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Water Quality Characteristics of Three Rain Gardens Located Within the Twin Cities Metropolitan Area, Minnesota

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A study was conducted by the United States Geological Survey (USGS) at three locations in the Twin Cities Metropolitan Area in Minnesota to assess the effect that bioretention areas, or rain gardens, have on water quality. The rain gardens are located at the University of Minnesota Landscape Arboretum (MLA), City of Hugo, and City of Woodbury. These sites were chosen because of their similar ages, differences in design, surrounding land use, precipitation patterns, and geology. This article reports the statistical analysis of six years of data obtained from these three sites. The data characterizes the water quality of the inflow, overflow, vadose zone, and groundwater of each rain garden. Nutrients analyzed included chloride, total suspended solids, ammonia, organic nitrogen, nitrate, and phosphorus. Lysimeters and wells had significantly lower nutrient concentrations compared to inflow for most nutrients. Increased nitrate occurred in the vadose zone at Woodbury and Hugo, suggesting some production of nitrate within the soil profile; however, groundwater beneath the rain gardens contained significantly lower concentrations of nitrate compared to the inflow, providing evidence of nitrate removal at deeper depths. Phosphorus concentrations were reduced in overflow and groundwater, with the exception of dissolved phosphorus at MLA. Rain garden and background wells often contained similar nutrient concentrations, suggesting that the rain gardens had little impact on the local ground water supplies. This unique six year study provides consistent evidence of the ability of these three rain gardens to reduce nutrient concentrations from urban stormwater.

Keywords

bioretention, rain garden, stormwater, low-impact development, best management practice

Acknowledgements

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INTRODUCTION

Low Impact Development (LID) is a fairly recent urban development strategy that focuses on treating stormwater runoff on-site by mimicking the original hydrologic functions of the landscape (Prince George's Co. Department of environmental Resources 1999). This goal is achieved by implementing Best Management Practices (BMPs) such as green roofs, permeable pavements, rain gardens, and rain barrels. Rain gardens have become especially popular due to their aesthetic appeal and low maintenance requirements.

Although the main purpose of a rain garden is to infiltrate stormwater runoff, the physico-chemical processes that occur as a result of soil, microbes and vegetation results in additional water quality benefits (Prince George's Co. Department of Environmental Resources 2007). Hydrologic benefits, such as reduced peak flows and increased lag times have been well documented (Dietz and Clausen 2005; Davis 2008; Hunt et al. 2008;); however, the fate of nutrients within rain gardens is still unclear and therefore, remains the focus of many studies. Both nitrate removal and export has been reported (Hsieh and Davis 2005; Davis et al. 2006; Dietz and Clausen 2006; Hunt et al. 2006; Hsieh et al. 2007). High removal rates of both ammonia concentrations and loads have consistently been reported (Dietz and Clausen 2005; Tornes 2005; Hunt et al. 2008). Phosphorus removal has been highly inconsistent among studies; ranging from exports to concentration [load] removals to no net removal (Hsieh and Davis 2005; Hunt et al. 2006; Li and Davis 2009; Passeport et al. 2009). Phosphorus removal has often been correlated with soils having a low P index score because these soils have a greater capacity to adsorb P compared to those with high P index scores (Hunt et al. 2006). Phosphorus exports have been attributed to disturbance of the rain garden soil at the beginning of studies. The disturbance loosens the media allowing phosphorus-laden sediment to be exported out of the system which would appear to be an addition of phosphorus to the system (Dietz and Clausen 2005).

Typical total suspended solid (TSS) reductions of 90-98% have been reported (Rusciano and Obropta 2007; Li and Davis 2009) and as a result potential problems with media clogging exist. Li and Davis (2008) observed decreasing hydraulic conductivities over time in soil columns. Replacement of the topsoil resulted in increased hydraulic conductivities comparable to original rates; however, the hydraulic conductivities once again declined over time, suggesting regular replacement of topsoil may be required. Although Li and Davis did not account for the role vegetation plays in reducing compaction and enhancing infiltration (Bharati et al. 2002; Devitt and Smith 2002), their results raise concerns about maintenance costs.

A majority of rain garden research has been conducted in the laboratory with soil columns or constructed boxes (Davis et al. 2001; Kim et al. 2003; Hsieh and Davis 2005; Davis et al. 2006; Hsieh et al. 2007; Rusciano and Obropta 2007). Typically, higher rates of nutrient removal have been found in field studies (Dietz and Clausen 2005; Tornes 2005; Hunt et al. 2006; Dietz and Clausen 2008; Passeport et al. 2009); however, most of these studies have been conducted in a controlled environment in which synthetic stormwater and/or simulated rain events were applied to the rain gardens. Results from field studies have recently become more available as rain gardens have become more prevalent in the landscape; however, there is still a gap in data concerning long term-effectiveness of rain gardens. Additionally, studies investigating the impacts of rain gardens on the local groundwater have mostly focused on recharge rates and/or hydrologic modeling of rain gardens (Shuster et al. 2007) leaving a gap in understanding how groundwater quality is affected by rain gardens.

The data presented in this study were collected by the United States Geological Survey (USGS) in coordination with the Metropolitan Council Environmental Services, located in St. Paul, MN to compare and contrast rain gardens with different designs, contributing land uses, and precipitation patterns. The objectives of this study were to determine whether: (1) nutrient and chloride concentrations were reduced in the overflow and ground water compared to the inflow and (2) changes in water quality would result from the different designs and surrounding land uses of these rain gardens.

METHODS

Site Descriptions

The three Minnesota rain gardens chosen for this study are located at the University of Minnesota Landscape Arboretum (MLA) in Chaska, Hugo City Hall (Hugo), and in the City of Woodbury (Woodbury). Construction of all three rain gardens was completed in late summer/early fall 2003. Detailed locations and characteristics of each site are given in Table 1. The soil at Hugo did not require any modifications, but MLA and Woodbury were back filled with sand to enhance infiltration. Each site has an overflow structure that typically leads to the existing stormwater infrastructure to accommodate rain events greater than the rain garden was designed to treat. Individual plants were planted at Hugo and MLA. The vegetation at both sites consists mainly of prairie forbs and grasses, including: *Sorghastrum nutans, Andropogon gerardii, Panicum virgatum, Liatrus spicata, Echinacea purperea, Dalea purpurea, and Aster novae-angleae*. Less extensive planting was completed at Woodbury, but some individual plants and grass seed were planted. Woodbury has a greater percentage of woody species compared to the other sites. Typical species at Woodbury include: *Sorghastrum nutans, Andropogon gerardii, Panicum virgatum, Hypericum perfatum, Salix spp., and Helianthus maximiliani*. MLA receives regular, weekly weeding, whereas Hugo and Woodbury only receive periodic weeding. Senescent vegetation was not removed from any of the sites. MLA is the only site that had mulch and it is only located around the perimeter of the basin.

Table 1. Characteristics of three Minnesota rain gardens monitored during the growing seasons of 2003-2008: Minnesota Landscape Arboretum (MLA), Hugo City Hall (Hugo), and City of Woodbury (Woodbury).

	MLA	Hugo	Woodbury
City, County	Chanhassen, Carver Co.	Hugo, Washington Co.	Woodbury, Washington Co.
Latitude; Longitude (DDMMSS)	445149; 0933655	450943; 0925939	445512; 0925644
Rain garden area (m^2)	405	405	4047
Estimated Contributing Area (m^2)	4371	4047	260,617
Bioretention: Drainage Area Ratio (%)	9	10	1.5

Table 2. Continued.

	MLA	Hugo	Woodbury
Rain Garden Depth (m)	0.7	0.6	2.0
Dominant Type of Runoff	Parking lot	Parking lot + Rooftop	Residential + Direct road
Drain Tile Present	Yes	No	No
Soil Series of Natural Soils	Lester-Kilkenny loam	Lino variant loamy fine sand	Rosholt sandy loam
Amended Soil Type	Medium sand	NA	Medium sand
Amended Soil Depth (m)	0.6	NA	1.7
Rain Garden Well Depth (m)	NA	5.8	3.3
Background Well Depth (m)	NA	6.7	6.1

Study Design

The USGS monitored the rain gardens during the growing seasons of 2003-2008. Representative water samples were collected from inflow, overflow, the unsaturated zone (vadose zone), and groundwater. Samples were analyzed for: TSS, chloride, ammonia (NH_3), total kjehldahl nitrogen (TKN), nitrite (NO_2), nitrite + nitrate (NO_2/NO_3), total phosphorus (TP), and dissolved phosphorus (DP). The scope of the study did not include measuring precipitation, flow, or infiltration; therefore, this paper will only report on water quality parameters.

Berms were not incorporated into the site designs allowing runoff to flow freely into the basins from all directions. As a result, one inflow location was chosen to represent total inflow entering the rain garden. This was typically located at a curb cut or culvert. Time weighted inflow samples were collected from the chosen inflow using an automatic ISCO sampler. The samples were processed at the USGS Water Science Center of Minnesota and sent to the USGS National Water Quality Laboratory for analysis. Processing consisted of compositing the samples in a churn splitter, filtering, and preserving according to standard USGS protocols. Three runoff and three non-runoff rain events were scheduled to be sampled; however, due to low precipitation during some years, this was not always achieved.

Overflow samples were intended to be collected as grab samples from overflow structures to represent runoff that had flowed through the garden but not infiltrated into the soil. Woodbury is the only site at which true overflow samples were collected. No overflow was ever observed at Hugo. At MLA, grab samples were collected from water flowing out of the drain tile and are better thought of as outflow since the water had infiltrated into the soil and presumably undergone some chemical reactions.

According to guidance by Wood (1976), a shallow sampling lysimeter and observation well were installed within the rain garden basin to obtain soil water and ground water samples, respectively. A 4.8 X 44.5 cm lysimeter was installed to a depth of approximately 1.5 meters.

Samples were hand pumped from the lysimeters after applying suction. Observation wells were installed approximately 1-2 meters below the water surface. Before sample collection, wells were purged with the equivalent of three well volumes. An additional lysimeter and well were installed outside of the rain garden to characterize the quality of the background groundwater. Lysimeters and wells were generally sampled monthly during the growing season; however, due to periods of low precipitation during the study this was not always achieved. The rain garden lysimeter at Hugo and the background lysimeters at all three sites were often dry and consequently, insufficient data were collected. The few data points that were collected were not included in analysis as they do not accurately reflect the entire study period.

Data Analysis

The data analyzed in this study are publicly available via the USGS National Water Information System Website (NWIS-Web)[1]. Due to the relatively small sample sizes and presence of censored data (data points reported as below detection limit), summary statistics were computed using the nonparametric Kaplan-Meier method (Antweiler and Taylor 2008). The Paired Prentice-Wilcoxon (PPW) test was used to test for a difference in median concentrations between sample locations. All PPW tests were conducted as two-sided tests at the 95% confidence level with the null hypothesis of no difference between median concentrations. All statistical analyses were performed in S+, version 8.1 (2008).

RESULTS

The number of samples collected from each site is given in Table 2. Sample numbers shown are the minimum number of samples collected. The actual number may vary by constituent. All samples were collected during the years 2003-2008 from approximately March to October.

Table 3. Number of samples collected from Minnesota Landscape Arboretum (MLA), Hugo, and Woodbury, Minnesota during the growing seasons of 2003-2008. Samples taken at the inflow, outflow/overflow, rain garden (RG) lysimeter, rain garden (RG) well, and background (BG) well for each location.

	Inflow	Overflow	RG Lysimeter	RG Well	BG Well
MLA	14	21	14	NA	NA
Hugo	23	0	5	18	22
Woodbury	20	10	7	15	15

Chloride

Chloride was significantly higher in ground water and overflow compared to inflow at MLA and Woodbury. At both sites, lysimeter samples contained the highest chloride concentrations (Table 3). Despite the apparent increase in chloride in the unsaturated zone, the wells at Woodbury were not significantly different from each other indicating that the rain garden was not adding chloride to the groundwater. The BG well at Hugo always contained the highest chloride concentrations.

[1] http://waterdata.usgs.gov/nwis

Specific conductivity exhibited similar patterns to chloride (data not shown), suggesting that dissolved solids behaved similar to chloride.

Table 4. Median concentration of chloride and total suspended solids (TSS) in the inflow, outflow/overflow, rain garden (RG) lysimeter, rain garden (RG) well, and background (BG) well for samples collected during the growing seasons of 2003-2008 at Minnesota Landscape Arboretum (MLA), Hugo, and Woodbury, Minnesota.

	Chloride (mg/L)			TSS (mg/L)		
	MLA	Hugo	Woodbury	MLA	Hugo	Woodbury
Inflow	2.13	5.16	9.27	105	53.5	36
Overflow	16.7*	NA	33.3*	<10*	NA	<10*
RG Lysimeter	19.1*	NA	678*	<10*	NA	NA
RG Well	NA	3.48	231*	NA	<10*	<10*
BG Well	NA	38.8**	241	NA	<10*	10.5

** = significantly different from inflow at the 95% confidence level;*
*** = significantly different from RG well at the 95% confidence level;*
NA = no samples.

A secondary standard of 250 mg/L of chloride has been established by the USEPA (2009). Woodbury was the only site to exceed this standard. All of the lysimeter samples, and approximately 75% and 50% of the BG and RG well samples, respectively, exceeded the standard (Figure 1).

Total Suspended Solids

Total suspended solids were reduced from the inflow at all sites. With the exception of the BG well at Woodbury, all the ground and surface water samples had median concentrations below the detection limit (Table 3). Despite this efficient removal of solids, there did not appear to be any clogging of the media that is typically associated with solids removal. If monitoring were to continue in the future, evidence of clogging may occur as more particles settle in the basin over time.

Nitrogen

Aside from NO_2/NO_3, concentrations of nitrogen species were significantly lower in groundwater compared to the inflow. Ammonia concentrations were lowest in the RG lysimeter, medium in the outflow and highest in the inflow at MLA, suggesting continual removal with depth (Table 4). The RG and BG wells at Hugo had similar concentrations of NH_3, indicating that the groundwater had not been affected by the rain garden. At Woodbury, NH_3 was lower in the overflow and RG well compared to the inflow; however, the BG well had the lowest concentration. Generally, TKN followed the same pattern as NH_3, suggesting that organic nitrogen was also effectively reduced from the inflow.

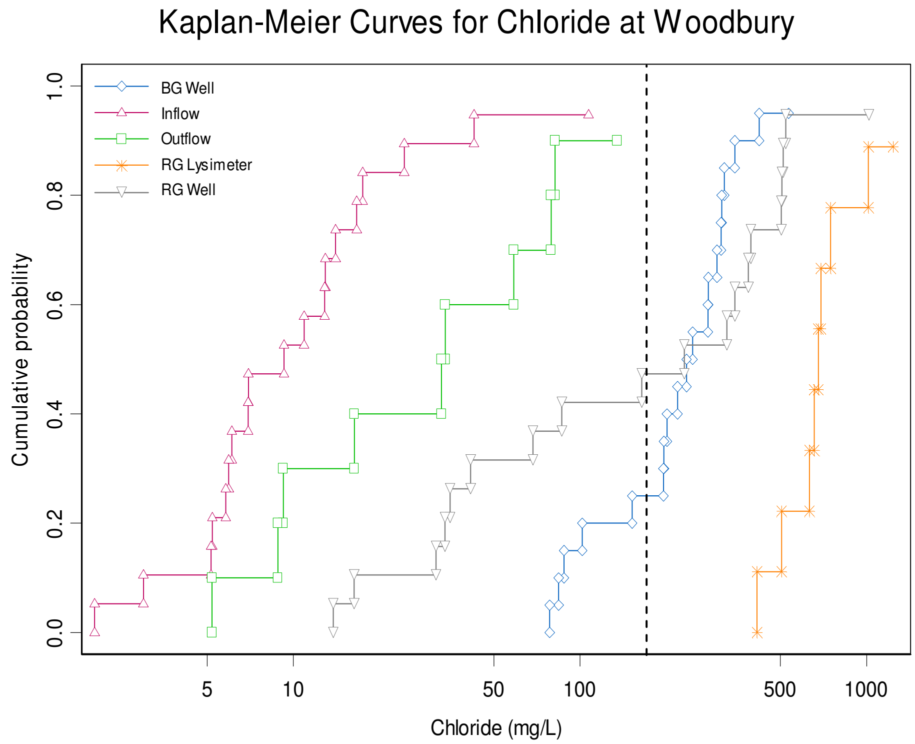

Figure 1. Distribution of chloride concentration in samples collected during the growing seasons of 2003-2008 from inflow, outflow, rain garden (RG) lysimeter, rain garden (RG) well, and background (BG) well at Woodbury, Minnesota. Dashed line indicates USEPA 250 mg/L standard.

Table 5. Median concentration of ammonia (NH_3) and total kjeldahl nitrogen (TKN) in the inflow, outflow/overflow, rain garden (RG) lysimeter, rain garden (RG) well, and background (BG) well for samples collected during the growing seasons of 2003-2008 at Minnesota Landscape Arboretum (MLA), Hugo and Woodbury, Minnesota.

	NH_3 (mg/L as N)			TKN (mg/L as N)		
	MLA	Hugo	Woodbury	MLA	Hugo	Woodbury
Inflow	0.59	0.22	0.69	3.19	1.18	3.49
Overflow	0.01*	NA	0.01*	0.38*	NA	0.75
RG Lysimeter	<0.005*	NA	0.027*	0.23*	NA	0.52*
RG Well	NA	<0.005*	0.048*	NA	0.13*	0.29*
BG Well	NA	<0.005*	<0.005*	NA	0.14	0.11

** = significantly different from inflow at the 95% confidence level;*
NA = no samples

Nitrite concentrations were significantly lower than the inflow at all locations. Although the RG lysimeter was not significantly different from the inflow at Woodbury, approximately half of the samples had higher concentrations of NO_2/NO_3 compared to the rest of the samples collected at this site (Figure 2). Despite the apparent production of NO_2/NO_3 at shallow depth, the RG well contained significantly lower concentrations of NO_2/NO_3 compared to the inflow suggesting that NO_2/NO_3 removal was occurring lower in the soil profile. Furthermore, Woodbury actually appeared to improve NO_2/NO_3 concentration in the groundwater because the RG well median concentration was below the detection limit, and significantly lower compared to the BG well (Table 5).

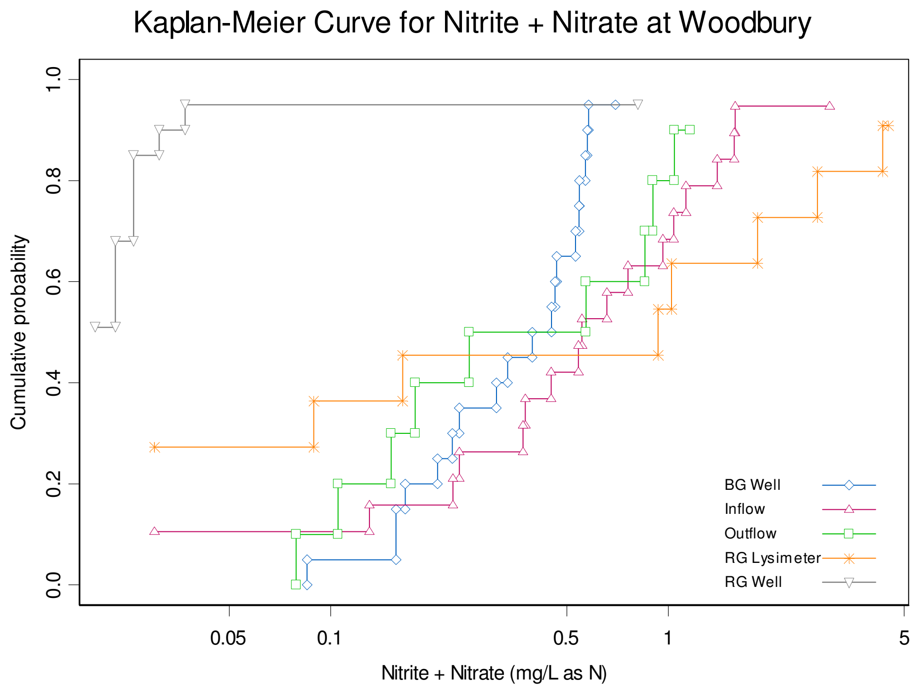

Figure 2. Kaplan-Meier curves of nitrite/nitrate concentration in samples collected during the growing seasons of 2003-2008 from background (BG) well, inflow, outflow, rain garden (RG) lysimeter, and rain garden (RG) well at Woodbury, Minnesota.

The highest median concentration of NO_2/NO_3 among the three sites was observed in the Hugo BG well (Table 5). Although there didn't appear to be any significant removal of NO_2/NO_3 within the rain garden, the inflow and RG well median concentrations were lower than the BG well. The median concentrations of NO_2/NO_3 at all sites were lower than the USEPA drinking water standard of 10 mg/L (USEPA 2009). The BG well at Hugo contained the highest concentrations of NO_2/NO_3 of all the sites and reached approximately half of the USEPA standard (Figure 3).

Table 6. Median concentration of nitrite (NO_2) and nitrite + nitrate (NO_2/NO_3) in the inflow, outflow, rain garden (RG) lysimeter, rain garden (RG) well and background (BG) well for samples collected during the growing seasons of 2003-2008 at Minnesota Landscape Arboretum (MLA), Hugo, and Woodbury, Minnesota.

	NO_2 (mg/L as N)			NO_2/NO_3 (mg/L as N)		
	MLA	Hugo	Woodbury	MLA	Hugo	Woodbury
Inflow	0.04	0.03	0.05	0.62	0.43	0.55
Overflow	0.001*	NA	0.01*	0.06*	NA	0.41
RG Lysimeter	<0.001*	NA	<0.001*	0.05*	NA	0.93
RG Well	NA	<0.001*	<0.001*	NA	0.6	<0.02*
BG Well	NA	<0.001*	<0.001*	NA	2.09*	0.42**

** = significantly different from inflow at the 95% confidence level;*
*** = significantly different from the RG well at the 95% confidence level;*
NA = no samples.

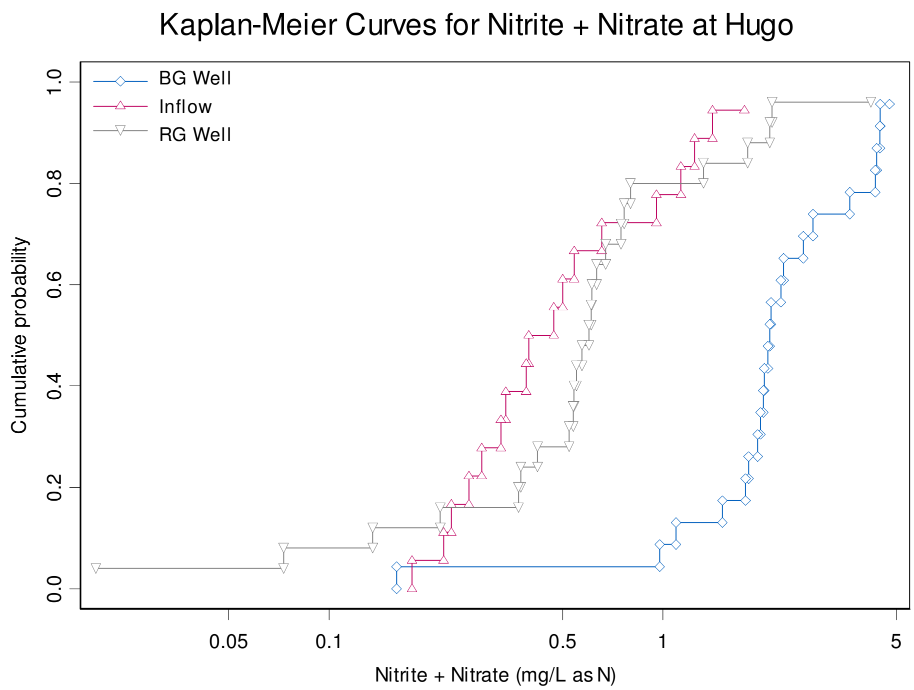

Figure 3. Kaplan-Meier curves depicting data distributions for nitrite/nitrate concentration in samples collected during the growing seasons of 2003-2008 from the background (BG) well, inflow, and rain garden (RG) well at Hugo, MN.

Phosphorus

Total phosphorus concentrations were lower in lysimeters and RG wells compared to inflow at all sites where samples were collected (Table 6). Although TP concentrations were lower in the RG well compared to the inflow, there was no significant difference between the RG and BG wells at Hugo and Woodbury. Dissolved phosphorus median concentrations in lysimeter, outflow, and inflow samples were very similar at MLA (Table 6). Rain garden wells at Hugo and Woodbury contained lower DP concentrations compared to the inflow. Overflow and lysimeter samples at Woodbury also contained lower DP concentrations. The groundwater appears to have been unaffected at Hugo and Woodbury as there was no significant difference between the RG and BG wells at these two sites.

Table 7. Median concentration of total phosphorus (TP) and dissolved phosphorus (DP) in the inflow, outflow, rain garden (RG) lysimeter, rain garden (RG) well, and background (BG) well for samples collected during the growing seasons of 2003-2008 at Minnesota Landscape Arboretum (MLA), Hugo and Woodbury, Minnesota.

	TP (mg/L as P)			DP (mg/L as P)		
	MLA	Hugo	Woodbury	MLA	Hugo	Woodbury
Inflow	0.29	0.43	0.42	0.03	0.22	0.23
Outflow/Overflow	0.04*	NA	0.13*	0.04	NA	0.10*
RG Lysimeter	0.04*	NA	0.05*	0.04	0.08	0.03*
RG Well	NA	0.06*	0.03*	NA	0.04*	0.02*
BG Well	NA	0.05	0.04	NA	0.05	0.03

** = significantly different from inflow at the 95% confidence level*

DISCUSSION

Chloride

Although the chloride results were confounded by irrigation at MLA and direct road runoff at Woodbury, valuable insight into the fate of chloride within these rain gardens has still been gained. The MLA and Woodbury sites appear to be holding some amount of chloride in the upper soil layers and slowly releasing it to the groundwater. The high concentration of chloride in lysimeter samples in the current study corresponds well with the results of Li and Davis (2009) who reported an export of chloride from a rain garden in Maryland. Despite the high chloride concentrations in the lysimeter, upon further examination of the groundwater data, it does not appear that a net export occurred as a result of the presence of the rain garden.

Although there are no groundwater samples to reference from MLA, behavior of chloride at this site appears to behave similarly to that of Woodbury. It might be expected that the presence of the drain tile would result in faster removal of chloride from the system compared to a rain garden without a drain tile since this type of design is intended to move water off site quickly. Similar to artificially drained agriculture lands that export nitrate to receiving waters (Jaynes et al. 2001; Dinnes et al. 2002), rain gardens with drain tiles may lead to the same source of pollution with respect to chloride. More runoff is being concentrated into a smaller area than normal, concentrating the mass of chloride, resulting in greater concentrations being infiltrated into the soil profile and, eventually receiving waters, or in cases without drain tiles the groundwater. Despite the potential for the drain tile to export chloride, the lysimeter at MLA contained the highest concentration of chloride at the site indicating that chloride was being leached to deeper depths. While the drain tile was installed to promote optimal infiltration, a sandy media was simultaneously added to the design for the same purpose. This could have important implications for rain garden designs that include drain tiles in which most of the water is assumed to be moved off site. Depending on the soil and geology, groundwater contamination may still be an issue.

Hugo appears to be the only site not contributing saline recharge to local groundwater supplies. This could be a result of the combination of low chloride inputs and a dilution effect. In addition to receiving direct runoff from the adjacent parking lot, the rain garden receives direct roof runoff from the City Hall via underground rain gutters. The roof runoff would not be expected to contain much, if any, chloride and therefore would serve as a source of water to dilute the incoming chloride load from the parking lot and eventually the groundwater below. While this process may not reduce the total mass of chloride entering the groundwater, it does reduce the concentration. Since EPA standards are based on concentrations this could help in remaining in compliance with the secondary standard.

A recent USGS report investigated shallow and drinking water wells in the Northern United States and found approximately 2% contained chloride concentrations above the USEPA standard (Mullaney et al. 2009). Statistical analysis of the chloride data in the Woodbury groundwater indicated that the rain garden provided no benefit in terms of chloride removal; however, a comparison of the samples to the standard showed that the rain garden is providing some dilution of the chloride because fewer of the rain garden well samples exceeded the standard.

In addition to the water quality problems chloride exports will have on receiving waters, high chloride concentrations may also adversely affect the vegetation of a rain garden. High concentrations of chloride may result in lower photosynthetic rates (Parida and Das 2005), affecting the aesthetics of the feature by producing stunted or discolored vegetation. Additionally, the ability to scavenge nutrients from the soil water may be inhibited (Flores et al. 2000).

Nitrogen

The ability of a rain garden to remove nitrogen has been linked to soil properties, abundance of oxygen, and presence of organic materials (Jetten 2001; Dietz and Clausen 2005; Davis et al. 2006; Dietz and Clausen 2006). Lower rates of nitrogen removal have been reported for sandy soils (Ho et al. 1992) due to faster infiltration rates and lower ion exchange capacity. Aside from isolated incidents of nitrate export, the three sites in this study appeared to effectively remove nitrogen from runoff despite the sandy nature of the respective soils.

Ammonia was efficiently removed from the inflow at all sites; however, while the groundwater at Hugo appeared to be relatively unaffected, the Woodbury rain garden well contained higher ammonia concentrations compared to background concentrations. At Hugo, where similar nutrient concentrations were observed between the RG and BG wells, the wells are located in similar soil types. As a result, we would expect similar chemical processes to occur within the soil profile at both locations. At Woodbury, where the rain garden appeared to add ammonia to the groundwater, there is a difference in soil type between the well locations. The soil surrounding the BG well is characterized as a Rosholt sandy loam by the National Resource Conservation Service, whereas the soil in the rain garden consists of a sandy back fill. More geochemical processes would be expected to occur in a sandy loam compared to sand due to the physico-chemical properties of the soil, which would typically contain more ion exchange sites due to higher amounts of surface area on soil particles.

It is hypothesized that the main ammonia removal process in the rain gardens was ammonia oxidation to nitrite. Additionally, since none of the sites appeared to have less than optimal infiltration rates throughout the study, it can be assumed that there was enough oxygen in the soil to allow oxidative processes to occur, converting ammonia to nitrite. Ammonia oxidation could result in the production of byproducts that may negatively impact the environment including: nitrite, nitrous oxide, and hydrogen ions; however, there did not appear to be any excessive exports of nitrite (or nitrate) and intermittent measurements of pH taken throughout the study (data not shown) revealed circum-neutral pH values.

Due to the sandy nature of the soils at these sites and results from previous research, it was expected that there would be little to no nitrate removal within the rain gardens. Overflow at Hugo was never observed by field staff and, therefore, it can be assumed that the site has high infiltration rates inhibiting the formation of an anaerobic saturated zone that would be required for denitrification to occur. The fact that the groundwater and inflow NO_2/NO_3 concentrations were similar supports that theory because it appears as if nothing is happening to this nutrient as the water travels through the feature. Surprisingly, lower NO_2/NO_3 concentrations were found in the vadose zone and groundwater compared to inflow at MLA and Woodbury. While NO_2/NO_3 was lower in the groundwater at Woodbury, there appeared to be NO_2/NO_3 production in the upper layers of the soil consistent with the findings of Davis et al. (2006). This could be expected as nitrification typically occurs in the top soil layers. These findings also indicate that a proper environment exists at depth to promote denitrification, removing nitrogen before it reaches the groundwater. More importantly, the groundwater directly beneath the Hugo and Woodbury rain gardens contained lower NO_2/NO_3 concentrations compared to the BG wells. This could simply represent lower loading of NO_2/NO_3 to the feature as opposed to the surrounding area, but does indicate that NO_2/NO_3 is not being added to the groundwater as a result of the presence of the rain garden.

One common source of NO_3 in groundwater is fertilizer. None of the sites in this study were heavily fertilized, which would reduce the amount of NO_3 entering the systems. The one exception is the BG well at Hugo where relatively high concentrations were typically found. This well is located adjacent to an athletic field where the city would be likely to fertilize in an effort to maintain the aesthetics of the field. Another common source of nitrate to ground water is wastewater. As none of the sites are close to wastewater treatment plants, it is not believed that this would be a major source of nitrate either. These observations explain the low concentrations of NO_3 found in the samples collected throughout this study.

Phosphorus

While phosphorus was removed from inflow, the rain gardens did not appear to provide any additional removal compared to the surrounding landscape. Due to the similar phosphorus concentrations between the RG and BG wells at Hugo and Woodbury, it can be assumed that the surrounding landscape is removing phosphorus just as efficiently as the rain gardens are. Turf grass landscapes exhibit similar patterns in terms of runoff abatement. The grass will slow the runoff to a certain extent allowing particles to settle out, thereby removing sediments and phosphorus bound to them (Steinke et al. 2007). Additionally, particulate phosphorus has been found to settle out within the top 5 cm of rain gardens (Hsieh and Davis 2005; Li and Davis 2008) which can be expected of turf grass landscapes also.

While it appears that MLA did not remove any dissolved phosphorus from the inflow, we cannot totally conclude that DP is not being removed. Removals based on concentration data often underestimate nutrient removal compared with those calculations taking flow measurements into account. As this study was purely qualitative, load calculations were beyond the scope of the project; however, assuming less water left MLA then entered it, we can assume that there was in fact a mass reduction. Another explanation for the apparent lack of removal could be that the concentration of dissolved phosphorus entering the system was at some lower threshold that prevented any further removal of the nutrient. In comparison to the other sites, the inflow concentration of dissolved phosphorus at MLA is much lower and more closely reflects concentrations in the groundwater.

CONCLUSION

This study provides good evidence of reduced nutrient concentrations in storm water runoff leaving three rain gardens via overflow or underground pathways. While insufficient data points prohibited exploration of trends and specifically, changes in rain garden performance over time, we can conclude that during the first 6 years of operation these three rain gardens performed relatively well by reducing the concentration of some nutrients, such as nitrogen and total phosphorus.

Chloride contamination of groundwater continues to pose a threat to the health of local aquifers since it appears to be continually leached through the unsaturated zone throughout the growing season. While there is no immediate health threat from chloride, continual loading over time could present a problem.

Although groundwater data were available from only two of the sites, it appears these rain gardens are not adversely affecting the local groundwater supply. While there may not always be a reduction in nitrogen or phosphorus concentration in the RG lysimeters, nitrogen and phosphorus concentration in the RG wells were often similar to the BG wells. In studies that have reported nitrogen or phosphorus exports, the exports have typically occurred at shallow depths. The results from this study indicate that although there may be exports at shallow depths, the nutrients are being removed before the recharge water reaches the groundwater.

Further field studies need to be conducted measuring total precipitation, flow, and nutrient mass balance to help complete our understanding of how well rain gardens function. Concentration data only provide a basic understanding of how effective rain gardens are at removing pollutants from storm water. This study provides developers with valuable evidence of the performance of rain gardens when exposed to the environment and all of its elements. The impact that rain gardens have on local groundwater supplies has not been fully explored; however, the evidence provided in this article suggests that there are no negative impacts to the groundwater directly resulting from these three rain gardens.

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