Simulating Water Quality Improvements in the Upper North Bosque River Watershed Due to Phosphorus Export through Turfgrass Sod

G. R. Stewart, C. L. Munster, D. M. Vietor, J. G. Arnold, A. M. S. McFarland, R. White, T. Provin

Abstract. *The Upper North Bosque River (UNBR) watershed is under a total maximum daily load (TMDL) mandate to reduce loading of soluble phosphorus (P) in impaired river segments. To address these problems, Texas A&M University researchers have developed a Best Management Practice (BMP) that removes excess nutrients from impaired watersheds through turfgrass sod. Harvest of manure-grown sod removes a thin layer of topsoil along with any residual P in this soil layer. In order to assess the impact of the turfgrass BMP on a watershed scale, the Soil and Water Assessment Tool (SWAT) was used to predict water quality changes among four scenarios in the UNBR watershed. The SWAT model was modified to incorporate turfgrass harvest routines for simulation of manure and soil P export during harvest of turfgrass sod. SWAT simulations of the four BMP scenarios predicted reductions of 20% to 36% for instream P loads in the UNBR depending on manure P rate and areas allotted to sod. In addition, total N load was reduced on average by 31% and sediment load declined on average 16.7% at the watershed outlet. The SWAT model predicted up to 176 kg/ha P was removed per harvest of sod top-dressed with 100 kg manure P/ha. Export increased to 258 kg/ha of P per harvest for the manure P application rate of 200 kg/ha. Depending on the implementation scenario, simulations indicated the turfgrass BMP could export between 262 and 784 metric tons of P out of the UNBR watershed every year.*

Keywords. *Manure, Modeling, Nitrogen, Nonpoint-source pollution, Phosphorus, Sediment, SWAT, Turfgrass BMP, Waste application fields, Water quality.*

Phosphorus (P) and nitrogen (N) are major pollutants in U.S. surface water. These nonpoint-source (NPS) contaminants can contribute to excessive algae and aquatic plant growth in urban and agricultural streams. Excess algal growth and decomposition can lead to water odor and taste problems, fish kills, and other environmental and aesthetic problems (TCEQ, 2003a). Elevated N and P levels and algal blooms have been identified within segments of the Upper North Bosque River (UNBR) in Erath County, Texas (McFarland and Hauck, 1998).

A turfgrass Best Management Practice (BMP) is being developed and evaluated to remove excess nutrients from impaired watersheds (Vietor et al., 2002) through turfgrass harvest and sod transport out of the watershed. Previous field studies demonstrated that this BMP could export 47% to 100% of applied manure P (Vietor et al., 2002; Choi et al., 2003) in a single sod harvest. The exported sod, which can be used for residential developments, sports complexes, and parks in urban or suburban sectors, could economically transport large amounts of manure nutrients out of impaired rural watersheds. This article uses the Soil Water Assessment Tool (SWAT) to evaluate the effectiveness of the turfgrass BMP to improve in-stream water quality in the UNBR watershed.

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Background of the Upper North Bosque River Watershed

The UNBR watershed comprises a large portion of Erath County, the leading milk-producing county in Texas, and forms the headwaters of the North Bosque River. This river begins north of the city of Stephenville, Texas, and continues southeast to Lake Waco. Lake Waco is the primary source of municipal water for the City of Waco and its 150,000 citizens (Keplinger and Hauck, 2002). The UNBR watershed is defined as the area drained by the North Bosque River from its headwaters north of Stephenville down to an outlet at Hico, Texas (fig. 1). At Hico, a Texas Institute for Applied Environmental Research (TIAER) gauging and sampling station is located where the UNBR crosses U.S. Highway 281. This station (BO70) marks the watershed outlet for this study.

A large portion of the dairy cows within the watershed are concentrated in confined animal feeding operations (CAFOs) (Munster et al., 2004). As of 1998, approximately 34,000 dairy cows were distributed among 100 dairies on the

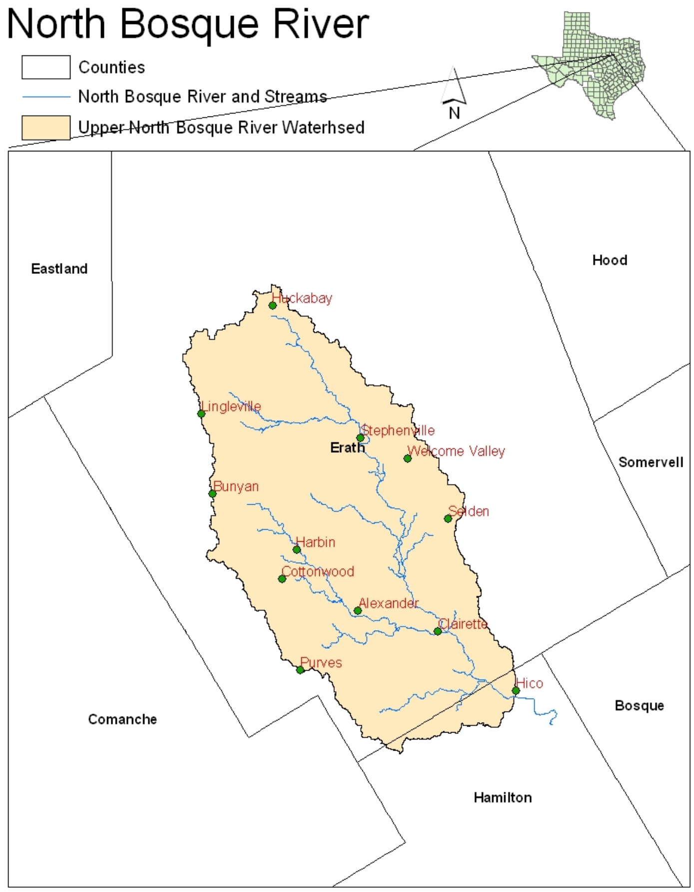

Figure 1. Location Upper North Bosque River watershed with stream segments, major towns, and counties also shown. The watershed outlet used in the model simulations was located in Hico, Texas.

93,250 ha of the UNBR watershed. In addition, the UNBR watershed is covered primarily by rangeland (McFarland and Hauck, 1998). The large amount of nutrient-rich dairy manure produced by these cows is spread over permitted waste application fields throughout the watershed. Manure nutrients accumulate on waste application fields (WAFs) and could be transported in surface runoff into nearby streams. It is estimated that 44% of the soluble P load in the UNBR comes from the WAFs, which constitute only 7.3% of the watershed area (McFarland and Hauck, 2001). Elevated soluble reactive P levels have placed the UNBR watershed on the EPA's 303(d) list as mandated by the Clean Water Act (USEPA, 2002). This list of impaired water bodies was prepared in Texas by the Texas Commission for Environmental Quality (TCEQ) for the U.S. EPA. In response, the TCEQ has established and submitted a total maximum daily load (TMDL) calling for a 50% reduction of soluble reactive P loading in the impaired segments of the UNBR (TNRCC, 2001).

To comply with TMDL-mandated P reductions, new BMPs are needed to remove excess manure nutrients from the UNBR watershed. The State of Texas currently subsidizes hauling of dairy manure from CAFOs to composting facilities in Erath County (Munster et al., 2004). However, BMPs are needed to use approximately 150,000 m^3 of surplus compost currently available in the watershed (TCEQ, 2003b; TWRI, 2004). Nutrients in these stockpiles of composted manure could be utilized by the turfgrass BMP and exported in sod harvests out of the UNBR watershed in a sustainable manner. The watershed would also benefit economically from the development of a turfgrass industry, which is currently almost non-existent in the area.

The Turfgrass BMP

Ongoing plot and field studies using three turf species indicated that 44% to 77% of the P top-dressed as fresh or composted dairy manure can be removed with sod harvests (Vietor et al., 2002). It is estimated that average annual exports of up to 150 kg per ha will occur if three sod crops are harvested every 2 years when each crop receives 200 kg of manure P ha^{-1}. The annual manure P export per hectare of sod is equivalent to the manure P produced yearly by 7.6 dairy cows (Munster et al., 2004).

Due to the short re-growth period prior to sod harvest, little or no leaching of P from the top 2.5 cm harvest layer occurs (Hay, 2003). However, top-dressing of composted dairy manure prior to re-growth of sod fields can increase the potential for P loss in surface runoff. Yet, rapid turfgrass establishment and re-growth on turfgrass production fields effectively traps sediment and limits nutrient loss in runoff. In paired 1.42 ha research fields, with and without composted dairy manure, only 3.8% of applied manure P was lost in surface runoff (Choi et al., 2003). These runoff P losses were small compared to mean exports of P in the soil, manure residue, and turfgrass. A total of 254 and 212 kg P ha^{-1} was exported in consecutive sod harvests from fields top-dressed with 75 and 127 kg P ha^{-1} total manure P (Vietor et al., 2004b). Additionally, turfgrass can aesthetically improve the landscape, increase water infiltration, and reduce runoff. Water infiltration rates with turfgrass are up to six times greater than with most other ground covers. In addition, a dense turfgrass sod is an excellent mechanism for soil stabilization and erosion control (Landscape Standards, 2004).

Application of composted dairy manure during sod production accentuates the benefits of turfgrass sod transplanted to urban landscapes. The organic nutrients in the residues of composted dairy manure are proximate to the roots in the sod layer and held with soil below a dense canopy of turfgrass. Therefore, transplanted manure-grown turfgrass sod can eliminate applications of inorganic P fertilizer for establishment and for annual turf maintenance. Previous studies indicated that sod transplanted from fields supplied with 190 kg P ha^{-1} of manure P and raised soil-test P at the receiving site to 130 mg P ha^{-1} (Vietor et al., 2004b). If return of clippings and the dense plant population in the sod layer minimizes annual loss of nutrients after transplanting (Kopp and Guillard, 2002; Kussow, 2004), then soil-test P can remain above turf P sufficiency levels for 10 to 15 years (Carrow et al., 2001). The elimination of P fertilizer applications on manure-grown sod transplanted to urban landscapes would be a benefit to water quality in urban streams. For example, the State of Minnesota passed legislation that requires homeowners in sensitive watersheds to restrict fertilizer P applications to reduce excess nutrients in runoff (MAWD, 2003). A turfgrass that requires no P applications would be ideal for these sensitive watersheds. Finally, turfgrass grown with manure P enhances turfgrass recovery and quality when transplanted (Angle, 1994).

Purpose of the Study

Plot and field scale research has demonstrated the effectiveness of the turfgrass BMP in manure nutrient removal from impaired watersheds. This article extends the field research to the watershed scale using Soil and Water Assessment Tool (SWAT) model simulations to assess the potential impact of the turfgrass BMP on water quality in the UNBR watershed. A total of 2,370 ha of suitable turfgrass production sites in the UNBR watershed had been previously identified (Munster et al., 2004) and was used in the model simulations (fig. 2).

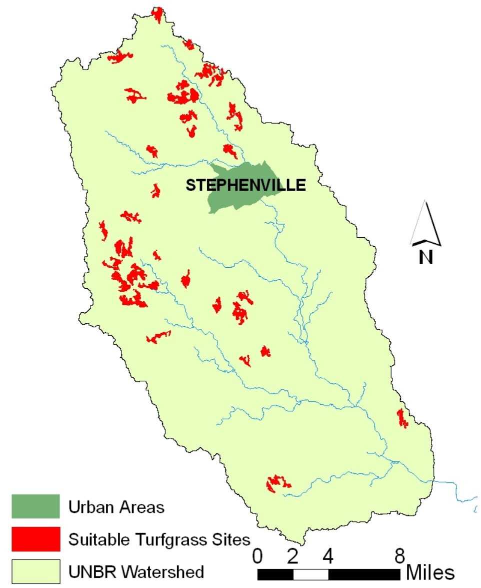

Figure 2 Suitable turfgrass production sites in the UNBR watershed. Sites were used in the SWAT model simulations to assess water quality improvements in the UNBR due to the turfgrass BMP (Munster et al., 2004).

The SWAT model simulates various aspects of a watershed, including surface and ground water hydrology, erosion and sedimentation, plant growth and management, and nutrient cycling with reasonable accuracy when the model is successfully calibrated and validated. In addition, the model incorporates point-source inputs of effluent discharges and accommodates spatial variability of soil types, land uses, weather, and topography (Neitsch et al., 2002a).

The SWAT model has been used previously for modeling the UNBR watershed (Hauck et al., 2003). This facilitated model calibration, validation, and simulation of BMP effects on the UNBR watershed. In addition, the TCEQ used the model to establish a TMDL for P in the UNBR. The Texas Institute for Applied Environmental Research (TIAER) also calibrated SWAT in combination with the Agricultural Policy/Environmental eXtender (APEX) model to determine P and N contributions to the UNBR from permitted WAFs (Saleh et al., 2000). Finally, the USDA Blacklands Research Center in Temple, Texas, also simulated N and P transport processes on the UNBR watershed (Santhi et al., 2001).

Materials and Methods

Model Selected

A modified version of the SWAT 2000 model was used to simulate four scenarios of commercial turfgrass production and to predict water quality impacts of the turfgrass BMP in the UNBR watershed. This model, developed by the USDA Agricultural Research Service (Arnold et al., 1998), is a physically based, semi-distributed model that runs on a variable continuous time step, optimized to efficiently handle large and complex watersheds (Arnold et al., 1998). The SWAT model is included in the EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software package and derives its inputs from GIS data layers through the BASINS pre-processor. This GIS interface expedites model setup, enhances accuracy, and reduces human error during the data input process.

SWAT Model Input Datasets

Most of the SWAT inputs were derived from GIS layers using the BASINS interface. When necessary, inputs were manually formatted and entered directly into the model. Topography, soil, and land use data sets were loaded into the BASINS pre-processor as raster or vector GIS layers. Stream inputs from the Stephenville wastewater treatment plant, temperature and rainfall, land management operations, and initial watershed conditions were all entered into the model.

Land Inputs

Topographical data of the UNBR watershed were downloaded from the USGS National Map Seamless Data Distribution System (USGS, 2004a), which is part of the National Elevation Dataset (NED). This Digital Elevation Model (DEM) is a 1:24,000 scale (30 m resolution) grid with elevation in meters above mean sea level. The elevation of

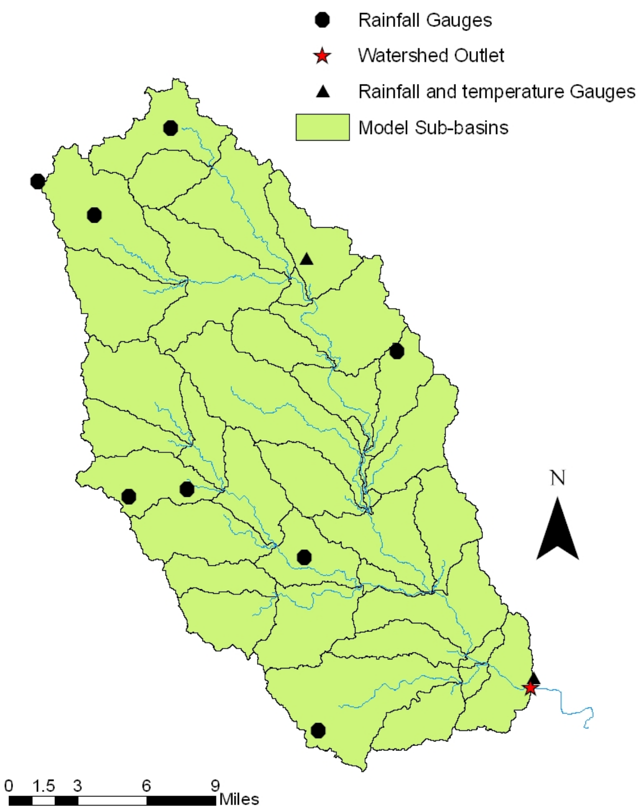

Figure 3. Distribution of the sub-basins used in the SWAT model simulations for the UNBR watershed. Locations of rainfall and temperature gauges and the watershed outlet are also shown.

the UNBR watershed ranges from 305 m to 496 m above MSL. This DEM was processed through BASINS to create 39 sub-basins for the SWAT simulation (fig. 3).

The soil dataset used in model simulations of the UNBR was the Soil Survey Geographic (SSURGO) dataset developed by the National Resource Conservation Service (NRCS). The SSURGO datasets for Erath and Hamilton Counties (fig. 1) were used to cover the extent of the UNBR watershed. Erath County data were available in SSURGO version 1 format, but Hamilton County had already been formatted in the new SSURGO version 2 format (NRCS, 2004). Development of a composite GIS vector dataset for the two counties required a link between spatial cells and the correct soil type and characteristics in the SWAT soils database. Manipulation of the database allowed the use of SSURGO high-resolution (1:24,000 scale) data in SWAT instead of the State Soil Geographic (STATSGO) soil inputs. This was done by linking the SSURGO geographical dataset with the STATSGO soils database.

The National Land Cover Dataset 1992 was obtained from the USGS. This dataset is a 1:24,000 scale grid derived primarily from Landsat imagery as part of the Multi-Resolution Land Cover project (USGS, 2004b). A data set with the size, shape, and location of the permitted WAFs within the UNBR watershed was provided by TIAER. This WAF GIS layer was combined with the NLCD layer to create a detailed land cover data layer.

The watershed is predominantly rural, and the only significant urban areas are Stephenville and part of the town of Dublin. The land cover in the UNBR watershed is primarily range land (table 1). BASINS was setup to use the

Table 1. Land use distribution in the UNBR watershed as determined from the NLCD.

Land Use	Area (ha)	Area (%)
Range land	57,142	61.4
Pasture	3,496	3.8
Agricultural	10,156	10.9
Urban	2,164	2.3
Waste application	6,776	7.3
Forest	11,701	12.6
Other[a]	1,699	1.8

[a] Other land uses include open water, wetlands, and barren ground.

land cover database in combination with the soils database to create hydrologic response units (HRUs) for each of 39 subwatersheds. The HRUs were established using an inclusion threshold of 5% for land use and 10% for soil type in order to filter out HRUs of little influence to the watershed. This resulted in a model with 471 HRUs.

The effluent from the Stephenville wastewater treatment plant flows into the UNBR and is the only permitted point discharge within the watershed. Biweekly sampling data collected by TIAER of the effluent discharge and monthly self-reporting data of discharge from the WWTP were summarized into monthly contributions to the UNBR. Another model input was the initial soil nutrient concentrations for the various land covers. Initial P and N concentrations in the soil were derived from previous SWAT model calibrations for the UNBR watershed by the Blacklands Research Center (Santhi et al., 2001) (table 2).

Weather

Rainfall data from 11 weather stations managed by The National Climatic Data Center (NCDC, 2003) or TIAER in the UNBR watershed were used for the SWAT simulations (fig. 3). Two of these weather stations also recorded temperature data. Total daily rainfall and daily maximum and minimum temperature data were used as SWAT inputs for a monthly time step calibration.

Land Management

Previous reports of land management by TIAER and other researchers in the UNBR watershed were used to develop inputs for agricultural land operations in SWAT simulations. Gassman (1997) described various cropping systems and manure and fertilizer application rates used for previous APEX simulations of the UNBR watershed. In addition, Gassman (1997) detailed management operations, including dates of fertilizer applications for each cropping system.

Table 2. Initial soil nutrient concentrations used in SWAT model calibrations based on prior model calibration (Santhi et al., 2001).

Land Use	Nutrient	mg/kg
Waste application fields	Organic N	5,000
	Organic P	700
	Mineral P	250
Pasture / range land	Organic N	850
	Organic P	150
	Mineral P	5
Agricultural	Organic N	1,100
	Organic P	200
	Mineral P	20
Urban	Organic N	2,000
	Organic P	400
	Mineral P	5

These detailed inputs were converted into SWAT crop management scenarios for each of the agricultural land uses.

Estimated total production of dry dairy manure in the UNBR watershed was 109,800 tons/year, which was uniformly distributed over the 6,554 ha of WAF for the SWAT model calibration. Therefore, the WAFs received 16,753 kg/ha/year of dry dairy manure.

SWAT Model Modifications

In the SWAT model simulations, dairy manure application was diverted from the WAFs to turfgrass sod production fields. The manure was composted before application during sod establishment or re-growth. The SWAT model was amended to include new management operations for turfgrass sod harvest. The new management operations simulated the removal of a thin layer of soil with the sod harvest. In addition, new SWAT management files were created using the management file utility to include the new harvest operations. These new management operations were then used in the HRUs that had turfgrass sod production fields.

In the SWAT model, the depth of soil removed in the turfgrass sod harvest operation was set to 25 mm to match actual sod harvest conditions. The new sod harvest routine killed the growing crop and removed 25 mm from the top of the soil profile. The soil nutrient concentrations removed during the sod harvest were recorded to a new SWAT output file. In addition, the soil profile was re-adjusted before the next sod crop was planted to exclude the top 25 mm of soil and the removed nutrients. The SWAT output file recorded the P concentrations in the crop and in the soil layer that was removed during the sod harvest in kg of nutrient ha^{-1} for each of the SWAT nutrient pools. These nutrient pools include organic P (both active and stable), fresh organic P, mineral P (in active, stable, and solution pools), as well as P in the plant (Neitsch et al., 2002b). These concentrations of P were then used to calculate the total mass of P exported during each turfgrass sod harvest. The mass of P exported determined the efficiency of removal for manure P top-dressed on turfgrass sod.

Calibration and Validation

Prior to running the simulations with the modified harvest routines, the model was calibrated and validated for existing conditions in the UNBR watershed based on the research done by TIAER (Saleh et al., 2000) and the Blacklands Research Center (Santhi et al., 2001). Simulated flow, sediment, and nutrient concentrations were compared to observed values on a monthly time step. Observed values were collected by TIAER at the outlet of the UNBR watershed in Hico, Texas (Easterling and McFarland, 2004) and combined with flow data into loadings using integration procedures outlined in McFarland and Hauck (2001).

Table 3. Results of the SWAT model calibration for the UNBR watershed for a five-year period (1994-1999) with the Nash Sutcliffe (NS) and correlation coefficients (r^2) shown for each constituent.

Constituent	NS	r^2
Flow	0.76	0.87
Sediment	0.80	0.94
Organic P	0.69	0.85
Mineral P	0.75	0.88
Organic N	0.71	0.87
Mineral N	0.60	0.80

During the calibration process, coefficients and parameters of the SWAT model were adjusted to represent the conditions in the UNBR watershed. The Nash and Sutcliffe (NS) coefficient (Nash and Sutcliffe, 1970) and regression coefficient (r^2) were used to evaluate the relationship between simulated and observed values. The NS coefficient ranges from $-\infty$ to 1.00, with 0.00 being equal to an average line through the data points and 1.00 representing a perfect fit.

The goal for the calibrated SWAT model was to achieve an NS coefficient greater than 0.50 for each simulated constituent at the outlet of the UNBR watershed. The SWAT model was calibrated for flow, sediment, organic P, mineral P, organic N, and mineral N, in that order. The calibration was performed for a five-year period (1994-1999), one constituent at a time, using the two previously discussed calibrations by Saleh et al. (2000) and Santhi et al. (2001) as starting points. Once a satisfactory calibration for a constituent was obtained, the calibration accuracy of preceding constituents was also confirmed. The calibration goal of NS > 0.50 was attained for all constituents on a monthly time step, as shown

Table 4. SWAT model variables adjusted during the model calibration. The adjusted value or the final amount of change from default SWAT values are shown.

Constituent	Variable	Description[a]	Adjusted Value or Percent Change
Flow	Alpha BF	Base flow alpha factor (days)	0.013
	GWQMN	Return flow threshold depth (mm)	150
	GW_REVAP	Ground water “revap” coefficient	0.02
	ESCO	Soil evaporation compensation factor coefficient	0.08
	CN2	Curve number	−8[b]
Sediment	SPCON	Linear parameter for channel sediment retained coefficient	−86%[b]
	SPEXP	Exponent parameter for channel sediment retained coefficient	10%
	CH_EROD	Channel erodibility factor coefficient	−10%[b]
Phosphorus	BC4	Rate constant for P mineralization at 20°C	0.07
Nitrogen	NPERCO	Nitrogen percolation coefficient	−80%[b]
	SOL_ORGN	Initial soil organic N concentration (PPM)	12%[b]
	SOL_NO3	Initial soil NO_3 concentration (PPM)	−80%[b]
	BIOMIX	Biological mixing efficiency	0.4
	BC3	Rate constant for N hydrolysis at 20°C	0.1

[a] Complete descriptions are available in the Soil and Water Assessment Tool user’s manual (Neitsch et al., 2002b).
[b] Represent an adjustment of the default SWAT model value.

Table 5. Results of the SWAT model validation for the UNBR watershed for a 14-month period (2001-2002) with the Nash Sutcliffe (NS) and correlation coefficients (r^2) shown for each.

Constituent	NS	r^2
Flow	0.80	0.92
Sediment	0.63	0.82
Organic P	0.58	0.89
Mineral P	0.37	0.82
Organic N	0.73	0.89
Mineral N	−0.04	0.57

in table 3. In addition, an r^2 coefficient greater than 0.80 for all constituents indicates that the model accurately simulates temporal changes as well. The changes required for the SWAT model calibration of the UNBR watershed are presented in table 4.

The calibrated model was validated by comparing simulated flow and nutrient concentrations to observed values from January 2001 to March 2002. The magnitude of NS coefficients achieved during validation (table 5) indicated a strong correlation between the simulated and observed constituents in the UNBR, except for mineral N. Mineral P was only slightly lower than the target NS value of 0.50. In addition, the NS coefficients indicated that the model accurately simulated stream responses to weather and management conditions in the UNBR watershed. All r^2 coefficients were greater than 0.80 for simulated constituents, except 0.57 for mineral N. The mineral N variance, reflected in both the NS and regression coefficients, was due primarily to a large spike in observed mineral N loads in the first four months of the validation period, which the SWAT model underpredicted. However, since the focus of the simulation was on P, and the organic N calibration was very strong, the model performance was considered to be acceptable.

Simulation

The calibrated and validated SWAT model was used to assess the water quality impact of four scenarios for the turfgrass BMP in the UNBR watershed. The scenarios were run for the same period as the model calibration, from 1991 to 1999 and analyzed from 1994 to 1999. The first three years (1991 to 1993) were used as a buffer to stabilize model variables and improve accuracy. In order to compare only nonpoint nutrient sources and to better present the impact of the turfgrass BMPs on water quality, the Stephenville wastewater treatment plant effluent point source was removed from the model simulations. This constant point source was removed from calibrated and simulation results to be able to calculate percent changes of nonpoint sources only.

Suitable turfgrass sod production sites identified by Munster et al. (2004) were utilized in the UNBR watershed. Two allocations of land resources for turfgrass sod production were simulated. One simulation scenario used 100% of the turfgrass sod production sites (2,008 ha) available in the UNBR watershed (fig. 4). The other scenario used 50% of suitable sites (1,004 ha). For the simulations using 50% of the suitable sod production sites, the largest fields were selected. The 50% allocation scenario represents the more realistic expectation for turfgrass BMP implementation in the UNBR watershed. The turfgrass sod production sites used in the model simulations did not overlap with existing dairy WAFs in the watershed.

For each land allocation scenario, two application rates (100 and 200 kg P ha^{-1} per harvest of top-dressed composted dairy manure) were evaluated for the turfgrass sod production sites with three harvests simulated every two years. The composted manure application rates were selected to match the supporting field research application rates (Vietor et al., 2002). The combinations of land allocation and manure application rates combined to form the four scenarios for the SWAT model simulations: (1) 100 kg P ha^{-1} applied to 2,008 ha after each harvest (scenario 100/100%), (2) 100 kg P ha^{-1} applied to 1,004 ha (scenario 100/50%), (3) 200 kg P ha^{-1} applied to 2,008 ha (scenario 200/100%), and (4) 200 kg P ha^{-1} applied to 1,004 ha (scenario 200/50%). The top-dressed composted dairy manure at these application rates represented compost depths of approximately 0.55 cm (100 kg P ha^{-1}) and 1.1 cm (200 kg P ha^{-1}).

To calculate the manure mass diverted away from WAFs to turfgrass sod production fields, P was used as the mass constant for converting fresh dairy manure to composted dairy manure. It was assumed that no P was removed during the composting process (Larney, 2004). This transfer of fresh dairy manure to the composting facilities for subsequent use on turfgrass sod reduced manure application to the WAFs (table 6). The fresh dairy manure application rates to WAFs

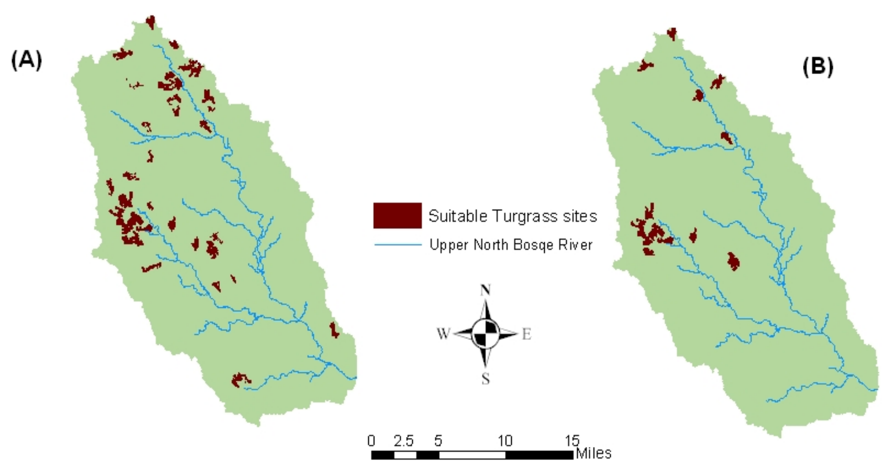

Figure 4. Location of turfgrass sod production sites in the UNBR watershed used in the SWAT model simulations. Map (A) represents 100% of the suitable sites, and map (B) represents 50% of the suitable turfgrass sites. None of these sites overlap with existing WAFs.

Table 6. Reduction of manure applied to the WAFs due to implementation of the turfgrass BMP for the four SWAT simulation scenarios.

	Manure Diverted Away from WAFs			
P Application Rate	100% of Suitable Sites (2008 ha)		50% of Suitable Sites (1004 ha)	
100 kg/ha	2,904 kg/ha	17.3%	1,523 kg/ha	9.1%
200 kg/ha	5,666 kg/ha	33.8%	2,904 kg/ha	17.3%

for the calibrated model, which represents current watershed conditions, was 16,753 kg/ha/year, which equates to 174 kg P/ha from the fresh dairy manure.

The SWAT model auto-fertilization routine was used to apply N as ammonium sulfate as needed for optimum growth in the management files for the turf-growing HRUs. Moreover, the auto-irrigation routine was also used to supply water for optimum production of turfgrass sod. The agricultural management operations applied to the HRUs with turfgrass sod production utilized commercial sod production standards.

Table 7. Comparison of changes in stream flow, sediment, and N forms at the watershed outlet at Hico, Texas, between the control simulation and the four turfgrass BMP scenario simulations. Positive changes represent reductions compared to the control simulation.

Scenario	Flow (%)	Sediment (%)	Mineral N (%)	Organic N (%)	Total N (%)
100/50%	−1.99	17.03	2.89	44.98	33.03
200/50%	−2.03	16.88	3.00	45.01	33.09
100/100%	−3.87	15.16	−5.26	42.63	29.04
200/100%	−3.84	15.16	−8.00	42.67	28.29
Average	−2.93	16.06	−1.84	43.82	30.86

Table 8. Comparison of changes in mineral P, organic P, and total P loads between the control simulation and the four BMP scenarios at the watershed outlet at Hico, Texas. Positive changes represent reductions with respect to the control simulation, in which all manure is allocated to WAFs.

Scenario	Mineral P (%)	Organic P (%)	Total P (%)
100/50%	29.73	39.93	35.66
200/50%	24.11	39.74	33.19
100/100%	14.48	36.12	27.05
200/100%	−1.05	35.72	20.33
Average	16.82	37.88	29.06

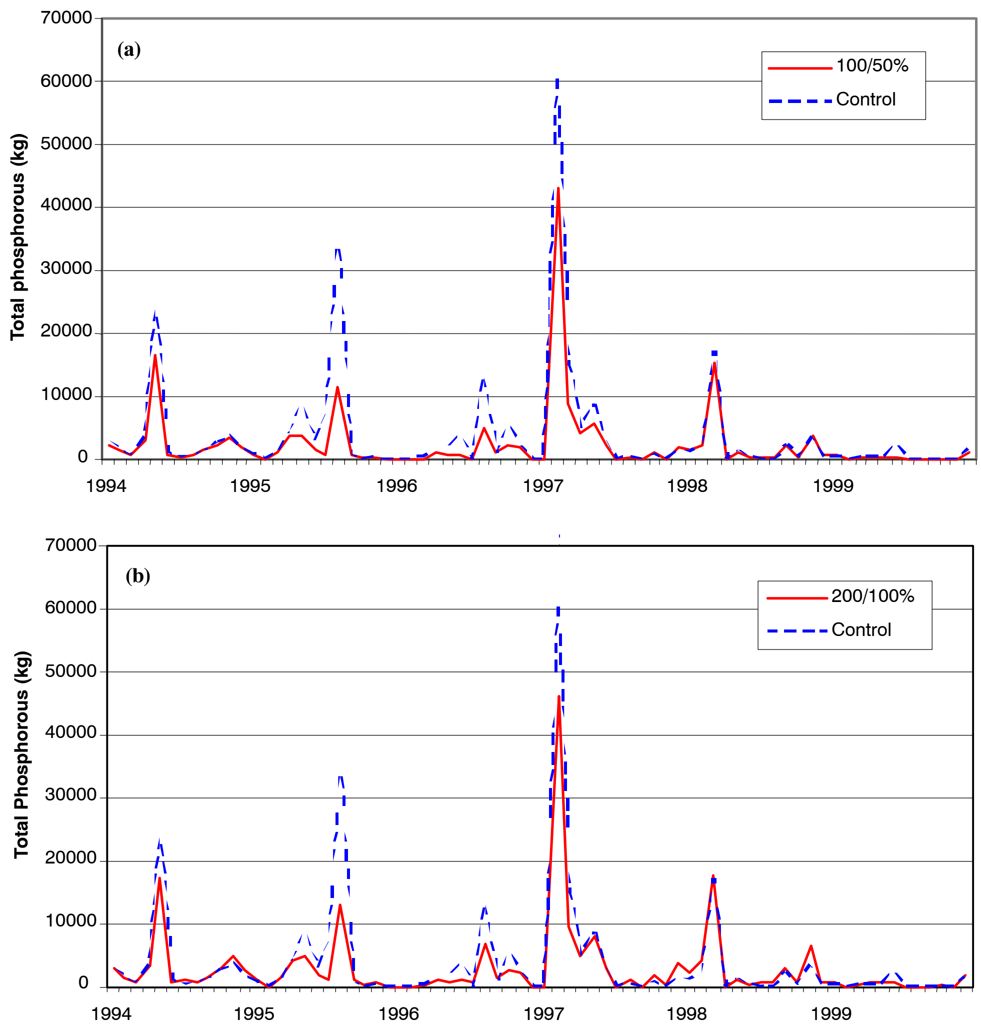

Figure 5. Total P loads for two of the turfgrass BMP simulation scenarios compared to the control simulation load at the watershed outlet at Hico, Texas. The turfgrass BMP scenarios are: (a) 100 kg P/ha application to 50% (1,004 ha) of the suitable turfgrass sites (100/50%), and (b) 200 kg P/ha application to 100% (2,008 ha) of the suitable turfgrass sites (200/100%).

Results and Discussion

The calibrated and validated SWAT model was used to simulate the four turfgrass BMP scenarios to predict the effectiveness of the BMPs in reducing P loads to the UNBR, as well as in exporting total P out of the watershed. The simulated results for the four turfgrass BMP scenarios were compared to a control simulation of nonpoint sources. An emphasis was placed on P, which was targeted in the current TMDL assessment of the UNBR. However, simulated flow, sediment, organic N, and mineral N in the stream outlet were similarly analyzed and compared to the control simulation for each scenario of sod production. All comparisons were based on simulated monthly total loads (kg/month) in the UNBR at the watershed outlet.

For all four scenarios, the SWAT model predicted a significant decrease in total nutrient loads in the UNBR compared to the control (tables 7 and 8), and the simulations indicated that turfgrass sod harvest effectively exported P from the watershed. The simulations are consistent with previous field research (Vietor et al., 2002, 2004a; Choi et al., 2003) and demonstrate the low P runoff and high P export potential of the turfgrass BMP at the watershed scale. Even though turfgrass sod generally increases water infiltration, there was little effect on stream flow. The regular irrigation needed at the proposed turfgrass sod production fields maintained high antecedent moisture conditions, which would offset potential reductions in runoff due to sod production. Sediment load was reduced in all four scenarios with average sediment loads reduced by 16% (table 7). Reduced sediment loads were attributed to the substitution of dense turfgrass sod production fields for more erodible row-crop fields in the watershed. Most of the areas targeted for turfgrass production are currently used to grow annual grains and forage crops. The reduction of simulated sediment loads resulted in decreased nutrient loads in the UNBR due to reductions of sediment-bound P (table 8). Figure 5 shows this reduction of P for two of the four simulated scenarios.

Compared to the control simulation, the predicted reductions of total N in the UNBR at the watershed outlet averaged 31%. Despite the total N reductions, predicted mineral N loads were similar to the control simulation. This is due to the required auto-application of large quantities of N fertilizer in the HRUs with turfgrass sod production. However, the predicted reduction of 44% for organic N in the UNBR outweighed the slight mineral N changes for all four BMP scenarios (table 7).

The use of only 50% of the suitable turfgrass areas for sod production reduced concentrations of both organic and mineral P and N in the UNBR more than the allocation of 100% of the suitable sites for sod production (table 8 and fig. 5). Allocation of 100% of suitable land to sod production increased the area of turfgrass fields as well as the percentage close to streams or the watershed outlet, as seen in figure 4. Since the 50% suitable turfgrass area scenario selected the largest contiguous fields, the 100% scenario also resulted in a larger perimeter-to-area ratio.

It is interesting to note that reductions of mineral and organic P in the UNBR become smaller as the manure P application rate and the turfgrass sod production areas for BMP scenarios increase. The SWAT simulations indicated that mineral P loading is more sensitive to increases of turfgrass production areas and manure application rates than is organic P and sediment load. Mineral P changes ranged from a 29.73% reduction for the 100/50% scenario to a 1.05% increase for the 200/100% scenario. Organic P declined only 4% between these respective scenarios. These simulations indicate that increased composted dairy manure P application rates to turfgrass sod will increase losses of mineral (dissolved) P in runoff (table 8). The predictions reflect the sensitivity of the SWAT model to mineral P concentrations in composted dairy manure and to the increasing application rates of composted manure. Yet, all four BMP scenarios predicted significant export of P in turfgrass sod harvests and a reduction of total P loads to the UNBR compared to the control simulation (table 9). The simulations of the four BMP scenarios predicted an average reduction of 29% for total stream P at the outlet. The 100/50% scenario was most effective in reducing P loads to the UNBR but exported the least amount of manure P from the watershed, consistent with the smaller area grown to sod (tables 8 and 9).

Table 9. Comparison of SWAT simulations of P exported (turf, soil, and total) from the UNBR watershed for the four BMP scenarios based on 11 years of model simulation. The simulations assume three turfgrass sod harvests every two years.

	Average Export per Harvest (kg/ha)			Total P Export per Year	
Scenario	Total P	P in Turf	P in Soil	kg/ha	tonne
100/50%	174.0	57.4	116.6	261.0	262.0
200/50%	256.4	60.8	195.6	384.5	386.1
100/100%	178.3	57.8	120.5	267.5	537.2
200/100%	260.3	60.9	199.3	390.4	783.9

In the model simulations, increases in sediment and nutrient transport in the UNBR occurred during high flows driven by storm events. A benefit of the turfgrass BMP is that manure is distributed over a larger area than the WAFs, resulting in lower site concentrations that reduce the potential for N and P in storm runoff (Vietor et al., 2004a). In addition, the dense growth of turfgrass effectively traps sediment and nutrients in the soil and root matrix.

Another benefit of the turf BMP is that simulated export of total P for all four turfgrass BMP scenarios was higher than the P applications (100 and 200 kg P/ha). Removal of soil P present before manure application contributes to P export in excess of the manure P that would be applied during crop establishment or re-growth (table 9).

The simulated P export in turfgrass sod harvests in excess of the manure P applied during production equates to total soil P concentrations between 151 and 218 mg/kg at turfgrass sod production sites. The suitable turfgrass production sites used for the simulation of the turfgrass BMP scenarios were primarily located on agricultural land in the control simulation, which used an initial soil total P concentration of 220 mg/kg (table 2). Therefore, these simulations suggest that the turfgrass BMP can export P accumulated near the soil surface at existing WAFs. This would extend the usefulness of the WAFs that exceed the 200 mg P kg^{-1} limit for land application of manure nutrients by exporting P from the surface soil in the turfgrass sod harvests.

Summary and Conclusion

Watershed-scale simulations of the turfgrass BMP quantified potential manure P export out of impaired watershed through turfgrass sod. The model simulations provided watershed-scale evaluations to complement plot and field scale research (Vietor et al., 2002; Choi et al., 2003). The SWAT model was customized to include turfgrass production and harvest operations and was calibrated and validated to measured UNBR watershed conditions. The calibrated and validated model effectively simulated four scenarios for the turfgrass BMP on the UNBR watershed. The four scenarios included turfgrass grown on 50% and 100% (1,004 or 2,008 ha) of the suitable turfgrass sites within the UNBR watershed (most of which are currently agricultural lands) and two rates of manure P (100 or 200 kg/ha P of composted dairy manure). All four BMP scenarios were effective in removing the applied P during harvest and in reducing P loads to the UNBR watershed. In addition, the model simulations predicted the removal of antecedent soil P in the top 25 mm layer of soil during each turfgrass sod harvest. In addition to the reduction in P in streams, the model predicted substantial reductions of total N (31%) and sediment loads (16%) in the UNBR at the watershed outlet at Hico, Texas.

Increasing stream loads of P associated with increasing in manure P application rates on WAFs can be offset by increases in P exports from the UNBR watershed through turfgrass sod produced on available agricultural land. Careful site selection during allocation of available land areas to turfgrass production will sustain the positive water quality effects of the turfgrass BMP. A balance between water quality benefits and manure P exports will be essential to the long-term sustainability of the turfgrass BMP's effectiveness.

The SWAT model simulations predicted higher P exports than reported by the field research. This was due to the removal of existing soil P along with the composted-manure applied P. Still, the reduction in runoff P and high concentrations in the exported sod show that the turfgrass BMP is effective in trapping P, confirmed by the loss of only 3.8% of applied P in the research fields (Choi et al., 2003). These simulations suggest that the proposed turfgrass BMP can effectively export excess manure nutrients out of the UNBR watershed. The simulations support implementation of this BMP to help achieve the TMDL mandate of 50% reduction in soluble reactive P in the UNBR. This BMP results in significant reductions in runoff P and can be implemented near any CAFO or composting facility where large amounts of organic nutrients are available. In addition, this turfgrass BMP can be installed on soils with existing high concentrations of P that must be reduced to prevent nonpoint transport in surface runoff. The WAFs in the UNBR watershed that exceed the 200 mg/kg P limit for land application of manure nutrients could benefit from production and export of manure-grown turfgrass sod. Another benefit of turfgrass sod produced with manure is the added value of transplanted sod soil that is rich in organic matter and manure nutrients. The manure residues in sod enhance the success of transplanting and establishment and can eliminate the need for P fertilization for decades (Carrow et al., 2001; Vietor et al., 2004b).

In summary, the UNBR watershed would benefit from reduced nutrient and sediment loads, and a new turfgrass industry would be introduced in the watershed. The turfgrass BMP presents a sustainable mechanism for exporting manure P from impaired watersheds.

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