Performance analysis of two relatively small capacity urban retrofit stormwater controls

James Houle, CPSWQ, CPESC, PhD: corresponding author, program director of the University of New Hampshire Stormwater Center. E-mail: james.houle@unh.edu

ABSTRACT

The objective of the two-year study (2013-2015) was to provide performance data on stormwater retrofits that could not be sized according to conventional standards. Sediment and metal removals for both undersized systems were high with median removal efficiencies (RE) in the Subsurface Gravel Wetland (SGW) system (SGWSC#1) of 75% for both Total Suspended Solids (TSS) and Total Zinc (TZn). The Durham Bioretention (Durham Bio) (IBSC#2) recorded median RE of 86% for TSS and TZn. Total Phosphorus (TP) RE were higher than conventional Bioretention systems with the SGW system achieving a median RE of 53% and the Durham Bio achieving a median RE of 40% for TP. Both systems reduced total nitrogen by approximately 20% (23% for SGW and 21% for Durham Bio). Performance for all pollutants with the exception of dissolved nitrogen species approached performance expectations for conventionally sized systems despite being "undersized" by 90% for the SGW and by 70% for the Durham Bio as compared to conventional sizing methods.

Keywords: Performance, stormwater, green infrastructure, undersized, water quality volume, retrofit, low impact development.

INTRODUCTION

Stormwater runoff from roadways, parking lots, rooftops, and other impervious urban/suburban areas is a leading contributor to water quality and aquatic life habitat impairments in New England surface waters. Surface waters are routinely overloaded with excessive storm flows and pollutants such as nutrients (nitrogen and phosphorus), pathogens, trace metals, and petroleum hydrocarbons that accumulate on impervious surfaces in between storms and are readily washed off during rain events. Numerous scientific investigations have explored the relationship between the biological/ecosystem health of streams and the amount of impervious cover in associated tributary watershed areas. Results of these investigations consistently reveal that even relatively small amounts of untreated impervious cover in tributary drainage areas are a significant causative factor to aquatic life impairments and non-attainment of state water quality standards (Klein 1979; Schueler 1994; Booth and Jackson 1997; Schueler and L. Fraley-McNeal et al. 2009; USGS 2009; USGS 2011).

Stormwater management in developed watersheds presents a unique challenge of achieving compliance with evolving permit requirements while maximizing use of limited financial resources and limited space. To that end, stormwater managers need to be able to optimize a mix of controls, and choose from a menu of control practices and varying design capacities that have credible performance information and can be implemented across the development environment for a variety of site conditions and space constraints.

METHODS AND MATERIALS

Experimental Design

The main research objective was to evaluate the effectiveness of small capacity stormwater retrofit systems including the implementation of a SGWSC and an IBSC. The overall assessment of project effectiveness was conducted through runoff water quality sampling at the influent and effluent locations to each control (example sample locations are identified in Figure 8 and Figure 11). Pollutant event mean concentrations (EMCs) were evaluated at the influent and effluent to each control for each storm event monitored, in order to discern the extent to which the project retrofits resulted in improved runoff quality.

Event mean concentrations (EMC's) are a parameter used to represent the flow-proportional average concentration of a given water quality parameter for a storm event. It is defined as the total constituent mass divided by the total runoff volume. When combined with flow measurement data, the EMC can be used to estimate the pollutant loading from a given storm. Most of the EMC data collected during this study were based upon direct measurement from flow-weighted composite samples. Due to the variability of precipitation events and resultant runoff conditions, the sample trigger conditions and flow-weighted sample pacing were variable and adjusted on a storm by storm basis according to the most up-to-date precipitation forecasts.

EMCs are compared for each pollutant parameter using simple statistics. The data provides a basis to evaluate the primary study question; i.e., to discern whether the SCMs have served to produce observable (and perhaps statistically significant) improvement in water quality.

In addition to EMCs storm influent and effluent storm volumes were calculated for each system through direct flow measurements. Observations on volume and pollutant load reductions are provided for the SGWCS-1, however due to the ultra-urban location and unique dual inlet configuration of IBSC-2 no direct influent volume measurements were collected for the entire system. A comparison of modeled influent vs measured effluent was developed.

Field Sampling Protocols

Performance evaluation was based on data from 16-19 storm events. Storm event criteria were adopted from, and are in compliance with, the NPDES Storm Water Sampling Guidance Document (EPA 833-B-92-001) and dictate the following:

- The depth of the storm must be greater than 0.1 inch accumulation.
- The storm must be preceded by at least 72 hours of dry weather.
- If possible, the total precipitation and duration should be within 50 percent of the average or median storm event for the area.

Only data from qualified sampling events were used in the calculation of pollutant EMCs and pollutant removal efficiencies.

An overview of the analytes used in this study for water samples, their respective analytical methods and quantification limits are listed in Table 1.

Table 1: Sensitivity and Quantification Limits

Analyte	Analytical Method	Sample Detection Limit (mg/L)	Method Detection Limit (mg/L)*
Total Suspended Solids	SM 2540 D	Variable, 1-10	0.4
Copper in water	EPA 200.7	0.05	0.0006
Zinc in water	EPA 200.7	0.05	0.02
Ammonia	SM 4500NH3-D	Variable	0.5
Nitrate/Nitrite in water	EPA 300.0A	0.1	0.008
Total Kjeldahl Nitrogen	ASTM D359002A	0.5	0.5
Particulate Nitrogen	Calculation**	TKN (0.5), NO3 (0.1), NO2 (0.1)	TKN (0.2), NO3 (0.004), NO2 (0.005)
Total Nitrogen	SM 4500NH3	0.5	0.5
Phosphate in water	EPA 365.3	0.01	0.009
Total Phosphorus	EPA 365.3	0.01	0.008

(Based on EPA NE worksheet 9b and 9c)
* Method detection limit is different than sample detection limit which will be often be higher as they are based on sample volume available for analyses. For samples where lower volumes are collected or where more analytes are measured sample detection limits may be higher due to less sample volume available.
** The analytical method for determination of Particulate Nitrogen is a calculation between TKN (ASTM D359002A), NO3 (EPA 300.0A) and NO2 (SM4500NO2B).

Data Evaluation

Data analyses cover a range of approaches including:

- evaluation of storm characteristics
- evaluation of event mean concentrations
- normalized performance efficiencies

Storm characteristics such as total depth of rainfall, peak intensity, total storm volume, antecedent dry period, among others were collected for each storm event. Results for all storms sampled are presented in Table 2 (Oyster River Road) and Table 3 (Durham IBSC) Event mean concentrations (EMC's) are a parameter used to represent the flow-proportional average concentration of a given water quality parameter for a storm event. It is defined as the total constituent mass divided by the total runoff volume. When combined with flow measurement data, the EMC can be used to estimate the pollutant loading from a given storm. The EMC data collected during this study were based upon direct measurement from flow-weighted composite samples. Due to the variability of precipitation events and resultant runoff conditions, the sample trigger conditions and flow-weighted sample pacing were variable and adjusted on a storm by storm basis according to the most up-to-date precipitation forecasts.

EMCs are compared for each pollutant parameter using simple statistics. The data provides a basis to evaluate the primary study question; i.e., to discern whether the SCM has served to produce observable (and perhaps statistically significant) improvement in water quality and reduction in peak flow.

The range of statistical analyses presented reveals a range of performance trends. Efficiency Ratio (ER) analysis was performed on the final dataset. For many performance datasets for stormwater treatment systems, the ER is a stable estimation of overall treatment performance as it minimizes the impact of low concentration values, or relatively clean storms with low influent EMCs. Whereas Removal Efficiencies (RE) reflect treatment unit performance on a storm by storm basis, ERs weight all storms equally and reflect overall influent and effluent averages across the entire data set. REs are presented as both an average and median of aggregate storm values. In general aggregate median RE values are more reliable in highly variable, non-normally distributed datasets such as those experienced in stormwater treatment unit performance studies. A review of REs on a per event basis, ERs for the entire period of monitoring, and EMCs per event will reveal the measured performance variations attributable to season, flow, concentration, and other factors.

RESULTS AND DISCUSSION

Storm Characteristics

The monitored storm event characteristics for the SGWSC and IBSC are in Table 6 and Table 7, respectively. Flow monitoring for these systems is conducted at the influent and effluent locations and includes bypass events. Observations on volume and pollutant load reductions are provided for the SGWCS-1, however due to the ultra-urban location and unique dual inlet configuration of IBSC-2 no direct influent volume measurements were collected for the entire system. A comparison of modeled influent vs measured effluent was developed. Modeled influent values were developed using measured rainfall depths the watershed area draining to the SCM and a runoff coefficient to get the influent volume.

Table 2: Oyster River Road SGWSC storm characteristics for 15 monitored events where volume balance is the percent difference between influent and effluent measured volumes.

Storm Date	Storm Event Duration (min)	RAINFALL Rainfall Depth (in)	RAINFALL Peak Intensity (in/5-min)	INFLUENT Peak Flow (gpm)	INFLUENT Total Volume (gal)	EFFLUENT Peak Flow (gpm)	EFFLUENT Total Volume (gal)	EFFLUENT Volume Balance	Season	Antecedent Dry Period
5/22/2014	1,135	0.17	0.01	5.9	2,683	2.8	1,715	44%	Spring	4
5/27/2014	2,845	0.30	0.03	16.9	10,263	9.5	5,839	55%	Spring	3
6/5/2014	1,760	0.20	0.02	10.6	2,290	6.6	2,497	-9%	Spring	5
6/13/2014	2,010	0.68	0.05	130.7	13,273	66.4	15,831	-18%	Spring	7
6/25/2014	1,150	0.87	0.11	185.3	12,202	133.5	12,908	-6%	Summer	11
7/13/2014	430	0.19	0.02	37.5	2,730	21.0	1,988	31%	Summer	3
7/23/2014	1,235	0.36	0.05	35.6	4,076	18.1	2,060	66%	Summer	6
7/27/2014	1,155	0.39	0.12	27.1	1,930	26.1	3,489	-58%	Summer	3
8/13/2014	1,695	2.46	0.19	600.0	80,112	263.8	62,114	25%	Summer	5
9/2/2014	545	0.56	0.12	58.7	2,396	44.7	3,163	-28%	Summer	19
10/4/2014	2,710	0.21	0.02	9.0	2,201	8.0	3,304	-40%	Fall	3
10/21/2014	4,460	1.86	0.09	265.3	60,762	179.9	62,074	-2%	Fall	4
11/1/2014	3,045	0.35	0.01	9.1	4,956	10.6	9,728	-65%	Fall	8
11/6/2014	1,670	0.26	0.02	12.9	4,815	9.8	5,542	-14%	Fall	4
11/17/2014	2,160	0.91	0.02	65.3	29,130	61.0	39,924	-31%	Fall	10
n	16	16	16	16	16	16	16	16		16
Average	1,854	0.63	0.06	96.6	15,412	57	15,225	-2%		6
Median	1,683	0.36	0.04	36.6	4,885	24	5,691	-7%		5
Min	430	0.17	0.01	5.9	1,930	3	1,715	-65%		2
Max	4,460	2.46	0.19	600.0	80,112	264	62,114	66%		19
SD	1,026	0.65	0.05	152.8	22,877	74	20,582	0.39		4

Table 3: Durham IBSC storm characteristics for 20 monitored events where volume balance is the percent difference between influent and effluent measured volumes.

Storm Date	Storm Event Duration (min)	RAINFALL Rainfall Depth (in)	RAINFALL Peak Intensity (in/5-min)	Modeled Volume (gal)	EFFLUENT Peak Flow (gpm)	EFFLUENT Total Volume (gal)	EFFLUENT Volume Balance	Season	Antecedent Dry Period
10/6/2013	1,400	0.26	0.02	2,598	2.0	876	99%	Fall	8
11/10/2013	180	0.11	0.02	1,099	2.6	418	90%	Fall	13
11/17/2013	915	0.27	0.04	2,698	7.3	1,795	40%	Fall	6
11/26/2013	1,430	1.87	0.05	18,686	30.7	7,506	85%	Fall	7
6/5/2014	425	0.19	0.02	1,899	5.8	2,029	-7%	Spring	5
6/13/2014	745	0.68	0.05	6,795	57.0	6,080	11%	Spring	7
6/25/2014	455	0.87	0.11	8,693	238.1	7,887	10%	Summer	11
7/13/2014	130	0.19	0.07	1,899	28.7	1,868	2%	Summer	3
7/23/2014	605	0.36	0.05	3,597	60.5	4,736	-27%	Summer	6
7/27/2014	150	0.39	0.12	3,897	37.7	2,459	45%	Summer	3
7/31/2014	155	0.11	0.03	1,099	4.3	994	10%	Summer	3
9/2/2014	90	0.56	0.12	5,596	57.0	2,674	71%	Summer	19
9/6/2014	165	0.12	0.01	1,199	3.0	515	80%	Summer	3
9/13/2014	175	0.12	0.01	1,199	2.8	895	29%	Summer	5
10/1/2014	1,445	0.32	0.02	3,198	6.2	3,284	-3%	Fall	9
10/4/2014	1,015	0.20	0.02	1,998	5.8	6,965	-111%	Fall	3
10/16/2014	1,070	0.54	0.03	5,396	117.7	8,030	-39%	Fall	11
11/1/2014	1,750	0.35	0.01	3,497	5.9	7,615	-74%	Fall	8
11/6/2014	1,490	0.26	0.02	2,598	5.6	4,789	-59%	Fall	4
11/17/2014	1,375	0.91	0.02	9,093	25.3	11,976	-27%	Fall	10
n	20	20	20	20	20	20	20		20
Average	758	0.43	0.04	4,337	35.2	4,169	11%		7
Median	675	0.30	0.03	2,948	6.8	2,979	10%		7
Min	90	0.11	0.01	1,099	2.0	418	-111%		3
Max	1,750	1.87	0.12	18,686	238.1	11,976	99%		19
SD	574	0.41	0.04	4,140	56.2	3,288	0.58		4

Field Monitoring Results

Influent and effluent EMC and RE values are presented in table 4 and table 5.

Statistics include:

- n = number of storms evaluated for each parameter
- mean = arithmetic average EMC of all monitored events
- DL = detection limit
- ER = efficiency ratio which is the percent difference between the influent and effluent mean EMC values
- AVG RE = arithmetic average removal efficiency of all monitored events

- Median RE = median removal efficiency of all monitored events
- SD = standard deviation of EMC values
- Cv = coefficient of variation which is the ratio of EMC SD to mean EMC. This gives the level of variability in the data set. The lower the Cv the more consistent the values in the data set.

Table 4: Simple statistics summarizing monitoring results for Oyster River Road SGWSC.

Pollutant	Statistic	Influent	Effluent	Pollutant	Statistic	Influent	Effluent
TSS (mg/L)	n	15	15	**Zn (mg/L)**	n	9	9
	mean	107	17		mean	0.03	0.01
	DL	1	1		DL	0.01	0.01
	ER		84%		ER		76%
	AVG RE		54%		AVG RE		54%
	Median RE		75%		Median RE		75%
	SD	197	17		SD	0.03	0.01
	Cv	1.84	0.99		Cv	0.91	0.75
TN (mg/L)	n	15	15	**TP (mg/L)**	n	15	15
	mean	2.1	1.5		mean	0.27	0.11
	DL	0.5	0.5		DL	0.01	0.01
	ER		29%		ER		58%
	AVG RE		25%		AVG RE		52%
	Median RE		23%		Median RE		53%
	SD	0.47	0.40		SD	0.12	0.07
	Cv	0.23	0.27		Cv	0.43	0.61
DIN (mg/L)	n	11	11	**PO_4 (mg/L)**	n	13	13
	mean	0.3	0.4		mean	0.14	0.07
	DL	0.1	0.1		DL	0.01	0.01
	ER		-3%		ER		52%
	AVG RE		-11%		AVG RE		50%
	Median RE		-17%		Median RE		47%
	SD	0.2	0.3		SD	0.05	0.04
	Cv	0.57	0.72		Cv	0.37	0.53

Note: n = number of storms; DL = detection limit; ER = efficiency ratio; AVG RE = average removal efficiency; SD = standard deviation; Cv = coefficient of variation

Table 5: Simple statistics summarizing monitoring results for Durham Bio (IBSC#2).

Pollutant	Statistic	Influent	Effluent	Pollutant	Statistic	Influent	Effluent
TSS (mg/L)	n	19	19	Zn (mg/L)	n	19	19
	mean	106	21		mean	0.11	0.02
	DL	1	1		DL	0.01	0.01
	ER		80%		ER		84%
	AVG RE		73%		AVG RE		83%
	Median RE		86%		Median RE		86%
	SD	91	28		SD	0.05	0.02
	Cv	0.85	1.31		Cv	0.48	1.06
TN (mg/L)	n	19	19	TP (mg/L)	n	18	18
	mean	1.9	1.4		mean	0.14	0.07
	DL	0.5	0.5		DL	0.01	0.01
	ER		29%		ER		52%
	AVG RE		19%		AVG RE		32%
	Median RE		21%		Median RE		40%
	SD	0.83	0.53		SD	0.07	0.06
	Cv	0.43	0.38		Cv	0.49	0.85
DIN (mg/L)	n	13	13	PO_4 (mg/L)	n	8	8
	mean	0.4	0.4		mean	0.04	0.03
	DL	0.1	0.1		DL	0.01	0.01
	ER		0%		ER		31%
	AVG RE		-24%		AVG RE		27%
	Median RE		0%		Median RE		38%
	SD	0.3	0.3		SD	0.02	0.01
	Cv	0.88	0.81		Cv	0.44	0.46

Note: n = number of storms; DL = detection limit; ER = efficiency ratio; AVG RE = average removal efficiency; SD = standard deviation; Cv = coefficient of variation

CONCLUSIONS

This study underscores the benefits of opportunistic implementation of SCMs. In other words, the data indicate that the benefits from opportunistic sizing of SGWC or IBSC exceed linearly scaled performance expectations of appropriately sized SCMs. Appropriate sizing assumes that we understand the hydraulic routing and unit operations and processes responsible for pollutant load reductions. This study would indicate that our conventional sizing and design criteria are conservative especially with respect to TSS and TZn removal and do not accurately represent the hydraulic routing or the long term performance of innovative SCMs. Larger capacity SCMs will still be needed to minimize the delivery of additional nutrients from new development projects.

This has very important planning implications as many systems are modeled with routine assumptions with respect to performance and never verified or calibrated by real time flow data. These monitoring data highlight the cumulative benefits provided by smaller capacity systems ("undersized") in regions like New England where the vast majority of rain events are small. It is necessary to account for all rain events and especially the more numerous, smaller sized events that are capable of washing off significant amounts of pollutants from impervious surfaces in order to most effectively address the long-term cumulative impacts of stormwater runoff.

For this study, the undersized systems in very tight soils resulted in negligible volume reductions even though some water quality improvements were impressive. An important aspect of design and selection of green infrastructure is to recognize that the ultimate intent is to improve receiving water quality as well as to address impairments. Therefore, green infrastructure systems should be selected with the receiving water characteristics and impairments in mind.

The results of this study indicate that additional modelling analyses are needed to improve model predictions to estimate long-term cumulative TN load removals and/or that greater detail with respect to design residence time, particularly for internal reservoir based systems, need to be further develop.

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