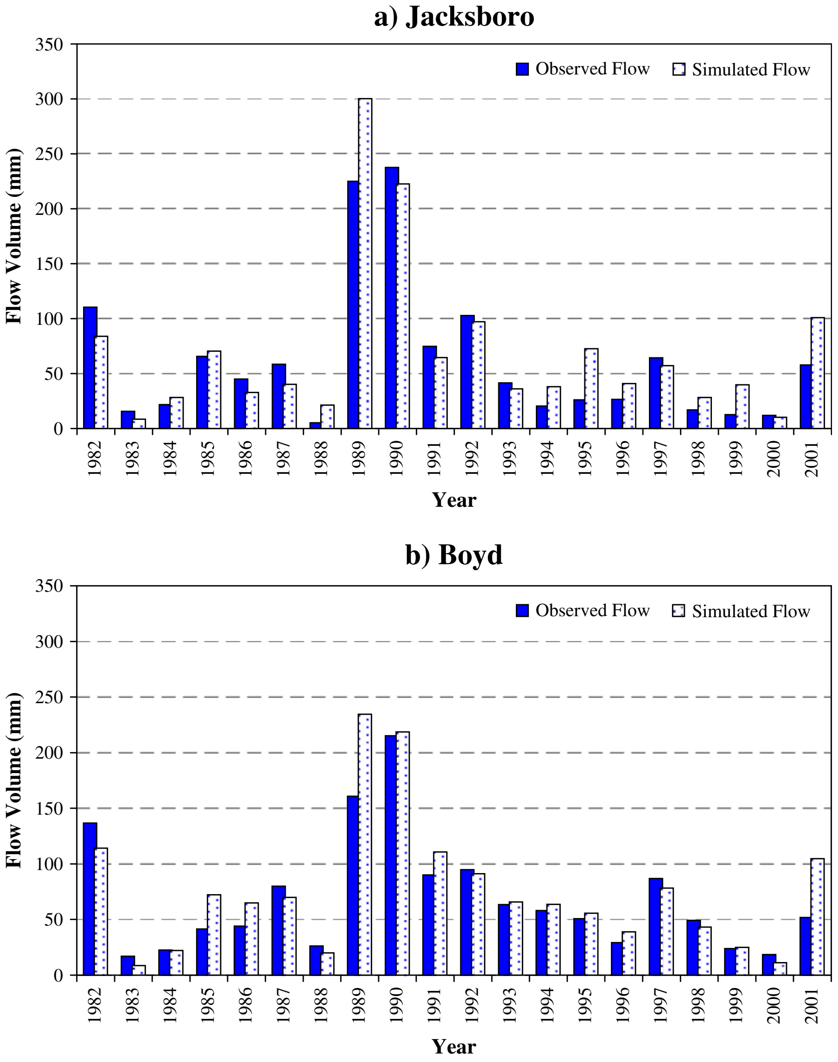

Fig. 2. Annual observed and simulated flows along two locations in the West Fork Watershed.

scenarios provided the percentage of reductions in nonpoint source pollution in the watershed.

For developing the scenarios, for each BMP, the key processes and related model parameters such as manure/fertilizer application rates, crops grown, C factor and P factor of USLE that need to modified to represent the pre- and post-BMP conditions were identified. Those parameters were modified in the appropriate SWAT input files such as management file, HRU file and crop database file. These modifications were made outside the SWAT GIS interface. Model runs were made for pre- and post-BMP scenarios to estimate the reductions in loadings.

2.5.1. Pre-BMP and post-BMP scenarios

There are several dairy operations in practice in the watershed area pertaining to segment 0810. Historically, landowners applied high rates of manure resulting

Table 3
Calibration results for flows at Jacksboro and Boyd in the West Fork Watershed

Variable	Station	Mean		Standard deviation		R^2	E_{NS}	P_E
		Obs	Sim	Obs	Sim			
Flow (mm/yr)	Jacksboro	62.05	69.70	65.15	71.73	0.88	0.84	0.93
Flow (mm/yr)	Boyd	68.02	75.66	51.97	60.65	0.86	0.78	0.89
Flow (mm/mon)	Jacksboro	4.42	5.80	10.84	15.93	0.61	0.12	0.66
Flow (mm/mon)	Boyd	5.60	6.44	12.41	14.68	0.81	0.72	0.92

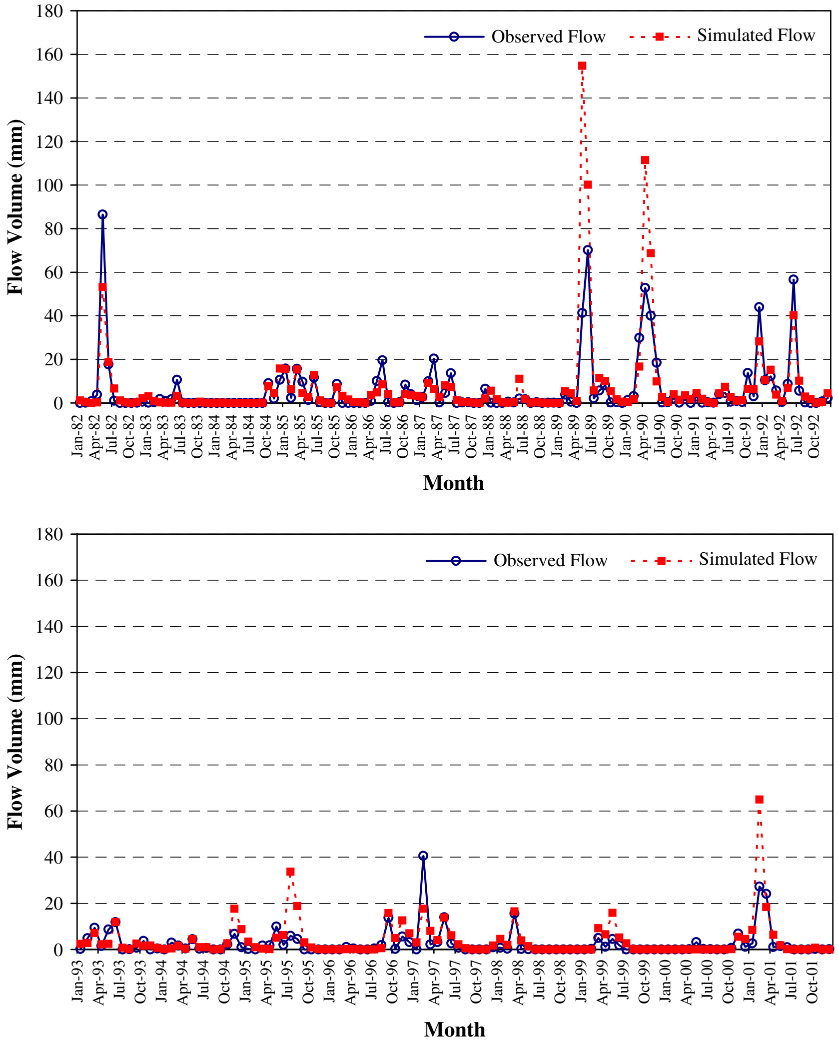

Fig. 3. Monthly observed and simulated flows near Jacksboro, Texas.

in a build-up of soil nutrients, especially phosphorus. Nutrient management practice was established on most of these farms through the 503 project. Additionally, several farms had brushland in both segments; this brush vegetation competed for water with grasses in pasture and rangeland. There were also erosion problems in several farms. During 319(h) project, several BMPs were implemented to overcome these problems. Field conditions and the relevant modeling inputs/parameters used for representing the main processes in simulating each BMP for the pre-BMP and post-BMP conditions are described below:

- *Nutrient management practices for manure applied farms:* Several farms that received dairy manure application were treated with the nutrient management practice BMP through 503 and 319 projects. For simulating these BMP farms as they exist in the watershed, growth of bermuda and klein grasses were simulated on pasture and hayland, and winter wheat on cropland, mainly for grazing. Grazing operation was simulated on pastureland and four hay cutting operations were simulated on hayland. These conditions remained same for pre-BMP and post-BMP conditions. For the 319 project farms, manure application rates of 45.0 Mg/ha and 11.6 Mg/ha were used for the pre-BMP and post-BMP conditions, respectively. For the 503 project farms, the manure application rate ranged from 1.0 Mg/ha through 12.0 Mg/ha. These rates were same for pre- and post-BMP conditions (Table 5). Initial soil test nitrogen and phosphorus concentrations available for the farms for the pre- and post-BMP conditions were used. Manure nutrient concentrations were taken from the literature for model simulation (Gassman, 1997).
- *Nutrient management practices for fertilizer applied farms:* These farms are similar in practice as of the above manure applied farm except that the commercial fertilizer is applied in these farms. As explained above, bermuda and klein grasses were

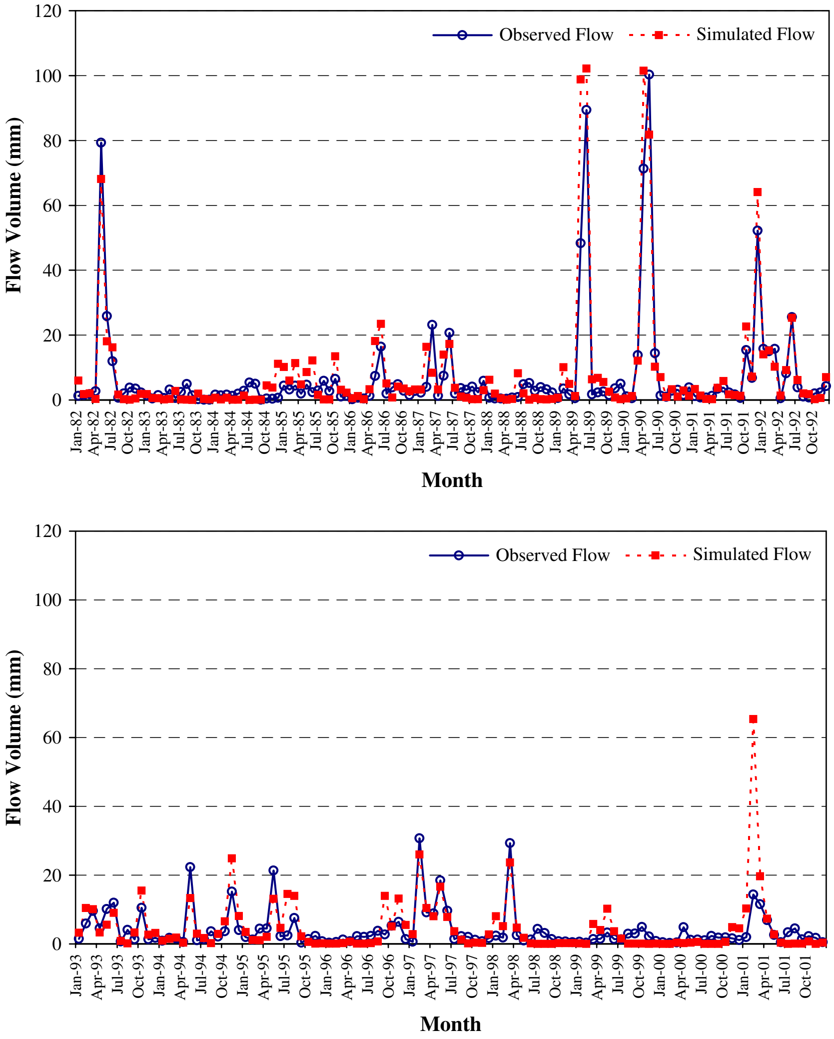

Fig. 4. Monthly observed and simulated flows near Boyd, Texas.

grown on pasture and hayland and winter wheat on cropland during the model simulation. For pre-BMP scenario, nitrogen and phosphorus fertilizers were applied on pasture, hayland and cropland to maintain crop growth. These application rates were collected through project personnel and county agents (Table 5). For post-BMP conditions, nitrogen and phosphorus fertilizers were applied on pasture, hayland and cropland following the recommendations of USDA-NRCS (2000) and TAMUS (2000). Other conditions remained the same between pre-BMP and post-BMP scenarios.

- *Forage harvest management:* Farmers often harvest the forage without leaving enough plant cover for re-growth. This practice impacts on erosion and nutrient losses. For pre-BMP scenario, these farms were simulated as hayland with two hay cuttings. Hay was removed entirely from the field (removal of 99% above ground biomass) during harvesting. For post-BMP scenario, these farms were simulated with

Table 4
Observed and simulated daily loadings at Boyd in the West Fork Watershed

Variable	No. of observations	Mean		Total		Standard deviation	
		Obs	Sim	Obs	Sim	Obs	Sim
Flow (m^3/s)	90	4.0	2.6	312.0	216.0	5.6	3.2
Sediment (Mg)	72	44.0	79.0	3160.0	5692.0	111.0	120.0
Mineral P (kg)	50	18.1	17.6	906.0	880.0	33.6	58.1
Total P (kg)	72	62.0	39.0	4639.0	2905.0	117.7	144.0
Mineral N (kg)	42	116.0	168.0	4867.0	7043.0	342.2	550.8

Table 5
Model parameters/management inputs used for representing pre-BMP and post-BMP conditions

BMP	Pre-BMP	Post-BMP
Nutrient management practice (manure applied)	319 BMPs: manure application rate: 45.0 Mg/ha 503 BMPs: 1.0–12.0 Mg/ha	319 BMPs: manure application rate: 11.6 Mg/ha 503 BMPs 1.0–12.0 Mg/ha
Nutrient management practice (fertilizer applied)	Cropland: 100–125 kg N and 20–25 kg P Pasture: 50–70 kg N and 10–15 kg P Hayland: 90–115 kg N and 15–20 kg P	Cropland: 112 kg N and 20 kg P Pasture: 67 kg N and 15 kg P Hayland: 104 kg N and 20 kg P
Forage harvest management	Hayland with cuttings; removal of 99% of above ground biomass	Hayland with cuttings; removal of 85% of above ground biomass
Residue management	Winter wheat: two tillage operations prior to planting and one after harvest	Winter wheat: one tillage operation prior to planting and leave residue after harvest
Brush management	Heavy mesquite and cedar	Range grass
Critical area planting	USLE's C factor: 0.400	USLE's C factor for range/pasture land: 0.003
Grade stabilization structure	Slope steepness: 0.23–0.33	Slope steepness: 0.045–0.066
Contour farming	USLE's P factor: 1.00	USLE's P factor: 0.2

optimal forage harvest by leaving enough plant cover for re-growth. These farms were simulated as hayland with two hay cuttings and a portion of the hay was left on the field during harvesting (removal of 85% above ground biomass).

- *Residue management:* In cropland, leaving adequate residue on the ground after harvest and prior to tillage for planting will reduce sheet and rill erosion. However, farmers often plow the land after harvest and turn-around the soil, which results in erosion. In the pre-BMP scenario, these farms were simulated with winter wheat and two tillage operations, one prior to planting and one after harvest. In the post-BMP scenario, these farms were simulated with a tillage operation prior to planting and leaving the residue on the ground after harvest (Table 5).
- *Brush management:* Brushland with heavy mesquite and cedar is commonly found on several farms in this watershed. Brushland is unproductive and the brush vegetation competes for water, space and sunlight with other grasses in the farm. It also causes erosion due to poor grass cover on the ground. For pre-BMP scenario, brushland areas were simulated with heavy mesquite (TWRI, 2000). For post-BMP scenario, brush was removed and pasture or range grass was grown to develop a good cover on the ground (TWRI, 2000) to reduce erosion (Table 5).
- *Range seeding:* Before 319 project implementation, some of the farms in the rangeland did not have adequate grass establishment and caused erosion. To reflect this condition, these farms were simulated with poor grass cover and management in the pre-BMP scenario. In the post-BMP scenario, grasses were simulated on these farms to maintain a good grass cover and thereby reducing the erosion.
- *Critically eroding area*: Critically eroding area is that usually cannot be stabilized by ordinary conservation treatment, poorly managed without any vegetative cover and causes severe erosion or sediment damage. For representing this condition, poor growth of grass was simulated on these farms with little grass cover and the USLE's crop cover (C) factor was set above the reported level for grass in the literature (Neitsch et al., 2002) (Table 5). During BMP implementation, these eroding lands are shaped and a good grass cover is maintained. In the post-BMP scenario, these areas were simulated with a good grass cover to reduce sediment erosion and the USLE's C factor was set at the reported level for grass (Table 5).
- *Grade stabilization structure:* Before BMP implementation, these areas had steep slope in the natural watercourse, causing bank sloughing and gully erosion. Hence, in the pre-BMP scenario, these areas were simulated with poor grass cover, steep land slope and increased cover (C) factor in the Modified Universal Soil Loss Equation to account for bank sloughing and gully erosion (Table 5). During BMP implementation, small earthen structures are built to stabilize channel grade and reduce gully erosion. Usually the impacted area of the structure is of 1.0–1.6 ha (3–4 acres) in size. Since simulating the structures within SWAT is complex, an alternate approach was used to simulate the erosion control process. In the post-BMP scenario, these areas were simulated with a good grass cover. Land slope value as estimated from the topography map and the USLE's C factor reported for grass were used (Table 5).
- *Contour farming:* Crops grown in the sloping lands cause sheet and rill erosion and transport of sediment and other nutrients. For the pre-BMP scenario, winter wheat was simulated with a higher support practice factor (P) of the USLE on these farms to simulate the erosion occurring on slopping areas (Table 5). For post-BMP scenario, winter wheat was

grown on these farms and the support practice factor (P) was set 0.2 to protect the soil erosion.

2.6. Reductions by individual BMPs

The percentage reductions of sediment and nutrients estimated from the model for some of the BMPs (e.g., nutrient management practices) were compared with available literature values as an additional validation for the model (NCAES, 1982; Osei et al., 2000) (Table 6). Experienced engineer's suggestions (S.T. Bednarz, USDA-NRCS, Temple, Texas, personal communication, 2003) were used to judge the reductions of some of the BMPs such as critical area planting and grade stabilization structures, when adequate literature information on reductions of sediment and nutrients were not available. According to the expert's assessment, reductions shown for these BMPs were judged reasonable. It should be noted that the range of reduction shown in the literature or in the current study varies widely due to variations in climate, land use, soil and other field/management conditions across BMP farms in each watershed and also across watersheds.

2.7. BMP analyses

The results are presented as percentage reductions in average annual sediment, total nitrogen (organic and mineral nitrogen) and total phosphorus (organic and mineral phosphorus) loadings at the farm level and at the watershed level. Loadings generated in the pre-BMP conditions were used as the base to estimate the percentage load reductions. Farm level reductions were estimated considering only the BMP implemented areas within each subbasin. Watershed level reductions were estimated at two stream locations along the West Fork River (Fig. 1). The two locations were (i) below Jacksboro (the outlet subbasin 52) where the drainage area of segment 0812 ends, and (ii) below Boyd (the outlet of subbasin 80), where drainage area of segment 0810 ends (also the outlet of the entire watershed) (Fig. 1). These locations also represent various upstream combinations of implemented BMPs (Santhi and Srinivasan, 2004).

Table 6
Predicted percentage reductions in sediment and nutrients for selected BMPs at the farm level

BMPs	Sediment model	Total N model	Total P model
Nutrient management plan	85–97	77–93[a]	53–78[b]
Forage harvest management	21–76	4–23	1–11
Crop residue management	29–41	14–36	12–25
Contour terrace	84–86	56–59	60–65
Brush management	40–64	1–37	8–42
Range seeding	97–98	89–92	77–88
Critical area planting	98–99	90–96	82–95
Grade stabilization structure	98–99	95–98	93–97

[a] Literature values: 35–94% (NCAES, 1982).
[b] Literature values: 14–91% (Osei et al., 2000).

2.8. Additional scenario

The modeling approach is useful in addressing several "what if" situations that might be helpful for the conservation managers in planning and implementation of the BMPs. In the existing conditions, the 319(h) project BMPs are implemented in less than 1% of the watershed area. An additional scenario was simulated assuming hypothetically that the current 319(h) project BMPs are extended over 10% of the watershed area in order to show the possible effects of implementing BMPs on a greater percentage of landscape and the expected load reductions. The simulation procedures remained the same as explained earlier.

3. Results and discussion

3.1. Reductions at the farm level for the existing BMP effort

Average annual sediment and nutrient reductions estimated at the farm level (Fig. 5) included areas where BMPs were implemented. Total loadings from all the BMP farms in each subbasin for the pre-BMP scenario (Table 7) were used as a baseline to estimate the reductions.

The predicted average annual reductions in sediment loading varied from 5% to 99% at the farm level across the subbasins (Fig. 5). A higher percentage of sediment reduction was predicted in some subbasins 44, 50, 68, 75 and 76 due to erosion control measures such as grade stabilization structures, critical area planting or their combination with residue management, pasture planting or range seeding. Critical area planting and other measures contributed for reductions in subbasins 65, 79 and 80.

The predicted average annual farm level nitrogen loading reductions varied from 5% to 90% (Fig. 5). Higher percentage of reductions in nitrogen loading observed for BMP farms in some of the subbasins were from nutrient management practices, residue management and pasture planting. Apart from the BMP farms with nutrient management practices, erosion control measures contributed for nitrogen reductions in organic forms due to higher sediment reductions in subbasins 50, 68 and 79.

Phosphorus is an important source of pollution in manure application areas because phosphorus applied

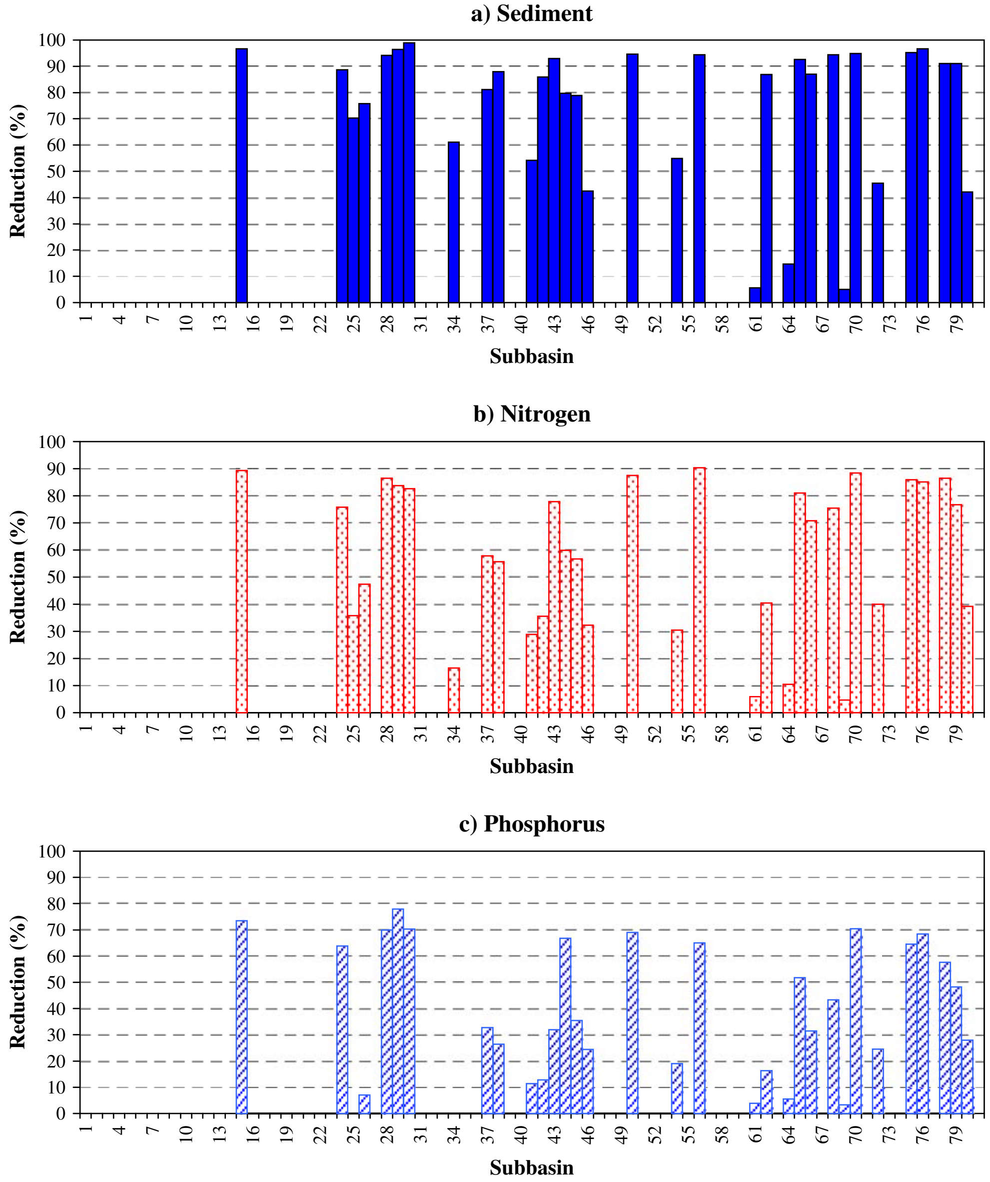

Fig. 5. Farm level percentage reductions in sediment and nutrient loadings in subbasins where BMPs were implemented.

through manure is often in excess of crop requirements (Edwards et al., 1996; Santhi et al., 2001a). Farm level reductions in phosphorus loading varied from 3% to 78% across the subbasins (Fig. 5). The reductions varied as a function of the manure or fertilizer application rates. In addition, history of manure applications in farms (how long the farm received manure) influenced soil phosphorus build-up and subsequently phosphorus loading in runoff.

Considering the total loading of sediment, nitrogen and phosphorus from all the BMP farms in both the segments, the estimated reductions of 56% in sediment, 45% in nitrogen and 32% in phosphorus indicate significant benefits of the 319(h) project at the farm level (Fig. 6).

3.2. Reductions along the West Fork River for the existing BMP effort

Although, some erosion control measures implemented showed significant reductions in sediment at the farm level, the implementation areas of these measures were very minor compared to the area of the watershed. Because of this fact, the average annual reductions in sediment loading were less than 1% along the West Fork River below Jacksboro and below Boyd (Fig. 7). The average annual reductions in nitrogen and phosphorus were less than 2% at these locations along the West Fork River. Nitrogen and phosphorus fertilizers are applied mainly on cropland (winter wheat for grazing) and in some pastureland for crop growth in this watershed. Even

Table 7
Mean annual sediment, nitrogen and phosphorus loadings predicted for the pre-BMP scenario at the farm level in subbasins where BMPs were implemented

Subbasins	Sediment (Mg)	Total N (kg)	Total P (kg)
15	52	121	16
24	41	76	9
25	13	32	9
26	32	73	9
28	68	187	31
29	230	418	71
30	155	117	24
34	7	15	2
37	27	76	13
38	36	77	9
41	32	86	15
42	254	1129	436
43	10	29	4
44	482	819	458
45	107	168	19
46	576	860	102
50	605	1712	303
54	337	532	69
56	29	55	10
61	1138	2718	572
62	226	890	310
64	868	2125	397
65	259	808	149
66	44	94	14
68	512	1816	440
69	678	1141	202
70	42	98	17
72	107	361	85
75	483	594	115
76	364	349	64
78	24	67	12
79	526	951	186
80	1816	5398	1170

if the BMPs are assumed to be 100% efficient, and given the area of BMP implementation (<1% of the watershed area), these reductions and benefits of the project are reasonable at the watershed level.

The number of BMP farms (Fig. 1) and the BMP implementation area in segment 0810 were more than segment 0812. Hence, the reductions below Boyd (apart from the upstream area contributions) were more compared to the reductions shown below Jacksboro.

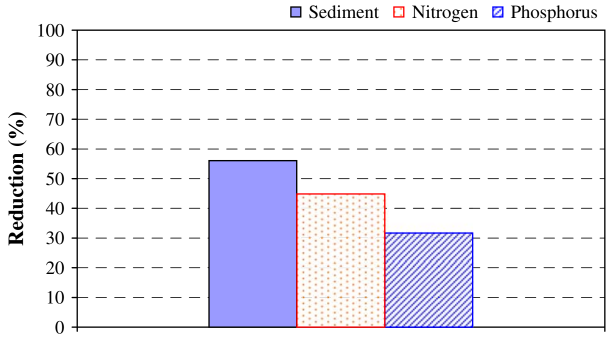

Fig. 6. Farm level percentage reductions in sediment and nutrient loadings for all BMPs.

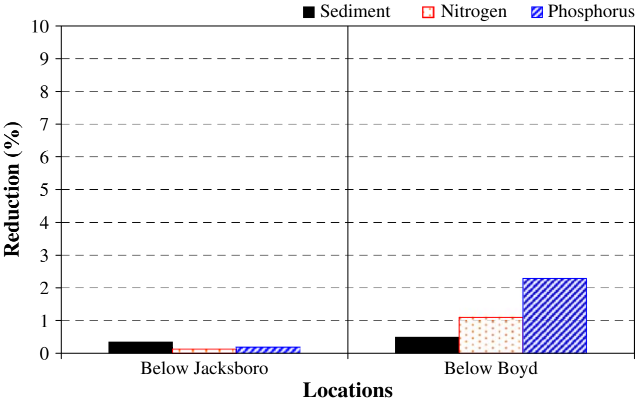

Fig. 7. Percentage reductions in sediment and nutrient loadings at two locations along the West Fork River due to the existing BMPs.

3.3. Reductions along the West Fork River for the additional scenario

The additional scenario has demonstrated that the effects of implementing BMPs on a greater percentage of landscape can bring increased load reductions. For brevity, the watershed level load reductions are discussed for the additional scenario, as watershed level benefits are important. The average annual reductions in sediment were 10% below Jacksboro and 12% below Boyd for the additional scenario (Fig. 8). Erosion control measures such as grade stabilization structures, critical area planting or their combination with other practices contributed for the increased sediment reductions. Below Jacksboro, reductions in nitrogen loading increased to 3%. The reduction in nitrogen loading was about 18% below Boyd (Fig. 8). Nitrogen load reductions were due to expanding the BMP practices such as nutrient management practices, residue management, and erosion control measures contributing reductions in organic form of nitrogen. For phosphorus, reductions were estimated to be higher (29%) below Boyd as compared to below Jacksboro (5%) (Fig. 8). Major sources of phosphorus reductions below Boyd were due to manure application practices in segment 810. Manure application rate and expansion in the manure application area have contributed for the increased reductions in phosphorus loadings for the additional scenario. In general, the load reductions were higher below Boyd because of the more numbers of BMPs installed and the increased BMP implementation area in segment 0810.

4. Conclusions

Through 319(h) project, TSSWCB provides funds to landowners to install BMPs in farms that had water

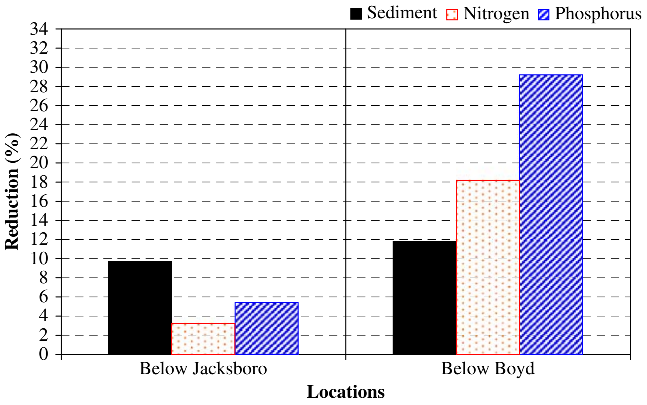

Fig. 8. Percentage reductions in sediment and nutrient loadings at two locations along the West Fork River for the additional scenario.

quality problems due to nonpoint sources mainly from agriculture. This study is focussed mainly on assessing the benefits of these 319(h) project BMPs. It is different from the typical TMDL project although this project complements such an effort. The TMDL project goes through a set of procedures and processes. TCEQ is in the process of collecting data to establish water quality goals, define target limits, estimate loads from sources and develop load allocation procedures and implementation plan for TMDL in this watershed. Those were beyond the focus of this study.

Federal and state regulatory agencies are making a substantial investment in implementing several conservation practices across the United States. Information on quantitative benefits of water quality management programs is necessary for future planning and resource allocation. As indicated by Park et al. (1994), extensive monitoring data and intensive observation of BMPs are essential for assessing the effects of BMPs in a watershed. Long-term monitoring data are not available for most watersheds due to the level of expense involved in collecting such data. Also, there is no adequate documentation or literature available showing the quantitative benefits of conservation practices/BMPs at the watershed level. Given these facts, a modeling approach is very helpful. It is desirable to have adequate measured data for model validation so as to reduce the uncertainty. However, most of the watersheds do not have continuous records of monitoring data due to the costs involved. Monitoring data at least for a few years are essential for validating the model and establishing the baseline conditions in representative watersheds. This paper describes a modeling approach used for estimating the benefits of the BMPs at different levels (and locations) in a watershed. This approach and scope can be improved as more resources and needs arise.

The modeling approach was applied to estimate the long-term effects of implementing the water quality management plans in the West Fork Watershed in Texas. These BMPs are implemented on less than 1% of the watershed area. The BMPs showed greater reductions in nonpoint source pollution (up to 99%, 90% and 78% in sediment, nitrogen and phosphorus, respectively) at the farm level. With the existing area of implementation, reductions in sediment were about 1% and in nitrogen and phosphorus about 2% at two locations along the West Fork River (Fig. 7). Given the area of BMP implementation (<1% of the watershed area), these reductions and benefits of the project are reasonable at the watershed level. An additional scenario was simulated to demonstrate the effects of installing the BMPs over a greater percentage of land (assuming the current BMPs are extended over 10% of the watershed area) and thereby increased load reductions that could be obtained in the watershed.

The need for implementing soil and water conservation practices is increasing extensively to manage the water quality and quantity concerns. The current modeling approach will be very useful for decision-makers to assess the benefits of BMPs individually and at the watershed level. It will be helpful for them to identify suitable BMPs for implementing BMPs newly in a watershed or to quantify the benefits of the BMPs in a watershed where they have been already implemented. The BMPs implemented in the case study have been discussed here. However, other practices can also be modeled according to the requirement of BMPs in other watersheds. The modeling approach can be extended to a regional or national level with appropriate configuration. It can also be extended to other water quality projects and basin-wide management efforts such as European Union water framework directive.

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