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ScienceDirect

Environmental Pollution 150 (2007) 321–328

ENVIRONMENTAL POLLUTION

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Nutrient flux in storm water runoff and baseflow from managed turf

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Received 22 November 2006; received in revised form 22 January 2007; accepted 27 January 2007

Phosphorus losses from golf courses exceed levels to guard against eutrophication.

Abstract

The urban landscape is comprised of many land uses, none more intensively managed than turfgrass; however, quantification of nutrient losses from specific land uses within urban watersheds, specifically golf courses is limited. Nitrate (NO_3-N) and dissolved reactive phosphorus (DRP) were measured on a golf course in Austin, TX, USA from April 1, 1998 to March 31, 2003. NO_3-N and DRP concentrations measured in storm flow were significantly greater exiting the course compared to those entering the course. Significant differences were also measured in baseflow NO_3-N concentrations. The measured loading from the course was 4.0 kg NO_3-N ha^{-1} yr^{-1} (11% of applied) and 0.66 kg DRP ha^{-1} yr^{-1} (8% of applied). The resulting concentrations contributed by the course were 1.2 mg L^{-1} NO_3-N and 0.2 mg L^{-1} DRP. At these levels, NO_3-N poses minimal environmental risk. However, the DRP concentration is twice the recommended level to guard against eutrophication.

Keywords: Nitrate; Dissolved reactive phosphorus; Urban; Water quality; Golf; Watershed

1. Introduction

There is a significant pressure in the political, economic, and scientific arenas related to soil and water resources to focus on watershed scale processes and impacts related to soil and water resources. It is at the watershed scale that water quality protection and regulation are generally addressed. A watershed may be defined as any area, regardless of size, that conveys, by gravity, excess rainfall or return flow via surface runoff to a single outlet. Management of watersheds to protect water quality or maintain ecosystem function requires the understanding of the total watershed. However, before the total watershed can be understood, it is first necessary to understand the many land uses that comprise the watershed. In broad terms, the three most common land use classifications are agriculture, urban, and forest, each with its own sub-classifications. For example, within the urban land use classification, land use may include lawns, residential area, parks, golf courses, industry, commercial, etc., while agriculture land use might include row crops, pasture, livestock, small grains, etc.

Several studies identify urban watersheds as substantial contributors to nitrogen and phosphorus loading to surface waters, second only to agriculture (Coulter et al., 2004; Groffman et al., 2004; Foley et al., 2005; Petrovic and Easton, 2005). Yet, only a limited number of studies have been conducted to measure the nitrogen and phosphorus losses from specific land uses within the urban landscape. In these studies, nutrient losses have been measured from parks (e.g. Petrovic and Easton, 2005), woods (Graczyk et al., 2003; Groffman et al., 2004), lawns (e.g. Graczyk et al., 2003), residential areas (e.g. Line et al., 2002), pervious and impervious road surfaces (Brabec et al., 2002; Gilbert and Clausen, 2006), commercial/industry (Line et al., 2002; Graczyk et al., 2003), and golf

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doi:10.1016/j.envpol.2007.01.038

course turf (Kunimatsu et al., 1999; King et al., 2001; Line et al., 2002; Winter and Dillon, 2006).

Of the land uses in the urban landscape, turf is the most intensively managed (Shuman et al., 2000). Precision management and substantial inputs of water and fertilizers are required to maintain healthy turf (Balogh and Watson, 1992; Witteveen and Bavier, 1999; Branham et al., 2005). The intense management of turf has fostered a perception (Shuman, 2002; Kohler et al., 2004; Schmidt, 2006) that nutrient loadings resulting from golf courses are substantial.

Plot scale turf studies indicate the potential for nitrogen and phosphorus transport in surface water (Cole et al., 1997; Linde and Watschke, 1997; Shuman, 2002; Easton and Petrovic, 2005); however, caution should be exercised when attempting to extrapolate those findings to the watershed scale because the interconnectedness and complexities at the watershed scale have not been considered. Larger watershed scale turf studies have been conducted (Kunimatsu et al., 1999; Mallin and Wheeler, 2000; King et al., 2001; Line et al., 2002; Graves et al., 2004; Winter and Dillon, 2005, 2006); however, nitrogen and phosphorus loading from the turf systems is scarcely cited.

Thus based on the critical need for loading data from all sources within the urban landscape, including golf courses, the general objective of this study was to quantify the surface water nutrient flux from a golf course watershed. Specifically, the objective was to measure nitrate nitrogen and dissolved reactive phosphorus concentrations and loads transported in surface runoff and baseflow from a golf course watershed.

2. Materials and methods

2.1. Experimental site and management

Morris Williams Municipal Golf Course (MWMGC), located in Austin, TX (Fig. 1), was selected for this study. MWMGC is an 18-hole golf course measuring approximately 76 ha located adjacent to the west side of the old Robert Mueller Municipal Airport between Manor Road and Martin Luther King Jr. Boulevard (Fig. 1). Manor Road is curbed, forcing all water from that street segment to the inlet of the golf course. MWMGC was constructed in 1963 and is managed and open for play year round.

Specifically, the area of interest for this study was the central portion of the course. The stream segment is characterized by a series of open channels, culverts, and casual water detention areas. Open channels convey water until the channel approaches a fairway. At that point, the drainage water enters a culvert which runs the width of the fairway before exiting to the surface channel. At the outlet of each of the culverts, stream bank erosion has widened the stream creating small detention areas. During large runoff events, drainage water not able to be conveyed by the culverts runs over and across the surface of the fairways. The drainage way conducts surface runoff from the course and old airport across holes #10, #15, #16, #17, #2, and #7 (Fig. 1). The topography is such that the contributing area (29 ha) contains 10 greens (0.73 ha), 7 full fairways and 1 partial fairway (8.23 ha) and 7 tees (0.30 ha). The managed areas (greens, fairways, and tees) represent 32% of the total area. The contributing area also contains approximately 6.5 ha of reduced-managed rough, with the remainder comprised of unmanaged trees and shrubs. Surface water from precipitation or irrigation on the course will either infiltrate the surface soils or follow the surface topography. The stream eventually drains into the Colorado River offsite of the golf course. The drainage way receives considerable input from the airport causing flows to peak rapidly.

MWMGC is situated in the heart of the Texas Blackland Prarie ecoregion, a 4.45 million ha area of fertile land extending from San Antonio north to the Red River. Soils on MWMGC were formed in alluvium, clayey bedrock, and marl bedrock but have been subjected to considerable disturbance and redistribution as a result of local construction projects. The study area is dominated by two soil types (Table 1): Travis (fine, mixed, thermic Ultic Paleustalfs) and Houston Black (fine, montmorillonitic, thermic Udic Haplusterts). Travis soils are located on the slopes while the Houston Black clays are located in the valleys and areas surrounding the stream. The Houston Black clays have a high shrink/swell potential and a very slow permeability (less than 1.52 mm h^{-1}) when wet (SCS, 1974). However, preferential flow resulting from soil cracking contributes to high infiltration rates when the soil is dry (Arnold et al., 2005; Allen et al., 2005).

During the study period (April 1, 1998 to March 31, 2003), management practices were typical of municipal courses in the Southern U.S. Fairways and greens were seeded with a hybrid bermudagrass cultivar. Greens were over-seeded in late fall with perennial ryegrass. The golf course was irrigated with a mixture of potable water from the city and water pumped from an

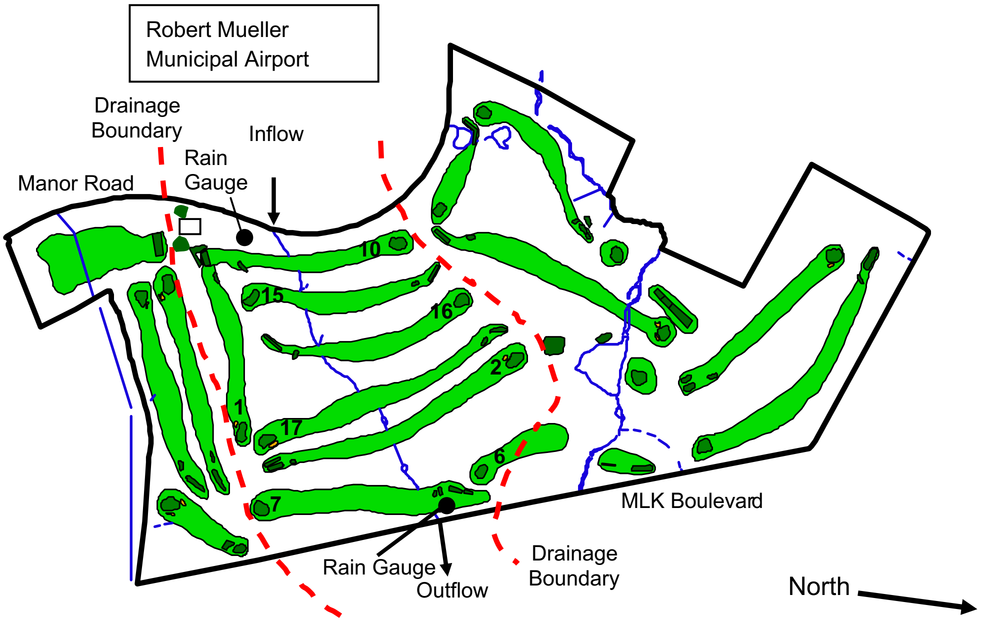

Fig. 1. Layout of Morris Williams Municipal Golf Course, study area boundaries (enclosed in red dashed lines), and measurement locations.

Table 1
Soil mapping units located in the study area at MWMGC

Soil mapping unit	Dominant texture	NRCS hydrologic soil group	Extent of unit (ha)	Percent of total area
Houston Black + Urban 1–3% slope	Gravelly clay	D	8.0	27.6
Travis + Urban 1–8% slope	Gravelly loamy sand over sandy clay/sandy clay loam	C	21.0	72.4

onsite, unlined reservoir. Irrigation was applied on an "as needed" basis, determined by course personnel, to replace evapotranspiration losses. When applied, single application irrigation amounts were not allowed to exceed 12.7 mm on greens and 8.5 mm on tees and fairways. This management approach assured no runoff resulting from irrigation applications. Median nutrient concentrations in the irrigation water ($n = 245$) were 0.2 mg L^{-1} NO_3-N and 0.05 mg L^{-1} DRP. Using the volume of irrigation water applied during the study period, average annual nutrient input to the course resulting from irrigation was 0.3 kg ha^{-1} NO_3-N and 0.08 kg ha^{-1} DRP.

Fertilizer was applied by both dry broadcast and spray techniques throughout the year as a combination of organic, bio-stimulant, slow release, and fast release formulations. The majority of the fertilizer was applied during the spring and summer when the plant requirements were greatest. Annual average commercial fertilizer application rates for greens, fairways, and tees were determined from course records (Table 2). Average annual commercial N application mass for the study area (29.0 ha) was 36.5 kg ha^{-1}, while P applications totaled 8.2 kg ha^{-1}. No efforts were made to quantify the amount of nutrients associated with decomposition of grass clippings dropped back on the course after mowing. Greens were mowed daily during the growing season and every two days following overseeding. Tee and fairway areas were mowed every 2–3 days depending on grass growth. The course is managed to the stream edge, no buffers or other structural management practices were present.

The climate in Austin is characterized by long, hot summers and short, mild winters. Austin averages 270 growing season days per year, generally lasting from mid-March to mid-November (NOAA, 1993). Thunderstorms during the summer generate short intense rainfalls. Moisture in the form of frozen precipitation can occur but is generally negligible. The 30-year normal precipitation (Fig. 2) is 810 mm (NOAA, 1993). Normal daily temperatures range from an average minimum of 4 °C in January to an average maximum of 35 °C in August.

2.2. Sample collection and analyses

Surface hydrology and water quality data was collected on site at the inflow and outflow locations (Fig. 1) for the duration of the study. Isco automated water samplers each equipped with an Isco 730 bubbler module were installed at the inflow and outflow locations of the study area. In addition, area velocity sensors were installed at the same locations. Stage and velocity were logged continuously on a 15-min interval and a stage-discharge relationship was developed for each site. Precipitation was measured using tipping-bucket rain gauges located at the inflow and outflow locations.

Table 2
Reported annual average commercial fertilizer application at MWMGC

Year	Nitrogen (kg ha^{-1})			Phosphorus (kg ha^{-1})		
1998[a]	612.8	115.1	219.0	69.3	0	39.8
1999	309.9	47.3	49.0	196.2	10.0	0
2000	505.2	206.2	82.9	161.0	63.8	27.6
2001	292.8	132.4	37.4	126.5	35.0	12.5
2002	220.1	195.6	48.9	84.0	48.9	0
2003[b]	97.3	0	0	39.1	0	0
Mean annual	407.6	193.3	87.4	133.2	32.0	16.0

[a] Apr. 1 to Dec. 31.
[b] Jan. 1 to Mar. 31.

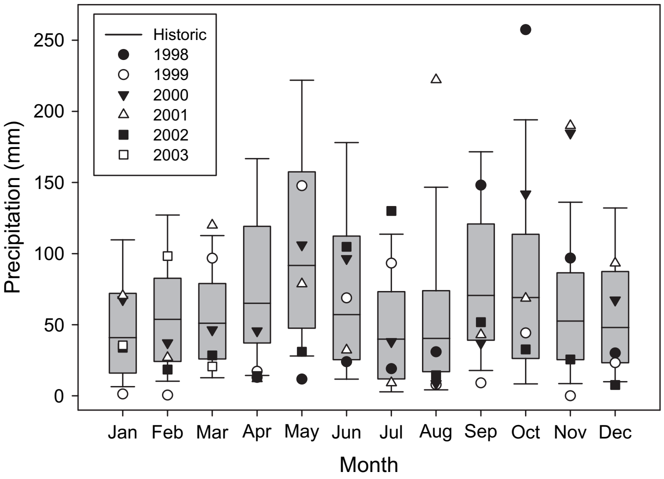

Fig. 2. Historical (1856–2005) precipitation reported by National Weather Service for Austin, TX (boxes are bound by 25th and 75th percentile values; line in the box represents the median; whiskers represent the 10th and 90th percentiles) and study period (April 1, 1998 to March 31, 2003) measured precipitation at the experimental watershed site.

Time interval composite samples with 6 aliquots per sample were collected automatically during storm runoff events to evaluate storm nutrient flux. An event was defined as any rainfall event producing a cumulative precipitation greater than 6.35 mm with no dry periods greater than 6 h. The first 24 aliquots were taken at 5-min intervals, the next 48 aliquots at 15-min intervals, the next 48 aliquots at 30-min intervals and the last 24 aliquots at 60-min intervals. Baseflow grab samples were collected on a near weekly basis. All samples were collected in midstream and a well-mixed condition was assumed.

Following collection, all samples were handled according to U.S. EPA method 353.3 for nitrate analysis and U.S. EPA method 365.1 for phosphorus analysis (U.S. EPA, 1983). Samples were acidified with concentrated HCL and iced for transport to the laboratory for analysis. Samples were stored below 4 °C until analysis. All samples were analyzed within a 28-day period. Samples were filtered through a 0.45 μm pore diameter membrane filter and analyzed colorimetrically for $NO_3 + NO_2$-N and PO_4-P concentrations using a Technicon Autoanalyzer IIC and methods published by Technicon Industrial Systems (1973, 1976). From this point forward $NO_3 + NO_2$-N will be expressed as NO_3-N. Here, PO_4-P is used synonymously with dissolved reactive phosphorus (DRP) and will be designated from this point forward as DRP.

Laboratory quality assurance was assessed on a ten sample frequency. Laboratory quality assurance analyses resulted in blank concentrations less than the published Technicon procedure detection limits. Replicates (precision limits) were all within 0–5%, and measured laboratory spikes (accuracy limits) were all within 0–8% of known concentrations; however, most were well below the 5% and 8% limits.

Nutrient load was calculated by multiplying the analyte concentration by the measured water volume for that respective sample and summing over the study duration of the study. The volume of water associated with any one sample was determined using the midpoint approach; the midpoint between each sample was determined and the volume of water calculated for that duration. The analyte concentration was assumed to be representative over that specific flow duration. All statistical analyses were conducted with Minitab statistical software (Minitab Inc, 2000) and methods outlined by Haan (2002). Since data were generally not normally distributed based on the Kolmogorov–Smirnoff test, statistical differences in median concentrations were evaluated with the Mann–Whitney nonparametric statistic ($\alpha = 0.05$).

3. Results

In this study, both concentrations and loading of NO_3-N and DRP were evaluated. Loadings and concentrations are important for monitoring nutrient dynamics in lentic and lotic ecosystems, but concentrations are used to identify aquatic organism exposure to potential chronic levels. Concentrations and loadings measured in the baseflow and storm event runoff are presented.

The monthly distribution of precipitation, during the study period, was representative of the long-term bimodal distribution (Fig. 2), with peak monthly totals in the spring and fall. Annual precipitation ranged from 510 mm in 1999 to 965 mm in 2001 (Table 3). Total measured storm water runoff from 115 runoff events was 659 mm or 17% of total precipitation (3829 mm). For the duration of the study, baseflow was estimated at 0.58 mm day^{-1} or 972 mm volumetric depth. There was no attempt to separate out baseflow during storm flow events. The cumulative baseflow amount represents only those times when storm flow runoff was not occurring. Mean annual baseflow accounted for 60% of total discharge.

NO_3-N and DRP concentrations were measured at the inflow and outflow locations during storm event runoff as well as during baseflow conditions. During the 5-year study, 1051 storm event inflow samples, 1063 storm event outflow samples, and 239 baseflow samples were collected. Median storm event concentrations of NO_3-N (Fig. 3) and DRP (Fig. 4) were significantly ($p < 0.05$) greater exiting the course than entering the course. The range of measured NO_3-N concentrations leaving the course in storm runoff was 0.01–3.5 mg L^{-1} with a median of 0.35 mg L^{-1} compared to an inflow concentration range of 0.0 to 2.3 mg L^{-1} with a median of 0.23 mg L^{-1}. The range of DRP concentration measured in the inflow was 0.01–0.90 mg L^{-1} with a median of 0.10 mg L^{-1} compared to a range of 0.0–0.99 mg L^{-1} with a median of 0.13 mg L^{-1} at the outflow location. Similarly, a statistically significant ($p < 0.05$) increase in the median baseflow concentration of NO_3-N (Fig. 3) was measured between the outflow and inflow locations; however, no statistical difference ($p > 0.05$) was measured in the baseflow DRP concentration (Fig. 4). The range of NO_3-N concentration measured in the baseflow at the inflow location was 0.0–1.8 mg L^{-1} with a median of 0.27 mg L^{-1} compared to a range of 0.0–2.4 mg L^{-1} and median of 0.73 mg L^{-1} at the outflow. Baseflow DRP concentrations ranged from 0.0 to 0.37 mg L^{-1} at the inflow with a median of 0.1 mg L^{-1} while outflow concentrations ranged from 0.0 to 0.27 mg L^{-1} with a median of 0.1 mg L^{-1}.

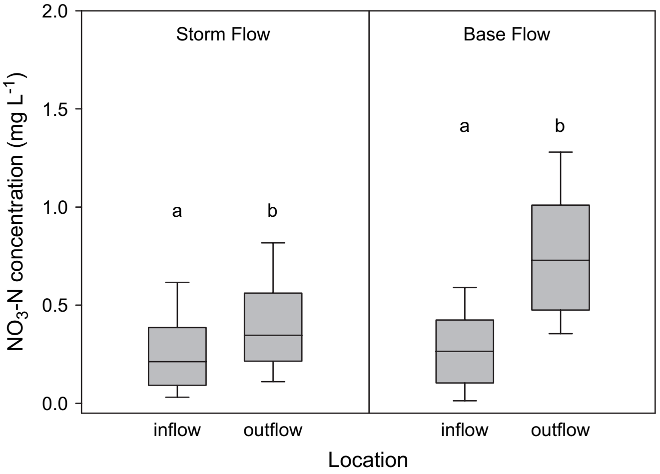

Fig. 3. Box and whiskers plot of measured NO_3-N concentrations at inflow and outflow (April 1, 1998 to March 31, 2003) for both storm event and baseflow conditions. Boxes are bound by the 25th and 75th percentile concentrations; the line in the box represents the median concentration. Whiskers represent the 10th and 90th percentile concentrations. Plots within each classification (storm flow and baseflow) noted with different letters indicate significant ($p < 0.05$) differences in median concentrations using the Mann–Whitney nonparametric test.

Table 3
Annual recorded precipitation, number of events, and resulting discharge from MWMGC study area

Year	No. of precipitation events	Precipitation (mm)	Max. 15-min rainfall (mm)	Discharge (mm)	Runoff coefficient
1998[a]	15	631	25.7	78.3	0.124
1999	17	510	30.5	143.3	0.281
2000	27	877	17.8	130.0	0.148
2001	29	965	30.5	165.3	0.171
2002	23	692	21.1	122.1	0.176
2003[b]	4	154	5.3	19.8	0.129

[a] Apr. 1 to Dec. 31.
[b] Jan. 1 to Mar. 31.

The measured nutrient concentrations and corresponding discharge volumes were combined and integrated over the duration of the study to provide both a storm and baseflow load estimate to the stream. The measured NO_3-N load in the baseflow was 2.8 kg ha^{-1} yr^{-1} compared to 1.2 kg ha^{-1} yr^{-1} delivered in storm event runoff (Fig. 5). The DRP load

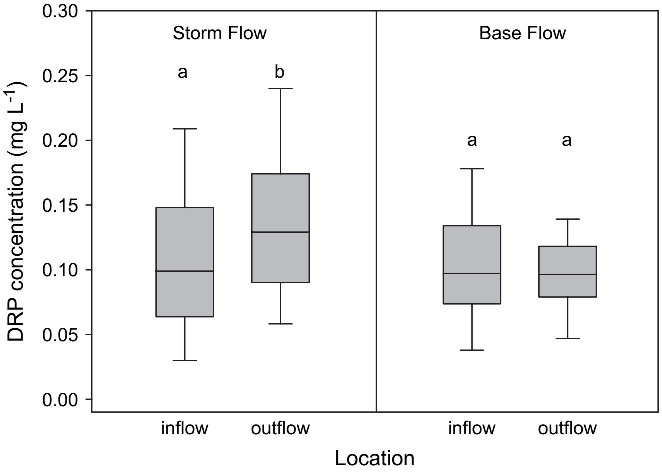

Fig. 4. Box and whiskers plot of measured DRP concentrations at inflow and outflow (April 1, 1998 to March 31, 2003) for both storm event and baseflow conditions. Boxes are bound by the 25th and 75th percentile concentrations; the line in the box represents the median concentration. Whiskers represent the 10th and 90th percentile concentrations. Plots within each classification (storm flow and baseflow) noted with different letters indicate significant ($p < 0.05$) differences in median concentrations using the Mann–Whitney nonparametric test.

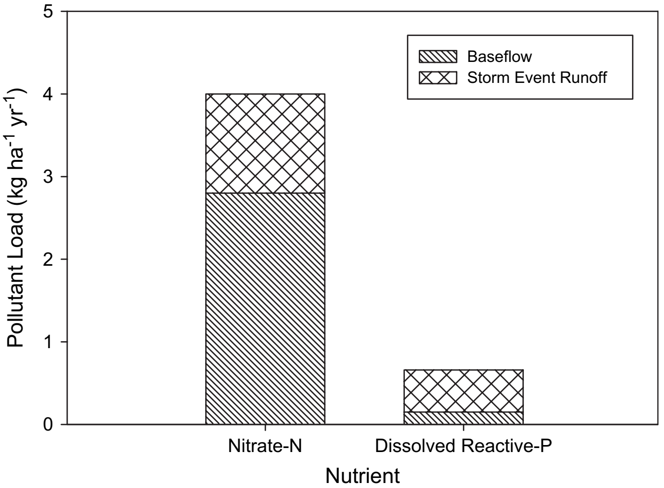

Fig. 5. NO_3-N and DRP load (kg ha^{-1} yr^{-1}) delivered in baseflow and storm event runoff from MWMGC during the period of study (April 1, 1998 to March 31, 2003).

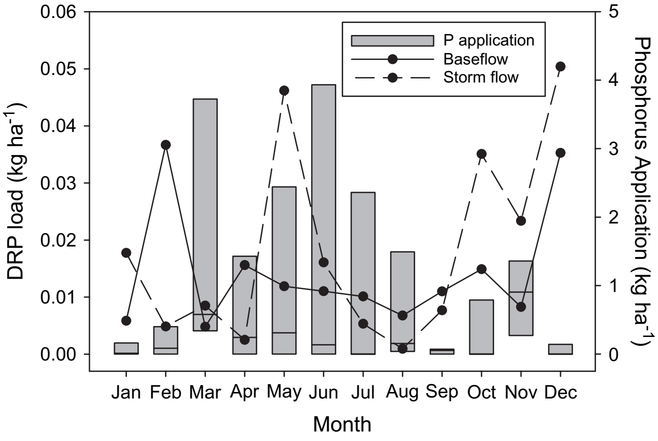

Fig. 7. Monthly phosphorus application range (boxes are bound by the 25th and 75th percentile concentrations; the line in the box represents the median concentration) and measured median monthly DRP loads resulting from baseflow and storm event runoff at Morris Williams Municipal Golf Course during period April 1, 1998 to March 31, 2003.

measured in the baseflow was 0.15 kg ha^{-1} yr^{-1} compared to 0.51 kg ha^{-1} yr^{-1} lost in storm runoff (Fig. 5). Monthly NO_3-N loads from baseflow were generally greater than like loads from storm flow, the exception occurring in late fall and early winter (Fig. 6). In contrast, the monthly DRP loads were generally greater in baseflow during spring and summer but greater in storm flow in fall and winter (Fig. 7).

4. Discussion

The measured inflow and outflow NO_3-N concentrations in the storm flow and baseflow were consistently well below the U.S. EPA (1977) drinking water standard, 10 mg L^{-1}. Even though this stream is not a drinking water supply and the standard applies to finished drinking water, the 10 mg L^{-1} standard is often used as a reference point for NO_3-N concentrations. In an effort to protect freshwater streams for general use purposes, The Texas Commission for Environmental Quality (TCEQ) has established screening levels for nutrients in freshwater streams (TCEQ, 2003). The goal of these screening levels is to guard against general water quality concerns rather than a specific use concern. When 25% of the water samples exceed the screening level, the streams ability to attain its general use purpose may be jeopardized. The TCEQ screening level threshold for NO_3-N is 2.76 mg L^{-1}. Five of the 1063 (0.5%) outflow storm event samples exceeded the TCEQ screening level. No inflow storm event or baseflow samples exceeded the TCEQ NO_3-N screening level. However, the observed NO_3-N concentrations were consistent with the NO_3-N range (0.05–1.85 mg L^{-1}) measured by Winter et al. (2002) who noted a significant difference in macroinvertebrate community structure when comparing data from golf course streams to those of reference streams.

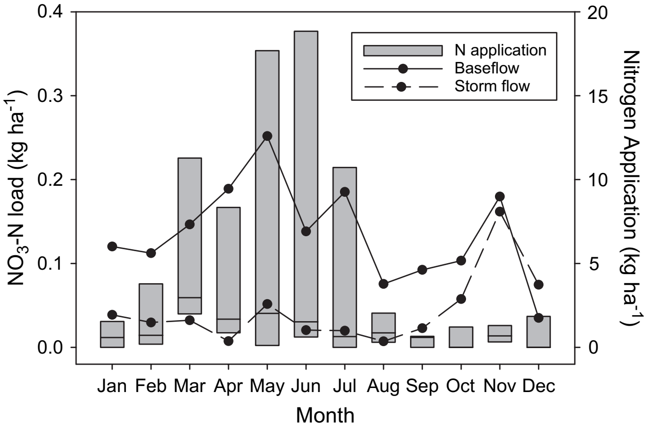

Fig. 6. Monthly nitrogen application range (boxes are bound by the 25th and 75th percentile concentrations; the line in the box represents the median concentration) and measured median monthly NO_3-N loads resulting from baseflow and storm event runoff at Morris Williams Municipal Golf Course during period April 1, 1998 to March 31, 2003.

In contrast, the DRP concentrations often exceeded the U.S. EPA (1986) recommendation of 100 μg L^{-1} for streams not discharging into lakes. In the case of baseflow, 106 inflow and 107 outflow samples (approximately 46% of the total collected) exceeded the 100 μg L^{-1} recommendation. This finding indicates that the DRP introduced by the golf course in baseflow is consistent with background concentrations of DRP in this stream. In the storm flow case, 512 samples or 49% of the inflow samples exceeded the recommendation while 738 or 69% of the outflow samples exceeded the 100 μg L^{-1} recommendation. Most phosphorus is being transported in the storm event runoff. These findings suggest a considerable risk of algal blooms and eutrophication in the stream transecting the golf course. This was evidenced by frequently observed algal blooms in the stream during the study. The TCEQ screening level for DRP is 500 μg L^{-1}, a value much less restrictive than the U.S. EPA recommendation of 100 μg L^{-1}. Using the TCEQ criteria, no baseflow samples exceeded the screening level and only nine inflow and outflow storm event samples (0.9%) exceeded the screening level.

Using the loading from the course along with the discharge, a stream concentration resulting from the course can be calculated. Dividing the storm flow load contributed by the course by the amount of water contributed by the course during storm flow resulted in an NO_3-N concentration of 0.91 mg L^{-1} and a DRP concentration of 0.39 mg L^{-1}. Similarly, a baseflow concentration can be calculated. In this case, the baseflow NO_3-N concentration contributed by the course was 1.82 mg L^{-1} while the DRP concentration was 0.10 mg L^{-1}. When comparing the calculated baseflow DRP concentration to that value estimated for storm flow, a substantial difference was noted. The DRP concentration from the course resulting from storm flow was 0.4 mg L^{-1}. This result suggests that a substantial amount of soluble phosphorus is available in the thatch and surface soil layer. Intense rainfalls will tend to have greater interaction with the surface soil interface and generally produce greater runoff volumes resulting in an increased potential for pollutant transport. The clayey soils found on this course also enhance the potential for surface runoff from precipitation events. In addition, although the current management strategy is to use a low-level phosphorus fertilizer, the residual phosphorus in soil from previous heavy applications during course establishment is still available for low-level losses in storm flow. Similar findings have been speculated (Shortle et al., 2001) and reported from agricultural land use areas (Gburek and Sharpley, 1998; Sims et al., 1998; Stamm et al., 1998).

The concentrations measured at this site were greater than but comparable to those from other studies; however, no studies were found that distinguished between baseflow and stormflow concentrations (Table 4). The mean measured baseflow NO_3-N concentration from the course was greater than any other reported concentrations measured on golf courses, but the storm flow concentration was in the range of values reported by Line et al. (2002) and Mallin and Wheeler (2000). The calculated DRP concentrations in both the baseflow and stormflow were greater than any reported for golf courses.

The total NO_3-N and DRP loads measured in this study represent 11% of applied N and 8% of applied P over the same time period. The losses tended to fluctuate with the climatic season. Both NO_3-N (Fig. 6) and DRP (Fig. 7) losses were elevated during times of application as expected; however, substantial losses were measured during the fall and winter (October through March). With respect to NO_3-N, 67% of the losses occurred during the fall and winter when the grass was generally dormant (the exception being the overseeded greens) and microbial activity is suppressed due to cooler temperatures. Similarly 58% (baseflow) and 62% (storm flow) of the DRP losses occurred from October through March.

A large portion of the total loads occurred during calendar years 1998 and 1999 when the course was undergoing reconstruction, and the use of soluble forms of fertilizers was elevated. Of the total NO_3-N losses measured during the study, 53% of the storm flow NO_3-N and 69% of the baseflow NO_3-N was measured in 1998 and 1999. Similarly, DRP baseflow losses in 1998 and 1999 were equivalent to 61% of the total baseflow DRP losses while 22% of the storm flow losses were measured during that time period. More slow release fertilizer formulations were used following reconstruction and grass establishment, and a decline in nutrient losses was observed.

The measured NO_3-N and DRP loadings from the MWMGC were comparable to those reported by Kunimatsu et al. (1999) from a golf course in Japan (Table 4). Line et al. (2002) reported an NO_3-N load of 4.8 kg ha^{-1} yr^{-1} from a golf course in North Carolina, while Winter and Dillon (2006) measured NO_3-N loads of 2.1 kg ha^{-1} yr^{-1} for golf courses in Canada. Neither of the latter studies reported DRP loading. The amount of nutrients recovered in the surface water expressed as a percentage of applied elemental fertilizer was greater than the 5% N and 2% P noted by Winter and Dillon (2006) but considerably less than the 32% N and 14% P recovered on a golf course in Japan (Kunimatsu et al., 1999). When compared to NO_3-N loads from heterogeneous agricultural watersheds (5.7 kg ha^{-1} yr^{-1}, Inamdar et al., 2001; 20.4 kg ha^{-1} yr^{-1}, Coulter et al., 2004), the loads observed in this study were notably less. In contrast, the DRP loads observed in this study are greater than like loads from agricultural catchments (0.07 kg ha^{-1} yr^{-1}, Inamdar et al., 2001; 0.13 kg ha^{-1} yr^{-1}, Novak et al., 2003; 0.28 kg ha^{-1} yr^{-1}, Coulter et al., 2004).

The findings from this study suggest a significant need to implement best management practices aimed at combating phosphorus losses in surface runoff. It is well understood that precipitation is a natural event whose predictability, with any confidence, is limited to two or three days. Thus,

Table 4
Comparison of NO_3-N and DRP concentrations and loads from Morris Williams Municipal Golf course to like concentrations and loads from other golf course studies

Reference	Concentration (mg L^{-1})		Load (kg ha^{-1} yr^{-1})		Study location
	NO_3-N	DRP	NO_3-N	DRP	
Winter and Dillon, 2006	0.3	–	2.1	–	Ontario, Canada
Line et al., 2002	1.02	–	4.8	–	North Carolina, USA
Kunimatsu et al., 1999	0.29	0.05	3.7	1.6	Japan
Mallin and Wheeler, 2000	0.6 - 1.49	0.004 - 0.06	–	–	North Carolina, USA
Graves et al., 2004	0.12	–	–	–	Florida, USA
This study					
Baseflow	1.82	0.1	2.8	0.15	Austin, TX, USA
Storm flow	0.91	0.4	1.2	0.51	

basing nutrient application and management solely around weather forecasts is risky. However, the implementation of best management practices in addition to managing based on weather forecasts can provide additional reduction in the surface losses of nutrients. Applying phosphorus at rates commensurate with plant needs will reduce the amount of phosphorus available for runoff losses. These rates can be determined using soil phosphorus tests. Accounting for all major sources of nutrients and factors affecting nutrient availability can increase nutrient use efficiency and reduce potential losses (King et al., 2000). Introducing grass buffers around streams helps to intercept flow, slow down runoff, increase infiltration, and significantly reduce nutrient losses (Cole et al., 1997). Managing buffers at graduated heights has been shown to reduce phosphorus losses by 11% (Moss et al., 2006). Nutrient placement has also been shown to be effective at reducing surface losses. Post application irrigation places the nutrients in the thatch and surface soil layer. This practice reduced phosphorus losses by more than 10% (Shuman, 2004). Maintaining a healthy dense turf promotes drainage and infiltration and can reduce runoff 15 fold (Leslie and Knoop, 1989; Easton and Petrovic, 2004). All else remaining equal, less runoff water results in less surface nutrient loss.

The turfgrasses used on golf courses are very efficient and aggressive at utilizing nitrogen (Turner and Hummel, 1992). As evidenced by the data collected over 5 years in this study, nitrogen losses are small and the measured concentrations are well below any level of concern and are fairly consistent with background levels. In contrast, the DRP concentrations do warrant some concern. But, with proper management and implementation of best management practices, the concentrations and loads of phosphorus lost in surface waters should decrease.

5. Conclusions

Hydrology and nutrient concentrations were collected for a 5-year period (April 1, 1998 to March 31, 2003) at the Morris Williams Municipal Golf Course located in Austin, TX, USA to determine the nutrient flux from managed turf in the urban landscape. This study had a unique approach in that both storm flow and baseflow contributions were measured. Based on the collected data from the MWMGC the following summary and conclusions may be drawn.

- Baseflow represented approximately 60% of the total discharge during the study period.
- The median measured outflow NO_3-N concentration in both baseflow and storm flow was significantly ($p < 0.05$) greater than the like inflow concentration.
- Storm flow DRP concentrations measured at the outflow were significantly ($p < 0.05$) greater than the median concentration measured at the inflow. No difference was noted in the baseflow DRP concentrations.
- The total NO_3-N load resulting from the golf course was 4.0 kg ha^{-1} yr^{-1} (2.8 kg ha^{-1} yr^{-1} in baseflow and 1.2 kg ha^{-1} yr^{-1} in storm flow). The total DRP load was 0.66 kg ha^{-1} yr^{-1} (0.15 kg ha^{-1} yr^{-1} in baseflow and 0.51 kg ha^{-1} yr^{-1} in storm flow).
- The NO_3-N load was equivalent to 11% of the applied N over the same period while the DRP load accounted for 8% of the applied P.

In conclusion, observed NO_3-N concentrations and loads, even though statistically significant, do not pose a significant environmental risk. In contrast, DRP concentrations exiting the golf course watershed exceeded recommended levels to guard against eutrophication. Additionally, DRP loads from golf course were considerably greater than similar losses from agricultural watersheds. These findings highlight the need for implementation of best management practices aimed at reducing DRP losses from managed turf.

Acknowledgments

We would like to acknowledge the analytical and technical expertise provided to this research effort by Mr. Robert Chaison and Ms. Georgie Mitchell and express to them our sincere thanks. Without their dedication and hard work, this research effort would not have been possible. We would also like to thank the superintendent and staff of Morris Williams Municipal Golf Course for providing management data to us. In addition, we wish to extend a special acknowledgement to Mr. Gene Faulk of the City of Austin Parks and Recreation for having the vision to see the importance of this type of research and permitting the use of the course for this effort. Finally, we would like to thank the U.S. Golf Association Green Section for funding provided toward this research.

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