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Limitations to vegetation establishment and growth in biofiltration swales

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Abstract

Limitations to vegetation establishment and abundance in biofiltration swales (also called biofilters or bioswales), vegetated storm-water facilities intended to improve runoff water quality, was studied through field monitoring and greenhouse experimentation. The various environmental factors influencing vegetation and organic litter abundance was investigated in eight bioswales in western Washington state, including three that were retrofitted. A nested 4 × 4 factorial greenhouse experiment tested the response of four turfgrass species commonly seeded in bioswales to three inundation regimes plus a control. In the greenhouse experiment and in the field, persistent inundation significantly suppressed germination and growth. Field monitoring further revealed that heavy shade overwhelms all other environmental factors. Where light is adequate, vegetation and organic litter biomass is strongly and inversely related to the proportion of time bioswales are inundated above 2.5-cm depth during the driest time of year (summer). For most bioswales, flow velocity and hydraulic loading during storm events appear too large to permit sedimentation of silt and clay particles, even with dense vegetation and abundant organic litter. Thus, herbaceous vegetation abundance may not provide a good indication of bioswale treatment performance, and actual storm-water treatment may be much poorer than is generally anticipated from previous studies.

Keywords: Biofiltration swale; Storm-water runoff; Nonpoint source water pollution; Inundation persistence; Hydraulic loading rate; Water quality

1. Introduction

Nonpoint source water pollution is considered to be the major cause of US surface water quality impairment (USEPA, 1997). Runoff from urban and suburban areas has become an increasingly common source of nonpoint source pollution and

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its associated habitat degradation. Acknowledging this problem, several governmental agencies, including the USEPA, have advocated construction of passive storm-water filtration facilities as a best management practice (Roesner et al., 1999; Claytor and Schueler, 1996). One such facility frequently used in the Puget Sound region is the biofiltration swale (also called biofilter or bioswale). Over 100 bioswales have been constructed in King County over the past 10 years to treat runoff associated with residential, commercial, and light industrial development.

Bioswales are vegetated channels designed to treat pollutants commonly occurring in storm-water runoff (Fig. 1). Storm water delivered by a network of storm sewers enters the channel at the inlet and receives treatment before it exits the outlet. Bioswales are generally at least 30 m (100 ft) long, 0.6 m (2 ft) wide, range in longitudinal slope from 0.5% to 6%, and located in series with detention ponds, which store runoff and reduce peak discharges. Although they are designed to convey runoff from the 100-year 24-h storm event, they are only intended to treat runoff effectively from much smaller and more frequent storms, typically up to the 2-year 24-h storm event (Ecology, 1996; King County, 1998). Bioswales are commonly confused with grassed waterways (also called swales), which are vegetated channels that convey, but do not necessarily treat, runoff (Novotny and Olem, 1994).

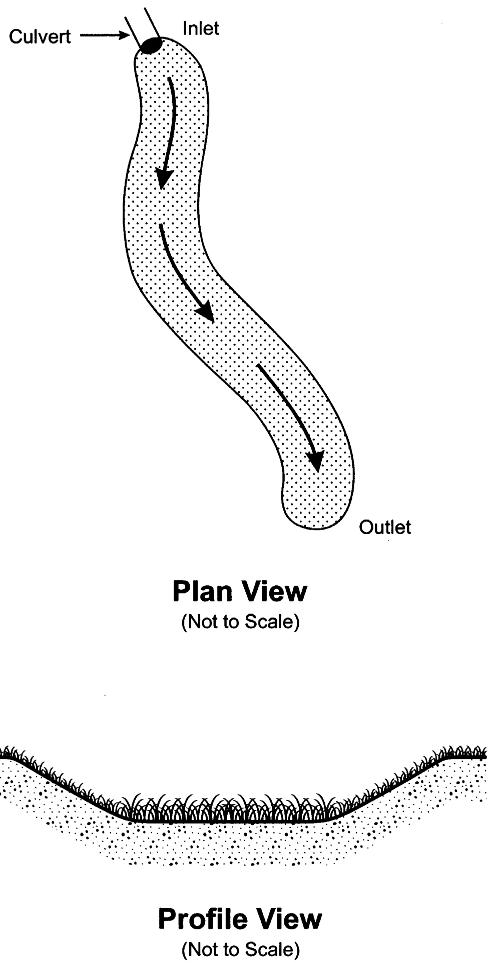

Fig. 1. Plan view and profile view schematic of typical bioswale (not to scale).

Pollutants in urban runoff, which include sediments, nutrients, metals, synthetic organics, pathogens, and hydrocarbons, are sequestered in the biofilter soil, sediment deposits, organic litter, and standing vegetation. Some pollutants, such as synthetic organic compounds, may then be transformed into less harmful substances via microbial decomposition. All captured contaminants may be removed when bioswale vegetation and/or soil are removed.

The treatment goal for bioswales in King County is 80% removal of total suspended solids (TSS), given typical TSS concentrations at the inlet (King County, 1998). Treatment efficiencies documented for bioswales and sections of grassed waterways (including roadside swales) have been documented to be 60–99% removal of TSS, 21–91% removal of metals, and 7.5 to more than 80% removal of total phosphorus (Kercher et al., 1983; Oakland, 1983; Harper et al., 1984; Yousef et al., 1985; Khan et al., 1992; USEPA, 1983; Goldberg et al., 1993; King County, 1995; Claytor and Schueler, 1996; Walsh et al., 1997). Treatment efficiency greatly depends upon inflow rate and pollutant concentration, both of which tend to vary considerably in storm-water runoff (Novotny and Olem, 1994; Tarutis et al., 1999).

Herbaceous cover in bioswales is generally considered to be well correlated with bioswale treatment efficiency. Aboveground plant parts (stems, leaves and stolons) are thought to induce sedimentation of particulates and their sorbed pollutants while plant roots stabilize sediment deposits, preventing sediment re-suspension (Horner et al., 1994; Claytor and Schueler, 1996; Kadlec and Knight, 1996). As most pollutants in urban runoff are in particulate form or adsorbed to sediment particles, sedimentation is believed to be the primary means by which vegetated control facilities improve runoff water quality (Horner et al., 1994; Claytor and Schueler, 1996). Vegetation and organic litter may uptake or absorb dissolved pollutants, but bioswales do not appear to capture dissolved pollutants very effectively (Khan et al., 1992; Horner et al., 1994). Regular (annual or more frequent) via mowing would permanently remove dissolved pollutants captured by vegetation and incur other benefits, such as increased flow resistance. However, mowing is costly and clippings are typically left in the biofilter, allowing pollutants to be released upon plant decomposition (Schultz, 1998).

A recent study found most bioswales in King County, Washington to be vegetationally depauparate and thus functionally inadequate (King County, 1995). Several environmental factors were blamed for the frequently poor vegetative cover in bioswales including prolonged inundation, high flow velocity, large fluctuations in surface water depth and soil moisture, excessive shade, poor soil, and improper installation. The relative importance of these limiting factors may vary widely amongst bioswales, and they can be a result of poor design, poor construction, and/or insufficient maintenance.

Our study monitored bioswales that represent the range of hydrologic condition and vegetation composition and abundance found in bioswales in western Washington. Seven of the eight swales examined in this study were built using the 1990 King County Surface Water Design Manual (King County, 1990) guidelines. For flows produced by the 2-year 24-h storm event, this manual specifies maximum permitted water depth of 10 cm (4 in.), flow velocity at 0.3 m/s (1.0 ft/s), and a design Manning's n of 0.035. No guidelines for inflow pollutant concentration limits or hydraulic loading rate (HLR) are provided by this manual.

Our study focused on the environmental factors that most influence vegetation establishment and abundance in bioswales. It also investigated aspects of bioswale design and the assumed direct correlation between herbaceous vegetation abundance and bioswale treatment efficiency. The principal objective of this research has been to develop recommendations for bioswale design that will improve their pollutant-removal performance.

2. Methods

2.1. Retrofit

Retrofits of three sparsely to moderately vegetated bioswales (SAY7, SAY8, and SAY9) were conducted to determine whether vegetative cover could be improved without altering bioswale hydrologic regime. The three swales, all located at the Saybrook Estates development in northern King County, were retrofitted in early fall 1996. Swale channels were widened to 1.6–1.8 m by trackhoe excavation. The top 15 cm of soil was removed and replaced with sandy loam. Soil layers were rototilled 8 cm below final grade and again at the soil surface. The bioswale soil was then rolled with a static roller to enhance erosion resistance. Although the original longitudinal slopes were retained, previous irregularities (dips and mounds) were smoothed.

The grasses *Agrostis stolonifera* (creeping bentgrass), *Festuca arundinacea* (tall fescue), *Poa pratensis* (Kentucky bluegrass), *Alopecurus geniculatus* (meadow foxtail), and *Festuca ovina* (sheep fescue) were hydroseeded on September 23, 1996. These species are all perennial turf and forage grasses that are native to or naturalized in the Pacific Northwest. Seeds were spread at a rate of 4 kg per 100 m^2 (8 lbs. per 1000 ft^2). Due to subsequent storm-induced erosion, SAY8 was hydroseeded a second time on October 1, 1996. To further prevent flow-induced erosion, hay bales were placed every 8 m (25 ft) down the length of this swale. SAY9 was also re-seeded due to poor initial establishment on August 18, 1997 by hand (using the same seed mix) after its water level had

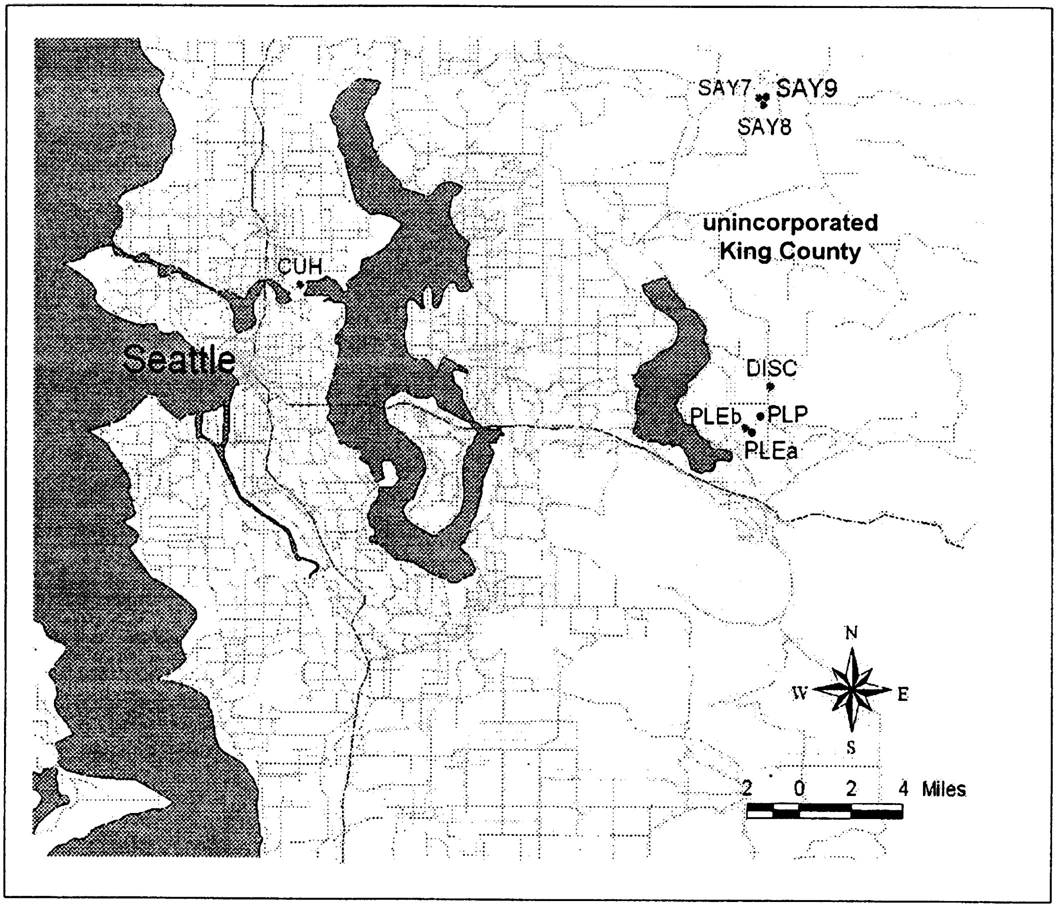

Fig. 2. Vicinity map showing bioswale locations.

dropped below the soil surface. Each swale's plant species composition and cover were recorded immediately before and 1 year following the retrofit. The details of this sampling methodology are discussed in the next section.

2.2. Field survey

Environmental factors thought to strongly influence vegetation establishment and abundance in bioswales were examined in eight bioswales, including the three that were retrofitted. These swales represent a wide spectrum of hydrologic, soil, and vegetative conditions and are located in three separate areas within King County (Fig. 2).

Bioswale dimensions ranged between 29 and 84 m length, 0.7–3.7 m width, and 0.23–1.95% slope. Three bioswales (PLP, PLEa, and PLEb) had check dams of crushed rock spaced 8 m (25 ft) apart down the channel length. The porous nature of the dams allowed seepage, albeit at relatively slow rates; thus, they were rarely overtopped during storm events. All swales, except those at Discovery Elementary (DISC) and the Center for Urban Horticulture (CUH), were situated immediately downstream of detention ponds.

Most swale conditions were measured at discrete stations (Fig. 3). The first station was situated 10 m (33 ft) from the swale inlet. Subsequent stations were spaced 15 m (50 ft) apart down the length of the swale. Due to the wide range in bioswale length, the number of measurement stations per bioswale varied from 2 to 5.

Relative cover by species was measured in June and September, 1997. Two adjacent 0.25 m^2 quadrats were used at each sampling station to visually estimate plant cover. In September 1997, all aboveground vegetation and surface organic litter contained within an open cylinder of diameter 0.12 m and height 0.1 m placed in the center of each quadrat was removed. This material was then oven-dried and weighed to determine each quadrat's aboveground biomass per unit area.

Aboveground biomass harvest was restricted to the layer of vegetation and organic litter occurring between the soil surface and 0.1-m height. Sampling this layer emphasizes its disproportionately strong influence on sediment trapping and pollutant decomposition and avoids having results skewed by plants, such as cattail (*Typha latifolia*) whose greater height provides no additional treatment. Biomass below 0.1-m height was sampled instead of stem density because a substantial portion of the species found were herbs rather than grasses; herbs may produce abundant aboveground biomass despite exhibiting low stem density.

Peak and instantaneous surface water depths were monitored weekly for 6- to 7-week periods during spring (April–May) and summer (August–September) of 1997 with crest-stage gauges placed on the upstream edge of each sampling station. Water depth data for all swales except PLEb and CUH were recorded during a 6-week period in January and February, 1996, and compared with hydrologic data for the spring sampling period. The interval of time a swale is inundated above 25 mm was measured weekly with the Inundation Sensor and Integrator (ISI), an electronic gauge developed by the senior author and Dr. Robin Cleveland, professor of mechanical engineering at Boston University. The ISI's timer is activated by the presence of water at or above 25-mm depth and de-activated when water fell below this depth. During weekly monitoring events, total time of inundation was recorded and the timer was reset. Soil moisture potential was assessed at each plot during the summer sampling period. Soil depth, percent gravel content, and bulk density were assessed after harvesting vegetation in September 1997.

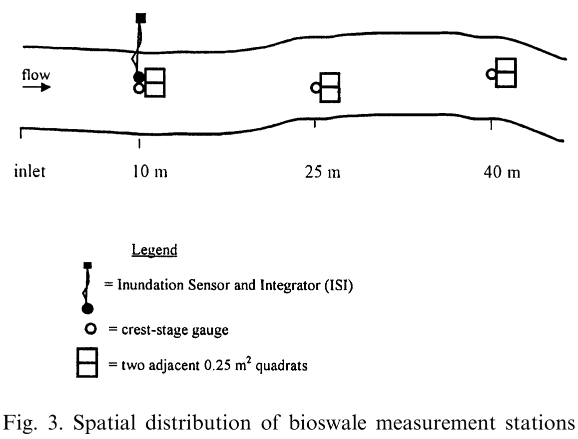

Fig. 3. Spatial distribution of bioswale measurement stations (not to scale).

Flow resistance coefficients (Manning's n) and stage–discharge relationships were established for each swale during storm flows. Flow widths were measured with a tape measure, flow depths were measured by the crest-stage gauge, and flow velocity was estimated by repeatedly timing the passage of a float through a measured distance. Both discharge and flow velocities were calculated for the mean peak, mean instantaneous, and highest peak ('maximum peak') flow depths of the spring and summer sampling period. Each bioswale's flow character and sedimentation potential were estimated by calculating the hydraulic residence time (HRT, the time required for an aliquot of water to travel from inlet to outlet) and hydraulic loading rate (HLR, the ratio of inflow discharge at the 10 m gauge to bioswale area).

County inspection records were examined to determine construction date, design discharges, and seeded species composition for all bioswales except the CUH swale, for which no records were kept. The NOAA 2-year 24-h isopluvial map was used to estimate the precipitation amount expected during the largest storm that bioswales are required to treat. Daily precipitation data taken from King County Land and Water Resources Division gauges at 1900 228th Ave NE ('MLU') was extrapolated for the Saybrook swales, each of which is within 2 km of this gauge. Data from the King County Land and Water Resources Division gauge on Old Black Nugget Road ('464') was extrapolated for all other bioswales except CUH. Daily precipitation data from a University of Washington campus rain gauge was used to estimate rainfall in the CUH bioswale catchment.

2.3. Greenhouse study

The greenhouse study tested the differential responses of four turfgrass species commonly seeded in bioswales to varying hydrologic regimes in a nested, 4×4 factorial experiment. Seeds of four grass species were placed in small pots (top length and width = 57 mm, depth = 83 mm) containing 30 mm of mulch/tackifier atop 40 mm of soil-less media (50% pumice, 35% peat, and 15% fine bark). The species used were the same as those seeded in the retrofit minus F. ovina. Nine replicates for each species/treatment combination produced a total of 144 pots. The hydrologic regime treatments were as follows:

- 'Control'...............no inundation; media kept moist, but not saturated throughout the experiment
- 'Dry'.................. 2 days inundated, 12 days with no watering
- 'Intermediate'.........7 days inundated, 7 days with no watering
- 'Wet'..................12 days inundated, 2 days with no watering

Inundation consisted of flooding pots 2–4 cm above the soil surface for continuous periods within two 14-day cycles. To gauge seed and seedling response to the treatments, aboveground biomass and leaf blade density were measured. Vegetation above the soil surface in each pot was harvested, oven-dried, and weighed at the experiment's end. Leaf blades per pot were counted twice per week throughout the experiment.

3. Results

3.1. Retrofit

Of the three bioswales retrofitted, only SAY7 developed a continuous and dense cover of grasses. The level of vegetation abundance and distribution attained would be judged adequate for effective biofiltration by King County and other agencies. Within two weeks of hydroseeding, SAY7 supported 10- to 50-mm tall *F. arundinacea* seedlings down the length of the swale. This species dominated vegetation throughout the study period, though *A. stolonifera* eventually established throughout the swale despite not germinating until eight months after hydroseeding. A small cluster of *A. geniculatus* established near the outlet where soils appeared slightly more moist. Neither of the other species (*P. pratensis* and *F. ovina*) seeded germinated in this swale. Mean herbaceous vegetation cover in SAY7 increased from 41% in September 1996 (immediately before the retrofit) to 98% in September 1997 (1 year after the retrofit). The average vegetation and organic litter biomass accrued in SAY7 was comparable to that of the other swales observed to exhibit high herbaceous cover even though these swales had been seeded 3–9 years beforehand.

The other two retrofitted swales, SAY8 and SAY9, attained only minimal germination due to persistent high flows (SAY8) or very persistent inundation (SAY9). Continuous base flow down the nearly 2% slope in SAY8 scoured soil and seeds alike. Drainage from the upstream retention pond appears to have deposited seeds of emergent herbaceous plants (e.g. *Alisma plantago-aquatica*) that subsequently established in shallow, low-energy areas. However, these areas were neither abundant nor densely vegetated. The much shallower slope of SAY9 (0.23%) impeded drainage, minimizing scour but prolonging inundation. The re-seeding on August 18, 1997 produced numerous seedling patches in the less shaded part of the swale (0–30 m). Except for a few *A. stolonifera* and *A. geniculatus* seedlings, however, most of the seeded vegetation did not survive through November 1997. Prolonged inundation combined with lower seasonal daylight appears to have suppressed seedling growth and establishment.

As the original seed mix was selected to tolerate a wide range of hydrologic conditions, it was expected that some species would establish in some bioswales more readily than in others. In SAY7, *F. arundinacea* was the first species to germinate and became the dominant species in the

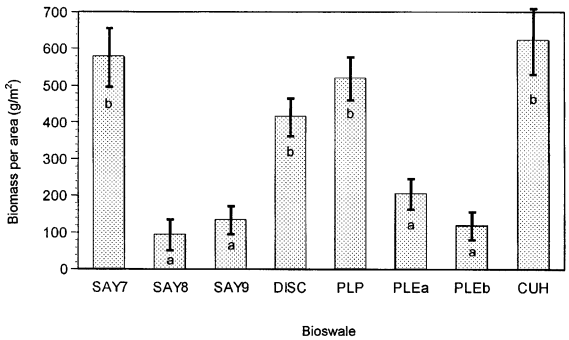

Fig. 4. Mean plant and organic litter biomass per bioswale.

swale. Upon establishing, it appeared to readily tolerate periods of surface water flow during the winter and the dry conditions that occurred during summer. Very few turf grasses grew in the other two retrofit swales, because conditions were so adverse to their establishment.

3.2. Field survey

3.2.1. Vegetation and organic litter abundance

A one-way ANOVA showed significant differences amongst the eight bioswales for mean plant and organic litter biomass. The Student Newman–Keul's post-hoc test distinguished two groups (Fig. 4). As the number of plots varied among swales, this test used a harmonic mean sample size of 3.45. SAY8, SAY9, PLEa, and PLEb are in the 'low-biomass group' (sparsely vegetated); SAY7, PLP, and CUH are in the 'high-biomass group' (well vegetated); and DISC belongs to both groups. Plant cover values were strongly correlated with plant and organic litter biomass ($r^2 = 0.90$), though cover tended to overestimate biomass in the mid-range values (Fig. 5).

Though nearly all of the biomass collected from SAY7 was derived from live grasses, organic litter and dead-standing vegetation constituted a majority of the total biomass in the other three swales of the high-biomass group. Most of the biomass collected from the swales in the low-biomass group appeared to be composed of organic litter.

3.2.2. Hydrologic and hydraulic characteristics of the bioswales

The hydrologic data revealed certain seasonal patterns common amongst all the bioswales surveyed in this study. One-tailed paired t-tests showed that mean peak and maximum peak depths were substantially, but not significantly, higher in winter than in spring. Slight significance ($P < 0.09$) was shown for differences between winter and spring instantaneous water depth. All measures of flow were significantly greater in spring than in summer.

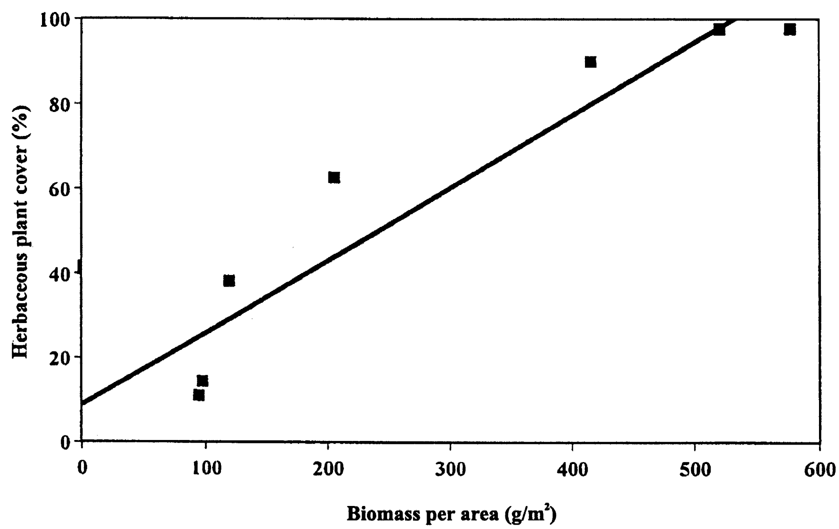

Fig. 5. Mean plant cover as a function of mean plant biomass. $r^2 = 0.90$, $n = 8$.

Table 1
Comparison of bioswale mean peak flow hydraulics, bioswale dimensions, presence of check dams, and vegetation abundance category

Bioswale	Spring sampling period			Summer sampling period							
	Mean peak water depth (mm)	Mean peak flow velocity (m/s)	Mean instantaneous water depth (mm)	Mean peak water depth (mm)	Mean peak flow velocity (m/s)	Mean instantaneous water depth (mm)	Slope (%)	Mean swale width (m)	Swale length (m)	Check Dams	Vegetation and Organic Litter Biomass Category
SAY7	44	0.15	2	2	0.02	0	1.9	1.8	65	no	high
SAY8	70	0.20	28	39	0.14	24	1.9	1.8	50	no	low
SAY9	59	0.10	40	39	0.08	11	0.2	1.9	50	no	low
DISC	88	0.13	6	104	0.14	11	1.8	2.0	84	no	high
PLP	147	0.03	29	21	0.01	8	0.7	3.7	60	yes	high
PLEa	76	0.02	23	57	0.01	34	0.4	1.3	29	yes	both
PLEb	102	0.03	43	13	0.00	9	0.5	2.2	66	yes	low
CUH	15	0.03	1	14	0.04	2	1.6	1.7	76	no	high
mean	75.1	0.07	21.5	36.1	0.06	12.4	1.1	2.1	60.0		
standard deviation	39.5	0.09	16.7	32.7	0.06	11.3	0.7	0.7	17.1		

Table 2
Comparison of bioswale maximum peak flow hydraulics during the spring sampling period

Bioswale	Water depth (cm)	Velocity (m/s)	Discharge (m^3/s)	HRT (min)	HLR (m/d)
SAY7	9.5	0.29	0.049	3.8	36.4
SAY8	15.5	0.34	0.098	2.5	93.2
SAY9	7.3	0.12	0.019	7.0	16.8
DISC	22.8	0.24	0.110	5.9	61.8
PLP	23.0	0.06	0.049	16.4	19.1
PLEa	15.5	0.03	0.006	16.9	13.1
PLEb	23.4	0.03	0.018	31.5	10.9
CUH	4.3	0.06	0.004	21.2	0.6
mean	15.2	0.15	0.044	13.2	31.5
standard deviation	7.6	0.13	0.041	10.1	31.3

However, each bioswale also has unique hydrologic and hydraulic characteristics determined by physical swale dimensions (e.g., longitudinal slope, presence of check dams, etc.), the presence of groundwater, and the size and imperviousness of the drainage area. Some aspects of bioswale hydraulics and physical dimension are compared with vegetation abundance category in Table 1. Hydraulic data collected during the maximum peak flow events of the spring sampling period are given in Table 2. Hydraulic data collected during the maximum peak flow events of the spring sampling period are given in Table 3.

The maximum peak flow events for both the spring and summer sampling periods occurred during storm events of much less intensity than what is regarded as the maximum treatable (2-year 24-h) for biofiltration according to King County (1990, 1998). Maximum peak flow during the spring sampling period occurred on 31 May, 1997 for most of the bioswales (SAY8, DISC, PLEa, PLEb, and CUH). Rainfall during this 24-h period varied between 51 and 58 mm, only 57–73% of the expected 2-year 24-h amount (90 mm). During the previous week, 22–36 mm of precipitation fell; this amount is only slightly higher than average weekly rainfall for the spring sampling period, which ranged from 17 to 29 mm. For the three other bioswales, precipitation during the week of 26 April–2 May produced the maximum peak water flow. Although the greatest 24-h precipitation during this week was not very high (18–30 mm), the weekly rainfall total ranged from 63 to 68 mm, which is over twice the average weekly total.

Despite these relatively modest rainfall totals, five of eight swales exhibited water depths during their respective maximum peak flows that were greater than the permitted maximum depths for the 2-year 24-h storm and thus did not meet King County (1990, 1998) performance standards. None of the swales exceeded the maximum permitted discharge (0.14 m^3/s) and only one swale (SAY8) exceeded the maximum permitted flow velocity (0.3 m/s). However, 4 swales had HRTs less than the recommended minimum (9 min) and 2 of these swales had HRTs less than the required minimum (5 min).

Only the CUH swale consistently exhibited both surface water depths and HRTs within the bounds of what is recommended for the 2-year 24-h storm event. Ironically, this is the only bioswale that was not specifically designed to meet King County (1990) standards. Disparities between storm-water facility design and performance have also been recognized by Booth and Jackson (1997), who report substantial differences between model predicted and actual discharges from detention ponds, and by Colwell (2000), who found that measured Manning's n values in bioswales commonly differed greatly from design specifications.

Table 3
Comparison of bioswale maximum peak flow hydraulics during the summer sampling period

Bioswale	Water depth (cm)	Velocity (m/s)	Discharge (m^3/s)	HRT (min)	HLR (m/d)
SAY7	0.5	0.04	0.000	30.0	0.2
SAY8	5.7	0.17	0.018	4.8	17.2
SAY9	6.2	0.10	0.014	7.8	12.8
DISC	31.7	0.29	0.190	4.9	96.7
PLP	9.5	0.03	0.012	36.3	4.6
PLEa	12.5	0.03	0.005	15.2	12.1
PLEb	6.1	0.01	0.002	89.3	1.3
CUH	2.8	0.05	0.003	23.5	1.5
mean	9.4	0.09	0.031	26.5	18.3
standard deviation	9.7	0.10	0.065	28.0	32.3

3.2.3. Correlations of bioswale biomass with environmental factors

Both field observations and greenhouse experimentation indicated a strong influence by hydrologic regime over herbaceous plant growth. However, hydrologic regime appears to have little influence in areas with chronically low light. The plots that were heavily shaded during the growing season (the 40-m plot at SAY9 and all plots at PLEb) supported very little standing vegetation and received much of their organic litter from overhanging trees. Because heavy shade appeared to override other environmental factors and greatly reduce bioswale vegetation and organic litter biomass, these plots were removed from the subsequent correlation analyses.

For the remaining plots, summer inundation persistence (IP) was the hydrologic variable with the most influence over bioswale plant and organic litter biomass ($r^2 = 0.97$) (Fig. 6). Persistent inundation during the summer sampling period, spanning multiple days, appeared to profoundly suppress swale biomass. Bioswales that were inundated for more than 35% of the time during summer contained significantly lower vegetation and organic litter biomass. In contrast, spring IP is only weakly correlated to bioswale biomass ($r^2 = 0.18$).

Mean instantaneous water depth during both spring and summer related had moderately strong negative correlations to bioswale biomass ($r^2 = 0.56$, $P < 0.1$ and $r^2 = 0.62$, $P < 0.05$, respectively). The correlation between swale biomass and spring mean instantaneous flow velocity was significant ($r^2 = 0.56$, $P < 0.1$). This relationship is collinear with the one between spring instantaneous depth and swale biomass since velocity increases exponentially with depth.

Although swale vegetation and organic litter biomass had no significant correlations with any of the physical soil variables measured (soil depth $r^2 = 0.09$, bulk density $r^2 = 0.20$, and relative gravel content $r^2 = 0.12$), soil depth was important to those plots exposed to summer drought (where mean soil moisture potential < -15 Mpa). Vegetation and organic litter biomass in these plots increased significantly with soil depth ($r^2 = 0.74$, $n = 10$).

The relationship between bioswale biomass and the HLR calculated for mean instantaneous water levels (Fig. 7) is similar to the relationship between bioswale biomass and summer period IP. However,

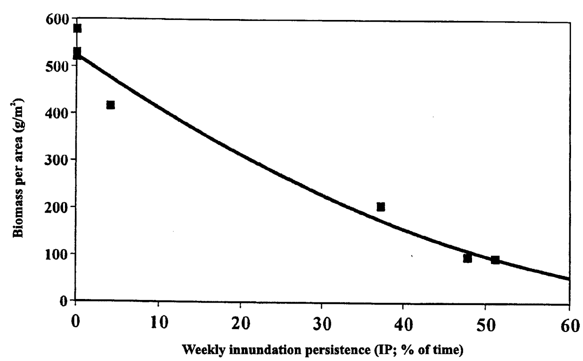

Fig. 6. Mean bioswale vegetation and organic litter biomass related to mean weekly IP during the summer period. $r^2 = 0.97$, $n = 7$.

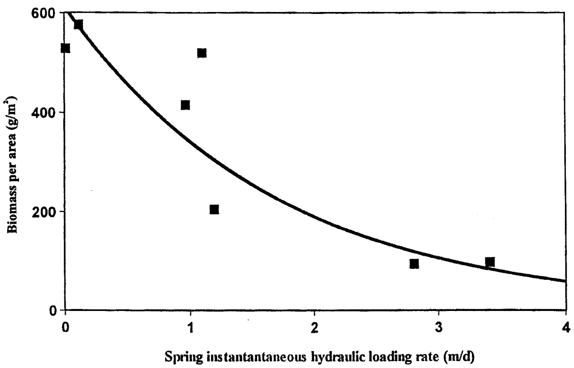

Fig. 7. Mean bioswale vegetation and organic litter biomas related to instantaneous HLR during the spring sampling period. $r^2 = 0.87$, $n = 7$.

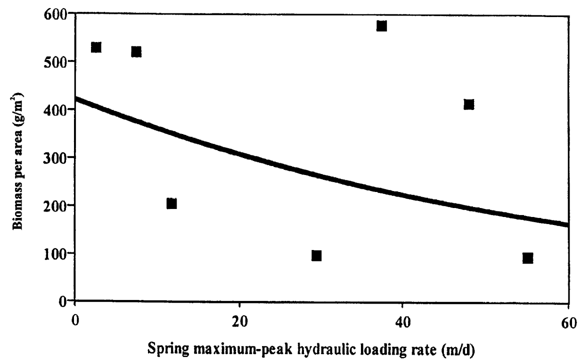

Fig. 8. Mean bioswale vegetation and organic litter biomas related to maximum peak HLR during the spring sampling period. $r^2 = 0.16$, $n = 7$.

HLRs calculated for maximum peak water levels have only a weak relationship with swale biomass (Fig. 8). The difference between the influence of mean instantaneous HLR versus maximum peak HLR upon vegetation and organic litter biomass occurs in both spring and summer data.

Within each species, final aboveground biomass and leaf blade accumulation was highest in 'Control' pots, where the media was kept continuously moist, but free from inundation. Final aboveground biomass and leaf blade accumulation was lowest in the 'Wet' pots, where inundation at 2–4 cm above the soil surface was maintained for 12 of 14 days for two 14-day treatment cycles (Fig. 9). The 'Wet' treatment produced equally minimal germination and growth amongst all species. For the 'Control,' 'Intermediate,' and 'Dry' treatments, *F. arundinacea* produced significantly ($P < 0.001$ for each treatment) more biomass than the other species tested. For each of these three treatments, *A. stolonifera* possessed significantly more leaf blades than the other species during the last three-quarters of the experiment. For all species, the largest increases in leaf blade number occurred during the times when pots were free from flooding.

4. Discussion

4.1. Environmental limitations to bioswale vegetation

Results of the field survey and the greenhouse experiment demonstrate that persistent, multi-day inundation severely limits germination and growth by grasses typically seeded in bioswales. In the field survey, persistence of inundation during the driest time of year (summer) was inversely related to bioswale vegetation and organic litter biomass. For all but the deeply shaded bioswale plots, the less inundation above 2.5-cm depth occurred during this period, the greater the vegetation and organic litter biomass. The relatively drier conditions in summer served as a window of opportunity for bioswale vegetation, allowing seed germination and encouraging plant growth.

For the grass species tested in the greenhouse study, persistent inundation was shown to significantly suppress germination and seedling growth. Conversely, aboveground biomass was greatest in pots that were kept moist but free from inundation (the 'Control' treatment).

Inundation severely inhibits germination and growth of plant species ill-adapted to living in

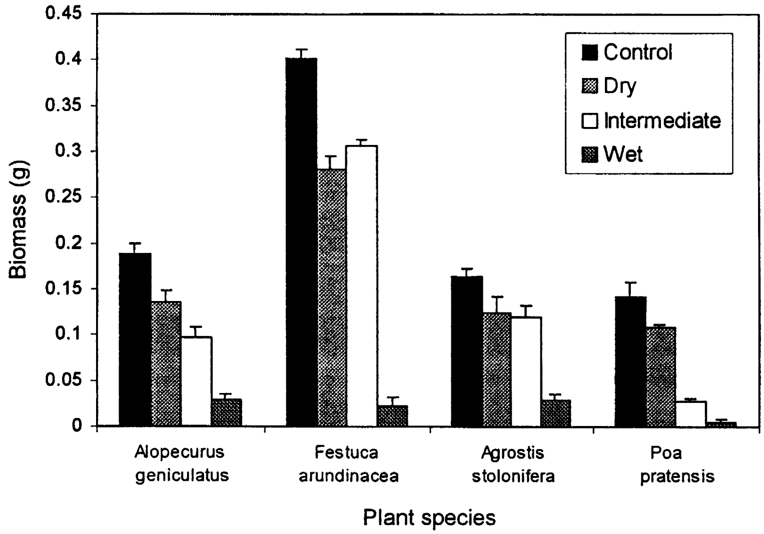

Fig. 9. Final dried biomass per species and treatment (+1 standard error indicated by error bars).

frequently flooded conditions. However, even plant species well adapted to inundation as mature individuals may be prevented from establishing in areas where inundation is persistent (Kozlowski, 1984; Ernst, 1990; Crawford, 1992, 1996; Ewing, 1996). This may partially explain why wetland areas with permanent standing water typically have both lower plant density and species richness than wetland areas with only seasonal or intermittent standing water (van der Valk et al., 1981; Emers, 1990; Cooke and Azous, 1993; Nielsen and Chick, 1997).

Bioswale vegetation abundance does not appear to be diminished by highly erosive flow, as long as such flows and/or inundation do not persist through the growing season. SAY7, DISC, and SAY8 all have relatively steep longitudinal slopes ($>1.5\%$) and high maximum peak flow velocities during spring (>0.2 m/s). Yet only SAY7 and DISC support dense herbaceous vegetation because unlike SAY8, these swales do not have year-round base flow. In the short-term ($\approx 1-14$ days), flowing water may be only slightly more harmful to grasses than standing water of the same duration (Temple, 1991).

Although often overlooked, light and soil conditions are also essential factors influencing vegetation abundance in bioswales. Germination and vigor of herbaceous plants is typically reliant upon at least moderate exposure to light (Gabriell, 1997). Those plots with heavy shading demonstrated consistently poor vegetation growth despite having other factors beneficial to vegetation abundance. Soil provides structural support and storage for nutrients, minerals, and water (Brady and Weil, 1996). Effective rooting depth appears especially important to vegetation survival in bioswales, an environment potentially subject to erosive flow and wide fluctuations in soil moisture.

4.2. Hydraulic indicators of bioswale performance

Given the wide variability of precipitation, pollutant removal efficiency in bioswales may be estimated by hydrologic characteristics, such as HRT and HLR better than by vegetation cover. Horner et al. (1994) state that bioswales require at least 9-min HRT for adequate pollutant attenuation. However, HLR may be a more appropriate surrogate for estimating treatment performance as it incorporates more complete information on channel length, channel width, and inflow discharge rate.

The hydraulic loadings that bioswales typically receive during storm events are far greater than those that allow effective treatment in overland flow wastewater treatment facilities. Typical HLR for overland flow wastewater treatment facilities, which are similar to bioswales in structure and intended function, is 0.01–0.1 m/d (Kadlec and Knight, 1996). This is approximately 3–4 orders of magnitude lower than the HLR that would occur in a bioswale with minimum dimensions (30-m length and 0.6-m width) under the maximum flow velocity (0.3 m/s) and water depth (0.1 m) permitted by King County (1990, 1998) Surface Water Manual for the 2-year 24-h storm event.

As mentioned above, the maximum peak flow event for all swales occurred during storm events of much less magnitude than the 2-year, 24-h storm event. Yet HLRs associated with maximum peak flow events were also very high, ranging from 6 to 932 times higher than the maximum that commonly occurs in overland flow wastewater treatment. Summer HLRs were lower than those in spring, but only SAY7 and PLEb supported mean peak HLRs below 0.1 m/d during this period.

Large HLRs in bioswales with longitudinal slopes less than 1.5% and/or flow constrictions characterize flow that is slow to moderately rapid and very deep. Large HLRs in bioswales with longitudinal slopes greater than 1.5% and no flow constrictions (e.g., check dams) indicate flow that is rapid and is moderately deep. In both cases, the flow is generally too deep and rapid to permit much deposition of the clay and silt-sized suspended sediments ($\leqslant 50$ μm diameter). This is especially unfortunate given that these particles, due to their strong sorption capacity, are often associated with the gravimetric majority of pollutants in urban runoff (Rexnord, 1984; Baker, 1992; Novotny and Olem, 1994).

Although most reported water-quality studies of bioswales neglect to describe the hydraulic or hydrologic aspects of the swales they study, several do provide sufficient information to determine that their bioswales received flows of much less magnitude than what appears to regularly occur in bioswales of King County. METRO (1992) reported good water-quality performance of a bioswale, but its flow was always shallow (<37 mm) and its HRT generally greater than 9 min. Flow in the bioswale monitored by Kercher et al. (1983) was so low that infiltration significantly reduced the volume upstream of the outlet during 10 of 13 storm events. Had inlet flow rates been more like those in most King County bioswales, pollutant removal may have been much less for these and other swales used inwater-quality studies.

4.3. Vegetation abundance and bioswale performance

Bioswale vegetation, regardless of abundance, did not appear to perform its intended function adequately – namely, inducing the sedimentation of suspended sediments and their sorbed contaminants via flow retardance. The rapid flow that occurred during even small rain storms did not appear to be strongly retarded in the swales with high aboveground biomass and longitudinal slopes greater than 1.5% (SAY7 and DISC). Conversely, the poor vegetative cover in PLEa and PLEb was well compensated by nonvegetal roughness (check dams), shallow slope ($<1\%$), and favorable swale geometry, which contributed to long HRTs.

Overall, this study found no relation between bioswale vegetation abundance and maximum peak flow HLR. Since HLR may be a plausible surrogate for treatment performance in bioswales, vegetative abundance is not useful or even relevant, at least under currently permitted hydrologic and hydraulic guidelines.

5. Recommendations

Establishing abundant herbaceous vegetation in bioswales is difficult, but achievable. Listed below in descending order of importance are some guidelines for achieving good vegetation cover:

- Avoid shading by adjacent vegetation, structures, or side slopes
- Minimize inundation during the dry season (prohibit continuous inflow bioswales)
- Install >0.2-m (0.7-ft) deep, moderately well-drained soil (e.g. sandy loam); soil should be lightly compacted with a static roller prior to first inundation
- Hydroseed during periods free from inundation and irrigate as necessary to facilitate plant establishment

- Minimize inter- and intra-seasonal hydrologic fluctuation by situating detention ponds upstream from bioswales, but avoid ponds with multi-day release periods
- Set biofilter longitudinal slope between 0.5% and 2% and maintain a constant gradient throughout the length of the swale.

Bioswales should only be located in areas that will remain clear of invading vegetation. Intact forests should not be cleared for bioswale construction due to the multitude of environmental benefits that forest provides. Swales should be mowed at least once per growing season to foster high stem density, but soil compaction should be avoided and clippings should be removed. Other efforts must be made as needed to prevent significant erosion and/or sediment deposition from occurring.

Although the above recommendations will improve the growth of herbaceous plants in bioswales, they probably will do little to improve bioswale treatment performance given current hydrologic and hydraulic design guidelines. To achieve significantly improved performance, these guidelines must be altered to ensure that inflow rates are greatly reduced. Erosion and flow convergence would be minimized if longitudinal slopes were not permitted to exceed 1.5%. Bioswale channel length and width should be sized such that resulting HLRs more closely approach those found with overland flow wastewater treatment facilities.

Vegetation abundance should not be considered an accurate indicator of treatment performance. Herbaceous vegetation may serve to facilitate the capture of sediments and their associated pollutants, but its influence appears minimal under the typically high flow found in bioswales during storm events.

Instead, we suggest that HLR be used as an estimate of sedimentation potential and treatment performance in bioswales and other storm-water treatment facilities. HLR is determined by flow rate and treatment area, factors that should predict treatment performance more accurately, and that are widely used in other evaluations of water-treatment processes. Using HLR thresholds as a basis for storm-water facility design would likely discourage the construction of bioswales in favor of large detention basins, which can more consistently improve storm-water quality across a broad range of storm events but require significantly more land to construct.

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