EMC Monitoring in Support of Pollutant Load Modeling

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1.0 Executive Summary

In the United States, pollution from stormwater runoff is regulated under the National Pollutant Discharge Elimination System (NPDES). In urban areas this stormwater runoff is often conveyed through Municipal Separate Storm Sewer Systems (MS4s). In order to effectively reduce the discharge of various pollutants through stormwater discharge a variety of best management practices (BMPs) have been developed. However there are many site specific factors that influence the effectiveness of individual BMPs, some of which are not fully understood (Gilroy and McCuen 2009). Given these issues, it is important that stormwater managers evaluate the effectiveness of their BMPs in order to properly represent their impact in the pollutant loading models by developing regionally appropriate model coefficients.

Grassed swales (swales) are a common BMP due to their relatively simple and cost effective nature. Swales are effective in reducing pollutant loads via reduction in contaminant concentration and by reducing total effluent volume through infiltration in the sediment. In Sarasota County, Florida (the County) swale drainage is a common feature in some residential neighborhoods. The County has developed a pollutant loading model which does not currently account for pollutant reductions due to swale drainage. In order to gain a better understanding of the functional pollutant reductions provided by these existing swales, this study was designed to compare stormwater runoff (both quality and quantity) in neighborhoods drained by swales to runoff in similar neighborhoods with traditional curb and gutter drainage.

The concentrations of most of the measured analytes were significantly reduced at swale sites relative to curb and gutter sites. Additionally the runoff coefficients were significantly lower at swale sites relative to curb and gutter sites. The greatest surficial runoff load reductions occurred for particulate pollutants such as lead, total suspended solids, and total Kjeldahl nitrogen. The concentrations of dissolved constituents such as nitrate+nitrite nitrogen and ortho-phosphorus were not significantly reduced at swale sites, however their loads in surficial runoff were greatly reduced due to the reduction if runoff volume.

The ultimate test of the functionality of the BMP is in its capacity to reduce loading. The two pathways to load reduction in stormwater are through reduction in pollutant concentration, and reduction in discharge. In general the swales monitored in this study are effective at reducing loads through both pathways, generating substantial load reductions of many regulated pollutants, including nutrients, metals and total suspended solids. The estimated load reduction of TSS from surficial runoff in this study is within the range observed in other studies of swales (Barrett et al 1998), and exceeds the EPA management measures in the Coastal Zone Act Reauthorization Amendments of 1990, which specifies an 80% target for removal of TSS. The impact of swale drainage on loading may vary on a site-specific basis, as there are a variety of features that will impact the efficacy of the swale drain feature as a BMP. The use of these results should be governed by that understanding. However, these results are consistent with findings in other studies, and likely represent a reasonable estimate of the overall impact of swale drainage in the region. It is therefore very rational to apply these pollutant reductions to the existing model in order to account for the impact of the swale BMP.

2.0 Introduction

In the United States, pollution from stormwater runoff is regulated under the National Pollutant Discharge Elimination System (NPDES). In urban areas this stormwater runoff is often conveyed through Municipal Separate Storm Sewer Systems (MS4s). In order to discharge stormwater runoff, MS4 operators are required to obtain an NPDES permit and to develop a stormwater management program. In order to facilitate a better understanding of the sources and destinations of stormwater runoff local stormwater management programs often generate pollutant loading models. When regulatory agencies find a receiving surface waterbody to be impaired based on its designated use, it may be necessary to reduce the pollutant discharges to that waterbody. In order to effectively reduce the discharge of various pollutants through stormwater discharge a variety of best management practices (BMPs) have been developed.

In many locations BMPs are adopted but the impact on stormwater runoff for the BMPs is not monitored. In studies where BMPs have been evaluated, they have been found to be effective in attenuating flow from small storms (Williams and Wise 2006), and in reducing overall runoff coefficient and decreasing peak discharge. However there are many site specific factors that influence the effectiveness of individual BMPs, all of which are not fully understood (Gilroy and McCuen 2009). Given these issues, it is important that stormwater managers evaluate the effectiveness of their BMPs in order to properly represent their impact in the pollutant loading models by developing regionally appropriate model coefficients.

Grassed swales (swales) are a common BMP, due to their relatively simple and cost effective nature. Swales are effective in reducing pollutant loads via reduction in contaminant concentration and by reducing total volume through infiltration in the sediment. Swales have been shown to be particularly effective in reducing particulate contaminants such as total suspended solids (TSS) and various other common pollutants (Han et al 2005, Deletic and Fletcher 2006), with reported reductions in TSS of up to 97%, and a wide range of reductions for other contaminants (Deletic 2005). In addition to reductions in pollutant concentrations, swales also provide flow attenuation and aquifer recharge. Yang and Li (2010) found that after development, runoff from a development drained by grassed swales increased by 26%, while runoff from a development drained by traditional curb and gutter increased by 110%. In general, the variability of change in pollutant concentrations, coupled with the variability in stormwater attenuation, can lead to a large range of (site and event specific) variability in overall pollutant loading.

In Sarasota County, Florida, swale drainage is a common feature in some residential neighborhoods. The County has developed a pollutant loading model which does not currently account for pollutant reductions due to swale drainage. In order to gain a better understanding of the functional pollutant reductions provided by these existing swales, this study was designed to compare stormwater runoff (both quality and quantity) in neighborhoods drained by swales to runoff in similar neighborhoods with traditional curb and gutter drainage. The results of this study will be used to further develop the County pollutant loading model.

3.0 Methods

3.1. Site Selection and Monitoring

Site selection was considered critical to study success. All sites selected fell within the County's Phillippi Creek watershed which is a fully developed region of the county. Extensive effort was expended to ensure that the selected sites were as close to "all else equal" as was possible, and that the physical characteristics of the sites were suitable for the sampling equipment. Five sites were selected, three sites with swale drainage and two sites with curb and gutter drainage. Stormwater runoff quantity was measured at all five sites (Figure 1), water quality was measured at all sites except the Swale 3 site. Site characteristics are listed in Table 1.

Figure 1. Aerial view of the sampling site locations

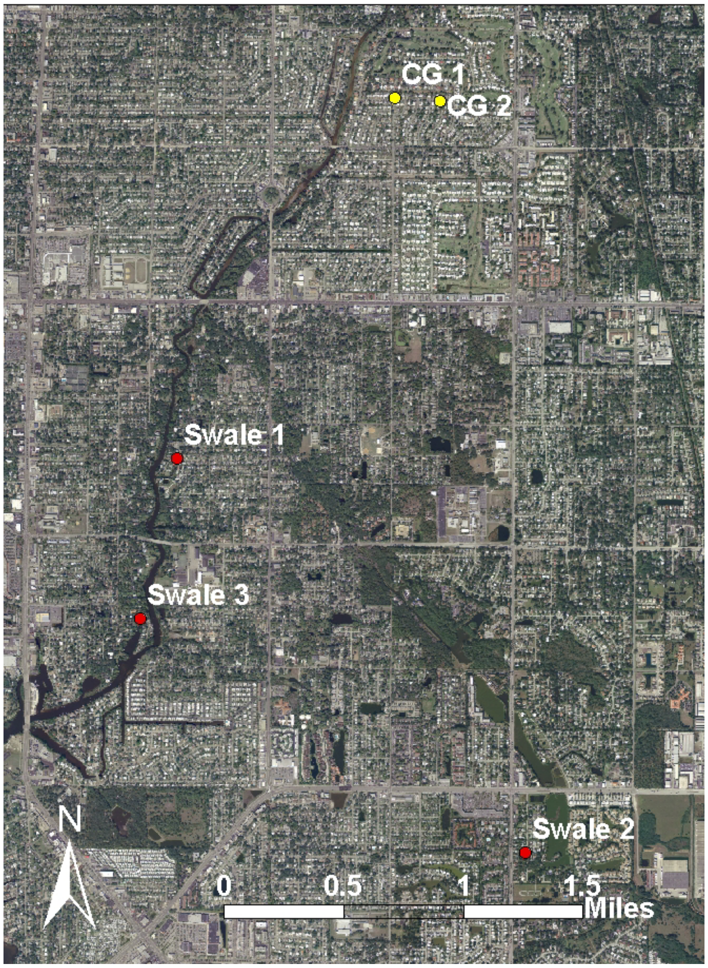

Table 1. Characteristics of stormwater sampling locations

StationID	Street Name	Site Type	Drainage Area (Acres)	Impervious Area (Acres)	Percent Impervious	Max Difference in Elevation (Ft)
C&G 1	Dawson	Curb and Gutter	3.84	1.67	43%	4.6
C&G 2	Darwin	Curb and Gutter	1.74	0.75	43%	4.4
Swale 1	Nassau	Swale	6.18	2.73	44%	18.5
Swale 2	Mirror Lake	Swale	0.99	0.27	27%	3.2
Swale 3	Admiral	Swale	2.69	0.7	26%	19.3

After sampling locations were selected, water quality and quantity were monitored using ISCO Avalanche model portable refrigerated samplers equipped with bubbler flow modules. The equipment was installed in outdoor storage bins adjacent to access points to drainage pipes. Curb and gutter site configurations consisted of placing the bubbler sensor and grab sample tubing in the downstream pipes leading out of the stormwater junction boxes. Swale site configuration consisted of placing the bubbler sensor and grab sample tubing in a pipe at the downstream terminus of a swale drainage area. The selected sites utilized both circular and elliptical pipes. Flows were calculated for the circular pipes using Manning’s equation, while flows for the elliptical pipes were calculated per Design Data 37 (Partial Flow Conditions Elliptical Concrete Pipe) of the American Concrete Pipe Association.

The installed samplers were programmed to collect flow weighted composite samples after a rainfall amount of 0.2 inch or greater in an hour or less. The flow weighting was programmed on a site-specific basis, and was adjusted over the course of the project as hydrologic conditions changed. The samplers composited the samples into a glass jar on a flow weighted basis and cooled them to 3 °C. All samples were handled in accordance with the relevant Florida Department of Environmental Protection (DEP) standard operating procedures (SOPs). The samplers also collected rainfall and flow measurements on a five minute interval.

Water quality monitoring was conducted in accordance with all pertinent DEP procedures and laboratory analyses were performed by Benchmark Enviroanalytical, a NELAC certified laboratory. The analytes selected for monitoring are listed in Table 2.

Table 2. Analytes selected for monitoring

Analyte	Method	MDL	Units
Ammonia Nitrogen	SM4500-NH3C	0.005	mg/l
Bicarbonate Alkalinity	SM2320B	0.594	mg/l
Biochemical Oxygen Demand	SM5210B	0.5	mg/l
Carbonate Alkalinity	SM2320B	0.594	mg/l
Lead	SM3113B	0.67	Ug/l
Nitrate + Nitrite as N	353.2	0.004	mg/l
Ortho-Phosphorus as P	365.3	0.002	mg/l
Total Alkalinity	SM2320B	0.594	mg/l
Total Kjeldahl Nitrogen as N	351.2	0.05	mg/l
Total Nitrogen as N	353+351	0.05	mg/l
Total Phosphorus as P	365.3	0.008	mg/l
Total Suspended Solids	SM2540D	0.57	mg/l
Zinc	200.7	1.4	ug/l

3.2. Data Management and QC

Water quality data were delivered by Benchmark Enviroanalytical Laboratory in an electronic format and stored in an Access database. Data management and quality control processes were performed using Microsoft Access and the SAS 9.2 software package. Quality control on these data involved qualifying data for known conditions that affected flow measurements (such as displaced sensors), and identification of data that were the result of staff maintenance on the equipment. Individual rain events were identified by a visual review of the data. Events were limited to coincident rainfall and discharge, thus rain events which did not generate discharge were not identified as events. At swale sites 1 and 3 there was intermittent but substantial baseflow. In order to separate surficial runoff from baseflow the rate of baseflow at the beginning and end of a discharge event was noted and a linear interpolation was performed to fill the baseflow data between those points. Any flow in excess of the baseflow was considered as surficial runoff.

3.3. Data Analysis

Data analyses were performed primarily using the SAS 9.2 software package. In addition to SAS, the Statgraphics Centurion XV v.15.0.08 software package was used for some data analysis tasks.

Runoff coefficients (c) were calculated for each rain event at each site by the following equation:

$$c=(\text{Discharge}_{\text{cubic feet}})/(\text{Rain}_{\text{feet}} * \text{Drainage Area}_{\text{square feet}})$$

The per event runoff coefficients were not normally distributed and the distribution did not improve with natural log transformation. Therefore, the Wilcoxon signed-rank test (Proc NPAR1WAY in SAS) was applied to the data rather than the t-test. As evidenced in Table 1, there is large variability in percent impervious between some of the sites. In order to adjust for these differences, the runoff coefficient for each event was divided by the site specific percent impervious area, to create a modified runoff coefficient. This adjustment was made to improve the validity of inter-site runoff comparison. For example, if there are two sites both having a runoff coefficient of 0.4. At Site 1 the percent impervious is 0.5 (50%) and at Site 2 it is 0.3 (30%). The modified runoff coefficients would be 0.8 at Site 1 and 1.3 at Site 2. In this analysis it is clear that, impervious area aside, there was substantially higher runoff from Site 2 than Site 1.

Water quality results were analyzed by comparing the grouped swales sites versus the grouped curb and gutter sites. The raw data were not normally distributed, however, natural log transformation of the data improved the data distribution to approximately normal for most analytes. T-tests were used in most cases (Satterthwaite method for unequal variances). In the cases where the data were not normally distributed, the Wilcoxon signed-rank test was used.

Univariate regressions (Discharge=Rainfall) were performed (for each site and site type) using the REG procedure in SAS to test the measured runoff versus summed lag periods for rainfall. Lag periods tested were in five minute intervals up to 30 minutes, followed by 15 minute intervals to one hour, followed by one hour intervals to one day. Linear regressions (Area normalized runoff=Lag period rainfall) were tested for each interval and the best fit (highest r^2) model was selected for each site. Multivariate regressions were also performed, selecting the best fit rainfall term from the univariate regression and the independent variables percent impervious area, groundwater level, temperature, and elevation change within the drainage area.

Stepwise multivariate regressions were performed on the data grouped by site type using the “stepwise” selection from the REG procedure in SAS. The dependent variable was area normalized discharge and the independent variables were rainfall (best fit lag that was previously selected from the univariate regression), percent impervious area, groundwater level (USGS Station 270959082203003), temperature (as a proxy for evapotranspiration) and maximum elevation change within the drainage area. Variables were allowed entry into the model if $p < 0.05$, and were retained based on the same criterion.

3.4. Pollutant Loads

The estimated annual total pollutant loads (including pollutant loads in baseflow) were generated using a rainfall factor that adjusted rainfall at each monitoring site to the 52.8 inch annual mean for Sarasota County (determined from SWFWMD data for Sarasota County). The rainfall factor was used to adjust the runoff observed at each site during the monitoring period to an average annual runoff. For example if 40 inches of rain fell at a site then the factor would be 1.32 (52.8/40). This factor was then applied to the surficial runoff and baseflow volumes at each site to estimate the discharge that would have occurred during a year with average annual rainfall. The mean concentration of each analyte over the study period at each site was applied to the normalized discharge figures to calculate the total load due to surficial runoff and due to baseflow. As no effort was made to generate separate EMC values for surficial runoff and baseflow the same EMC value was used for both types of discharge. The total estimated load is the combined load due to surficial runoff and baseflow.

3.5. Regional Conditions

In order to put the study conditions in the appropriate context relative to long term hydrologic patterns, rainfall data were downloaded from the Southwest Florida Water Management District (SWFWMD) website (http://www.swfwmd.state.fl.us/data/wmdbweb/rainfall_data_summaries.php), and surficial groundwater data were downloaded from the USGS website (http://waterdata.usgs.gov/fl/nwis/dv/?site_no=270959082203003&referred_module=gw). The rainfall data represent countywide composite monthly rainfall totals beginning in 1915. Rainfall data for the period of record were compared to study period values. The groundwater data are available in raw daily form for the site, which is located approximately 15.5 miles southeast of Sarasota (Lat 27°09'59", Long 82°20'30") and the period of record goes back to July 1981. Data from 1982 and later were used in the analysis of long term statistics.

4.0 Results

4.1. Regional Conditions

The results of the comparison of study period rainfall to historic rainfall (Table 3) indicate that the rainfall during the study period was "average" in terms of the historical record in that it was near the long term median value. During the March-September 2010 study period 38.99 inches of rainfall was the composite total for Sarasota County, compared to the long term March-September mean total of 40.65 inches and the long term median of 38.63 inches. More of the rain fell earlier in the study period than would be normal, with 7.21 inches falling in March compared to a long term mean rainfall of 2.96 inches.

Table 3. Comparison of long term (1915-2009) rainfall with study period (highlighted)

Month	Mean (inches)	Maximum (inches)	Median (inches)	Minimum (inches)	2010 Rainfall (inches)
Jan	2.28	8.09	1.82	0	2.76
Feb	2.63	9.29	2.35	0.01	2.4
Mar	2.96	10.14	2.25	0.13	7.21
Apr	2.43	10.52	1.99	0	2.93
May	3.05	10.11	2.55	0.2	1.56
Jun	7.61	22.45	6.94	2.22	5.69
Jul	8.25	16.05	7.95	2.45	5.7
Aug	8.59	19.08	7.73	2.37	11.22
Sep	7.75	18.63	7.25	3.27	4.68
Oct	3.32	10.9	2.42	0	
Nov	1.86	6.71	1.39	0	
Dec	2.02	9.29	1.49	0	

Surficial water levels during the beginning of the study were unusually high, with March and April levels being near the historical high levels (Table 4). Water level dropped substantially from April through June before increasing as rains increased near average in the wet summer months. Based on the regional rainfall and nearby groundwater levels the study period appears to be a near normal period. The outlier would be the high groundwater levels at the beginning of the study, which may have led to less infiltration than would normally be expected to occur.

Table 4. Comparison of long term (1982-2009) groundwater levels with study period (highlighted) at USGS site 270959082203003

Month	Mean (ft)	Maximum (ft)	Median (ft)	Minimum (ft)	2010 Elevation (ft)
Jan	16.95	18.77	16.94	14.79	18.73
Feb	16.84	19.05	17.06	14.31	18.66
Mar	16.82	19.07	16.98	14.06	18.67
Apr	16.52	18.42	16.43	13.98	18.36
May	15.84	18.41	15.52	14.18	17.16
Jun	16.49	19.11	16.44	14.06	16.13
Jul	17.91	18.97	18.3	15.7	18.38
Aug	18.5	19.34	18.69	16.95	18.99
Sep	18.58	19.23	18.79	17.28	18.55
Oct	17.8	19.03	17.77	16.81	
Nov	17.26	18.91	17.04	15.84	
Dec	17.01	19.03	16.91	15.26	

4.2. Water Quality

Sampling was conducted from March 2010 through September 2010. After pooling the data by site type (swale or curb and gutter), there were 19 samples at swale locations and 23 samples at curb and gutter locations. Carbonate alkalinity was reported below the detection level in every sample, and is not discussed further. Total alkalinity is the sum of bicarbonate and carbonate alkalinity. In this case, it is equivalent to bicarbonate alkalinity and was not analyzed separately.

4.3. Bicarbonate Alkalinity

A t-test was applied to the natural log transformed bicarbonate alkalinity data grouped by site type. Bicarbonate alkalinity was significantly higher at the swale sites than at the curb and gutter sites (p=0.03). This likely indicates the influence of baseflow at the swale sites. Mean bicarbonate alkalinity was 55% lower at curb and gutter sites than at swale sites (Table 3).

Table 3. Summary statistics for Bicarbonate Alkalinity

Parameter	Units	Statistic	CG	Swale
Bicarbonate Alkalinity (CaCO3)	mg/l	Mean	18.72	41.68
Bicarbonate Alkalinity (CaCO3)	mg/l	Standard Deviation	6.36	39.25
Bicarbonate Alkalinity (CaCO3)	mg/l	Median	17.00	21.50
Bicarbonate Alkalinity (CaCO3)	mg/l	Maximum	32.00	148.00
Bicarbonate Alkalinity (CaCO3)	mg/l	Minimum	10.00	9.50

4.4. Ammonia Nitrogen

A t-test analysis was applied to the natural log transformed ammonia nitrogen data grouped by site type. Ammonia nitrogen was significantly lower at swale sites compared to curb and gutter sites (p=.003). The difference in the data populations is readily apparent in the summary statistics (Table 4). On average, the mean concentration indicates that ammonia nitrogen was 73% lower at swale sites than at curb and gutter sites. The median ammonia nitrogen value was 61% lower at swale sites than curb and gutter sites.

Table 4. Summary statistics for Ammonia Nitrogen

Parameter	Units	Statistic	CG	Swale
Ammonia Nitrogen	mg/l	Mean	0.45	0.12
Ammonia Nitrogen	mg/l	Standard Deviation	0.36	0.07
Ammonia Nitrogen	mg/l	Median	0.31	0.12
Ammonia Nitrogen	mg/l	Maximum	1.22	0.30
Ammonia Nitrogen	mg/l	Minimum	0.01	0.01

4.5. Total Kjeldahl Nitrogen

A t-test was applied to the natural log transformed total Kjeldahl nitrogen (TKN) data grouped by site type. Total kjeldahl nitrogen was significantly lower at swale sites than at curb and gutter sites ($p<0.0001$). Mean TKN (Table 5) was 72% lower at swale sites, and median TKN was 70% lower. The maximum TKN value at the swale sites was 48% lower than the average value at curb and gutter sites.

Table 5. Summary statistics for Total Kjeldahl Nitrogen

Parameter	Units	Statistic	CG	Swale
Total Kjeldahl Nitrogen	mg/l	Mean	5.62	1.55
Total Kjeldahl Nitrogen	mg/l	Standard Deviation	4.18	0.61
Total Kjeldahl Nitrogen	mg/l	Median	4.97	1.51
Total Kjeldahl Nitrogen	mg/l	Maximum	14.70	2.90
Total Kjeldahl Nitrogen	mg/l	Minimum	0.34	0.53

4.6. Nitrate + Nitrite as N

A Wilcoxon signed-rank test was applied to the untransformed nitrate + nitrite (NOx) data grouped by site type. There was no significant difference (p=.409) between NOx concentrations at swale and curb and gutter sites. The mean and median values (Table 6) are slightly lower at swale locations versus curb and gutter locations, however the overall data values are quite similar between site types (Figure 2).

Figure 2. Boxplots of Nitrate + Nitrite as N grouped by site type

Table 6. Summary statistics for Nitrate + Nitrite as N

Parameter	Units	Statistic	CG	Swale
Nitrate + Nitrite as N	mg/l	Mean	0.55	0.43
Nitrate + Nitrite as N	mg/l	Standard Deviation	0.45	0.35
Nitrate + Nitrite as N	mg/l	Median	0.42	0.33
Nitrate + Nitrite as N	mg/l	Maximum	1.80	1.62
Nitrate + Nitrite as N	mg/l	Minimum	0.004	0.066

4.7. Total Nitrogen

A t-test was applied to the natural log transformed total nitrogen (TN) data grouped by site type. Total nitrogen was significantly lower at swale sites than at curb and gutter sites (p=0.0002). This is logical, as the majority of the TN was comprised of TKN and the large differences in TKN between the swale and curb and gutter sites are documented previously. Mean TN was 68% lower at swale sites than curb and gutter sites (Table 7).

Figure 3. Boxplots of total nitrogen grouped by site

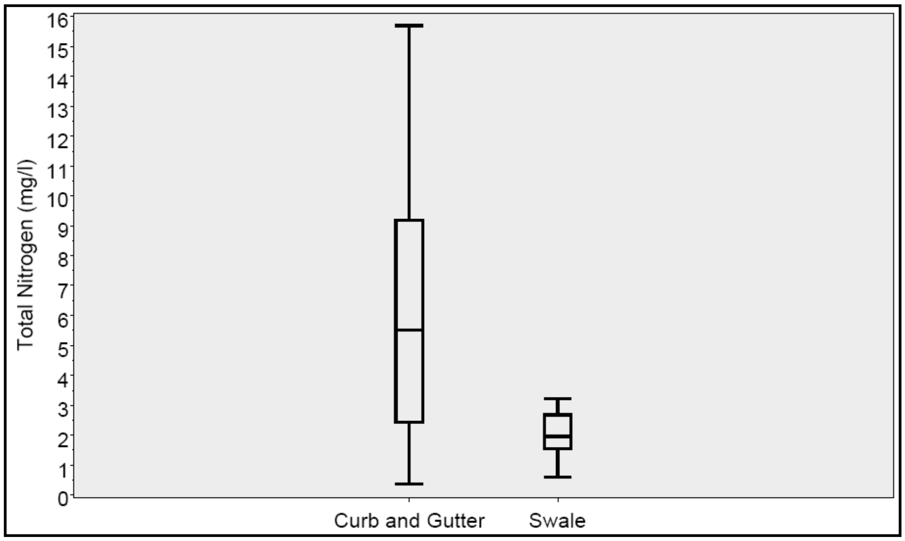

Table 7. Summary statistics for Total Nitrogen

Parameter	Units	Statistic	CG	Swale
Total Nitrogen as N	mg/l	Mean	6.17	1.98
Total Nitrogen as N	mg/l	Standard Deviation	4.41	0.75
Total Nitrogen as N	mg/l	Median	5.50	1.96
Total Nitrogen as N	mg/l	Maximum	15.70	3.20
Total Nitrogen as N	mg/l	Minimum	0.37	0.60

4.8. Ortho-Phosphorus as P

A t-test was applied to the natural log transformed ortho-phosphorus (OP) data grouped by site type. There was no significant difference (p=0.531) between the OP concentrations at curb and gutter and swale sites. Mean OP (Table 8) was slightly lower at swale sites, however median OP was slightly higher.

Table 8. Summary statistics for Ortho-Phosphorus as P

Parameter	Units	Statistic	CG	Swale
Ortho-Phosphorus as P	mg/l	Mean	0.52	0.43
Ortho-Phosphorus as P	mg/l	Standard Deviation	0.51	0.24
Ortho-Phosphorus as P	mg/l	Median	0.34	0.37
Ortho-Phosphorus as P	mg/l	Maximum	1.91	1.09
Ortho-Phosphorus as P	mg/l	Minimum	0.03	0.10

4.9. Total Phosphorus

A t-test was applied to the natural log transformed total phosphorus (TP) data grouped by site type. There was no significant difference in TP between the swale and curb and gutter sites. Mean and median TP (Table 9) were both lower at the swale sites than the curb and gutter sites, however the data populations are fairly similar (Figure 4).

Figure 4. Boxplots of total phosphorus grouped by site

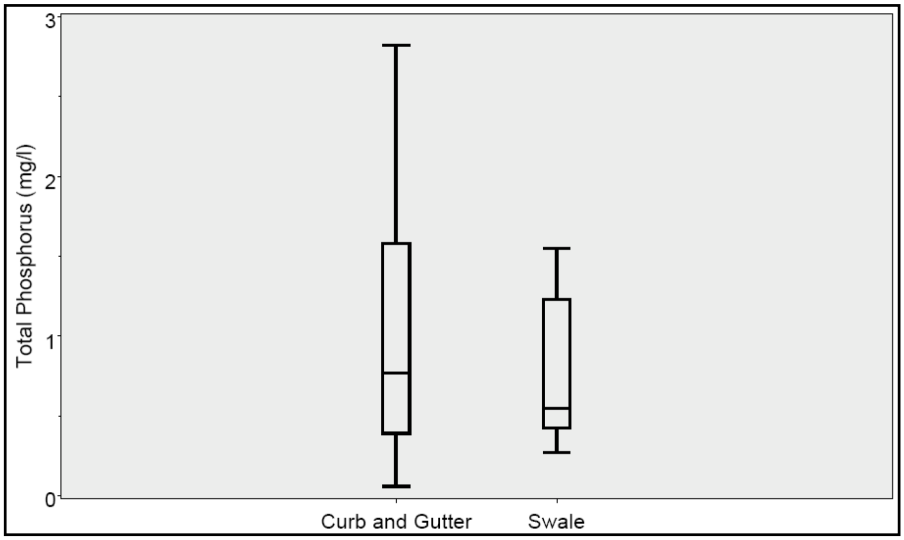

Table 9. Summary statistics for Total Phosphorus

Parameter	Units	Statistic	CG	Swale
Total Phosphorus as P	mg/l	Mean	0.99	0.74
Total Phosphorus as P	mg/l	Standard Deviation	0.77	0.45
Total Phosphorus as P	mg/l	Median	0.77	0.55
Total Phosphorus as P	mg/l	Maximum	2.82	1.55
Total Phosphorus as P	mg/l	Minimum	0.06	0.27

4.10. Total Suspended Solids

A t-test was applied to the natural log transformed total suspended solids (TSS) data grouped by site type. Total suspended solids were significantly lower at swale sites compared to curb and gutter sites (p=0.0002). Mean TSS was 78% lower at swale sites than at curb and gutter sites, and maximum TSS at swales sites was the equivalent of average TSS at curb and gutter sites (Table 10). The differences in the data populations are clearly displayed in Figure 5.

Figure 5. Boxplots of Total Suspended Solids grouped by site

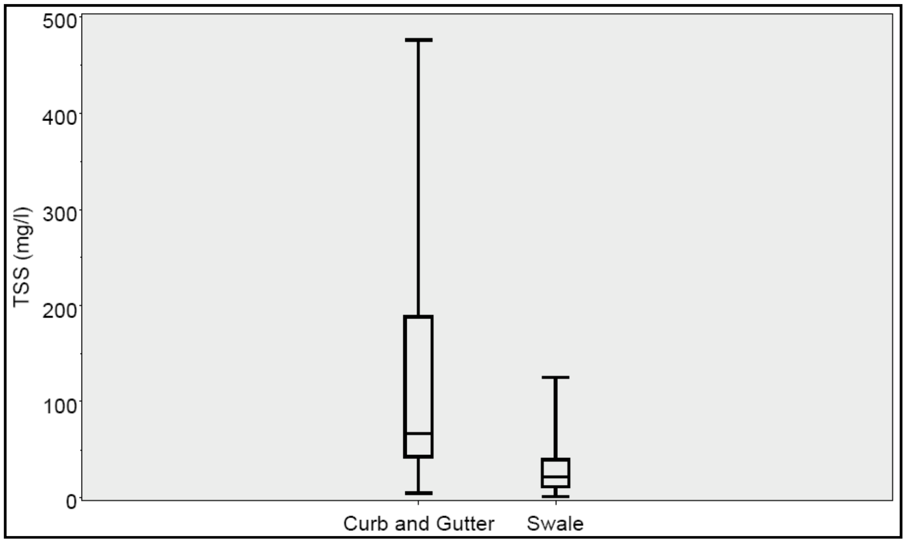

Table 10. Summary statistics for Total Suspended Solids

Parameter	Units	Statistic	CG	Swale
Total Suspended Solids	mg/l	Mean	127.73	28.44
Total Suspended Solids	mg/l	Standard Deviation	129.37	28.07
Total Suspended Solids	mg/l	Median	66.80	21.80
Total Suspended Solids	mg/l	Maximum	476.00	125.00
Total Suspended Solids	mg/l	Minimum	4.60	0.80

4.11. Biochemical Oxygen Demand

A Wilcoxon signed-rank test was applied to the untransformed biochemical oxygen demand (BOD) data grouped by site type. Biochemical oxygen demand was significantly lower at the swale sites than at the curb and gutter sites (p=0.0004). The difference in the data populations is clear in the boxplot of the data (Figure 6). Mean BOD (Table 11) was 71% lower at the swale sites than at the curb and gutter sites, while median BOD was similarly lower (72%).

Figure 6. Boxplots of biochemical oxygen demand grouped by site type

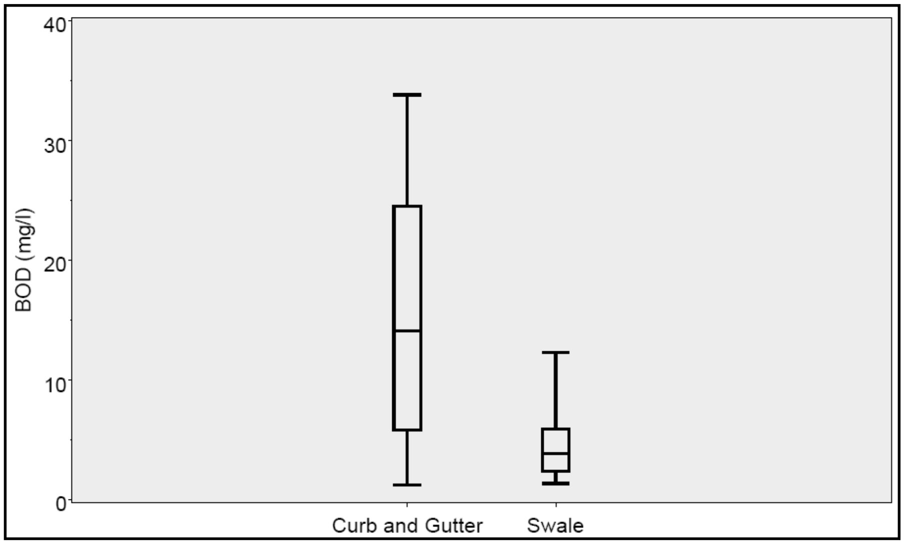

Table 11. Summary statistics for Biochemical Oxygen Demand

Parameter	Units	Statistic	CG	Swale
Biochemical Oxygen Demand	mg/l	Mean	15.35	4.44
Biochemical Oxygen Demand	mg/l	Standard Deviation	10.52	2.75
Biochemical Oxygen Demand	mg/l	Median	14.10	3.90
Biochemical Oxygen Demand	mg/l	Maximum	33.80	12.30
Biochemical Oxygen Demand	mg/l	Minimum	1.22	1.35

4.12. Lead

A Wilcoxon signed-rank test was applied to the untransformed lead data grouped by site type. Lead was significantly lower at the swale sites than at the curb and gutter sites (p=.0004). The maximum lead concentration at the swale site (Table 12) was lower than the mean concentration at the curb and gutter sites, while mean concentration at swale sites was 81% lower than the mean concentration at curb and gutter sites.

Table 12. Summary statistics for Biochemical Oxygen Demand

Parameter	Units	Statistic	CG	Swale
Lead	ug/l	Mean	9.42	1.77
Lead	ug/l	Standard Deviation	10.93	1.74
Lead	ug/l	Median	5.12	0.67
Lead	ug/l	Maximum	37.40	7.36
Lead	ug/l	Minimum	0.67	0.67

4.13. Zinc

A t-test was applied to the natural log transformed zinc data grouped by site. Zinc was significantly lower at swale sites compared to curb and gutter sites. There was a distinct difference between the zinc concentrations at the two swale sites, with Swale 1 having uniformly low zinc values and Swale 2 having high zinc values. This may be due to the samples at Swale 2 coming from within a galvanized iron pipe. Nonetheless mean zinc values were 22% lower and median zinc values were 60% lower at swale sites than at curb and gutter sites (Table 13).

Table 13. Summary statistics for Zinc

Parameter	Units	Statistic	CG	Swale
Zinc	ug/l	Mean	83.08	64.72
Zinc	ug/l	Standard Deviation	52.77	71.21
Zinc	ug/l	Median	69.70	27.70
Zinc	ug/l	Maximum	210.00	223.00
Zinc	ug/l	Minimum	11.50	5.90

4.14. Rainfall and Stormwater Runoff

The relationship between rainfall and stormwater runoff was explored through several analyses. Calculation of runoff coefficients, univariate linear regression of area normalized discharge to rainfall, and multivariate regression of area normalized discharge were all performed to better understand the discharge at swale sites relative to curb and gutter sites.

4.15. Runoff Coefficients

The population of runoff coefficients was not normally distributed and natural log transformation did not improve the distribution, therefore the Wilcoxon signed-rank test was applied to the data. There were a total of 121 runoff events from the two curb and gutter sites and 112 runoff events from the 3 swale sites. Runoff coefficients were significantly lower at the swale sites compared to the curb and gutter sites ($p<0.0001$). Summary statistics (Table 14) indicate a 70% reduction in mean flow and an 83% reduction in median flow. The maximum coefficient was 48% lower at the swale sites. Modified runoff coefficients (corrected for impervious area) were significantly lower at the swale sites compared to the curb and gutter sites ($p<0.0001$). Summary statistics (Table 15) indicate a 58% reduction in mean flow and a 74% reduction in median flow after the correction for impervious area. In addition to these reductions, there was an average of 1.73 inches of rain (CG1=1.35, CG2=2.11) that fell at the curb and gutter sites during the study period without generating runoff. There was an average of 5.18 inches of rain (SW1=3.03, SW2=7.69, SW3=4.82) that fell at the swale sites without generating runoff events.

Figure 7. Boxplots of runoff coefficients by site type

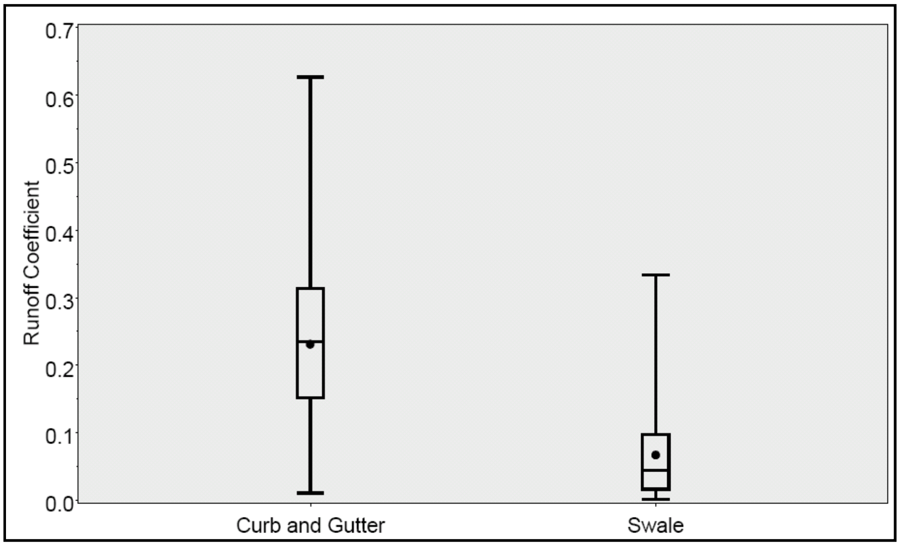

Table 14. Summary statistics for the runoff coefficient by site type

Statistic	Curb and Gutter	Swale
Mean	0.23	0.07
Standard Deviation	0.11	0.06
Median	0.24	0.04
Maximum	0.63	0.33
Minimum	0.01	0.00

Figure 8. Boxplots of impervious area corrected runoff coefficients by site type

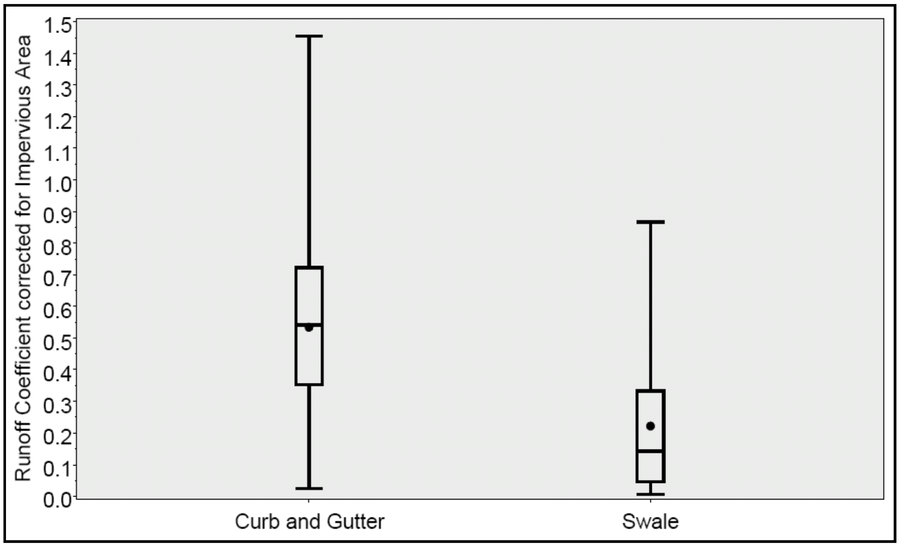

Table 15. Summary statistics for the modified runoff coefficient by site type

Statistic	Curb and Gutter	Swale
Mean	0.53	0.22
Standard Deviation	0.26	0.22
Median	0.54	0.14
Maximum	1.45	0.87
Minimum	0.02	0.01

4.16. Univariate Regressions

Univariate linear relationships between various lag term rainfall and area normalized discharge were performed for each sampling site and for combined swale, and combined curb and gutter sites. The raw data did not meet the assumptions for regression analysis, however the results are still very informative for our purposes (Table 16). Statistically significant ($p < 0.05$) models were available for all attempted analyses. The y intercept for all models was ~0, indicating that when there is no rainfall there is no runoff. The best fit lag rainfall period for combined curb and gutter sites was 15 minutes, versus a 30 minute lag period at combined swale sites. This indicates that swale sites attenuate flow over longer time periods, and require longer period rain events to generate flow. There was a range of 20-45 minutes at the swale sites, indicating that there are probably site specific factors that influence the flow attenuation at the site. The r^2 values were higher at the curb and gutter sites than at the swale sites. This indicates that rainfall alone is responsible for a greater proportion of the runoff at curb and gutter sites than at swale sites. Stated another way, factors other than rainfall have a greater influence on discharge at swale sites than at curb and gutter sites, and these other factors lead to a greater degree of variability in the flow response to a given rainfall event. The slopes of the relationships at the curb and gutter sites are higher than the slopes at the swale sites. This indicates that discharge volume increases more rapidly per unit rainfall at curb and gutter sites than at swale sites. It must be considered that the swale sites have a longer lag period of rainfall, and thus the rainfall values will be higher in the swale models relative to the curb and gutter models. A direct comparison of the slopes is not directly appropriate if the lag period rainfall is not the same. For a direct comparison the runoff coefficients are a better tool than the slopes of the regressions.

Table 16. Results of univariate regressions

StationID	Rainfall Lag	p-value	r^2	Y-intercept	Slope
CG1	15 Minute	0.0000	0.832	-0.0000	0.00839
CG2	15 Minute	0.0000	0.805	-0.0000	0.01127
All CG	15 Minute	0.0001	0.797	-0.0000	0.00997
Swale 1	45 Minute	0.0000	0.542	0.0000	0.00064
Swale 2	20 Minute	0.0000	0.561	-0.0000	0.00161
Swale 3	30 Minute	0.0000	0.554	-0.0000	0.00146
All Swale	30 Minute	0.0001	0.525	-0.0000	0.00115

4.17. Multivariate Regressions

The results of stepwise multiple regressions are presented in Tables 17 and 18. The rainfall to area normalized discharge relationship remains the same as in the univariate regressions. There were two additional independent variables that met the criterion ($p<0.05$) for entry into the curb and gutter site model. These variables were the maximum change in elevation over the drainage area and the percent impervious within the drainage area. These additional variables did not appreciably change the r^2 of the model. All four additional independent variables met the criterion for entry into the swale site model. As was the case with the curb and gutter model, the additional independent variables did not appreciably change the r^2 of the model. Although the additional independent variables (other than rainfall) were statistically significant contributors to the model, they do not explain much of the variability in runoff, indicating the rainfall is by far the factor with the most influence on runoff.

Table 17. Results of the stepwise multiple regression on the pooled curb and gutter data

Independent Variable	Partial r^2	Model r^2	Slope	p
15 Min Rain	0.797	0.797	0.00997	0.0001
Max change in Elevation	0.0003	0.797	-0.000003	0.0001
% Impervious Area	0.0000	0.797	-0.00036	0.013

Table 18. Results of the stepwise multiple regression on the pooled curb and gutter data

Independent Variable	Partial r^2	Model r^2	Slope	p
30 Min Rain	0.5245	0.5245	0.00115	0.0001
Temperature	0.0005	0.525	-0.0000003	0.0001
Max change in Elevation	0.0001	0.5251	0.0000003	0.0001
Groundwater Level	0.0001	0.5252	-0.0000047	0.0001
% Impervious Area	0.0001	0.5252	-0.0000001	0.0001

4.18. Pollutant Loads

The estimated annual loads for a normal rainfall year are listed for each sampled analyte in Tables 19 and 20. Estimated loading due to surficial runoff was lower at swale sites than at curb and gutter sites for all monitored analytes. The percent difference in loading due to surficial runoff ranged from a decrease of 44% in bicarbonate alkalinity to a decrease of 96% in lead, with all analytes other than bicarbonate alkalinity having at least an 80% reduction. The second component of flows, baseflow, occurred only at swale sites. There was large variability in baseflow between swale sites (as evidenced by the difference in loading shown in Table 20), with almost no baseflow occurring at the Swale 2 site. This difference in baseflow may result from differences in slope within the two study sites. The Swale 1 drainage area has relatively large vertical relief, while the Swale 2 drainage area is essentially flat (Table 1). After adding the baseflow loads to the surficial runoff loads the differences ranged from an increase of 360% in bicarbonate loads at swale sites, to a decrease of 85% in lead at swale sites.

Table 19. Estimated annual pollutant loads at Curb and Gutter and Swale sites

	Mean Estimated Load (kg) in Surficial Runoff per acre*year		Mean Estimated Load (kg) in Baseflow per acre*year		Estimated Total Load (kg) per acre*year	
Analyte	**Curb and Gutter**	**Swale**	**Curb and Gutter**	**Swale**	**Curb and Gutter**	**Swale**
Ammonia Nitrogen	0.68	0.04	0.00	0.20	0.68	0.24
Bicarbonate Alkalinity	27.61	15.46	0.00	111.54	27.61	127.00
Biochemical Oxygen Demand	23.49	1.57	0.00	9.16	23.49	10.73
Lead	0.02	0.00	0.00	0.00	0.02	0.00
Nitrate + Nitrite as N	0.80	0.15	0.00	0.98	0.80	1.13
Ortho-Phosphorus as P	0.77	0.15	0.00	0.88	0.77	1.03
Total Kjeldahl Nitrogen	8.81	0.53	0.00	2.67	8.81	3.21
Total Nitrogen	9.60	0.69	0.00	3.65	9.60	4.34
Total Phosphorus	1.53	0.27	0.00	1.66	1.53	1.93
Total Suspended Solids	205.58	9.29	0.00	31.60	205.58	40.89
Zinc	0.13	0.02	0.00	0.02	0.13	0.04

Table 20. Estimated annual pollutant loads for each monitored site

	Estimated Load (kg) in Surficial Runoff per acre*year				Estimated Load (kg) in Baseflow per acre*year				Estimated Total Load (kg) per acre*year			
Parameter	**CG1**	**CG2**	**SW1**	**SW2**	**CG1**	**CG2**	**SW1**	**SW2**	**CG1**	**CG2**	**SW1**	**SW2**
Ammonia Nitrogen	0.56	0.79	0.04	0.04	0.00	0.00	0.41	0.00	0.56	0.79	0.45	0.04
Bicarbonate Alkalinity	28.14	27.07	24.62	6.30	0.00	0.00	222.96	0.12	28.14	27.07	247.58	6.42
Biochemical Oxygen Demand	17.71	29.28	2.02	1.12	0.00	0.00	18.31	0.02	17.71	29.28	20.33	1.14
Lead	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00
Nitrate + Nitrite as N	0.93	0.67	0.22	0.09	0.00	0.00	1.95	0.00	0.93	0.67	2.17	0.09
Ortho-Phosphorus as P	0.73	0.81	0.19	0.11	0.00	0.00	1.76	0.00	0.73	0.81	1.96	0.11
Total Kjeldahl Nitrogen	5.24	12.38	0.59	0.48	0.00	0.00	5.34	0.01	5.24	12.38	5.93	0.49
Total Nitrogen	6.17	13.04	0.81	0.57	0.00	0.00	7.30	0.01	6.17	13.04	8.10	0.58
Total Phosphorus	1.11	1.95	0.37	0.17	0.00	0.00	3.32	0.00	1.11	1.95	3.69	0.17
Total Suspended Solids	84.41	326.75	6.95	11.62	0.00	0.00	62.97	0.22	84.41	326.75	69.93	11.85
Zinc	0.09	0.17	0.00	0.03	0.00	0.00	0.04	0.00	0.09	0.17	0.05	0.04

Note: CG1=C&G 1, CG2= C&G 2, SW1=Swale 1, SW2=Swale 2

5.0 Discussion

The effectiveness of grassed areas as a particulate filter for stormwater runoff is well documented in the literature (Deletic and Fletcher 2006, Han et al. 2005). Particulate filtration is a physical rather than a biological process, and removal efficiencies tend to be higher during lower flow events. The results of this study support the concept that pollutant removal by grass strips is primarily a physical process, with particulate analytes such as TSS, TKN, zinc, and lead having significantly lower concentrations in swale drainages, and dissolved analytes such as NOx and OP having similar concentrations in swale and curb and gutter drainages. However even when the concentrations of analytes were not statistically different, the average concentrations were lower at swale sites than at curb and gutter sites. The exception to this was bicarbonate alkalinity which was found in significantly higher concentrations at swale sites compared to curb and gutter sites. This is likely due to the influence of groundwater baseflow in the swales. The majority of the total nitrogen in the runoff at our sites was in the form of TKN rather than NOx. The reduction in concentration of total nitrogen by swale drainage is likely dependent upon the nitrogen being in this form. The removal of TSS by grass filters has been well studied, with various removal efficiencies reported, including 61-86% (Deletic and Fletcher 2006), 85% (Han et al 2005).

After runoff coefficients were adjusted for site specific variation in percent impervious area (by creating the modified runoff coefficient), runoff was significantly reduced at swale sites relative to curb and gutter sites. This is critically important, because it indicates that even if swale and curb and gutter sites discharged at the same concentrations, loads would still be significantly reduced at swale sites. Therefore, parameters such as NOx and TP, which did not have significantly different concentrations, would still have substantially different loads (because the mean concentration was slightly lower at the swale sites). It is also important to note that for the calculation of runoff coefficients, only storm events which generated runoff, were considered. There were a number of rain events at swale sites for which the entire rainfall volume was fully attenuated on site.

It is clear that swales are reducing the volume of stormwater runoff and providing water quality treatment. In this study swales also generated baseflow to varying degrees. It appears that the factor most important to the generation of baseflow in this study is the slope at the swale site. Swale sites 1 and 3 both had substantial slopes (relative to much of southwest Florida), and generated considerable baseflow, while Swale 2 had very little baseflow. Swale sites 1 and 3 were frequently observed to be flowing several days after large rain events. There are several caveats to the estimates of loading due to baseflow presented in Table 20. First, the same drainage was used for both the baseflow and surficial runoff calculations despite the fact that the drainage area for the baseflow is likely substantially larger than the area for surficial runoff. This means that the estimated loads due to baseflow per acre in Table 20 could be substantial overestimates. In addition the concentrations of pollutants measured during storm events were applied to the baseflow volumes to generate baseflow loads. The concentrations of most constituents were probably lower in the baseflow than in the surficial runoff, and this probable decrease in concentration is not accounted for in Table 20. The baseflow load estimates, while not accurate, are nonetheless important to generate a complete understanding of the impacts from swale drainage.

The ultimate test of the functionality of the BMP is in its capacity to reduce loading. The two pathways to load reduction in stormwater are through reduction in pollutant concentration, and reduction in discharge. In general the swales monitored in this study are effective at reducing loads through both pathways, generating substantial load reductions of many regulated pollutants, including nutrients, metals and total suspended solids. The estimated load reduction of TSS in this study is within the range observed in other studies (Barrett et al 1998), and exceeds the EPA management measures in the Coastal Zone Act Reauthorization Amendments of 1990, which specifies an 80% target for removal of TSS. The impact of swale drainage on loading will vary on a site-specific basis, as there are a variety of features that will impact the efficacy of the swale drain feature as a BMP. The use of these results should be governed by that understanding, however, these results are consistent with findings in other studies, and likely represent a reasonable estimate of the overall impact of swale drainage in the region. Additionally, except for unusually high rainfall and groundwater levels at the beginning of the study, the hydrologic conditions during the study were fairly normal for the region. The methodology utilized was different from the common influent versus effluent studies. Conducting influent versus effluent studies in grassed swales is problematic, as filtration happens quite rapidly, and the comparison of treated water to other treated water yields misleading results (Barrett et al 1998). Ultimately it appears that swale drainage is providing excellent stormwater treatment in this area, and is quite effective as a BMP.

6.0 References

Balascio C.C. and C.L. Lucas, 2009. A survey of storm-water management water quality regulations in four Mid-Atlantic States. Journal of Environmental Management 90, 1-7.

Barrett M.E., P.M. Walsh, J.F. Malina Jr., R.J. Charbeneau, 1998. Performance of Vegetative Controls for Treating Highway Runoff. Journal of Environmental Engineering 124 (11), 1121-1128.

Barrett M.E., 2008. Comparison of BMP Performance Using the International BMP Database. Journal of Irrigation and Drainage Engineering

Charbeneau R.J. and M.E. Barrett, 1998. Evaluation of methods for estimating stormwater pollutant loads. Water Environment Research 70 (7), 1295-1302.

Deletic A., 2005. Sediment transport in urban runoff over grassed areas. Journal of Hydrology 301, 108-122.

Deletic A. and T.D. Fletcher, 2006. Performance of grass filters used for stormwater treatment, a field and modeling study. Journal of Hydrology 317, 261-275.

Gilroy K.L. and R.H. McCuen, 2009. Spatio-temporal effects of low impact development practices. Journal of Hydrology 367, 228-236.

Han J., J.S. Wu, C. Allan, 2005. Suspended Sediment Removal by Vegetative Filter Strip Treating Highway Runoff. Journal of Environmental Science and Health 40, 1637-1649.

Park M.H., X. Swamikannu, M.K. Stenstrom. Accuracy and precision of the volume-concentration method for urban stormwater modeling. Water Research 43, 2773-2786.

Scholes L., D.M. Revitt, J.B. Ellis, 2008. A systematic approach for the comparative assessment of stormwater pollutant removal potentials. Journal of Environmental Management 88, 467-478.

Wise, E.S and Williams, W.R. 2006. Hydrologic impacts of alternative approaches to storm water management and land development. Journal of the American Water Resources Association (JAWRA) 42(2). 443-455.

Yang B. and M.H. Li, 2010. Ecological engineering in a new town development: Drainage design in The Woodlands, Texas. Ecological Engineering 36, 1639-1650.

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