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Bosque River Environmental Infrastructure Improvement Plan: Phase II BMP Modeling Report

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EXECUTIVE SUMMARY

The Bosque River Watershed is located in the Brazos River Basin in central Texas and is facing a suite of water quality issues resulting in sediment, nutrient and bacteria loading. These loadings are potentially derived from improperly managed cropland and grazing land, land-applied dairy waste, and effluent discharge from eight wastewater treatment plants. The first phase of the project developed an effective methodology for determining priority areas in the watershed where best management practice (BMP) implementation would likely yield the greatest improvements in water quality. The objectives of this project (Phase II) are to apply the Soil and Watershed Assessment Tool (SWAT) model to simulate and evaluate the impacts of implementing several best management practices (a) in the entire watershed, and (b) at incremental levels in high, medium, and low priority areas of the watershed, identified using three different impact indices.

Initially, the SWAT model was calibrated for long-term annual and monthly flow at a USGS gaging station located in the lower portion of the watershed for the period from 1980 through 2005 and was validated at the same location for the period 1960 through 1979. The model was also calibrated, at a monthly time step, for water quality parameters including sediment, organic and mineral nitrogen, and phosphorus at two locations, Hico and Valley Mills. Model performance statistics (coefficient of determination and Nash-Sutcliffe modeling efficiency) indicated that model performance was satisfactory and could be used for evaluating the impacts of alternative management scenarios to reduce nonpoint source pollution.

BMPs including streambank stabilization, gully plugs, recharge structures, conservation tillage, terraces, contour farming, grazing management, manure incorporation, edge-of-field filter strips, and PL-566 reservoirs were simulated as being implemented in the watershed areas that met the respective practice's specific criteria for implementation. These BMPs were simulated individually and the resulting farm level (HRU level), subwatershed level, and watershed outlet level impacts were quantified for each BMP. Reductions in sediment load at the watershed outlet, as a result of implementing these BMPs individually, was as much as 37 percent while reductions in total nitrogen (TN) ranged from 1 percent to 24 percent and total phosphorus (TP) varied from a 3 percent increase to a 30 percent decrease. The 3 percent increase is indicative of conservation tillage and is likely caused by the lack of soil inversion and mixing, which yields an accumulation of dissolved (mineral) phosphorus in the soil's surface layer. At subwatershed levels, reductions brought about by implementing the BMPs were relatively greater as compared to the watershed outlet reductions. Reductions in sediment were as high as 47 percent and reductions in TN and TP were 37 percent and 32 percent, respectively.

Subwatersheds were categorized into "high," "medium," and "low" priority based on calibrated simulation results. Considering sediment, TN, and TP (as pollutants), three types of total impact indices were estimated. The "Concentration Impact Index" is based on pollutant concentrations (SWAT output values extracted from the 'reach output file'), considers contributions from the subwatershed as well as the entire upstream watershed, and is effective in determining priority areas for addressing localized pollution problems in low and high flow conditions. The "Load Per Unit Area Impact Index" is based on the total pollutant load coming from a specific area (SWAT output values extracted from the 'subbasin output file'), considers contributions from an

individual subwatershed, and is used to effectively assign a priority to each subwatershed. The "Load Impact Index" is based on pollutant loads from subwatersheds and upstream areas (SWAT output values extracted from the 'reach output file') and portrays the cumulative effects of pollutant loading throughout the entire watershed.

Priority areas in the watershed varied based on which impact index was used in the evaluation; therefore, the areas where BMP implementations were evaluated differed between simulations. Despite varying BMP implementation sites, all BMPs were modeled incrementally, first on high priority subwatersheds followed by medium and low priority subwatersheds. BMPs considered for implementing in prioritized subwatersheds included streambank stabilization, recharge structures, conservation tillage, terracing, grazing management, and manure incorporation. When comparing the reductions achieved from implementation of BMPs using the three impact indices, load per unit area criteria typically yielded higher pollutant reductions. This outcome is likely a result of the majority of BMPs simulated in this study addressing upland pollutant reductions rather than in-stream reductions. Therefore, these BMPs resulted in larger pollutant reductions because they targeted local upland areas that typically generate higher pollutant loads. Implementing these BMPs in the entire watersheds resulted in sediment, TN, and TP load reductions of 73 percent, 43 percent, and 68 percent, respectively.

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LIST OF ABBREVIATIONS

AI1	Fraction of algal biomass that is nitrogen
ARS	Agricultural 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^{o}C (day^{-1})
BC4	Rate constant for mineralization of organic P to dissolved P in the reach at 20^{o}C (day^{-1})
BMP	Best Management Practice
CDN	Denitrification exponential rate coefficient
C-factor	Land surface cover factor
CFRG	Coarse Fragment 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
CII	Concentration Impact Index
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 10mm of soil
GIS	Geographical Information system
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
LII	Load Impact Index
LUAII	Load per Unit Area Impact Index
MinN	Mineral Nitrogen
MinP	Mineral Phosphorus
MUMAX	Maximum specific algal growth rate (day^{-1})
N	Nitrogen
NCDC	National Climatic Data Center
NID	National Inventory of Dams
NPERCO	Nitrate percolation coefficient

NRCS	Natural Resources Conservation Service
NSe	Nash-Sutcliffe Efficiency
NWS	National Weather Service
OrgN	Organic Nitrogen
OrgP	Organic Phosphorus
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 $20^{o}C$ (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
SLSUBBSN	Slope Length
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
TCEQ	Texas Commission on Environmental Quality
TIAER	Texas Institute for Applied Environmental Research
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
TSSWCB	Texas State Soil and Water Conservation Board
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
WAF	Waste Application Field
WWTP	Wastewater Treatment Plant

INTRODUCTION

The Bosque River Watershed (including the North Bosque – HUC 12060204 and the South and Middle Bosque – HUC 12060203) encompasses an area of 4,282 km^2 or 428,198 ha in the Brazos River Basin. The watershed covers parts of Erath, Bosque, McLennan, Coryell, Hamilton, and Somervell counties (Figure 1) and originates in Erath County. The North, Middle and South Bosque Rivers eventually drain into Lake Waco, which serves as the primary drinking water supply for more than 200,000 people in the greater Waco area and provides water for agricultural production, recreational fishing, and swimming. The major cities/towns in the watershed include Stephenville, Dublin, Hico, Meridian, Clifton, Valley Mills, and McGregor.

In 2000, the North Bosque River (Segment 1226) was listed as an impaired water body in the *Texas Water Quality Inventory* for concerns of elevated levels of bacteria, chlorophyll a, and nutrients entering the segment from tributary watersheds. Segment 1255 (Upper North Bosque) was also placed on the 303(d) list for elevated levels of sediment, nitrogen (N), phosphorus (P), chloride, sulfate, and chlorophyll a. These impairments have mainly been associated with the dairy industry in the northern part of the watershed that, by 1998, had expanded to include about 100 dairies with more than 40,000 dairy cows, but other sources throughout the watershed may also contribute to the overall problems in the watershed.

Parts of Bosque River Watershed have been well instrumented and monitored since 1991 by the Texas Institute for Applied Environmental Research (TIAER). Data collected during this and other monitoring was analyzed and, as a result, two Total Maximum Daily Load (TMDL) plans were developed for segments 1255 (Upper North Bosque) and 1226 (North Bosque River) with a goal of reducing the soluble reactive P concentration and load at 5 sites by an average of 50 percent as compared to the conditions in year 2000 (Srinivasan, 2006; TCEQ, 2002).

Ultimately, this project aims to provide critical information to landowners, local officials, and agency personnel who will use this information to guide future implementation efforts targeted to reduce concentrations and loadings of nutrients and sediment to the Bosque River system. A third and final phase of the project is anticipated and will constitute an economic analysis that quantifies the costs of implementing a practice on a per unit basis and compares it to the expected load or concentration reduction per unit. Combined, the three phases of the project will layout an effective plan for reducing pollutant loading to the Bosque in the most cost-effective manner.

CURRENT STUDY

This study is a continuation of Phase I of the Bosque River Environmental Infrastructure Improvement Plan (Srinivasan, 2006) and also continues previous work conducted by Santhi, et al. (2001a, 2001b, 2001c). Phase I of the project focused on developing and employing a strategic approach to identify priority areas in the watershed where detailed field investigations should be focused to determine optimum BMPs implementation sites. Results of the earlier modeling studies by Santhi et al. (2001a), Santhi et al. (2001b), and Santhi et al. (2001c) were used as a starting point for developing the methodology to prioritize BMP implementation. A scientific advisory committee formed during the Phase I of this project provided recommendations on feasible BMPs that should be evaluated as potential practices to implement and improve the environmental infrastructure in the Bosque River Watershed. The BMPs recommended by the scientific advisory committee include:

On-Farm BMPs

- Applying chemical agent to high P fields to reduce P solubility
- Implementing subwatershed soil conservation and erosion control plans
- Improving PL566 structures to increase sediment retention
- Installing crops that can be removed from the watershed (hay, biofuel, turfgrass sod)
- Installing grazing management practices
- Contour ripping/pasture renovation to maintain permeability of soils and increase residence time of water on soils
- Terracing to reduce sediment transport
- Developing nutrient management plans
- Educating landowners
- Applying a waste injection program to directly inject fertilizer/manure/etc. into soils

Between Field and Creek BMPs

- Developing recharge structures to reduce runoff and sediment yield
- Installing vegetation buffers – polishing strips

In Stream or Gully BMPs

- Installing permeable reactive barriers/check dams along downstream gully systems to reduce sediment and dissolve P in runoff
- Implementing a watershed riparian restoration program – streambank stabilization
- Installing permeable check dams in upper reaches of the watershed with ponds at the lower extent to reduce concentrated flow
- Developing constructed wetlands

Universal BMPs

- Damming ephemeral gullies or installing porous “gully plugs”
- Implementing range re-vegetation practices – management for species beneficial to water detention on land

City BMPs

- Developing construction site runoff management for pre/post construction activities
- Treating storm runoff and water quality by temporary storm storage in retention ponds and/or associated wetland
- Developing plans for recreation areas, including storm water planning for surrounding residential areas

The overall goal of the Phase II study was to use the SWAT model to quantify the effectiveness of implementing individual BMPs or suites of BMPs to remove pollutants from surface runoff and improve water quality. The specific objectives were to:

- calibrate the SWAT model for flow, sediment, and nutrients using measured data at two monitoring locations in the Bosque River Watershed;
- employ the impact indices developed in Phase I of the project to prioritize subwatersheds in the basin, as high, medium, and low priority, based on load, load per unit area, and concentrations of constituents (sediment, total nitrogen [TN], and total phosphorus [TP]);
- use the calibrated SWAT model to evaluate the impacts on flow and water quality realized by implementing BMPs:
  - in the entire watershed
  - in incremental levels across high, medium, and low priority areas of the watershed.

LITERATURE REVIEW

In the past, field studies have been the primary means of evaluating the effects of BMPs. These studies utilize two main methods to assess the effectiveness of BMPs: (1) assessing the trends in measured data with respect to time (Edwards et al. 1997; Walker and Graczyk 1993; Meals 1987); and/or (2) direct comparison of field measured data from paired fields/watersheds (Sharpley and Smith 1994; Sharpley et al. 1996; Edwards et al. 1997; Chow et al. 1999; Bishop et al. 2005). While these methods are highly effective, costs and timeliness are limiting factors that decrease their utility. Recently, advancements in computing technology and hydrologic/watershed simulation modeling have enabled the evaluation of BMPs in multiple locations without actual implementation. Several studies using this methodology have been conducted to identify the sources that contribute pollution to the watershed and to evaluate the potential impacts of implementing BMPs in the watershed to address these concerns. Information on previous modeling and water quality monitoring studies in the Bosque River Watershed can be found in Srinivasan (2006); McFarland and Hauck, 1999; Rosenthal and Hoffman, 1999; McFarland et al., 2000; Santhi, et al., 2001a; Santhi, et al., 2001b; Santhi, et al., 2001c; Di Luzio et al., 2004a; Easterling and McFarland, 2004; Hanzlik, et al., 2004; McFarland, 2006; Stewart, et al., 2006).

Walker and Graczyk (1993) analyzed water quality data from two watersheds (size of 14 km^2 and 27.2 km^2) in southern Wisconsin and collected data in the pre-BMP and transitional period of BMP implementation. This study found that the BMPs including conservation tillage, contour strip-cropping, streambank protection, and barnyard-runoff control, significantly reduced the mass transport of ammonia (NH_3-N) by 30 percent and suspended solids by 45 percent in one watershed while the other watershed showed no detectable change. Variations in the results were attributed to insufficient data collection in the latter watershed. In a similar study, Park et al. (1994) used measured flow and water quality data to evaluate the impacts of BMPs on runoff, sediment, and nutrient yields over the 1,464 ha Nomini Creek Watershed in Virginia. They found 20 percent, 42 percent, and 35 percent reductions in sediment concentration, Total Kjeldahl Nitrogen (TKN), and TP concentrations, respectively, as a result of implementing no-till planting, critical area planting, grazing land protection, diversions, and sediment retention structures BMPs. Sharpley and Smith (1994) studied seven dryland field-sized watersheds (size ranging from 1.6 ha to 4.8 ha) in the southern plain regions of Kansas, Oklahoma, and Texas and found that implementing no-till practices resulted in 95 percent, 75 percent, 80 percent, and 20 percent reductions in sediment, TN, and particulate-P, and bioavailable-P losses, respectively, as compared to conventional tillage practices. They concluded that the 183 percent increase in dissolved P under no-till practices was attributed to possible leaching of P from crop residue material and preferential transport of clay-sized particles.

These studies were plot- or field-scale experiments with good instrumentation and monitoring data associated with the landuse/management changes. As a result, these studies were able to evaluate the effectiveness of implementing BMPs either by direct comparison of the field data or statistical analysis of the field-monitored data. Though highly effective, this type of study is time consuming and expensive. More recent BMP evaluations have utilized computer modeling to evaluate the efficacy of implementing individual or multiple BMPs in various locations of a watershed without actually implementing the practices, and, as a result, at a much lower cost.

King et al. (1996) applied the Environmental Policy Integrated Climate (EPIC) model to simulate sediment and nitrate losses on clay soils over six small watersheds (size ranging from 4.0 ha to 8.4 ha) in Riesel, Texas. They found an 89 percent reduction in sediment losses and 52 percent reduction in soluble nitrate losses when tillage practices where converted from conventional to no-till. Phillips et al. (1993) evaluated the impacts of continuous corn and corn-soybean rotation under conventional till and no-till practices on sediment and nutrient exports in Illinois using the field-scale EPIC model. They found 80 percent less sediment loss on land under no-till cropping than in conventional tillage. While there were considerably larger organic N and P losses under conventional till, nitrate N and P losses in surface runoff were higher in no-till compared to conventional tillage.

Studies quantifying the cumulative effects of agricultural management practices on water quality using a modeling approach at the watershed scale are limited in number. Vache et al. (2002) used the SWAT model to quantify the impacts of conservation tillage, strip intercropping, rotational grazing, riparian buffers, engineered wetlands, and filter strips over the 51.3 km^2 Walnut Creek and 88.2 km^2 Buck Creek watersheds in central Iowa. Generally, these BMPs resulted in 15 percent to 60 percent decreases in median Total Suspended Solids (TSS) loading and 57 percent to 70 percent decreases in median nitrate loading. Bracmort et al. (2006) evaluated the long-term water quality impacts of structural BMPs (grassed waterways, grade stabilization structures, field borders, and parallel terraces) in two subwatersheds (6.23 km^2 and 7.3 km^2) of the Black Creek Watershed in northeastern Indiana using the SWAT model. Their study concluded that the listed structural BMPs reduced the average annual sediment yield by 16 percent to 32 percent and average annual P yield by 10 percent to 24 percent. Secchi et al. (2007) also used SWAT to analyze land set-asides, terraces, grassed waterways, contouring, conservation tillage, and nutrient reduction strategies in 13 Iowa watersheds (ranging in size from 2,051 km^2 to 37,496 km^2). When compared to baseline conditions, implementing these practices resulted in 6 percent to 65 percent reductions in predicted sediment losses, 28 percent to 59 percent reductions in TP losses, and 6 percent to 20 percent reductions in nitrate losses at the watershed outlet.

In 2005, Gitau et al. summarized published information on BMP effectiveness for controlling P pollution; this work found that conservation tillage reduced TP losses by a maximum of 95 percent, whereas filter strips resulted in a maximum reduction of 93 percent. Gitau et al. (2005) also found an increase in dissolved P from conservation tillage system, which was attributed to build-up of soluble pollutants at the surface due to the lack of soil inversion and mixing. Yuan et al. (2002) used AnnAGNPS 2.1 version to model the effectiveness of installing cover crops, filter strips, grade control pipes, and impoundments in combination with conventional tillage, reduced, and no-till tillage in a 12 ha subwatershed in the Mississippi Delta. This study found that without any additional BMPs, the no-till system was able to reduce the sediment yield by 50 percent as compared to the conventional tillage system. Combining conventional tillage and a constructed wetland was able to reduce the sediment yield by more than 50 percent. Grade stabilization pipes reduced sediment yield by 28 percent to 48 percent for all tillage systems while filter strips reduced sediment yield by 18 percent to 26 percent. Sediment yield reduction for cover crops ranged from 32 percent to 41 percent.

A study by Dalzell et al. (2004) in the 650 km^2 Sand Creek Watershed in south central Minnesota found that 40 percent, 50 percent, 75 percent, and 100 percent conversions of cropland from conventional tillage to conservation tillage resulted in reduced sediment losses of 20 percent, 26 percent, 33 percent, and 40 percent, respectively. This same scenario also yielded respective P reductions of 2 percent, 6 percent, 7 percent, and 10 percent. Santhi et al. (2006) used SWAT modeling to evaluate the impacts of nutrient management, waste utilization, forage harvest management, brush management, pasture planting, range seeding, critical area planting, and grade stabilization structures on sediment and nutrient loadings in a 4,554 km^2 watershed in the West Fork of the Trinity River in north central Texas. The model predicted that critical area planting and grade stabilization structures resulted in the highest percentage reduction in sediment and nutrients of all the BMPs modeled at farm level. Predictions of the average annual reductions at the farm level across the subbasins for all BMPs modeled in the study ranged from 5 percent to 99 percent for sediment, 5 percent to 90 percent for N, and 3 percent to 78 percent for P (Santhi et al., 2006). A comprehensive water quality assessment study by Chen et al. (2000) using the EPIC model to determine the impacts of agriculture on surface and ground water quality in Trinity River Basin found respective sediment reductions of 84 percent and 72 percent due to implementing a no-tillage system and reduced tillage system as compared to conventional tillage system. Gassman et al. (2006) evaluated the effectiveness of installing selected agricultural management practices including terraces, no till farming, contouring, in-field contour buffers, and grassed waterways in the 162 km^2 upper Maquoketa River Watershed in northeastern Iowa using the APEX and SWAT models. Results showed a minimum reduction of 60 percent in sediment and a reduction of more than 70 percent in organic N and P at the watershed level due to implementing terraces. In-field contour buffers resulted in 44 percent, 47 percent, and 48 percent reductions in sediment, organic N, and organic P, respectively; similar reductions were seen from grassed waterways. Manure incorporation resulted in increased sediment and nutrient losses. Nitrate increases occurred in several scenarios, including no-till, incorporation and injection, terraces, contouring, and in-field contour buffers. This increase was attributed to the fact that these practices resulted in increased infiltration or deeper placement of N in the soil profile, which caused increased leaching of N to subsurface layers. Inamdar et al. (2001) reported that no-tillage, filter strips, and nutrient management implemented in the 14.63 km^2 Nomini Creek Watershed reduced average annual loads and flow-weighted concentrations of N by 26 percent and 41 percent while total P reductions were 4 percent and 24 percent, respectively. Increases in nitrate-N, dissolved P (Ortho-P and dissolved organic-P) increased after BMP implementation were also observed in this study. Narasimhan et al. (2007) reported that streambank erosion can contribute as much as 30 percent of the total annual sediment load into Cedar Creek Watershed in north central Texas and that in-stream BMPs such as streambank stabilization can potentially reduce sediment load at the watershed outlet by 15 percent.

METHODOLOGY

SWAT Model

The SWAT model is a hydrologic/water quality model developed by the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) (Arnold, 1998; Neitsch et al., 2002; http://www.brc.tamus.edu/swat/). SWAT is also one of the models within the U.S. Environmental Protection Agency's Better Assessment Science for Integrated Point and Nonpoint Sources (USEPA's BASINS) program that USEPA supports and recommends for state and federal agency use to address point and nonpoint source pollution problems. SWAT is a physically based, distributed, continuous scale model that operates on a daily time-step. The model has the capability to simulate a variety of land management practices and has been used to assess water resources and pollution problems across a wide range of spatial scales at locations around the world. SWAT is distributed in the sense that it divides the watershed/river basin into a number of subwatersheds based on topography and a user-defined threshold drainage area (minimum area required to begin a stream). Each subwatershed is then further divided into Hydrologic Response Units (HRUs), which are a unique combination of soil, landuse, and land management. HRUs are the smallest landscape component of SWAT and are used for computing the hydrologic processes in the watershed. Major components in the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural management. A complete review of SWAT including historic developments and applications can be found in Gassman et al. (2007) and a detailed description of the components and mathematical equations representing the processes can be found in Neitsch et al. (2005).

Flow, sediment, and nutrient routing within the model are largely determined by modeled runoff. SWAT has the option of using a modification of U.S. Department of Agriculture – Soil Conservation Service (USDA-SCS) Curve Number method (1972) or the Green and Ampt (1911) infiltration method to estimate surface runoff. In the curve number method, surface runoff is estimated as a function of daily curve number adjusted for the moisture content of the soil on that day. SWAT uses the modified Universal Soil Loss Equation (USLE) (Williams, 1975) and modified Bangold's equation (Bagnold, 1977) to estimate erosion and deposition. The QUAL2E model (Brown and Barnwell, 1987) has been incorporated into SWAT to process in-stream nutrient dynamics.

N is modeled by SWAT in the soil profile and in shallow aquifers. Organic nitrogen (OrgN) associated with humus, mineral forms of N held by soil colloids and in dissolved N are the three major forms of N simulated. External sources of N include rain, fertilizer or manure application or residue, and bacterial fixation; all of these can be manually adjusted within the model to better represent the area being modeled. N is removed from the soil by plant uptake, leaching, volatilization, denitrification, and erosion. Amounts of nitrate transported with runoff, lateral flow, and percolation are estimated as mass of nitrate lost from the soil layer by multiplying volume of water and concentration of nitrate N in the soil layer. The amount of OrgN transported off-site with sediment lost is a function of its concentration in the top 10 mm of the soil, sediment yield on a given day (metric tons), and the N enrichment ratio, which is the ratio of the concentration of OrgN transported with the sediment to the concentration in the soil surface layer.

Similar to N, the three major forms of P that the model tracks include organic phosphorus (OrgP) associated with humus, insoluble forms of mineral phosphorus (MinP), and plant-available P in soil solution. P may be added to the soil by fertilizer, manure, or residue application and removed from the soil by plant uptake and erosion. Soluble P transported in surface runoff is estimated based on the amount of P in solution in the top 10 mm of the soil, surface runoff on a given day, soil bulk density in the top 10 mm, and the P soil partitioning coefficient (ratio of the soluble P concentration in the surface 10 mm of soil to the concentration of soluble P in surface runoff). Sediment bound P transport is similar to OrgN transport described earlier.

SWAT has been extensively applied for a variety of issues ranging from hydrology, climate change, pollutant load assessment, and best management practice verification at various spatial and temporal scales. There have been several applications of SWAT to evaluate the impacts of best management practices (BMPs) on water quality (Santhi et al., 2001a, 2001b, 2001c; Arabi et al., 2006; Bracmort et al., 2006; Santhi et al., 2006, Secchi et al., 2006; Vache et al., 2002). This study used the latest version of SWAT model, SWAT2005 and the ArcView Geographic Information System interface of SWAT2005 (AVSWAT-X), an upgrade of AVSWAT (Di Luzio et al., 2004a) with added SEA extension (Di Luzio et al., 2004b) to process and manage SSURGO (soil survey geographic) soil dataset to derive inputs required by the SWAT model.

Watershed Description and Model Inputs

The Bosque River Watershed encompasses an area of 4,282 km^2 that covers parts of Erath, Bosque, McLennan, Coryell, Hamilton, and Somervell counties (Figure 1). The Bosque River drains into Lake Waco and the watershed is comprised mostly of rangeland, pastureland, and cropland landuse types (Figure 2). According to the State Soil Geographic (SSURGO) soil database, there are 246 different soil types in the watershed (Figure 3). A digital elevation model (DEM) of 30m resolution, 1:24,000 scale USGS landuse map, and SSURGO soil dataset were used to derive topographic parameters and hydrologic response units (HRUs). Table 1 lists the sources of different datasets used in model setup. Using SWAT, the Bosque River Watershed was divided into 48 subwatersheds (Figure 4), which were further divided into 2,680 HRUs. There are currently eight WWTPs in the watershed located at Stephenville, Hico, Iredell, Meridian, Clifton, Valley Mills, Crawford, and McGregor (Figure 4); these were incorporated into the model as point sources. Daily effluent discharge volume, total suspended sediment, and OrgN, mineral phosphorus (MinN), OrgP and MinP were also input as point sources.

A total of 88 reservoirs, or PL-566 structures, in the watershed (Figure 5) were input as ponds. Reservoir information including surface area and storage at principal and emergency spillway for each PL-566 was cumulatively incorporated into the model because there was more than one reservoir in a subwatershed and SWAT model allows inputting only one pond per subwatershed. Careful attention was given when calculating the combined drainage areas for the reservoirs within a subwatershed so that the drainage areas are not accounted for more than once in the case of nested reservoirs. Lake Waco was represented in the model as the watershed outlet and not a reservoir because BMP implementation impacts the loadings entering the lake; therefore, the model predicts the load entering Lake Waco as the “outlet load.”

Daily precipitation data was obtained from 11 weather stations and temperature (minimum and maximum) data was obtained from seven stations located in and around the watershed (Figure 6). The source of this weather data was the National Weather Service (NWS) National Climatic Data Center (NCDC). Other weather parameters including wind speed, solar radiation, and relative humidity were simulated by the SWAT model using its built-in weather data simulator.

A map of waste application fields (WAFs) was overlaid on the land use map to identify areas where dairy manure was applied to the landscape. Mineral fertilizer was applied to the non-waste application fields at a typical agronomic rate for the area. Pastureland was simulated as improved pasture with typical nutrient application rates and four hay cuttings per year. Corn, winter wheat, and grain sorghum were the major crops modeled in the watershed. Tillage operations, fertilizer application dates and rates were considered typical and extracted from the earlier study (Santhi et al., 2001a, 2001b). For the WAFs, total manure generated by all the dairies within a subwatershed was calculated and was land-applied on the WAFs within that subwatershed.

Model Calibration and Validation

Although the SWAT model is physically based, there are some model parameters/variables that are either not well defined physically or were developed based on field experiments conducted in geographical locations other than this project’s study. These parameters (i.e. curve number) can be adjusted within the practical range to fit the model predicted and measured values at specific locations.

Streamflow records at the USGS gaging station (08065200) at Valley Mills (Figure 7) were analyzed using the Baseflow Filter Program (Arnold and Allen, 1999; Arnold et al., 1995) to determine the appropriate Baseflow proportion and it was found to be 42 percent of recorded annual streamflow. During calibration, care was also given to match the proportions of surface flow and baseflow because components account for the bulk of streamflow and ensuring that these proportions are right is critical before fine-tuning other calibration parameters. SWAT was calibrated for long-term annual and monthly streamflow using the streamflow records from USGS gaging station at Valley Mills for the period from 1980 through 2005. The model was then validated for flow at the same location for the period from 1960 through 1979. Water quality calibration (sediment, MinN, OrgN, MinP, and OrgP) was conducted using data from two available monitoring stations at Hico and Valley Mills (Figure 7) using the monthly measured data obtained from TIAER for the period January 1993 through July 1998 at Hico and for the period January 1996 through July 1998 at Valley Mills. Model simulation began in 1990 to allow for a three year pre-run period in order to define the initial conditions for parameters such as soil moisture and aquifer depths within the model. The time period used for calibrating water quality was shorter than the time period used to calibrate flow due to limited available data. Table 2 lists the model variables, component(s) that the variable influences on model outputs, a brief description about the variable, acceptable range of values, and the actual value used for calibration.

Model Performance Evaluation

Mean, standard deviation, coefficient of determination (R^2), and Nash-Sutcliffe modeling efficiency (NS_e) were used to evaluate model predictions during calibration and validation. R^2 is the ratio of the explained variation to the total variation and it denotes the strength of the linear association between observed and predicted values. NS_e is a measure of relative model efficiency, developed as a sum of squares. Possible values of NS_e range from $-\infty$ to 1 and a value of 1 means that modeled results are a perfect match to recorded data. NS_e uses the mean of observed values and, therefore, may not be appropriate for non-normal data; however, it gives a measure of deviation of predicted values from the perfect fit (1:1) line.

BMP Representation

The scientific advisory committee formed during Phase I of this project provided suggestions on 22 BMPs that can be implemented to improve the environmental infrastructure in the Bosque River Watershed. The suggested BMPs included 'On-Farm BMPs', 'Between field and Creek BMPs', 'In-Stream or Gully BMPs', 'Universal BMPs', and 'City BMPs'. In this phase of the project, some of these BMPs including **streambank stabilization, damming ephemeral gullies (or gully plugs), recharge structures, conservation tillage, terraces, contour farming, grazing management, manure incorporation, edge-of-field filter strip, and PL-566 structures** were simulated using the SWAT model to quantify their effectiveness in reducing sediment and nutrient (TN and TP) loads from the Bosque River Watershed. A brief description of each management practice and its representation during the pre- and post-BMP condition is given below along with the associated NRCS standard practice code, when applicable. A more detailed description of each of the 22 recommended BMPs can be found in *Descriptions and Expectations of Recommended BMPs for Improving the Bosque River Watershed* (Gregory and Meier, 2008); this document also presents general information on areas where the practices are applicable, what implementation and operation and maintenance costs can be expected for each practice, and where technical and financial assistance may be accessed.

Stream Bank Stabilization (NRCS Practice Code 580: Streambank and Shoreline Protection)

Stream bank stabilization uses vegetation or structural techniques to stabilize and protect banks of streams or constructed channels, and the shorelines of lakes, reservoirs, and estuaries against scour and erosion. The main purposes of this practice are to prevent bank erosion, thereby reducing the sediment loads causing downstream pollution and associated damage; maintain the flow capacity of streams and channels; prevent loss of land mass; improve streams for recreation; enhance fish and wildlife habitat; control channel meandering; and protect facilities adjacent to streambanks. A suite of BMPs exists related to streambank stabilization, which can influence channel erodibility, streambank cover, and channel roughness.

The streambank stabilization BMP was represented using channel erodibility (CH_EROD), channel cover factor (CH_COV), and Manning's "n" value (CH_N(2)) for the main channels (3rd order and above). In the pre-BMP condition, streambanks were represented as having less cover and being more erodible. The values of the variables used to represent pre- and post-BMP conditions are given in Table 3.

Porous Gully Plugs

Gullies plugs are a practice that is installed in a small gully and uses rocks or logs to reduce the velocity of concentrated flow, thereby reducing the erosive power of flowing water and facilitating sediment settling. Porous gully plugs are generally installed in ephemeral gullies and are not intended for use in a stream channel. In this study, areas where gully plugs were applied were represented as being more erodible in the pre-BMP conditions, similar to the way streambanks were. The effect of gully plugs was represented in terms of Manning's "n" value for the tributary channel (CH_N (1)). The pre-BMP channel was represented with a CH_N (1) value of 0.014 and the rougher post-BMP with gully plugs implemented was modeled with a CH_N (1) value of 0.05 (Table 3). All subbasins with subbasin-slope greater than 5 percent were selected for porous plug BMP implementation. In total, the selected subbasins had a total tributary channel length of 959 km.

Recharge Structures

Recharge structures are small dams designed to retain a portion of water moving through a channel and let the water infiltrate and percolate to reach underlying shallow ground water tables. Additionally, recharge structures decrease energy in the stream, thereby reducing its sediment carrying capacity. Recharge structures can be used in almost any location, but will be most effective in areas with higher soil permeability. To simulate these characteristics in the model, recharge structures were simulated in terms of effective hydraulic conductivity and channel roughness based on Manning's roughness coefficient of the tributary channels in the subbasins. This practice was applied in all subbasins regardless of soil permeability. A value of 25mm/hr was used for the effective hydraulic conductivity and a value of 0.08 was used for the channel Manning's "n" to represent recharge structures in the post-BMP condition (Table 3). All 48 subbasins were selected for implementing recharge structures based on recommendations from the Phase I report.

Conservation Tillage (NRCS Practice Code 328)

Conservation cropping practices can include a variety of tillage practices, but in general, they are practices that result in less soil disturbance than conventional tillage. As a result, higher amounts of crop residue remain exposed in the field after harvest and until the next crop is planted. Conservation cropping was simulated by using appropriate Soil Conservation Service curve number (CN) values and by maintaining residue on the surface.

Pre-planting intensive tillage operations such as tandem disk plow in the pre-BMP condition were 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). Tandem disk has EFFMIX of 0.75 whereas EFFMIX specified for conservation tillage operation is 0.25. The CN for these areas was reduced by 2 from the calibration values in the post-BMP conservation tillage representation (Table 3).

Terraces (NRCS Practice Code 600)

Terraces are broad earthen embankments or channels constructed across the slope of a field to intercept runoff water and control erosion. Terraces effectively decrease hill-slope length, help prevent the formation of gullies, and redirect intercepted runoff to a safe outlet. In this study, terraces were represented by conservation support practice factor (P-factor) and CN. The P-factor (PUSLE) is defined as the ratio of soil loss with a specific support or conservation practice to the corresponding loss with cultivation up-and-down the slope. Table 4 shows P-factor values recommended for different conservation practices and the corresponding upland slope. It is a widely used empirical value within the USLE equation that has a direct influence on the erosion rate. In the pre-BMP condition, P-factor was set to 1.0 whereas in post-BMP condition P-factor of the terraced areas was set to 0.10 or 0.12 depending on the average upland slope and also considering waterways or graded channel outlets in conjunction with terraces (Table 4, column (e) x 0.2). Curve number values were reduced by 5 from the calibration CN values (Table 3); this is a common practice and has been done by others. For instance, Bracmort et al. (2006) simulated the effect of parallel terraces by modifying curve number (CN2), USLE support factor (USLE_P), and slope length (SLSUBBSN). Secchi et al. (2007) used P-factor to represent contouring and terraces based on the slope range.

Contour Farming (NRCS Practice Code 330)

Contour farming consists of performing field operations including plowing, planting, cultivating, and harvesting along the contour of the field. Contouring intercepts runoff and reduces the development of rills in addition to increasing infiltration by retaining more water in the field. In this study, representation of contour farming was very similar to that of terracing. As in terraces, the contour farming practice was represented by USLE_P and CN. In the pre-BMP condition, P-factor was set to 1.0 whereas in post-BMP condition it was set to 0.5 or 0.6 depending on the average upland slope (table 4, column (e)). The CN was reduced by 2 from the calibration values to represent the reduction in runoff from contour farming increasing infiltration (Table 3).

Grazing Management

Excessive vegetation removal and overgrazing exposes soil on the surface, leads to increased soil compaction and reduced infiltration, thus increasing surface runoff and sediment, nutrient and/or pollutant losses. Grazing management is effectively managing the harvest of vegetation on grazing lands (rangeland and pasture land) with grazing animals in such a way that adequate ground cover is always maintained, thereby minimizing erosion. In the pre-BMP scenario, the overgrazed condition was simulated by removing 99 percent of above ground biomass whereas in the post-BMP situation only 85 percent of the above ground biomass was removed (Table 3). These values are based on those used by Santhi et al. (2006) to represent forage harvest management as improperly harvested forage and overgrazed land are similar in terms of erosion potential.

Manure Incorporation

Manure incorporation is a management practice where manure is directly injected below the soil surface using a knifing or deep-banding technique. Solid manures can also be incorporated by surface applying the manure and immediately mixing it with the soil using a heavy plowing technique; however, this practice is not advisable in all locations. For the pre-BMP scenario, the manure was applied on the surface (top 1 cm of the soil surface) and in the post-BMP scenario, 20 percent of the fertilizer is applied to the top 10 mm and the remainder to the 1st soil layer underneath.

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

Filter strips are strips of herbaceous vegetation situated between cropland, grazing land, or any disturbed land and an environmentally sensitive area. Filter strips trap sediment, thereby reducing the sediment and sediment-bound contaminants in runoff. In the present study, filter strips were represented in terms of edge-of-field filter strip (FILTERW) variable in SWAT. In the pre-BMP condition, no filter strip (FILTERW = 0m) was simulated whereas in the post-BMP condition, a FILTERW of 6 m was specified.

PL-566 Structures

The Watershed Protection and Flood Prevention Act (PL 83-566), August 4, 1954, as amended, authorized 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, floodplain management studies, and flood insurance studies. NRCS also assists the public in developing watershed plans that mitigate flood damages and promote the conservation, development, utilization and disposal of water while ensuring the proper conservation and utilization of natural resources. The focus of these plans is to identify solutions that use conservation practices, including nonstructural measures, to solve problems (USDA-NRCS, 2007a). As a result of the PL-566 efforts, a number of small upstream dams were built in late 1950s, 1960s, and early 1970s that provided flood protection as well as served as sources of water for municipal water supplies, wildlife habitat, and livestock and recreation. The Bosque River Watershed contains 88 of these PL-566 reservoirs with drainage areas ranging from as small as 0.5 km^2 to 76 km^2 (Figure 5). In the present study, these PL-566 reservoirs were simulated as existing even in the pre-BMP conditions because of their existence during the period considered for model calibration. PL-566 reservoirs were modeled as ponds using .pnd files in the SWAT model. Reservoir data including the locations and dimensions were obtained from the U.S. Army Corps of Engineers National Inventory of Dams (NID) dataset. The impact of these PL-566 structures on sediment, TN and TP were evaluated by doing SWAT model simulation without these structures and quantifying the increase in sediment, TN, and TP loads.

BMP Evaluation

The effects of BMP implementation on water quality are presented as percentage reductions in average annual sediment, TN (OrgN and MinN), and TP (OrgP and MinP) loadings at the HRU, subwatershed, and watershed levels. HRU and subwatershed level percentage reductions are the overland load reductions due to BMP implementation whereas watershed level reductions include cumulative load reductions considering overland pollutants and their routing through the stream network. Load reduction summaries on the HRU level consider only BMP areas whereas load reductions summarized at the subwatershed level consider both BMP and non-BMP areas within the subwatershed. Watershed outlet output includes both BMP and non-BMP areas along with the channel routing. The calibrated model setup is used as the reference (or baseline) condition with which the model predicted loads after BMP implementation are compared to estimate the percentage load reduction. Watershed level reductions were estimated at the location just upstream of Lake Waco (inlet to subbasin 30). The percentage reduction is calculated as:

percent reduction = 100*(Baseline – with BMP) / Baseline Equation 1

Prioritizing Subwatersheds for BMP Implementation

Three types of impact indices (Concentration Impact Index-CII, Load Impact Index-LII, and Load per Unit Area Impact Index-LUAII) were developed based on the recommendations of the scientific advisory committee in order to identify the subwatersheds that need the most improvement and should therefore receive priority when BMPs are implemented. In this project, the methodology used to derive these impact indices was adopted from the Phase I project whereas the data used to derive the impact indices was extracted out of the model predicted results with baseline set up of Phase II. SWAT predicted values from the baseline evaluation were used to calculate sediment, TN, and TP yield values for each type of the three impact indices. These three impact indices were then combined to get a cumulative index that assigns a numerical ranking to each subwatershed indicating its priority (Figure 8).

Cumulative Impact Index Estimation

Concentration Impact Index, Load Impact Index, and Load per Unit Area Impact Index consider constituent values expressed in terms of concentration (mg/L), load in terms of tons (or kg), and load per unit area in terms of tons/ha (or kg/ha), respectively (Figures 9-11). The Load per Unit Area Impact Index relates to individual subwatersheds and does not include the influence of upstream watersheds whereas the Concentration and Load Impact Indices include both the subwatershed contribution and the entire upstream watershed contribution. Calculation of Concentration Impact Index was based on the values extracted from the reach output file from the baseline SWAT simulation. Information specific to this index will be useful in addressing localized concerns in tributaries under low and high flow conditions. The Load Impact Index was developed based on sediment, TN, and TP loads extracted from the reach output file in the baseline SWAT run. The load impact index produces useful information for implementing BMPs in high flow streams and their contributing upstream drainage areas. Load per Unit Area Index was developed based on the load per unit area data extracted from the subbasin output file of SWAT simulation and yields information that will assist in addressing localized concerns at the subwatershed scale. Sediment, TN, and TP yields estimated based on the type of impact index were categorized into high, medium, or low using the Natural Breaks method. A rating value was selected for each category using a log base 2 similar to the Phosphorus Index method (NRCS, 2006). Therefore, the categories high, medium, and low were given a value of 4, 2, and 1, respectively. The sum of the sediment, TN, and TP ratings yielded a cumulative rating value, or the total impact index, which was categorized into high, medium, or low priority for each of the three types of impact indices (Table 5; Figure 8).

Streambank stabilization, recharge structures, conservation tillage, terraces, grazing management, and manure incorporation were implemented in prioritized subwatersheds using SWAT simulation. These six BMPs were incrementally implemented on all high, medium, and low priority watersheds as designated by each impact index. Therefore, the BMPs were implemented in high priority subwatersheds first, then in medium priority subwatersheds. Finally, low priority areas were equipped with BMPs resulting in implementation throughout all subwatersheds. BMPs were implemented following the criteria mentioned in Table 3. The effect of BMP implementation is reported in terms of a percent reduction in sediment, TN, and TP loads at the watershed outlet (Lake Waco), as compared to the baseline condition (Equation 1).

RESULTS AND DISCUSSION

Model Calibration and Validation

Flow

The SWAT model was calibrated over a 26-year period using available streamflow records from the USGS gaging station at Valley Mills (Figure 7) from 1980-2005. The drainage area at Valley Mills totals 70 percent (3,014 km^2) of the upstream Bosque River Watershed. Measured and simulated annual and monthly flow for the calibration period at Valley Mills matched well (Figure 12a & 12b, Table 6). The absolute percentage difference between measured and simulated flows, at annual and monthly time steps were 3 percent and 4 percent, respectively. Both the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NS_e) were ≥ 0.73 (Table 6). Validation of the model was conducted using annual and monthly flow data at Valley Mills from 1960-1979 (Figure 13a & 13b, Table 6). Measured and simulated annual and monthly flows for the validation period differed by approximately 7 percent. The coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NS_e) were 0.6 and greater (Table 6) indicating that SWAT simulated stream flows were in close agreement with measured streamflow at this location.

Sediment

The model performance statistics after calibration for monthly flow and water quality data at Hico and Valley Mills (Figure 7) are presented in Tables 7 and 8. Figures 14b and 15b show the time series (temporal variation) of sediment loadings at Hico and Valley Mills, respectively. Both R^2 and NS_e of 0.73 at Hico and R^2 value of 0.78 and NS_e value of 0.73 at Valley Mills indicate that the measured and simulated monthly sediment loads matched quite well at both the monitoring locations.

Nutrients

Time series plots of loadings of OrgN, OrgP, MinN, and MinP are shown in figures 14c-f (Hico), and Figures 15c-f (Valley Mills). Model performance statistics shown in Tables 7 and 8 indicate that the means of simulated OrgP matched well with the measured values at both Hico and Valley Mills even though the NS_e was -0.26 for OrgP at Hico. OrgN was under predicted at both locations and the mineral forms of N and P (MinN and MinP) were over predicted at the Valley Mills location. Modeled results at Hico closely mirrored measured values of MinN and MinP.

Percent Reductions due to BMP Implementation in all Watershed Subbasins

Streambank Stabilization

Stream reaches selected for simulating the streambank stabilization BMP (shown in Figure 16) totaled 245 km in length. Streambank stabilization resulted in a reduction in sediment by 213 metric tons per km of stream stabilized or an overall reduction of 35 percent at the watershed outlet. TN and TP reduction per km stabilized channel were 60 kg and 22 kg, respectively, and equated to 1 and 5 percent reductions as compared to baseline values (Table 9). Implementing streambank stabilization in the 10 highest priority subwatersheds resulted in sediment reduction ranging from 3 percent to 51 percent, reduced TN up to 9 percent and reduced TP by as much as 7 percent at the subwatershed level (this calculation considered upstream contributions) (Figures 17a, b, and c; Table 11).

Porous Gully Plugs

Gully plugs were simulated as being implemented on the tributary channels of subbasins with an average slope greater than 5 percent. Tributary channels in the selected subbasins totaled 959 km and yielded reductions of 7.5 metric tons of sediment per km, 7.4 kg/km TN and 0.9 kg/km TP when the gully plugs were implemented. This is equivalent to 5.3 percent, 4.8 percent, and 4.9 percent reductions in sediment, TN, and TP at the watershed outlet, respectively (Table 9). Individual subwatershed benefits resulting from implementing gully plugs ranged from 1.4 percent to 30.3 percent in sediment, 0.6 percent to 22 percent in TN, and 0.5 percent to 16 percent in TP (Figures17a, b, and c; Table 11).

Recharge Structures

The total length of tributary channels in all 48 subbasins of the Bosque River Watershed totaled 1,302 km. Recharge structures were implemented in all 48 subbasins using SWAT and resulted in reductions of 14 metric tons/km of tributary channel length in sediment, 18 kg/km in TN and 2 kg/km in TP. At the watershed outlet level, recharge structures were as effective as streambank stabilization measures and they reduced sediment, TN, and TP by 37 percent, 24 percent, and 30 percent respectively (Table 9). Recharge structures reduced surface runoff by 23 percent when implemented in all 48 subwatersheds. Reductions in sediment from recharge structure implementation in individual subwatersheds ranged from 15.5 percent to 73.7 percent while reductions in TN and TP ranged from 8.2 percent to 61.3 percent and 7.2 percent to 54.6 percent, respectively (Figure 17; Table 11).

Conservation Tillage

Implementing conservation tillage on individual HRUs resulted in sediment reductions of 5 percent to 42 percent (Figure 17). When estimating the overall overland load reduction of both BMP and non-BMP areas (the subwatershed level), conservation tillage reduced sediment by 4.6 percent, TN by 3.6 percent, and TP by 1.4 percent (Table 10). Conservation tillage was implemented on 432 km^2, or about 10 percent of the watershed, and resulted in a reduction in sediment and TN by 3 percent each at the watershed outlet (Table 9). Similar to other studies (Sharpley and Smith, 1994; Gitau et al., 2005), dissolved P increased as a result of implementing conservation tillage (Table 9, Figures 17b and 17c; Table 11) and is likely attributed to the possible increase of dissolved (mineral) P from increased residue and the buildup of soluble pollutants at the surface due to the lack of soil inversion and mixing.

Terraces

Terraced areas reduced sediment at the farm or HRU level by 57 percent to 95 percent; TN by 39 percent to 95 percent; and TP by 16 percent to 88 percent (Figure 17; Table 11). Terraces were applied to the same land area as conservation tillage and resulted in 25 percent sediment, 21 percent TN, and 21 percent TP reductions at the subwatershed level (Table 10). At the watershed outlet, terraces curtailed sediment, TN, and TP load by 17 percent, 19 percent, and 27 percent, respectively (Table 9).

Contour Farming

Implementing contour farming reduced sediment by 28 percent to 67 percent, TN by 25 percent to 68 percent, and TP by 10 percent to 62 percent at the farm or HRU level (Figure 71a, b, and c; Table 11). At the subwatershed level, contour farming resulted in 16 percent, 12 percent, and 11 percent reduction in sediment, TN and TP, respectively (Table10) whereas at the watershed level, it resulted in respective reductions of 10 percent, 10 percent, and 16 percent (Table 9) for sediment, TN, and TP.

Grazing Management

Pasture and rangeland are the dominant landuse types in the watershed, and as a result, implementing proper grazing management on all pasture and rangeland covered a total of 2820 km^2 or 66 percent of the total watershed area. Simulated managed grazing resulted in reduced sediment loss of 7.4 percent, decreased TN losses by 5.3 percent and reduced TP losses by 4.0 percent at the watershed outlet (Table 9). At the subwatershed level, managed grazing resulted in average respective reductions of 10.4 percent, 7.0 percent and 5.3 percent in sediment, TN, and TP (Table 10). On the farm or HRU level, the reduction in sediment obtained ranged from 0.0 percent to 56 percent, TN ranged from 0.0 percent to 54 percent and TP ranged from 0.0 percent to 46 percent (Figures 17a, b, and c; Table 11).

Manure Incorporation

Incorporating manure had no effect on sediment losses but reduced TN and TP by 2 percent and 21 percent, respectively, (Table 9) at the watershed outlet. TN was reduced by 3 percent and TP was reduced by 10 percent in the overland load (Table 10) when considering both BMP and non-BMP areas together at the subwatershed level. These reductions at the subwatershed and watershed levels are relatively significant considering that the area of implementation totaled only 2 percent of the total watershed area. At the HRU level, maximum sediment reduction brought about by incorporating manure ranged from 0.0 percent to 37 percent, reduction in TN ranged from 14 percent to 83 percent, and TP ranged from 22 percent to 83 percent (Figures 17a, b, and c; Table 11).

Edge-of-Field Filter Strip

Edge-of-field filter strips were simulated for all cropland and all WAFs, a total area of 499 km^2 (11.6 percent of the total watershed). A 6 m wide filter strip was modeled and reduced the sediment load at the watershed outlet by 9.4 percent, TN by 15.5 percent, and TP by 25.7 percent (Table 9). The effectiveness of the filter strips at the farm or HRU level ranged from 25 percent to 63 percent in reducing sediment, 62 percent to 64 percent in reducing TN and TP (Figures 17a, b, and c, Table 11). Overland reductions achieved by filter strip at the subwatershed level were 17 percent, 18 percent, and 20 percent in sediment, TN, and TP, respectively (Table 10).

PL-566

The impact of PL-566 structures on water quality of the Bosque River was evaluated by removing these structures from the watershed and running the model without them in place. This evaluation indicated that PL-566 structures reduce loadings at the watershed outlet (Lake Waco) by 9.3 percent for sediment, TN by 15.2 percent, and TP by 17 percent (Table 9). In the absence of PL-566s, sediment, TN, and TP loading at the subwatershed level increased by 25 percent, 17 percent, and 19 percent, respectively (Table 10).

Prioritized Subwatersheds for BMP Implementation

Figures 9-11 show the subwatersheds prioritized as high, medium, and low for different types of impact indices. The priority assigned to each subwatershed by the three impact indices is highly dependent on the criteria for expressing each specific index. The load per unit area index achieved the highest reductions in sediment, TN, and TP at the watershed outlet as compared to the other two indices when implementing the six chosen BMPs in "High" priority subwatersheds (Table 12). This reduction is partly because a majority of the BMPs simulated in the prioritized subwatersheds address upland pollutant losses rather than in-stream losses and yield greater reductions from targeting the main sources of these pollutants. Implementing BMPs on high priority subwatersheds based on load impact and load per unit area impact indices produced the same percentage reduction in sediment loss while BMPs implemented based on the concentration impact index yielded half of the sediment loss reductions (Figure 18; Table 12).

The source of TN and TP in the watershed is primarily from cropland, WAFs, rangeland, and pasture land**.** Upland BMPs geared towards minimizing these nutrients included terraces, conservation tillage, and grazing management with terraces and conservation tillage being the most effective in reducing erosion rates. The load per unit area index and concentration index will identify as high priority specific subwatersheds that will benefit from implementing these types of BMPs because these indices place more emphasis on upland areas that are the source of these pollutants. Targeting BMP implementation in "high" priority subwatersheds based on these two indices resulted in 21 percent and 16 percent reduction in TN compared to a 7 percent reduction obtained by implementing based on recommendations of the load impact index criteria. Similarly, load per unit area and concentration impact indices obtained a reduction of 27 percent and 23 percent in TP compared with 11 percent under the load impact index criterion (Table 12). In addition, the load per unit area impact index criterion results in significant reductions in sediment, TN, and TP when implementing the BMPs on and medium priority subwatersheds. The concentration impact index and load impact index also exhibit similar trends in sediment loading but are almost linear when considering TN and TP reductions (Figure 18).

The total area or stream length of BMP implementation corresponding to high, medium, and low priority watersheds for different impact indices are shown in table 13. The greatest area/stream length of BMP implementation was in high and medium priority subwatersheds identified by the load per unit area index. As a result, higher percent reductions for sediment, TN, and TP were seen for BMPs implemented based on load per unit area impact index when compared with either the concentration impact index or load impact index.

CONCLUSIONS

The SWAT model was used to simulate the hydrologic and water quality processes in the Bosque River Watershed as affected by the various management techniques applied to cropland and grazing land, WAFs, effluent discharge from eight wastewater treatment plants, and PL-566 reservoirs. Calibration and validation of SWAT using flow and water quality data available in the watershed resulted in a modeled representation of the watershed that was well within acceptable standards. Based upon this acceptable correlation between modeled and observed output, SWAT was able to effectively simulate the impacts of implementing various BMPs throughout the watershed in order to evaluate their efficacy in reducing nonpoint source pollution in the watershed.

BMPs simulated included streambank stabilization, gully plugs, recharge structures, conservation tillage, terrace, contour farming, grazing management, manure incorporation, edge-of-field filter strip, and PL-566 reservoirs. First, these BMPs were simulated one at a time. Farm level (HRU level), subwatershed level, and watershed outlet level reductions were quantified for each BMP. Significant reductions were achieved at the farm level due to BMP implementation, as observed from model predicted values. Terracing proved to be the most effective BMP and achieved reductions of approximately 95 percent in sediment, TN, and TP at the farm level. Incorporating manure reduced TN and TP by approximately 83 percent at the farm level. Edge-of-field filter strips brought about 25 percent to 63 percent reduction in sediment and about 64 percent reduction in TN and TP. Farming along the contour of the fields is equally beneficial as it reduced the erosion rates from 28 percent to 67 percent, reduced TN by 25 percent to 68 percent and TP by 10 percent to 62 percent. Table 11 summarizes the benefits of the other BMPs evaluated in this modeling study

The percentage reduction in sediment load at the watershed outlet as a result of implementing these BMPs individually was up to 37 percent. Reductions in TN and TP at the watershed outlet ranged from 1 percent to 24 percent and 3 percent increase to a 30 percent decrease respectively. TP load at the watershed outlet increased by 3 percent due to conservation tillage increasing residue and the buildup of soluble pollutants at the surface.

An attempt was made to prioritize the subwatersheds into “high”, “medium”, and “low” priority for BMP implementation. Considering sediment, TN, and TP (as pollutants), three types of total impact indices were estimated based on pollutant load; pollutant concentration, and pollutant load per unit areas. For each type of impact index, all selected BMPs (streambank stabilization, recharge structures, conservation tillage, terrace, grazing management, and manure incorporation) were implemented incrementally, first on high priority subwatersheds, then on medium and low priority subwatersheds. Priority subwatersheds, as well as area/stream length, of BMP implementation were different for each impact index. In comparing the reductions achieved due to implementation of BMPs using the three impact indices, load per unit area impact index achieved the greatest reductions as this index targets the control measures on the local upland areas and a majority of the BMPs simulated in this study addressed upland pollutant reduction, which generate higher pollutant loads than in-stream sources.

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Figures

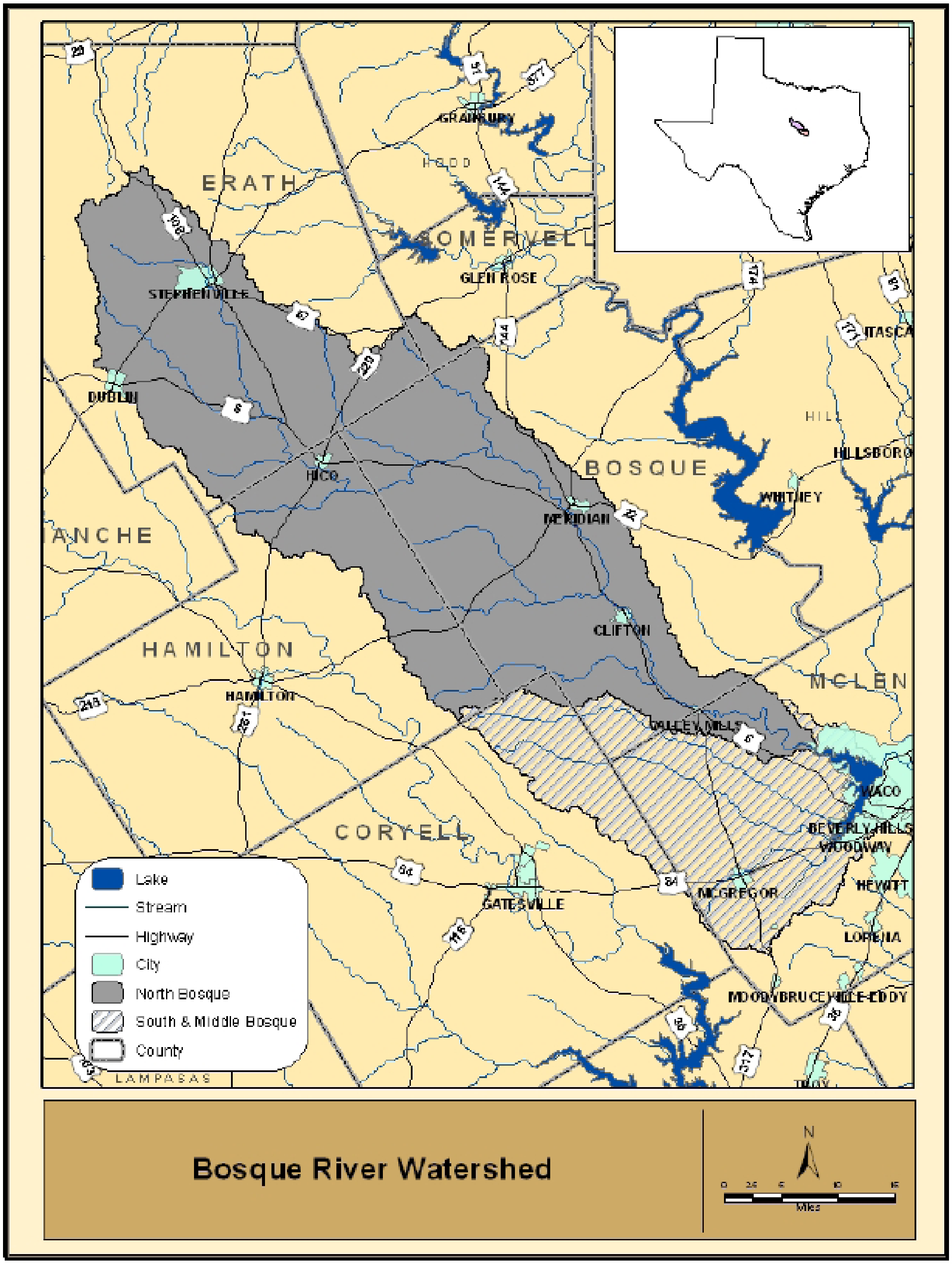


Figure 1: Location Map of Bosque River Watershed

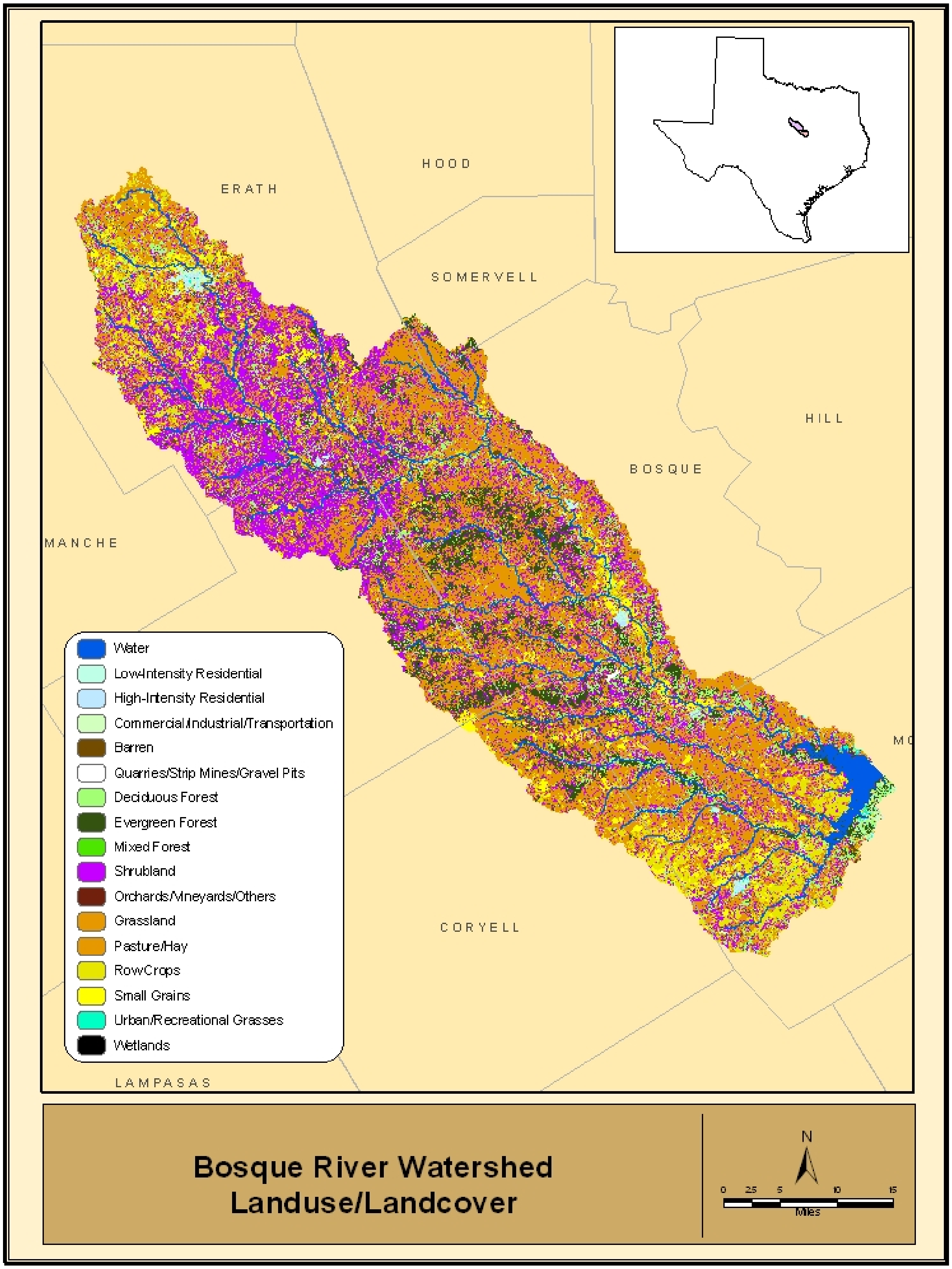


Figure 2: Landuse/Landcover Map of Bosque River Watershed

Figure 3: SSURGO based soil map of Bosque River Watershed

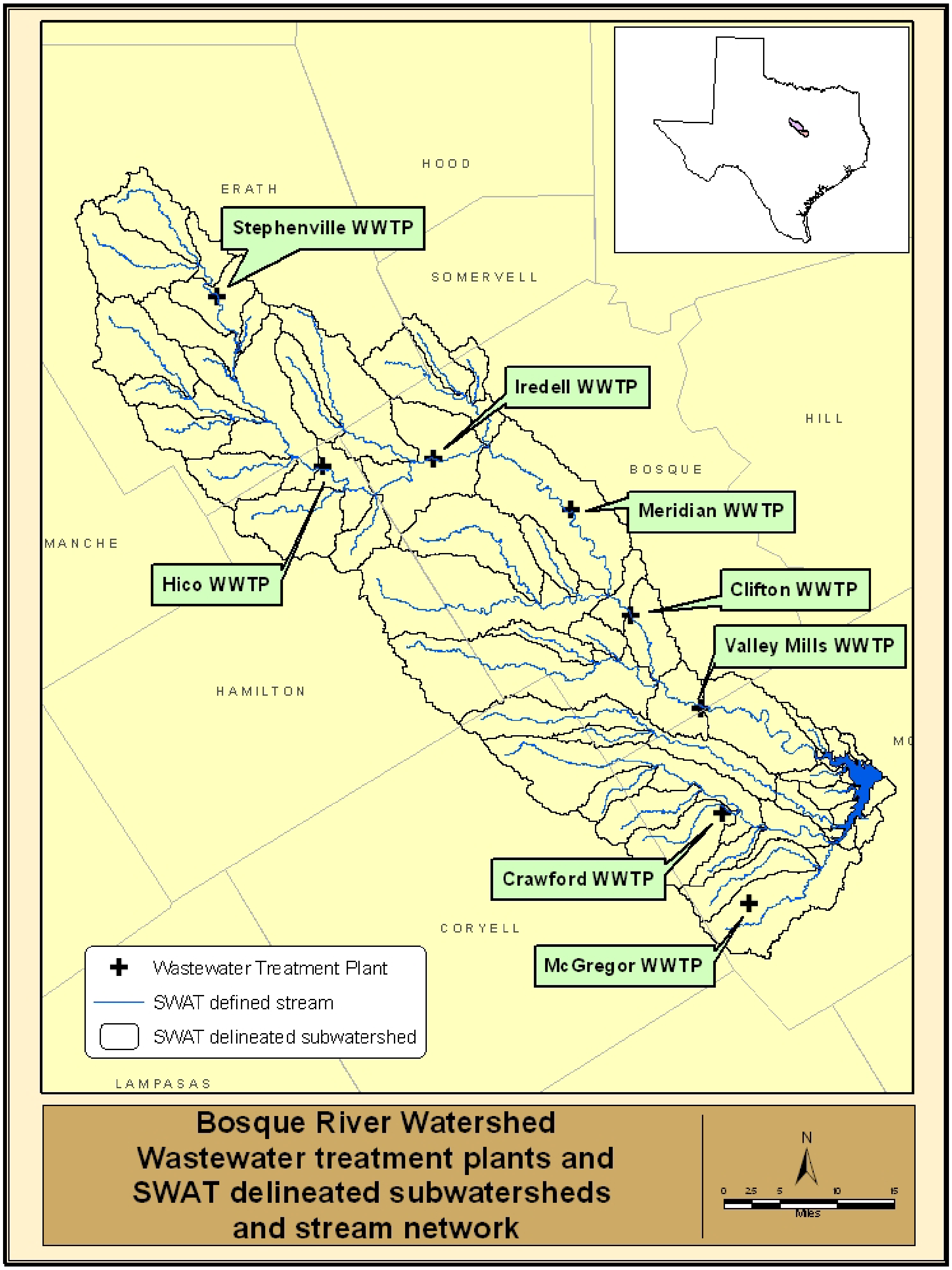


Figure 4: Bosque River Watershed with locations of 8 wastewater treatment plants and SWAT model delineated subwatersheds and streams.

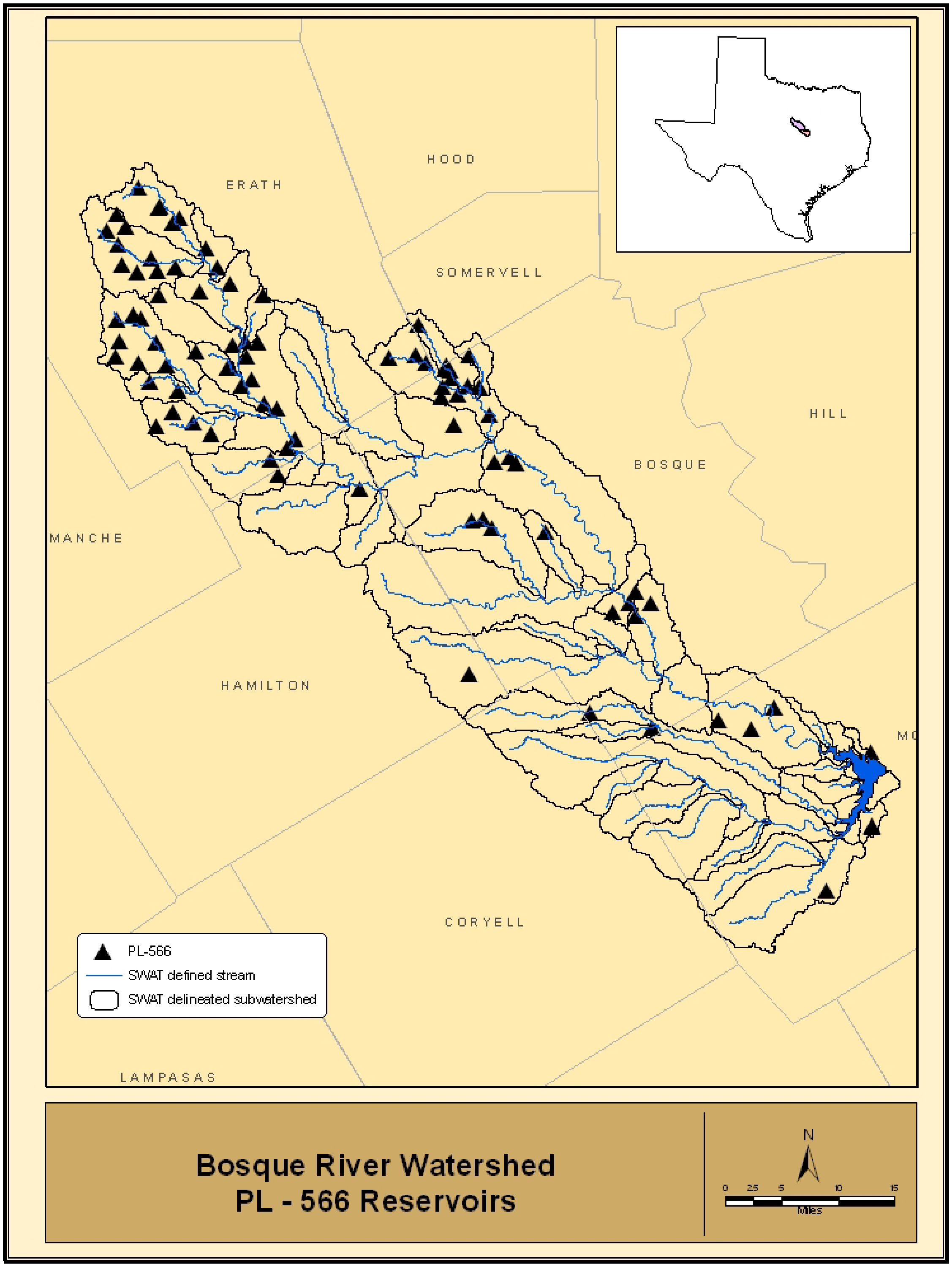


Figure 5: Location map of PL – 566 reservoirs in Bosque River Watershed

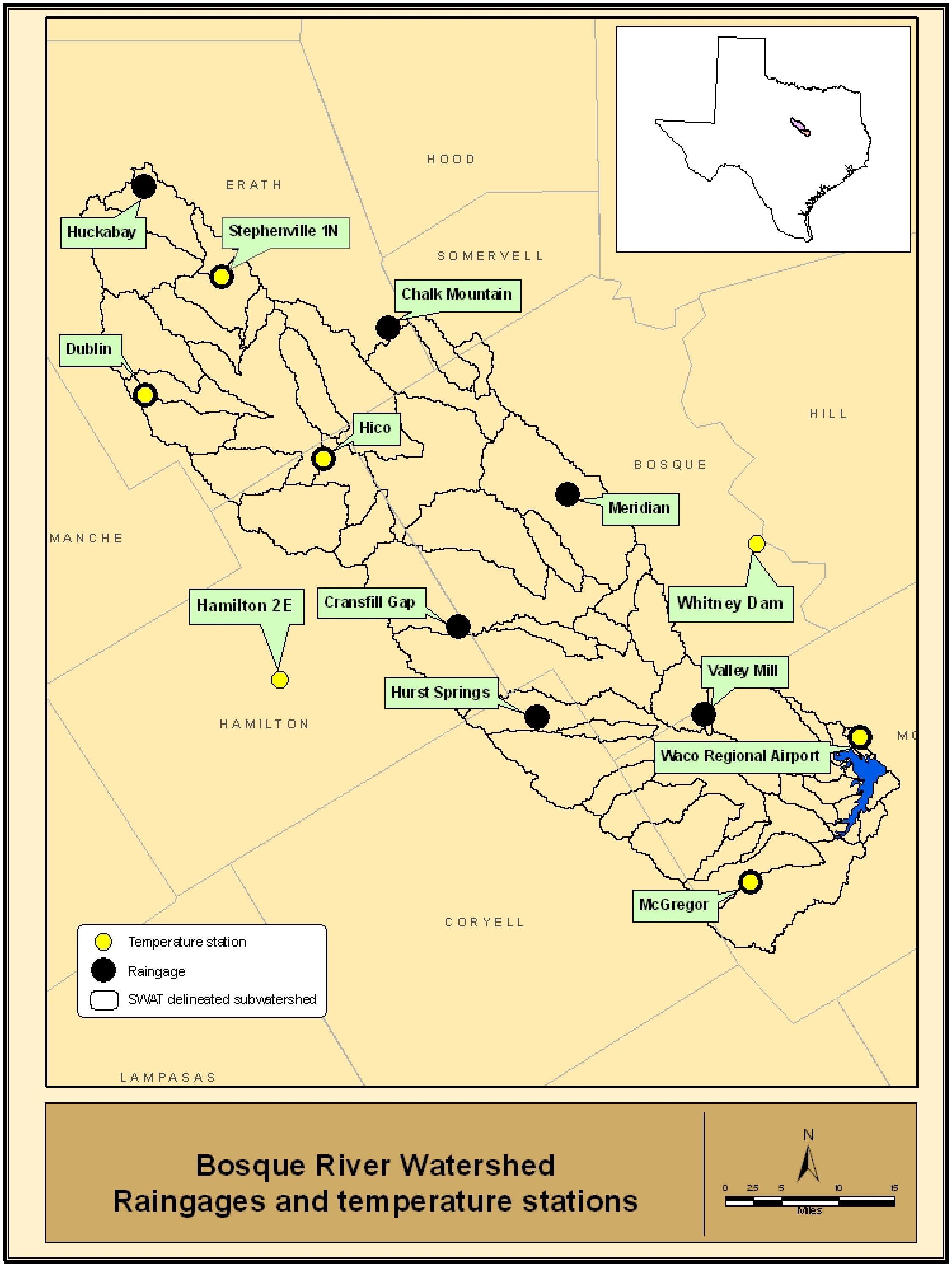


Figure 6: Location of 11 precipitation and 7 temperature stations in and around Bosque River Watershed that were used to obtain daily rainfall amounts and maximum and minimum temperature values for SWAT simulation model

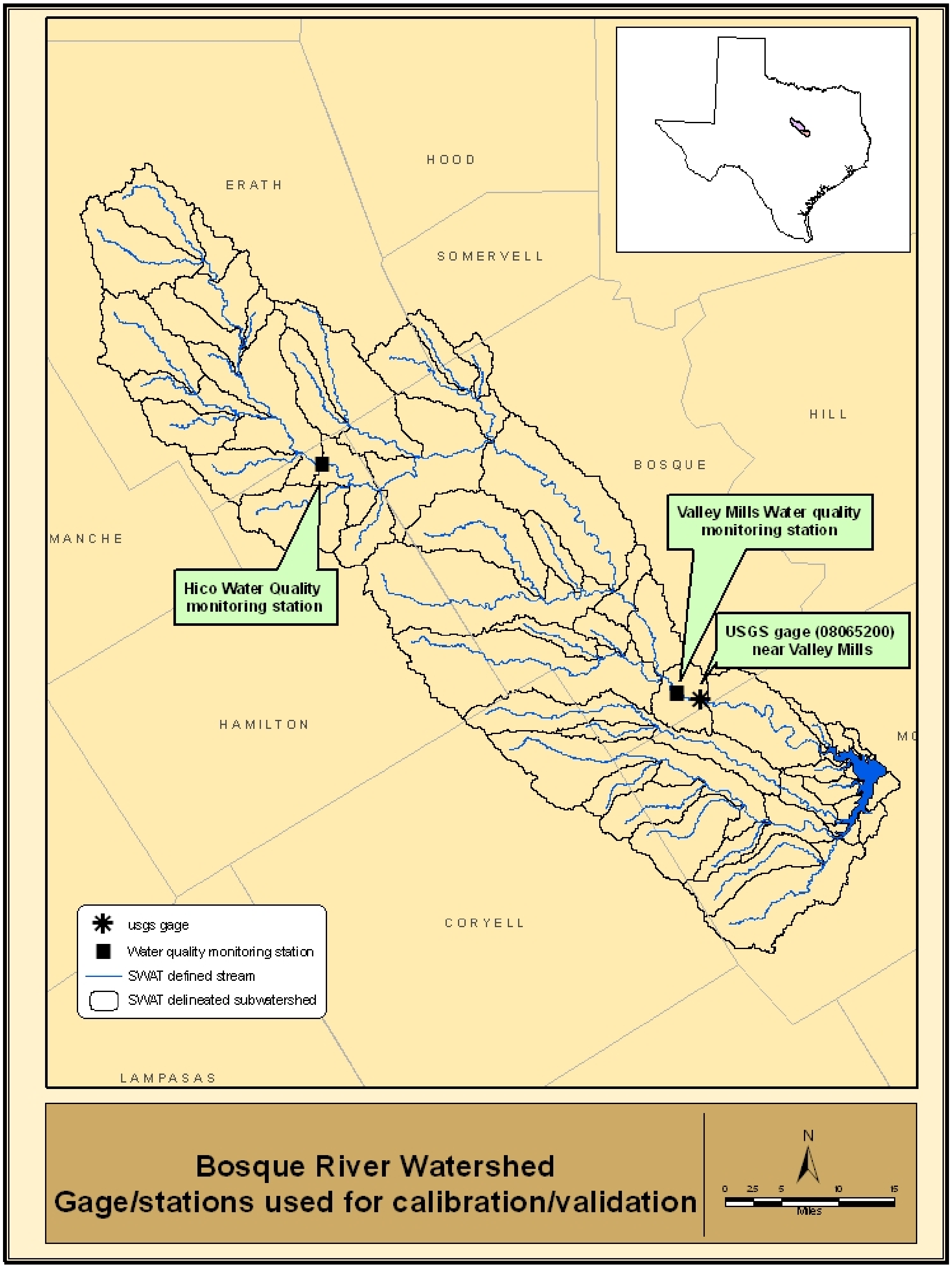


Figure 7: USGS gaging station at Valley Mills used for flow calibration, and monitoring stations at Valley Mills and Hico used for water quality calibration

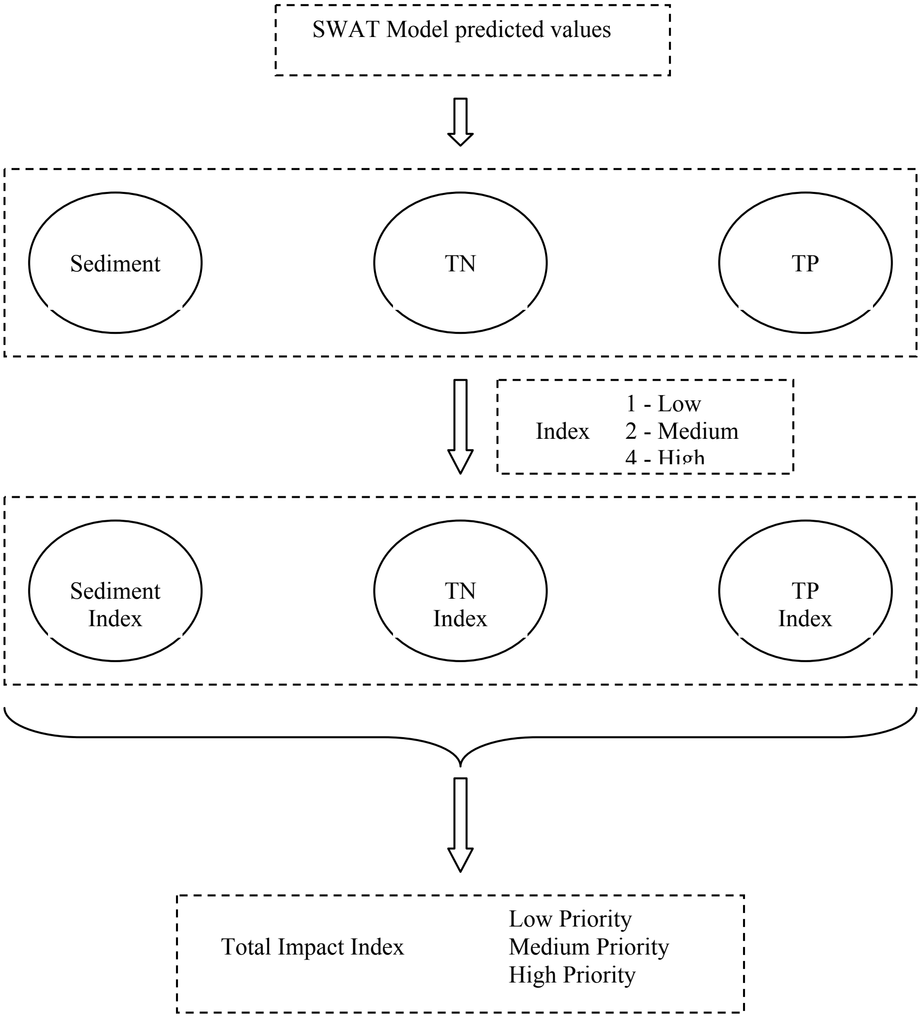


Figure 8: Total Impact Index Implementation

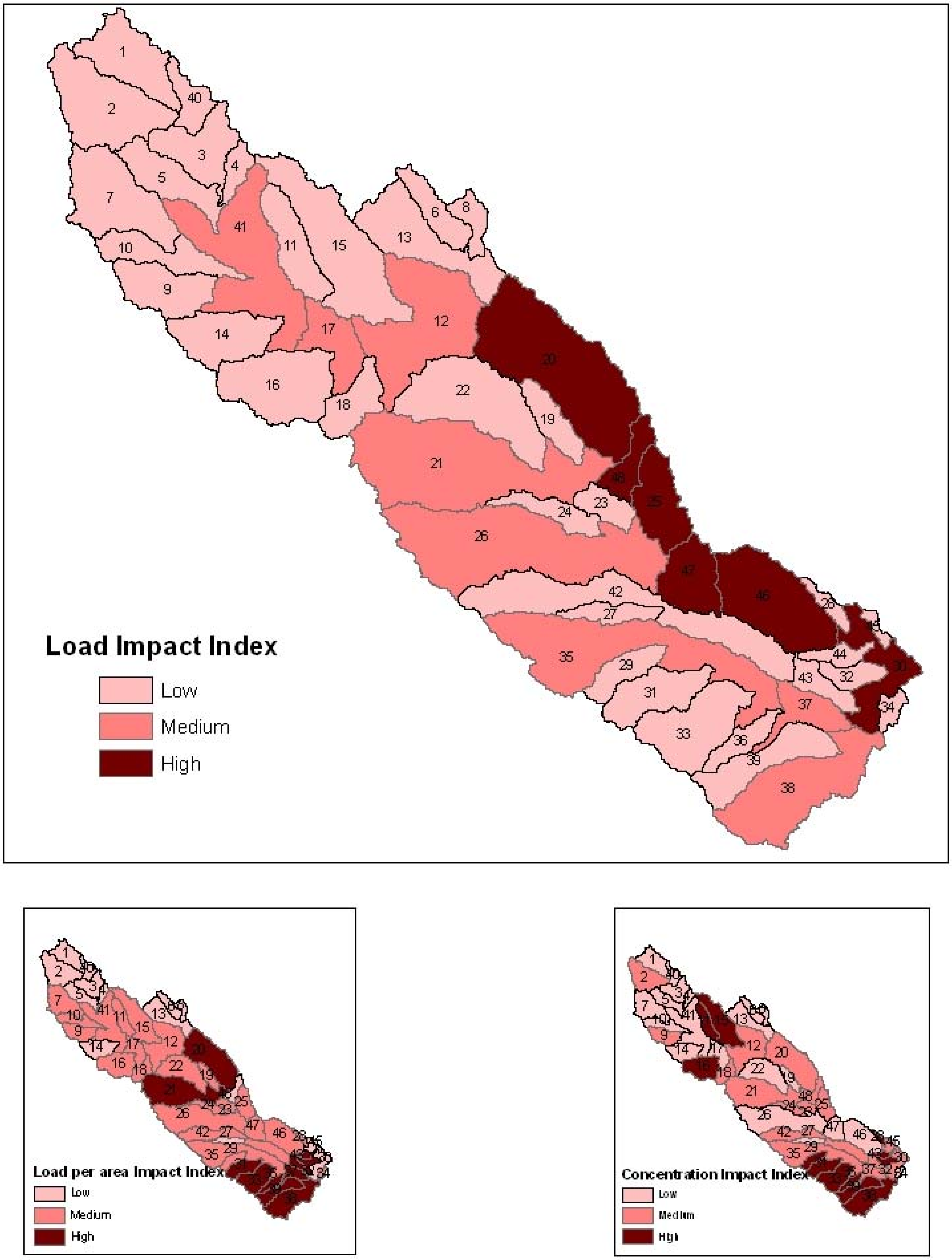


Figure 9: Load Impact Index

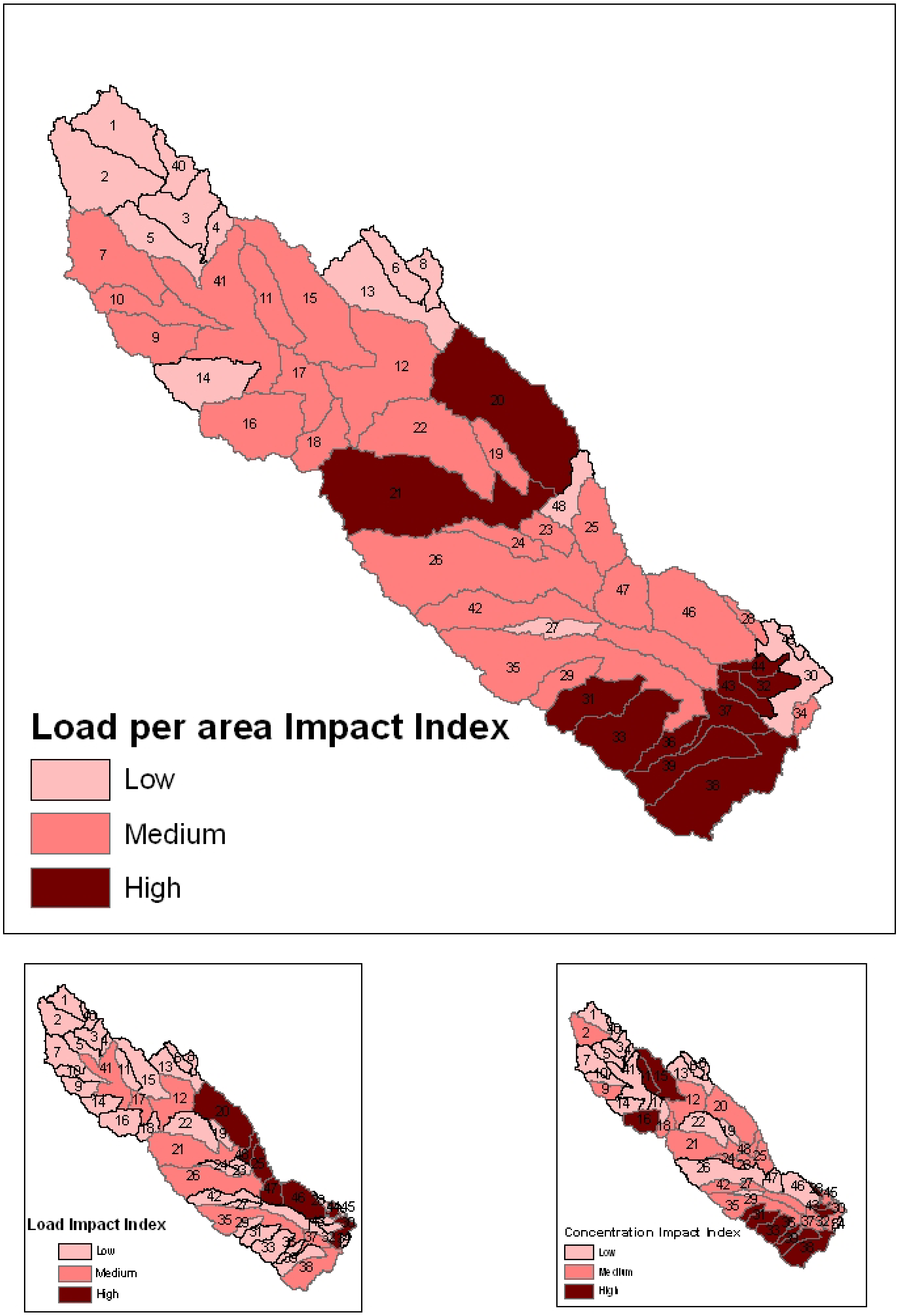


Figure 10: Load per unit area Impact Index

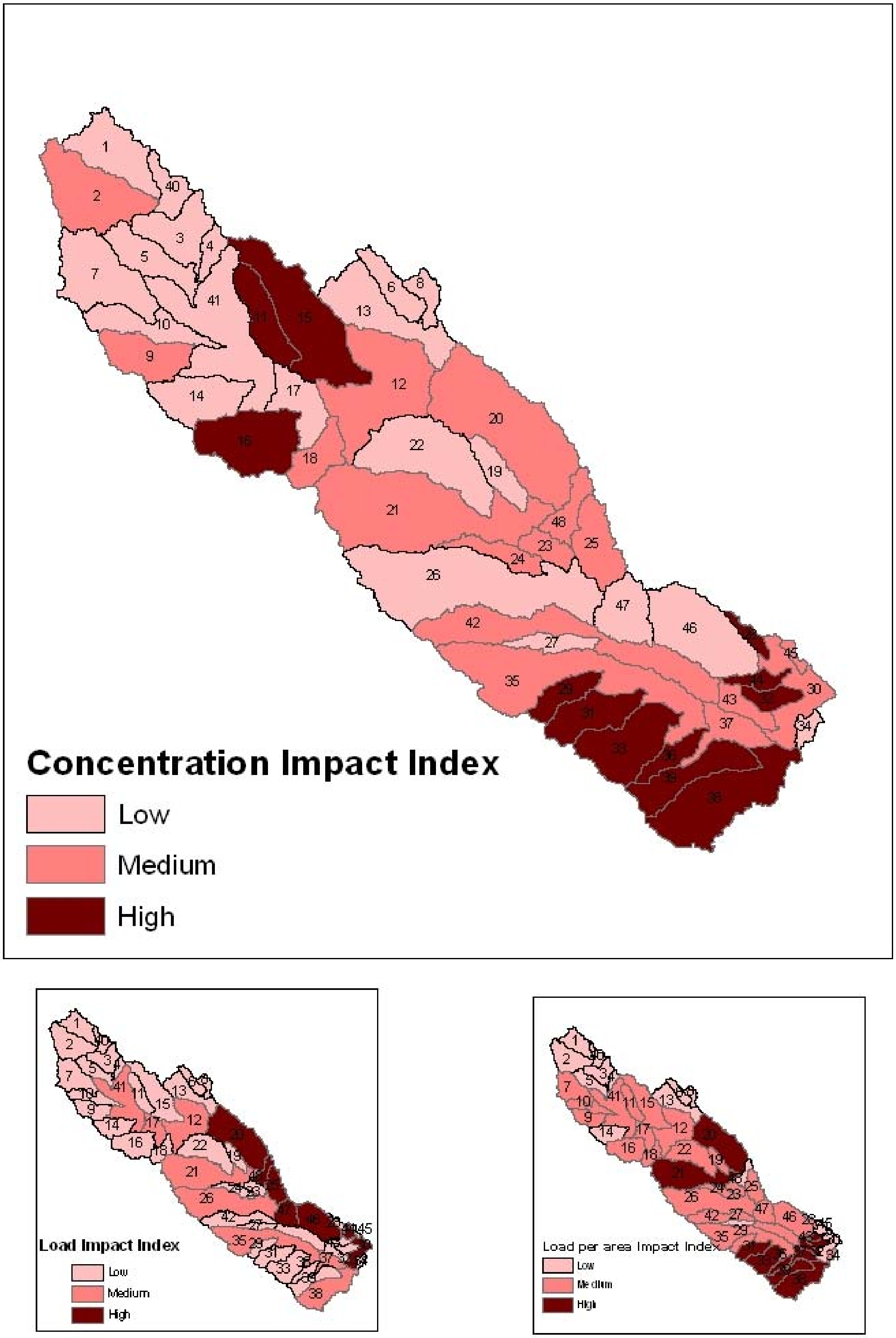
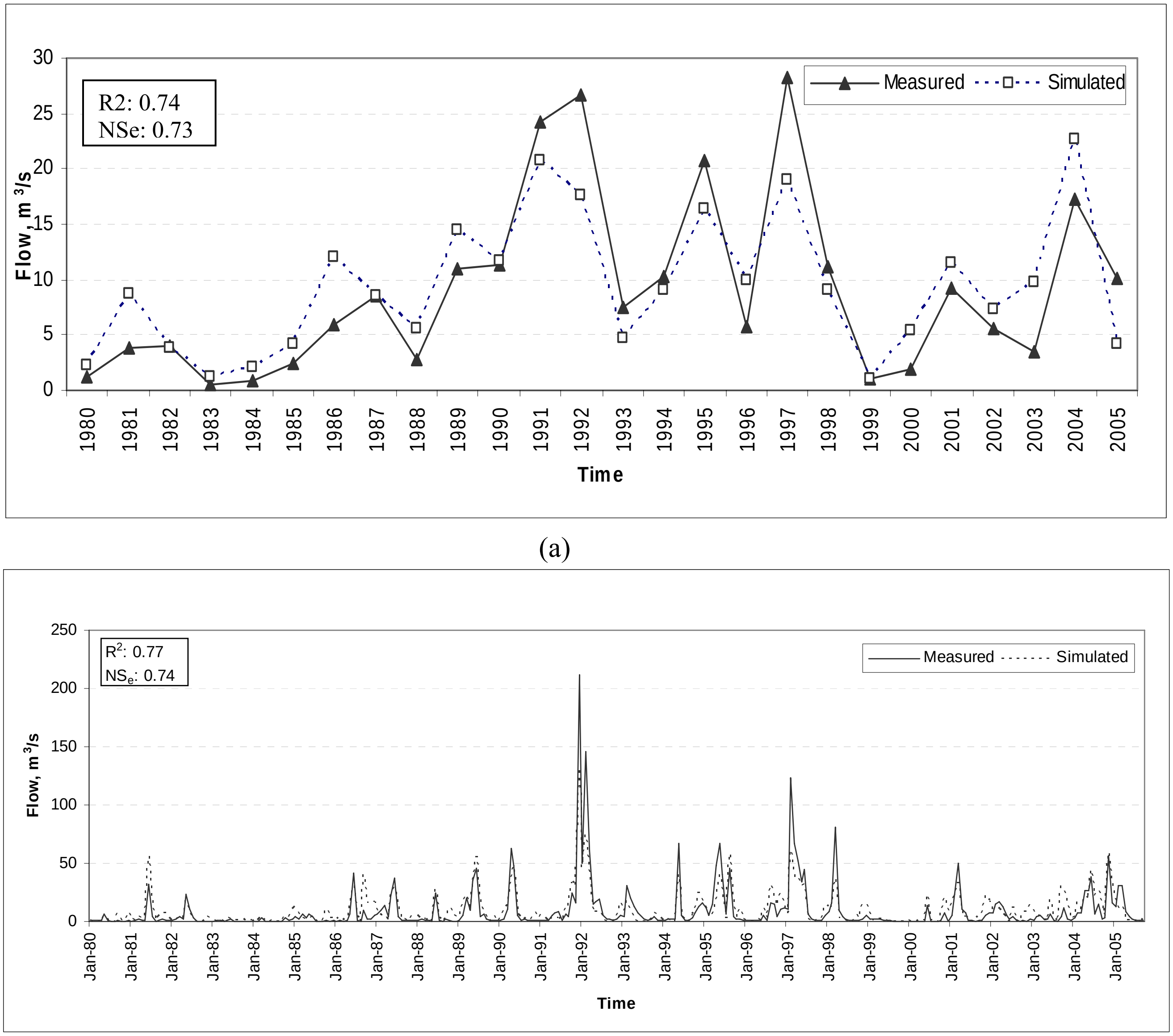
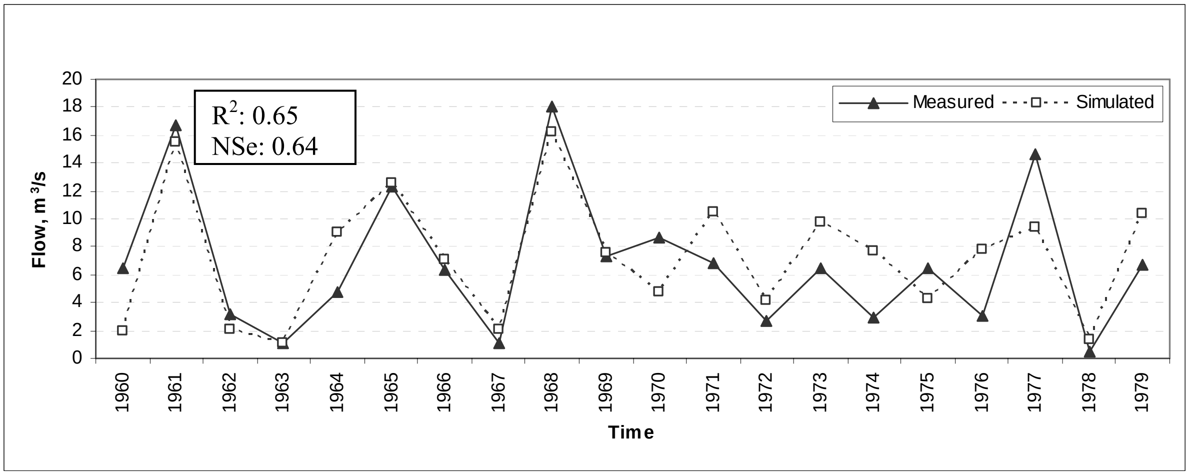


Figure 11: Concentration Impact Index

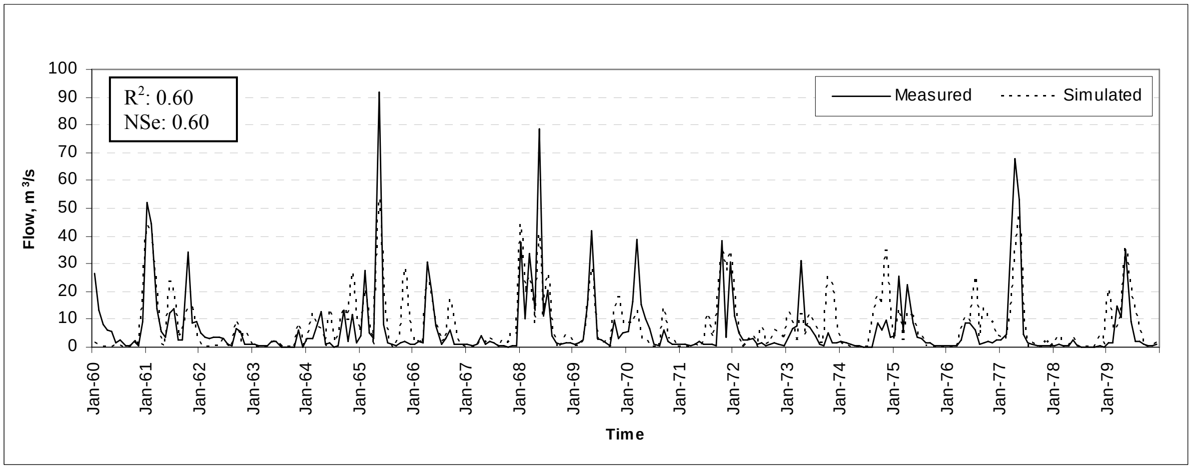


(b)

Figure 12: Measured and simulated (a) annual and (b) monthly flow at Valley Mills for the calibration period (1980-2005)

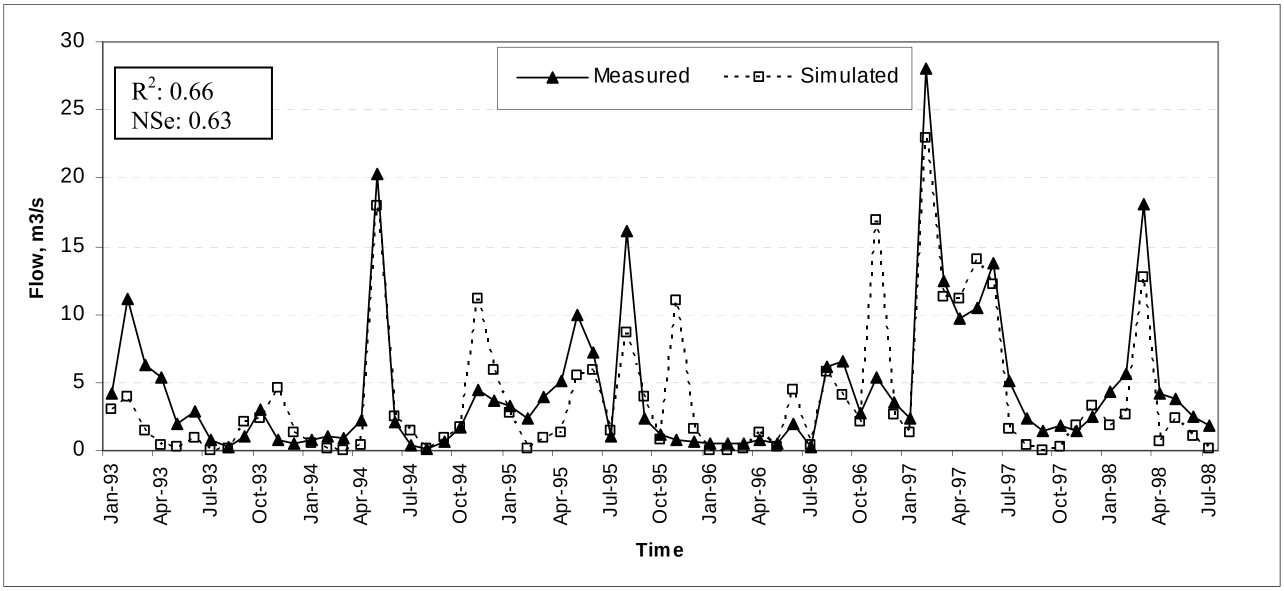


(a)

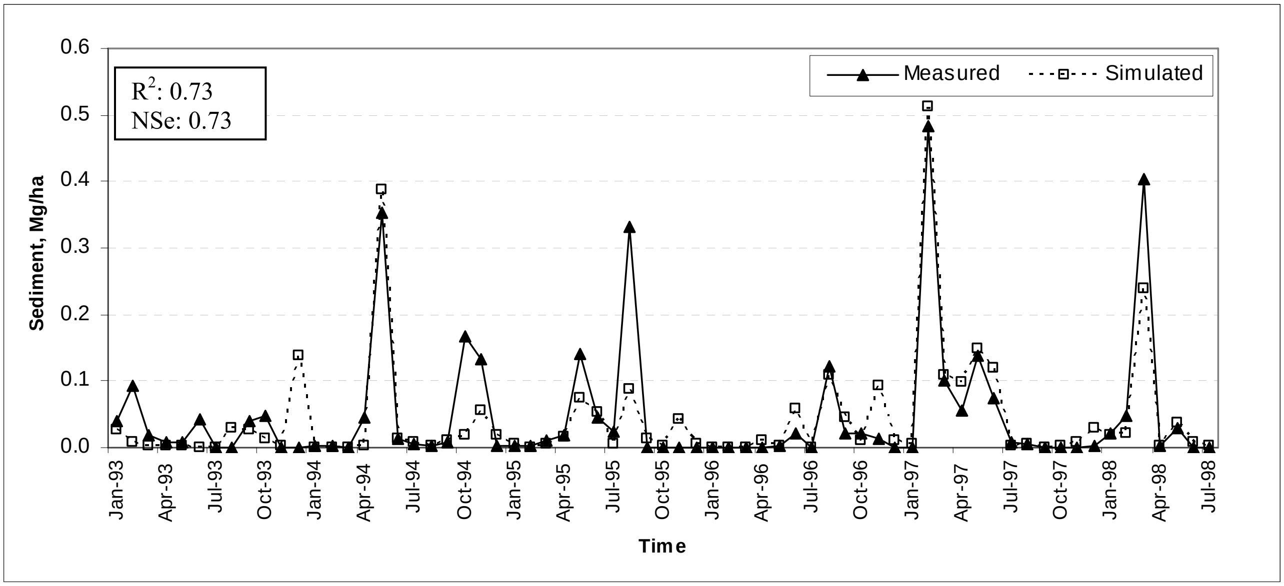


(b)

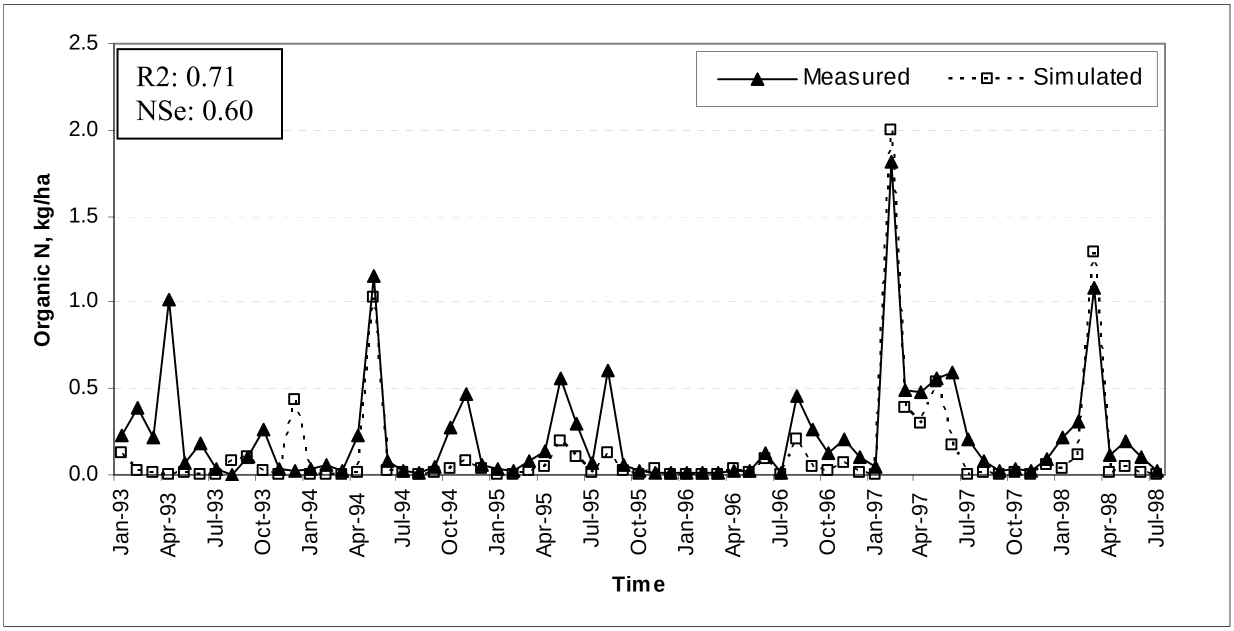
Figure 13: Measured and simulated (annual) and (b) monthly flow at Valley Mills for the validation period (1960-1979)


R^2: 0.66
NSe: 0.63
Measured
Simulated
Flow, m3/s
0
5
10
15
20
25
30
Jan-93
Apr-93
Jul-93
Oct-93
Jan-94
Apr-94
Jul-94
Oct-94
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Time

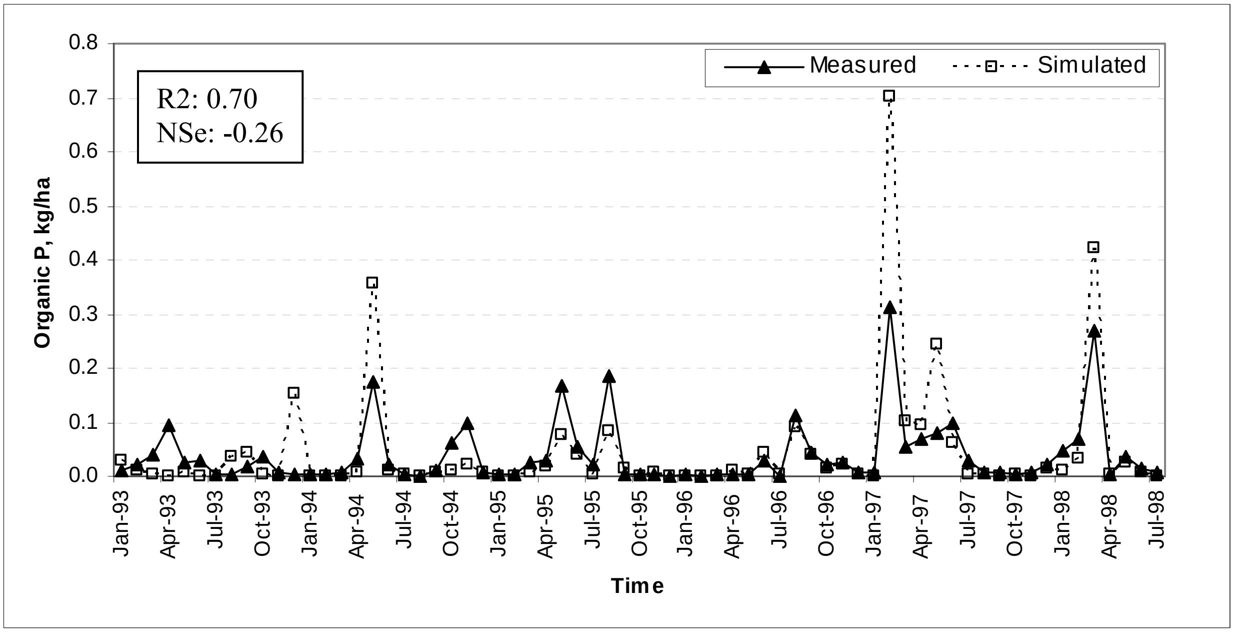
(a)


R^2: 0.73
NSe: 0.73
Measured
Simulated
Sediment, Mg/ha
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Jan-93
Apr-93
Jul-93
Oct-93
Jan-94
Apr-94
Jul-94
Oct-94
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Time

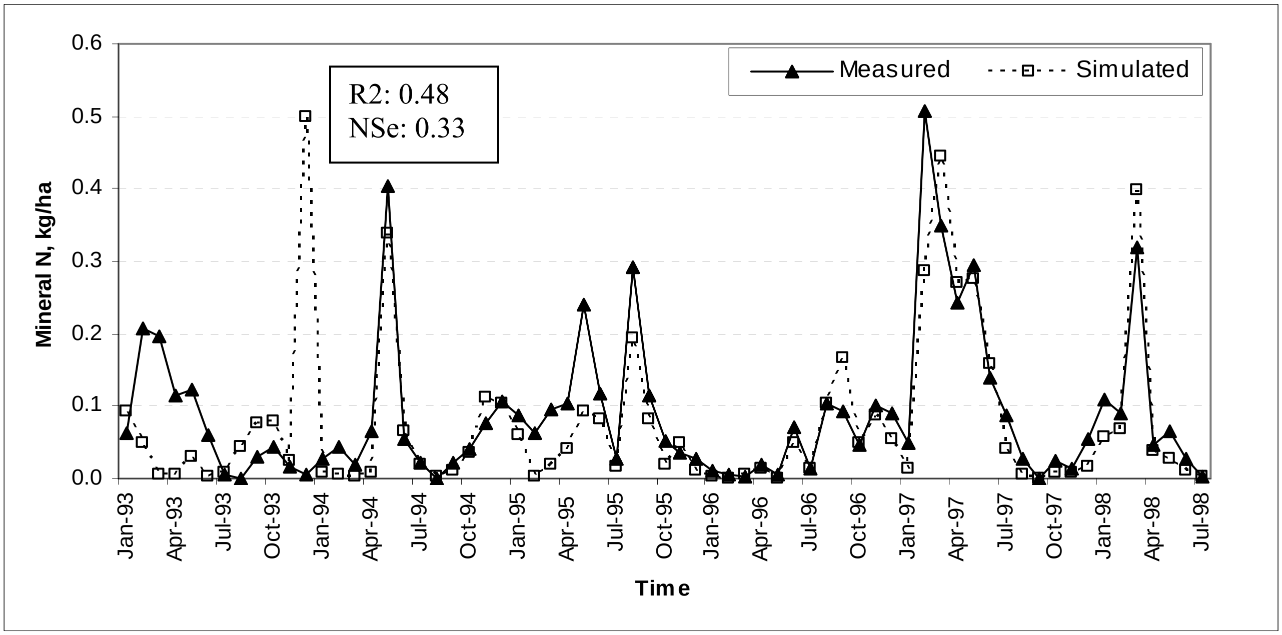
(b)


R2: 0.71
NSe: 0.60
Measured
Simulated
Organic N, kg/ha
2.5
2.0
1.5
1.0
0.5
0.0
Jan-93
Apr-93
Jul-93
Oct-93
Jan-94
Apr-94
Jul-94
Oct-94
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Time

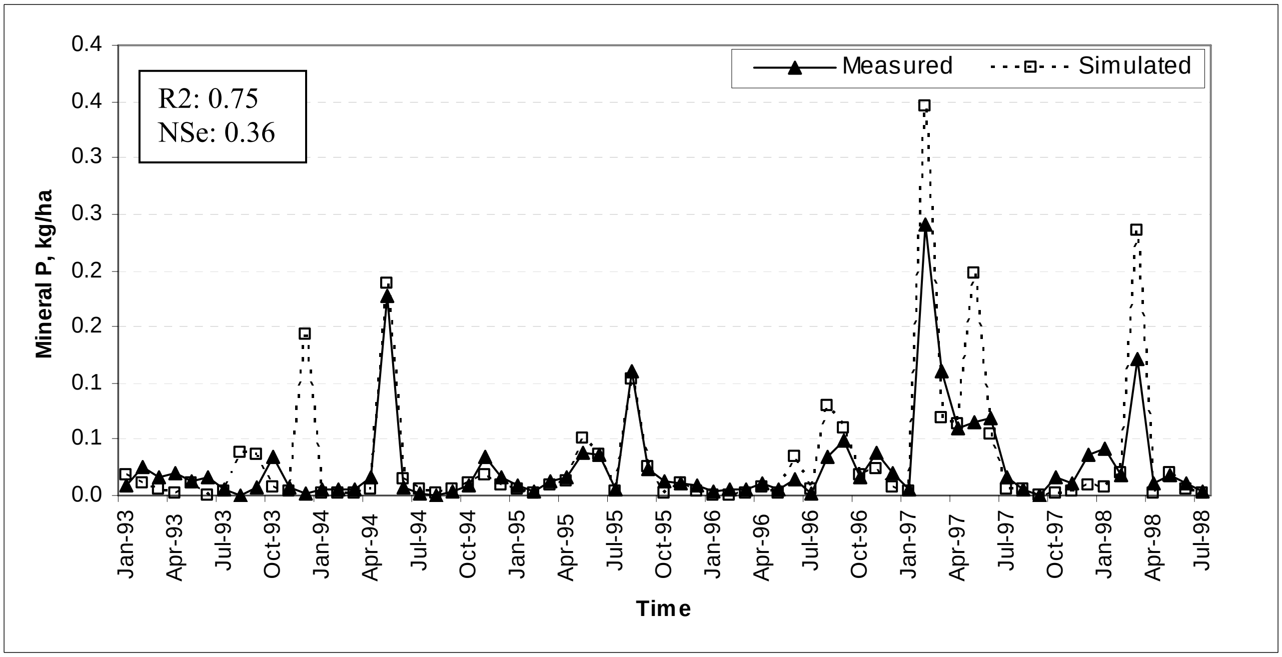
(c)


R2: 0.70
NSe: -0.26
Measured
Simulated
Organic P, kg/ha
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Jan-93
Apr-93
Jul-93
Oct-93
Jan-94
Apr-94
Jul-94
Oct-94
Jan-95
Apr-95
Jul-95
Oct-95
Jan-96
Apr-96
Jul-96
Oct-96
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Time

(d)

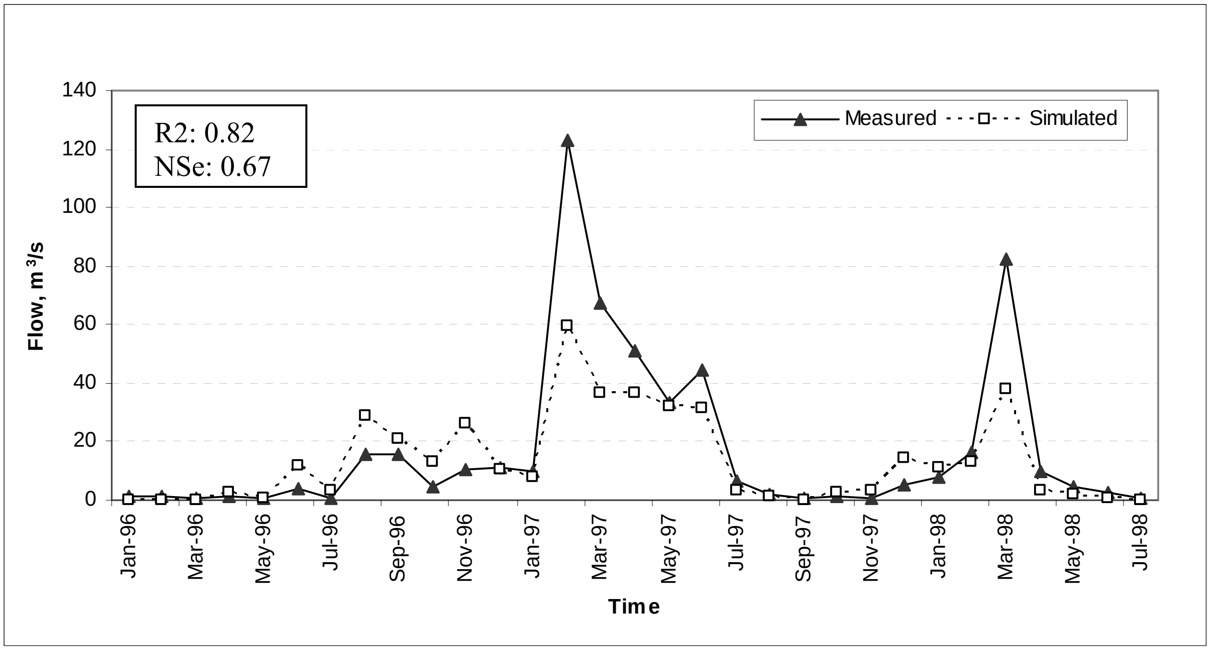


(e)



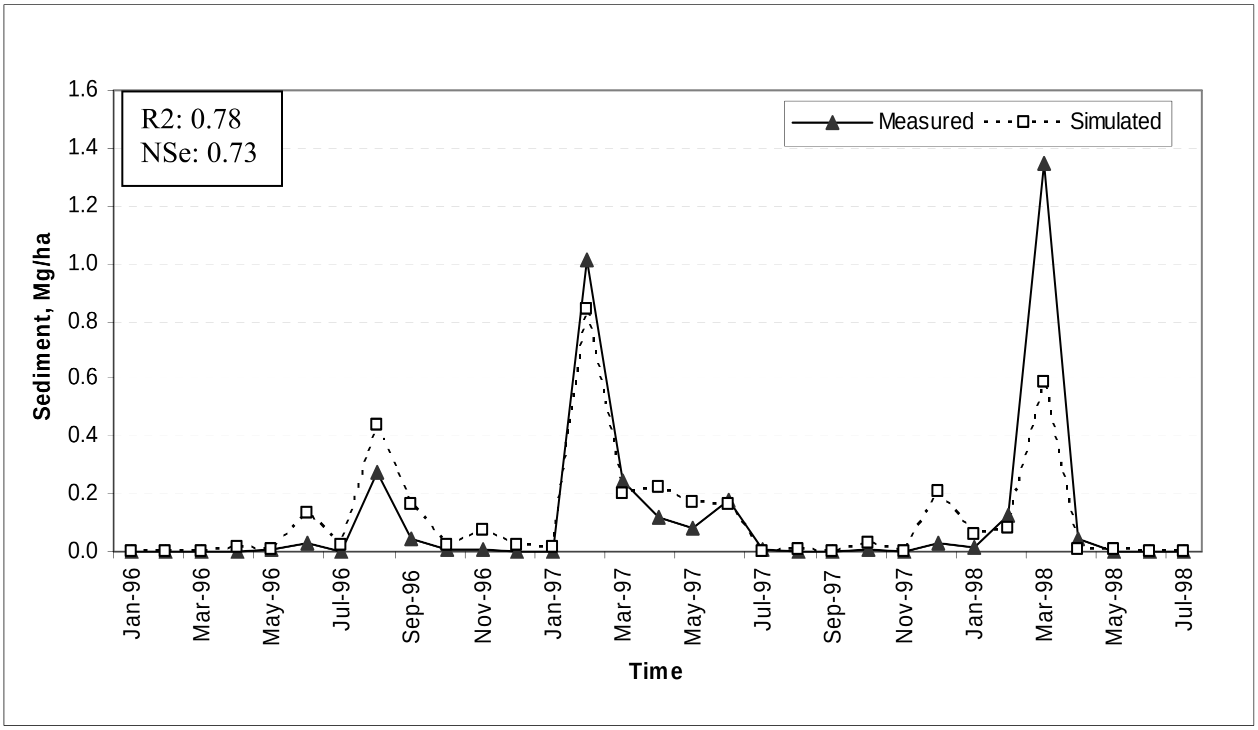
(f)

Figure 14(a-f): Measured and simulated monthly (a) flow, (b) sediment, (c) organic N, (d) Organic P, (e) Mineral N, and (f) mineral P at Hico during the calibration period (Jan 1993 - July 1998)



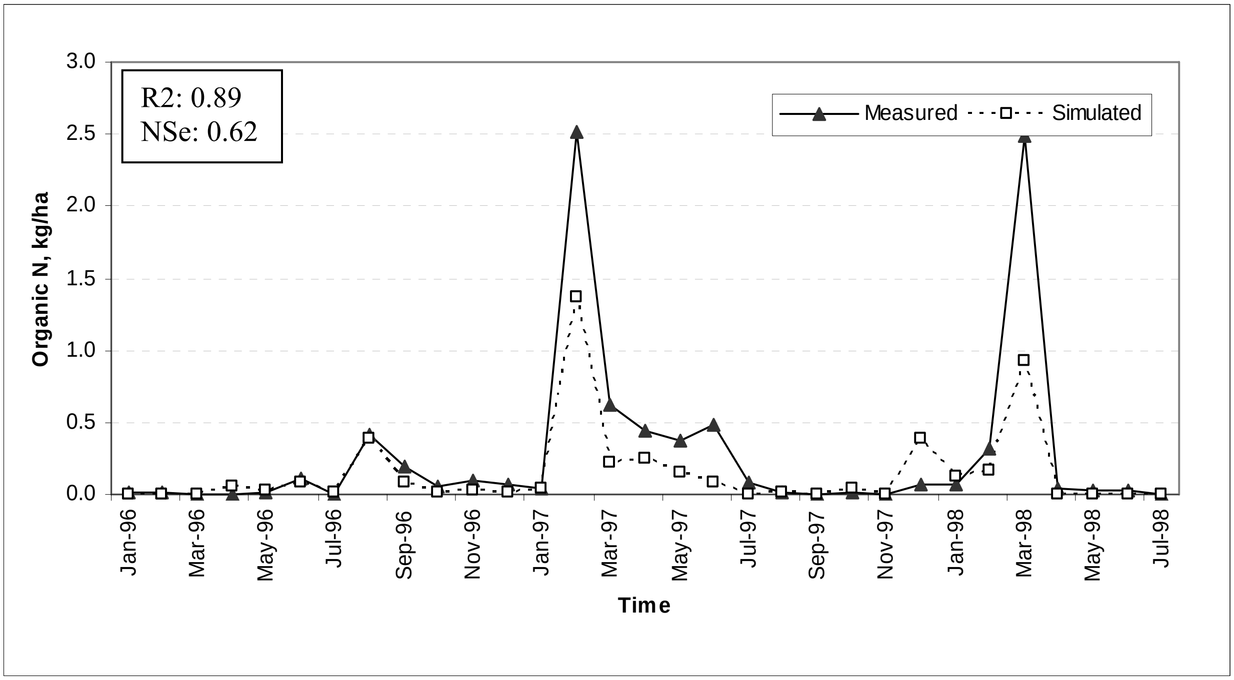
R2: 0.82
NSe: 0.67
Measured
Simulated
Flow, m³/s
140
120
100
80
60
40
20
0
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Time

(a)

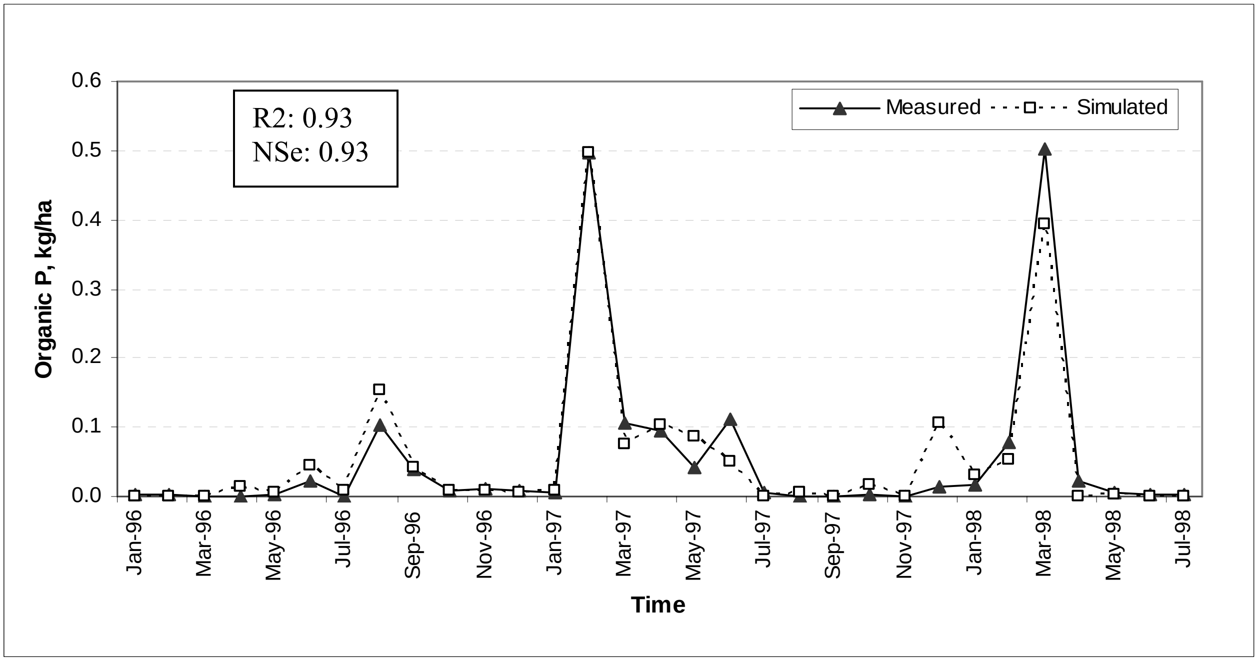


R2: 0.78
NSe: 0.73
Measured
Simulated
Sediment, Mg/ha
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Time

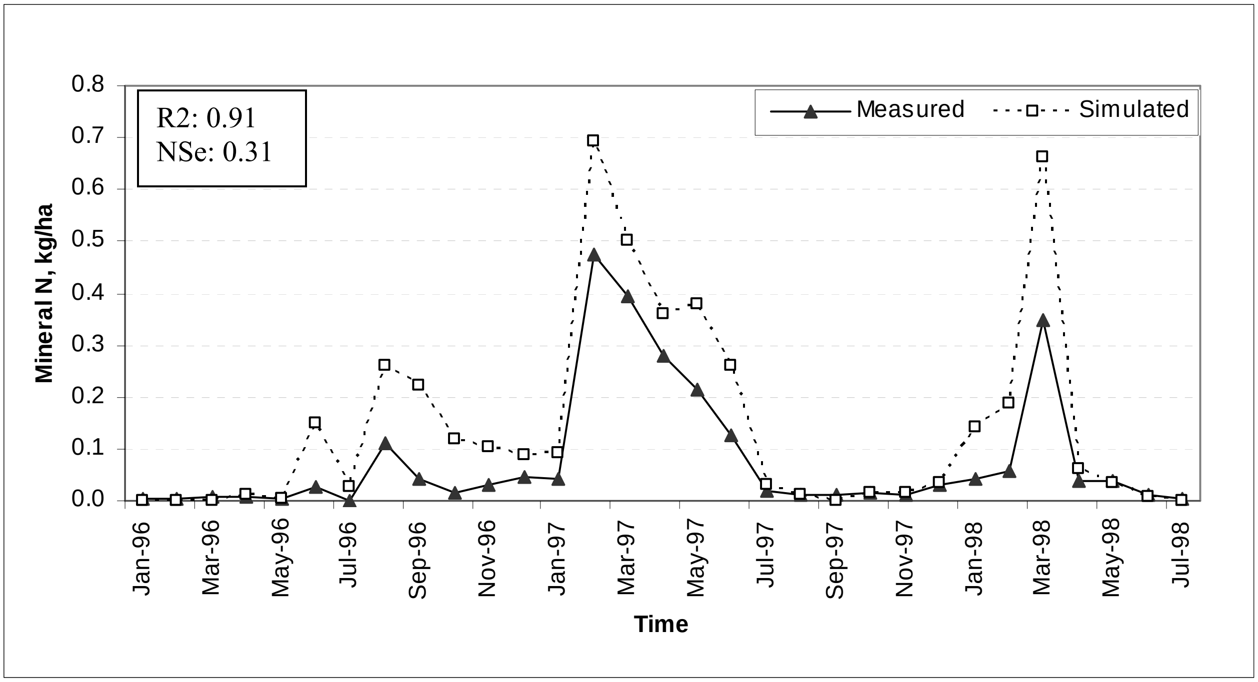
(b)


R2: 0.89
NSe: 0.62
Measured
Simulated
Organic N, kg/ha
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Time

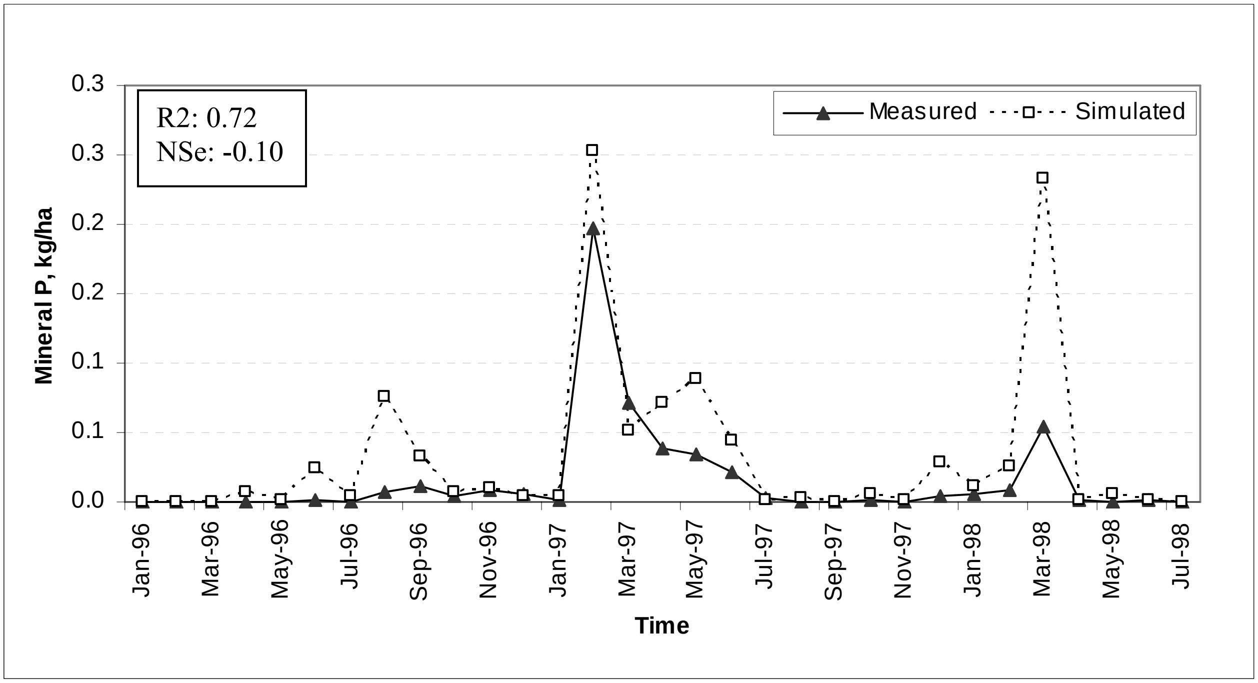
(c)


R2: 0.93
NSe: 0.93
Measured
Simulated
Organic P, kg/ha
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Jan-96
Mar-96
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Time

(d)



(e)



(f)

Figure 15(a-f): Measured and simulated monthly (a) flow, (b) sediment, (c) organic N, (d) Organic P, (e) Mineral N, and (f) mineral P at Valley Mills during the calibration period (Jan 1996 - July 1998)

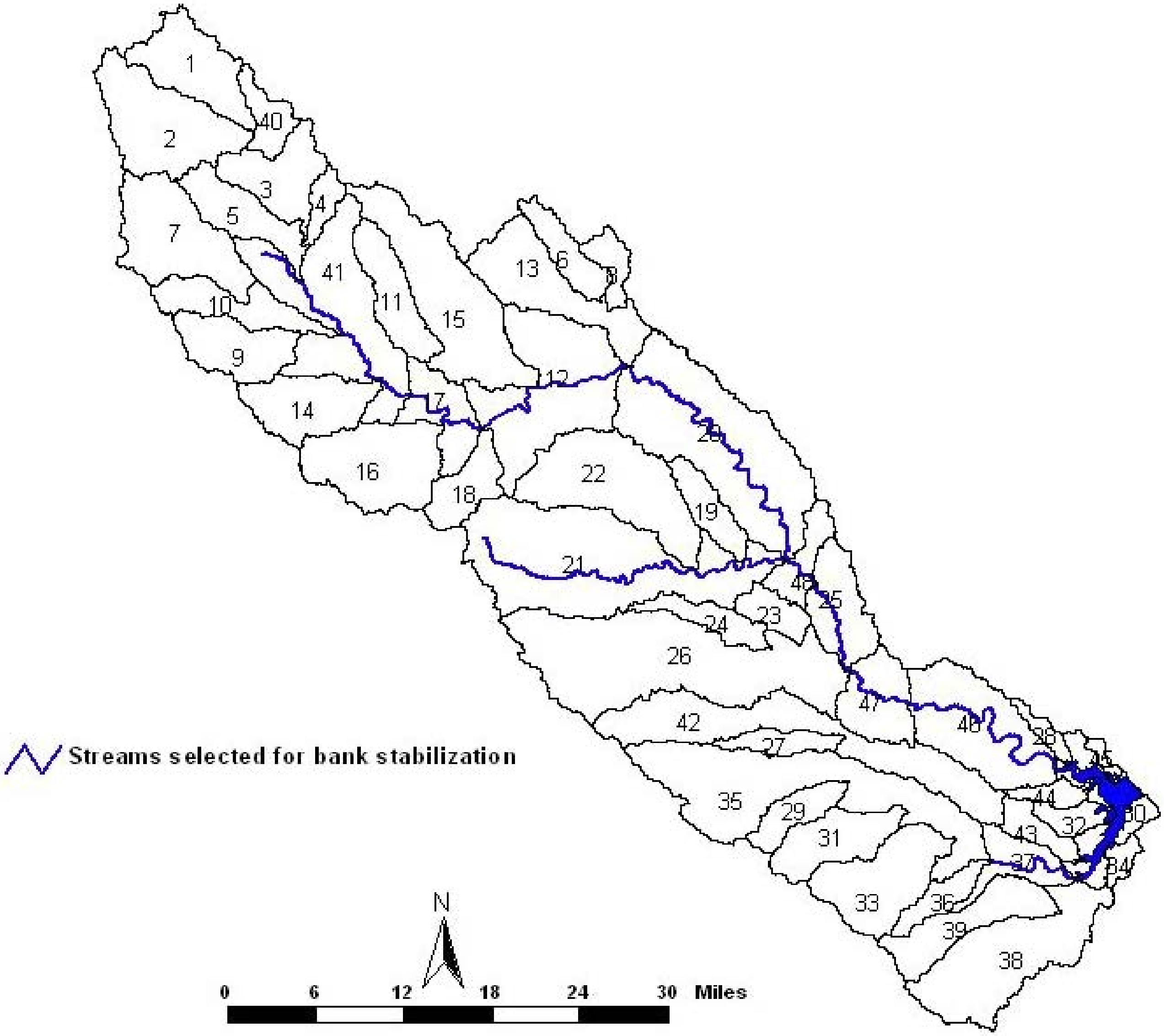
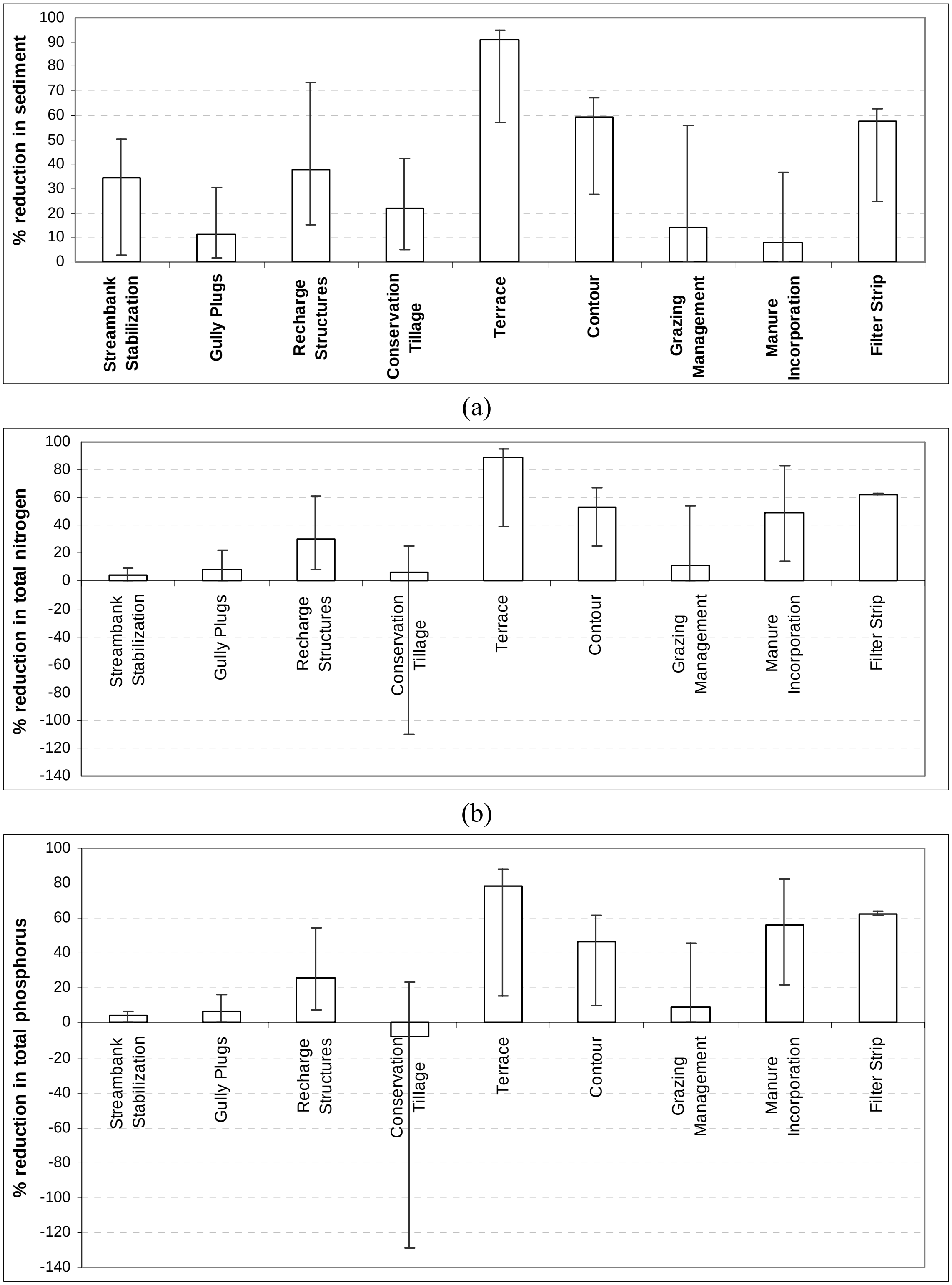


Figure 16: Streams selected for streambank stabilization, with a total stream length of 245 km

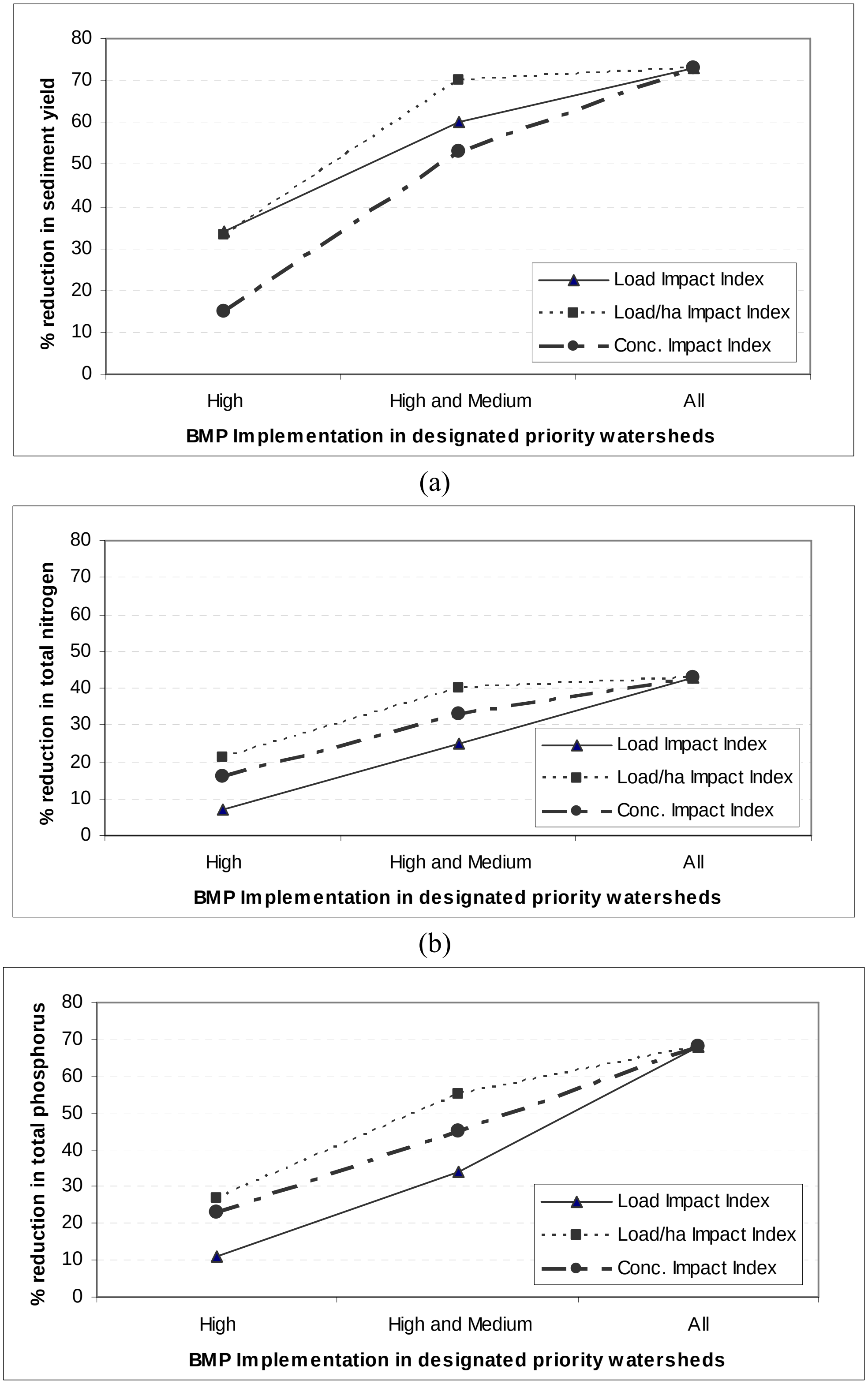


(a)

(b)

(c)

Figure 17: Long-term (30 years) HRU average (bars) and range (minimum and maximum represented by the line through the bars) percent reduction in (a) sediment, (b) total nitrogen, and (c) total phosphorus for various BMPs



(a)

(b)

(c)

Figure 18: Cumulative annual average percent reductions from implementing BMPs incrementally in high, medium and all subwatersheds over a long-term (30 years): (a) sediment, (b) total nitrogen, and (c) total phosphorus

Tables

Table 1: Model input data type, scale, and source for Bosque River Watershed

Type	Scale	Source
Topography/DEM	1:24,000 (30m 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
Weather (Precipitation and Temperature)	11 precipitation stations 7 temperature stations	National Weather Service-National Climatic Data Center (NWS-NCDC)
Land Management Information on Waste and non-Waste Application Fields	---	TIAER / Santhi et al. (2001a, 2001b) / expert opinion

DEM: Digital Elevation Model
NWS-NCDC: National Weather Service-National Climatic Data Center
SSURGO: Soil survey Geographic
TIAER: Texas Institute of Applied Environmental Research
USGS NLCD: United States Geological Survey National Land cover Dataset
USDA-NRCS: United States Department of Agriculture-Natural Resources Conservation service

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	-3
ESCO	Flow	Soil evaporation compensation factor	0.01 – 1.00	0.6
EPCO	Flow	Plant uptake compensation factor	0.01 – 1.00	1.0
GW_REVAP	Flow	Groundwater revap coefficient	0.02 – 0.40	0.08
GWQMN	Flow	Threshold depth of water in the shallow aquifer required for return flow to occur	0.0 – 300.0	50
C-factor	Sediment	Land surface cover factor	0.003 to 0.45	Corn: 0.08 Sorghum: 0.08 Range: 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		Denitrification exponential rate coefficient	0.0 – 3.0	3.0
CMN		Rate factor for humus mineralization of active organic nutrients (N and P)	0.0001 – 0.0003	0.0001
NPERCO	Mineral nitrogen	Nitrate percolation coefficient	0.01 – 1.0	0.01
PPERCO	Mineral phosphorus	Phosphorus percolation coefficient	10.0 – 17.5	10
PHOSKD	Mineral phosphorus	Phosphorus soil partitioning coefficient	100 - 175	100
RSDCO	Sediment and nutrients	Residue decomposition coefficient	0.01 – 0.05	0.01

BC2	Nitrogen 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	Phosphorus 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	Phosphorus in reach	Organic phosphorus settling rate in the reach at 20°C (day^{-1})	0.001 – 0.1	0.1
AI1	Nitrogen in reach	Fraction of algal biomass that is nitrogen	0.07 – 0.09	0.09
AI2	Phosphorus in reach	Fraction of algal biomass that is phosphorus	0.01 – 0.02	0.02
MUMAX	Nitrogen and phosphorus in reach	Maximum specific algal growth rate (day^{-1})	1.0 – 3.0	2.0
SDNCO	Nitrogen	Denitrification threshold water content (fraction of field capacity water content above which denitrification takes place		0.975

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
Streambank stabilization	• Reduce sediment load in streams • Maintain channel capacity	Main stream(3rd, 4th order and above	CH_COV CH_EROD CH_N(2)	0.4 0.008 – 0.05 0.014	0.25 Reduced by 50% 0.03
Porous gully plugs	• Reduce ephemeral gully erosion • Reduce velocity of flow • Trap sediment	Subbasins with slope > 5%	CH_N(1)	0.014	0.05
Recharge structures	• Increase ground water recharge • Facilitate sediment settling	Subbasins with soils of hydrologic group A and B	CH_K(1), mm/hr CH_N(1)	0.5 0.014	25 0.08
Conservation tillage	• Reduce velocity of flow • Reduce erosion	All cropland	EFFMIX DEPTIL, mm CN2	0.70 – 0.75 75 – 100 varies	0.25 100 CN2 reduced by 2 from the calibration values
Terrace	• Reduce overland flow and conduct runoff to a safe outlet • Reduce sheet erosion	All cropland	CN2 P-factor	Varies 1.0	CN2 reduced by 5 from the calibration values 0.10, if slope = 1 to 2% 0.12, if slope = 3 to 8%
Contour farming	• Reduce sheet erosion	All cropland	CN2 P-factor	Varies 1.0	CN2 reduced by 3 from the calibration values 0.5, if slope = 1 to 2% 0.6, if slope = 3 to 8%
Manure incorporation	• Reduce nutrients loading in runoff	All Waste Application Fields	FRT_SURFACE	1.0	0.0

Grazing management	• Reduce sediment	All pasture land and rangeland	HI	0.99	0.85
Filter strip	• Reduce sediment, dissolved contaminants, and sediment adsorbed organics in runoff	All cropland and WAF	FILTERW	0.0	6.0m

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/hr)
DEPTIL: Depth of mixing caused by the tillage operation (mm)
EFFMIX: Mixing efficiency of tillage operation
FRT_SURFACE: Fraction of fertilizer applied to top 10mm of soil
FILTERW: Width of edge-of-field filter strip (m).
HI: Harvest Index

Table 4: Conservation practice factor P for the Universal Soil Loss Equation (USLE)

Farming up and down slope				P = 1.0	
For contour farming					
	Maximum slope length (feet)			P factors	
(a) Land slope (percent)	(b) Contouring	(c) Strip cropping	(d) Maximum strip width	(e) Contour	(f) Strip Crop
1 to 2	400	800	130	0.6	0.3
3 to 5	300	600	100	0.5	0.25
6 to 8	200	400	100	0.5	0.25
9 to12	120	240	80	0.6	0.3
13 to16	80	160	80	0.7	0.35
17 to 22	60	120	60	0.8	0.4
21 to 25	50	100	50	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 x 0.2		
Loss from terrace with underground outlet			Contour p factor x 0.1		

Source: Schwab et al. 1995, originally based on Wischmeir and Smith 1978

Table 5: Rating values for the three impact indices

	Concentration Impact Index	**Load Impact Index**	**Load per unit area Impact Index**
Low	1 to 4	1 to 3	1 to 4
Medium	5 to 7	4 to 7	5 to 8
High	8 to 12	8 to 12	9 to 12

Table 6: Calibration and validation results at USGS gaging station at Valley Mills

Flow (m^3/s)	**Mean**		**Std. dev.**		**R^2**	**NS_e**
Calibration (1980 to 2005)	Measured	Predicted	Measured	Predicted		
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

Table 7: Monthly calibration at Hico for the period Jan-93 to Jul-98

Component (unit)	**Mean**		**Std. dev.**		**R^2**	**NS_e**
	Measured	Predicted	Measured	Predicted		
Flow (m^3/s)	4.36	3.68	5.28	4.96	0.66	0.63
Sediment (t/ha)	0.05	0.04	0.10	0.09	0.73	0.73
Organic N (kg/ha)	0.22	0.12	0.32	0.32	0.71	0.60
Organic P (kg/ha)	0.04	0.04	0.06	0.11	0.70	-0.26
Mineral N (kg/ha)	0.09	0.07	0.10	0.11	0.48	0.33
Mineral P (kg/ha)	0.03	0.03	0.04	0.06	0.75	0.36

Table 8: Monthly calibration at Valley Mills for the period Jan-96 to Jul-98

Component (unit)	**Mean**		**Std. dev.**		**R^2**	**NS_e**
	Measured	Predicted	Measured	Predicted		
Flow (m^3/s)	17.34	13.41	28.45	15.38	0.82	0.67
Sediment (t/ha)	0.12	0.11	0.30	0.19	0.78	0.73
Organic N (kg/ha)	0.28	0.14	0.62	0.29	0.89	0.62
Organic P (kg/ha)	0.06	0.06	0.12	0.11	0.93	0.93
Mineral N (kg/ha)	0.08	0.14	0.13	0.19	0.91	0.31
Mineral P (kg/ha)	0.02	0.03	0.04	0.06	0.72	-0.10

Table 9: Long-term (30 years) annual average percent reduction at the watershed outlet (load into Lake Waco), with BMPs implemented in all possible areas of the watershed (high, medium, and low priority subwatersheds)

Type of BMP	**Sediment**	**TN**	**TP**	**length (km) or area (km^2) of BMP implementation**
Streambank stabilization	34.6	0.9	4.0	245 km*
gully plug	5.3	4.8	4.9	959 km**
Recharge structures	37.2	24.4	29.6	1302 km**
Conservation tillage	3.0	3.1	-3.3	432 km^2
Terrace	17.2	18.5	27.0	432 km^2
Contour	9.6	10.20	15.60	432 km^2
Grazing management	7.4	5.3	4.0	2820 km^2
Manure incorporation	0.0	1.7	20.9	88 km^2
Filter strip	9.4	15.5	25.7	499 km^2
Removal of current PL-566 structures	-9.3	-15.2	-16.9	

*length of main channel in the subbasins considered
**length of tributary channels within the subbasins considered

Table 10: Long-term (30 years) annual average overland percent load reduction, with BMPs implemented in all possible areas of the watershed (high, medium, and low priority subwatersheds)

Type of BMP	Sediment	TN	TP
Gully plug	12.9	7.8	6.8
Recharge structures	46.7	36.8	31.7
Conservation tillage	4.6	3.6	1.4
Terrace	24.6	21.3	20.5
Contour	15.9	11.9	11.5
Grazing management	10.4	6.9	5.3
Manure incorporation	0	2.8	9.7
Filter strip	16.8	17.6	20.1
Removal of current PL-566 structures	-25.4	-16.6	-18.8

Table 11: Long-term (30 years) annual average field level percent load reduction, with BMPs implemented in all possible areas of the watershed (high, medium, and low priority subwatersheds)

	Sediment	**TN**	**TP**
Streambank stabilization	3 – 51	0 – 9	0 – 7
Gully Plugs	1 – 30	0.6 – 22	0.5 – 16
Recharge Structures	16 – 74	8 – 61	7 – 55
Conservation Tillage	5 – 42	-110 – 26	-129 – 23
Terrace	57 – 95	39 – 95	16 – 88
Contour Farming	28 – 67	25 – 68	10 – 62
Grazing Management	0 – 56	0 – 54	0 – 46
Manure Incorporation	0 – 37	14 – 83	22 – 83
Filter Strip	25 – 63	62 – 63	62 – 64

Table 12: Long-term (30 years) percent reductions in sediment, TN, and TP due to BMP (including streambank stabilization, recharge structures, conservation tillage, terrace, grazing management, and manure incorporation) implementation in "high" priority "medium and high" priority, and all subwatersheds

% reduction in sediment yield

	Load Impact Index	Load/ha Impact Index	Conc. Impact Index
High	34	33	15
High and Medium	60	70	53
All	73	73	73

% reduction in total nitrogen

	Load Impact Index	Load/ha Impact Index	Conc. Impact Index
High	7	21	16
High and Medium	25	40	33
All	43	43	43

% reduction in total phosphorus

	Load Impact Index	Load/ha Impact Index	Conc. Impact Index
High	11	27	23
High and Medium	34	55	45
All	68	68	68

Table 13: Percent of total watershed area (or stream length) under the particular BMP corresponding to the high, medium, and low priority subwatersheds for different impact indices

	Load Impact Index			**Load/area Impact Index**			**Conc. Impact Index**		
	High	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
Streambank stabilization	46	54	0	44	51	4	0	64	36
Recharge structures	12	25	63	24	54	23	23	36	40
Conservation tillage	11	27	62	42	38	20	40	34	27
Terrace	11	27	62	42	38	20	40	34	27
Grazing management	14	34	52	25	57	18	20	40	41
Manure incorporation	0	14	86	0	59	40	26	25	49