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Performance of grass swales for improving water quality from highway runoff

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ABSTRACT

The performance of grass swales for treating highway runoff was evaluated using an experimental design that allowed for influent and effluent flow and pollutant concentration measurements to be taken at specific intervals through each storm event. Two common swale design alternatives, pre-treatment grass filter strips and vegetated check dams, were compared during 45 storm events over 4.5 years. All swale alternatives significantly removed total suspended solids and all metals evaluated: lead, copper, zinc, and cadmium. The probability of instantaneous concentrations exceeding 30 mg/L TSS was decreased from 41–56% in the untreated runoff to 1–19% via swale treatment. Nutrient treatment was variable, with generally positive removal except for seasonal events with large pulses of release from the swales. Nitrite was the only consistently removed nutrient constituent. Chloride concentrations were higher in swale discharges in nearly every measurement, suggesting accumulation during the winter and release throughout the year. Sedimentation and filtration within the grass layer are the primary mechanisms of pollutant treatment; correspondingly, particles and particulate-bound pollutants show the greatest removal via swales. Inclusion of filter strips or check dams had minimal effects on water quality.

1. Introduction

In an effort to reduce the effects of non-point source pollution, which accounts for almost 50% of the total water pollution in the developed world (Novotny and Harvey, 1994), water resources engineers and managers continue to emphasize cost-effective stormwater control measures (SCMs). One increasingly common technique is the inclusion of Low Impact Development (LID) technologies, which stress reduction of runoff generation and management of runoff through filtration and infiltration practices. Performance information on LID practices in roadway applications is necessary so that these practices can be integrated into highway planning, design development, construction processes, and existing project retrofits.

Grass swales are one such LID technology that has been employed for the conveyance of stormwater runoff in highway designs for many years. Swales are shallow, grass-lined, typically flat-bottomed channels that receive flow laterally through vegetated side slopes. Water quality enhancements can be realized in swales through infiltration, sedimentation (due to the low velocity induced by the vegetation), filtration by the grass blades, and likely some biological processes. While recent studies have revealed them as an effective LID technology, good performance data and mechanistic understanding of swale design parameters are less prevalent.

Previous studies have shown that grass swales tend to be very effective in reducing Total Suspended Solids (TSS), with reported EMC removal values ranging from 48 to 98% (Schueler, 1994; Barrett et al., 1998; Yu et al., 2001; Bäckström, 2003;

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Barrett, 2005). Field and laboratory-scale studies of TSS removal by grass swales and filter strips (Deletic, 2001; Bäckström, 2002, 2003; Deletic and Fletcher, 2006) suggest that the primary treatment mechanism in swales is sedimentation, with filtration playing a much smaller role. As such, particulate removal is governed by Stokes' Law and is related to both hydraulic residence time and particle size (Bäckström, 2002).

Nutrients, including nitrogen compounds (nitrate, nitrite, ammonium, organic N) and phosphorous can accelerate eutrophication in receiving water bodies. Studies of nitrogen removal by grass swales show wide variability (Barrett et al., 1998; Wu et al., 1998; Rushton, 2001; Barrett, 2005). A study of grass swales in a parking area in Florida concluded that nitrate mass loads were reduced due to storage and infiltration, however the resulting nitrate concentrations were unaffected by grass swale treatment (Rushton, 2001). Field studies of phosphorus removal by grass swales also vary greatly. Some studies have shown significant total phosphorus removal, from 12 to 60% (Schueler, 1994; Barrett et al., 1998; Yu et al., 2001), while others have demonstrated significant total phosphorus export (Wu et al., 1998; Rushton, 2001; Barrett, 2005).

High variability in nutrient removal can be attributed, in part, to extraneous organic matter, such as grass or other vegetation, which can leach significant quantities of nutrients (Yu et al., 2001). Swale maintenance activities, such as mowing or fertilizing, may also impart nutrients, with Cowen and Lee (1973) noting a 3-fold increase in soluble phosphorus leached from cut leaves rather than intact leaves.

Grass swales have been shown to be successful at removing metals of concern in highway runoff. Zinc is typically the most successfully removed metal with event mean concentration (EMC) reductions of 75–91% (Barrett et al., 1998) and total mass removals of 47–81% (Schueler, 1994; Rushton, 2001; Bäckström, 2003). Lead concentration reductions of 17–41% were documented by Barrett et al. (1998), while total lead mass has been reduced by 18–94% (Schueler, 1994; Rushton, 2001). Similarly, swales have been shown to reduce total copper mass by 14–81% (Schueler, 1994; Rushton, 2001; Bäckström, 2003).

Inclusion of a grass filter strip pre-treatment area adjacent to grass swales is required by several stormwater design manuals. Most studies regarding pre-treatment areas focus only on TSS reduction. Barrett et al. (1998) concluded that pre-treatment is important to the TSS removal process by determining that TSS concentrations in grab samples did not vary greatly along the length of field-scale swales. A similar study by Wu et al. (1998) agreed that including a pre-treatment area can improve runoff quality, although not to the degree suggested by Barrett et al. (1998). Other studies suggest that sedimentation along the swale length is the most important process in removing runoff pollutants (Schueler, 1994; Bäckström, 2003). These studies conclude that, while a pre-treatment area might provide pollutant removal, it is primarily due to extending the retention time for the runoff and does not supersede the importance of the grass swale.

In-line check dams are also used to increase hydraulic retention time within the swale, thereby promoting sedimentation and infiltration. Yu et al. (2001) found that the inclusion of check dams significantly improved runoff treatment efficiency, particularly for long duration, low-intensity storm events. A study by Deletic and Fletcher (2006) found an exponential decay of TSS concentrations with distance in a field-scale grass filter strip, suggesting that TSS treatment efficiency could be improved by increasing hydraulic residence time via increasing swale length, increasing channel roughness, decreasing slope, and/or installing check dams.

The goal of this study is to quantify the water quality performance of grass swales and evaluate the effects of several swale design alternatives, including a vegetated filter strip and in-line vegetated check dams. In total, 45 storm events were monitored over the course of 4.5 years with respect to a range of water quality parameters including TSS, nitrate, nitrite, Total Kjeldahl Nitrogen (TKN), total phosphorus, chloride, lead, copper, zinc, and cadmium. These pollutants were selected due to their prevalence in highway runoff, potential harmful environmental impact, and/or regulatory status, e.g., total maximum daily load (TMDL) limits. While not known to be of particular concern for highways, nutrients are included here due to the great emphasis on nutrient control for many water bodies. By concurrently monitoring influent and effluent flow and concentrations, treatment efficiencies are presented both in terms of dynamic response, as pollutant-duration curves, and at the storm event summary scale, as EMC or total mass. Pollutant-duration curves are introduced as an analog of flow-duration curves, which present the cumulative distribution of influent and effluent concentrations. These figures are valuable in identifying differences in treatment capabilities and compared to specific water quality goals. Pollutant-duration curves can be generalized to evaluate any number of stormwater SCMs in future studies.

2. Methods and materials

2.1. *Site description*

The monitoring location for this study was MD Route 32, a four-lane limited access highway near Savage, Maryland, USA. The project is designed as an input/output study, with additional site details presented in Davis et al. (2012). Two grass swales, one with a filter strip, designated FS, and one without, designated No-FS, receive runoff laterally from comparable roadway areas. Flow measurements and water quality samples were taken at the discharge point of each swale and were considered their treated output.

Both swales have identical cross-sections (side slopes of 3:1 (33%) and 4:1 (25%) on either side of the swale), with a 0.61 m bottom width and approximately 1.4% longitudinal slope. No-FS and FS drain 0.224 and 0.225 ha of roadway area, respectively. The swales measure 198 and 138 m in length for the No-FS and FS swales, respectively, and were originally planted with a mix of 90% tall fescue, 5% Kentucky bluegrass, and 5% perennial ryegrass. Topsoil used in the swales was classified as loam or sandy loam, per the USDA soil texture classification system. Because direct monitoring of input parameters would be intrusive and potentially affect output, an indirect method was employed. A concrete channel, designated HWY, which drains a roadway area comparable to the 2 swales is considered equivalent to the swale inputs. Sampling of the FS and No-FS swales (and HWY) occurred between November 2004 and May 2006, resulting in a total of 18 monitored storm events.

Following the initial round of sampling, 2 sets of 1-m wide grass check dams were installed along the swale centerlines (designated CD), leaving the swale cross-sections unchanged. Each check dam was planted with *Panicum virgatum* 'Heavy Metal' in three staggered rows, 0.31 m on center. *Panicum virgatum* is a sturdy plant that remains standing in heavy rain or snow. Sampling of the FS-CD and No-FS-CD swales (and HWY-CD) occurred between April 2007 and July 2009 and produced 27 monitored storm events.

2.2. *Sampling program and analytical methodology*

Hydraulic measurements and water quality samples were taken at plywood vee-notch weirs using ISCO Model 6712 Portable Samplers with bubble flow meters. Events were triggered when the head behind the weir reached 3.05 cm, corresponding to a flow of approximately 0.43 L/s. One ISCO 674 Tipping Bucket Rain Gauge with 0.254-mm sensitivity was installed on site and logged rainfall depth in 2-min increments.

Flow data and water samples for all three channels were taken over 6–8 h sampling periods at regular intervals, resulting in 12 samples for each channel to be analyzed for the indicated water quality parameters: TSS, nitrate, nitrite, TKN, total phosphorus, chloride, lead, copper, zinc, and cadmium. Individual nitrogenous constituents were analyzed to calculate total nitrogen and to assist in identifying any biological/chemical reactions occurring in the swales. Laboratory analytical methodologies for pollutant measurements followed Standard Methods (APHA et al., 1995) and are summarized in Table 1.

2.3. *Water quality parameter calculations and data evaluation*

For each pollutant, total mass (M) is calculated as:

$$M = \int_0^{T_d} QC dt. \tag{1}$$

where Q is the measured stormwater flow rate, C is the pollutant concentration for each sample during the event, T_d is the event duration and dt is the sampling interval. Concentrations between samples are calculated by linear interpolation. Measurements below detection limits are assumed to be half the detection limit for summary calculations. The only measurements found below detection limits in this study were for nitrite and cadmium.

As in Davis et al. (2012), flows are adjusted to account for the additional drainage area associated with the swales themselves. Because direct rainfall is assumed to have negligible pollutant concentrations, mass calculations are unaffected. However, when calculating the EMC, this additional runoff tends to dilute the sample, resulting in lower concentrations. Therefore, water quality evaluations were performed using the normalized event mean concentration (N-EMC), which represents the concentration that would occur if only runoff from the roadway entered the swales (V_R) and the resulting total storm event discharge was collected in one container. The N-EMC is calculated as:

$$N - EMC = \frac{M}{V_R} = \frac{\int_0^{T_d} Q(t)C(t)dt}{\int_0^{T_d} Q(t)dt - V_{Swale}} \tag{2}$$

where V_{swale} represents the contribution of rainfall landing directly on the swales to the water balance, estimated using the NRCS method described in Davis et al. (2012). All concentration analyses are based on N-EMC to allow for direct comparisons.

Probability plots and water quality targets were employed for performance analysis, as in Li and Davis (2009). Events that produced no measurable outflow are plotted as 0 EMC. Care was taken to follow recent trends in SCM reporting, avoiding metrics like percent concentration reduction that do not consider influent concentrations, in favor of metrics such as percent exceedance that provide context to treatment effectiveness.

Pollutant-duration curves were created using concentration measurements, linearly interpolated at 2 min intervals to match the flow measurement interval. These figures summarize dynamic concentrations across all monitored storm events in a single distribution. As such, they offer

Table 1 – Analytical methods for determination of pollutant concentrations.

Pollutant	Standard method (APHA et al., 1995)	Detection limit (mg/L)
Total Suspended Solids, TSS	2540D	1
Total Phosphorus	4500-P	0.05–0.24
Total Kjeldahl Nitrogen, TKN	4500-N_{org}	0.14
Copper	3030 E	0.002
Lead	3030 E	0.002
Zinc	3030 E	0.025
Cadmium	3030 E	0.002
Nitrite	4500-NO_2^- B	0.01 as N
Nitrate	Dionex DX-100 ion chromatograph	0.1 as N
Chloride	Dionex DX-100 ion chromatograph	2

a cumulative perspective to evaluate peak concentrations and allow for the calculation of instantaneous exceedance durations and probabilities. The ratio of normalized EMC to measured EMC (without subtracting V_{swale}) was used to adjust instantaneous pollutant concentrations to account for additional runoff contribution from the vegetated areas.

3. Results and discussion

In total, 18 storm events without check dams and 27 storm events with check dams were monitored and analyzed. Of the 18 non-check dam storm events, 8 produced measurable discharge from the swales, while 13 of the 27 check dam storm events produced measurable discharge. The remainder were completely captured and infiltrated by the swales.

The storm events are identical to those described in Davis et al. (2012) except for 6 non-check dam storm events and 1 check dam storm event that were omitted from water quality analysis. The water quality storm events are representative of the historical distribution of rainfall events in Maryland (Kreeb and McCuen, 2003) both with respect to rainfall volume ($\chi^2 = 2.15$, $p = 0.71$) and duration ($\chi^2 = 10.96$, $p = 0.09$). The No-CD events closely resemble the historical distribution with respect to duration, but slightly over-represent larger rainfall events, while the CD storm events have a slight emphasis on medium (4–13 h) duration events.

Hydraulically, the swales operate in three phases: completely infiltrating the smallest 40% of storm events, reducing the total runoff volume for an additional 40% of events, and performing simply as flow conveyance with negligible volume attenuation for the largest 20% of events. Volume reduction was found to be statistically significant for all swale designs except for the FS swale during moderate storm events, defined as storm events with influent volumes up to 1×10^5 L (3.7 cm over the highway area) (Davis et al., 2012). Volumetric reduction due to infiltration is an important water quality consideration, as it contributes to the total pollutant mass reduction of the swales.

3.1. *Total suspended solids (TSS)*

All grass swale designs significantly removed TSS from stormwater runoff, both in terms of N-EMC (Table 2) and total mass (Table 3). With influent (HWY, HWY-CD) event mean concentrations ranging from 8 to 582 mg/L, mean TSS effluent concentrations were 7 and 9 mg/L for the No-FS and FS swales, respectively; mean effluent TSS EMCs were 19 and 52 mg/L for the No-FS-CD and FS-CD swales from an input range of 8–582 mg/L. Probability plots (Fig. 1a) further confirm the successful removal of TSS, with 50–60% of events completely infiltrated, and the remainder of events consistently below influent concentrations. TSS treatment efficiencies are within expected ranges when compared to previous studies which showed TSS reductions of 65–98% (Schueler, 1994), 85–87% (Barrett et al., 1998), 68% (Yu et al., 2001), 79–98% (Bäckström, 2003), and 48% (Barrett, 2005).

Removal of suspended solids in the swale is attributable first to an initial capture of the highly concentrated “first flush” (Bertrand-Krajewski et al., 1998; Sansalone and Cristina, 2004; Bach et al., 2010) by infiltration and then to sedimentation and filtration once the swales begin to discharge. A typical pollutograph (Fig. 2) clearly exhibits these treatment mechanism responses, infiltrating the characteristic first flush of TSS in the HWY runoff and then reducing TSS concentrations throughout the remainder of the storm event. This treatment pattern is further corroborated by the statistically significant reduction of both TSS mass and mean concentrations.

Pollutant-duration curves demonstrate that the swales consistently lower instantaneous TSS concentrations during peak discharges, as well during moderate discharges (Fig. 3a and b). The duration of exceedances of the TSS water quality goal of 30 mg/L (typical wastewater treatment plant effluent benchmark) is reduced from 41.2% in the direct roadway runoff to 1.2% and 2.6% in the No-FS and FS non-check dam swales (Fig. 3a, Table 2), respectively and from 55.7% to 18.0% and 19.2% in the No-FS-CD and FS-CD swales, respectively (Fig. 3b, Table 2).

Inclusion of a grass filter strip pre-treatment area or vegetated check dam did not significantly improve TSS reduction. To the contrary, paired comparisons show that the non-filter strip swales outperform swales with the filter strip for N-EMC and total TSS mass reduction (Table 4). The difference in these storm event summary statistics is made clearer by the pollutant-duration curves (Fig. 3a and b), which show a pronounced cross-over point for both the non-check dam and check dam swales, suggesting that filter strips reduce low and medium TSS concentrations while allowing greater releases of TSS during periods of high influent concentrations. This seemingly anomalous result may be explained by resuspension or erosion from the filter strip during high intensity events.

Employing a two-way ANCOVA design, using influent N-EMC (HWY or HWY-CD) as covariate to control for within-group variance, showed that the four swale design alternatives significantly differed in TSS reduction ($F = 4.97$, $p = 0.003$), with the greatest difference attributed to the inclusion of check dams. The negative difference indicates that the absence of check dams improved TSS reduction. This conclusion is further supported visually by Figs. 1and 3, which show better water quality in the non-check dam swales. This finding may be explained by the significantly lower runoff volume produced by check dam swales, as discussed in Davis et al. (2012), which tends to decrease total volume, but in turn would increase the resulting TSS concentration. This explanation is further supported by greater TSS mass removal in check dam swales than in non-check dam swales.

Regardless of the differences across the 4 swale design alternatives, it is important to note that reduction of TSS remained significant for all designs and the swale itself remained the primary treatment measure. Treatment mechanisms for TSS removal by the swales include sedimentation and filtration within the grass layer. Sedimentation and filtration are in turn controlled by time of concentration, flow path length, and roughness, as well as the influent particle size distribution. The greatest TSS removal occurs along the length of the swales, which have a much longer flow path (198 m and 137 m in No-FS and FS, respectively) and shallower slope (1.6% and 1.2% in No-FS and FS, respectively) than the pre-treatment filter strip, with a lateral flow distance of only 15.2 m.

Table 2 – Mean and range of N-EMC and number of analyzed storm events for each swale for all storm events (No-FS, FS, No-FS-CD, FS-CD). Negative values signify export of constituent. A concentration of zero represents complete capture. Paired statistical significance is presented, with * representing $p < 0.1$ and ** representing $p < 0.05$.

	Water Quality Goal	HWY		No-FS			FS			HWY-CD		No-FS-CD			FS-CD		
Constituent	mg/L	mg/L	Exceed. (%)	n	mg/L	Exceed. (%)	n	mg/L	Exceed. (%)	mg/L	Exceed. (%)	n	mg/L	Exceed. (%)	n	mg/L	Exceed. (%)
TSS	30	98 (10–309)	41.2	16	7 (0–31)	1.2	18	9 (0–72)	2.6	126 (8–582)	55.7	27	19 (0–109)	18.0	27	52 (0–232)	19.2
Total nitrogen	1.5	5.53 (2.30–12.7)	42.0	6	2.12 (0–12.7)	7.2	8	2.63 (0–9.9)	8.4	4.80 (1.00–19.1)	62.2	19	2.27 (0–12.9)	18.7	19	4.34 (0–65.2)	10.9
Nitrate	0.2	2.25 (0.77–3.81)	100	7	1.76 (0–10.40	22.8	9	1.93 (0–8.2)	22.4	1.79 (0.27–16.3)	98.9	20	0.74 (0–6.4)	27.8	20	0.27 (0–2.6)	17.4
Nitrite	1	0.33 (0.06–1.47)	10.1	16	0.04 (0–0.15)	0	18	0.03 (0–0.15)	0	0.10 (0.02–0.34)	0.5	27	0.02 (0–0.18)	0	27	0.02 (0–0.13)	0
TKN	1.3	3.38 (0.83–10.2)	41.8	14	0.94 (0–2.97)	32.9	16	0.81 (0–3.2)	19.8	2.94 (0.31–12.1)	44.7	25	1.98 (0–14.7)	33.0	25	3.35 (0–62.4)	21.7
Total Phosphorous	0.05	0.55 (0.08–2.28)	100	16	0.29 (0–1.20)	37.9	18	0.20 (0–1.1)	28.7	0.34 (0.07–1.52)	99.2	27	0.24 (0–1.29)	54.0	27	0.16 (0–0.58)	42.7
Chloride	860	19 (2–146)	0	14	68 (0–388)	0.2	16	126 (0–717)	1.1	123 (4–1880)	3.5	25	220 (0–3700)	7.4	25	327 (0–5590)	5.8
Metals	μg/L	μg/L		n	μg/L		n	μg/L		μg/L		n	μg/L		n	μg/L	
Lead	65	24 (2.0–70)	3.2	11	4.4 (0–30)	0	13	6.6 (0–45)	0	82 (5.6–960)	4.4	23	12 (0–63)	2.0	23	17 (0–150)	3.6
Copper	13	56 (12–190)	84.9	12	7.1 (0–42)	20.0	14	7.9 (0–53)	14.3	70 (15.3–182)	91.5	25	19 (0–160)	40.1	25	20 (0–117)	31.3
Zinc	120	440 (54–1650)	88.1	12	61 (0–310)	26.6	14	67 (0–220)	15.3	510 (115–2320)	81.2	25	54 (0–440)	8.9	25	52 (0–210)	13.9
Cadmium	2	3.0 (1–6.2)	54.1	11	0.3 (0–1.2)	0.8	13	0.4 (0–1.4)	0	1.3 (1–2.7)	8.6	26	0.7 (0–3.7)	4.1	26	0.6 (0–4.0)	5.8**

Table 3 – Mean and range of Mass and number of analyzed storm events for each swale for all storm events (No-FS, FS, No-FS-CD, FS-CD). Negative values signify export of constituent. Paired statistical significance is presented, with * representing $p < 0.1$ and ** representing $p < 0.05$.

Constituent	HWY	No-FS			FS			HWY-CD	No-FS-CD			FS-CD		
	g	n	g	Mean reduc. (%)	n	g	Mean reduc. (%)	g	n	g	Mean reduc. (%)	n	g	Mean reduc. (%)
TSS	4080 (260–30,380)	16	680 (0–5740)	44.1	18	1430 (0–11,990)	45.6 *	5360 (40–27,970)	27	1910 (0–23,620)	82.7**	27	4060 (0–60,720)	68.8 **
Total nitrogen	194 (45–351)	6	242 (0–853)	(−5.7)	8	315 (0–979)	(−25.6)	173 (4–778)	19	97 (0–1220)	77.2**	19	56 (0–760)	85.6 **
Nitrate	118 (11–287)	7	182 (0–696)	(−19.6)	9	198 (0–814)	(−25.2)	62 (1–616)	20	22 (0–182)	71.7**	20	10 (0–136)	88.9 **
Nitrite	7.5 (1.7–22.9)	16	3.0 (0–26.0)	63.2 **	18	3.7 (0–24.9)	50.5 **	2.4 (0.2–10.3)	27	1.1 (0–9.1)	67.1**	27	0.8 (0–8.6)	71.5 **
TKN	89 (20–373)	14	73 (0–372)	(−47.0)	16	100 (0–502)	(−50.3)	126 (1–677)	25	175 (0–2553)	(−106)	25	49 (0–615)	77.4 **
Total Phosphorous	18 (1–99)	16	27 (0–215)	(−27.5)	18	34 (0–175)	(−49.2)	20 (0–183)	27	21 (0–163)	14.7	27	9 (0–124)	68.7
Chloride	430 (80–1830)	14	4900 (0–37,630)	(−1740) *	16	14,670 (0–77,890)	(−4410) **	6220 (11–105,420)	25	11,080 (0–136,470)	(−104)*	25	7710 (0–84,430)	(−77.6) *
Metals	mg	n	mg		n	mg		mg	n	mg		n	mg	
Lead	930 (90–5560)	11	500 (0–2950)	37.0	13	1450 (0–14,220)	26.7	3410 (10–33,170)	23	630 (0–3400)	61.6**	23	700 (0–7480)	60.9**
Copper	1370 (360–4500)	12	900 (0–4450)	42.3	14	1030 (0–4850)	46.2 **	2840 (40–11,290)	25	1070 (0–5950)	74.5**	25	840 (0–6180)	81.1**
Zinc	11,730 (2510–44,590)	12	4700 (0–29,790)	52.9*	14	9460 (0–61,910)	18.0	25,300 (270–123,630)	25	4560 (0–24,180)	88.4**	25	2530 (0–14,330)	92.6**
Cadmium	124 (8–465)	11	35 (0–122)	71.6**	13	79 (0–423)	43.5 **	54 (0–382)	26	34 (0–239)	41.4**	26	17 (0–109)	63.7**

3.2. Nitrogen

The nitrogenous species nitrate, nitrite, and TKN, which make up total nitrogen (TN), were analyzed separately in an effort to quantify nitrogen treatment and further evaluate the treatment mechanisms within grass swales. The roadway nitrogen composition at this site closely matches similar studies of urban stormwater runoff (Vaze and Chiew, 2004; Taylor et al., 2005; Collins et al., 2010), with nitrate representing 39% of the total nitrogen concentration, nitrite making up 4%, and TKN representing the remaining 57% on average.

Water quality sampling shows greater variability in effectiveness for treating nitrogen than suspended solids. The effect of swales on TN is difficult to test statistically because it relies on measurements of all three components and technical difficulties in nitrate analysis greatly reduced the number of valid samples. However, the trend in TN appears to be moderate removal for the majority of storm events with a small number of events showing high export of nitrogen, particularly during the summer months. This treatment pattern is consistent with removal of dissolved species (nitrate, nitrite, and the dissolved portion of TKN) by infiltration or plant uptake and removal of particulate organic nitrogen (a component of TKN) by sedimentation. The intermittent export of nitrogen during summer storms is likely caused by the organic nature of the swales, perhaps tied to extraneous sources of nutrients, such as mowing, leaf litter, or other organic debris (Kruzic and Schroeder, 1990).

The oxidized nitrogen compounds nitrate and nitrite are present as dissolved species in stormwater runoff, being highly soluble and not well retained by soil particles (Henderson et al., 2007). Treatment in grass swales is therefore dependent on infiltration, plant uptake, and chemical/biological processes. The swales in this study significantly decreased nitrite concentrations (0.33–0.03–0.04 and 0.10–0.02 mg-N/L) and mass (50.5–71.5%), while showing variable effect on nitrate concentrations (Tables 2 and 3). Nitrate removal patterns follow the seasonal pattern described for TN, with moderate removal during the majority of events and export during a small number (10–20%) of summer storms. Similar patterns were seen in Rushton (2001), with significant mass reduction by infiltration, but occasional increases in mean concentration.

The primary removal mechanism for nitrate is infiltration, as shown by pollutant-duration curves with very similar input and output curves and a large gap due to captured events (Fig. 3c and d). Nearly all of the instantaneous HWY nitrate measurements exceed the target benchmark criteria of 0.2 mg/L for excellent water quality in the Potomac River Basin (Davis and McCuen, 2005), but infiltration reduces the exceedance durations to 17.4–27.8% (Table 2).

Inclusion of pre-treatment filter strips and vegetated check dams improved nitrate removal, with the greatest improvement attributable to check dams. This is particularly noticeable in pollutant-duration curves (Fig. 3c and d), which show that peak nitrate concentrations for the No-FS and FS swales exceeded influent concentrations, whereas effluent from the No-FS-CD and FS-CD swales remained below influent concentrations.

The consistent removal of nitrite by approximately an order of magnitude, regardless of nitrate export, suggests that nitrite treatment is related to mechanisms other than simply

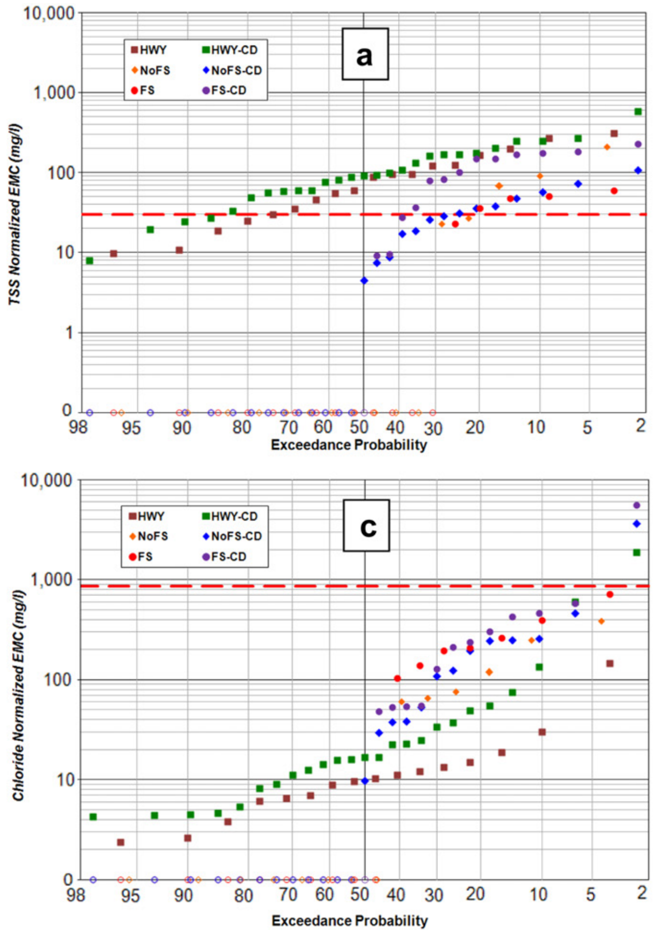

Fig. 1 – Lognormal probability plots of N-EMC showing influent (HWY, HWY-CD) and swale discharge (No-FS, FS, No-FS-CD and FS-CD). Hollow points represent storm events with complete capture of inflow. Dashed (—) line represents selected water quality targets (US EPA, 2002; Davis and McCuen, 2005).

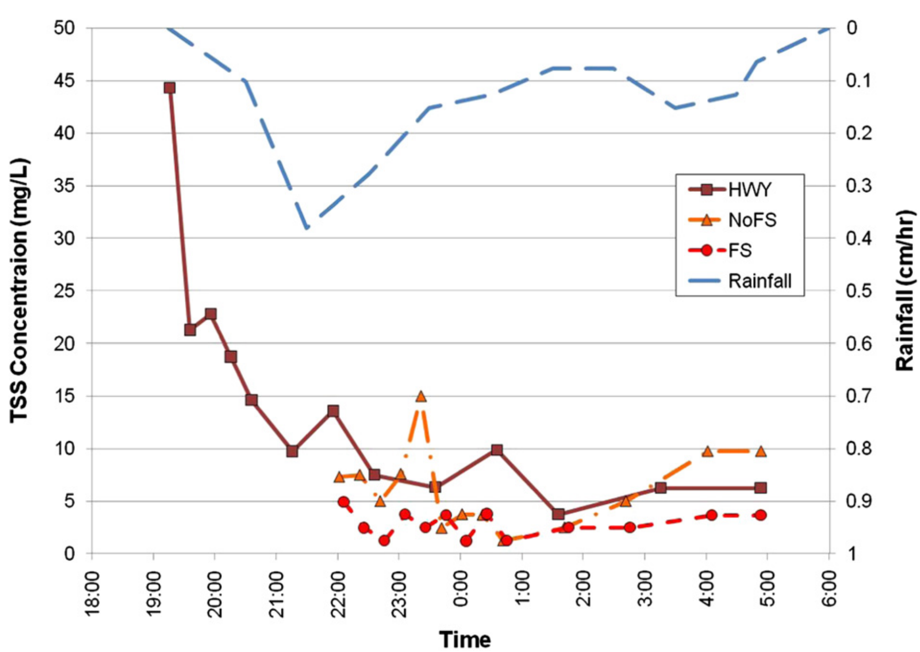

Fig. 2 – Total suspended solid (TSS) pollutograph showing measured concentrations with time for the 10/24/2005 storm event.

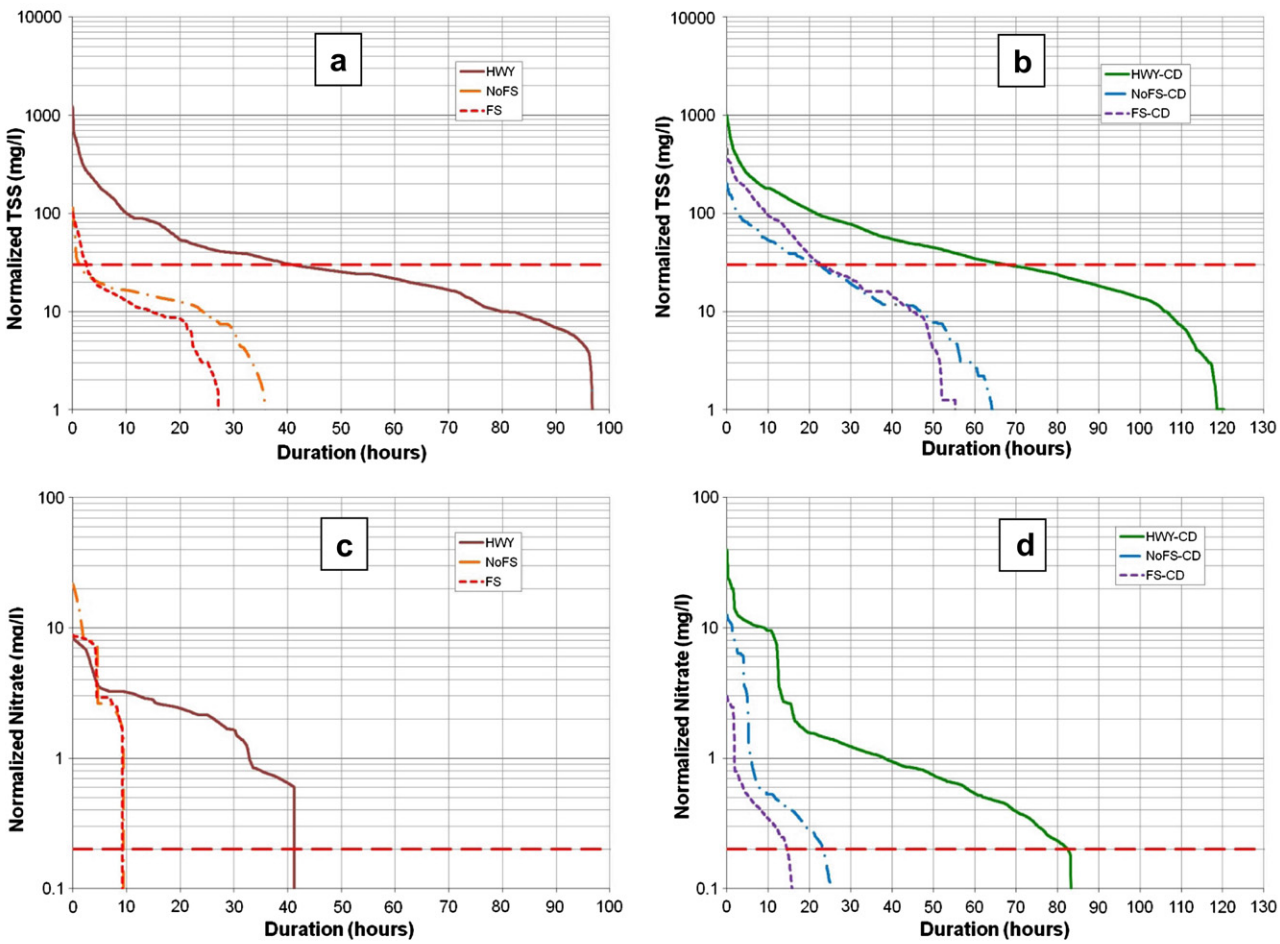

Fig. 3 – Pollutant-duration curves for TSS and nitrate. Dashed (—) line represents selected water quality targets (US EPA, 2002; Davis and McCuen, 2005).

Table 4 – Comparison of no filter strip design (No-FS, No-FS-CD) and filter strip design (FS, FS-CD) effluent N-EMC and total mass. Samples are paired by storm event. Positive values indicate that the FS design reduced effluent concentration or mass, while negative values indicate that the No-FS design was more successful at reducing concentrations or mass. Statistical significance is presented, with * representing $p < 0.1$ and ** representing $p < 0.05$.

Constituent	N-EMC		Mass (%)	
	Mean (No-Fs)-(FS)	Stat. Signif.	Mean (No-Fs)-(FS)	Stat. Signif.
TSS (mg/L)	(−47)	**	(−9.2)	**
Nitrate (mg/L)	0.98		11	
Nitrite (mg/L)	0.004		(−0.25)	
TKN (mg/L)	(−1.6)		110	
TP (mg/L)	0.20	**	31	
Cl (mg/L)	(−170)	*	(−920)	**
Lead (μg/L)	(−6.2)		2.4	
Copper (μg/L)	(−0.23)		11	*
Zinc (μg/L)	9.5		5.3	
Cadmium (μg/L)	0.13		13	**

infiltration. This may be explained by oxidation of nitrite to the more stable nitrate mediated by aerobic mixing in the swale, as in the final stage of nitrification. Because nitrate concentrations are significantly larger than nitrite, it is not possible to verify this assumption through a mass balance.

Little difference was found among the swale alternatives with respect to nitrite.

TKN in urban stormwater runoff is composed primarily of dissolved and particulate organic nitrogen, with a small portion of dissolved inorganic NH_4–N (Taylor et al., 2005). Measurements of swale effluent suggest that the swales decrease TKN concentrations across the majority of storm events, with intermittent export of TKN (Table 2). These releases of TKN coincide with releases of nitrate, suggesting similar sources, such as mowing. Filter strip and check dam alternatives do not affect removal significantly.

Because TKN measures both dissolved constituents (ammonium and dissolved organic nitrogen) and particulate organic nitrogen, its removal mechanisms include those described for nitrate and nitrite (infiltration, plant uptake, microbial action, and nitrification) as well as sedimentation and filtration. Assuming that particulate nitrogen removal follows TSS removal, which was successful for all swale designs, it appears that the variability in TKN removal is due to fluctuations in the dissolved species. This is likely caused by the same seasonal influx of organic detritus noted for nitrate and nitrite.

3.3. *Phosphorous*

The swales show relatively little capability for decreasing total phosphorous (TP) levels in highway runoff, showing mean N-EMC inputs of 0.55 and 0.34 mg/L, with discharges of 0.16–0.29 mg/L (Table 2). This is not unexpected, as Wu et al. (1998) found successful removal of all tested runoff constituents, except for total phosphorous.

The swales are most capable of treating storm events with influent TP concentrations greater than 0.7 mg/L, while less capable during storm events with low influent phosphorous concentrations (Fig. 4). The lower treatment limit may be caused by limitations in the treatment mechanism for phosphorous. Phosphorous in urban stormwater runoff tends to be distributed with approximately 70% bound to particulates and 30% in dissolved form (Wu et al., 1998). The majority of particulate phosphorous is bound to relatively fine particles, between 11 and 150 μm in diameter (Vaze and Chiew 2004). The lower phosphorous removal limit is likely related to the portion of phosphorous adsorbed to very fine particles that cannot be removed by sedimentation due to low settling velocities. Similar removal limits have been noted in bioretention studies (McNett et al., 2011), although the relevant treatment mechanisms likely differ.

Inclusion of a filter strip significantly improves removal of TP by an average of 0.2 mg/L. This effect is also evident with regard to dynamic TP concentrations, with pollutant-duration curves showing that filter strips decrease both peak and moderate TP concentrations (Fig. 5a and b). Inclusion of a check dam has negligible effect on phosphorous treatment.

3.4. *Chloride*

Analysis of chloride data suggest that the swales export, rather than remove, chloride from highway runoff for the majority of measured storm events, producing highly negative removal rates (Tables 2 and 3). The mean increase in chloride concentrations for all swale designs ranges from 36 to 203 mg/L. Additionally, increases in chloride mass release are statistically significant for all monitored swale design alternatives (Table 3). As an unreactive dissolved constituent, any removal of chloride is expected to occur by infiltration.

While application of NaCl as a de-icing agent is seasonal, chloride concentrations discharged from the swales remain elevated throughout the year. Assuming that de-icing salts are the sole source of chloride in the system and that chloride is a conservative pollutant, it follows that chloride accumulates in the roadside grass and soil and is released slowly during storm events throughout the year. Conversely, highway runoff has relatively low chloride concentrations for much of the year. This suggests that a small number of large chloride pulses occur during the winter, which are not captured by the monitoring program. This explanation is supported by two events sampled in early spring, following the application of salt, that produced high roadway chloride concentrations, 600 and 1880 mg/L, which exceeded swale effluent. Because sampling occurred only for storm events and no meltwater was analyzed, there are presumably more winter storm events with large HWY chloride pulses that would complete the annual chloride mass balance. This mechanism is supported by Kaushal et al. (2005), who found that chloride concentrations in streams throughout the northeast United States remain elevated long after the application of road salt in watersheds with significant impervious areas.

It is important to note that swale effluent N-EMCs exceeded a level considered acutely dangerous to freshwater aquatic life (860 mg/L, US EPA, 2002) during approximately 5% of measured storm events and instantaneous chloride concentrations exceeded this benchmark during 0.2–7.4% of the measured runoff discharge duration (Table 2).

Filter strips significantly increase the additional chloride exported from the swales by an average of 170 mg/L. This may be due to pre-treatment areas functioning as additional area to retain and later release chloride throughout the year. Inclusion of check dams had no effect on swale effluent chloride concentrations.

3.5. *Heavy metals*

Swales were generally effective with regards to metals treatment, with removal following the order: zinc > copper > lead > cadmium. This removal hierarchy agrees with other grass swale treatment studies (Schueler, 1994; Barrett et al., 1998). All swale designs were capable of significantly reducing the total mass and N-EMC for all monitored metals (Tables 2 and 3). The inclusion of check dams or pre-treatment filter strips has no significant effect on metal treatment efficacy, partly because of the effectiveness of the swales alone.

Metal removal by swales is primarily due to sedimentation and filtration because metals are predominantly bound to particulates in highway runoff (Morrison et al., 1983; Hallberg et al., 2007), with lesser portions in the dissolved phase. Zinc and cadmium tend to have a larger fraction in the dissolved phase, while lead tends to be almost entirely bound to particulates and organics (Legret and Pagotto, 1999). Copper

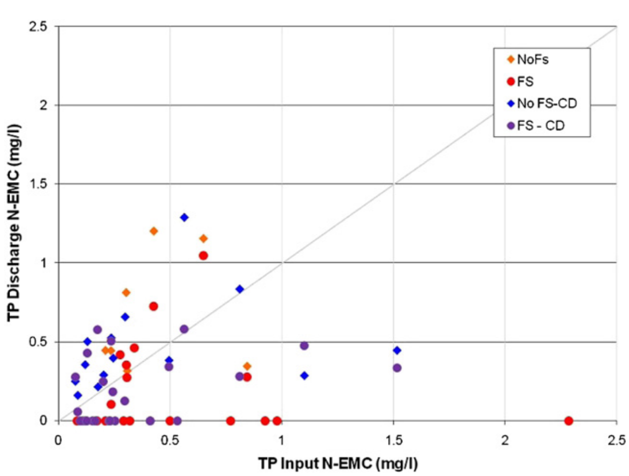

Fig. 4 – Total phosphorous (TP) event mean concentration (N-EMC) discharged by the swales plotted against influent runoff concentration (HWY). The 1:1 line is plotted for reference, representing no reduction in effluent concentration. Completely captured storms are plotted on the abscissa.

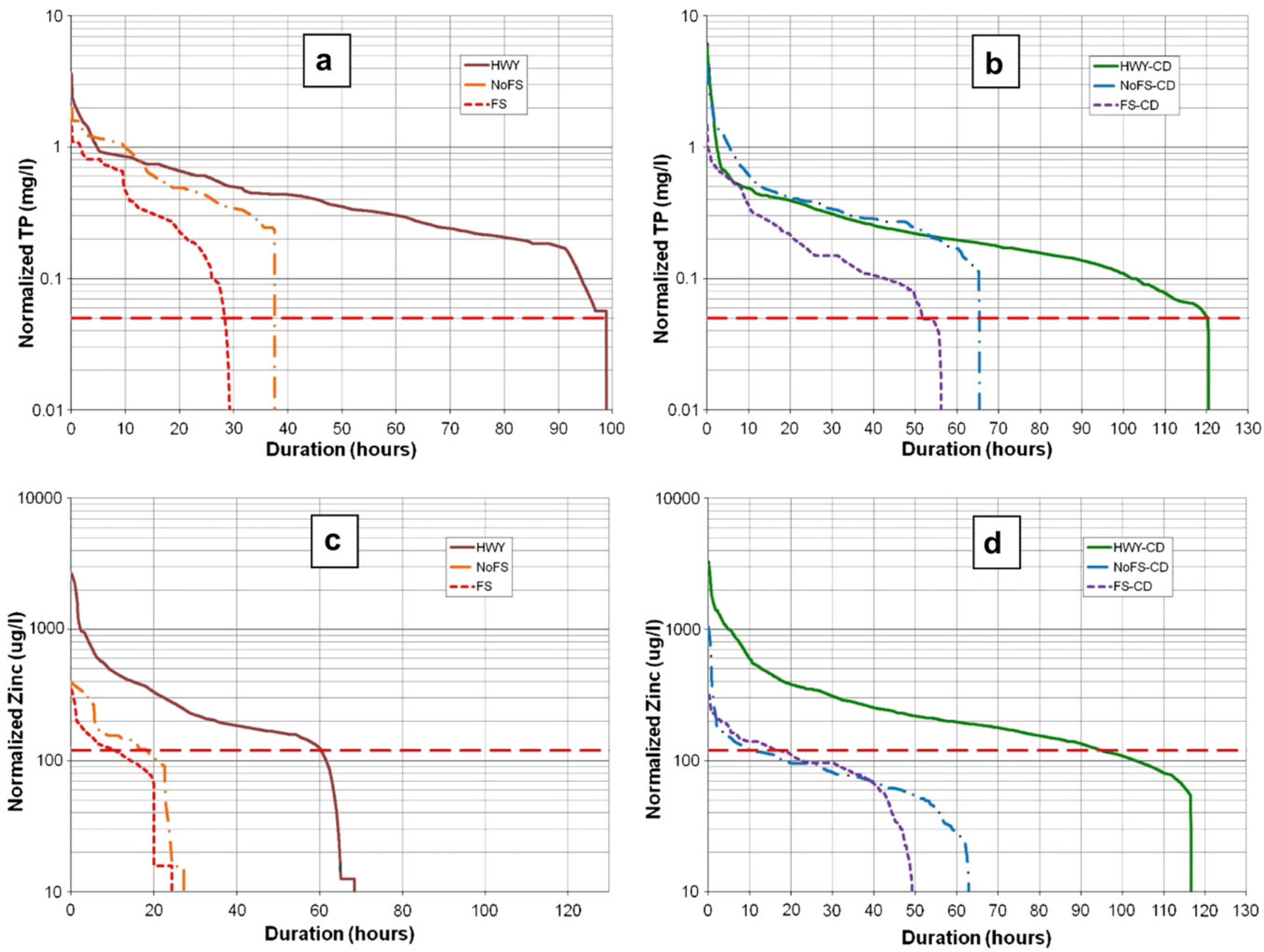

Fig. 5 – Pollutant-duration curves for TP and zinc. Dashed (—) line represents selected water quality targets (US EPA, 2002; Davis and McCuen, 2005).

speciation is much more dependent on rainfall conditions and is common in both the particulate and dissolved phases.

Zinc is the most prevalent heavy metal in highway runoff and also shows the greatest removal by the grass swale system. Mean zinc effluent concentrations ranged from 8.6 to 18.4 μg/L (from inputs of 440–510 μg/L), with mass reduction showing a wider range (18.0–92.6%) (Table 3). These findings agree well with previous studies that show zinc EMC reductions of 75–91% (Barrett et al., 1998) and mass removals between 46% and 81% (Schueler, 1994; Rushton, 2001; Bäckström, 2003). The likelihood of a storm EMC exceeding the National Recommended Water Quality Criteria zinc acute and chronic freshwater limit of 120 μg/L (US EPA, 2002) is decreased from 90 to 95% to 10–20% by the inclusion of grass swales (Fig. 1d). The likelihood of instantaneous exceedances is decreased from 81.2 to 88.1% to 8.9–26.6% by the swales (Fig. 5c and d). The successful removal of zinc, a metal with a greater dissolved portion than the other tested metals, may be due to zinc's high influent concentrations. Successful removal of dissolved species may also occur because the dissolved phase tends to dominate during less intense storm events (Prych and Ebbert, 1986), when infiltration is most effective.

The swales show a moderate capacity for removing copper from roadway runoff. Mean effluent copper N-EMCs range from 7.1 to 20 μg/L from inputs of 56–70 μg/L and reductions are statistically significant for all swale designs (Table 2). Copper mass removal by the swales was statistically significant for all swales except for No-FS and range from 42.3 to 81.1% (Table 3). These results agree well with similar studies that report mass reductions of 14–67% (Schueler, 1994) and 23–81% (Rushton, 2001). The FS swale significantly reduced mean copper concentrations; however, copper removal by the No-FS swale (5.7%) was not statistically significant. Pollutant distribution curves show that the probability of exceeding the acute copper toxicity limit (13 μg/L, US EPA, 2002) is reduced from 84.9 to 91.5% to 31.3–40.1% in swales with check dams and to 14.3–20.0% in swales without check dams (Fig. 1b).

Mean lead N-EMCs are significantly reduced (to 4.4–17 μg/L) by the swales (from 24 to 82 μg/L mean EMC input), while mass reduction (26.7–74.5%) is only significant for swales with check dams (Table 3). Two outlier storm events produced extremely high lead discharges relative to their input concentrations. These individual storm events also showed high export of TSS, which follows logically because lead is predominantly bound to particulate and organic matter in highway runoff (Dean et al., 2005).

The swales appear capable of reducing cadmium concentrations (0.6–3.0 μg/L) and decreasing total cadmium mass (41.4–71.6%). However, many of the swale effluent samples were at or below detection limits for cadmium (2 μg/L), complicating an exact calculation of removal.

4. Conclusions

The performance of field-scale grass swales was evaluated as a simple and effective stormwater control measure for highway pollutant treatment and to characterize the effect of two alternative designs, namely the inclusion of a grass filter strip and vegetated check dams. In addition to overall performance metrics, sampling methodology allowed for monitoring of flow and water quality at specified intervals throughout the storm duration, providing important information regarding constituent delivery duration.

The grass swales significantly reduced pollutant mass and mean concentrations for several of the water quality constituents considered, including TSS and the metals lead, copper, zinc, and cadmium. Nutrient treatment was variable, effective for the majority of storm events, but showing large pulses during a few extreme events. This effect is seasonal, typically occurring during the summer months, and is likely caused by extraneous nutrient sources, such as mowing or other organic material. Nitrite was the only nutrient consistently removed by the swales. Except for a few late winter de-icing events, the swales increased effluent chloride concentrations by an order of magnitude. It is likely that high-chloride events were missed during winter.

Inclusion of a grass pre-treatment area adjacent to a swale of this size (~200 m length) produces mostly negligible improvement with respect to water quality. The pre-treatment area was responsible for reducing total phosphorous mean concentrations by an average of 0.2 mg/L, the only constituent for which the filter strip improved water quality. To the contrary, paired comparisons suggest that the non-filter strip swales outperform swales with a filter strip for TSS removal. This effect appears to be caused by successful treatment of low and moderate TSS concentrations by the filter strip, while allowing releases of TSS during periods of high influent concentrations.

Vegetated check dams had a negligible effect as well, improving grass swale performance only for nitrate removal. This may be attributable to longer travel times, greater infiltration and potential vegetative uptake. Check dams slightly decreased swale performance with regard to TSS treatment, likely from increased infiltration, causing decreased total volume and increased concentrations.

This research suggests that grass swales generally improve highway runoff water quality and can be employed, where physical limitations allow, to treat non-point source pollution. They should be considered as a cost-effective alternative that is capable of providing some protection for surface and ground waters, special living resources, wetlands, streams and other sensitive habitats. The swales themselves provide the primary mechanism for pollutant removal, capturing the first flush of high pollutant concentrations through infiltration, and then reducing the subsequent lower concentrations by sedimentation, filtration, and possibly biological/chemical processes. Inclusion of additional design features, such as pre-treatment filter strips or vegetated check dams, may provide some benefit, yet this effect is typically negligible by comparison.

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