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Assessment of a turfgrass sod best management practice on water quality in a suburban watershed

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Abstract

The disposal of manure on agricultural land has caused water quality concerns in many rural watersheds, sometimes requiring state environmental agencies to conduct total maximum daily load (TMDL) assessments of stream nutrients, such as nitrogen (N) and phosphorus (P). A best management practice (BMP) has been developed in response to a TMDL that mandates a 50% reduction of annual P load to the North Bosque River (NBR) in central Texas. This BMP exports composted dairy manure P through turfgrass sod from the NBR watershed to urban watersheds. 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 sod grown with composted dairy manure to assess water quality changes due to this BMP. The SWAT model was calibrated to simulate historical flow and estimated sediment and nutrient loading to Mary's Creek near Fort Worth, Texas. The total P stream loading to Mary's Creek was lower when manure-grown sod was transplanted instead of sod grown with inorganic fertilizers. Flow, sediment and total N yield were the same for both cases at the watershed outlet. The SWAT simulations indicated that the 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.

Keywords: Manure; BMPs; Urban water quality; Nutrient export; Phosphorus; Turfgrass; Watershed modeling; SWAT; TMDL

1. Introduction

In 2001, the Texas Commission on Environmental Quality (TCEQ) and the United States Environmental Protection Agency (USEPA) approved the recommendations of two separate total maximum daily load (TMDL) assessments that suggested a 50% reduction of soluble reactive phosphorus (SRP) to sections of the North Bosque River in 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 phosphorus (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% 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

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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) in cooperation with the US Army to revegetate areas of the Fort Hood Western Training Grounds (TWRI, 2004a). However, new markets that do not require subsidies are needed to utilize the approximately 150,000 m^3 of surplus compost currently available in the watershed (TCEQ, 2003; TWRI, 2004b).

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 proposed sod farms in the UNBR watershed. The top-dressed (surface applied) 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 would 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 (Hanzlik et al., 2004).

Turfgrass produced with top-dressed 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). Therefore, the increased amount of manure P and organic matter adds value to the manure-grown sod. Import of manure P in sod can eliminate applications of inorganic P fertilizer for establishment and for annual turf maintenance. Previous studies indicated sod transplanted from fields supplied with 190 kg P/ha of manure P raised soil-test P at the receiving site to 130 mg P/kg soil (Vietor et al., 2004). If return of clippings and the dense plant population in the sod layer minimizes annual loss of nutrients after transplanting (Kopp and Guillard, 2002; Kussow, 2004), soil-test P can remain above turf P sufficiency levels for 10–15 years (Carrow et al., 2001). In addition, 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 5219 ha of suitable sites were identified in Erath County (Munster et al., 2004). In addition, the market for turfgrass sod is expanding in the Dallas/Fort Worth (DFW) metroplex, which is only 160 km from the UNBR watershed (Hall, 1999). Currently, the DFW metroplex purchases and hauls about 60% of transplanted sod from distant locations, including the Texas Gulf Coast and Oklahoma (Munster et al., 2004). The proximity of this growing urban market, which is connected to the UNBR watershed by major roads, favored the expansion of dairy production in the UNBR watershed in the 1980s and 1990s. Munster et al. (2004) estimated approximately 396 440 kg P/year could be exported from Erath County alone if manure was applied at a rate of 200 kg/ha to turfgrass production sites totaling 2643 ha.

Vietor et al. (2004) demonstrated that sod grown with top-dressed manure P can be transplanted without increasing runoff losses of total dissolved P (TDP) when compared to transplanted turfgrass sod fertilized with inorganic P. It was also demonstrated that losses of TDP and total Kjeldahl N (TKN) from turfgrass top-dressed with manure or inorganic 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) (Neitsch et al., 2002).

Limited streamflow, sediment and nutrient data were available for Mary's Creek. A USGS gauging station located at the outlet of Mary's Creek provided historic streamflow data from 1998 to 2002 for model calibration. Moreover, Bednarz and Srinivasan (2002) successfully used this streamflow data for SWAT model simulations of sediment transport. However, previous modeling studies have simulated effects of changes in land management without calibrating the watershed model to measured data (He, 2003; Santhi et al., 2003; Tripathi et al., 2004). In addition, techniques are available for estimating sediment and nutrient loads needed for calibration of watershed models. Tripathi et al. (2003) utilized a pre-calibrated and validated SWAT model to identify critical sub-watersheds to aid in the development of effective management plans in India. Chen et al. (2000) used crop yields and experimental field data to calibrate sediment and nutrient loads in the Environmental Policy Integrated Climate Model or Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1984). 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. This technique separates nutrient and sediment losses into stormflow and baseflow losses.

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.

The primary objective of this paper was to assess water quality changes in a suburban watershed due to a turfgrass BMP that imports sod transplanted from turfgrass fields where top-dressed composted dairy 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 the turfgrass BMP.

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

2. Materials and methods

2.1. Watershed selection

The Mary's Creek watershed with the proposed Walsh Ranch development was chosen to receive the turfgrass grown with composted dairy manure due to its proximity (100 km) to the UNBR. Economically, the distance from the UNBR to Mary's Creek is within an acceptable hauling distance for turfgrass sod (Munster et al., 2004). The Walsh Ranch development is a 2800 ha planned community that is scheduled to begin construction 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 2800 ha of the Mary's Creek watershed, however, the majority of the Mary's Creek watershed will remain rangeland after construction of Walsh Ranch (Table 1).

Mary's Creek is a perennial stream located west of the DFW metroplex that drains approximately 14 272 ha of predominately range and pasture (Fig. 1). Mary's Creek begins in Parker County and terminates at the Clear Fork of the Trinity River (CFTR) in Tarrant County and is located in the prairie and lakes of Texas on the upper margins of the coastal plain. The terrain is mostly open prairie and rangeland with rolling hills that range from 150 to 250 m in elevation. The climate varies between

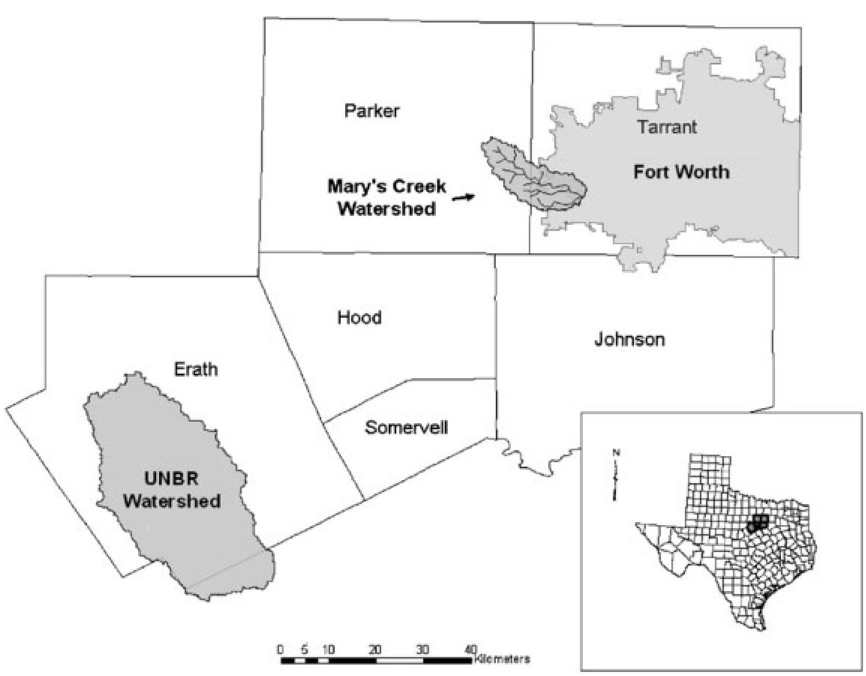

Fig. 1. The location of the Mary's Creek watershed, the UNBR watershed, and Fort Worth, Texas, with county boundaries shown.

subtropical and continental with summers that are hot and humid with 38 °C days common. The winters are characteristically mild with short-lived periods of extreme cold where −7 °C can occur and snowfall is rare. The annual precipitation ranges from less than 500 to more than 1250 mm with an average of approximately 800 mm/year. The majority of the rainfall occurs in the spring (USDA-TAES, 1981) and the historical streamflow records from the United States Geological Survey (USGS) gauging station (08047050) on Mary's Creek reflects this trend with highest flows occurring in March. This gauging station is located near the confluence of Mary's Creek and the CFTR and daily streamflow records were available from June 1, 1998 to September 30, 2002.

Currently, 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. Watersheds similar to Mary's Creek in the DFW metroplex area are not typically impaired by nutrients (USGS, 1999).

2.2. The SWAT model

The SWAT 2003 model was used in this study and was interfaced with ArcView 3.2 to integrate geospatial data into the simulations. The SWAT model simulations allowed for the assessment of water quality changes in a developing suburban watershed due to the import of turfgrass sod grown with composted dairy manure. The SWAT model is capable of detecting changes in water yield, sediment, nutrient and pesticide loading due to the effects of land use and agricultural management 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 land uses as consistent sources of sediment and nutrient loads (USEPA, 1983) and therefore does not need large inputs of observed data from urban areas. In addition, the SWAT model allows the user to manipulate management routines and incorporates a crop growth model that includes detailed plant protection, management, and harvest information.

2.3. SWAT data sets

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 provided detail about urban land uses and the TAES classification detailed agricultural land uses. The collective map contained both the urban and agricultural data.

Soils data were 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-m 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 generator function but also allows the user to input weather data. Weather data from the Aledo (Station ID 480129) and Benbrook Dam (Station ID 480691) weather stations were available through the National Climatic Data Center (NCDC). These weather stations were located within an 8 km radius of the Mary's Creek watershed (Fig. 2). 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 1990–2003. 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.

2.4. 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-m resolution DEM was delineated through AVSWAT-X and a 200 ha threshold was used to divide the watershed into 37 sub-basins (Fig. 2). The AVSWAT-X interface also linked the land use layers to the SWAT databases for land cover and plant growth. In addition, the software integrated the soil layer to a corresponding table of specific soil parameters. The watershed outlet was set at the USGS gauging station (08047050) resulting in a watershed area of 13 976 ha (Fig. 2). The SWAT model uses hydrologic response units (HRUs) to combine areas of a sub-basin into areas of unique land use and soil groups. The threshold at which HRUs are created can be changed based upon the resolution of the input data and the desired output. The HRUs in this study were constructed similar to the Bednarz and Srinivasan (2002) study with the land use threshold set at 5% and the soil threshold set at 10%. This resulted in a total of 470 HRUs.

The datasets from the Aledo and Benbrook Dam weather stations and the SWAT weather generator database were utilized during the SWAT model simulations.

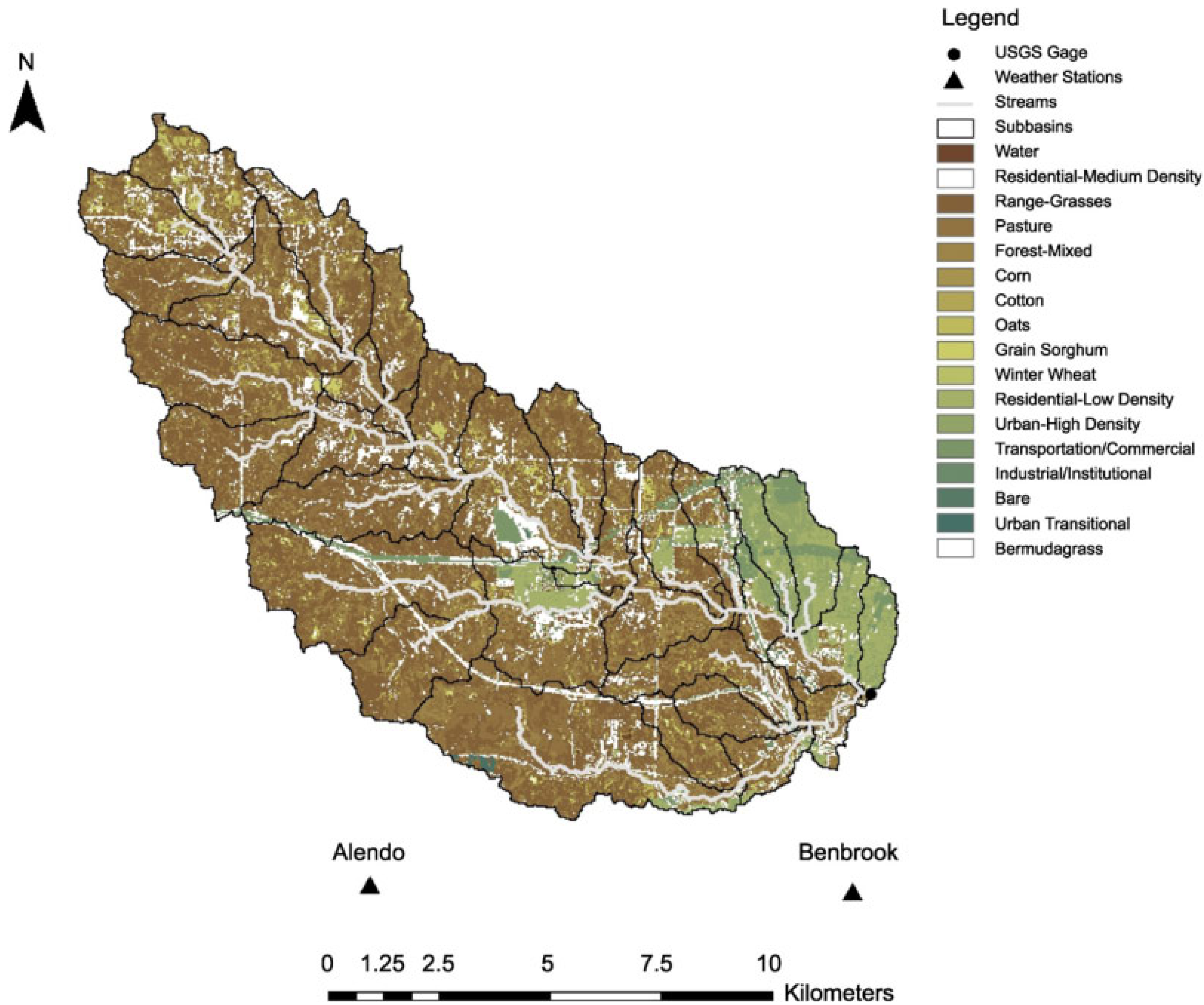

Fig. 2. The stream network and current SWAT land uses in the Mary's Creek watershed with the location of the Aledo and Benbrook weather stations, the USGS stream gage (0804750), and the sub-basins used in the SWAT model simulations also shown. Refer to DiLuzio et al. (2002) for SWAT land use class abbreviations.

The SCS CN method was used to simulate surface runoff and the Priestly–Taylor equation 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. Soils in the watershed do not exhibit preferential flow and therefore the crack flow routine in the model was not activated. SWAT's water quality and in-stream channel degradation routines were not activated due to the lack of field collected data necessary for the use of these routines.

2.5. SWAT model calibration

The MRLC/TAES land use map was used to represent land use for the calibration of the SWAT model. 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. A Nash Sutcliffe (NS) statistic (Nash and Sutcliffe, 1970) of greater than 0.50 was used as the criteria for a successful calibration. The NS statistic measures how well the predicted mean agrees with the observed values. An NS value of 1.0 means that the prediction is perfect. The actual simulation period for flow calibration started January 1, 1990 and concluded September 30, 2002 to allow for an adjustment period for model equilibrium among soil, water, and plant processes. The SWAT model was calibrated for average monthly stream flows in a similar manner to previous SWAT model simulation studies in the nearby Bosque River watershed by Saleh et al. (2000), Santhi et al. (2001) and Stewart et al. (2006). After calibration, the predicted monthly average streamflow produced an NS statistic of 0.72 and a root mean square error (RMSE) of 0.54 when compared to the observed monthly average streamflow at the watershed outlet.

Initially, model monthly flow estimates were higher than observed monthly flows. Therefore, the SWAT model parameters were adjusted as shown in Table 2 until the predicted flow was approximately equal to the observed flow. At the start of the model calibration, the base flow fraction was calculated using a base flow filter developed by

Arnold et al. (1995). The base flow alpha factor (ALPHA_BF) was adjusted to 0.158 according to the filter results. Then, to bring the simulated flow rate down further, all CNs (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 also adjusted down. Temporal adjustments to the peak flows and baseflows 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 2
The SWAT model parameters adjusted during the model calibration for stream flow

Parameter	Default value	Calibration value
ALPHA_BF	0.0	0.158
CH_K2	0.0	1.0
CN2	0	−8[a]
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]All CNs were adjusted downward by −8.

Two annual sediment loading estimations were averaged to estimate an average annual sediment loading to Mary's Creek of 2400 metric tons. The TRWD used sediment removal records below the junction of Mary's Creek and the CFTR to estimate an annual sediment loading of 3200 metric tons in Mary's Creek.

In addition, three separate sources of data were used to estimate sediment load due to stormflow and baseflow as proposed by Bhuyan et al. (2003). Sediment sources for stormflow loadings were assumed to be from urban and rangeland/pasture land uses only. Urban sediment stormflow loads were calculated using a USGS regression equation developed from local data (Baldys et al., 1998). Rangeland/pasture sediment stormflow loads were calculated using event mean concentration (EMC) values based on the average annual stormflow volume (Newell et al., 1992; Baird and Ockerman, 1996). Baseflow sediment data were collected in the summer of 2004 for this study and the average sediment concentration was multiplied by the average annual baseflow volume to calculate the annual baseflow sediment load. The average annual sediment loading from the three data sources was 1600 metric tons (Table 3).

Table 3
The stormflow, baseflow and total average annual sediment load values used to estimate the average annual sediment load at the outlet of Mary's Creek

Source of load	Sediment (tons/year)
Urban storm[a]	570
Rangeland/Pasture storm[b]	820
Baseflow[c]	210
Total	1600

[a]Calculated from USGS regression equation developed by Baldys et al. (1998).
[b]Calculated from event mean concentration (EMC) values (Newell et al., 1992; Baird and Ockerman, 1996).
[c]Observed from baseflow sampling of Mary's Creek conducted May–July 2004.

The SWAT model was calibrated for average annual sediment loading over the period from January 1, 1990 to December 31, 2000. This was the same time period in which sediment loading was estimated (Table 3). The simulated average annual sediment yield after calibration was 2830 metric tons. The SWAT prediction was approximately 18% higher than the calculated average annual sediment yield of 2400 metric tons.

No in-stream nutrient data was available for Mary's Creek and therefore, N and P loads in Mary's Creek had to be estimated. Total N, nitrate and nitrite-N, and total P average annual loads to Mary's Creek were estimated from local urban storm EMC data collected by the USGS (Baird and Ockerman, 1996; Newell et al., 1992), and the baseflow stream samples collected during this study (Table 4). The average annual nutrient load was estimated using the same procedure (Bhuyan et al., 2003).

Table 4
The estimated stormflow, baseflow and total average annual nutrient load at the outlet of Mary's Creek

Source of load	Total N (kg/year)	NO_2 and NO_3 (kg/year)	Organic N (kg/year)	Total P (kg/year)
Urban storm[a]	7700	2690	5010	1930
Rangeland/Pasture storm[b]	17 590	3790	13 800	1400
Baseflow[c]	42 280	140	42 140	12 230
Total	67 570	6620	60 950	15 560

[a]Calculated from USGS regression equation developed by Baldys et al. (1998).
[b]Calculated from EMC values (Newell et al., 1992; Baird and Ockerman, 1996).
[c]Observed from baseflow sampling of Mary's Creek conducted May–July 2004.

The baseflow values for total N, organic N, and total P were disproportionately high compared to the stormflow values due to the higher volume of baseflow per year in Mary's Creek (60%). Also, the baseflow values were heavily weighted to the summer season level of nutrients since baseflow values were calculated from sampling of Mary's Creek conducted May–July 2004.

The SWAT model was calibrated for total average annual N loading over the same period as the sediment calibration (January 1, 1990–December 31, 2000). The average annual organic N yield was estimated by assuming

$$N_{\text{organic}} = N_{\text{total}} - NO_3 - NO_2. \tag{1}$$

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

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 yields after calibration were approximately 4% higher than the calculated average annual nitrate- and nitrite-N yields (Table 5).

The stream monitoring data for Mary's Creek did not breakdown P into organic and mineral components. Therefore, the SWAT model was calibrated to predict total P (organic and mineral P combined). The simulated average annual total P yield after calibration was approximately 0.1% higher than the estimated average annual total P yield (Table 5).

Without calibration, the SWAT model predicted average annual sediment and nutrient yields greater than the estimated yields. The SWAT model parameters (Table 6) that were adjusted during the nutrient calibration were as follows. The average slope length (SLSUBBSN) was reduced to 5 m (Neitsch et al., 2001), the average slope steepness (SLOPE) was adjusted down to 0.02 m/m and the universal soil loss equation soil erodibility factor (USLE_K1) was decreased by approximately 60% for all soils in the watershed to reduce the HRU contribution of sediment. 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) and the depth of the top layer of the Aledo soil (SOL_Z1) were decreased to reduce nitrate- and nitrite-N loading to the stream. Also, the saturated hydraulic conductivity (SOL_K) of three soils was reduced in the bottom layers to trap nitrate and nitrite in the soil profile. The nitrogen percolation coefficient (NPERCO) was adjusted to increase the N percolation to the stream from the shallow aquifer and the initial soil organic P concentration (SOL_ORGP) was raised to increase P additions to the stream (Santhi et al., 2001).

Table 5
The results of the SWAT model calibration for in-stream nutrients at the outlet of Mary's Creek

Constituent	Simulated annual load (kg/year)	Estimated annual load (kg/year)	Difference (%)
Total N	59 940	67 570	−11
NO_2 and NO_3	6880	6620	4
Organic N	53 060	60 950	−13
Total P	15 580	15 560	0.1

Simulated nutrient loads were compared to estimated nutrient loads.

Table 6
The SWAT model parameters adjusted during the model calibration for stream sediment and nutrient loads

Parameter	Default value	Calibration value
SLOPE	0.129	0.020
SLSUBBSN	24.390	5.000
USLE_K1 (all soils)	Various	−60%
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
SOL_ORGP	0	4000

2.6. SWAT simulations

2.6.1. SWAT turfgrass transplant routine

Sod is typically 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 had 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 are typically transplanted with turfgrass sod would most likely have greater clay content than the soils in the Mary's Creek watershed. Therefore, the SWAT simulations would be conservative with respect to nutrient transport as turfgrass sod with higher clay contents would have increased water holding capacity and decreased nutrient transport capability. The turfgrass import routine required 12 new inputs to the model. A month and day of sod input allowed the user to control the time of the transplant within the model. The additional sod and soil was integrated at the input time into the SWAT routines for runoff, sediment loss, nutrient loss and crop growth.

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.

2.6.2. *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 in the Walsh Ranch development. The status quo simulated only the current land uses in the Mary's Creek watershed.

2.6.2.1. 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. Therefore, 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).

2.6.2.2. The conventional treatment. The conventional treatment utilized turfgrass sod transplanted from fields grown with inorganic P fertilizer. Additionally, the turfgrass was top-dressed annually with inorganic P fertilizer after transplanting into the Walsh Ranch development. The new SWAT turfgrass transplant routine was used to simulate the import of the inorganic fertilizer-grown sod on residential, commercial and public landscapes planned for the Walsh Ranch development. The physical and chemical properties of the imported turfgrass sod in the conventional treatment were set as found in field experiments. Table 7 shows the summary of the experimental data for conventionally treated sod (Choi et al., 2003; Vietor et al., 2002). The soil organic P content, which was similar between conventional and manure-grown sod, was calculated as the difference between total P and P quantified in soil-test extractions. Conventional fertilizer applications of inorganic N and P were applied to the turfgrass sod as needed for continued growth after transplanting. Inorganic N was applied to the transplanted sod at the rate of 60 kg/ha/year and inorganic P was applied at the rate of 18 kg/ha/year. The conventional treatment transplanted turfgrass sod to approximately 1400 ha of the Walsh Ranch development which affected 25 SWAT model HRUs in the Mary's Creek watershed (Fig. 3).

2.6.2.3. The BMP treatment. In the BMP treatment, turfgrass sod transplanted from fields top-dressed with composted dairy manure was also 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 was 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 as found in field experiments. Table 7 shows the summary of field data from turfgrass so field research for BMP treated sod (Choi et al., 2003; Vietor et al., 2002, 2004). The manure application during sod production, which supplied P that was largely soluble (75% of total P) in soil-test extractions, increased soluble but not organic P content compared to fertilizer-grown sod at sod harvest. After turfgrass sod was transplanted to the Walsh Ranch development, inorganic N fertilizer was applied as needed (60 kg/ha/year), but no inorganic P fertilizer was added. The turfgrass was placed on the same 1400 ha and in the same 25 HRUs of the SWAT model as simulated in the conventional treatment.

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 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)	18 000 kg/ha	18 000 kg/ha

2.6.3. *Simulation procedures*

An initial SWAT simulation was performed to demonstrate the effects of the Walsh Ranch development infrastructure (roads, removal of trees, etc.) on streamflow, sediment and nutrient loading without the turfgrass present. The residential, commercial, and public landscapes that would eventually be planted with turfgrass sod were simulated as unfertilized pasture. This simulation predicted

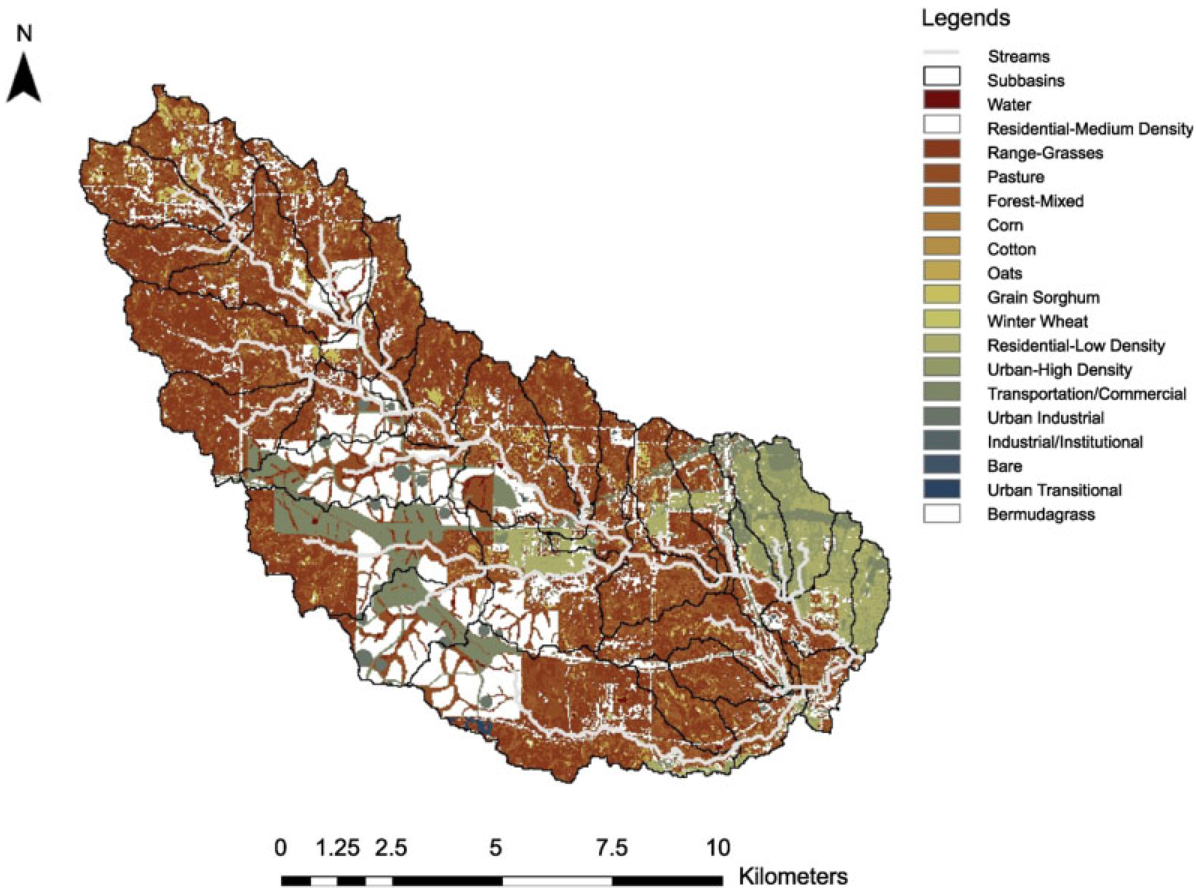

Fig. 3. The Mary's Creek watershed with areas where turfgrass was installed (land-use category Bermudagrass and Residential-Medium Density) in the Walsh Ranch development. This land cover map was used for the SWAT simulations of both the conventional and BMP treatments.

monthly flow and yearly sediment and nutrient loading for a 5-year period (1986–1990) preceding the conventional and BMP turfgrass sod simulations.

Two SWAT simulations were performed to analyze each turfgrass sod treatment. The first model simulation predicted monthly flow and yearly sediment and nutrient loading for a 10-year period (1991–2000). For simulations of the conventional and BMP treatments, the SWAT management files were revised to simulate imports of the contrasting turfgrass sod sources into the Walsh Ranch development on February 1 of year one of the 10-year period (1991). The newly installed turfgrass sod utilized the auto-fertilization and auto-irrigation routines in the SWAT model to ensure that the turfgrass sod was not stressed by lack of nutrients and water. This effectively simulates the management treatment that new sod would receive after transplanting. 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. The SWAT model auto-fertilization and auto-irrigation routines were not utilized in the status quo simulation.

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 treatments. The transplant of turfgrass for the conventional and BMP treatments took place on February 1 of year one (1950) and auto-fertilization and auto-irrigation was also used. Again, the land use classifications for the simulation of the status quo were unchanged.

3. Results

3.1. *Influence of development*

Construction of the Walsh Ranch development added 160 ha of impervious cover within the watershed and resulted in an increase of surface runoff. The effect of this additional impervious area on streamflow, 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 with impervious surfaces but without the installation of turfgrass. The green spaces in the development were simulated as unfertilized pasture. The simulation demonstrated the effects of the land use changes in the Mary's Creek watershed that were not related to the turfgrass transplant. This allowed these land-use change effects to be removed from the results of the model simulations after turfgrass was installed in the Mary's Creek watershed. The simulated average increase of streamflow was 0.03 m^3/s. Other increases were 636 tons/year for sediment, 17 838 kg/year for organic N, 1142 kg/year for nitrate-N, and 4965 kg/year for total P at the outlet of Mary's Creek.

3.2. 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/month for the BMP and conventional turfgrass treatments when compared to the status quo (Fig. 4a).

The monthly streamflow increase (0.03 m^3/s/month) caused by the development of the watershed was removed from the BMP and conventional turfgrass treatments as shown in Fig. 4b. As shown in Fig. 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.

The long term, 50-year simulations (1950–2000) of the BMP and conventional turfgrass treatments produced very similar streamflows in Mary's Creek at the watershed outlet (Fig. 5). Compared to the status quo, however, the BMP and conventional treatments increased streamflow 5.3% during the long-term simulation (Fig. 5). The

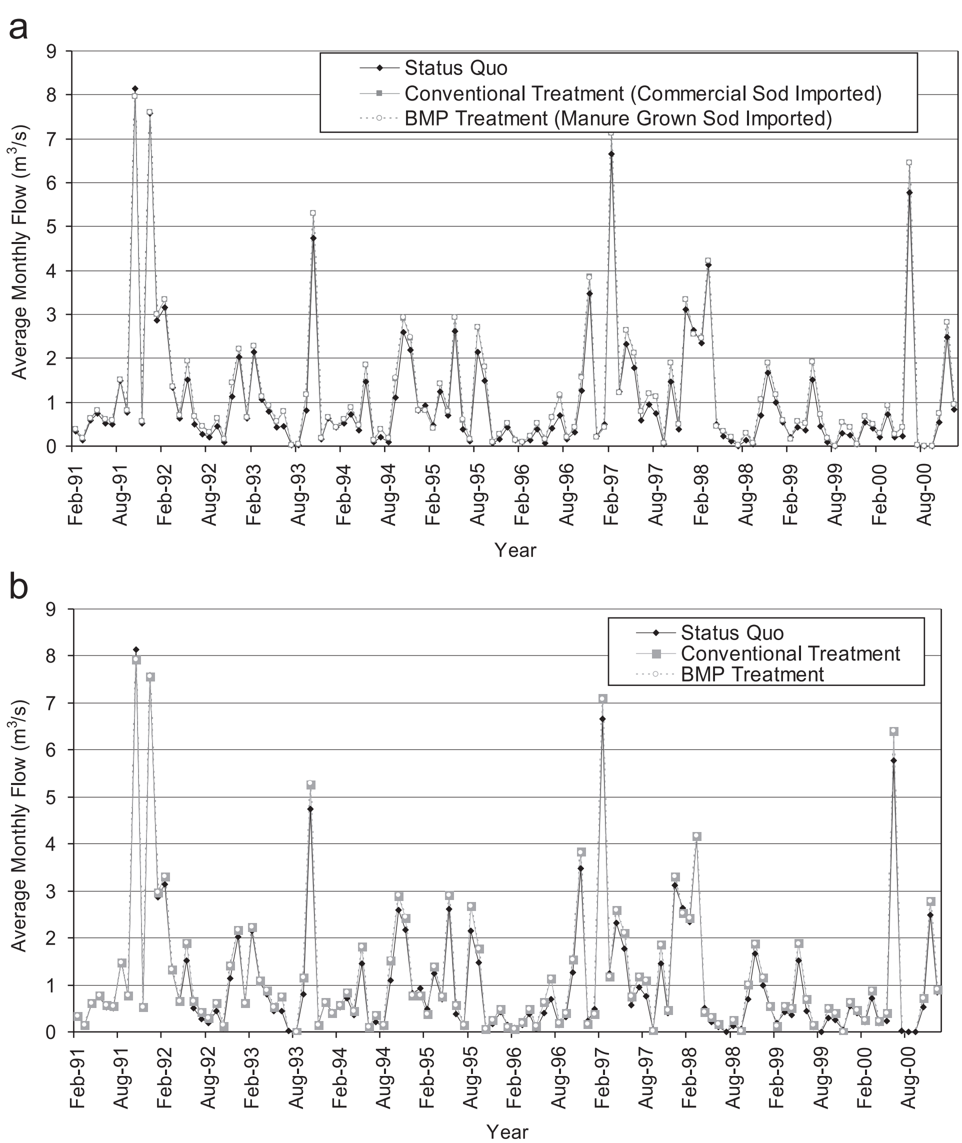

Fig. 4. The simulated average monthly flow for the three treatments at the outlet of the Mary's Creek watershed with the runoff from impervious urban surfaces (a) included in the BMP and conventional treatments, and (b) not included in the BMP and conventional treatments.

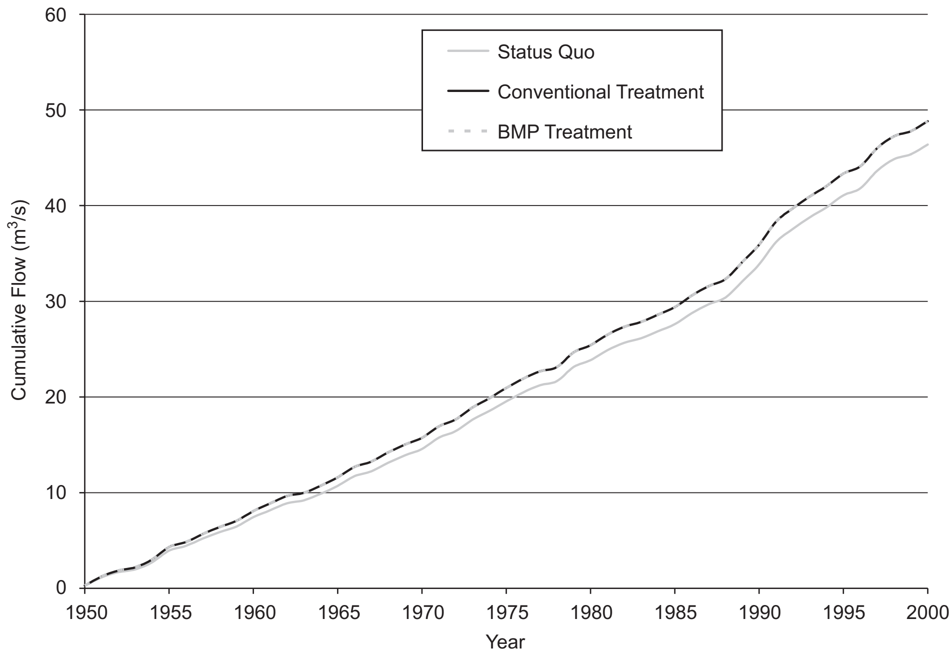

Fig. 5. The cumulative annual SWAT simulated streamflow for the three turfgrass treatments (status quo, conventional and BMP) at the outlet of the Mary's Creek watershed.

influence of the impervious surfaces in the Walsh Ranch development was not factored out of the long-term simulation and caused this long-term increase.

3.3. 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 turfgrass 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 turfgrass 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 tons/year) caused by the development of the watershed was factored out of the short term simulation. This estimation method revealed the sediment loads contributed by just the turfgrass treatments (Fig. 6b). As shown in Fig. 6b, removing the influence of impervious surfaces in the development demonstrates that the turfgrass sod treatments reduced sediment loading to the stream when compared to the status quo treatment.

Monthly factors such as time of year and plant growth stage may have exerted greater influence on sediment loss in the status quo simulation than in the transplanted sod treatments. However, variation of annual rainfall was not significantly related to variation of sediment load for any of the simulated treatments. The adjusted R^2 values resulting from a regression analysis between variation of annual rainfall and the sediment loads predicted by SWAT for the turfgrass treatments in the Mary's Creek watershed were 0.208 for the transplanted sod treatments (conventional and BMP) and 0.168 for the status quo treatment.

3.4. Nutrients

The simulated increases in streamflow and sediment loading predicted for imports of manure-grown sod (BMP) and fertilizer-grown sod (conventional) were also reflected in the simulated differences in stream nutrient loading between the status quo, BMP and conventional turfgrass treatments in the long term simulations (Table 8).

The simulated in-stream organic N loading differed by 550 300 kg between the status quo and imports of fertilizer-grown (conventional) and manure-grown (BMP) turfgrass sod. Compared to the status quo, the in-stream nitrate-N loading was 42.5% greater for the BMP treatment and

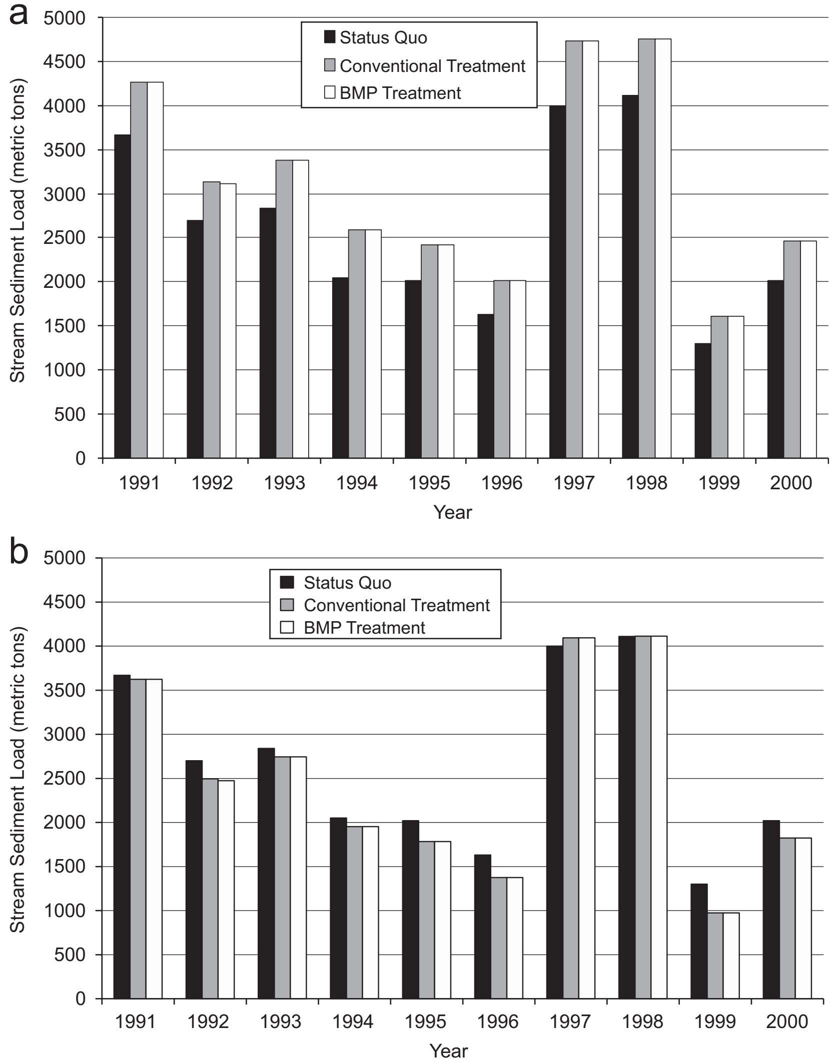

Fig. 6. The SWAT simulated annual stream sediment load for the three turfgrass treatments (status quo, conventional and BMP) at the outlet of the Mary's Creek watershed with (a) the sediment due to increases in runoff from urban impervious surfaces included in the BMP and conventional treatments and (b) the sediment due to increases in runoff from urban impervious surfaces removed from the BMP and conventional treatments.

Table 8
SWAT simulated in-stream nutrient loading at the outlet of the Mary's Creek watershed for the three turfgrass treatments (status quo, conventional and BMP) 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

42.1% greater for the conventional treatment. A portion of the organic N imported with the manure-grown turfgrass sod of the BMP treatment was converted to nitrate-N over time, which led to slightly higher nitrate-N stream loading (0.09%) when 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 a close comparison between the manure-grown (BMP) and fertilizer-grown (conventional) treatments that were imported into the watershed. A linear regression analysis was performed to assess 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 which is to be expected as the organic fraction is attached sediments within the model. The adjusted R^2 values resulting from a regression analysis between in-stream annual sediment load and the annual organic N load predicted by SWAT for the turfgrass treatments at the outlet of Mary's Creek were 0.893 for the transplanted sod treatments (conventional and BMP) and 0.908 for the status quo treatment.

The simulated organic N load in Mary's Creek comparing the status quo and BMP and conventional turfgrass treatments is shown in Fig. 7a. The average in-stream organic N load (17 838 kg/year) 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 Fig. 7b. Removing the influence of the Walsh Ranch development revealed that both turfgrass treatments (conventional and BMP) reduced organic N loads to the stream when compared to the status quo treatment. This is due to the reduction of range, unfertilized pasture and forest land uses.

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 30 000 kg in 1992 (Fig. 8a). 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 1620 kg of nitrate N more to Mary's Creek than the BMP turfgrass treatment.

The SWAT model simulated applications of inorganic N fertilizer based on an N stress threshold of 0.9, where 0.0 indicates no plant growth due to N stress and 1.0 indicates

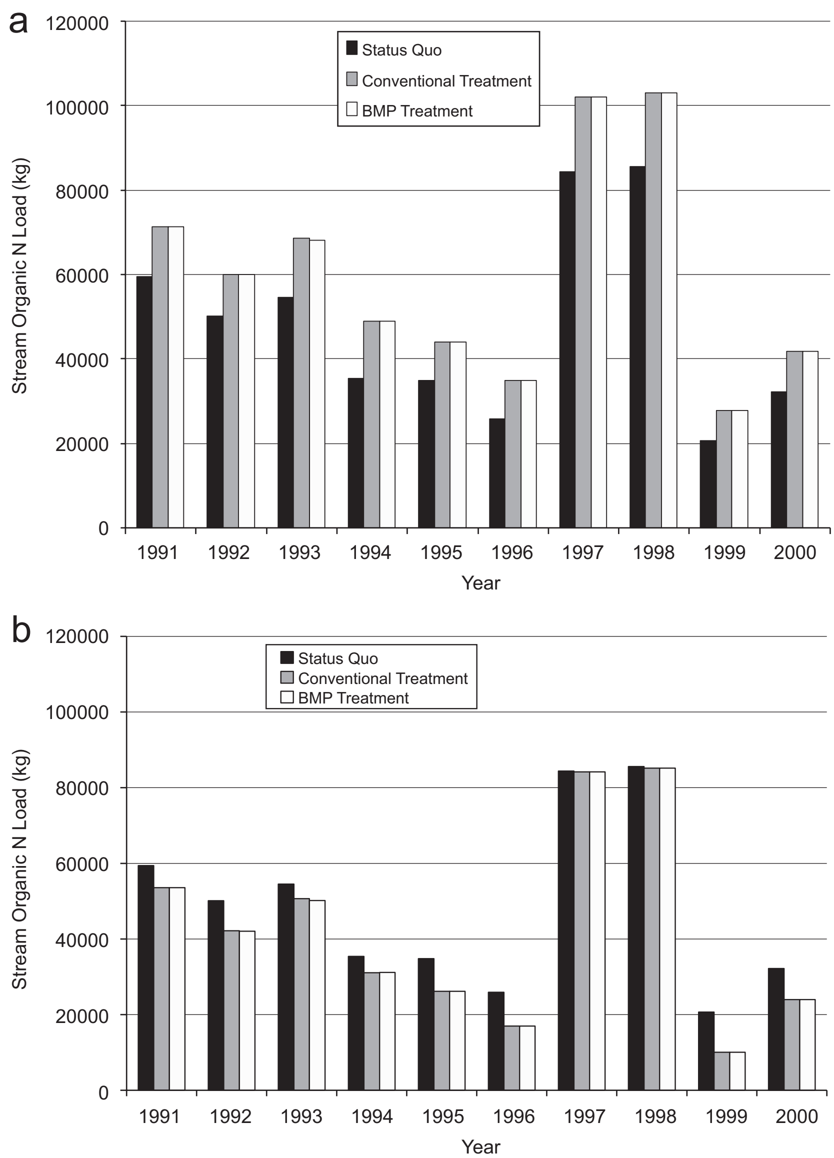

Fig. 7. The SWAT simulated in-stream annual organic N load for the three treatments (status quo, conventional and BMP) at the outlet of the Mary's Creek watershed with increases in runoff from urban impervious surfaces (a) included in the BMP and conventional treatments, and (b) removed from the BMP and conventional treatments.

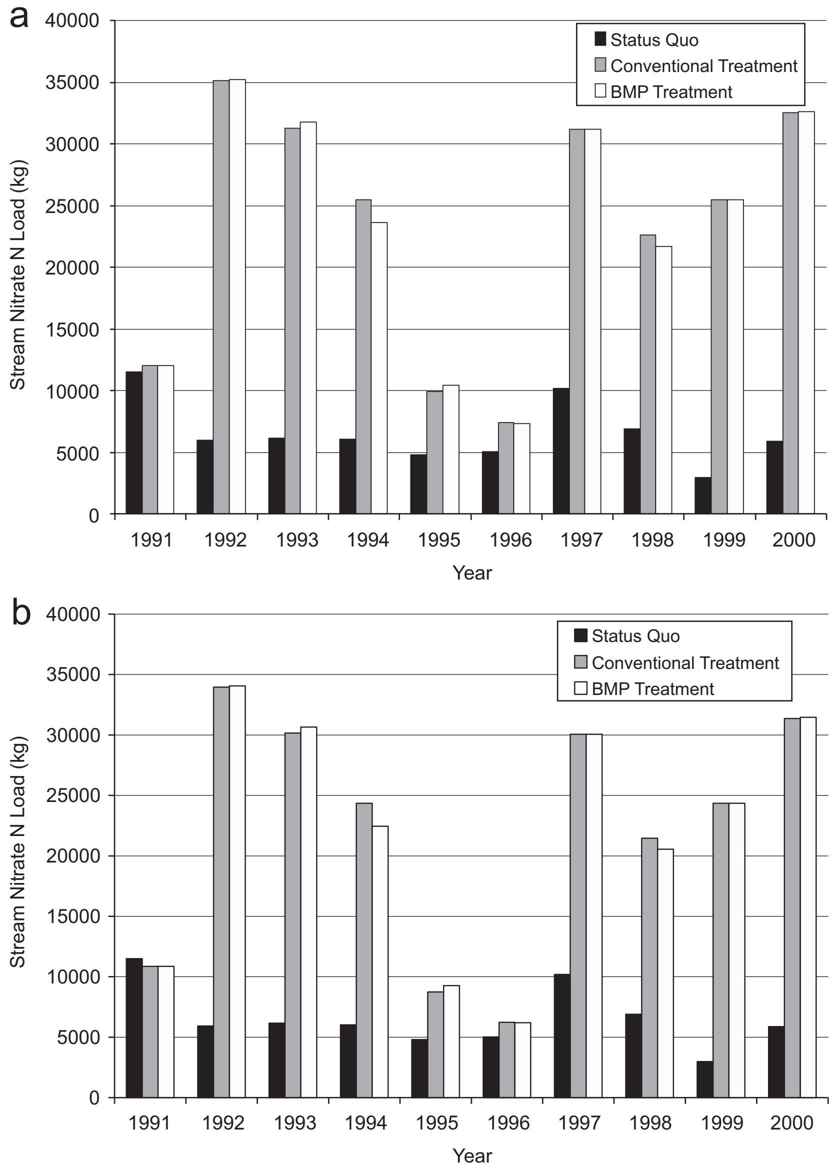

Fig. 8. The SWAT simulated in-stream annual nitrate N load for the three turfgrass treatments (status quo, conventional and BMP) at the outlet of the Mary's Creek watershed with increases in runoff from urban impervious surfaces (a) included in the BMP and conventional treatments and (b) removed from the BMP and conventional treatments.

no reduction in plant growth due to N stress. Therefore, the SWAT model applied ample 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 in the turfgrass sod 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 (1142 kg/year) 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 Fig. 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.

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 (Fig. 9a) and may be explained as follows. Approximately, 11 kg/ha less organic P was imported with the BMP treatment when compared to the conventional

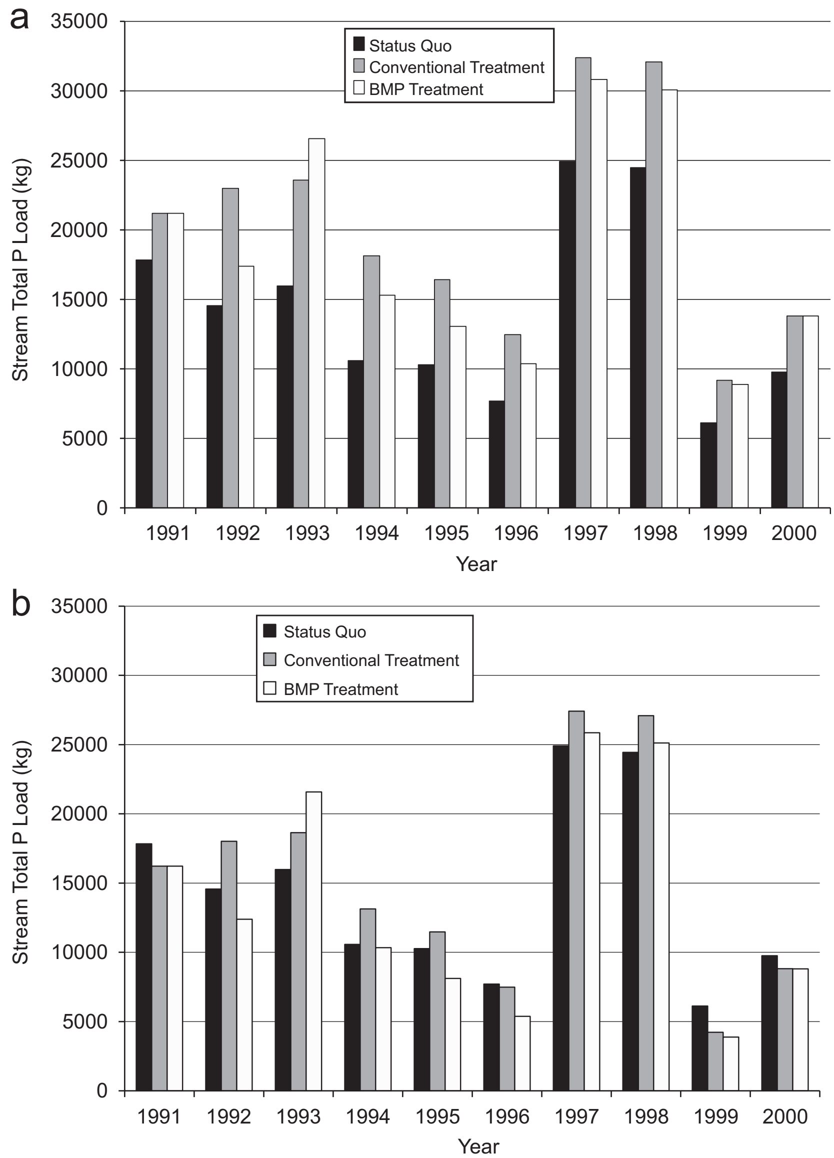

Fig. 9. The SWAT simulated in-stream annual total P load for the three turfgrass treatments (status quo, conventional and BMP) at the outlet of the Mary's Creek watershed with increases in runoff from urban impervious surfaces (a) included in the BMP and conventional treatments, and (b) removed from the BMP and conventional treatments.

treatment. In addition, 41 kg/ha more soluble P and 6 kg/ha more biomass P was imported by the BMP treatment. This additional soluble P was not lost immediately in the BMP treatment, but was released 3 years after the transplant when P was dissolved and transported through surface runoff events. 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 in-stream total P load (4965 kg/year) 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 Fig. 9b. Removing the influence of the development revealed that the BMP turfgrass treatment reduced total P loading to Mary's Creek when 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).

A linear regression was performed to relate variation of annual total rainfall amount to annual variation of in-stream nutrient loads for the turfgrass treatments. This analysis indicated that the variation of annual rainfall did not account for a significant portion of variation of the in-stream nutrient loads due to the treatments, except for the predicted nitrate-N load of the status quo treatment (Table 9). The low R^2 for the regression between nitrate-N and rainfall amount for the transplanted turfgrass sod treatments reaffirms that the in-stream nitrate-N loads for these treatments are related more to fertilizer application than streamflow or rainfall amount.

Table 9
The adjusted R^2 values resulting from a regression analysis between annual rainfall and in-stream nutrient loads predicted by SWAT for the turfgrass treatments

Treatments	Adjusted R^2 value		
	Organic N	Nitrate N	Total P
Conventional	0.149	−0.076	0.127
BMP	0.149	−0.076	0.141
Status quo	0.146	0.793	0.164

4. Conclusions

Through model simulation, the proposed turfgrass BMP was found to reduce total P loading to urban streams when compared to conventional commercial turfgrass sod imported and maintained with inorganic P fertilizer. The proposed turfgrass BMP was also found to reduce total P loading to the stream when 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. Losses of total P were 1.1 times higher from the conventionally grown imported sod compared to the proposed turfgrass BMP, yet only 10% of the watershed area was influenced by this treatment. This reaffirms the findings of Vietor et al. (2004) in which commercially top-dressed sod losses of TDP were found to be three times greater than that of transplanted manure grown sod on small plots (100% effective area).

The turfgrass BMP increased in-stream nitrate N loading when compared to the status quo treatment due to increased N fertilizer applications. However, the increase was equivalent to the impact of importing conventional turfgrass sod grown with inorganic fertilizers. This additional in-stream nitrate-N load could be reduced by utilizing urban nutrient BMPs and by homeowner education of proper lawn nutrient application.

The SWAT model simulations indicate that the turfgrass 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 lost from the turfgrass on the watershed scale.

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