Seasonal Performance Variations for Storm-Water Management Systems in Cold Climate Conditions

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Abstract: Lack of widespread adoption of low-impact development (LID) designs in northern climates is in large part due to concerns about poor winter performance relating to (1) frozen filter media; and (2) dormant biological functions. An examination of six varied LID designs, in contrast with conventional best-management practices (BMPs) and manufactured systems illustrated that seasonal functionality was evident for many systems; however, the LID designs were consistently top storm water management performers. The designs were tested and monitored for cold climate performance from 2004–2006 to assess: filter media frost penetration, hydraulic efficiency, and seasonal variations of contaminant removal efficiency. LID systems evaluated included: two types of bioretention systems, a surface sand filter, a subsurface gravel wetland, a street tree, and porous asphalt. The LID performance data were contrasted with conventional structural BMPs (swales, retention pond) and some select manufactured storm-water systems (hydrodynamic separators); (3) a filtration system, and a subsurface infiltration system. Seasonal performance evaluations indicate that LID filtration designs differ minimally from summer to winter, while smaller systems dependent largely on particle settling time demonstrated a marked winter performance decline.

DOI: 10.1061/(ASCE)0733-9372(2009)135:3(128)

CE Database subject headings: Stormwater management; Best management practice; Performance characteristics; Water quality; Seasonal variations; Pollutants; Runoff; Cold regions.

Introduction

The widespread adoption of low-impact development (LID) designs for use in storm-water management is hampered by the perception that the systems are both new and untested, this despite the volumes of quality research to the contrary. One such range of challenges includes the reduced performance in cold climate, both for water quality treatment and hydraulic efficiency, resulting from frozen filter media, high chloride loads, and dormant biological functions Oberts (2003). Challenges of storm-water management for cold climates include: hydrology of snowmelt, temperature dependent changes in aquatic chemistry, water density, ion exchange capacity, and the large store of contaminants in rain on snow storage volumes during winter runoff events. Sansalone and Buchberger (1996), Sansalone and Glenn (2002), and Glenn and Sansalone (2002) detail the accumulation and partitioning of contaminants in urban snow. Snow dumping and hauling are commonplace and can have impacts of increased contaminant concentrations with varying impacts depending on the receiving waters (Pierstorff and Bishop 1980). Understanding the characteristics of heavy metals, organics, and inorganic compounds, as demonstrated by Sansalone and Glenn, in urban rain on snow runoff are an essential component to the development of effective management strategies.

For this study, six LID systems were evaluated: two types of bioretention systems, a surface sand filter, a subsurface gravel wetland, a street tree, and a porous asphalt system. The systems were monitored to examine seasonal variations in contaminant removal and hydraulic performance. The LID system performance data were contrasted with conventional structural best-management practices (BMPs) (swales, retention ponds), and select manufactured storm-water systems. The devices were configured and tested in parallel, with a single influent source providing nearly identical loading to each system. Treatment strategies were uniformly sized to target a rainfall-runoff depth equivalent to 90% of the daily precipitation frequency: for this site, a 2.5 cm daily rainfall depth (Table 1). Under the parallel and uniformly sized configuration, a normalized performance evaluation is possible because different treatment strategies of the same scale receive runoff from events of the same duration, intensity, peak flow, volume, antecedent dry period, water quality, and watershed loading.

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Note. Discussion open until August 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on February 20, 2007; approved on September 23, 2008. This paper is part of the ***Journal of Environmental Engineering***, Vol. 135, No. 3, March 1, 2009. ©ASCE, ISSN 0733-9372/2009/3-128–137/$25.00.

Table 1. Engineering Design Criteria for Tested Systems

Design specifications	Value	Unit
Rainfall-runoff depth	25.4	mm
Catchment area	0.4	ha
Treatment peak flow	2,450	m^3/day
10-year peak storm flows	8,570	m^3/day
Treatment volume	92	m^3
Volume drain time	24–48	h

LID Technologies

The implementation of the Phase II rules under the Clean Water Act requires the design and implementation of local storm-water management plans, and many communities are in need of more effective treatment strategies to be in compliance. This is especially poignant for areas with impaired waters under total maximum daily load (TMDL) jurisdiction that prohibit a net increase of contaminants by future development. The state of the practice currently focuses predominantly on peak flow reduction, with some attention also paid to sediment removal and volume reductions. Alternative LID designs are commonly subjected to increased scrutiny, especially with respect to cold climate performance while the same concerns for conventional and some manufactured treatment systems are more apt to be overlooked. A wide range of research exists for sand filters (Roseen et al. 2006; Urbonas et al. 1996; Veenhuis et al. 1989; Wanielista 1981) and bioretention systems (Davis et al. 1998, 2003; Dietz 2007; Dietz and Clausen 2007; Hsieh and Davis 2005; Hunt et al. 2006; Roseen et al. 2006; Winogradoff 2001). Less research is available on the use of subsurface gravel wetlands for storm water (Egan et al. 1995; Reuter et al. 1992; Roseen et al. 2006). Hood et al. (2007) demonstrated improved lag times and peak reduction for a LID development. Oberts (2003) characterized cold climate affects on BMPs and discusses the use of infiltration and filtration mechanisms for treatment of the first flush of meltwater as a viable storm-water management strategy. For manufactured storm-water devices, people are left largely to manufacturer claims for product efficiency, while for conventional systems there is an overall lack of data on cold climate specific performance. Some field assessments of hydrodynamic separators (Bannerman 2005) have indicated poor performance. Improved performance data will assist with municipal decisions and resource allocation relative to reducing contamination in surface waters.

Methodology

Study Area

The study site is located at the University of New Hampshire Stormwater Center (UNHSC) field facility and the data in this paper reflect events monitored between Aug. 2004 and Aug. 2006. A total of 27 rainfall-runoff events of varying characteristics were monitored over a period of two summers and two winters (Table 2). The UNHSC is located on the perimeter of a 3.6 ha (900 parking space) commuter parking lot at the University of New Hampshire (UNH) in Durham, N.H. The parking lot, installed in 1996, is standard dense mix asphalt, completely curbed, and is used to near capacity throughout the academic year. Activity is a combination of passenger vehicles and routine bus traffic. The runoff time of concentration for the lot is 22 min. With slopes ranging from 1.5–2.5%. The area is subject to frequent plowing, salting, and sanding during the winter months (typically November–April). Literature review comparisons of site runoff water quality indicate that contaminant concentrations are above or equal to national norms for parking lot runoff. The climatology of the area is characterized as coastal, cool temperate. Average annual precipitation is 122 cm uniformly distributed throughout the year, with average monthly precipitation of 10.2 cm+/−1.3 cm. The mean annual air temperature is 9°C, with the average low in Jan. at −9°C, and the average high in July at 28°C. Winter monitoring events (Table 2) coincide with colder months (November–April) where rain on snow events generated substantial runoff volumes. Snowfall events were not characterized as runoff was not generated by these events. Common cold climate conditions consist of: increased runoff due to rain on snow events and limited ground infiltration capacity; frost-related impacts on system performance associated with reduced or no infiltration capacity; change in roughness characteristics due to snow and ice cover; obstruction by freezing of piping or hydraulic control structures; chloride toxicity related to deicing practices; reduced particle settling velocities due to low temperature, high viscosity, and high chloride content runoff; dormant vegetation; and required depth of design for infiltration. This last point is substantial with respect to the freeze thaw consideration for designs of infiltration systems. In New Hampshire, the depth of frost ranges between 48−52″ from coast to inland. Additionally, for pervious pavements, greater depth of frost is as much of a concern as the rate of cycling between freeze and thaw, which is highest near the coast.

Storm-Water Management Site Design

The UNHSC field site was designed to function with uniformly sized, hydrologically isolated, parallel treatment systems. The site as a whole was designed to deliver “dirty storm water” to each device, without significant transmission impacts such as sedimentation from the distribution system or routing of the hydrograph. Rainfall runoff is evenly divided at the headworks of the facility. Effluent from each system flows by gravity into a sampling gallery, where sampling and flow monitoring are conducted. The parallel configuration normalizes the treatment processes for event and watershed-loading variations. Site design began in 2002 with construction completed in June 2004.

The original site surficial geology was almost entirely marine clays, which allowed for strict mass balance controls of influent and effluent flows. Within the systems, there are virtually no losses to or additions from groundwater, leaving changes in mass to “within-system” losses. The term “infiltration” here refers to the class of systems, the amount of which would be dependent on soil type.

Presented in this study are results from 15 treatment strategies tested at the UNHSC field facility. This includes three conventional BMPs (a stone-lined swale, vegetated swale, and retention pond), six LID devices (a surface sand filter, bioretention systems I and II, a subsurface gravel wetland, a street tree, and porous asphalt), and seven proprietary manufactured systems (two treatment trains including a hydrodynamic separator followed by a filter system, and a multichambered pretreatment system followed by a large subsurface infiltration device; and three hydrodynamic separators). The hydrodynamic separators (HSs) are presented in aggregate, as the intent of this paper is to present treatment strategies and, not individual product performance, and the overall performance within the HS class was similar. This is not to sug-

Table 2. Rainfall-Runoff Event Characteristics for 24 Storm Events, Durham, N.H.

Rainfall event	Peak intensity (mm/h)	Duration (min)	Total depth (mm)	Peak flow (m^3/day)	Volume (m^3)	Antecedent dry period (days)	Season
9/8/2004	27	1,590	59	2,523	184	7.0	Summer
9/18/2004	15	1,075	50	627	152	7.0	Summer
10/30/2004	21	705	11	964	31	13.0	Summer
11/24/2004	9	705	18	488	59	3.5	Winter
1/14/2005	24	645	17	2,345	115	1.3	Winter
2/10/2005	6	1,520	32	493	88	3.6	Winter
3/8/2005	3	1,220	20	260	45	5.7	Winter
3/28/2005	12	1,685	60	853	342	3.4	Winter
4/20/2005	12	480	15	475	113	5.9	Winter
5/7/2005	3	965	16	207	86	4.0	Summer
5/21/2005	6	1,150	23	421	102	3.0	Summer
6/22/2005	15	95	8	1,013	30	4.0	Summer
8/13/2005	24	765	13	2,045	57	10.0	Summer
9/15/2005	18	30	5	2,143	37	10.0	Summer
9/26/2005	27	400	14	1,587	35	5.0	Summer
10/8/2005	6	120	5	462	24	8.0	Summer
11/6/2005	12	100	7	1,163	63	10.8	Winter
11/30/2005	9	810	18	1,051	175	5.0	Winter
12/16/2005	18	630	35	1,073	216	5.5	Winter
1/11/2006	15	320	15	1,202	100	5.8	Winter
2/17/2006	12	110	3	342	4	2.5	Winter
3/13/2006	12	170	7	601	38	2.5	Winter
5/2/2006	12	1,920	60	938	323	7.0	Summer
5/9/2006	3	565	14	142	21	5.6	Summer
6/1/2006	125	485	51	9,017	365	10.7	Summer
7/22/2006	40	50	5	3,552	34	7.5	Summer
9/6/2006	30	585	16	3,169	211	4.5	Summer

gest that within the class of HS important differences do not exist, but rather not with respect to seasonal variations among devices. Some of the treatment systems are categorized as filtration systems (sand filter, bioretention, gravel wetland, street tree, and porous asphalt), and infiltration systems (the proprietary subsurface infiltration device).

The treatment strategies were uniformly sized to treat the same peak flows and runoff volumes, and convey or bypass large flows. Design criteria were based on a regional rainfall frequency analysis to determine a rainfall-runoff depth equivalent to 90% of the daily precipitation frequency.

Treatment unit designs and selection were primarily based on manuals from the New York Dept. of Environmental Conservation (NYDEC 2003), New Hampshire (NHDES 1996), and the Federal Highway Administration (Brown et al. 1996; FHwA 2002).

Sample Monitoring and Data Network

Detailed sample monitoring of the rainfall events occurred between August 2004 and August 2006. The monitoring strategy and data network are previously described (Roseen et al. 2006). Sample monitoring occurred at two primary locations, the influent distribution box, and the effluent sampling gallery. Sampling is performed using automated 6712SR ISCO samplers fitted with water quality probes, and a depth meter behind a Thelmar composite weir. An on-site rain gauge provides site specific hyetographic data. Runoff constituent analyses routinely include total suspended solids (TSSs), total petroleum hydrocarbons-diesel range (TPH-D), dissolved inorganic nitrogen (DIN, comprised of nitrate, nitrite, and ammonia), total phosphorous (TP), and total zinc (TZn). Samples are stored at 4°C or frozen until analyzed. All sample analyses are performed by a laboratory that is state certified for drinking water and wastewater.

Filter Media Frost Penetration and Hydraulic Efficiency

Seasonal variations in hydraulics were examined as changes in frost penetration and hydraulic efficiency measures of peak flow reduction and lag time. Filter media frost penetration was monitored throughout the winter months on both a weekly and rainfall-runoff event basis (before and after events). Frost penetration was monitored using a method developed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) (Ricard et al. 1976). Daily air temperatures, snow depth, rainfall, and runoff volumes were monitored. Frost penetration was then compared to rainfall-runoff characteristics to evaluate hydraulic efficiency. Hydraulic efficiency was evaluated by calculating a range of characteristics associated with the runoff hydrograph in comparison with the same characteristics from summer months. These characteristics are lag time (k_L) and a peak flow reduction coefficient (k_p), both calculated for a range of storm events. Lag time

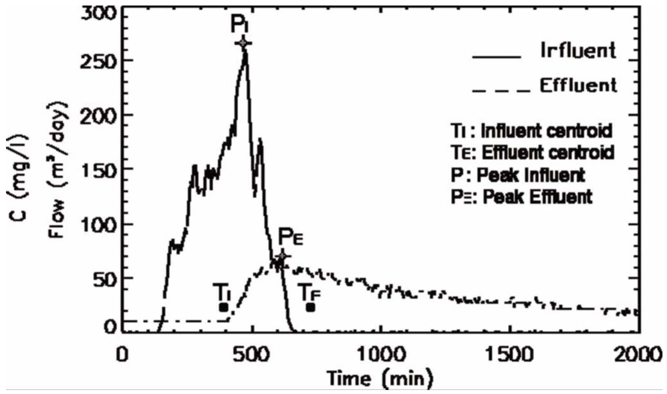

Fig. 1. Idealized hydrograph depicting use of peaks and centroids for lag (k_L) and peak reduction (k_p) coefficients

was measured as the difference in time between the centroid of mass for the influent hydrograph and the centroid of mass for the effluent hydrograph (Fig. 1). Peak flow reduction was measured as a peak flow reduction coefficient, which is a ratio of the effluent (P_E) to influent (P_I) hydrograph peaks. A peak reduction coefficient (k_P) less than 1 indicates that peak flow attenuation occurred. The lag coefficient (k_L) is the ratio of effluent hydrograph time to centroid (T_E) to influent hydrograph time to centroid (T_I). A lag coefficient greater than 1 indicates the runoff was delayed, typical of treatment systems with storage.

Seasonal Variations of Contaminant Removal Efficiency

Seasonal variations in water quality were examined using multiple performance efficiency measures using event mean concentrations (EMCs) for the range of treatment systems tested here over a period of two winters and two summers. All events were rainfall events, even in winter. Winter events were typically rain on plowed pavements and surrounding snowbanks. Two performance measures were calculated: removal efficiencies (RE), which can be defined mathematically as: $\mathrm{RE}_i = 1 - \mathrm{EMC}_{\mathrm{Outlet}}/\mathrm{EMC}_{\mathrm{Inlet}}$, where $i = \text{storm } 1, 2, 3 \cdots n$, and the value expressed is the median of the entire dataset; and efficiency ratios (ER), defined mathematically as: $\mathrm{ER} = 1 - \text{average } \mathrm{EMC}_{\mathrm{Outlet}}/\text{average } \mathrm{EMC}_{\mathrm{Inlet}}$. Values were split into climatic subsets and examined for seasonal differences. Seasons were assigned as 6-month intervals, summer (May–Oct.) and winter (November–April). A total of 15 (summer) and 12 (winter) storms were sampled for influent, while the number of storms reported for each system varied due to many factors, including system installation dates, maintenance, sampling and processing errors, and quality assurance reviews. Normalization of performance evaluations is accomplished by computing the RE and ER for the entire period of monitoring and seasonally (Strecker et al. 2002).

Results and Discussion

Filter Media Frost Penetration and Hydraulic Efficiency

Impacts due to cold climate were observed, yet were not substantial with regard to changes in hydraulic efficiency. Frost penetration was observed for nearly all of the filtration systems; however, it did not affect overall hydraulic performance. A predictable frost penetration cycle was observed that included frost penetration into a filter media before a rain and snowmelt event, which served to thaw the frozen filter media, followed again by frost penetration in the subsequent below-freezing days (Fig. 2). This cycle was observed throughout 70 days of the winter monitoring season in 2005, and 100 days of the winter monitoring season in 2006. The second winter season shows greater frost penetration overall that is not entirely explained by temperature differences. While 2006 appeared warmer overall, the month of February 2006 was far colder than 2005 and may be due to cumulative cooling degree days. An additional review of cumulative cooling degree days for the 2 years might explain the differences. It is conceivable that a system could thaw slowly and result in failure to properly attenuate a storm; however, this was not observed. It should be noted that frost penetration does not necessarily equate to filter media permeability: frozen media may still have significant porosity and permeability.

Examination of seasonal hydraulic efficiency impacts is illustrated in Table 3. The subsurface infiltration system showed the least seasonal variability, attributable to its location almost 2 m below the ground surface. For the surface filtration and infiltration systems, minimal change in the lag and delay coefficients was observed when compared to the annual average. All systems trended towards greater lag time in the winter, presumably from frozen filter media. Variations may be due to seasonal differences in rainfall pattern, which were not accounted for in this study, or due to changes in water viscosity due to temperature and attendant changes to percolation rate through filter media.

All filtration and infiltration systems (surface and subsurface) exhibited similar peak flow reduction performance between summer and winter. If hydraulic efficiency were to decline (frost in the system further reduces the influent peak), the k_P would decrease, which was not the case. The stone-lined swale was the only system for which a pronounced decline in winter performance was observed for both peak flow and lag time. The change in swale performance would be attributed to the change in Manning's roughness coefficient with the snow and ice coverage (approximately $n = 0.01$) over top the 15–20 cm diam stone and weeds (approximately $n = 0.04$).

Seasonal Variations on Contaminant Removal Efficiency

Figs. 3–6 illustrate annual, winter, and summer EMC variations for systems. Table 4 presents EMC statistics for the influent and effluent processes monitored. With the exception of nitrate, seasonal contaminant removal performance varied little for the filtration, infiltration systems, and retention pond. Only the stone-lined swale and the hydrodynamic separators suffered a noticeable seasonal performance decline in the winter. System performance statistics are presented in Tables 5–7 and illustrate substantial winter performance declines for TSS for the HS from summer (37%) to winter (15%), for the stone-lined swale from summer (80%) to winter (8%), and for the vegetated swale from summer (68%) to winter (13%) for both efficiency ratios and removal efficiencies. ER is a more stable estimation of overall treatment performance as it minimizes the impact of low concentration values, or relatively clean storms with low influent EMC concentrations. Whereas REs reflect treatment unit performance on a storm-by-storm basis, ERs weigh all storms equally and reflect overall influent and effluent concentrations across the entire data set.

The seasonal decline for the swale is likely due to similar

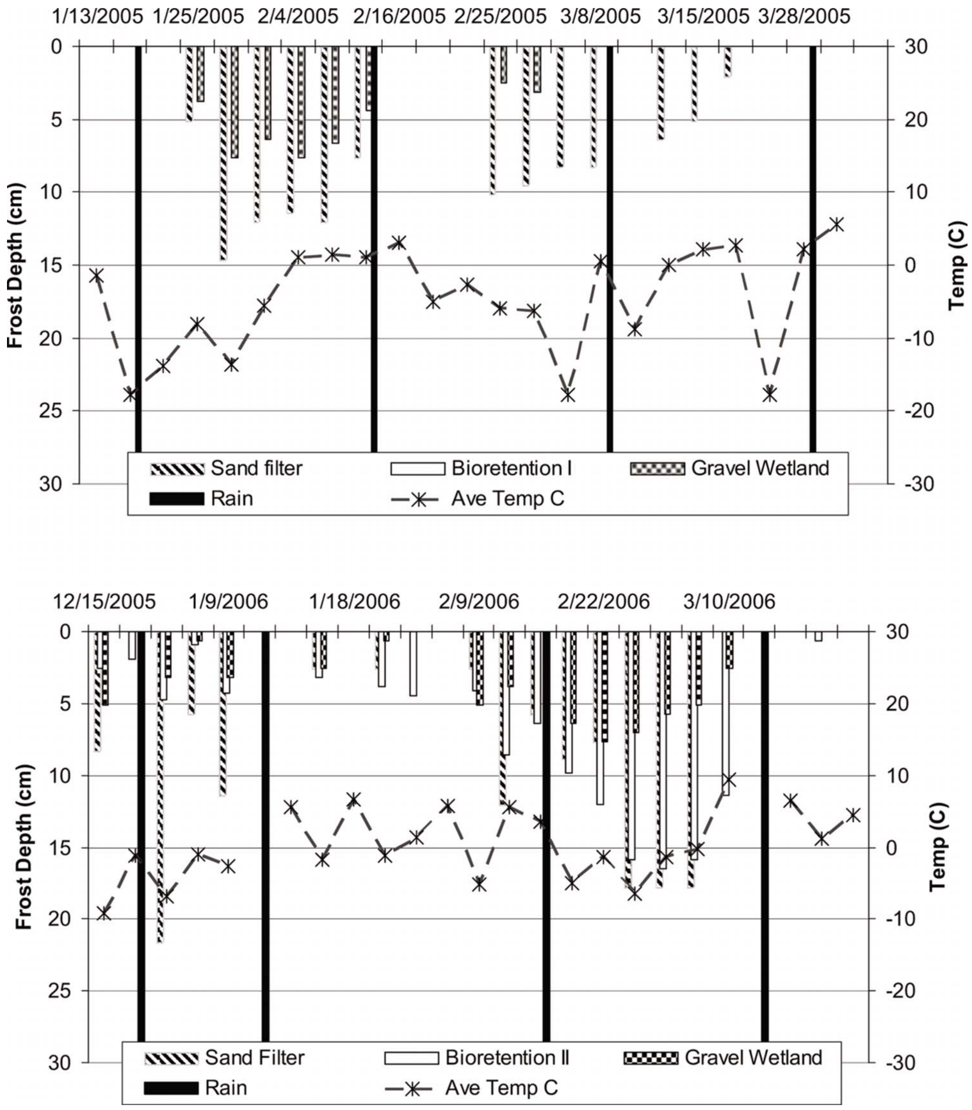

Fig. 2. Filter media frost penetration for 2004–2005 and 2005–2006 winters for a range of LID systems

reasons as described for its hydraulic performance due to cover with snow and ice. Interestingly all the HS devices showed a dramatic winter performance decline. The type of HS was not a factor for seasonal performance. Certainly there are differences between the HS that account for performance variations (inlet and outlet elevations, depth of sump, proprietary inserts), but these physical differences are time invariant. The HS seasonality occurred despite the higher sediment loading resulting from winter deicing practices. Examination of the theoretical settling velocities, in both transitional and turbulent conditions, demonstrates a dramatic effect from the viscosity of the rainfall runoff, influenced heavily by two seasonal factors: temperature and chloride concentration. The theoretical settling velocity for 100 μ spheres at 30°C with no chloride goes from 3.4 cm/sec to 1.6 cm/sec at 0°C with a chloride content equivalent to 1/3 the salinity of sea water (observed during this study for winter runoff). The median particle size (d_{50}) for the sediment captured within the three hydrodynamic separators was 410 μ. In this size range (<500 μ approximately), transitional settling can be expected (Minton 2006). Oberts (2003) discusses the change in viscosity attributed both to temperature and salinity as an important factor for settling velocity. This is consistent with design guidance from Jokela and

Table 3. Mean Annual and Seasonal Hydraulic Efficiency Lag (k_L) and Delay (k_P) Coefficients; Bioretention Is a Composite of the Two Systems Monitored

Device	Measure	Annual	Winter	Summer
Subsurface	K_1	1.6	1.7	1.5
Infiltration	K_p	0.13	0.15	0.12
Surface	K_1	1.5	1.5	1.3
Sand filter	K_p	0.27	0.27	0.26
Retention	K_1	1.8	1.9	1.8
Pond	K_p	0.13	0.16	0.10
Bioretention	K_1	1.7	2.0	1.3
	K_p	0.20	0.23	0.17
Gravel	K_1	1.6	1.6	1.6
Wetland	K_p	0.13	0.14	0.11
Swale	K_1	1.0	1.0	1.0
	K_p	0.56	0.77	0.39
Porous	K_1	4.5	4.72	3.8
Asphalt	K_p	0.18	0.24	0.13
Street tree/	K_1	1.2	1.28	1.18
Tree filter	K_p	0.69	0.75	0.60

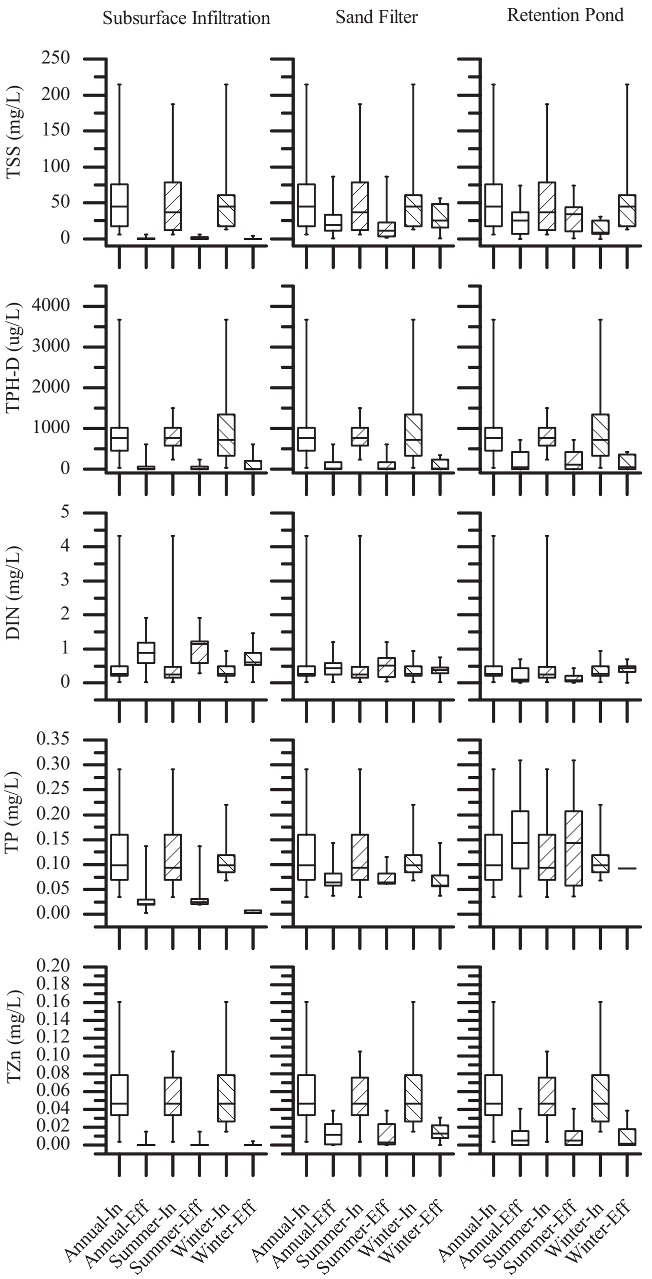

Fig. 3. Annual and seasonal influent and effluent EMCs for a subsurface infiltration system, a surface sand filter, and a retention pond; box and whisker plots indicate maximum, minimum, 75th, and 25th percentiles, and median; annual-In=annual influent; Annual-Eff=annual effluent; Summer-In=summer influent; Summer-Eff=summer effluent; Winter-In=winter influent; and Winter-Eff=winter effluent

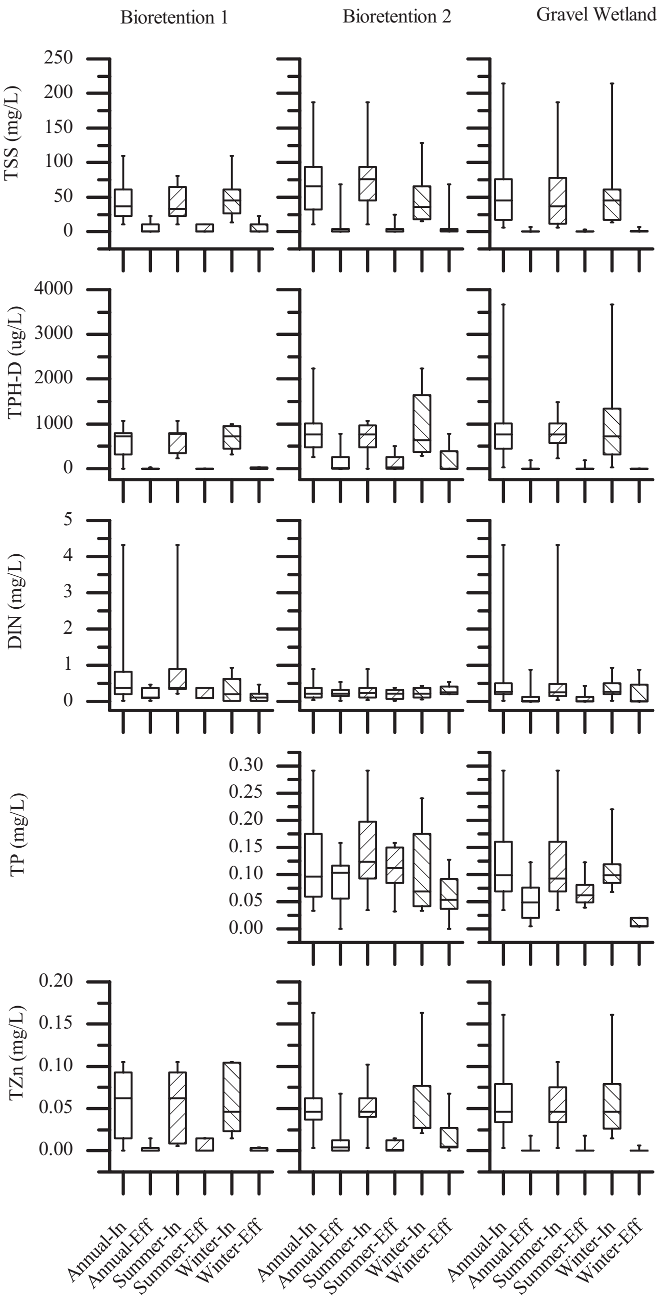

Fig. 4. Annual and seasonal influent and effluent EMCs for two bioretention systems and a gravel wetland; box and whisker plots indicate maximum, minimum, 75th, and 25th percentiles, and median; Annual-In=annual influent; Annual-Eff=annual effluent; Summer-In=summer influent; Summer-Eff=summer effluent; Winter-In=winter influent; and Winter-Eff=winter effluent

Bacon (1990) indicating a 50% decline in settling velocities from summer to winter. The poor overall performance for the HS is consistent with that presented by Bannerman (2005) who demonstrated a range of 5–19% performance as determined by a summation of loads for two popular HS devices in a northern climate. Although Bannerman does not attribute performance declines to changes in runoff density, he does note that the large discrepancies between field testing and laboratory testing methods have much to do with particle sizes and the range of observed flows often leading to resuspension of sediment.

DIN removal is not observed, as expected, in nonvegetated systems. Of the vegetated systems, the retention pond had the greatest seasonal decline in performance, followed by the bioretention system. The gravel wetland showed almost no seasonal variation. This lack of change is likely due to it being a subsurface treatment technology. Overall, the LID systems had less seasonal variations than the conventional structural BMPs.

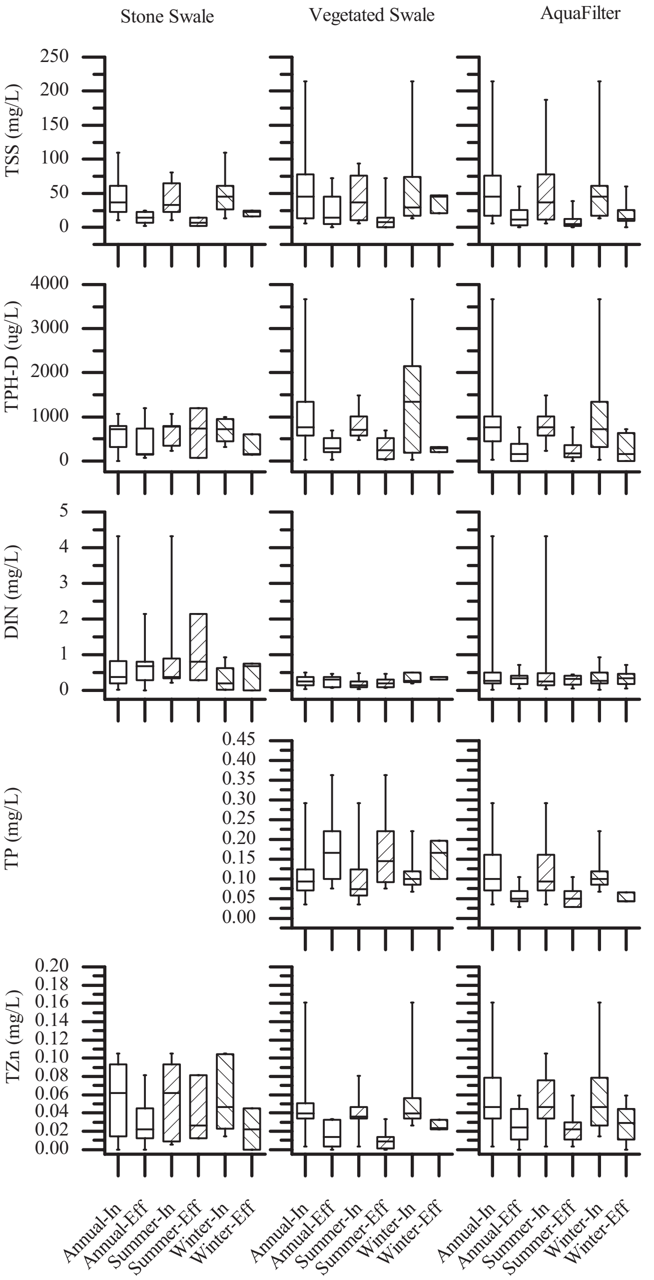

Fig. 5. Annual and seasonal influent and effluent EMCs for two swale systems and a proprietary filter system (AquaFilter); box and whisker plots indicate maximum, minimum, 75th, and 25th, percentile, and median; Annual-In=annual influent; Annual-Eff =annual effluent; Summer-In=summer influent; Summer-Eff =summer effluent; Winter-In=winter influent; and Winter-Eff =winter effluent

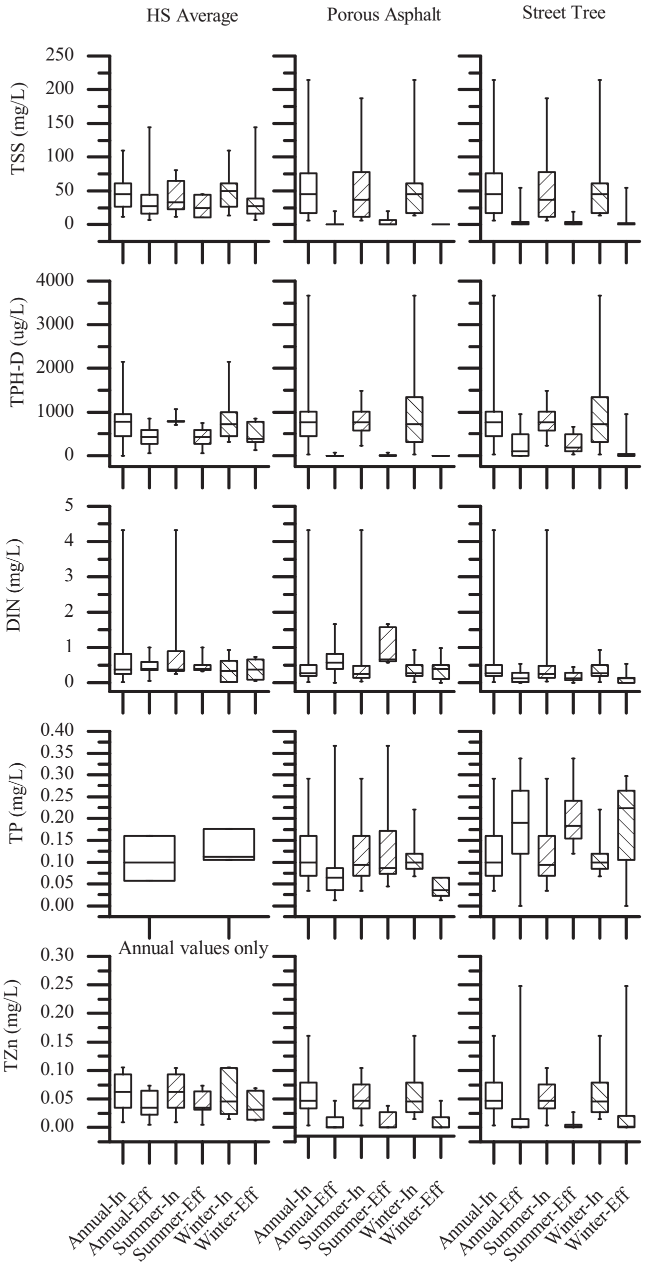

Fig. 6. Annual and seasonal influent and effluent EMCs for three hydrodynamic separator systems, a porous asphalt parking lot, and a street tree; box and whisker plots indicate maximum, minimum, 75th, and 25th percentiles, and median; Annual-In=annual influent; Annual-Eff=annual effluent; Summer-In=summer influent; Summer-Eff=summer effluent; Winter-In=winter influent; and Winter-Eff=winter effluent

Conclusions

Performance evaluations indicate that LID designs have a high level of functionality during winter months and that frozen filter media do not reduce performance. In contrast, the hydrodynamic separators and the swales exhibit large variations in seasonal performance. Conceivably this might lead to the need to oversize such systems in order to meet minimum performance expectations under worse case scenarios in which reduced settling velocity must be accounted for. The need for independent field testing of proprietary devices is underscored based on the differences observed between field testing (particularly during winter) and performance results commonly reported under laboratory settings. These results support the use of LID systems in cold climates and should dispel the concerns of reduced winter performance for fear of filter media freezing. It is interesting to note that many of the systems used routinely, without concern for reduced winter performance, are showing otherwise.

Table 4. Pollutant Event Mean Concentrations Statistics for Influent and Effluent of Systems Tested

System/pollutant	Statistic	Influent	Sub infil	Sand filter	Retention pond	Bioret 1	Bioret 2	Gravel wetland
TSS (mg/l)	Mean	55.54	0.93	26.10	24.33	6.47	7.26	0.80
	n	27	18	17	15	7	19	18
	SD	50.65	1.79	23.15	21.09	8.51	16.71	1.66
	Cv	0.91	1.92	0.89	0.87	1.32	2.30	2.07
TPH-D (ug/l)	Mean	894.0	69.7	111.0	186.5	4.3	157.5	15.5
	n	24	17	17	15	5	20	16
	SD	750.14	156.06	168.30	231.11	9.52	225.08	46.53
	Cv	0.84	2.24	1.52	1.24	2.24	1.43	3.00
DIN (mg/l)	Mean	0.49	0.92	0.45	0.22	0.19	0.24	0.14
	n	27	17	17	15	7	20	17
	SD	0.80	0.47	0.30	0.22	0.17	0.14	0.24
	Cv	1.64	0.52	0.66	0.99	0.86	0.58	1.77
TP (mg/l)	Mean	0.125	0.033	0.077	0.156	No data	0.094	0.057
	n	15	9	9	9	0	22	8
	SD	0.07	0.04	0.03	0.09	NA	0.04	0.04
	Cv	0.58	1.23	0.42	0.60	NA	0.47	0.66
TZn (mg/l)	Mean	0.05	0.00	0.01	0.01	0.00	0.01	0.00
	n	27	19	19	16	8	21	17
	SD	0.04	0.00	0.01	0.01	0.01	0.02	0.00
	Cv	0.67	2.77	0.89	1.22	1.87	1.70	2.25

System/pollutant	Statistic	Influent	Stone swale	Vegetated swale	Aqua filter	HS average	Porous asphalt	Street tree
TSS (mg/l)	Mean	55.54	14.57	22.26	14.93	36.18	2.22	6.59
	n	27	6	11	18	42	13	17
	SD	50.65	8.78	22.87	15.71	34.16	5.72	13.70
	Cv	0.91	0.60	1.03	1.05	0.94	2.58	2.08
TPH-D (ug/l)	Mean	894.0	482.4	318.2	266.6	458.2	6.5	225.0
	n	24	6	11	16	36	13	16
	SD	750.14	438.68	210.12	267.31	299.14	19.54	301.35
	Cv	0.84	0.91	0.66	1.00	0.65	3.01	1.34
DIN (mg/l)	Mean	0.49	0.78	0.27	0.32	0.46	0.66	0.18
	n	27	6	11	17	36	14	16
	SD	0.80	0.74	0.13	0.19	0.27	0.49	0.17
	Cv	1.64	0.95	0.50	0.60	0.59	0.73	0.93
TP (mg/l)	Mean	0.125	No data	0.172	0.060	0.126	0.094	0.192
	n	15	0	11	6	9	10	11
	SD	0.07	NA	0.08	0.03	0.04	0.11	0.10
	Cv	0.58	NA	0.49	0.44	0.33	1.12	0.50
TZn (mg/l)	Mean	0.05	0.03	0.02	0.03	0.04	0.01	0.02
	n	27	6	11	17	42	12	16
	SD	0.04	0.03	0.01	0.02	0.02	0.02	0.06
	Cv	0.67	0.92	0.78	0.72	0.57	1.46	2.63

Note: *n*=number of storms; SD=standard deviation; Cv=coefficient of variation; and Sub infil=subsurface infiltration.

Table 5. Seasonal Performance Statistics for TSS and TPH-D from 2004–2006

		Annual		Summer		Winter	
Analyte	Process	ER (%)	RE (%)	ER (%)	RE (%)	ER (%)	RE (%)
TSS	Sub infil	98	100	98	100	99	100
	Sand filter	53	51	56	83	53	50
	Retention	56	72	41	55	77	77
	Bioret 1	86	97	92	98	86	94
	Bioret 2	86	99	95	100	72	95
	Gravel	99	100	99	99	98	100
	Stone swale	68	50	85	80	64	8
	Vegetated swale	52	60	69	68	36	13
	Aqua filter	73	62	79	70	68	50
	HS average	34	27	49	37	24	15
	Porous	96	100	91	97	100	100
	Street tree	88	96	91	95	86	99
TPH-D	Sub infil	96	100	98	100	88	100
	Sand filter	93	98	94	99	90	96
	Retention	89	95	90	83	85	95
	Bioret 1	99	100	100	100	99	100
	Bioret 2	84	100	83	98	83	100
	Gravel	99	100	99	100	100	100
	Stone swale	28	33	67	9	72	52
	Vegetated swale	53	67	83	60	75	77
	Aqua filter	82	59	88	82	72	33
	HS average	72	42	78	42	55	50
	Porous	100	100	99	100	100	100
	Street tree	86	91	87	75	82	99

Table 6. Seasonal Performance Statistics for DIN and TZN from 2004–2006

		Annual		Summer		Winter	
Analyte	Process	ER (%)	RE (%)	ER (%)	RE (%)	ER (%)	RE (%)
DIN	Sub infil	−87	—	−72	—	—	−92
	Sand filter	9	−33	13	−36	−12	−27
	Retention	46	54	77	77	−9	48
	Bioret 1	75	44	69	73	43	39
	Bioret 2	41	14	31	26	26	−17
	Gravel	72	100	84	99	44	100
	Stone swale	−2	−72	−81	—	−34	−11
	Vegetated swale	65	−13	61	−5	1	−13
	Aqua filter	35	−18	54	−18	−3	−23
	HS average	10	−11	18	−4	−20	−20
	Porous	−35	—	−62	—	−22	−45
	Street tree	62	37	65	26	56	38
TZn	Sub infil	97	100	96	100	99	100
	Sand filter	75	77	79	97	76	75
	Retention	80	93	79	93	81	92
	Bioret 1	95	100	90	100	98	100
	Bioret 2	80	84	89	96	67	67
	Gravel	96	100	95	100	98	100
	Stone swale	48	64	18	72	64	56
	Vegetated swale	72	88	73	92	58	17
	Aqua filter	50	52	49	56	54	44
	HS average	21	24	18	26	27	25
	Porous	79	96	77	96	81	95
	Street tree	55	96	89	96	33	81

Table 7. Seasonal Performance Statistics for TP from 2004–2006

		Annual		Summer		Winter	
Analyte	Process	ER (%)	RE (%)	ER (%)	RE (%)	ER (%)	RE (%)
TP	Sub infil	74	81	62	67	96	95
	Sand filter	38	33	3	31	37	35
	Retention	−26	16	—	10	22	23
	Bioret 1	0	0	−78	0	N/D	N/D
	Bioret 2	27	13	27	19	41	13
	Gravel	54	55	38	33	90	89
	Stone swale	0	61	31	61	N/D	N/D
	Vegetated swale	−38	−95	−40	—	—	−64
	Aqua filter	52	26	47	22	55	30
	HS average	−1	1	16	4	12	−6
	Porous	24	38	−17	−49	66	57
	Street tree	−54	—	−61	—	—	−88

Acknowledgments

UNHSC is housed within the Environmental Research Group (ERG) at UNH in Durham, N. H. Funding for the program was provided by the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) and the National Oceanic and Atmospheric Administration (NOAA).

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