WATER QUALITY IMPROVEMENTS IN THE UPPER NORTH

BOSQUE RIVER WATERSHED DUE TO PHOSPHOROUS

EXPORT THROUGH TURFGRASS SOD

A Thesis

by

GEORGE R. STEWART

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Biological and Agricultural Engineering

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Approved as to style and content by:

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(Member)	(Head of Department)

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ABSTRACT

Water Quality Improvements in the Upper North Bosque River Watershed due to
Phosphorous Export Through Turfgrass Sod. (December 2004)

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Chair of Advisory Committee: Dr. Clyde L. Munster

The Upper North Bosque River (UNBR) watershed is under a Total Maximum
Daily Load (TMDL) mandate to reduce Phosphorus (P) due to excess nutrients in the
watershed. To address these problems, Texas A&M University researchers have
developed a turfgrass sod Best Management Practice (BMP) to remove excess nutrients
from impaired watersheds. Turfgrass harvest of manure fertilized sod removes a thin
layer of topsoil with most of the manure applied P. Plot and field scale research has
demonstrated the effectiveness of turfgrass to remove manure phosphorus (P). 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 in the UNBR watershed.
The SWAT model was modified to incorporate turfgrass harvest routines to predict
manure and soil P export through turfgrass sod and soil during harvest. SWAT
simulations of the BMP predicted stream load reductions of 20 to 36% for P loads in the
UNBR depending on the implementation scenario, an average reduction of 31% for total
N and 16.7% for sediment for all the scenarios, at the watershed outlet. The SWAT
model also predicted up to 176 kg/ha P removed per sod harvest when fertilized with
100 kg manure P/ha, and 258 kg/ha of P removed per sod harvest when the manure P
application rate was 200 kg/ha. In addition, depending on the implementation scenario,
the turfgrass BMP could export between 262 and 784 metric tons of P out of the UNBR
watershed every year.

Manure fertilized turfgrass has the advantage of slow releasing nutrients from the
composted dairy manure, so it would not require any additional P for life. This means
reduced urban non-point source pollution and lower maintenance cost compared to

regular sod. These modeling simulations complement the wealth of research that shows the effectiveness of the turfgrass BMP.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The United States (U.S.) has invested heavily in water quality and water body remediation projects over the past 30 years yet in a year 2000 survey, approximately 40% of the rivers surveyed by the Environmental Protection Agency (EPA) were not clean enough for fishing or swimming (USEPA, 2002). Economic activities like farming, fishing, manufacturing and tourism that rely on clean water are worth close to $300 billion a year in the U.S. (Water Quality Financing Act 2003). The main pollutant of these water bodies is excess nutrients. Excess nutrients, mainly Phosphorous (P) and Nitrogen (N), come mostly from urban and agricultural Non-Point Sources (NPS), and cause excessive algae and aquatic plant growth. This unbalanced algal growth lead to water smell and taste problems, decreasing water body aesthetics or even fish kills (TCEQ, 2003). The Upper North Bosque River (UNBR) in Erath County, Texas is one of the affected streams with elevated N and P levels (McFarland et al. 1998).

A new Best Management Practice (BMP) being studied at Texas A&M University for the removal of excess nutrients from impaired watersheds is the establishment of commercial turfgrass sod operations. Turfgrass sod for use in housing and urban development, sports complexes and parks can remove large amounts of nutrients from the soil since the sod is harvested with a thin layer of top soil. This nutrient removal would result in NPS pollution decrease. Plot and field scale research at Texas A&M have demonstrated the nutrient removal effectiveness of this BMP. Now the turfgrass sod BMP needs to be tested at watershed scale.

Computer watershed modeling can simulate watershed scale production of turfgrass and its impact on water quality in a cost effective way. Hydrologic models like the Soil and Water Assessment Tool (SWAT) can model the hydrology along with sediment and nutrient loads transported in watersheds (Arnold et al., 98). Simulating

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This thesis follows the style and format of *Transactions of the ASAE*.

turfgrass operations in an impaired watershed through modeling is the most effective and inexpensive method of testing the BMP at a watershed scale prior to investing in actual BMP implementation.

Impaired Watershed

Erath County, Texas has a high concentration of dairy cows, most of them in Confined Animal Feeding Operations (CAFOs), it is the largest producer of milk in Texas (Hanzlik, 2003). The large amount of nutrient rich dairy manure produced by the cows is applied over permitted waste application fields throughout the watershed. The manure nutrients accumulate in the Waste Application Fields (WAFs) and during storms events these nutrients are transported to the streams in surface runoff and into the UNBR. In fact it is estimated that 44% of the soluble P load to the watershed comes from the WAFs which constitute only 3% of the watershed area (Keplinger and Hauck, 2002). The elevated nutrient levels have placed the UNBR watershed in the EPA's 303 (d) list of the Clean Water Act, a list of impaired waters prepared in Texas by the Texas Commission for Environmental Quality (TCEQ) (McFarland et al., 2001). TCEQ in response has established a Total Maximum Daily Load (TMDL) plan for the UNBR that calls for a 50% reduction of soluble P contributions to the stream (TNRCC, 2001). Soluble P was determined to be the limiting nutrient in algal blooms, so reducing P is the most effective method for improving water quality in the UNBR (Kiesling et al., 2001).

The UNBR is the head waters of the North Bosque River. The North Bosque River begins north of the city of Stephenville Texas in Erath County and continues south east all the way to Lake Waco, near the City of Waco. Lake Waco is the source of municipal water to the City of Waco and its 150,000 citizens (Keplinger and Hauck, 2002). The North Bosque River also provides sustenance to towns of Stephenville, Clifton, Iredell, Meridian and Valley Mills. The UNBR watershed is defined as the area drained by the North Bosque River from its beginning north of Stephenville and downstream to Hico TX. Marking its outlet is a United States Geological Survey (USGS) gauging station (08094800) located were the river crosses U.S. Highway 281.

Figure 1 shows the location of the North Bosque River and the Upper North Bosque River watershed.
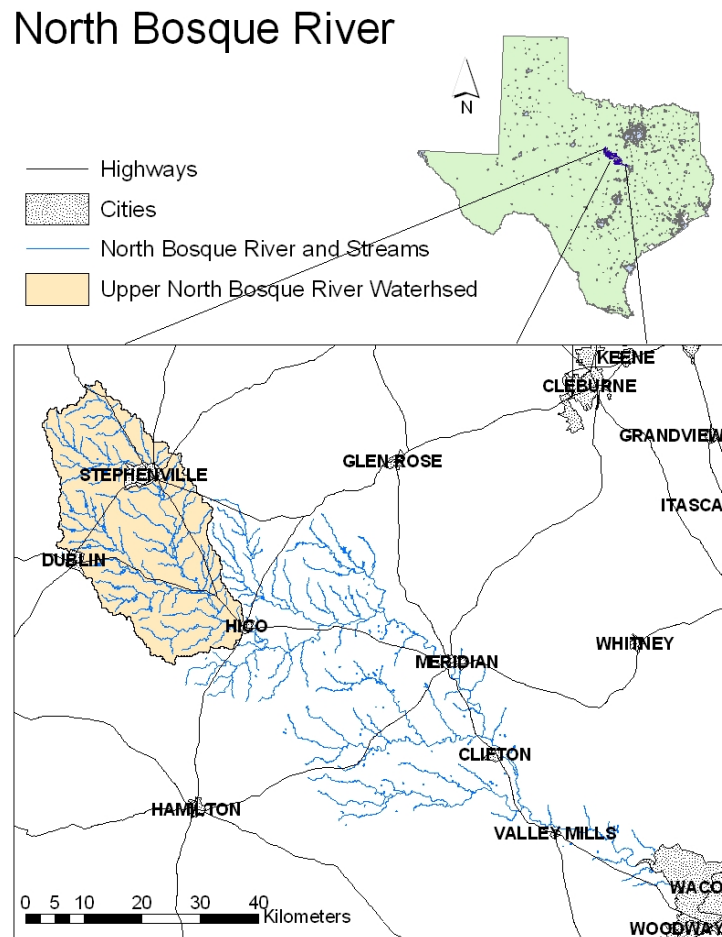
Figure 1. Upper North Bosque River watershed location

The entire 316,220 ha North Bosque River watershed has an estimated 43,000 heads of dairy cattle, but it is permitted for 72,000 cows (Keplinger and Hauck, 2002). The smaller UNBR watershed has an area of 93,250 ha covered mostly by rural land. This sub-watershed had approximately 34,000 dairy cows in 100 dairies as of 1998 (McFarland et al., 1998). Since 1998 there has been a consolidation of dairies, but the number of cows has not changed significantly. The only significant urban areas in the watershed are the city of Stephenville and a small portion of Dublin, TX. This mostly

rural watershed is covered mainly by pastures and rangeland, Table 1 shows the land use distribution of the UNBR watershed. The outlet for the Stephenville waste water treatment flows into the Upper North Bosque River and is the only permitted point discharge within the UNBR watershed. This point source is required to have advanced waste water treatment in order to reduce outlet loads and attain stream nutrient load standards (McFarland and Hauck, 1999). Point source loads like the waste water treatment plant are easy to monitor, NPS are more difficult to determine and quantify their contributions. In the Upper North Bosque River watershed the main contributor of nutrients are NPS, primarily the manure WAFs.

Table 1. Land use distribution in the UNBR watershed

Land Use	Area (ha)	% Area
Range land	57142	61.4%
Pasture	3496	3.8%
Agricultural	10156	10.9%
Urban	2164	2.3%
Waste Application	6776	7.3%
Forest	11701	12.6%
Other[1]	1699	1.8%

[1]Other land uses include open water, wetlands and barren grounds.

The 34,000 dairy cows in the UNBR watershed produce approximately 134,000 tons of dray mass manure per year (ASAE Standards, 2000). This massive load is spread over the waste application fields, and has raised soil P and runoff P concentration to excessive levels. A new sink is needed for the excess manure nutrients, and there are several ideas being tested, implemented or researched. One solution being tested is to compost the dairy manure and then use compost as fertilizer and amendments for poor soils, roadside cuts or parks and home lawns. The state of Texas subsidizes hauling of dairy manure from the CAFOs to the composting facilities to foment this plan (Hanzlik, 2003). The problem has been finding a way to utilize and consume this compost. The cost of hauling the compost itself is higher than most of the benefits it provides, so the compost has been accumulating in the composting facilities. Currently it is estimated

that composting facilities in Erath County stock close to 500,000 tons of nutrient rich composted dairy manure (Personal Communication, Dr. Tony Provin). Turfgrass sod production could consume this compost source, using it as fertilizer to top-dress the crop. Turfgrass sod exports would then represent a sustainable export mechanism for the composted dairy manure.

Turfgrass Sod BMP

In Texas, turfgrass was a $6 billion industry in 1993 with a total house hold turfgrass area of 82,651 ha. The Texas Department of Transportation (TxDOT) maintains approximately 770,000 ha of turfgrass along the states highways. Also in 1993 turfgrass producers had 8,707 ha of turf production (Lard et al., 1996). All the produced turfgrass was harvested with a thin layer of topsoil and transplanted, with turfgrass fields averaging 1.5 harvests per year. It is estimated that approximately 150 kg of P per ha can be removed yearly in turfgrass sod harvest when the turfgrass is fertilized with 200 kg of P per ha from composted dairy manure. This represents exporting the P in manure produced yearly by 7.6 dairy cows in each ha of turfgrass production (Hanzlik, 2003).

Ongoing plot and field scale research at Texas A&M University have demonstrated the effectiveness of the turfgrass BMP to remove manure nutrients, specifically P, through sod harvest. Research plots with a variety of commercial sod grasses removed between 44% and 77% of the P applied to it from composted dairy manure (Vietor et al., 2002). These plots were all top dressed with composted dairy manure and supplemented with nitrogen fertilizer. Larger field scale research showed also that turfgrass is very effective in trapping the P in top-dressed composted dairy manure. In those fields only about 3% of the P applied in composted dairy manure was lost in surface runoff (Choi et al., 2003). This means that most of the P stayed in the turfgrass fields and could be removed during sod harvest.

Along with the nutrient transport potential demonstrated by the Texas A&M University researchers, turfgrass has other well documented beneficial properties. Turfgrass is well known for aesthetically improving landscape, but it also improves soil water infiltration and reduces runoff. Turfgrass has about 6 times the infiltration rate of

most other ground covers. Turfgrass sod is an excellent mechanism for soil stabilization, and erosion control. A healthy lawn can also serve to filter pollutants from runoff water and to dissipate heat. The average front lawn has the cooling capacity of a 10-ton air conditioning unit (Hall, 1999).

Turfgrass sod fertilized with composted dairy manure has added benefits over regular sod. The organic nature of the nutrients in the composted dairy manure means they are stable in the soil matrix and slowly released. Such turfgrass transplanted into an urban development would probably not need any additional P from fertilizer for the life of the sod (T. Provin and R. White, Personal Communication). This reduces sod maintenance costs and prevents over-fertilization of home lawns. Over fertilization of home lawns has become one of the leading sources of NPS pollution. The state of Minnesota has passed legislation that requires home owners to do soil testing of their lawns before selling fertilizers to home owners in order to reduce excess nutrients in runoff (MAWD, 2003). A sod that would require no P amendments would solve this problem, reducing both nutrient loads in runoff and the expenses involved in soil testing. The organic P source also enhances turfgrass establishment after transplant due to better rooting of the turfgrass.

The plot and field scale research has demonstrated the effectiveness of the turfgrass BMP, and the benefits of turfgrass are well known and documented. The next step prior to watershed scale implementation of the BMP is to run modeling simulations to predict watershed scale impact of the turfgrass BMP. Modeling presents an inexpensive research tool to further understand the impacts to water quality of using large scale commercial turfgrass operations to export manure nutrients out of impaired watersheds. Suitable turfgrass production areas within the UNBR watershed have already been identified through several iterations of a GIS query matrix supported by ground truthing (figure 2). This analysis yielded 2,370 ha of suitable turfgrass land within the UNBR watershed, in fields no smaller than 20 ha (Hanzlik, 2003).
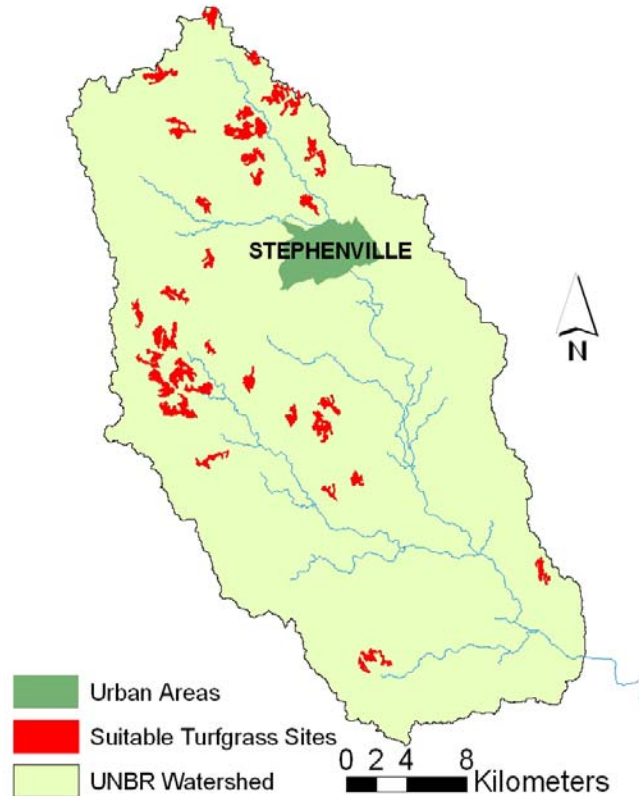
Figure 2. Selected turfgrass suitable sites in the UNBR watershed

Research Objectives

       In order to properly simulate turfgrass sod operation in the UNBR watershed using a hydrologic model like the SWAT model three key steps need to be taken. The model must first be properly calibrated and then validated to existing watershed conditions. Secondly, an accurate routine to model turfgrass harvest, with its unique soil layer removal, need to be developed and implemented. The final step would then be to simulate the introduction of turfgrass sod operations into the UNBR watershed, and use the model results to determine the impact this BMP would have on water quality as well as quantify nutrient removal rates in turfgrass.

       Calibration of the model begins with gathering all the available and useful data for the watershed. There is a wealth of data for the UNBR watershed from the multiple

monitoring projects. Data for modeling the UNBR watershed is available from both governmental institutions such as the USGS or the National Oceanographic an Atmospheric Administration (NOAA) and research institutions like the Texas Institute for Applied Environmental Research (TIAER). Model calibration also benefits from prior projects that successfully modeled the UNBR watershed.

Specifically a couple of recent projects have used the SWAT model to determine nutrient contributions to the UNBR from the permitted WAFs. One project by TIAER coupled the SWAT model with the Agricultural Policy/Environmental eXtender (APEX) model, the watershed was predominantly simulated using the SWAT model, while APEX handled the simulation of the WAFs only. The outputs were then combined in the stream routing. This study determined that the manure applied in WAFs was the major contributor of N and P. Its modeling results showed that the WAFs were responsible for approximately 35% of the total N and 79% of the total P contributions to the UNBR (Saleh et al., 2000). Another similar project conducted by the Blacklands Research Center, developers of the SWAT model, tested the SWAT model by calibrating it to the UNBR watershed. They successfully calibrated flow, along with sediment and nutrient loadings in the watershed to a monthly time step (Santhi et al., 2001). The success in calibration and validations of both projects makes them ideal guidelines for subsequent calibrations of hydrologic models to simulate existing conditions in the UNBR watershed or test watershed scale changes and determine their impact.

Calibration of the SWAT model for the UNBR watershed will be tested by comparing simulated outputs of flow, sediment, organic P, mineral P, organic N and mineral N using the Nash-Sutcliffe coefficient (NS) (Nash et al., 1970). Below is the NS equation were Q_{obs} equals observed values, Q_{sim} equals simulated values and Q_{mean} the average measured values.

$$N.S. = 1 - \frac{\sum_{i=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{n}(Q_{obs} - \overline{Q_{mean}})^2}$$

A simple regression analysis (R^2) will complement the N.S. coefficient to ensure that the variations occur at the correct points in time.

Currently there is no embedded method in any hydrologic model that simulates the unique harvest of turfgrass sod. The removal of a thin layer of topsoil presents a new modeling challenge. A routine that simulates this sod and soil removal needs to be developed before it is possible to simulate turfgrass sod operations in a watershed. Once developed these routines plus a properly calibrated model would be used to determine the effectiveness of a watershed scale turfgrass BMP.

Simulating watershed scale turfgrass sod operations will supplement the plot and scale research ongoing at Texas A&M, to better understand the turfgrass BMP and quantify its effectiveness. Simulations on the UNBR watershed would provide a preview of the turfgrass BMPs ability to reduce nutrient loading to the UNBR and reduce soil P concentrations. By quantifying these reductions and estimating nutrient exports in the UNBR watershed through modeling it will be easy to calculate how watershed scale turfgrass operations would aid in attaining the TMDL mandate to the UNBR.

CHAPTER II

MATERIALS AND METHODS

The primary pollutants in U.S. surface water are excess Phosphorous (P) and Nitrogen (N). These Non-Point Sources (NPS) contaminants from both urban and agricultural sectors cause excessive algae and aquatic plant growth. Often, this unbalanced algal growth leads to odor and taste problems, fish kills and other environmental and aesthetic problems (TCEQ, 2003). The Upper North Bosque River (UNBR) in Erath County Texas is one of these impaired streams due to elevated N and P levels (McFarland and Hauck., 1998). The United States (U.S.) has invested heavily in improving water quality projects over the past 30 years, yet a 2000 survey indicated approximately 40% of the rivers surveyed by the Environmental Protection Agency (EPA) were periodically not clean enough for fishing or swimming (USEPA, 2002).

A new turfgrass Best Management Practice (BMP) is being developed and evaluated to remove excess nutrients from impaired watersheds (Vietor et al., 2002). Plot and field scale research at Texas A&M has demonstrated the effectiveness of this BMP (Vietor et al., 2002 and Choi et al., 2003) to export manure nutrients through commercial turfgrass sod operations. The turfgrass sod, which is used for residential developments and sports complexes and parks in urban or suburban sectors, can economically transport large amounts of manure nutrients out of impaired rural watersheds.

An evaluation of this turfgrass sod BMP on water quality at the watershed scale using SWAT model simulations is the objective of this paper. Computerized simulation models are a cost effective way to simulate water quality impacts a BMP at the watershed scale since they are capable of modeling the hydrology along the sediment and nutrient loads in watershed streams (Arnold et al., 1998).

Impaired Watershed

Erath County is the leading milk producing county in Texas. A large portion of the dairy cows are concentrated in confined animal feeding operations (CAFOs) within

the county (Hanzlik, 2003). As of 1998, approximately 34,000 dairy cows are distributed among 100 dairies on the 93,250 ha of the UNBR watershed, most of which are covered 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 are vulnerable to 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 3% of the watershed area (Keplinger and Hauck, 2002). Elevated soluble reactive P levels have placed the UNBR watershed on the EPA's 303 (d) list mandated by the Clean Water Act. This list of impaired waters is prepared in Texas by the Texas Commission for Environmental Quality (TCEQ) for the U.S. EPA (McFarland et al., 2001). In response, the TCEQ has established and submitted a Total Maximum Daily Load (TMDL) for the UNBR that calls for a 50% reduction of soluble reactive P loading in the impaired segments of the UNBR (TNRCC, 2001).

The UNBR forms the head waters of the North Bosque River. It 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). In addition, the North Bosque River provides water to the towns of Stephenville, Clifton, Iredell, Meridian and Valley Mills. 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 (figure 3). At Hico, a Texas Institute for Applied Environmental Research (TIAER) gauging and water sampling station is located were the UNBR crosses U.S. Highway 281. This station (BO70) marks the watershed outlet for this study.
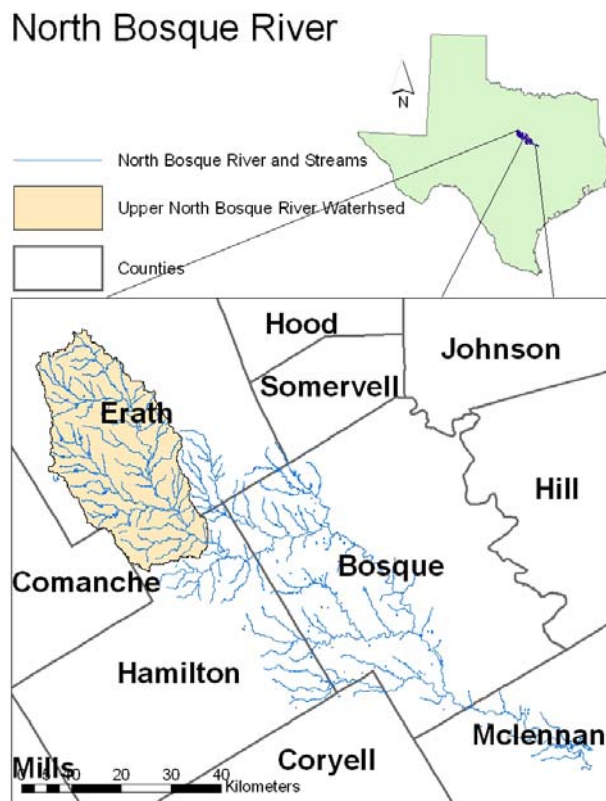
Figure 3. The location of the North Bosque River and the Upper North Bosque River Watershed. The watershed outlet is located in Hico, Texas.

To comply with the TMDL mandated P reductions, new BMPs are needed to remove excess manure nutrients out of the UNBR watershed. The State of Texas currently subsidizes the hauling of dairy manure from CAFOs to composting facilities in Erath County (Hanzlik, 2003). However, compost has been accumulating at the composting facilities and BMPs are needed to use this resource. Currently, it is estimated that composting facilities in Erath County have stockpiles close to 500,000 tons of composted dairy manure (Personal Communication, Dr. Tony Provin). Nutrients in these stockpiles of composted manure could be utilized by the turfgrass sod BMP and exported in sod harvests out of the UNBR watershed in a sustainable manner.

Turfgrass BMP

Ongoing plot and field studies of three turf species at two locations indicated that 44 to 77% of the P top dressed as fresh or composted dairy manure can be removed in the first sod harvest (Vietor et al., 2002). It is estimated that up to 150 kg of the 200 kg of manure P applied ha^{-1} can be removed yearly in turfgrass sod harvests. The annual manure P export per hectare of sod represents the manure P excreted yearly by 7.6 dairy cows (Hanzlik, 2003).

Due to the short growth period prior to sod harvest, little or no leaching of P from the top 2.5 cm harvest layer occurs (F. J. Hay, 2003). Therefore, the potential for P loss during turfgrass sod crop production is primarily through surface runoff. Yet, rapid turfgrass establishment and re-growth on turfgrass production fields effectively traps sediment and prevents nutrient loss in runoff. In paired 1.42 ha research fields with and without composted dairy manure, 3.8% of manure P was lost in surface runoff (Choi et al., 2003). Mean export of P in soil, manure residue, and turfgrass totaled 254 and 212 kg P /ha in consecutive sod harvests from fields top-dressed with 75 and 127 kg P /ha total manure P (Vietor et al., 2004).

In addition to providing a pathway for cycling of manure nutrients, turfgrass provides other benefits. Turfgrass can aesthetically improve the landscape, increase infiltration and reduce runoff. Water infiltration rates in turfgrass are up to six times greater than most other ground covers. In addition, a dense turfgrass sod 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 does not need additional P fertilizer for the life of the sod (T. Provin and R. White, Personal Communication). The elimination of P requirements for manure grown turfgrass transplanted to urban landscapes is a benefit to water quality in urban streams. The State of Minnesota passed legislation that requires home owners in sensitive watersheds to restrict 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).

In summary, plot and field scale research has demonstrated the effectiveness of the turfgrass BMP in manure nutrient removal from impaired watersheds. This paper presents the results of model simulations that assess the watershed-scale 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 were identified (Hanzlik, 2003) and used in the model simulations (figure 4).
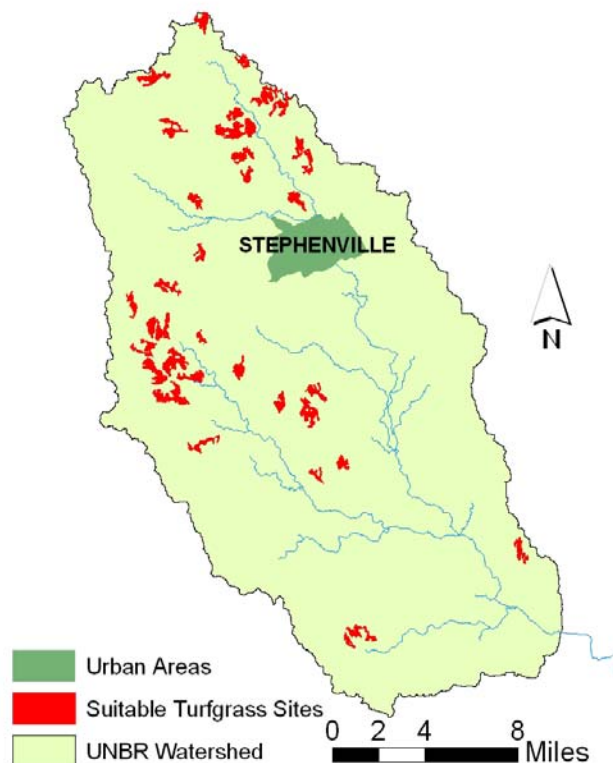

Figure 4. **Suitable turfgrass production sites in the UNBR watershed used in the SWAT model simulations to assess water quality improvements in the UNBR due to the turfgrass BMP (Hanzlik, 2003).**

Model Selection

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

The SWAT model has several components that allow it to accurately simulate various aspects of a watershed such as surface and ground water hydrology, erosion and sedimentation, plant growth and management, and nutrient cycling. In addition, the model accommodates spatial variability of soil types, land uses, weather, and topography, and incorporates point source inputs of effluent discharges for simulation (SWAT, 2000b).

The SWAT model has been used for modeling the UNBR watershed (Hauck et al. 2003), which facilitated model calibration and simulation of BMP effects on the UNBR watershed. The TCEQ used the model to establish a TMDL for P in the UNBR. The Texas Institute for Applied Environmental Research (TIAER) successfully 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). In addition, the USDA Blacklands Research Center in Temple, Texas, also simulated the N and P transport processes on the UNBR watershed (Santhi et al., 2001). These studies built a guideline for accurately calibrating the SWAT model for the UNBR watershed.

SWAT Model Input Datasets

Most of the SWAT inputs were derived from GIS layers using the BASINS interface while other 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. Inputs for a wastewater treatment plant (Stephenville), temperature and rainfall conditions, land management operations, and initial watershed conditions were all entered manually in the model.

Land Inputs

Topographical data of the UNBR watershed was 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 (MSL). The elevation of the UNBR watershed ranges from 305 m to 496 m MSL. This DEM was processed through BASINS to create 39 sub-watersheds for the SWAT simulation. Figure B 1 in Appendix B shows the DEM for the UNBR watershed and figure B 2 shows the delineation of the UNBR watershed into 39 sub-basins.

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 both Erath and Hamilton Counties were used to cover the extent of the UNBR watershed. Erath county data was available in SSURGO version 1 format, but Hamilton County had already been formatted in the new SSURGO version 2 format (NRCS, 2004). Figure B 3 in Appendix B shows the SSURGO soils map for the UNBR watershed. 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. Use of SSURGO data provided improved spatial detail over STATSGO data.

The National Land Cover Dataset 1992 (NLCD 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 pasture and rangeland (table 2). BASINS used the land cover database in combination with the soils database to create Hydrologic Response Units (HRUs), for each of 39 sub-watersheds. HRUs were established using a inclusion threshold of 5% for land use and 10% for soil type in order to filter out HRUs of little significance and simplify the model. This resulted in a model with 471 HRUs. Figure B 4 in Appendix B shows the land cover map for the UNBR watershed

Table 2. The distribution of land use in the UNBR watershed as determined from the NLCD.

Land Use	Area (ha)	% Area
Range land	57142	61.4%
Pasture	3496	3.8%
Agricultural	10156	10.9%
Urban	2164	2.3%
Waste Application	6776	7.3%
Forest	11701	12.6%
Other[1]	1699	1.8%

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

The effluent from the Stephenville waste water treatment flows into the UNBR and is the only permitted point discharge within the watershed. This effluent was summarized into monthly contributions to the UNBR and was included in the model calibration.

Another model input was the initial soil nutrient concentrations for the various land covers. Initial P and N concentrations in the soil were based on previous SWAT model calibrations for the UNBR watershed by the Blacklands Research Center (Santhi et al., 2001) (table 3).

Table 3. The initial soil nutrient concentrations used in SWAT model calibrations from prior model calibration (Santhi, et al., 2001)

Land Use	Nutrients	mg/kg
Waste Application Fields	Organic N	5000
	Organic P	700
	Mineral P	250
Pasture / Rangeland	Organic N	850
	Organic P	150
	Mineral P	5
Agricultural	Organic N	1100
	Organic P	200
	Mineral P	20
Urban	Organic N	2000
	Organic P	400
	Mineral P	5

Weather

Rainfall data from 11 weather stations managed by The National Climatic Data Center (NCDC, 2003) or TIAER in the UNBR watershed was used for the SWAT simulations. 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. Figures 5 and B 5 in Appendix B shows the sub-basin delineation and weather input map with more detail.
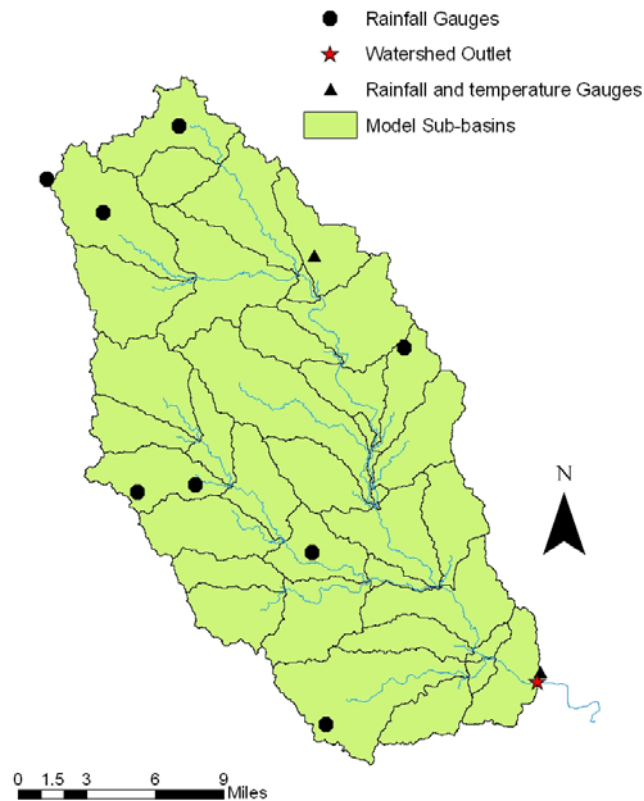
Figure 5. The sub-basins used in the SWAT model simulations of the UNBR watershed with the locations of rainfall and temperature gauges and the watershed outlet are shown.

Land Management

Previous reports of land management by TIAER ad other researchers in the UNBR watershed practices were used to develop inputs for agricultural land operations in the SWAT simulations. Gassman (1997), described previously various cropping systems and manure and fertilizer applications used for previous APEX simulations of the UNBR watershed. Gassman detailed management operations, including dates of fertilizer applications for each cropping system. 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 6554 ha of WAF for the SWAT model calibration. Therefore, the WAFs received 16,753 kg/ha/year of dry dairy manure.

SWAT Model Modifications

Dairy manure application was diverted from the WAFs for used in turfgrass sod production fields as composted dairy manure to run SWAT model simulations of the turfgrass BMP and its effects on water quality. The SWAT model was amended to accept new management operations for turfgrass sod harvest that included the removal of a thin layer of soil. New SWAT management files were created using a management file utility to add the new operations and the operation characteristics. These management files were then used in the HRUs that had turfgrass sod production fields.

The soil removal depth for the turfgrass sod harvest operation was set to 25 mm. The harvest operation kills the current crop and re-adjusts the soil profile for the next operation. In addition, the turfgrass harvest operations creates a SWAT output file that lists the P concentrations in the plant and soil layers of the harvest, in kg P / ha. This output file has a record of the P concentration in each of the soil P pools: organic P both active and stable, fresh organic P, mineral P in active, stable and solution pools as well as P in the plant (SWAT, 2000b) for each turfgrass HRU and each harvest. These concentrations of P are then used to calculate total mass of P exported during turfgrass sod harvest. The mass of P exported determines the efficiency that the turfgrass BMP will have in removing the manure P top-dressed on turfgrass sod.

Calibration and Validation

The model was first calibrated and validated for existing conditions in the UNBR watershed. Model predicted 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, TX.

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

The calibration goal for the SWAT predicted values of the UNBR watershed was a NS of 0.50 for each modeled constituent. The calibration was performed for one constituent at a time. Once the calibration for a modeled constituent was finalized, the calibration accuracy of the preceding constituents was reviewed. The SWAT model was calibrated for flow, sediment, organic P, mineral P, organic N, and mineral N in that order. The calibration goal of NS > 0.50 was attained for all constituents on a monthly time-step as seen in table 4. In addition, an R^2 coefficient greater than 0.80 for all constituents indicates that the model reacts well to temporal changes as well. Figure A 1 in Appendix A compares the observed loads to the SWAT model calibration predicted loads. The changes required for the SWAT model calibration of the UNBR watershed are presented in table 5. Figure A 2 in Appendix A shows the comparison between the calibrated model predicted loads and the observed loads for the validation period.

Table 4. The Nash Sutcliffe (NS) and correlation coefficients (R^2) for each constituent used in the Swat model calibration for the UNBR watershed for the time period 1994-1999.

Constituent	NS	R^2
Flow	0.76	0.87
Sediment	0.80	0.94
Org P	0.69	0.85
Min P	0.75	0.88
Org N	0.71	0.87
Min N	0.60	0.80

Table 5. **The SWAT model variables adjusted during the model calibration with the adjusted value or final amount of change from default SWAT values also shown**

Constituent	Variable	Description*	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**
Sediment	SPCON	Linear parameter for channel sediment retained coefficient	-86%**
	SPEXP	Exponent parameter for channel sediment retained coefficient	10%
	CH_EROD	Channel Erodability Factor coefficient	-10%**
Phosphorous	BC4	Rate constant for P mineralization at 20°C	0.07
Nitrogen	NPERCO	Nitrogen Percolation coefficient	-80%**
	SOL_ORGN	Initial soil organic N concentration (PPM)	12%**
	SOL_NO3	Initial soil NO3 concentration (PPM)	-80%**
	BIOMIX	Biological mixing efficiency	0.4
	BC3	Rate constant for N hydrolysis at 20°C	0.1

*Further descriptions available in the Soil and Water Assessment Tool Manual (SWAT, 2000a)

**Represent an adjustment of the default SWAT model value.

The calibrated model was validated by comparing the predicted constituent to observed constituents from January 2001 to March 2002, temporally different data from the calibration period. The high NS coefficients achieved during validation indicated a strong correlation between the simulated constituents and the observed constituents in the UNBR, except for mineral N (table 6). All R^2 coefficients were greater than 0.80 (except for mineral N 0.57) for the simulated constituents and the high NS coefficients indicate that the model accurately responds to weather and management conditions that exist currently in the UNBR watershed. The mineral N variance was due primarily to one large spike in observed mineral N loads, over the first four months of the validation period, which the SWAT model under predicted. However, since the focus of the model simulations was on P and the N calibration was very strong, the model validation was considered to be acceptable. The poor overall mineral N validation was unlikely to affect the overall model simulation results.

Table 6. The Nash Sutcliffe (NS) and correlation coefficients (R^2) for each constituent reviewed in the Swat model validation for the UNBR watershed for the time period 2001-2002.

Constituent	NS	R^2
Flow	0.80	0.92
Sediment	0.63	0.82
Org P	0.58	0.89
Min P	0.37	0.82
Org N	0.73	0.89
Min N	-0.04	0.57

Simulation

After calibration and validation, SWAT model simulations were used to assess the water quality impact of the turfgrass sod BMP in the UNBR watershed. Suitable turfgrass sod production sites identified by Hanzlik (2003) were utilized in the UNBR watershed to evaluate the turfgrass BMP. Two different implementation scenarios for turfgrass sod production were simulated. One simulation scenarios used 100% of the

turfgrass sod production sites (2008 ha) available in the UNBR watershed, while the other scenario only utilized 50% of the suitable sites (1004 ha) (figure 6). The production sites utilized in the 50% scenario were largest fields that were available for turfgrass production in the UNBR watershed. The 50% allocation scenario represents the more realistic expectation for turfgrass BMP implementation in the UNBR watershed. The turfgrass sod production sites for both the allocation of 100% and 50% suitable land used in the model simulations did not overlap with existing WAFs.

For each implementation scenario, two application rates (100 kg P/ha and 200 kg P/ha) of top-dressed, composted dairy manure per harvest, were evaluated for the turfgrass sod production sites. The combination of land allocation and manure application rates combined to form four scenarios for the SWAT model simulations: 1)100 kg P/ha applied to 2008 ha after each harvest (Scenario 100/100%), 2) 100 kg P/ha applied to 1004 ha (Scenario 100/50%), 3) 200 kg P/ha applied to 2008 ha (Scenario 200/100%), and 4) 200 kg P/ha applied to 1004 ha (Scenario 200/50%). The top dressed composted dairy manure at these application rates added approximately 0.55 cm (100 kg P/ha) and 1.1 cm (200 kg P/ha) of compost depth over each turfgrass sod crop.

To calculated 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 as turfgrass sod fertilizer reduced manure application to the WAFs (table 7). The fresh dairy manure application rates to WAFs for the calibrated model, which represents current watershed conditions, was 16,753 kg/ha/year, this equates to 174 kg P/ha from the fresh dairy manure.

Table 7. The reduction of manure application to the WAFs due to implementation of the turfgrass sod BMP for the four SWAT simulation scenarios.

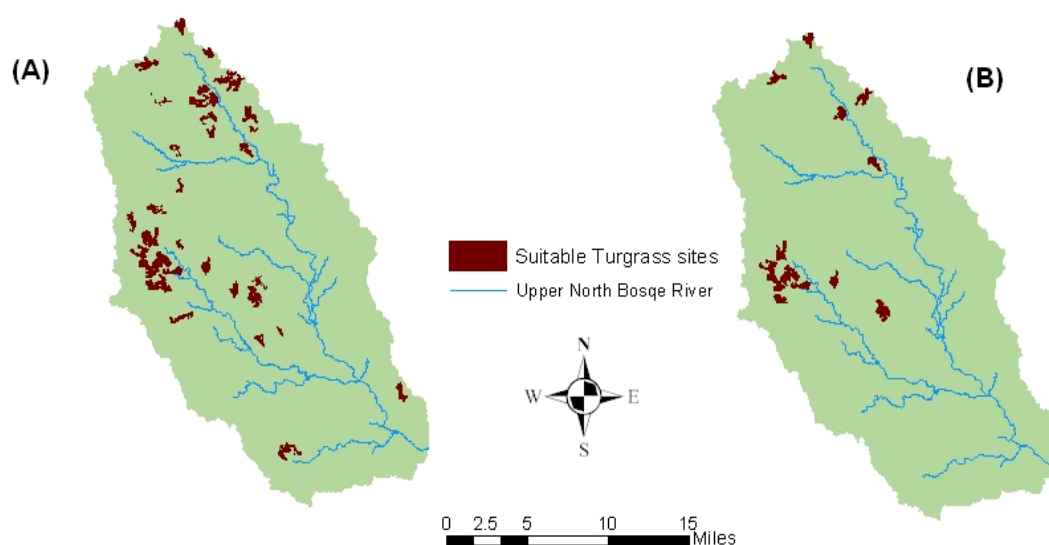| P Application Rate	Phosphorous diverted away from WAFs			
	100% suitable sites (2008 ha)		50% suitable sites (1004ha)	
100 kg/ha	2904 kg/ha	17.3%	1523 kg/ha	9.1%
200 kg/ha	5666 kg/ha	33.8%	2904 kg/ha	17.3%

Figure 6. The locations in the UNBR watershed used in the SWAT model simulations of the turfgrass sod BMP where (A) represents 100% of the suitable areas and (B) represents 50% of the suitable turfgrass areas. None of these sites overlap with existing WAFs.

For each of the SWAT simulation scenarios, turfgrass sod production was assumed to achieve three harvests every two years (R. White, Personal Communication) and each turfgrass sod crop was fertilized with composted dairy manure at rates of 100 kg P/ha or 200 kg P/ha. In addition, the SWAT model auto-fertilization routine was used to apply N as ammonium sulfate as needed for optimum growth. Moreover, the auto-irrigation routine was also used to irrigate the turfgrass sod for optimum production. The

agricultural management operations applied to the HRUs with turfgrass sod production was matched as closely as possible to the field research operations ongoing at the Texas A&M turfgrass research farms.

Results and Discussion

The calibrated and validated SWAT model was used to simulate the four turfgrass BMP scenarios. In order to compare only non-point nutrient sources and better present the impact of the turfgrass BMP to water quality, the Stephenville wastewater treatment plant effluent point source, the only permitted point discharge in the watershed, was removed from the model simulations. Therefore, the simulated results of the four turfgrass BMP scenarios could be compared to a control simulation of actual conditions in the UNBR watershed that did not include the effluent of the wastewater treatment plant, comparing only non-point sources. An emphasis was placed on P, which was targeted in the current TMDL plan for the UNBR. However, flow, sediment, organic N and mineral N were similarly analyzed and compared for each scenario to the control simulation to determine changes due to the turfgrass BMP. All comparisons were made for monthly total loads (kg / month) in the UNBR.

For all four scenarios, the SWAT model predicted a significant decrease in nutrient loads in the UNBR compared to the control (tables 8 and 9). The simulations indicate turfgrass sod harvest effectively exported P from the watershed. Even though turfgrass sod generally increases infiltration, there was little effect on stream flow as the constant irrigation at commercial turfgrass production sites maintains high antecedent moisture conditions, which offsets the potential for a decrease in runoff (figure A 3, Appendix 3). Sediment was reduced in all four scenarios with an average sediment reduction of 16% (table 8). Reduced sediment is most likely due to the substitution of dense turfgrass sod production fields for more erodable row-crop fields in the watershed as most of the areas suitable for turfgrass were previously used for production of animal grains and forage crops (figure 7). The reduction of sediment loads also corresponds with decreased nutrient loads for the four simulation scenarios. The predicted reduction
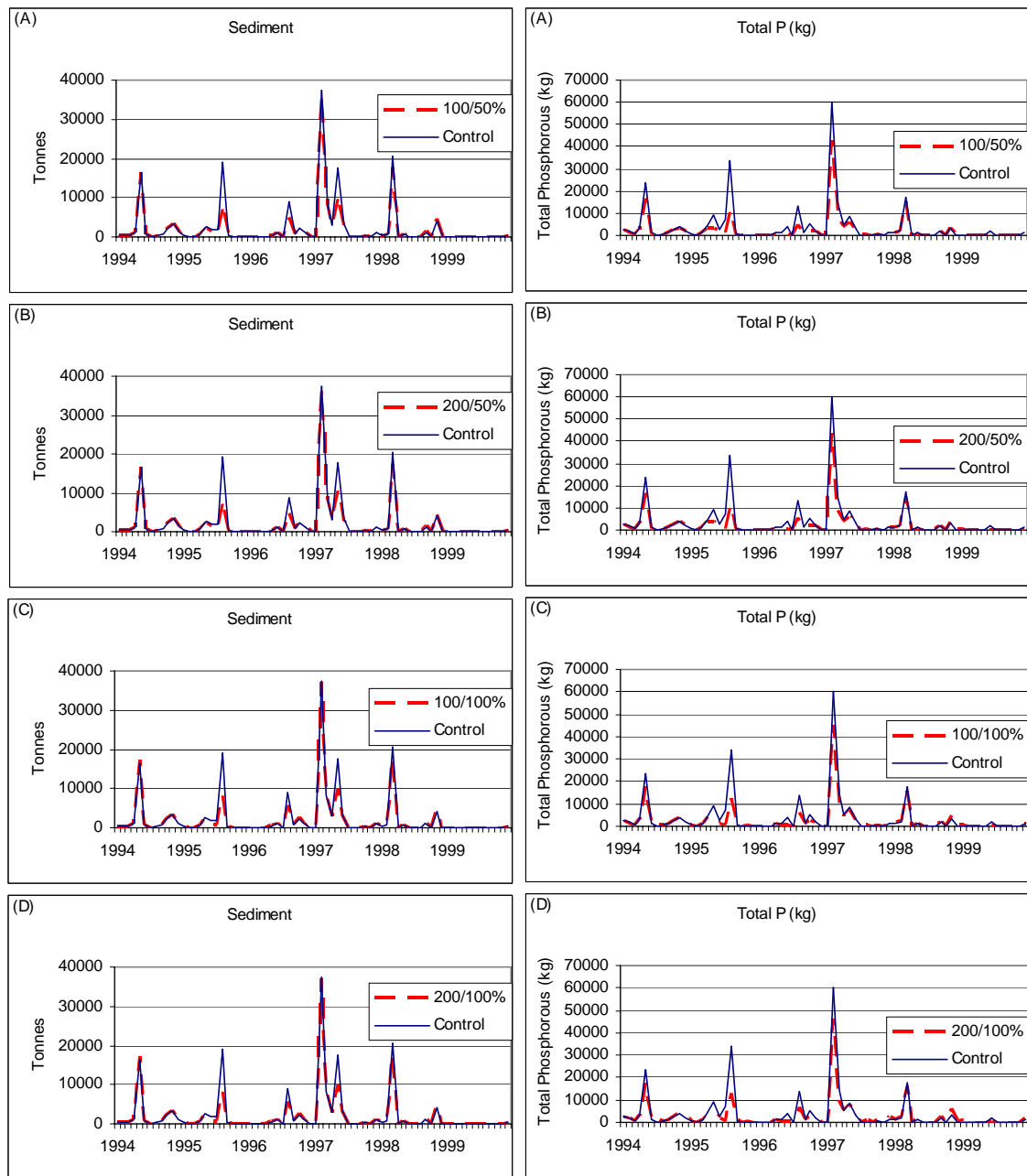
Figure 7. UNBR simulations comparing sediment and total P for the four turfgrass BMP scenarios to control simulation output at the watershed outlet. The turfgrass BMP scenarios are: (A) 100 kg P/ha application to 50% (1004 ha) of sites, (B) 200 kg P/ha application to 50% (1004 ha) of sites, (C) 100 kg P/ha application to 100% (2008 ha) of sites, (D) 200 kg P/ha application to 100% (2008 ha) of the sites.

of total P in the UNBR for simulated scenarios when compared to the predicted loads in the control simulations could be attributed mostly to reductions of sediment-bound P (figure 7). Figure A 4 in Appendix A compares between the turfgrass BMP simulation and the control simulation output of organic P and mineral P.

The mean reduction of total N for the four BMP scenarios predicted by the model at the watershed outlet was 31% less than the control simulation. Despite the total N reductions, mineral N loads predicted were similar to the control simulation since turfgrass sod production requires large quantities of N fertilizer to grow rich green turf for commercial markets. However, the reduction of 44% for organic N in the UNBR out weighted the slight mineral N changes when the four BMP scenarios were compared to the control simulation (table 8). Figure A 5 in Appendix 5 shows the comparison between turfgrass BMP simulation and control simulation organic N and mineral N loads at the outlet of the UNBR watershed.

Table 8. A comparison of changes in stream flow, sediment and N forms at the watershed outlet at Hico, TX, between the control simulation and the four turfgrass BMP scenario simulations. Positive changes represent reductions compared to the control simulation in which all manure was allocated to WAFs.

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%

The use of only 50% of the suitable turfgrass areas for sod production reduced concentrations of both organic P and mineral P and N in the UNBR more than the allocation of 100% of the suitable sites for sod production (table 9 and figure 7). A possible explanation for this is t that the allocation of 100% of suitable land to sod production increased the area of turfgrass fields that are proximate to streams or close to the watershed outlet (figure 6).

Table 9. A 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, TX. Positive changes represent reductions with respect to the control simulation in which all manure is allocated to WAFs.

Scenario	Mineral	Organic	Total
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%

It is interesting to note that BMP reductions for both mineral and organic P are smaller as the manure P application rate and the turfgrass sod production areas increase. The SWAT simulations indicate 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 ranges from a 29.73% reduction for the 100/50% scenario to a 1.05% increase for the 200/100%. Organic P reductions have only a 4% change between scenarios. These simulations indicate increases of composted dairy manure P application rates to sod will increase losses of mineral (dissolved) P in runoff (table 9). This shows that the SWAT model is sensitive to the high mineral P concentration in composted dairy manure, and responds to the higher composted manure application rates. Yet, all four BMP scenarios predict a reduction of total P loads to the UNBR compared to the control simulation, and significant export of P in turfgrass sod harvests (table 10). 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 exports the least amount of manure P from the watershed (tables 9 and 10).

In the model simulations, increases in sediment and nutrient transport in the UNBR occurred during high flows which were driven by rainfall events. A benefit of the turfgrass BMP is that manure is distributed over a larger area than the WAFs, which reduces the potential for N and P in surface runoff (Vietor et al., 2004). 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 the simulated export of total P for the all the four turfgrass BMP scenarios was higher than the P applications (100 kg P/ha and 200 kg P/ha). Removal of existing soil P present before manure application contributes to P export in excess of the manure P applications during crop establishment or re-growth (table 10).

Table 10. A 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.

Scenario	Average Export per harvest			Total P export	
	Total P	P in turf	P in soil	kg/ha	Metric Tons
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

The simulated P exported during sod harvest that is in excess of the manure P applied during production equates to between 151 mg/kg and 218 mg/kg of total P initially in the soil at the 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 3). Therefore, these simulations indicate that the turfgrass BMP can export P accumulated near the surface at existing WAFs. The turfgrass sod BMP may be utilized to extend the usefulness of WAFs that exceed the 200 mg P/ kg limit for land application of manure nutrients by exporting P from the surface soil in the turfgrass harvests.

CHAPTER III

SUMMARY AND CONCLUSION

Watershed-scale simulations of the turfgrass BMP indicate that P can be exported out of impaired watershed in turfgrass sod. The model simulations successfully provided watershed-scale evaluations to complement plot and field scale research conducted by Texas A&M University. The SWAT model was customized to include turfgrass production and harvest operations and then was calibrated and validated to actual UNBR watershed conditions. This model was then used to simulate four scenarios for the turfgrass BMP on the UNBR watershed. The four scenarios included turfgrass grown on 50% and 100% (1004 ha or 2008 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 BMP scenarios were effective in removing the applied P during harvest and in reducing P loads to the UNBR watershed. In addition, the model predicted the removal of antecedent soil P in the 25 mm layer of soil during each turfgrass sod harvest.

Diminishing stream load reductions of P with increases in manure P application rates and application areas are offset by increases in P exports from the UNBR watershed. It is possible that turfgrass production site selection can be used to attenuate the diminishing positive water quality effects, but a balance between water quality benefits and manure P exports may be the sensible long term solution for sustainable turfgrass BMP effectiveness.

In addition to the reduction in P, the model predicted a mean reduction of 31% for total N in the UNBR at the watershed outlet at Hico, TX. In addition, simulated sediment loads in the UNBR decreased by 16%, reducing sediment bound nutrients.

These simulations demonstrate 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 for commercial turfgrass sod production. In addition, this turfgrass BMP can be installed on soils with existing high concentrations of P that must be reduced to prevent non-point transport in surface runoff. The WAFs in the UNBR watershed exceeding the 200 mg/kg P limit for land application of manure nutrients could benefit from this soil P and could still utilize this land for manure grown sod. Another benefit of turfgrass sod produced with manure is the added value of transplanted sod soil that is rich in organic matter and slow release manure nutrients. This enhances transplant and establishment, eliminates the need for P fertilization for up to 20 years (T. Provin and R. White, Personal Communication), and reduces the potential runoff of soluble P fertilizer from urban lawns.

The SWAT was also complemented by the new routines that allow it to accurately model turfgrass sod harvest. These routines were expensively tested to ensure soil and P balance accuracy. Even though these routines will require some extra coding to make them available through the Arc View SWAT interface which is friendlier, researchers who need to model watershed scale impacts of turfgrass sod production now utilize the SWAT model and these new harvest routines.

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

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APPENDIX A

CALIBRATION, VALIDATION AND SIMULATION GRAPHS
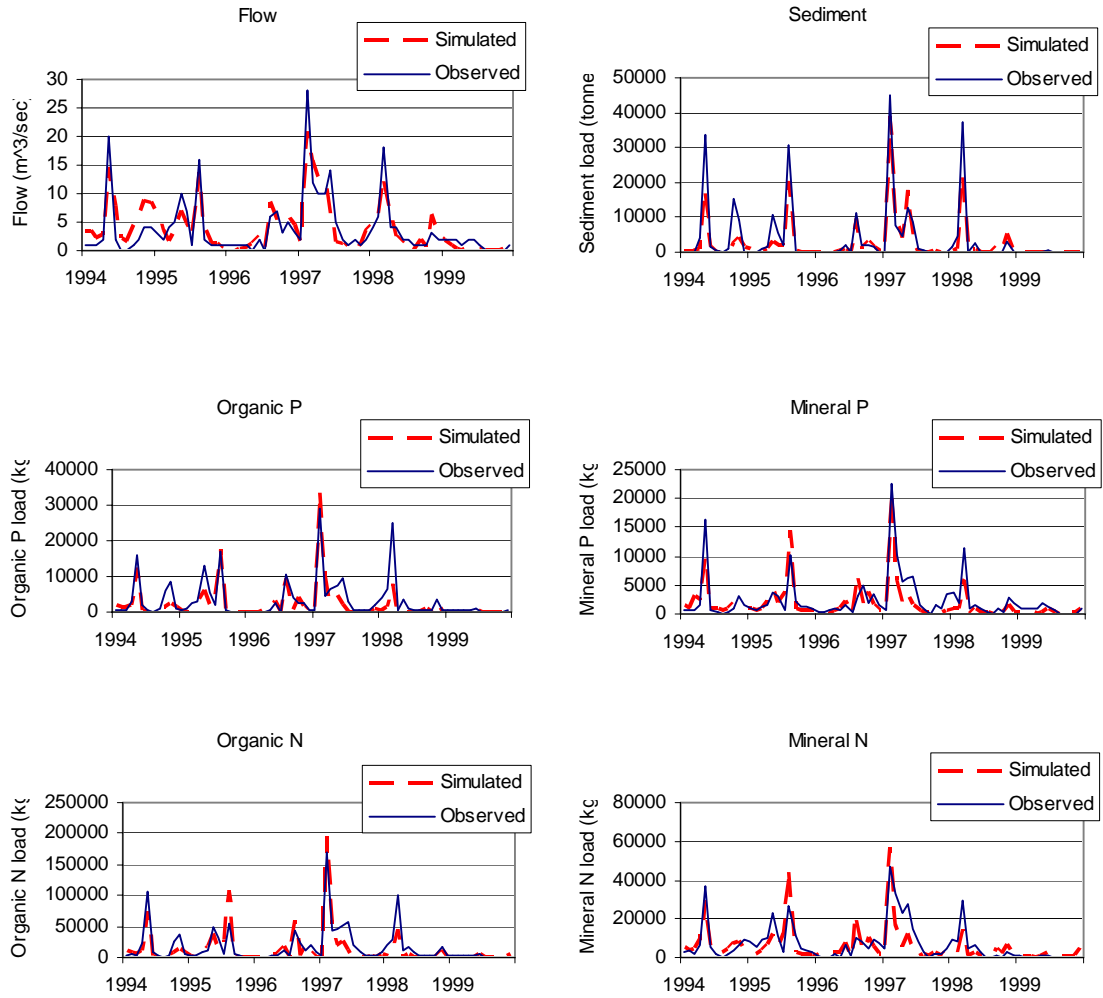
Figure A 1. Calibration of the SWAT model to current condition in the UNBR watershed.
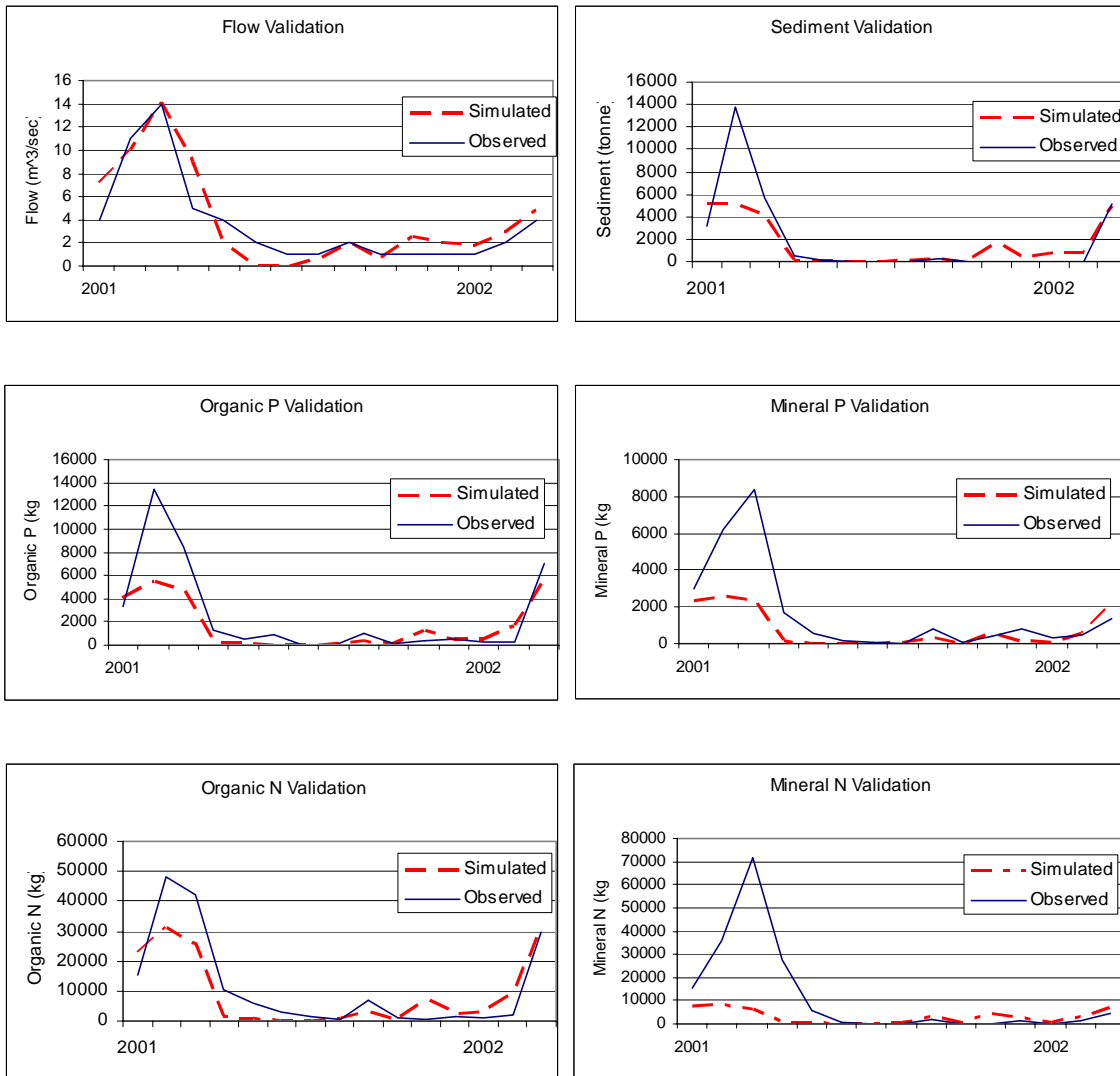
Figure A 2. Validation graphs for the calibration of the SWAT model to current condition of the UNBR watershed.
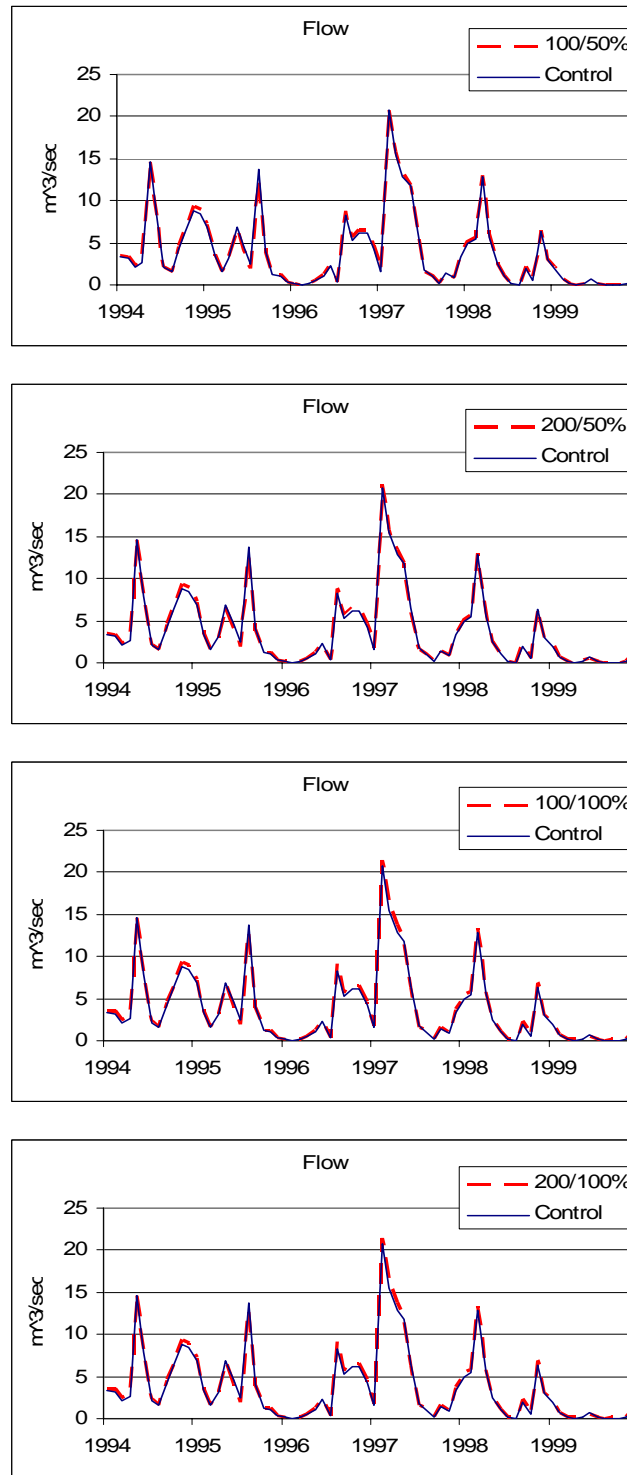
Figure A 3. SWAT model simulations of the UNBR comparing flow for the four turfgrass BMP scenarios to calibrated model output at the watershed outlet at Hico, TX.
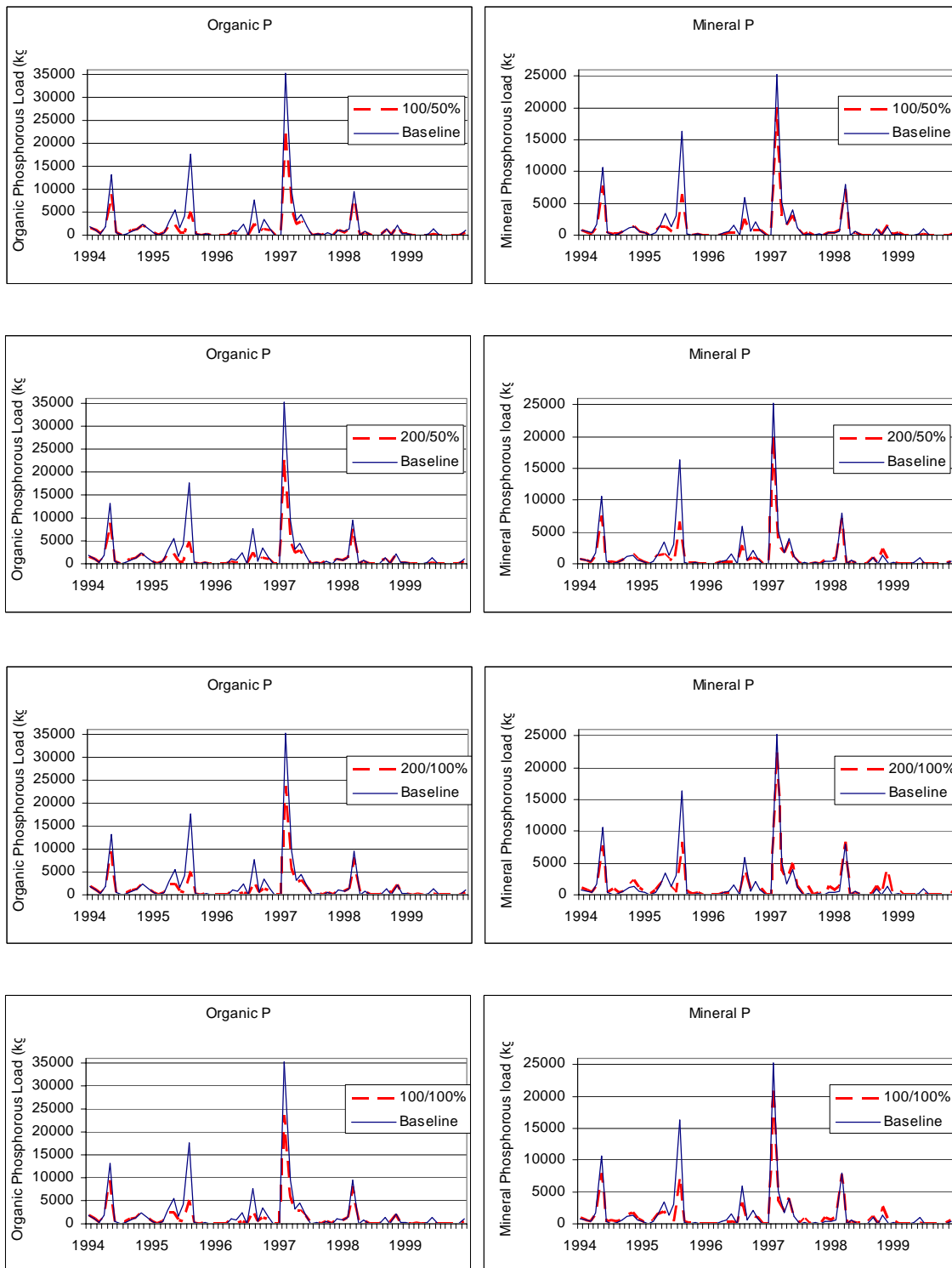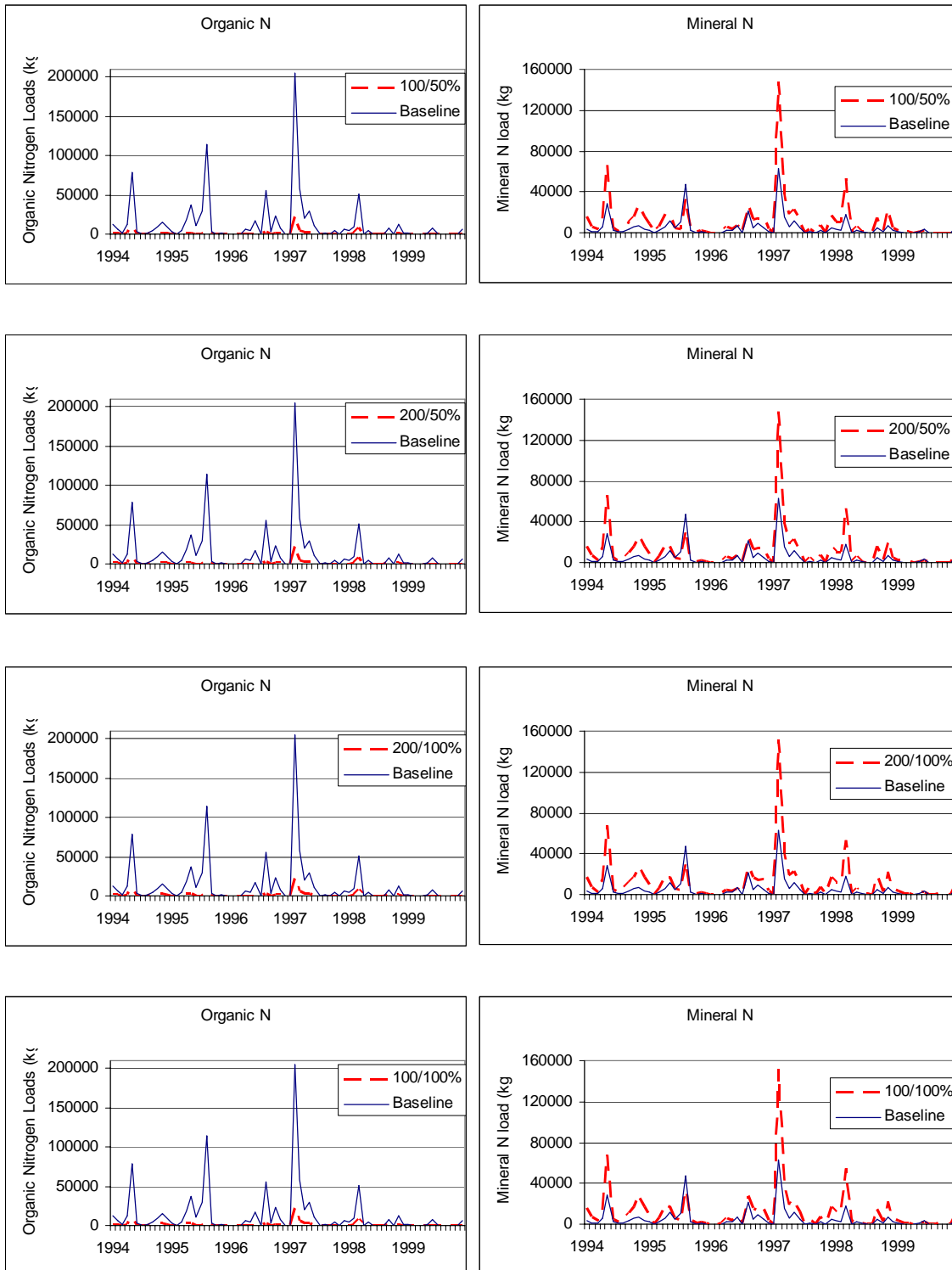
Figure A 4. SWAT model simulations of the UNBR comparing organic and mineral P for the four turfgrass BMP scenarios to calibrated model output at the watershed outlet at Hico, TX.

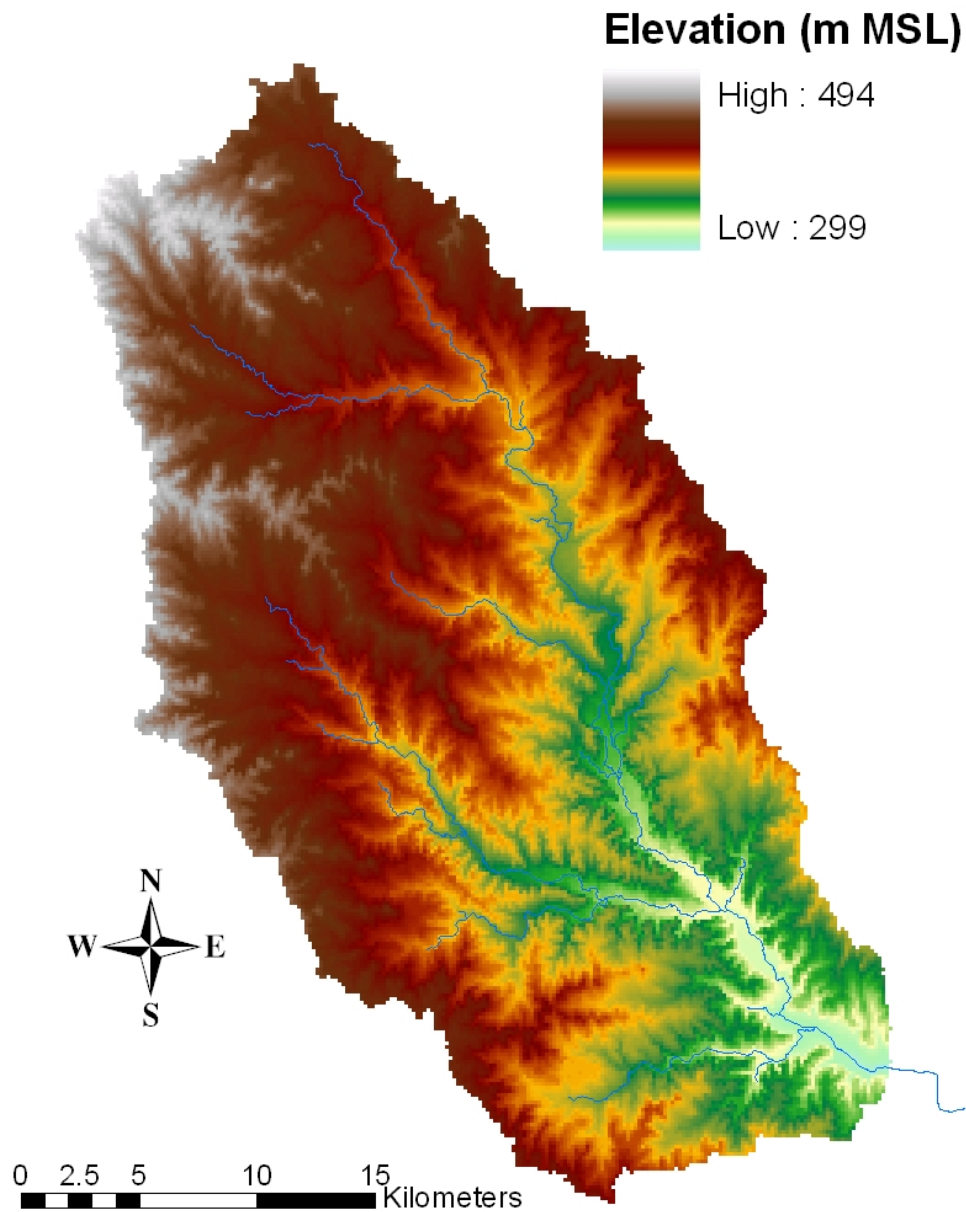**Figure A 5. SWAT model simulations of the UNBR comparing organic and mineral P for the four turfgrass BMP scenarios to calibrated model output at the watershed outlet at Hico, TX.**

APPENDIX B

MODEL SETUP DATABASES

Figure B 1. Digital Elevation Model used for watershed delineation. 30 meter resolution grid from USGS National Elevation Dataset.
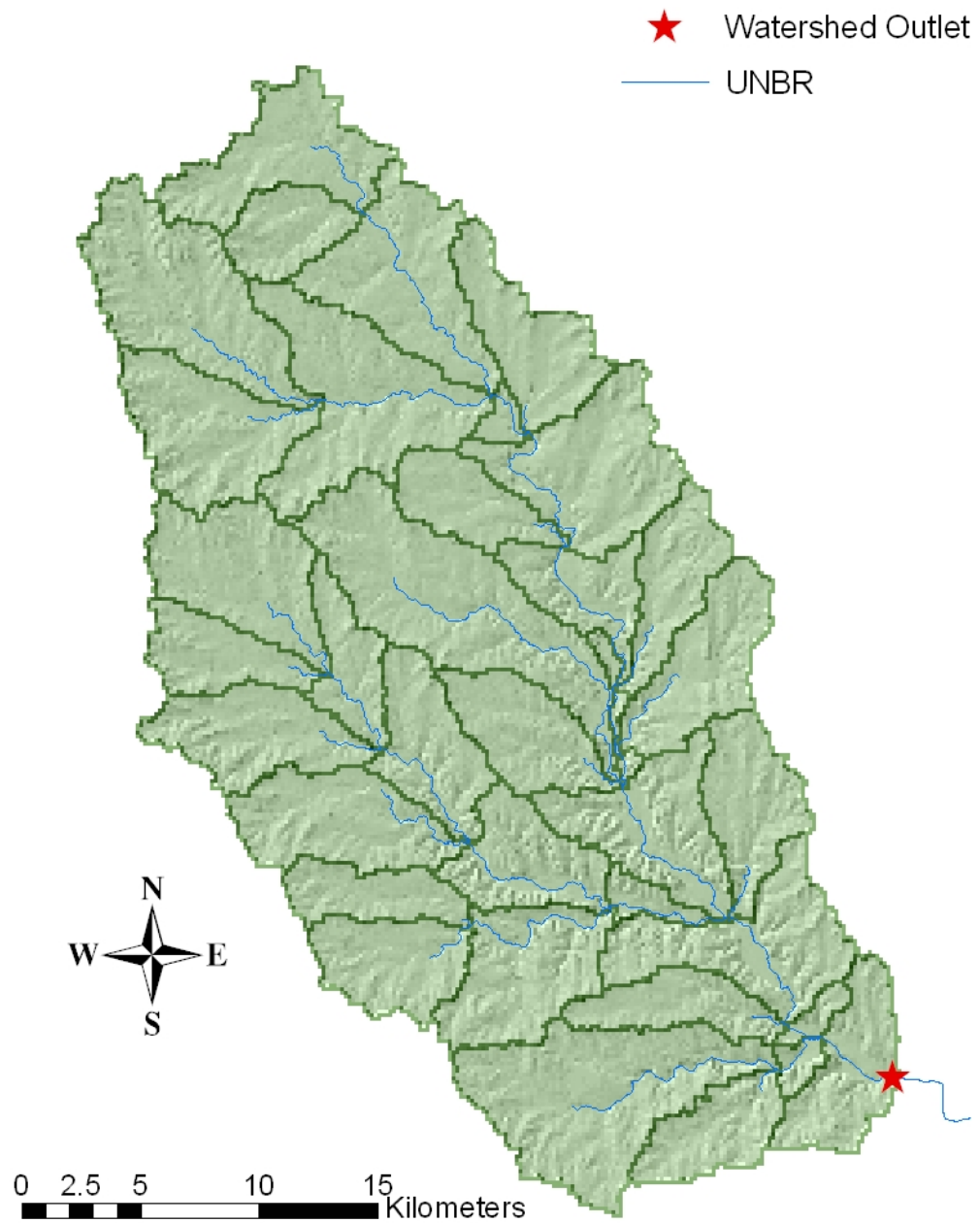
Figure B 2. Watershed delineation used for SWAT model. Delineation was made from the DEM through the EPA BASINS automatic watershed delineation.
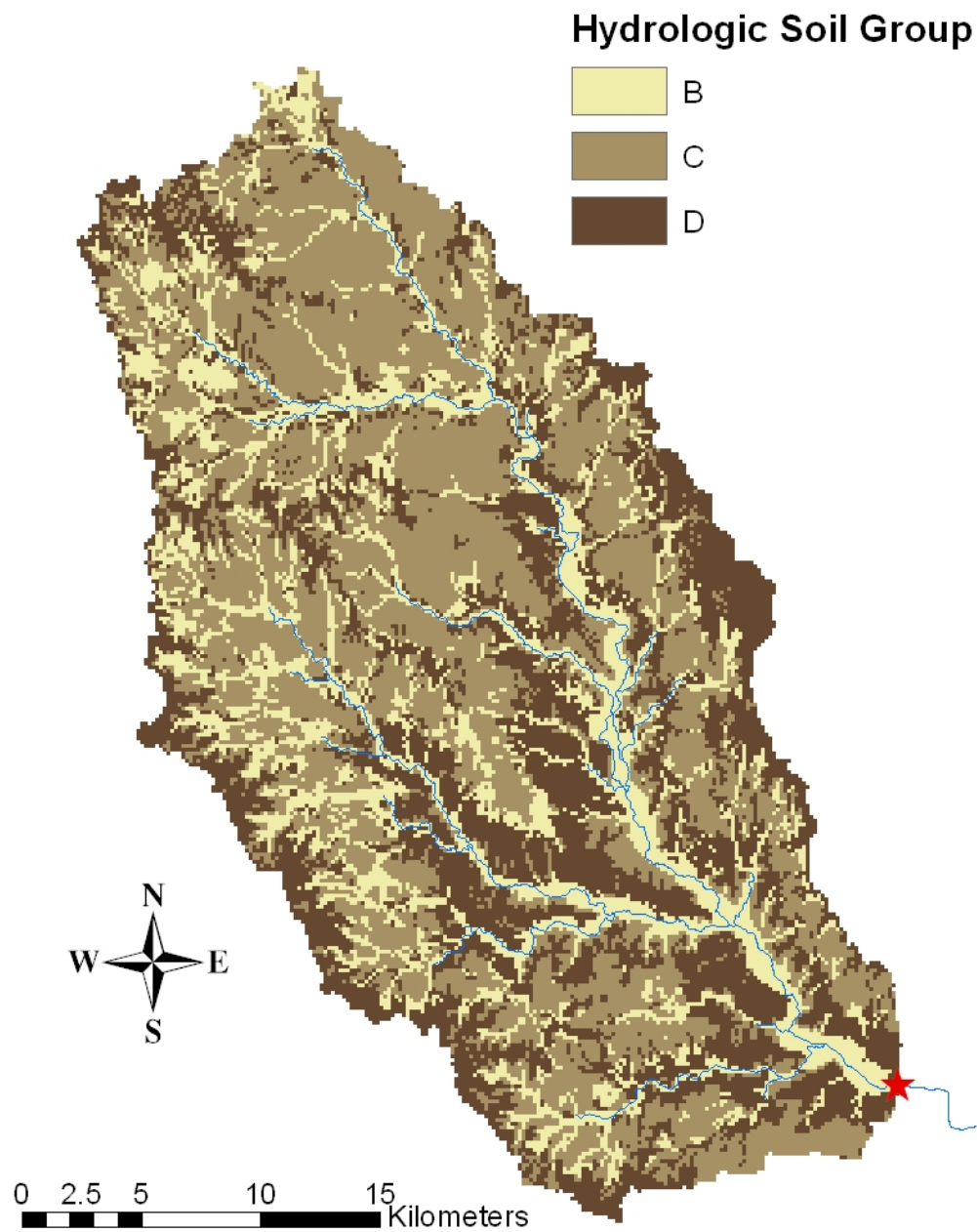
Figure B 3. SSURGO soils map used for SWAT model HRU definition. The SSURGO vector dataset was converted into a 10m resolution grid for HRU distribution.
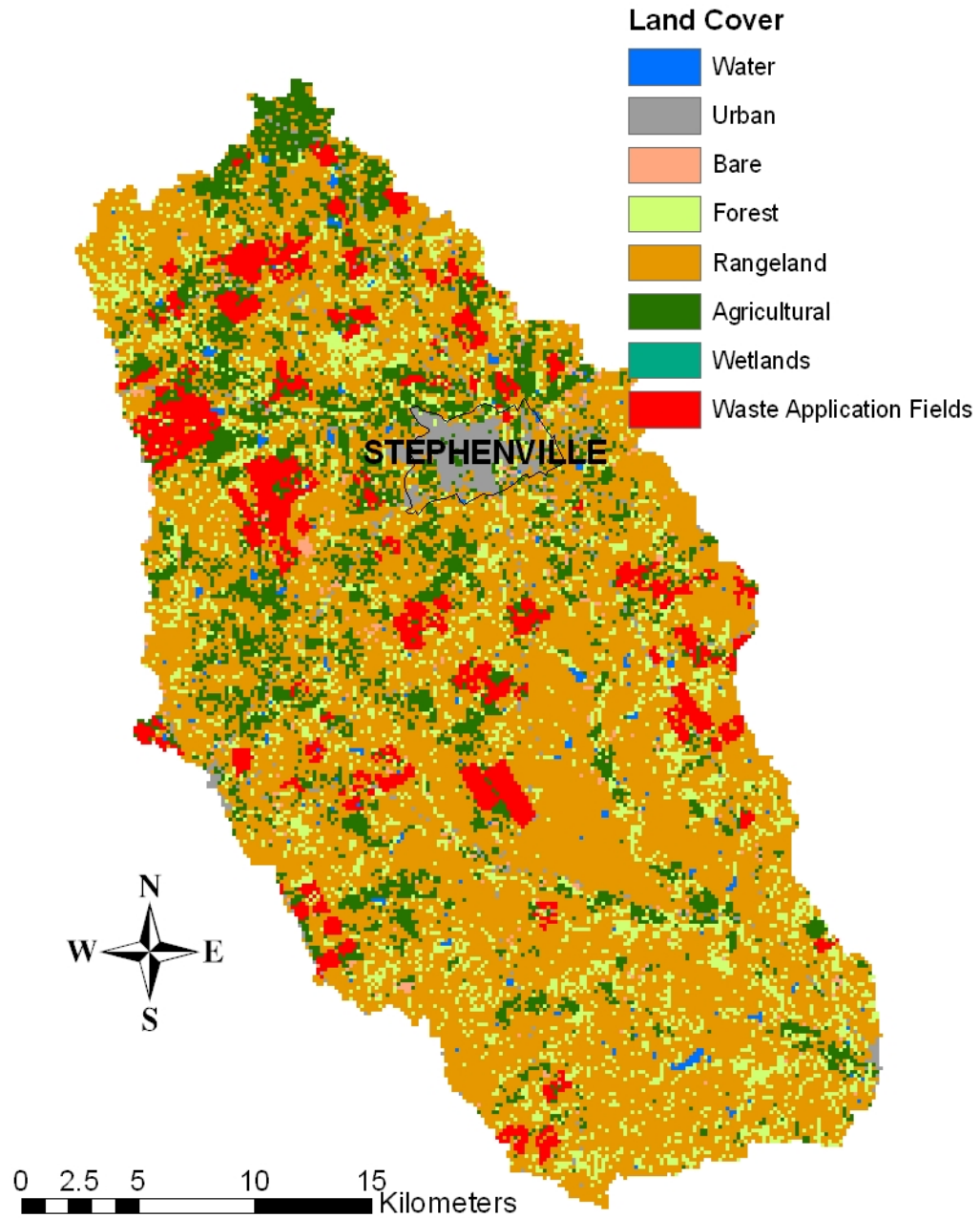
Figure B 4. Land cover grid for the UNBR watershed. This 30m resolution grid is part of the USGS National Land Cover Dataset.
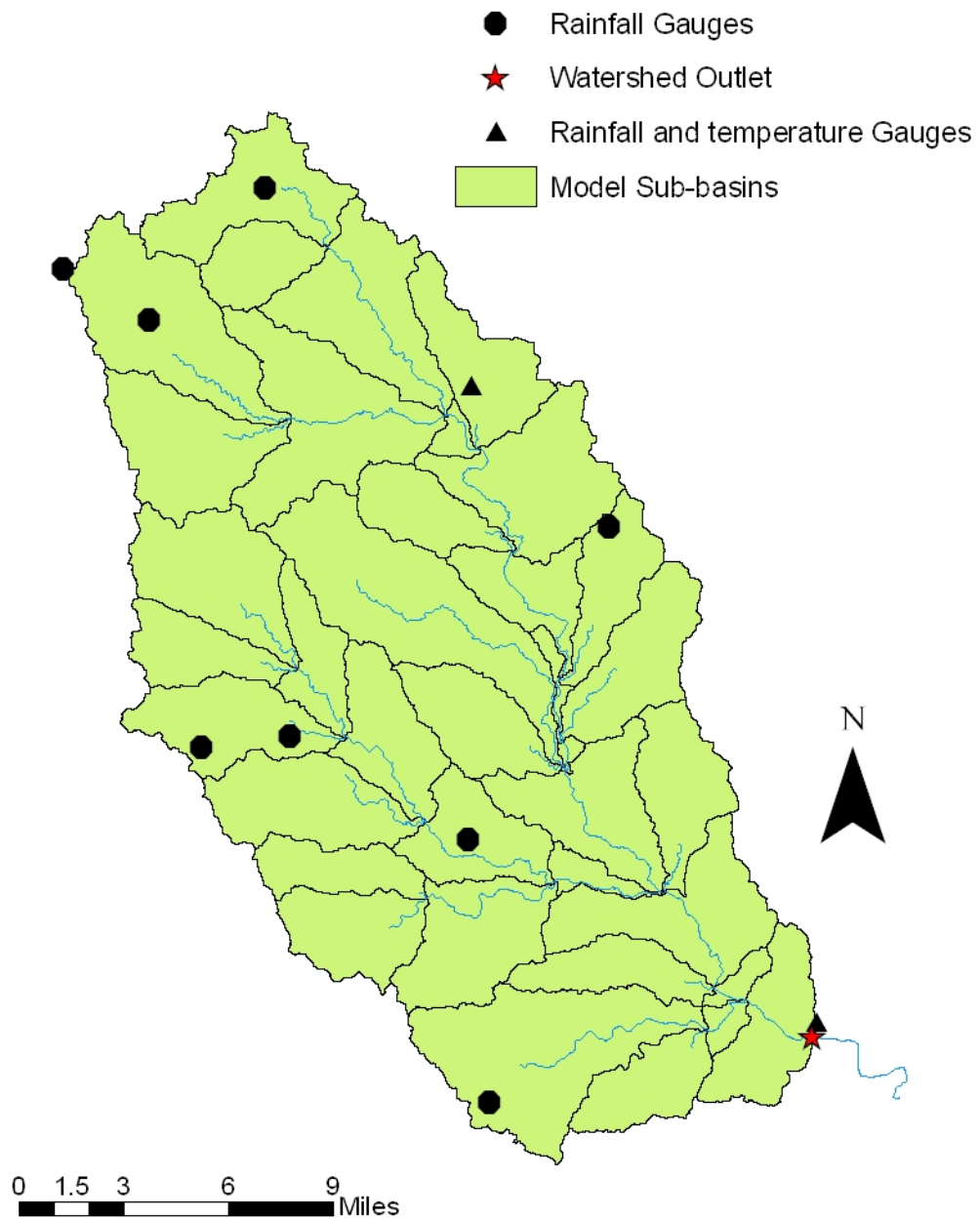
Figure B 5. Weather inputs for the UNBR watershed used for SWAT model simulation. Also highlighted is the watershed outlet in Hico, TX.

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