A WATER QUALITY ASSESSMENT OF THE IMPORT OF TURFGRASS SOD GROWN WITH COMPOSTED DAIRY MANURE INTO A SUBURBAN WATERSHED

A Thesis

by

CHAD EDWARD RICHARDS

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:

Clyde Munster (Chair of Committee)	Donald Vietor (Member)
Saqib Mukhtar (Member)	Gerald Riskowski (Head of Department)

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ABSTRACT

A Water Quality Assessment of the Import of Turfgrass Sod Grown with Composted
Dairy Manure into a Suburban Watershed. (December 2004)
Chad Edward Richards, B.S., Texas A&M University
Chair of Advisory Committee: Dr. Clyde Munster

Concentrated animal feeding operations (CAFOs) have caused water quality concerns in many rural watersheds, sometimes forcing the State of Texas to conduct Total Maximum Daily Load (TMDL) assessments of stream nutrients such as nitrogen (N) and phosphorus (P). One suggested Best Management Practice (BMP) is the export of phosphorus (P) through turfgrass sod produced with composted dairy manure from an impaired rural watershed to an urban watershed. The manure-grown sod releases P slowly and would not require additional P fertilizer for up to 20 years in the receiving watershed. This would eliminate P application to the sod and improve the water quality of urban streams.

The Soil and Water Assessment Tool (SWAT) was used to model a typical suburban watershed that would receive the transplanted sod. The objective of the modeling was to determine the water quality changes due to the import of sod transplanted from turf fields and grown with composted dairy manure. The SWAT model was calibrated to simulate historical flow and sediment and nutrient loading to Mary's Creek. The total P stream loading to Mary's Creek was lower when manure-grown sod was imported instead of commercial sod grown with inorganic fertilizers. Yet, flow, sediment yield, and total N yield increased equally for both cases at the watershed outlet. The SWAT simulations indicate that a turfgrass BMP can be used effectively to import manure P into an urban watershed and reduce in-stream P levels when compared to sod grown with inorganic fertilizers.

DEDICATION

This work would not have been possible were it not for my family and friends who supported me emotionally, financially, and physically. Thus, I would like to dedicate this to all of you. Thank you for your love, loyalty, and patience.

ACKNOWLEDGMENTS

I would like to acknowledge the members of my graduate committee: Clyde Munster, Donald Vietor, and Saqib Mukhtar for the support and direction they provided toward the completion of this study.

I am also indebted to those at the Blackland Research Center in Temple, TX who took the time to provide modeling assistance, namely Jeff Arnold, Nancy Sammons, and Steve Bednarz.

The data used in this study was collected by a large number of researchers and individuals. I would like to thank Woody Frossard of the Tarrant Regional Water District for his assistance and data and also Richard White and Tony Provin of the Department of Soil Science for sharing their expertise and time. Special thanks to the graduate researchers who shared data and experience on this project: Brandon McDonald, Nels Hansen, Jim Kerns, and John Hay. Thanks also to the student workers who diligently constructed the entire infrastructure used in this project and aided in the collection of much of the data: Jake Helfer, Les Wright, Jason Hubertus, Ryan Hill, Matt Goodson, Gary Nolan and others.

Lastly, I am grateful to our research group, Jason Afinowicz, Shane Porter, George Stewart, Jeremy Hanzlik, Philip Taucer, Inho Choi, and Yuli Suhurnato. Thank you for helping me when you could and making me smile when you could not.

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CHAPTER I

INTRODUCTION

Despite advances in national water quality due to increased federal regulations, 57% of the nations sampled streams remain phosphorus (P) enriched and 61% remain nitrogen (N) enriched (USGS, 1999a). The majority of nutrient excess is linked to urban and agricultural land use through non-point source (NPS) pollution (USGS, 1999a; USGS, 1999b; USEPA, 2002). Agriculture is the leading source of NPS pollution to the nation's rivers, streams, lakes, ponds, and reservoirs (USEPA, 2002).

NPS pollution to streams and rivers is an economical burden to municipalities, agribusiness, and governmental agencies. Nutrients can cause excessive aquatic plant growth leading to congested water intake pipes, reduced recreational value, and foul smelling and tasting water. It is estimated that tens of billions of dollars each year are spent to mitigate and prevent the damaging effects of soil erosion alone (U.S. House Committee on Conservation Needs and Opportunities, 1986). The North Bosque River (NBR) watershed is an example of the complexity of the social, political, and economic ramifications of NPS pollution remediation.

The NBR lies within 6 north central Texas counties (Erath, Somervell, Hamilton, Bosque, McLennan, and Coryell) and is approximately 316,600 ha in size. The watershed terminates at Lake Waco, making up 74 percent of the lake's contributing drainage area (Hauck, 2002). Lake Waco is the major water supply for approximately

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This thesis follows the style and format of the *Transactions of the American Society of Agricultural Engineers*.

150,000 people including the City of Waco (Keplinger and Hauck, 2002). The City of Waco has spent an estimated $3.5 million in efforts to remove excess P at their water treatment plants since 1995. An April 2004 lawsuit against eight of the dairies within the watershed is an example of the city's determination to prevent P pollution from reaching the river (A.P., 2004).

The Texas Natural Resource Conservation Commission (TNRCC), now the Texas Commission on Environmental Quality (TCEQ), first included the NBR (Segment 1226) and the Upper North Bosque River (UNBR) (Segment 1255) in the Texas Clean Water Act Section 303(d) List in 1992 as impaired stream segments with excessive nutrients (McFarland et al., 2001) and both segments currently remain on the list. Kiesling et al. (2001) revealed that P is the limiting nutrient in the NBR and Lake Waco and the primary cause of the excessive aquatic plant growth that brought the river onto the 303(d) List. Water quality monitoring data collected by the Texas Institute for Applied Environmental Research (TIAER) has been used to show that dairy waste application fields (WAFs) located in the watershed contribute the largest loadings of P to the river (McFarland and Hauck, 1999). Erath County, which contains the headwaters of the watershed, is the largest milk producing county in the State of Texas (USDA-ARS, 2003). The number of dairies in the watershed is constantly changing as a function of feed costs and milk prices (Hauck, 2002), but approximately 80 active dairies and 40,000 cows were distributed throughout the watershed in 2002 (Munster et al., 2004). Consolidation is the current trend in the dairy industry; the state annual milk production is rising, yet the total number of dairies continues to fall. There could be as few as 300 dairy producers in the state by 2010 as opposed to the 1000 present in March 2001 (Glasson, 2002).

In 2001, the TCEQ and the U.S. Environmental Protection Agency (USEPA) approved the recommendations of two total maximum daily load (TMDL) assessments that suggested a 50% reduction of soluble reactive P (SRP) to the NBR segments on the 303(d) List. Through the TMDLs, point sources and NPSs were encouraged to reduce SRP loadings by a watershed average of 50 percent (TNRCC, 2001). The TMDL also identified the most controllable sources of SRP to be wastewater treatment plants and WAFs (TNRCC, 2001).

As a result of the stakeholder concerns surrounding the NBR, the State of Texas spent $5.1 million to initialize composting facilities in Erath County and throughout the UNBR watershed (*U.S. Water News Online*, 2000). Composting can reduce the manure volume by approximately 50 percent (TCEQ, 2003) thus reducing the cost of exporting the nutrients out of the watershed. In September 2000, the TCEQ and the Texas State Soil and Water Conservation Board (TSSWCB) began providing subsidies to transport fresh manure from dairies to the composting facilities located in the UNBR and the Leon River watersheds (TCEQ, 2003). This compost is currently being used by the Texas Department of Transportation (TxDOT) to stabilize roadside construction projects (TCEQ, 2003) and by the Texas Water Resources Institute (TWRI) and the U.S. Army to revegetate areas of the Fort Hood Western Training Grounds (TWRI, 2004b). Markets are still needed to fully utilize the amount of compost generated in the watershed (TCEQ, 2003; TWRI, 2004a).

The amount of funding directed towards alleviating the nutrient problem in the NBR watershed continues to escalate in the form of private and public water quality monitoring, academic and government studies, and the state- and federal- funded TMDL implementation plan. The implementation plan states that "land application remains one of the best and most appropriate methods for dealing with large amounts of animal wastes" (TCEQ, 2002). Successful land application is achieved when nutrient transport into surface waters is minimized (TCEQ, 2002) and crop nutrient uptake is maximized so that a large percentage of the applied nutrients can be harvested and exported.

The composted dairy manure can be applied to a variety of crops suitable for agricultural production in central Texas, but turfgrass sod has an increased potential to efficiently remove manure nutrients from the NBR watershed through harvested biomass and topsoil. Also, the dense turfgrass is typically grown on level areas reducing the sediment load, increasing infiltration, and enhancing the quality of runoff water. While the current compost subsidy system is a short duration public works project, privately grown turfgrass sod is a highly valued crop that could permanently offset the cost of land applied dairy manure. Dairies, turfgrass producers, and the composting facilities could benefit from the additional market.

The amount of land in turfgrass production in Texas in 1993 was approximately 8,707 ha (Lard, 1996), but it is mostly concentrated near the coast. Although, there are no turfgrass production sites in the NBR watershed, approximately 5,219 ha of suitable sites exist in Erath County (Munster et al., 2004). It is estimated that the additional production sites in Erath County would represent a 30% increase in the state's turfgrass production (Munster et al., 2004). This is an industry that contributes $6 billion to the Texas economy yet has room to expand (Hall, 1999).

The nearest (within 160 km) major turfgrass market to the NBR watershed is the Dallas/Fort Worth (D/FW) metroplex. The market for turfgrass in D/FW is expanding (Hall, 1999), but the cities receive most of their turfgrass from the Texas Gulf Coast and Oklahoma. The availability of this urban market caused the initial expansion of dairy production around the NBR in the 1980s and 1990s. Efficient transportation of goods is possible through major roads that connect the NBR watershed to both cities. Munster et al. (2004) estimated approximately 396,440 kg P/yr could be exported from Erath County alone if manure was applied at a rate of 200 kg/ha to turfgrass production sites totaling 2,643 ha.

Phosphorous is known to accumulate in the upper soil layer causing susceptibility to stormwater runoff through erosion. Livestock WAFs are especially susceptible to excessive nutrient losses through runoff, but long-term excessive P applications can also lead to a reduced soil P sorption capacity and eventually P leaching (Sims et al., 1998). For this reason, scientific studies have specifically evaluated land application of confined animal feeding operation (CAFO) waste and the subsequent nutrient uptake by crops and vegetation. Manure wastes are typically applied on a limited amount of sites close to the production area due to the prohibitive cost of hauling. If unregulated, the manure is usually applied according to the N requirements of the crop causing P soil levels to escalate due to the low N:P ratio of most manures and the high N:P requirements of most crops (Sharpley et al., 1994). These manure applications cause both immediate and lasting losses of P, a large proportion of which can be available for in-stream algal uptake (Daniel et al., 1994). Generally, P losses in stormwater are less than 5% of that applied (Daniel et al., 1994, Choi et al., 2003), but continuous long-term P additions to a stream will lead to accelerated eutrophication.

Manure applications based on P crop requirements can be problematic also. This can exclude the use of many WAFs due to existing high P soil concentrations. Clearly there is a need for nutrient management plans that avoid elevating P levels in the soil while providing an economical method of moving nutrients.

The role of turfgrass sod as a nutrient Best Management Practice (BMP) has been explored by researchers at Texas A&M University. Vietor et al. (2002) demonstrated through plot-scale experiments that 46 to 77% of applied manure P can be removed through a single harvest of turfgrass sod and that most of the nutrients are concentrated in the soil component of the sod. Vietor et al. (2002) also found that the amount of nutrients exported increased proportionally to the manure application rates. At a turfgrass production site, even the nutrients not captured in the first harvest may be captured in the second as nutrients become available for plant uptake and the soil is sequentially removed. The research suggests that it may be possible to apply annual rates above the P requirements of the turfgrass in a sustainable manner.

Choi et al. (2003) quantified through field-scale experiments a loss of approximately 3.8% of total P (TP) applied from composted dairy manure at rates of 75 kg/ha and 130 kg/ha to turfgrass sod. It was also demonstrated that sod grown with manure P can be imported to a new site without increasing runoff losses of total dissolved P (TDP) compared to turfgrass sod grown and established using commercial fertilizers (Vietor et al., 2004). Vietor et al. (2004) demonstrated that losses of TDP and total Kjeldahl N (TKN) from turfgrass topdressed with manure or fertilizer can approach three times that lost from transplanted composted manure grown sod. The export of nutrients through turfgrass sod is feasible under controlled plot conditions and at the field scale. The impact on the watershed scale needs to be further evaluated.

The existing composting facilities around the NBR watershed currently produce more composted dairy manure than there is a market for. The composted dairy manure is an excellent source of P for the proposed turfgrass production BMP. Lammers-Helps (1991) states that composted manure N is almost exclusively in the organic form thereby reducing N runoff losses compared to fresh manure. The organic N is converted slowly into plant available forms prolonging the benefits of application. Composted nutrients are more stable and typically do not create problems associated with fresh manure, such as foul odors, weeds, and pathogens. However, the composted nutrients tend to be less plant available (Mitchell and Browne, 1992). Composted manure can be easier than fresh manure to handle and distribute onto agricultural fields if it is of high quality and is cheaper to transport because of its low water content. The composting facilities established in the NBR watershed must produce compost that meets TCEQ specifications for quality in order to receive rebates and hauling reimbursements (TCEQ, 2003). This reassures that quality compost will be available for use in turfgrass production in the NBR watershed.

Models are an effective but sometimes expensive way to evaluate the effectiveness of BMPs at the watershed level. Hydrologic modeling is becoming an accepted tool in watershed management, but there is a need to validate as well as expand the use of these models. The UNBR watershed is an excellent example of proper scientific use of hydrologic modeling that influenced public policy decisions. The UNBR watershed has been modeled several times by TIAER in conjunction with the TCEQ as part of the State's TMDL efforts. Saleh et al. (2000) used the Soil and Water Assessment Tool (SWAT) hydrologic model to estimate flow and sediment and nutrient loading for the watershed. It was demonstrated that conversion of land application fields to pristine grassland could alleviate the P loading by 79%, which reaffirmed the earlier sample-based findings of McFarland and Hauck (1999). Santhi et al. (2001) also modeled the NBR watershed in an effort to simulate the effectiveness of several dairy and wastewater treatment plant (WWTP) BMPs. The modeling results were mostly accepted by the State and used in the formulation of the TMDL mandate (TNRCC, 2001). Most recently, a modeling effort is underway that examines the effect turfgrass farms may have on the UNBR water quality when composted dairy manure is applied in order to export P (Stewart et al., 2003).

Turfgrass produced with composted dairy manure can be sold at a premium because of its unique properties: increased establishment rate, cation exchange capacity, aggregation, organic matter, and water content (Murray, 1981). The increased amount of P in the sod also adds to the value. If the turfgrass is properly managed, there may be enough P transplanted with the sod to satisfy the turfgrass needs for decades or longer

(T. Provin, personal communication, 29 January 2004; R. White, personal communication, 29 January 2004). This could reduce urban NPS P pollution caused by over-fertilization of green spaces, a phenomenon which led to a partial P fertilizer ban in Minnesota (MAWD, 2003).

The goal of this study was to contribute to the knowledge base concerning the sustainable use of turfgrass sod to export N and P in animal waste from agricultural watersheds to suburban watersheds. Specifically, the water quality impact of importing turfgrass sod fertilized with composted dairy manure to a suburban watershed was determined to assure that the turfgrass BMP is a sustainable method of P export.

The following objectives were selected to achieve the goals of the research:

1. Calibrate and validate the Soil and Water Assessment Tool (SWAT) model for a developing suburban watershed that is suitable for the import of turfgrass sod grown with composted dairy manure from the UNBR watershed.
2. Develop a method of using SWAT to model the transport of turfgrass sod including the manure nutrients that incorporates field data from turfgrass sod research.
3. Use the calibrated SWAT model to simulate changes in sediment and nutrient loading to streams in response to the import of turfgrass sod grown with composted manure to the developing suburban watershed.

CHAPTER II

ASSESSMENT OF WATER QUALITY IN A SUBURBAN WATERSHED DUE TO A TURFGRASS SOD BEST MANAGEMENT PRACTICE

Synopsis

The turfgrass sod BMP has the potential to export manure P through turfgrass sod produced with composted dairy manure. Turfgrass harvested in the NBR watershed would be shipped to developing urban and suburban areas in the D/FW metroplex, which may include the Mary’s Creek watershed, a tributary of the Trinity River. The impact on water quality of manure P imported to the Mary's Creek watershed needs to be assessed. The SWAT model was calibrated in this study to the historic flow and sediment and nutrient yield of the Mary's Creek watershed. The SWAT simulations revealed that the total P stream loading to Mary's Creek was lower when manure-grown sod was imported instead of commercial sod grown with inorganic fertilizers. Yet, flow, sediment yield, and total N yield increased equally for both cases at the watershed outlet. The SWAT simulations indicate that a turfgrass BMP can be used effectively to import manure P into an urban watershed and reduce in-stream P levels when compared to sod grown with inorganic fertilizers.

Introduction

In 2001, the Texas Commission on Environmental Quality (TCEQ) and the US Environmental Protection Agency (USEPA) approved the recommendations of two total maximum daily load (TMDL) assessments that suggested a 50% reduction of soluble reactive phosphorus (SRP) to sections of the North Bosque River in north central Texas. One of these sections at the headwaters of the North Bosque River is known as the Upper North Bosque River (UNBR) watershed. The UNBR watershed is located in Erath County, the largest milk producing county in the State of Texas (USDA-ARS, 2003). The number of dairies in the watershed constantly changes as a function of feed costs and milk prices (Hauck, 2002), but approximately 80 active dairies and 40,000 cows were distributed throughout the watershed in 2002 (Munster et al., 2004).

McFarland and Hauck (1999) demonstrated that the largest P loadings to the North Bosque River originated from dairy waste application fields (WAFs). In response to the TMDL recommendations, the State of Texas subsidized manure composting facilities in the UNBR watershed in order to move approximately 50 percent of the manure off of the dairies (TCEQ, 2003) and reduce the cost of exporting the nutrients out of the watershed. In September 2000, the TCEQ and the Texas State Soil and Water Conservation Board (TSSWCB) began subsidizing the transport of fresh manure from dairies to the composting facilities located in the UNBR and the Leon River watersheds (TCEQ, 2003). This compost has been used by the Texas Department of Transportation (TxDOT) to stabilize roadside embankments at construction sites (TCEQ, 2003) and by the Texas Water Resources Institute (TWRI) and the U.S. Army to revegetate areas of the

Fort Hood Western Training Grounds (TWRI, 2004b). However, new markets that do not require subsidies are needed to utilize the large amount of manure compost available in the watershed (TCEQ, 2003; TWRI, 2004a). Approximately 150,000 cubic meters of surplus compost has been generated, although this compost did not meet the Texas Department of Transportation requirements of quality for application to State roadsides at construction sites (C. Gerngross, personal communication, 23 July 2004).

The UNBR TMDL implementation plan states that "land application remains one of the best and most appropriate methods for dealing with large amounts of animal wastes" (TCEQ, 2002). Successful land application is achieved when nutrient transport into surface waters is minimized (TCEQ, 2002) and crop nutrient uptake is maximized so that a large percentage of the applied nutrients can be harvested and exported. The suggested turfgrass sod BMP utilizes P in the composted dairy manure to grow turfgrass at sod farms in the UNBR watershed. The manure-grown sod would be harvested an average of 1.5 times per year and each harvest would remove the sod, the composted dairy manure and a thin layer of topsoil. The sod and topsoil would be exported out of the UNBR watershed to suburban developments in nearby watersheds. The value of the turfgrass sod will allow growers to transport the manure nutrients from the dairies to the turfgrass fields and ultimately out of the UNBR watershed. This turfgrass sod BMP has the potential to eliminate the need for state subsidies to move excess manure from impaired watersheds.

Turfgrass produced with composted dairy manure can be sold at a premium because of its unique properties, including accelerated establishment rate and increased cation exchange capacity, aggregation, organic matter, and water holding capacity of the soil (Murray, 1981). The increased amount of manure P and organic matter adds value to the manure-grown sod. If the turfgrass is properly managed, there will be enough P transplanted with the sod to satisfy the turfgrass requirements for decades or longer (T. Provin, personal communication, 29 January 2004; R. White, personal communication, 29 January 2004). The residual manure P in the transplanted sod will eliminate the need for P fertilizer applications and will reduce urban non-point source (NPS) P pollution. The import of manure P with sod over time could alleviate regulatory constraints similar to partial P fertilizer bans in Minnesota (MAWD, 2003).

Although turfgrass sod is not produced in the UNBR watershed at this time, approximately 5,219 ha of suitable sites were identified in Erath County (Munster et al., 2004). In addition, the market for turfgrass sod near to the UNBR watershed is expanding within the Dallas/Fort Worth metroplex (within 160 km of the UNBR) (Hall, 1999). Currently, the metroplex purchases and hauls about 60% of needed sod from distant locations, including the Texas Gulf Coast and Oklahoma (Munster et al., 2004). The proximity of this growing urban market favored expansion of dairy production in the UNBR watershed in the 1980s and 1990s. Major roads connect the UNBR watershed to both cities. Munster et al. (2004) estimated approximately 396,440 kg P/yr could be exported from Erath County alone if manure was applied at a rate of 200 kg/ha to turfgrass production sites totaling 2,643 ha.

Vietor et al. (2004) demonstrated that sod grown with manure P can be imported to a new site without increasing runoff losses of total dissolved P (TDP) compared to turfgrass sod fertilized with inorganic P before and after transplanting. It was also demonstrated that losses of TDP and total Kjeldahl N (TKN) from turfgrass topdressed with manure or fertilizer can approach three times that lost from sod transplanted from fields where composted dairy manure was applied (Vietor et al., 2004). However, the impact of importing this turfgrass sod containing manure nutrients on water quality needs to be evaluated for suburban watersheds.

Bednarz and Srinivasan (2002) simulated the impact of suburban development on flow and sediment yield at the outlet of a suburban stream named Mary's Creek near Fort Worth, Texas. The study predicted increases in flow and sediment yield for Mary's Creek after the construction of a proposed development named Walsh Ranch through simulations of a hydrologic model known as the Soil and Water Assessment Tool (SWAT). In this study, the SWAT simulations were used to predict nutrient transport responses to two turfgrass import treatments on the Walsh Ranch development. The first treatment was sod transplanted from fields where inorganic fertilizer was applied. The second treatment was turfgrass transplanted from fields where composted dairy manure was applied.

Unfortunately, only limited streamflow, sediment and nutrient data were collected on Mary's Creek. However, hydrologic simulation models, including SWAT, can simulate this type of un-gaged and un-monitored watershed. Previous modeling studies simulated and evaluated changes in land management without calibrating the watershed model to measured data (He, 2003; Santhi et al., 2003). In addition, techniques are available for estimating sediment and nutrient loadings needed for calibration of watershed models. Chen et al. (2000) used crop yields and experimental field data to calibrate sediment and nutrient loads in the Environmental Policy Integrated Climate Model (EPIC). Land cover and surface flow were considered the predominant control factors in simulations of sediment and nutrient export from the watershed. Wickham and Wade (2002) similarly demonstrated that land use was a major factor in N and P transport and loss in surface waters. For the Walsh Ranch study, a technique proposed by Bhuyan et al. (2003) was used to calibrate the SWAT model. The technique separated nutrient and sediment losses into stormflow and baseflow losses.

The primary objective of this thesis is to assess water quality changes in a suburban watershed due to a turfgrass BMP that imports sod transplanted from turfgrass fields where composted diary manure was applied. This assessment used field data from turfgrass sod field research and the SWAT hydrologic simulation model to analyze changes in flow and sediment and nutrient loading for Mary's Creek in response to turfgrass BMP.

Materials and Methods

Watershed Selection

The Mary's Creek watershed in Fort Worth, Texas was chosen to receive the turfgrass grown with composted dairy manure due to its proximity to the UNBR and the proposed Walsh Ranch development. This Walsh Ranch development requires installation of turfgrass sod in green areas and is a reasonable hauling distance from the UNBR watershed. In addition, a gaging station located at the outlet of Mary’s Creek provided historic streamflow data for model calibration. Moreover, Bednarz and

Srinivasan (2002) successfully used the streamflow data for SWAT model simulations of sediment transport.

Mary's Creek is a perennial stream located west of the Dallas/Fort Worth (D/FW) metroplex that drains approximately 14,272 ha of predominately range and pasture (fig. 1). Construction of a planned community within the watershed, Walsh Ranch, will begin as early as 2020 (W. Frossard, personal communication, 23 June 2003). The development will resemble a small, self-sufficient community with schools, industrial areas, residential sites, public parks, and a community center and will require turfgrass for residential, commercial, and industrial areas. The Walsh Ranch development includes approximately 2,800 ha of the Mary’s Creek watershed. The majority of the Mary's Creek watershed will remain rangeland after construction of Walsh Ranch (table 1). The Walsh Ranch development and the Mary's Creek watershed are located approximately 100 km from the UNBR watershed. Economically, the distance from the UNBR to Mary's Creek is within an acceptable hauling distance for turfgrass sod (Munster et al., 2004).

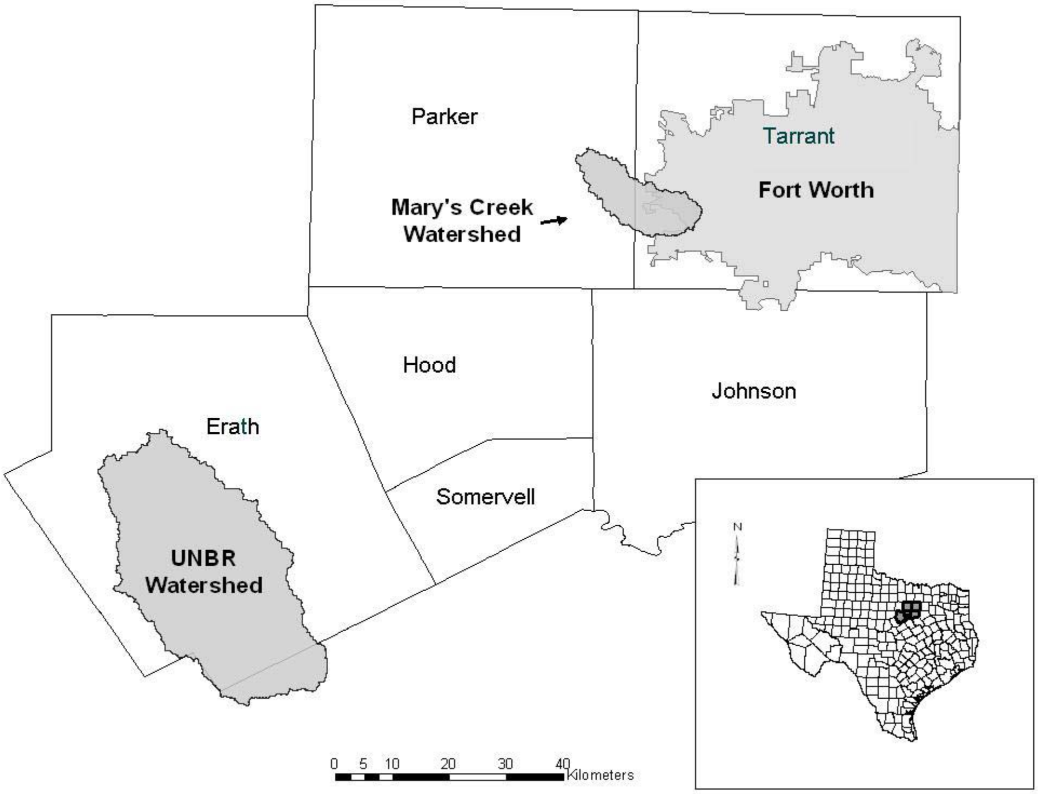

Figure 1. The location of the Mary's Creek watershed, the UNBR watershed, and Fort Worth, Texas with county boundaries shown.

Mary's Creek begins in Parker County and terminates at the Clear Fork of the Trinity River (CFTR) in Tarrant County within the city limits of Fort Worth. Approximately 41% of the land in the Mary's Creek watershed is rangeland and only 22% is allocated to urban land uses (table 1). Very few nutrients are now applied in the watershed (Jon R. Green, personal communication, 17 October 2004), and there are no wastewater treatment plants that discharge into the stream. Although nutrient data was not collected for the stream, watersheds similar to Mary's Creek in the D/FW metroplex area are not typically impaired by nutrients (USGSa, 1999; USGSb, 1999).

Table 1. The land use distribution of the Mary's Creek watershed for major land uses present before and after the construction of the Walsh Ranch development.

Land use	**Watershed Area Pre-development (%)**	**Watershed Area Post-development (%)**
Urban-High Density	2.39	2.41
Pasture	19.30	18.85
Range-Grasses	40.57	31.30
Forest-Mixed	17.88	14.75
Industrial/Institutional	0.06	0.72
Transportation/Commercial	3.58	8.13
Residential-Medium Density	11.30	19.03
Residential-Low Density	4.92	4.81

A United States Geological Survey (USGS) gaging station (08047050) was located on the stream near the confluence of Mary's Creek and the CFTR. Daily streamflow records were available from the gaging station from June 1, 1998 to September 30, 2002

Mary's Creek begins in Parker County and terminates at the Clear Fork of the Trinity River (CFTR) in Tarrant County within the city limits of Fort Worth. Approximately 41% of the land use in the Mary's Creek watershed is rangeland and only 22% is an urban land use classification (Table 1). Very few nutrients are now applied in the watershed and there are no wastewater treatment plants that discharge into the stream. Although nutrient data is not collected for the stream, watersheds similar to Mary's Creek in the D/FW metroplex area typically are not impaired by nutrients (USGSa, 1999; USGSb, 1999).

The SWAT Model

SWAT 2003 was used in this study interfaced with ArcView 3.2 to allow the model to integrate geospatial data, which is often readily available. SWAT model simulations allowed the assessment of water quality changes due to the import of sod transplanted from turf fields where composted dairy manure was applied to a suburban watershed. The SWAT model is capable of detecting changes in water yield and sediment, nutrient, and pesticide loading due to the effects of land use and agricultural management changes on a river basin scale (Arnold et al., 1998). The model is a daily time-step, distributed parameter model that uses the Soil Conservation Service (SCS) curve number (CN) method to predict runoff (USDA-SCS, 1972) and the Modified Universal Soil Loss Equation (MUSLE) to predict sediment yield (Williams and Berndt, 1977). The SWAT model simulates impervious cover associated with urban landuses as consistent sources of sediment and nutrient loads (USEPA, 1983). The SWAT model was chosen for this study to simulate sediment and nutrient transport without large inputs of observed data. In addition, the SWAT model allows the user to manipulate management routines and incorporates a crop growth model that includes detailed plant production, management, and harvest information.

SWAT Datasets

SWAT requires inputs of land use, soil, and elevation data. A raster layer (30-m resolution) of land use data was available from the Tarrant Regional Water District (TRWD) and the Blackland Research Center (BRC). The layer consisted of 1992 National Land Cover Data (NLCD) meshed with a regional Texas Agricultural

Experiment Station (TAES) land use map developed from 1997 Landsat 5 imagery. The Multi-Resolution Land Characteristics (MRLC) consortium derived the NLCD from Landsat 5 Thematic Mapper satellite imagery. The MRLC classification provides detail about urban land uses and the TAES classification details agricultural land uses. The collective map contains both the urban and agricultural data.

Soils data was collected from the Natural Resources Conservation Service (NRCS), which provided detailed Soil Survey Geographic (SSURGO) datasets with scales ranging from 1:12,000 to 1:24,000. These datasets were digitized from published county soil surveys (USDA-NRCS, 1995). A 10-meter raster Digital Elevation Model (DEM) of the area and a digitized stream network created by the City of Fort Worth were also available from the BRC.

The SWAT model includes a weather generating function and allows the user to input weather data. The National Climatic Data Center (NCDC) was a source of historic data for weather stations across the U.S. Weather data from Aledo (480129) and Benbrook Dam (480691) which were located within an 8 km radius of the Mary's Creek watershed (fig. 2), were available through NCDC. Both stations reported daily precipitation totals and the Benbrook Dam station reported daily maximum and minimum air temperature data. The Aledo weather station data spanned the period from 1960 to 2003 and Benbrook Dam weather station data were available for 1990 to 2003.

An extensive SWAT weather database was used to generate relative humidity and solar radiation data based on inputs from regional weather stations near Fort Worth.

SWAT Model Configuration

An Arcview 3.2 interface, AVSWAT-X (DiLuzio et al, 2003), was used to process SWAT model inputs for land use, elevation, and soil. The 10-meter DEM was delineated through AVSWAT-X. A 200 ha threshold was used to divide the watershed into 37 sub-basins (fig. 2). The AVSWAT-X interface linked the land use layers to the SWAT databases for land cover and plant growth. In addition, the software integrated a soil layer to a corresponding table of specific soil parameters. The watershed outlet was set at the USGS gaging station, 08047050, which limited the area of the watershed to 13,976 ha (fig. 2). The hydrologic response units (HRUs) were constructed similar to the Bednarz and Srinivasan (2002) study. The land use threshold was 5% and the soil threshold 10%, which resulted in 470 HRUs.

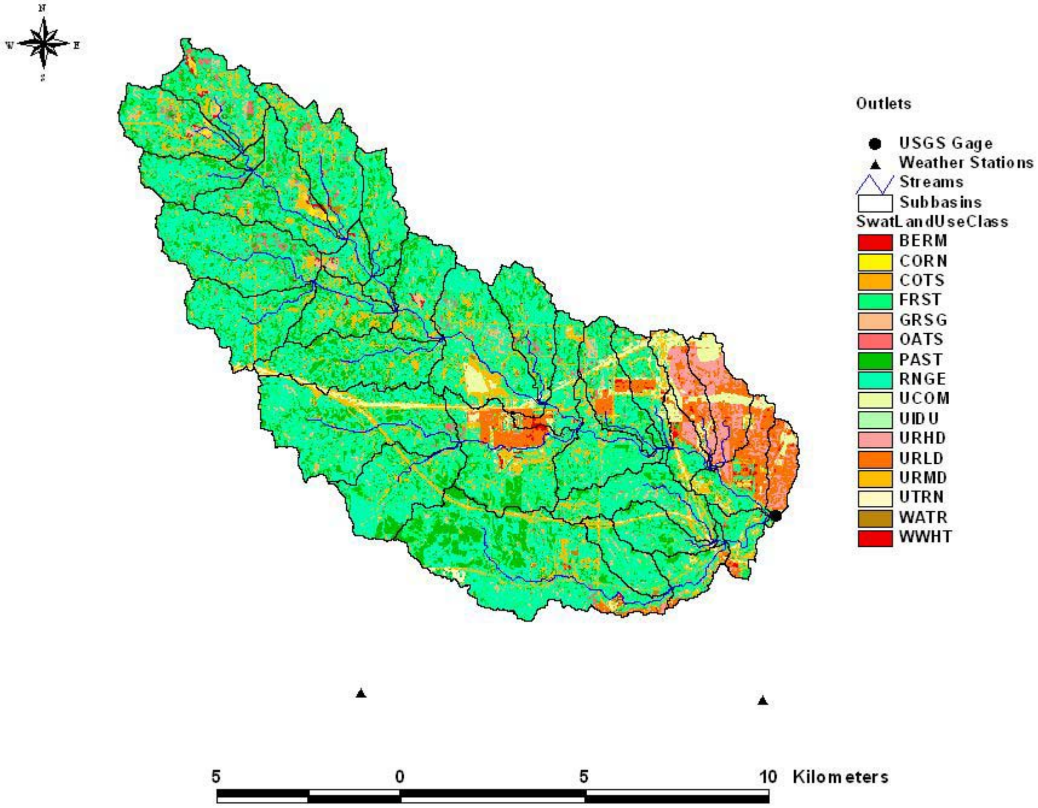

Figure 2. The current land uses of the Mary's Creek watershed with the location of the Aledo and Benbrook weather stations, the USGS stream gage (0804750), and the sub-basins used in the SWAT model simulations also shown.

The datasets from the Aledo and Benbrook Dam weather stations and the SWAT weather generator database were activated during the SWAT model simulations. The SCS Curve Number method was used to simulate surface runoff and the Priestly-Taylor method was used to simulate potential evapotranspiration. The Manning's roughness coefficient of the stream channel was set at the SWAT default value (0.014) and potential heat units (PHUs) were used to simulate biomass production. There was no evidence of preferential flow in the watershed and the crack flow routine in the model was not activated. Similarly, in-stream channel degradation and water quality routines were not activated for simulations.

SWAT Model Calibration

The MRLC/TAES land use map was used to represent recent land use during SWAT model calibration. The SWAT model was calibrated for flow using historic daily streamflow data from the USGS gage (08047050) over the period from June 1998 to September 2002 until the Nash Sutcliffe (NS) statistic (Nash and Sutcliffe, 1970) was greater than 0.50. The actual simulation period for flow calibration started January 1, 1990 and concluded September 30, 2002. The duration of the calibration allowed an eight year adjustment period for equilibrium among soil, water, and plant processes before simulating the period in which historic streamflow data was available. After calibration, the predicted monthly average streamflow compared to the observed monthly average streamflow produced a NS statistic of 0.72 and a root mean square error (RMSE) of 0.54.

Separate annual sediment loading estimations were averaged to predict an average annual sediment loading to Mary’s Creek of 2,400 metric tons (table 2). The TRWD used sediment removal records below the junction of Mary's Creek and the CFTR to estimate an annual sediment loading in Mary's Creek equal to 3,200 metric tons. This study estimated the average annual sediment loading to be 1,600 metric tons using USGS local urban sediment storm loading data, event mean concentration data

(Newell et al., 1992; Baird and Ockerman, 1996), and baseflow sediment data collected during this study.

Table 2. The average annual sediment load estimations used to derive the Mary's Creek average annual sediment load calibration value for the SWAT model simulations.

	Average Annual Sediment Estimation (tonnes/yr)
TRWD	3,200
Current Study	1,600
Average of Estimations	**2,400**[1]

[1] The average annual sediment loading value used to calibrate the SWAT model calculated from the average annual sediment load estimations by TRWD and the current study.

The estimation made by this study utilized the three separate sources of data to estimate stormflow and baseflow as proposed by Bhuyan et al. (2003). The land use sources of storm loading were assumed to be comprised of urban and rangeland/pasture land use only. Urban storm loads were calculated through a USGS regression equation developed from local data (Baldys et al., 1998). Rangeland/pasture storm loads were calculated using event mean concentration values based upon the average annual stormflow volume. Baseflow data was collected in the summer of 2004 for this study. The average constituent concentration was calculated from the collected samples and multiplied by the average annual baseflow volume for the calculation of annual load (table 3).

Table 3. The storm, baseflow and total average annual sediment load values used to estimate the average annual sediment load for this study and the sources of each.

Source of Load	**Sediment (tonnes/yr)**
Urban Storm[1]	570
Rangeland/Pasture Storm[2]	820
Baseflow[3]	210
Total	**1,600**

[1] Calculated from USGS regression equation developed by Baldys et al. (1998).

[2] Calculated from EMC values (Newell et al., 1992; Baird and Ockerman, 1996).

[3] Observed from baseflow sampling of Mary's Creek conducted May through July 2004.

The SWAT model was calibrated for average annual sediment loading over the period from January 1, 1990 to December 31, 2000, which was the same time period in which sediment loading was predicted. The prediction of average annual sediment yield after calibration was 2,830 metric tons. The SWAT prediction was approximately 18% higher than the calculated average annual sediment yield of 2,400 metric tons (table 2).

No nutrient data was available from the TRWD for Mary's Creek. Therefore, N and P loads in Mary's Creek were estimated. Total N, nitrate and nitrite-N, and total P average annual loadings were calculated from the local urban storm loading data collected by the USGS, event mean concentration data (Newell et al., 1992; Baird and Ockerman, 1996), and the baseflow stream samples collected during this study (table 4). The SWAT model was calibrated for total average annual N loading over the same period as the sediment calibration (January 1, 1990 to December 31, 2000). The average annual organic N yield was estimated by assuming:

$$N_{organic} = N_{total} - NO_3 - NO_2 \quad (1)$$

The calculated values for total average annual organic N, nitrate-N and nitrite-N loads (table 4) were used to calibrate SWAT.

Table 4. The storm, baseflow and total average annual nutrient load values used to estimate the average annual nutrient load and the sources of each.

Source of Load	**Total N (kg/yr)**	**NO_2 and NO_3 (kg/yr)**	**Organic N (kg/yr)**	**Total P (kg/yr)**
Urban Storm[1]	7,700	2,690	5,010	1,930
Rangeland/Pasture Storm[2]	17,590	3,790	13,800	1,400
Baseflow[3]	42,280	140	42,140	12,230
Total	**67,570**	**6,620**	**60,950**	**15,560**

[1] Calculated from USGS regression equation developed by Baldys et al. (1998).

[2] Calculated from EMC values (Newell et al., 1992; Baird and Ockerman, 1996).

[3] Observed from baseflow sampling of Mary's Creek conducted May through July 2004.

The simulated average annual total N yield at the outlet of Mary's Creek after calibration was approximately 11% lower than the calculated average annual total N yield (table 5). The predicted average annual organic yield after calibration was approximately 13% lower than the calculated average annual organic N yield (table 5). Lastly, the predicted average annual nitrate and nitrite-N yield after calibration was approximately 4% higher than the calculated average annual nitrate and nitrite yield (table 5).

Monitoring data for organic and mineral P were not available for calculating stream loads of each P form and calibration of SWAT. The model was calibrated to predict total P (organic and mineral P). The calibration period was the same as for sediment and N (January 1, 1990 to December 31, 2000). The predicted average annual total P yield after calibration was approximately 0.1% higher than the calculated average annual total P yield (table 5).

Table 5. A comparison of the SWAT simulated average annual nutrient loading after calibration.

Constituent	**Simulated Annual Load**	**Calculated Annual Load**	**% Difference**
Total N (kg/yr)	59,940	67,570	-11
NO_2 andNO_3 (kg/yr)	6,880	6,620	4
Organic N (kg/yr)	53,060	60,950	-13
Total P (kg/yr)	15,580	15,560	0.1

SWAT Simulations

SWAT Turfgrass Transplant Routine

Sod is transplanted in squares or unrolled in strips to form an instant layer of vegetation. There were no management practices in the SWAT model to simulate this instant addition of soil and biomass. Therefore, a separate turfgrass transplant routine was created that modified the SWAT model management practices to instantly add a layer of soil and mature grass to the soil profile of HRUs that receive transplanted sod. The transplant routine assumed that the layer of soil added was of the same characteristics of the soil presently in the HRU. This did not account for the soil characteristics of the soil transplanted with the turfgrass sod, but simplified the analysis of the nutrient import. Soils that may be transplanted with the sod would most likely have greater clay content than the existing soils and would thus increase the amount of water stored in the soil of the HRU and decrease the amount of nutrients that reach the stream. The turfgrass import routine required twelve inputs to the model (table 6).

Table 6. The SWAT model inputs required for the new turfgrass transplant management practice.

Turfgrass Transplant Input	**Unit**
MON (Month)	2-digit month
DAY (Day)	2-digit day
HEATU (Heat units to maturity of sod)	Heat Unit
SODLAI (leaf area index of sod)	Leaf Area Index
SODBION (N content of biomass)	kg/ha
SODBIOP (P content of biomass)	kg/ha
SODPPLT (depth of soil added)	mm
SODORGN (organic N content of soil)	kg/ha
SODORGP (organic P content of soil)	kg/ha
SODNO3 (nitrate content of soil)	kg/ha
SODSOLP (soluble P content of soil)	kg/ha
SODBIOM (biomass of sod)	kg/ha

The addition of the turfgrass transplant routine allowed the SWAT model to simulate the implementation of the turfgrass BMP in the Walsh Ranch development. The SWAT simulations were used to evaluate the effects of importing turfgrass sod fertilized with composted dairy manure on water quality in the Mary's Creek watershed.

Turfgrass Treatments

The SWAT model was used to simulate three turfgrass treatments. The treatments included the BMP treatment, a conventional treatment, and the status quo. The BMP and conventional treatments were implemented on the Walsh Ranch development. The status quo simulated only the current land uses in the Mary's Creek watershed.

Status Quo

The land use classifications for the status quo were not changed from the calibration simulations. The simulation of the current land uses in Mary’s Creek provided a control for evaluation of the Walsh Ranch development on water quality. Both the BMP and conventional treatments could be compared to water quality predictions for current land uses in the Mary's Creek watershed (table 1).

The Conventional Treatment

The conventional treatment comprises turfgrass sod transplanted from fields grown with inorganic P fertilizer and top-dressed annually with inorganic P fertilizer after transplanting into the Walsh Ranch development. The new SWAT turfgrass transplant routine was used to simulate import of the fertilizer-grown sod on residential, commercial and public open landscapes planned for the Walsh Ranch development. The physical and chemical properties of the imported turfgrass sod in the conventional treatment were adjusted to simulate conventional commercial sod grown with inorganic fertilizer (Vietor et al., 2002; 2004; Choi et al., 2003) (table 7). Conventional fertilizer applications of inorganic N and P were applied to the sod as needed for production and establishment after transplanting. The conventional treatment added turfgrass sod to approximately 1,400 ha of the Walsh Ranch development. In the SWAT model, 25 HRUs in the Mary's Creek watershed were affected (fig. 3).

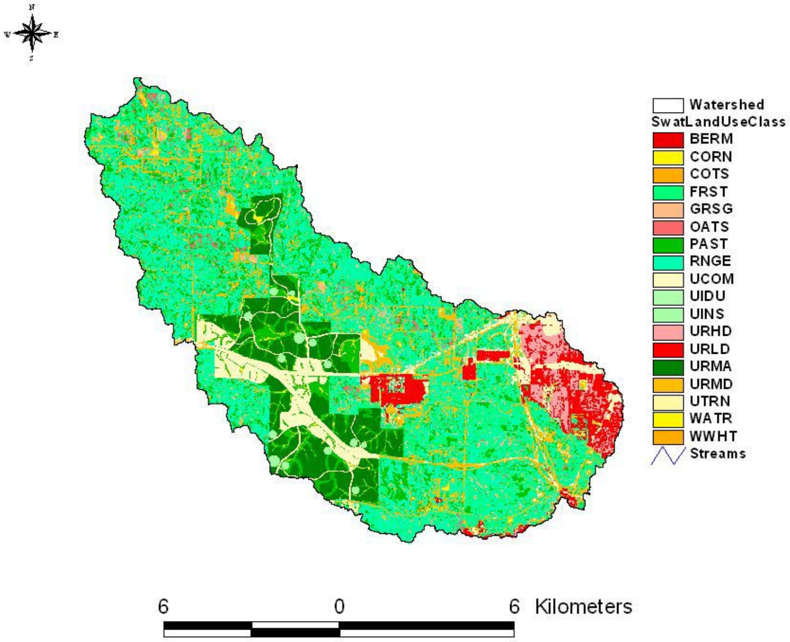

Figure 3. The Mary’s Creek watershed with areas where turfgrass was installed (land use category URMA) in the Walsh Ranch development. This land cover map was used for both the conventional and BMP treatments.

Table 7. The SWAT model inputs used to simulate the conventional and BMP treatments for the installation of turfgrass sod into the Mary's Creek watershed.

Turfgrass Sod Import Input	**Conventional Treatment Value**	**BMP Treatment Value**
MON (Month)	02 (February)	02 (February)
DAY (Day)	01	01
HEATU (Heat units to maturity of sod)	3000	3000
SODLAI (leaf area index of sod)	4.0	4.0
SODBION (N content of biomass)	225 kg/ha	244 kg/ha
SODBIOP (P content of biomass)	36 kg/ha	42 kg/ha
SODPPLT (depth of soil added)	25 mm	25 mm
SODORGN (organic N content of soil)	370 kg/ha	540 kg/ha
SODORGP (organic P content of soil)	126 kg/ha	115 kg/ha
SODNO3 (nitrate content of soil)	3 kg/ha	3 kg/ha
SODSOLP (soluble P content of soil)	36 kg/ha	77 kg/ha
SODBIOM (biomass of sod)	18000 kg/ha	18000 kg/ha

The BMP Treatment

In the BMP treatment, turfgrass sod transplanted from fields top-dressed with composted dairy manure was simulated using the new turfgrass import routine. The manure-grown sod was transplanted into the same residential, commercial and public landscapes in the Walsh Ranch development as simulated in the conventional treatment. The properties of the transplanted sod were adjusted in the BMP treatment to represent nutrient levels of turfgrass grown with composted dairy manure and inorganic N fertilizer (Vietor et al., 2002; 2004; Choi et al., 2003) (table 7). After sod transplant to the Walsh Ranch development, inorganic N fertilizer was applied to the sod as needed, but no inorganic P fertilizer was added. The turfgrass was placed on the same 1,400 ha and in the same 25 HRUs of the SWAT model as simulated in the conventional treatment.

Simulation Procedures

An initial SWAT simulation was performed to demonstrate the effects that the Walsh Ranch development infrastructure (roads, removal of trees, etc.) would have on streamflow and sediment and nutrient loading without the turfgrass present. The residential, commercial, and public landscapes that the turfgrass sod was imported to was simulated as pasture. This simulation predicted monthly flow and yearly sediment and nutrient loading for a 5-year period preceding the sod analysis simulations (1986-1990)

Two SWAT simulations were performed to analyze each sod treatment. The first model simulation predicted monthly flow and yearly sediment and nutrient loading for a

10-year period (1991 to 2000). For simulations of the BMP and conventional treatments, the SWAT management files were revised to simulate imports of the contrasting sod sources into the Walsh Ranch development on February 1 of year one of the 10-year period (1991). The newly installed turfgrass sod was fertilized and irrigated as needed. However, no inorganic P was applied to the BMP treatment after transplanting. For the status quo, no turfgrass sod was installed and land use classifications were not changed.

A second model simulation was run to predict yearly flow and sediment and nutrient loading from 1950 to 2000 for each sod treatment. These simulations compared long term water quality impacts of the turfgrass BMP to that of the status quo and conventional treatment. The BMP and conventional treatments turfgrass transplant took place on February 1 of year one (1950) and fertilization and irrigation occurred as needed. Again, the land use classifications for the simulation of the status quo were unchanged.

Results

Influence of Development

Construction of the Walsh Ranch development added 160 ha of impervious cover within the watershed causing an increase of surface runoff (table 8). The effect of this additional impervious area on streamflow and sediment and nutrient loads in the Mary's Creek watershed was calculated from a 5-year SWAT simulation from 1986 to 1990. This simulation modeled the Walsh Ranch development without the installation of turfgrass. The green spaces in the development were simulated as pasture. The average increase due to the Walsh Ranch Development without turfgrass above the status quo for streamflow and sediment and nutrient loads is shown in table 8.

Table 8. The simulated average increase of streamflow and sediment and nutrient load in Mary's Creek due to the Walsh Ranch development without turfgrass for a 5-year SWAT simulation from 1986 to 1990.

Constituent	**Average Increase Due to Development**
Streamflow	0.03 m^3/s (per month)
Sediment	636 tonnes/yr
Organic N	17,838 kg/yr
Nitrate N	1,142 kg/yr
Total P	4,965 kg/yr

Flow

The 10-year SWAT simulation revealed streamflow was 10% greater for the BMP and conventional turfgrass treatments than for the status quo without any development. The simulated annual streamflow did not differ between the BMP and conventional turfgrass treatments. Simulations of average monthly flow predicted an increase of 0.14 m^3/s per month for the BMP and conventional turfgrass treatments when compared to the status quo (fig. 4A).

The monthly streamflow increase (0.03 m3/s per month) caused by the development of the watershed was removed from the BMP and conventional turfgrass treatments as shown in figure 4B. As shown in figure 4B, the BMP and conventional turfgrass treatments continued to increase streamflow due to the irrigation of the turfgrass. The constant irrigation kept the soil water of the HRUs containing the sod near field capacity resulting in more runoff than the status quo treatment.

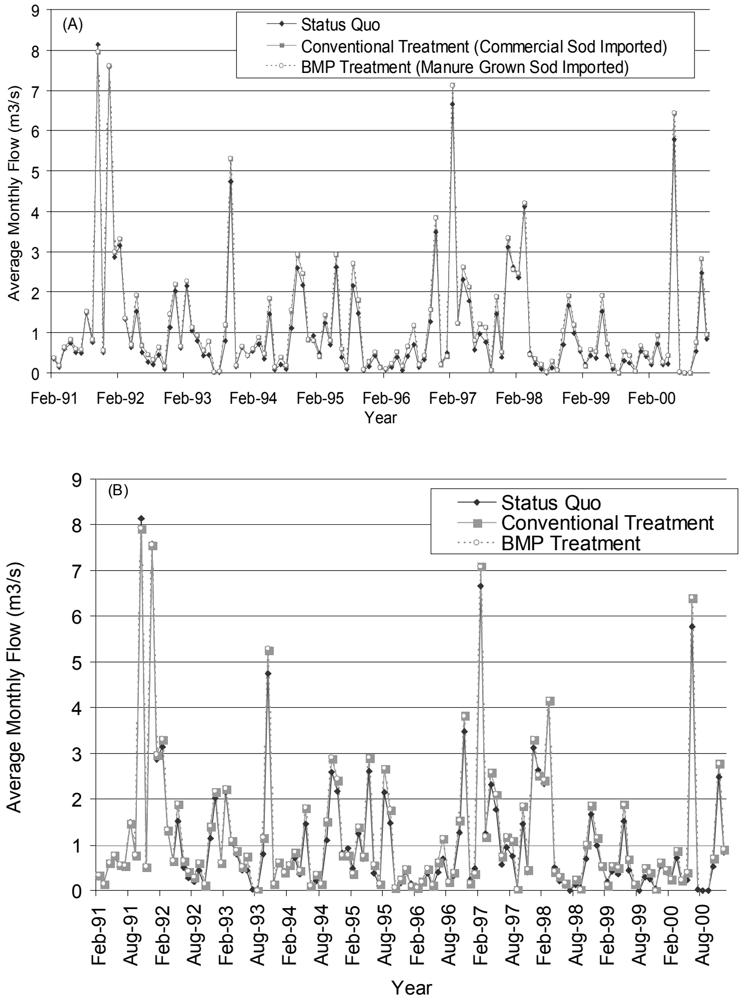

Figure 4. The simulated average monthly flow for the three treatments at the outlet of the Mary’s Creek watershed with, (A) the runoff from impervious urban surfaces included in the BMP and conventional treatments, and (B) the runoff from impervious urban surfaces not included in the BMP and conventional treatments.

The long term, 50-year simulations (1950 to 2000) of streamflow in Mary's Creek were similar between the BMP and conventional turfgrass treatments at the watershed outlet. Compared to the status quo, the BMP and conventional treatments increased streamflow 5.3% during the long term simulation (fig. 5). The influence of the impervious surfaces in the Walsh Ranch development was not factored out of the long term simulation.

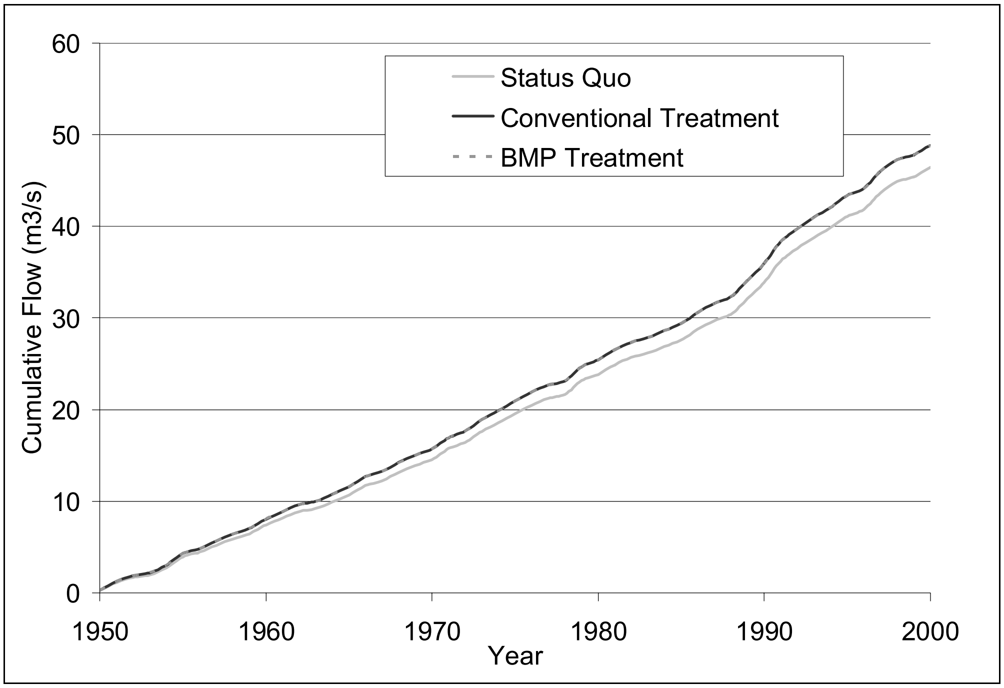

Figure 5. The cumulative annual simulated streamflow for the three treatments at the outlet of the Mary's Creek watershed.

Sediment

The SWAT simulations indicated both the conventional and BMP turfgrass treatments contributed equally to the sediment loadings of Mary's Creek. The dense growth of turf plants and similar physical properties between manure-grown and conventionally-grown turfgrass minimized sediment losses for both treatments (Vietor et al., 2004). Yet, the short term (10 year) simulation demonstrated that the BMP and conventional turfgrass treatments consistently produced greater sediment loads (135 metric tons cumulative) when compared to the status quo which represented the undisturbed watershed (fig. 6A). The principal difference between the imported sod treatments and the status quo was erosion prior to turfgrass installation due to the increased impervious area within the Walsh Ranch development. The Walsh Ranch development (roads, buildings, sidewalks, driveways, etc.) was in place throughout the 10-year simulation. Similarly, the long term 50-year simulation indicated that the BMP and conventional turfgrass treatments each contributed a total of 23,710 metric tons more sediment to the stream than the status quo or undisturbed watershed. As postulated for the short-term simulation, the additional sediment loading for both the BMP and conventional turfgrass treatments resulted from erosion before the sod was transplanted on disturbed soil and from increased runoff due to the increased impervious areas within the watershed throughout the simulation.

The average sediment load (636 tonnes/yr) caused by the development of the watershed was factored out of the short term simulation revealing the sediment loads contributed by just the turfgrass treatments (fig. 6B). As shown in figure 6B, removing the influence of impervious surfaces in the development revealed that the turfgrass sod treatments reduced sediment loading to the stream when compared to the status quo treatment.

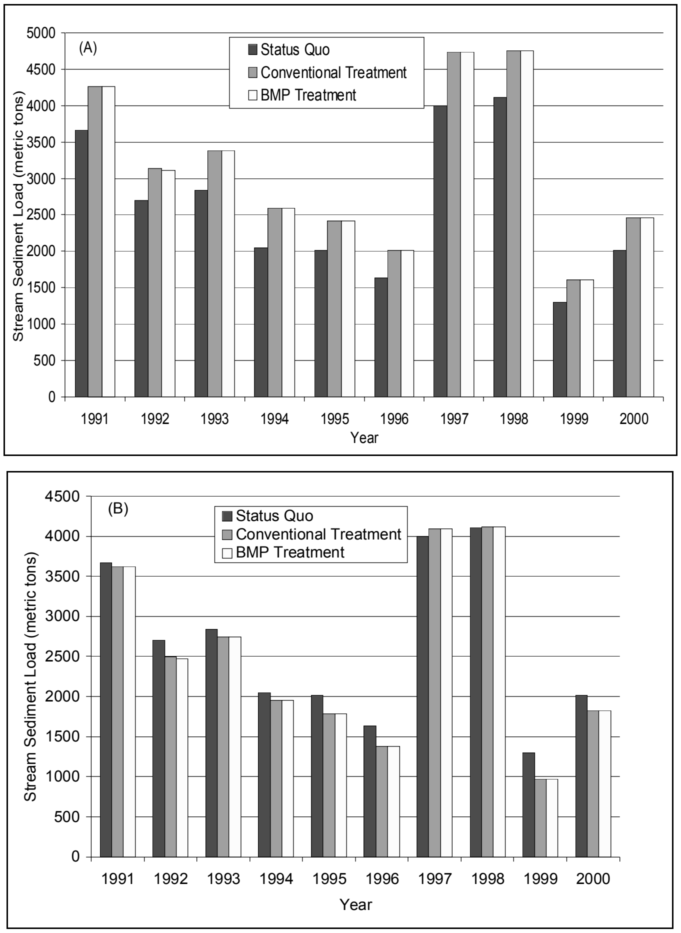

Figure 6. The simulated annual stream sediment load for the three treatments at the outlet of the Mary's Creek watershed with, (A) the sediment due to increases in runoff from urban impervious surfaces included in the BMP and conventional treatments, and (B) the sediment due to increases in runoff from urban impervious surfaces removed from the BMP and conventional treatments.

Variation of annual total rainfall amount accounted for a greater portion of the annual variation of sediment load for the transplanted sod treatments than for the status quo treatment as determined by a linear regression analysis (table 9). Monthly factors such as time of year and plant growth stage could have exerted greater influence on sediment loss in the status quo simulation than in the transplanted sod treatments. Yet, variation of annual rainfall was not significantly related to variation of sediment load for any of the simulated treatments.

Table 9. The adjusted R-square values resulting from a regression analysis between variation of annual rainfall and the sediment loads predicted by SWAT for the turfgrass treatments.

Treatments	**Adjusted R-Square Value**
Transplanted Sod (Conventional and BMP)	0.208
Status Quo	0.168

Nutrients

The increases in streamflow and sediment loading predicted for imports of manure-grown sod (BMP) and fertilizer-grown sod (conventional) were also reflected in the predicted differences in stream nutrient loading between the status quo and the BMP and conventional turfgrass treatments during the long term simulations (table 10).

Table 10. Simulated nutrient loading at the outlet of the Mary's Creek watershed for the three treatments from 1950 to 2000.

	Conventional Treatment	**BMP Treatment**	**Status Quo**
Organic N (kg)	2,660,860	2,660,860	2,110,560
Nitrate-N (kg)	484,490	484,930	340,880
Total P (kg)	816,017	804,282	635,200

The simulated stream organic N loading differed by 550,300 kg between the status quo and imports of each fertilizer-grown (conventional) and manure-grown (BMP) sod. Compared to the status quo, the stream nitrate-N loading was 42.5% greater for the BMP treatment and 42.1% greater for the conventional treatment. A portion of the organic N imported with the manure-grown sod of the BMP treatment was converted to nitrate-N over time, which led to slightly higher nitrate-N stream loading (0.09%) compared to the conventional treatment. After imports of fertilizer-grown sod (conventional), total P loading to the stream was 28.5% greater than the status quo treatment. Similarly, predicted P loading for the BMP treatment was 26.6% larger than the status quo. The P fertilizer addition to the fertilizer-grown (conventional) sod increased total P stream loading by 1.5% compared to the BMP treatment.

The short term simulation allowed between the manure-grown (BMP) and fertilizer-grown (conventional) treatments that were imported into the watershed. A linear regression was performed to relate variation of predicted annual sediment load to that of the predicted annual organic N load for the turfgrass treatments. The regression indicated predicted annual sediment load accounted for a significant portion of variation in organic N load among treatments (table 11).

Table 11. The adjusted R-square values resulting from a regression analysis between annual sediment load and the annual organic N load predicted by SWAT for the turfgrass treatments.

Treatments	**Adjusted R-Square Value**
Transplanted Sod (Conventional and BMP)	0.893
Status Quo	0.908

The simulated organic N load in Mary's Creek comparing the status quo and BMP and conventional turfgrass treatments is shown in figure 7A. The average stream organic N load (17,838 kg/yr) caused by increased runoff from impervious surfaces in the development was factored out of the 10-year simulation for the BMP and conventional turfgrass treatments as shown in figure 7B. Removing the influence of development revealed that both turfgrass treatments reduced organic N loading to the stream when compared to the status quo treatment.

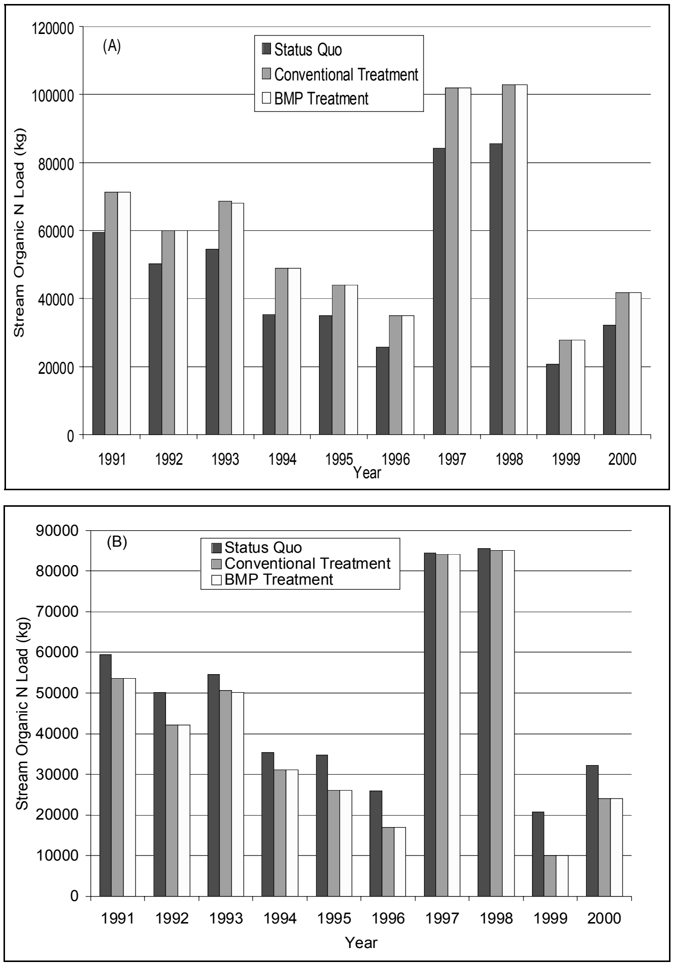

Figure 7. The simulated annual organic N stream load for the three treatments at the outlet of the Mary's Creek watershed with, (A) the organic N due to increases in runoff from urban impervious surfaces included in the BMP and conventional treatments, and (B) the organic N due to increases in runoff from urban impervious surfaces removed from the BMP and conventional treatments.

In contrast to organic N, the simulated nitrate N load in the stream at the outlet increased significantly after the installation of the two turfgrass treatments due to inorganic N fertilization (fig. 8A). The difference in simulated nitrate N loads between the status quo and the turfgrass treatments peaked at approximately 35,000 kg in 1992. Low stream flows (fig. 4) combined with a reduction in application of inorganic N fertilizer lowered the stream nitrate N load in the conventional and BMP turfgrass treatments during years 1995 and 1996. When summed over the 10 year period, the conventional turfgrass treatment contributed 1,620 kg of nitrate N more to Mary's Creek than the BMP turfgrass treatment.

The SWAT model applied inorganic N fertilizer based upon a N stress threshold of 0.9 (where 0.0 indicates no plant growth due to N stress and 1.0 indicates no reduction in plant growth due to N stress). The SWAT model applied enough inorganic N fertilizer to replace N losses due to plant growth, surface runoff and leaching.

The BMP turfgrass treatment imported approximately 170 kg/ha more organic N than the conventional turfgrass treatment. This additional organic N was originally associated with the humus but was eventually released in years 1993 and 1995 when conditions such as the amount of soil water allowed for the decay and mineralization of the additional organic N.

The average stream nitrate N load (1,142 kg/yr) caused by increased runoff from urban impervious surfaces in the development was factored out of the 10-year simulation for the BMP and conventional turfgrass treatments as shown in figure 8B. Removing the influence of the development revealed that the turfgrass treatments were the major source of the nitrate N load due to lawn fertilization.

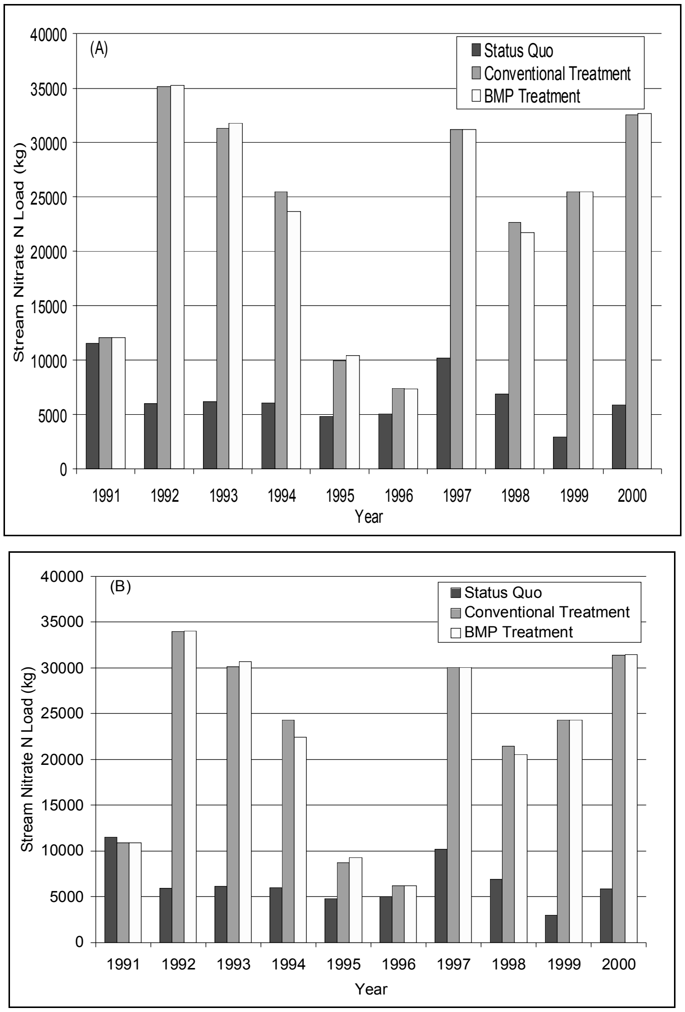

Figure 8. The simulated annual nitrate N stream load for the three treatments at the outlet of the Mary's Creek watershed with, (A) the nitrate N due to increases in runoff from urban impervious surfaces included in the BMP and conventional treatments, and (B) the nitrate N due to increases in runoff from urban impervious surfaces removed from the BMP and conventional treatments.

The total P stream loading for the 10 year simulation was greatest for the conventional treatment (fig. 9A). The simulation of total P loading to Mary’s Creek for fertilizer-grown sod (conventional treatment) was 14,843 kg greater than the manure-grown sod (BMP treatment) for the 10-year period. The simulated total P loading to Mary’s Creek for the BMP treatment was 69,988 kg greater than the status quo treatment. The simulated total P load of the BMP treatment exceeded the conventional treatment in 1993 only and may be explained as follows (fig. 9A). Approximately 11 kg/ha less organic P was imported with the BMP treatment compared to the conventional treatment and 41 kg/ha more soluble P and 6 kg/ha more biomass P was imported by the BMP treatment (table 7). This additional soluble P was not lost immediately in the BMP treatment, but was immobilized and released three years after the transplant either when conditions allowed for mineralization of the organic P or when the organic P was transported through sediment loss (erosion). Following this release in 1993, the total simulated P load to Mary’s Creek for the BMP turfgrass treatment remained at or below the conventional turfgrass treatment.

The average stream total P load (4,965 kg/yr) caused by increased runoff from urban impervious surfaces in the development was factored out of the 10-year simulation for the BMP and conventional turfgrass treatments as shown in figure 9B. Removing the influence of the development revealed that the BMP turfgrass treatment reduced total P loading to Mary’s Creek compared to the status quo treatment. The conventional treatment increased total P loading to Mary’s Creek compared to the status quo treatment after the influence of development was removed (fig. 9B).

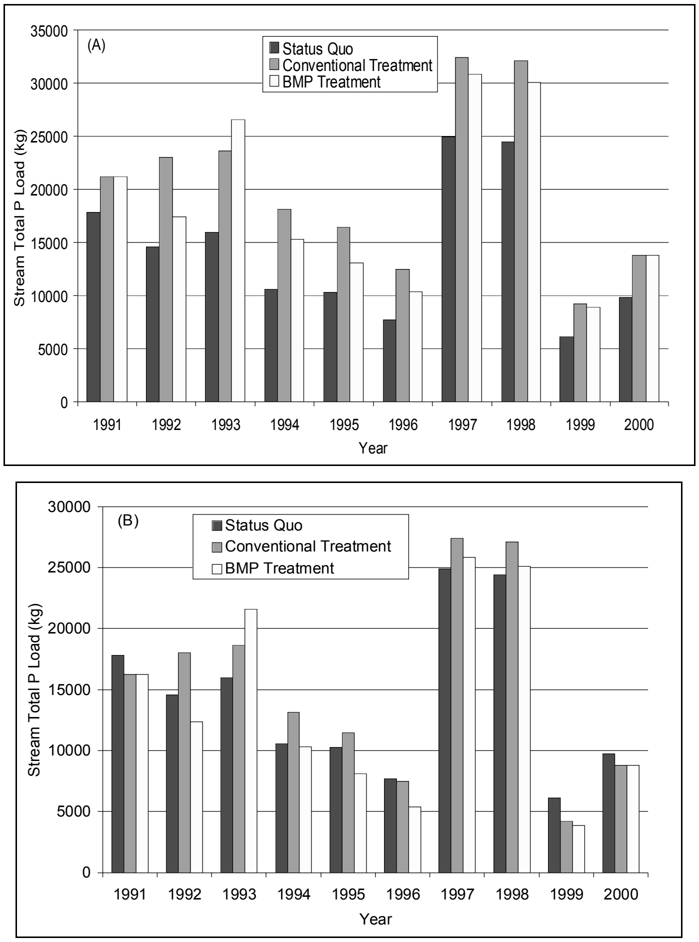

Figure 9. The simulated annual total P stream load for the three treatments at the outlet of the Mary's Creek watershed with, (A) the total P due to increases in runoff from urban impervious surfaces included in the BMP and conventional treatments, and (B) the total P due to increases in runoff from urban impervious surfaces removed from the BMP and conventional treatments.

A linear regression was performed to relate variation of annual total rainfall amount to annual variation of nutrient loads for the turfgrass treatments. The variation of annual rainfall did not account for a significant portion of variation of nutrient loads of treatments, except for the predicted nitrate N load of the status quo treatment (table 12).

The low R-square for the regression between nitrate N and rainfall amount for the transplanted sod treatments reaffirms that the nitrate N loads for these treatments are related more to fertilizer application than streamflow or rainfall amount.

Table 12. The adjusted R-square values resulting from a regression analysis between annual rainfall and the nutrient loads predicted by SWAT for the turfgrass treatments.

	Adjusted R-Square Value		
Treatments	Organic N	Nitrate N	Total P
Conventional Treatment	0.149	-0.076	0.127
BMP Treatment	0.149	-0.076	0.141
Status Quo	0.146	0.793	0.164

Discussion

The model simulations of the turfgrass BMP indicate that the BMP is an effective means of importing manure nutrients from impaired watersheds without raising the in-stream nutrient levels above conventional commercial turfgrass levels. In fact, the turfgrass BMP treatment reduced all in-stream nutrient levels except nitrate N when compared to the status quo treatment after the effects of increased runoff from impervious surfaces in the development were removed. However, field studies should be conducted to confirm the amount of nutrient loss caused by the transplanted turfgrass sod grown with composted manure. Water quality sampling of a pilot suburban stream, such as Mary's Creek, after receiving turfgrass grown with composted manure would be useful for validating the amounts of nutrient loss from the turfgrass on the watershed scale.

CHAPTER III

CONCLUSIONS

Through model simulation, the proposed turfgrass BMP was found to reduce total P loading to urban streams when compared to conventional commercial sod imported and maintained with inorganic P fertilizer. The proposed turfgrass BMP was also found to reduce total P loading to the stream compared to an undeveloped suburban watershed (the status quo treatment) when the effect of the Walsh Ranch development was factored out of the model results. The turfgrass BMP increased the nitrate N stream loading compared to the status quo treatment due to N fertilization. However, the increase was equivalent to the impact of importing conventional commercially-grown sod. The additional nitrate N stream loading could be reduced by utilizing urban nutrient BMPs and by homeowner education of proper lawn nutrient application.

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APPENDIX A

SWAT MODEL CALIBRATION ADJUSTMENTS

Initially, the model monthly flow estimates were higher than the observed monthly flows. The SWAT model parameters in Table 13 were adjusted until the predicted flow was approximately equal to the observed flow. The base flow fraction was first calculated using a base flow filter developed by the BRC. The base flow alpha factor (ALPHA_BF) was adjusted to 0.158 according to the filter results. In order to bring the simulated flow rate down further, the curve numbers (CN2) were adjusted down by a factor of 8, the CN2 limits were adjusted down by 10% and the soil evaporation compensation factor (ESCO) and the plant water uptake compensation factor (EPCO) were adjusted down. Temporal adjustments to the peak flows and baseflow were made by increasing the groundwater delay coefficient (GW_DELAY) and increasing the effective hydraulic conductivity of the main channel alluvium (CH_K2). Finally, to accurately simulate the amount of water returning to the stream, the amount of shallow aquifer water that moved into the soil profile (GW_REVAP) was increased and the threshold depth of water in the shallow aquifer for this "revap" to occur (REVAPMN) was decreased.

Table 13. The SWAT model parameters adjusted during the flow calibration of the Mary's Creek watershed.

Parameter	**Default Value**	**Calibration Value**
ALPHA_BF	0.0	0.158
CH_K2	0.0	1.0
CN2	0	-8
EPCO	1.0	0.0
ESCO	0.95	0.01
GW_DELAY	31	93
GW_REVAP	0.02	0.2
REVAPMN	1.0	0.0

A limited amount of sediment loading data was available for Mary’s Creek. The following sources were available to estimate the average annual sediment load:

- Sediment loading was estimated from sediment removal records from the Clear Fork of the Trinity River (CFTR) below the intersection of Mary’s Creek.
- Sediment storm loading from urban areas was estimated from a regional regression analysis using data collected by the USGS from D/FW watersheds.
- Sediment storm loading from rangeland/pasture was estimated from an event mean concentration value (EMC) calculated from a nearby watershed.
- Sediment baseflow loading was estimated from baseflow sampling of Mary's Creek.

Records of sediment removal from the CFTR below Mary's Creek were available from the TRWD. TRWD estimated 3,200 metric tons per year were removed from the junction of Mary's Creek and the CFTR. Although some sediment from Mary's Creek may remain suspended beyond this junction, this estimate also takes into account the settled sediment from the CFTR. Therefore, most of this sediment originated in Mary's Creek but it is impossible to determine if this estimate is high or low.

A local regression analysis developed by Baldys et al. (1998) was also used to estimate the average annual sediment loading to Mary's Creek. The regression utilized data collected as a part of the D/FW National Pollutant Discharge Elimination System (NPDES) permit application for urban storm water. Data collected for this permit included sediment concentrations, nutrient concentrations, and other water quality parameters from the storm flows of 26 small, single land use watersheds. Baldys et al. (1998) flow-weighted these parameters to allow their estimation from other flow-gaged watersheds in the area. The regression equation used seven explanatory variables: total storm rainfall (TRN), total contributing drainage area (DA), impervious area (IA), industrial land use (LUI), commercial land use (LUC), residential land use (LUR), and nonurban land use (LUN). Antecedent dry days and maximum 5-minute intensity were not used as explanatory variables because there was no significant statistical difference in the results when these were included. The regression equation was given by,

$$\begin{aligned} LOAD = b_o &* (TRN)^{b_1} * (DA)^{b_2} * (IA+1)^{b_3} * (LUI+1)^{b_4} * (LUC+1)^{b_5} \\ &* (LUR+1)^{b_6} * (LUN+1)^{b_7} * BCF \end{aligned} \tag{2}$$

The bias correction factor (BCF) provides an unbiased estimate of the mean response through a parametric method. The BCF is defined by

$$BCF = 10^{(1.1515(SE)^2)} \tag{3}$$

The standard error (SE) of the regression equation measures the deviation about the regression. The regression equation coefficients for suspended solid estimation are shown in table 14 as taken from Baldys et al. (1998).

Table 14. The regression analysis coefficients for estimating the sediment load to Mary's Creek.

Coefficient	**Value**
b_o'	5.85
b_1	0.889
b_2	0.544
b_3	0.913
b_4	0.463
b_5	0.170
b_6	0.328
b_7	--
BCF	1.52
SE	115

The local regression was applied to each SWAT sub-basin. TRN was calculated from the rain gage data that is described in the SWAT datasets section over the period of 1990 to 2000. Land use and land use characteristics were obtained through the MRLC/TAES land use raster layer using a land use classification and land use imperviousness database. The sediment load was found to be 530 metric tons per year. This load can only be attributed to storm events on urban areas (the non-urban coefficient was not available).

The remainder of the Mary's Creek watershed is predominantly rangeland and pasture land uses. The forest land use in Mary's Creek is primarily located near the stream as riparian vegetation and was not considered in this calculation because the sediment loading from forest land uses are generally lower than from rangeland and pasture areas (Newell et al., 1992). Sediment loading was estimated from the remainder of the watershed through the use of an EMC value. EMC values allow the comparison of pollutant loads between watersheds of different sizes and between storms that may have different characteristics. They are calculated by dividing the pollutant load by the volume of storm runoff. This is done by using the flow-weighted average of the concentration of the pollutant collected from samples gathered during the course of a storm event or by combining these samples into a single, flow-averaged sample.

The sediment EMC value (70 mg/L) utilized in this study is the median of EMC values calculated from "open" land use watersheds by the USEPA (1983). This EMC value was also applied to rangeland/pasture land use areas near Houston by Newell et al. (1992). This value was selected because it has been used to predict loadings from rangeland/pasture dominated watersheds in east Texas and is a large value that will tend to overestimate the sediment loading rather than underestimate. The average annual storm sediment loading due to rangeland/pasture was calculated to be 820 metric tons as given by,

$$\text{LOADING} = \text{EMC} * \text{STORM RUNOFF VOLUME} \tag{4}$$

The storm runoff volume was found by subtracting the baseflow fraction (0.375) calculated using the BRC baseflow filter from the total flow through the USGS gage 08047050 over the 1998 to 2002 period. The EMC method assumes that pollutant concentration is a function of land use and flow only and that neighboring watershed land uses mimic each other.

Water quality grab samples that corresponded with baseflow conditions were obtained from Mary's Creek on May 18 and 26, and June 14, 2004. Water quality samples were also collected for a one week period (May 18, 2004 to May 25, 2004) with the assistance of an automatic ISCO sampler set to composite six samples into a separate bottle every twelve hours. The total suspended solid concentration was calculated for these samples and the average baseflow sediment concentration was found to be approximately 30 mg/L. The baseflow loading was then,

$$\text{LOADING} = \text{AVG. BASEFLOW CONC.} * \text{BASEFLOW VOLUME} \qquad (5)$$

The average annual sediment loading during baseflow was calculated as 210 metric tons.

Finally, the total average annual sediment loading was found to be approximately 1,600 metric tons by adding the urban stormwater contribution, the rangeland/pasture stormwater contribution, and the baseflow contribution.

The average of average annual sediment loads calculated from the TRWD sediment removal records and the combination of urban, rangeland/pasture stormflow, and baseflow estimation was found to be 2,400 metric tons.

The SWAT model was calibrated to predict an average annual sediment load of 2,400 metric tons over the period from January 1, 1990 to December 31, 2000. This period was chosen because it coincides with the time periods that were used to estimate sediment loading. The model was run on a yearly basis for the period of January 1, 1985 to December 31, 2000 to give the model a five year adjustment period.

Without any calibration, the SWAT model predicted an average annual sediment yield greater than the calculated average annual sediment yield. The SWAT model parameters shown in table 15 were then adjusted until the predicted average annual sediment yield was approximately equal to the calculated average annual sediment yield. The average slope length (SLSUBBSN) was reduced to 10 meters as this is a parameter that is commonly over-estimated. Also, the average slope steepness (SLOPE) was adjusted down to 0.02 m/m to reduce the HRU contribution of sediment further. The universal soil loss equation soil erodibility factor (USLE_K1) was decreased by approximately 60% for all soils in the watershed to further reduce the sediment entering the stream.

Table 15. The SWAT model parameters adjusted during the sediment calibration of the Mary's Creek watershed.

Parameter	**Default Value**	**Calibration Value**
SLOPE	0.129	0.020
SLSUBBSN	24.390	5.000
USLE_K1 (all soils)	Various	-60%

The predicted average annual sediment yield after calibration was 2,830 metric tons, approximately 18% higher than the calculated average annual sediment yield.

There was little nutrient loading data available for the Mary's Creek watershed. The TRWD and the BRC did not make nutrient loading estimates during their studies and the USGS did not collect water quality samples at the gaging station, 08047050. For this reason, the same estimation method that was utilized for sediment loading was used to estimate the total N, nitrate and nitrite N, and total P loadings. First, the urban stormwater average annual nutrient loading was calculated using the local regression analysis developed by Baldys et al. (1998). Then, the average annual nutrient loading due to the rangeland/pasture stormwater contribution was calculated using an EMC value. Lastly, the baseflow contribution was calculated from the sampling routine conducted as a part of this study. The calculated values for each nutrient are shown in table 16.

Table 16. The calculated average annual nutrient loadings in kg/yr from the Mary's Creek watershed.

	Total N (kg/yr)	**NO_2 andNO_3 (kg/yr)**	**Total P (kg/yr)**
Urban Storm	7,700	2,690	1,930
Rangeland/Pasture Storm	17,590	3,790	1,400
Baseflow	42,280	140	12,230
Total	67,570	6,620	15,560

The SWAT model was calibrated to predict an average annual total N load of 67,570 metric tons over the same period as the sediment calibration (January 1, 1990 to December 31, 2000). The model was again run on a yearly basis for the period of January 1, 1985 to December 31, 2000 to give the model a 5 year adjustment period. The average annual organic N yield was calculated to be 60,950 metric tons by subtracting the nitrate and nitrite N yield from the total N yield. This allowed calibration of the average annual organic N load and the average annual nitrate and nitrite N load in conjunction with the average annual total N load.

Without any calibration, the SWAT model over-predicted the average annual total N yield compared to the calculated average annual total N yield. The average annual organic N and nitrate and nitrite N yields were then calibrated to the calculated average annual organic N and nitrate and nitrite N yields. The biological mixing efficiency (BIOMIX) and the organic N enrichment ratio (ERORGN) were increased to improve the ratio of organic N to nitrate and nitrite N. The initial soil organic N concentration (SOL_ORGN) and the initial residue cover (RSDIN) were increased to enlarge the organic N yield. The N in rainfall (RCN) was decreased to reduce nitrate and nitrite loading to the stream. The depth of the top layer of the Aledo soil (SOL_Z1) was reduced because it contributed a large portion of N to the stream. Also, the saturated hydraulic conductivity (SOL_K) of three soils was reduced in the bottom layers to allow nitrate and nitrite to percolate into the deep aquifer and stay out of the stream. Lastly, the nitrogen percolation coefficient (NPERCO) was adjusted to increase the N percolation to the stream from the shallow aquifer. The total N, organic N, and nitrate and nitrite N parameters adjusted during the N calibration are shown in table 17.

Table 17. The SWAT model parameters adjusted during the N calibration of the Mary's Creek watershed.

Parameter	**Default Value**	**Calibration Value**
BIOMIX	0.92	0.20
ERORGN	0.0	5.0
NPERCO	0.20	0.35
RCN	1.0	0.3
RSDIN	0	10,000
SOL_ORGN	0	10,000
SOL_K (Aledo, Maloterre, Purves)	Various	-100%
SOL_Z1 (Aledo)	101.6	50

The predicted average annual total N yield after calibration was 59,940 metric tons, approximately 11% lower than the calculated average annual total N yield. The predicted average annual organic yield after calibration was 53,060 metric tons, approximately 13% lower than the calculated average annual organic N yield. Lastly, the predicted average annual nitrate and nitrite N yield after calibration was 6,880 metric tons, approximately 4% higher than the calculated average annual nitrate and nitrite yield.

After calibration of flow, sediment, and nitrogen, the simulated average annual total P yield was close to the calculated average annual total P yield without any calibration adjustments. The initial soil organic P concentration (SOL_ORGP) was raised to increase P additions to the stream slightly. This adjustment is shown in table 18.

The SWAT model was calibrated to an average annual total P yield of 15,560 metric tons. The distinction between the organic and mineral P components could not be made because of a lack of regression and EMC data concerning these different phases. The calibration period was the same as for sediment and N (January 1, 1990 to December 31, 2000) and the model was run for the January 1, 1985 to December 31, 2000 period for the additional adjustment period.

Table 18. The SWAT model parameters adjusted during the P calibration of the Mary's Creek watershed.

Parameter	**Default Value**	**Calibration Value**
SOL_ORGP	0	4,000

The predicted average annual total P yield after calibration was 15,580 metric tons, approximately 0.1% higher than the calculated average annual total P yield.

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