Nutrient Load Generated by Storm Event Runoff from a Golf Course Watershed

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ABSTRACT

Turf, including home lawns, roadsides, golf courses, parks, etc., is often the most intensively managed land use in the urban landscape. Substantial inputs of fertilizers and water to maintain turf systems have led to a perception that turf systems are a major contributor to nonpoint source water pollution. The primary objective of this study was to quantify nutrient (NO_3–N, NH_4–N, and PO_4–P) transport in storm-generated surface runoff from a golf course. Storm event samples were collected for 5 yr (1 Apr. 1998–31 Mar. 2003) from the Morris Williams Municipal Golf Course in Austin, TX. Inflow and outflow samples were collected from a stream that transected the golf course. One hundred fifteen runoff-producing precipitation events were measured. Median NO_3–N and PO_4–P concentrations at the outflow location were significantly ($p < 0.05$) greater than like concentrations measured at the inflow location; however, median outflow NH_4–N concentration was significantly less than the median inflow concentration. Storm water runoff transported 1.2 kg NO_3–N ha^{-1} yr^{-1}, 0.23 kg NH_4–N ha^{-1} yr^{-1}, and 0.51 kg PO_4–P ha^{-1} yr^{-1} from the course. These amounts represent approximately 3.3% of applied N and 6.2% of applied P over the contributing area for the same period. NO_3–N transport in storm water runoff from this course does not pose a substantial environmental risk; however, the median PO_4–P concentration exiting the course exceeded the USEPA recommendation of 0.1 mg L^{-1} for streams not discharging into lakes. The PO_4–P load measured in this study was comparable to soluble P rates measured from agricultural lands. The findings of this study emphasize the need to balance golf course fertility management with environmental risks, especially with respect to phosphorus.

Extent of Turfgrass and Golf Courses

THERE ARE an estimated 17 million hectares of turfgrass (home lawns, roadsides, commercial property, golf courses, parks, recreational resorts, schools, churches, cemeteries, airports, and sod farms) in the U.S. with an annual value of $40 to 60 billion (Morris, 2006). The largest percentage of turfgrass is found in home lawns while an approximate four million turfgrass hectares are located on roadside right-of-ways (Federal Highway Administration, 2004). In some rapidly urbanizing regions of the U.S., turfgrass is rivaling corn and soybeans as the number one crop, a phenomena that is expected to continue with urban sprawl (Shuman et al., 2000).

The nation's 16 052 golf courses (National Golf Foundation, 2006) account for approximately 3% of all turf in

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the United States. (King and Balogh, 2006). Golf courses are the most intensively managed systems in the urban landscape (Walker et al., 1990; Smith and Bridges, 1996; Shuman et al., 2000). Management is an integral part of developing and maintaining high quality, efficient turfgrass systems. Judicious irrigation, fertilization, mowing, aeration, and pest control all contribute to maintenance of healthy turfgrass (Walker and Branham, 1992; Balogh and Anderson, 1992; Balogh and Watson, 1992; Turgeon, 1996; Witteveen and Bavier, 1999). However, the perception (Pratt, 1985; Peacock et al., 1996; Smith and Bridges, 1996; Shuman, 2002; Kohler et al., 2004) and potential (Balogh and Walker, 1992) for turf management to lead to offsite transport of nutrients and pesticides does exist.

Nitrogen and Phosphorus Studies on Golf Courses

Periodic nutrient applications are an integral and essential part of establishing and maintaining high quality turf (Branham et al., 2005). However, these applications increase the potential for nutrients to be transported off site in surface runoff or through subsurface drainage features exiting to surface water. Runoff and nutrient loss research from turf has been conducted at the field (Morton et al., 1988; Cole et al., 1997; Linde and Watschke, 1997; Gaudreau et al., 2002; Easton and Petrovic, 2005) and to a lesser extent the watershed scale (Kunimatsu et al., 1999; Mallin and Wheeler, 2000; King et al., 2001; Winter and Dillon, 2005; Starrett and Bhandari, 2006).

The general conclusions of the small-scale studies indicate that with well maintained turf the amount of runoff is small and the concentrations of nutrients in the surface runoff are well below any level of major concern. While studies on small scales are valuable they may not represent the diversity and connectivity associated with a watershed-scale system. The data collected from plot studies is also limited with regard to the temporal domain, many conducted for less than 2 yr.

Watershed-scale golf course assessments indicate that concentrations from water features on the golf courses are generally of the same magnitude with those reported in plot scale studies (Mallin and Wheeler, 2000; Winter and Dillon, 2005; Starrett and Bhandari, 2006). Cohen et al. (1999) reported that a survey of runoff on seventeen golf courses in the United States did not contain any cases of NO_3–N exceeding the drinking water standard of 10 mg L^{-1}. The median NO_3–N value recorded in that survey was 0.38 mg L^{-1}. Nutrient loading is greater from the watershed scale systems when compared to plot studies.

Based on the limited published findings on nutrient fate and transport from turf systems, we formulated the following hypothesis: NO_3–N, NH_4–N, and PO_4–P losses in storm event runoff from a well managed turfgrass

watershed (golf course) will not pose an environmental risk. Thus, the objective of this research was to assess and quantify the potential for nutrients (NO_3–N, NH_4–N, and PO_4–P) to be transported in storm event runoff from a golf course.

MATERIALS AND METHODS

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), seven full fairways and one partial fairway (8.23 ha), and seven 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 (Allen et al., 2005; Arnold et al., 2005).

During the study period (1 Apr. 1998–31 Mar. 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 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, 0.06 mg L^{-1} NH_4–N, and 0.05 mg L^{-1} PO_4–P. 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, 0.1 kg ha^{-1} NH_4–N, and 0.08 kg ha^{-1} PO_4–P.

Table 1. Soil mapping units located in the study area at Morris Williams Municipal Golf Course (MWMGC).

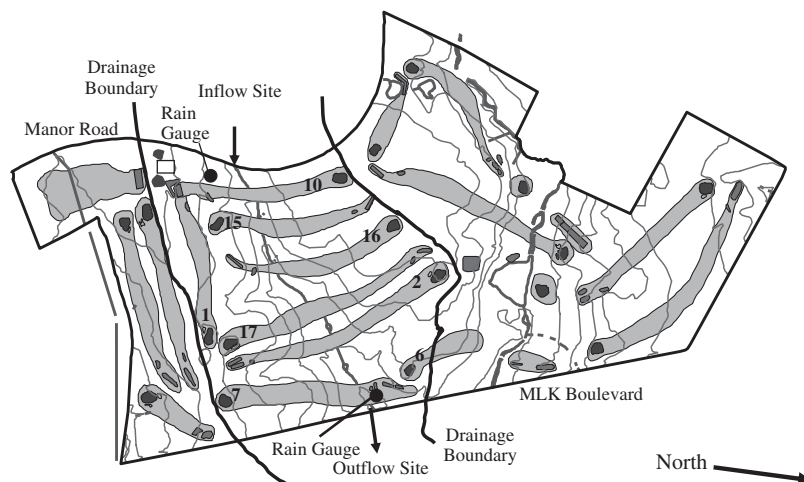| Soil mapping unit	Dominant texture	NRCS Hydrologic soil group	Extent of unit	Total area
			ha	%
Houston Black + Urban 1 to 3% slope	gravelly clay	D	8.0	27.6
Travis + Urban 1 to 8% slope	gravelly loamy sand over sandy clay/ sandy clay loam	C	21.0	72.4

Fig. 1. Layout of Morris Williams Municipal Golf Course. Area located between drainage boundaries, Manor Road, and MLK Boulevard was used in the study.

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. 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 2 d following overseeding. Tee and fairway areas were mowed every 2 to 3 d 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 yr normal precipitation (Fig. 2) is 810 mm (NOAA, 1993). Precipitation is characterized as bimodal with peaks in late spring and early fall (Fig. 2). Normal daily temperatures range from an average minimum of 4°C in January to an average maximum of 35°C in August.

Sample Collection and Analysis

Hydrology data was collected on site at the inflow and outflow locations (Fig. 1) for the duration of the study. Automated water samplers equipped with a 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.

Time-weighted composite samples with six aliquots per sample were collected automatically as long as stream stage exceeded the predetermined baseflow stage. For this study, 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. Samples were collected in midstream and a well mixed condition was assumed.

Following rainfall events, samples were removed from the automated sampler, acidified, and iced for transport to the laboratory for analysis. All samples were filtered through a 0.45-μm pore diameter membrane filter and analyzed color-
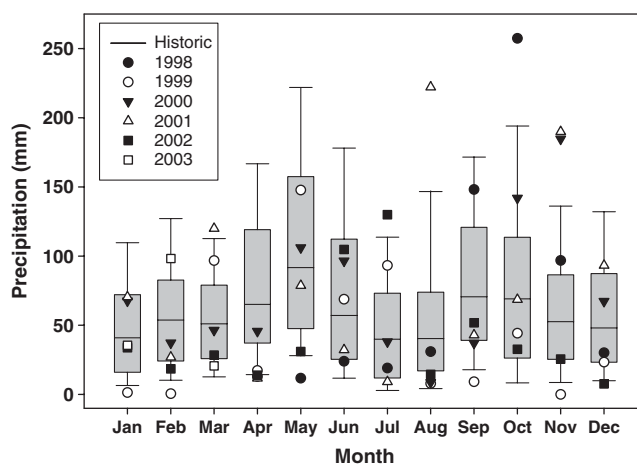

Fig. 2. Historical (1856–2005) precipitation reported by National Weather Service for Austin, TX (boxes are bound by 25th and 75th percentile values; line in the box represents the median; whiskers represent the 10th and 90th percentiles) and study period (1 Apr. 1998–31 Mar. 2003) measured precipitation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

imetrically for $NO_3 + NO_2$–N, NH_4–N, and PO_4–P concentrations using flow injection analysis and methods published by Technicon Industrial Systems (1973a, 1973b, 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. Nutrient load was calculated by multiplying the analyte concentration by the measured water volume for that respective sample and summing over the duration of the runoff event.

All statistical analyses were conducted with Minitab statistical software (Minitab Inc., 2000) and methods outlined by Haan (2002). Normality was tested using the Kolmogorov and Smirnof test. Distributions were generally not normally distributed, thus median values were tested using the Mann–Whitney nonparametric statistic ($\alpha = 0.05$).

RESULTS AND DISCUSSION

Hydrology

One hundred fifteen precipitation/runoff events were measured during the study period (1 Apr. 1998–31 Mar. 2003). The distribution of measured monthly rainfall generally mirrored the long-term distribution (Fig. 2). Recorded monthly precipitation exceeded the historical 90th percentile amounts 10% of the time during the study period. Annual rainfall amounts ranged from a relatively low 510 mm in 1999 to 965 mm in 2001 (Table 3). The 510 mm amount has a 92% probability of being exceeded in any given year while the wetter year (965 mm in 2001) has only a 30% chance of being exceeded in any given year (Fig. 3). The annual number of events ranged from 17 in 1999 to 29 in 2001. Mean precipitation for all events measured 30.8 mm while the median precipitation amount was 19.8 mm. A maximum precipitation amount of 187 mm was recorded on 17 Oct. 1998. Fifteen minute rainfall intensities for all events ranged from 0.5 to 30.5 mm with a mean of 5.8 mm. Annual maximum 15-min intensities ranged from 17.8 mm in 2000 to 30.5 mm measured in 1999 and 2001 (Table 3).

Table 2. Reported annual average commercial fertilizer application at Morris Williams Municipal Golf Course (MWMGC).

Year	Nitrogen			Phosphorus		
	Greens	Tees	Fairways	Greens	Tees	Fairways
	kg ha^{-1}					
1998†	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‡	97.3	0	0	39.1	0	0
Mean annual	407.6	139.3	87.4	133.2	32.0	16.0

† 1 Apr. to 31 Dec. 1998.
‡ 1 Jan. to 31 Mar. 2003.

Table 3. Annual recorded precipitation, number of precipitation events, and resulting discharge from Morris Williams Municipal Golf Course (MWMGC) study area.

Year	Number of precipitation events	Precipitation	Max recorded 15-min rainfall	Areal weighted irrigation	Surface runoff	Q/P
		mm				%
1998†	15	631	25.7	172	78.3	12.4
1999	17	510	30.5	227	143.3	28.1
2000	27	877	17.8	218	130.0	14.8
2001	29	965	30.5	98	165.3	17.1
2002	23	692	21.1	115	122.1	17.6
2003‡	4	154	5.3	2	19.8	12.9

† 1 Apr. to 31 Dec. 1998.
‡ 1 Jan. to 31 Mar. 2003.

Runoff is often described as a runoff coefficient. The runoff coefficient is expressed as a Q/P ratio, where Q is the volumetric runoff depth and P is the precipitation depth. The runoff coefficient is defined as the fraction of precipitation measured as runoff. Annual surface runoff ranged from 122 mm in 2002 to 165 mm in 2001, volumes equivalent to approximately 17% of the precipitation measured during the same time interval. Annually, the runoff coefficient ranged from 0.13 to 0.28 (Table 3) while on a monthly basis the mean runoff coefficient range (Table 4) was 0.09 (August) to 0.25 (July). For all events, the runoff coefficients ranged from 0.002 to 0.61 with a mean of 0.16.

Analysis of monthly runoff from MWMGC indicated that runoff volumes were greatest in May followed by July and then October. The runoff volumes in October were attributed to greater precipitation amounts, approximately 17 mm per event (Table 4) more than the mean May event. However, May and July runoff volumes suggest that course irrigation management may, in part, be responsible for the increased runoff volumes. Based on course management records, the greatest amount of irrigation water was added to the course during May and July (Fig. 4) resulting in a greater antecedent soil moisture. In May, rainfall is also greatest. The larger mean runoff volumes in July are the result of a single significant rainfall event (90 mm) in July 2002, 49% of which ran off.

The percentage of rainfall exiting the course as runoff (Q/P) was also examined on a monthly basis (Table 4). This analysis indicated that substantially more rainfall left the course as runoff (on a percent basis) during the months of May and July compared to all other months. This may have also been due to the irrigation management at MWMGC. During months of green up and growth (April through September), more irrigation water is generally applied to meet evaporative demand (Fig. 4). The application of irrigation water creates a high soil moisture content that increases the potential for runoff. Even though moisture contents were not measured, the results from this study suggest that in the months of May and July, course-wide irrigation may have been followed by a significant rainfall event resulting in greater amounts of runoff.

A significant linear relationship was shown to exist between precipitation and runoff (Fig. 5). The linear model accounted for 63% of the variability observed in the measured data. However, the 0.22 slope from the linear model suggests a greater runoff coefficient than the mean 0.16 runoff coefficient calculated from all events. The 0.22 coefficient was influenced by three intense events which produced significant runoff compared to precipitation (Fig. 5). The greater runoff coefficients were generally associated with more intense high volume rainfall events. The monthly runoff coefficients measured in this study were in the range
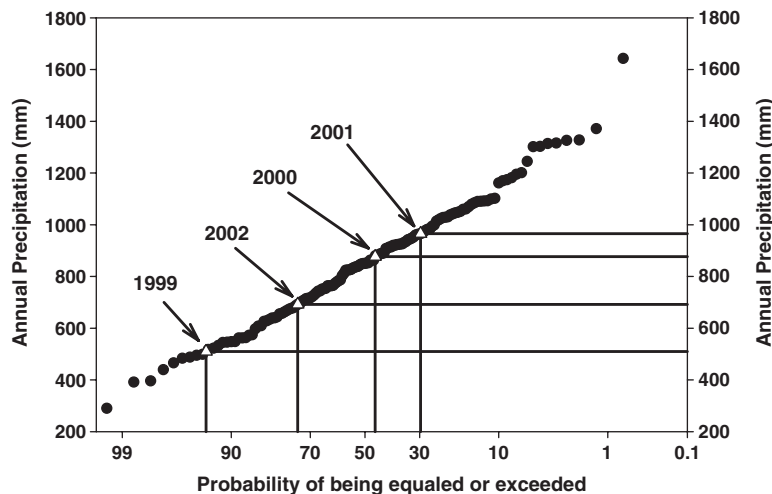

Fig. 3. Exceedance probability plot of annual precipitation for Austin, TX (1856–2005) and measured annual rainfall recorded during study period.

Table 4. Mean (standard deviation) number of events, event precipitation, discharge, and runoff coefficient by month.

Month	Precipitation events per year	Event precipitation amount†	Event discharge amount†	Event Q/P†
		— mm —		%
Jan.	1.4	28.0 (13.7)	4.5 (4.1)	0.16 (0.12)
Feb.	1.2	26.8 (26.8)	3.5 (3.9)	0.14 (0.13)
Mar.	2.8	20.1 (10.4)	3.2 (3.0)	0.14 (0.08)
Apr.	1.0	15.1 (5.8)	2.3 (1.6)	0.15 (0.07)
May	2.2	32.7 (29.6)	9.6 (15.3)	0.21 (0.16)
June	2.6	22.1 (15.9)	3.4 (3.1)	0.15 (0.10)
July	1.8	28.7 (25.5)	9.2 (12.4)	0.25 (0.18)
Aug.	1.0	50.7 (68.5)	7.1 (13.6)	0.09 (0.06)
Sept.	1.6	32.1 (25.3)	2.9 (2.1)	0.12 (0.08)
Oct.	2.4	49.5 (47.2)	8.9 (11.4)	0.17 (0.10)
Nov.	2.4	41.2 (40.8)	8.4 (16.3)	0.14 (0.12)
Dec.	2.6	24.7 (16.0)	4.0 (3.4)	0.15 (0.06)

† There were no statistically significant differences in values within each column.

with those reported from other turf studies (Smith and Bridges, 1996; Linde and Watschke, 1997; Shuman, 2002; Easton and Petrovic, 2005; Schwartz and Shuman, 2005).

Climate, soils, and irrigation management all impact the amount of runoff from turf systems. In the case of MWMGC, the largest 10% of rainfall events (11 events) accounted for approximately 33% of the total rainfall and 44% of the measured runoff during the study. Periodic irrigation (management) during the growing season not only ensures a healthy growing turf but also maintains greater antecedent soil moisture, thus, when convective storms develop or climatic fronts pass through the area, the runoff potential is greater. In addition, the soils on the golf course are generally clayey or silty clays with low hydraulic conductivities, thus the ability of the soil to absorb water from greater intensity storms is limited, resulting in a greater runoff potential. One might expect a greater amount of runoff because of the clayey soils and compaction associated with high traffic areas on golf courses; however, well
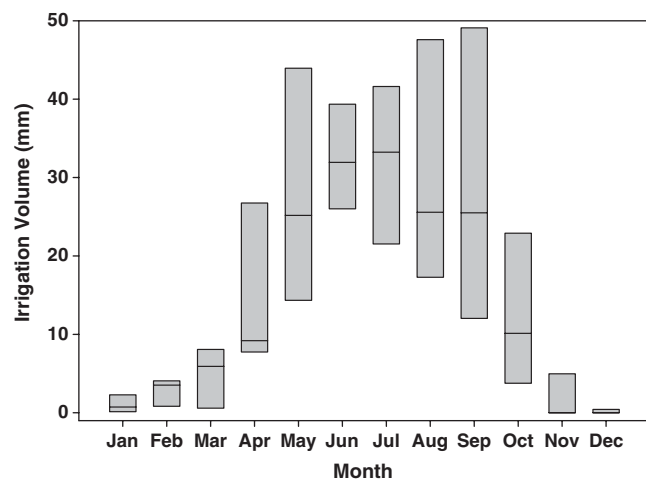

Fig. 4. Annual areal weighted irrigation volumes for managed turf (tees, greens, and fairways) at Morris Williams Municipal Golf Course (MWMGC). Boxes are bound by 25th and 75th percentile values; line in the box represents the median. Monthly volumes were calculated from applied volume multiplied by fractional area: volume applied to greens × 0.025 + volume applied to tees × 0.01 + volume applied to fairways × 0.284.
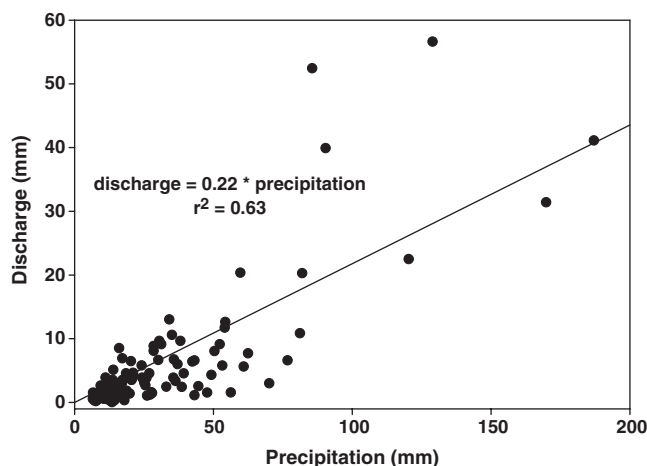

discharge = 0.22 * precipitation
$r^2 = 0.63$

Fig. 5. Relationship between 115 precipitation events and resulting runoff for Morris Williams Municipal Golf Course (MWMGC) during study period (1 Apr. 1998 to 31 Mar. 2003).

maintained high density turf can actually reduce the runoff potential.

Nutrient Concentrations

Nutrient (NO_3–N, NH_4–N, and PO_4–P) concentrations were determined from water samples collected at the inflow and outflow locations during each storm runoff event. Across all runoff events, 1051 samples were collected at the inflow site while 1063 samples were collected at the outflow site. Based on the collected runoff data (Table 5), the golf course contributed to statistically significant ($p < 0.05$) increases in median NO_3–N concentrations ($+0.12$ mg L^{-1}) and PO_4–P concentrations ($+0.03$ mg L^{-1}), and decrease in NH_4–N concentrations (-0.01 mg L^{-1}).

The median NO_3–N concentration exiting the course was 0.35 mg L^{-1}, while the mean NO_3–N concentration leaving the course was 0.44 mg L^{-1}. An investigation of the median monthly inflow concentrations yielded a similar result. Outflow concentrations, while small in magnitude, were significantly ($p < 0.05$) greater than inflow concentrations throughout the year. The measured NO_3–N concentrations were within the range of NO_3–N concentrations reported in other turfgrass studies (Linde and Watschke, 1997; Cohen et al., 1999; Kunimatsu et al., 1999; Shuman, 2002; Winter and Dillon, 2005). The maximum measured NO_3–N concentration was 3.52 mg L^{-1}. Even though the stream that was measured is not a source of drinking water, it should be noted that the NO_3–N concentrations recorded in this study were well below the EPA drinking water standard (10 mg L^{-1}) and consistent with the aforementioned turf studies. Additionally, the NO_3–N concentrations were less than concentrations reported from crop production agriculture (Richardson and King, 1995; Inamdar et al., 2001; Harmel et al., 2004; Harmel et al., 2006) and even treated wastewater permitted to be discharged into streams (Asano et al., 1984; Reilly et al., 2000; Marti et al., 2004). The measured NO_3–N concentrations, in stream discharge from this course,

Table 5. Statistical analysis† of storm flow nutrient concentrations (mg L^{-1}) measured at inflow and outflow locations on Morris Williams Municipal Golf Course (MWMGC) for a 5-yr period of record (1 Apr. 1998 to 31 Mar. 2003).

| Parameter | Storm flow concentrations‡ | | | | | |
| | $NO_3–N$ | | $NH_4–N$ | | $PO_4–P$ | |
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
	mg L^{-1}					
Mean	0.30	0.44	0.10	0.09	0.12	0.15
Median	0.23a	0.35b	0.05a	0.04b	0.10a	0.13b
Maximum	2.25	3.52	4.04	3.23	0.90	0.99

† Medians for each constituent followed by different letters are significantly different ($p < 0.05$) using Mann–Whitney nonparametric test.
‡ $n = 1051$ for inflow; $n = 1063$ for outflow.

pose minimal environmental risk. In the case of $NH_4–N$, a significant ($p < 0.05$) reduction, although small in magnitude, was measured in the concentration entering and leaving the course. This reduction is most likely a result of $NH_4–N$ sorption to stream sediments or organic matter, nitrification to $NO_2–N$, and/or volatilization. The $NH_4–N$ concentrations measured in this study were consistent with those reported by Mallin and Wheeler (2000) from various water features from five different golf courses in North Carolina.

There was a significant increase ($p < 0.05$) in surface water $PO_4–P$ concentrations leaving the course compared to those entering the course. The median $PO_4–P$ concentration leaving the course was 0.13 mg L^{-1} compared to 0.10 mg L^{-1} entering the course (Table 5). Investigation of the monthly inflow and outflow concentrations indicated that in 11 of the 12 months (August being the exception) median outflow concentrations were greater than inflow concentrations, but not always statistically significant. The maximum concentration of $PO_4–P$ measured in surface discharge was 0.99 mg L^{-1}. The measured median $PO_4–P$ concentrations from this study were approximately 200% greater than similar concentrations reported on golf courses by Kunimatsu et al. (1999) and Mallin and Wheeler (2000). The median $PO_4–P$ concentrations (inflow and outflow) were greater than the USEPA (1986) recommendation of 0.1 mg L^{-1} for streams not discharging into lakes, suggesting modification to course management may improve the quality of discharge waters. The most significant management practices used to control or reduce nutrient runoff losses from established turf are: (i) consideration of all major sources of nutrients and factors affecting nutrient availability (King et al., 2000), (ii) maintenance of healthy turf (Watschke, 1990), (iii) control of irrigation scheduling and volume based on plant

requirement (Balogh and Watson, 1992; Murphy, 2002; Bastug and Buyuktas, 2003), (iv) establishment and maintenance of buffer zones (Cole et al., 1997; Bell and Moss, 2005), and (v) protection of trees and wetlands (Kohler et al., 2004; Reicher et al., 2005). The data collected in this study indicate that the golf course is contributing significant ($p < 0.05$) amounts of phosphorus to the stream that need to be addressed. However, just as noteworthy is the fact that the concentrations coming into the golf course were equivalent to the USEPA recommended threshold level.

Nutrient Loadings

The median $NO_3–N$ event load measured at the outflow site (1.0 kg) was significantly ($p < 0.05$) different from that observed at the inflow site (0.5 kg) (Table 6). There was also a small, but nonsignificant increase (0.04 kg) in the median $NH_4–N$ event load between the course inflow and outflow points. The $NO_3–N$ course load was 1.20 kg ha^{-1} yr^{-1} while the $NH_4–N$ load was 0.23 kg ha^{-1} yr^{-1}. The mean annual $NO_3–N$ load was substantially greater than the range reported by Gross et al. (1990) (0.035–0.084 kg ha^{-1} yr^{-1}) and Linde and Watschke (1997) (0–0.2 kg ha^{-1} yr^{-1}) on plot-scale studies but comparable to the golf course watershed load (3.7 kg ha^{-1} yr^{-1}) reported by Kunimatsu et al. (1999) on a golf course in Japan. One possible reason for this discrepancy from the plot-scale research was the applied nitrogen formulation. Gross et al. (1990) and Linde and Watschke (1997) applied nitrogen primarily in the form of urea. High levels of the urease enzyme in turfgrass thatch that promote volatilization of ammonia from urea have been reported (Titko et al., 1987). At MWMGC, the detection of relatively high loads of $NO_3–N$ in runoff was attributed to the application of

Table 6. Statistical analysis† of storm event loads (kg) measured at the inflow and outflow locations on Morris Williams Municipal Golf Course (MWMGC) for 115 precipitation/runoff events spanning 1 Apr. 1998 to 31 Mar. 2003.

| Parameter | Storm flow loads‡ | | | | | |
| | $NO_3–N$ | | $NH_4–N$ | | $PO_4–P$ | |
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
	kg					
Mean	1.0	2.5	0.33	0.62	0.7	1.4
Median	0.5a	1.0b	0.13a	0.17a	0.2a	0.5b
Maximum	14.7	45.8	5.4	15.0	11.7	14.7

† Medians for each constituent followed by different letters are significantly different ($p < 0.05$) using Mann–Whitney nonparametric test.
‡ $n = 115$ events.

some soluble nitrogen fertilizer (ammonium nitrate). This was especially evident in the first year of study when the course was undergoing renovation and turf establishment and greening was a premium. While ammonium nitrate is not a typical golf course fertilizer it was applied in the first year of this study. When compared to loading rates from agricultural watersheds (9.6 kg ha^{-1} yr^{-1}, Inamdar et al., 2001; 3 to 32 kg ha^{-1} yr^{-1}, Harmel et al., 2004; and 20.4 kg ha^{-1} yr^{-1}, Coulter et al., 2004), the rates observed from MWMGC were notably smaller in magnitude.

The NO$_3$–N load expressed as a percentage of applied nitrogen for the same area was equivalent to 3.3%. This percentage was comparable to the 2% recovery reported on turfgrass plots by Linde and Watschke (1997) and Shuman (2002) but only one tenth of the estimated 32% combined runoff and leachate loss reported at the watershed scale by Kunimatsu et al. (1999). Of the 174 kg total NO$_3$–N transported in storm event runoff, 48% was lost in the largest 10% of precipitation events, and nearly 18% of the total was transported with the largest precipitation event (187 mm). Investigation of the timing of nitrogen losses revealed that significant losses were occurring at different times than those of fertilizer application (Fig. 6), most likely a function of the grasses nitrogen use efficiency and climate. In fact, the NO$_3$–N losses during times of intense fertilization (March–July) totaled one-half the measured losses recorded for the remainder of the year. Turfgrasses are generally very efficient nitrogen users and often recommended and used to provide a nitrogen sink (Bergstrom and Jokela, 2001; Keeney and Hatfield, 2001; Dinnes et al., 2002). As demonstrated with the data from this study, even during times of intense fertilization the turf was able to utilize the applied nitrogen; however, during the dormant periods the grass was not able to utilize the available nitrogen resulting in substantially greater NO$_3$–N losses. Compounding the lack of utilization by the plant during the dormant period

is suppressed microbial activity (less N sequestration) due to colder temperatures.

The median PO$_4$–P event load during the study was 0.3 kg. The median event load measured at the outflow (0.5 kg) was significantly greater ($p < 0.05$) than that measured at the inflow (0.2 kg). The annual PO$_4$–P load resulting from storm event runoff was 0.51 kg ha^{-1} yr^{-1}. The mean annual PO$_4$–P load was substantially greater than like loads from plot-scale studies documented by Gross et al. (1990) (0.01–0.12 kg ha^{-1} yr^{-1}) and Easton and Petrovic (2005) (0.12 kg ha^{-1} yr^{-1}). However, the PO$_4$–P loads measured in the runoff from MWMGC were approximately one third of the total phosphorus export reported by Kunimatsu et al. (1999) (1.6 kg ha^{-1} yr^{-1}) from a golf course in Japan. When compared to agricultural crop production systems, the PO$_4$–P loads from MWMGC were generally greater but in the same range (Sonzogni et al., 1980; Inamdar et al., 2001; Novak et al., 2003; Harmel et al., 2004; Coulter et al., 2004; Harmel et al., 2006). In the Novak et al. (2003) study, the primary transport mechanism was baseflow, which is in contrast to the storm flow contributions observed in this study.

The 0.51 kg PO$_4$–P ha^{-1} yr^{-1} loading is approximately 6.2% of the applied phosphorus for the same time period, a loading rate within the range of rates measured in agricultural cropland (Harmel et al., 2006). Shuman (2002) reported 15% PO$_4$–P recovery from a plot-scale study. Of the 74 kg PO$_4$–P lost during the study period, 46% was lost during the largest 10% of precipitation events, 13.3% occurring with the third largest precipitation event (129 mm). As was the case with NO$_3$–N, the greatest losses of PO$_4$–P do not generally correspond to the timing of application (Fig. 7), the month of May being the exception. The greatest losses (approximately 56%), of PO$_4$–P, were measured during the fall and winter months when the grass was dormant.

The considerable amount of PO$_4$–P loss measured from this course suggests that phosphorus may be more

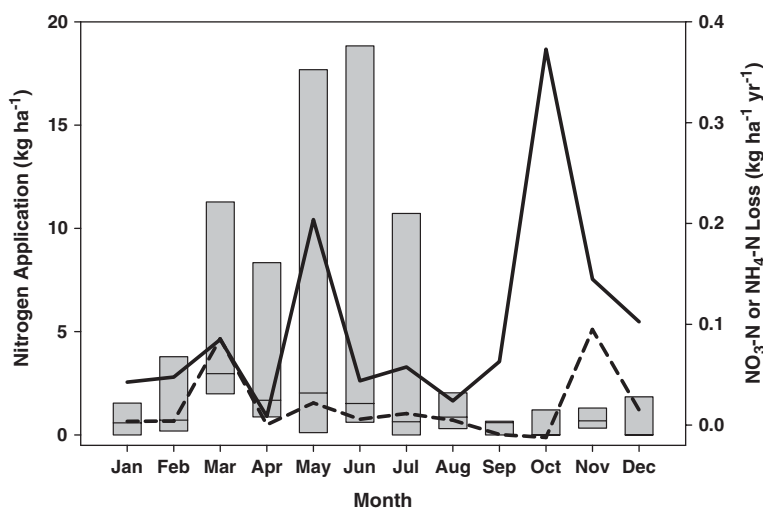Fig. 6. Monthly nitrogen application (box plot), mean measured NO$_3$–N loss (solid line), and mean measured NH$_4$–N loss (dashed line) at Morris Williams Municipal Golf Course (MWMGC) for the 5-yr study period. Boxes are bound by 25th and 75th percentile values; line in the box represents the median.
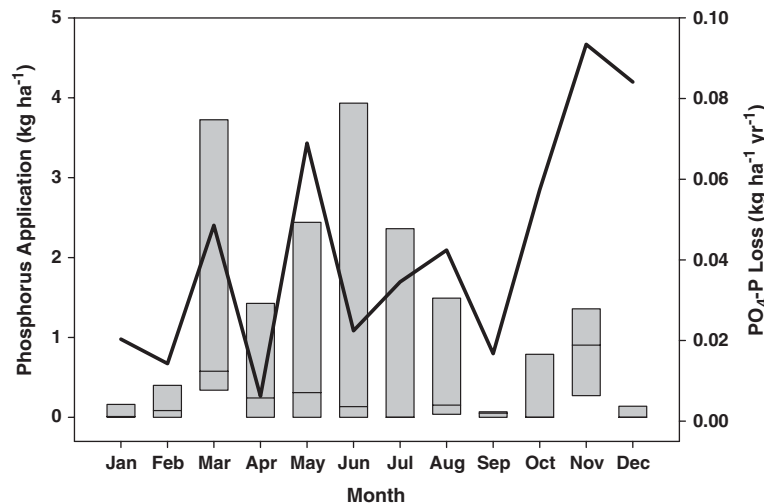
Fig. 7. Monthly phosphorus application (box plot) and mean measured PO_4–P loss (solid line) at Morris Williams Municipal Golf Course (MWMGC) for the 5-yr study period. Boxes are bound by 25th and 75th percentile values; line in the box represents the median.

of an environmental concern than nitrogen, a finding consistent with that of Petrovic and Easton (2005). The substantial losses of phosphorus can be explained in two ways: current fertility management and historical practices during course construction. First, fertility management plans should aim to balance the nutritional requirements of the plant with the potential for offsite transport. In many cases, fertility plans and subsequent fertilizer applications are based solely on nitrogen requirements, ignoring the amount of phosphorus in the selected fertilizer. Second, during course construction, it is common practice to apply large amounts of phosphorus for root development and establishment (Turner and Hummel, 1992). In many cases, the amount of applied phosphorus is not adjusted once the grass is established, leading to phosphorus-saturated soils. The residual phosphorus in the soil is readily available for transport with surface runoff, and additional phosphorus applications further enhance the potential for runoff losses (Gburek and Sharpley, 1998; Sims et al., 1998; Stamm et al., 1998; Shortle et al., 2001). Use of periodic soil samples and adherence to the recommendations may, in time, reduce the phosphorus losses.

CONCLUSIONS

Data was collected for a 5-yr period (1 Apr. 1998 to 31 Mar. 2003) at the inflow and outflow locations of a stream that transects the Morris Williams Municipal Golf Course (MWMGC) to test the hypothesis: NO_3–N, NH_4–N, and PO_4–P losses in storm event runoff from a well managed turfgrass watershed (golf course) will be insignificant. Based on the data collected from the 115 precipitation/runoff events during the study, NO_3–N and NH_4–N losses, while statistically significant ($p < 0.05$) between the inflow and outflow points, pose minimal environmental risk. However, the measured PO_4–P concentrations and losses warrant concern and the need to implement and/or enhance management practices to address the elevated levels of PO_4–P being transported from the course.

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