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Performance analysis of two relatively small capacity urban retrofit stormwater controls

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TASK 1: EQUIPMENT INSTALLATION AND FIELD STUDIES

EXECUTIVE SUMMARY

Field investigations were conducted into the performance of small capacity urban retrofit stormwater control measures (SCMs). The objective of the two year study was to provide performance data to support ongoing programs to develop cumulative nutrient reduction performance estimates for a range of design capacities for SCMs using the BMP Decision Support System (BMPDSS) and SUSTAIN, and build an adaptive, science-based SCM selection approach necessary for the effective control of nitrogen and phosphorus loads emanating from impervious cover (IC) to the environment.

This study introduces data on an innovative bioretention design with a water treatment residual (WTR) admixture filter media and an internal storage reservoir and an undersized linear subsurface gravel wetland with an internal storage reservoir sized to optimize both phosphorus and nitrogen removal. In this study systems retrofitted into existing developed areas were sized at less than the water quality volume (undersized systems). The bioretention system was constructed in the town of Durham, NH in summer 2011 and the subsurface gravel wetland system constructed in a linear drainage right of way in a residential neighborhood of Durham, NH in the fall of 2013. Data are being used by EPA Region 1 to calibrate and verify SCM models for developing long-term cumulative performance estimates for these SCM for design capacities ranging from small to large.

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. Orthophosphate (OrP), the most bioavailable form of phosphorus, was generally reduced in the SGW system, with median RE of 53% and effluent concentrations consistently below 0.06 mg/L. The Durham Bio system did achieved moderate reductions of OrP concentrations with median RE of 38% and effluent concentrations consistently below 0.02 mg/L. Both systems reduced total nitrogen by approximately 20% (23% for SGW and 21% for Durham Bio) with median effluent concentrations of 1.4 mg/L. Reduction in nitrate was limited to storms that were at or below the design storm event in the SGW only, median effluent concentrations for the SGW and Durham Bio were 0.3 mg/L and 0.2 mg/L, respectively.

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.

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.

BACKGROUND

Hybrid system philosophy

In stormwater control measure (SCM) systems, phosphorus is most effectively removed from stormwater by filtration in unsaturated soil media whereas nitrogen is most effectively removed by de-nitrification in anaerobic zones. The ability of natural wetlands to remove nitrogen from the lithosphere and hydrosphere has been mimicked in constructed subsurface gravel wetland systems, which demonstrated 75% annual median DIN removal efficiency at the University of New Hampshire Stormwater Center (UNHSC) West Edge Facility from 2004 to 2010 (UNH Stormwater Center et al. 2012). Multiple column studies were conducted in 2011-2013 to investigate various Bioretention soil mixes and SCM design configurations on the overall effectiveness for phosphorus and nitrogen treatment. Bioretention soil mix compositions examined included the use of different combinations and percentages of sand, soil, compost, water treatment residuals, co-valiant iron, and slag. Structural SCM design configurations included the use of internal reservoirs composed of stone in relation to holding/residence time and the ratio of internal storage reservoir (ISR) volume to water quality treatment volume.

Hybrid System Components

ISR Design – The anaerobic zone in the ISR is maintained in the subsurface gravel wetland by the installation of an elevated outlet above the gravel layer plus there being insignificant to no infiltration to the soil. Native soil below the gravel layer is compacted or lined to discourage infiltration so that the gravel layer remains saturated and becomes anaerobic due to bacterial respiration activity. The several pathways for nitrogen retention are typically slower processes than those which remove other pollutants. Some of these processes occur between, rather than during, rain events in a system. Subsurface gravel wetland systems tend to have large footprints due to the need for an extended travel path. UNHSC design specifications recommend a minimum horizontal flow path length of 30 feet (UNH Stormwater Center et al. 2012). One study concluded that nitrogen retention is a rate-dependent process, based on a study of outlet controlled bioretention mesocosms, which retained more than double the nitrogen oxides (NO_x) and total nitrogen than their free-flowing counterparts (Lucas and Greenway 2011b). By combining elements of each of these systems (filter media from the bioretention system and an internal storage reservoir from the subsurface gravel wetland), removal of both nitrogen and phosphorus should be improved over typical bioretention designs.

Water Treatment Residuals (WTR) – The Bioretention soil mix (BSM) in this study utilized water treatment residuals (WTR) from the Durham drinking water treatment plant. The Durham Drinking Water Treatment Plant uses polyaluminum chloride (PACl) as a coagulant for drinking water treatment. The sludge that settles after the coagulation/flocculation process contains amorphous aluminum and iron (hydr)oxides, which are highly reactive with dissolved phosphorus and have a large surface area for adsorption to occur (Lucas and Greenway 2011a; Makris et al. 2004). According to Makris et al. (2004), WTRs contain internal micropores in which diffusion occurs. An elevated activation energy of desorption within the micropores immobilizes sorbed P, increasing its stability.

WTR processing – Critical to the use of WTR is processing to reduce the water content of the WTR sludge material which is typically generated at the water treatment plant in the range of 90-99%. In 2011 UNHSC researchers identified that freezing WTR sludge decreased water content from 98% to 60-70% (Table 1) and maintained a readily mixable granular consistency resembling dried coffee grounds. Since 2012 UNHSC researchers generate roughly 15 cubic yards of processed WTR material by filling a large 30 cubic yard container next to the Durham WTR lagoon and aging it over the winter through several freeze/thaw cycles. As sludge-free ice is created on the surface, it is periodically removed. Figure 1 through Figure 4 depicts the transformation of the WTR from the unprocessed sludge material to the processed granular material over the course of one winter.

Table 1: Results of moisture content analysis on several water treatment residual (WTR) samples taken from the Durham, NH Water Treatment Plant settling lagoon.

Test Date	Sample Description*	Processed** (Y/N)	Moisture Content (%)
7/12/2011	WTR taken from bottom of 5-gallon bucket after 1-hour of settling	N	98%
7/12/2011	WTR taken from top of 5-gallon bucket after 1-hour of settling	N	98%
7/12/2011	WTR sample taken in Feb. 2011 into 5-gallon bucket and placed in freezer. Sample thawed and water decanted off the top. Sample stored at room temp for two months while excess water periodically decanted off the top. Sample taken from bottom of bucket.	Y	67%
7/14/2011	WTR from driest area of lagoon.	N	91%
7/18/2011	WTR from driest area of lagoon. Top 2" crust layer.	N	81%
7/18/2011	WTR from driest area of lagoon. Middle 2" layer.	N	88%
7/18/2011	WTR from driest area of lagoon. Black greasy layer.	N	90%
4/9/2012	WTR from 30yd dumpster that was filled in July 2011 and allowed to evaporate through summer then freeze and thaw through winter.	Y	59%

* All water treatment residual (WTR) samples taken from Durham, NH Water Treatment Plant's settling lagoon.

** Processed is defined by whether the sample was frozen to separate water from colloid.

Figure 1: WTR Lagoon at the Durham, NH Drinking Water Treatment Plant

Figure 2: WTR loaded directly into 30 cubic yard dumpster in the fall.

Figure 3: WTR in early spring beginning to thaw.

Figure 4: WTR in mid-summer.

BSM Materials

The University of New Hampshire Stormwater Center (UNHSC) BSM designs have historically consisted of four materials: coarse sand, commercial loam, shredded wood chips, and food and yard waste compost. In 2012 UNHSC published reports on column studies with various soil mixes demonstrating dissolved nutrient export when compost is used. Results also demonstrated the benefits of using water treatment residuals (WTRs) to amend BSM to boost phosphorus removal. Since that time UNHSC modified all BSM designs at a minimum to eliminate compost (which is commonly a source of Phosphorus) and where phosphorus reductions are desired to add WTR to BSM soil mixes at 3-10% of the BSM by volume. Current BSM soil recommendations are 50-60% coarse sand, 20-30% top soil or loam, 20% wood chips and 3-10% WTR. In addition to a specification on the material portions, UNHSC also desires infiltration capacities of the BSM generally higher than 10 inches per hour as well as fines content (less than #200 sieve) of the final bioretention soil mixture less than 5%.

Study Area

For the research presented here, three sites were originally established and monitored however monitoring continued at only two sites due to detection of high numbers of coliform bacteria at the third (Horne Street) which implied a cross connection between the stormwater and wastewater systems. UNHSC is working with the City of Dover to identify the possible source and location of this cross connection. The following information was compiled for the three study site locations:

1.) Oyster River Road, Durham NH – Subsurface Gravel Wetland Stormwater Control #1 (SGWSC#1)

- Completion Date: October 2nd, 2013
- System Online: October 2nd, 2013

2.) Durham Bioretention - Innovative Bioretention Stormwater Control #2 (IBSC#2)

- Completion Date: July 22, 2011
- System Online: July 23, 2011
- Maintenance: August 28,2014

3.) Horne Street 2, Dover, NH - Innovative Bioretention Stormwater Control #3 (IBSC#3)
*Note monitoring efforts discontinued due to detection of high levels of coliform bacteria.

- Completion Date: October 22, 2013
- System Online: October 22, 2013

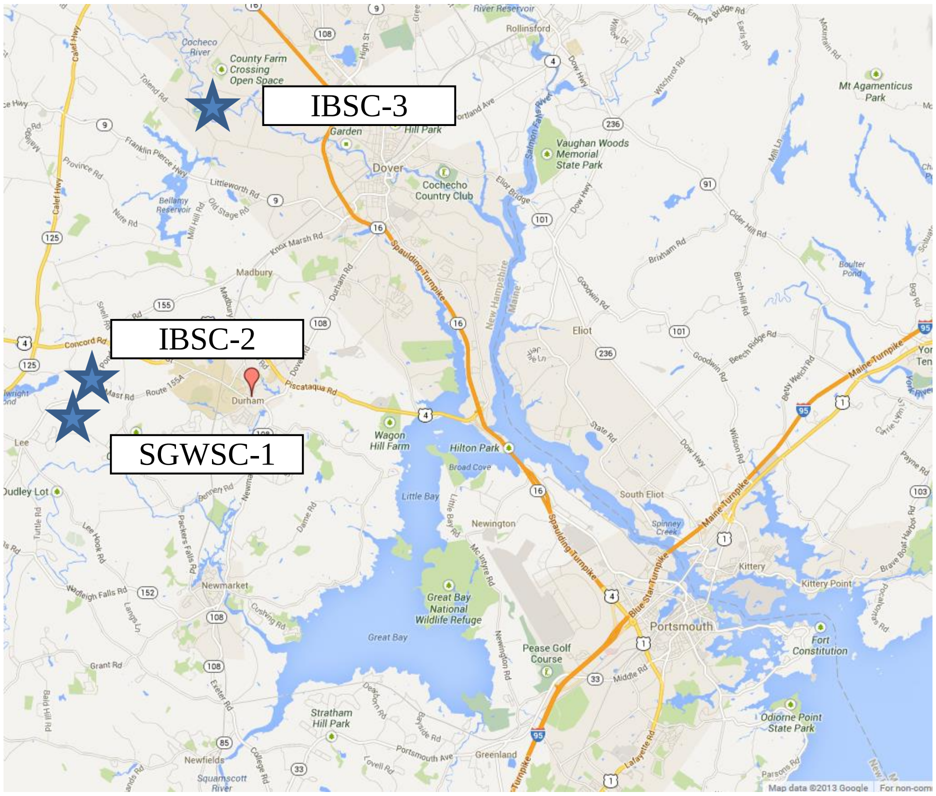

Figure 5: Geographic locations of IBSC-2 at 5 Madbury Road in Durham NH 03824, SGWSC-1 at Oyster River Road, Durham, NH67 and IBSC-3 at Horne Street in Dover, NH 03820

System Characteristics

The researched SCMs have the following characteristics:

- IBSC-2 and IBSC-3 SCMs are vegetated filtration systems that use non-proprietary soil admixtures in filter media optimized for P-sorption. Each system used water treatment residual amended to the soil media at (10% by volume). SGWSC-1 has a vegetated surface of wetland soil. A particle size distribution and soil characterization is provided in Table 2.

- All SCMs have an anaerobic internal storage reservoir (ISR) for N-removal. SGWSC-1 has an ISR Volume to Water Quality Volume ratio of 0.05 or 5%, IBSC-2 has an ISR Volume to Water Quality Volume ratio of 0.10 or 10% and, IBSC-3 has an ISR Volume to Water Quality Volume ratio of 0.11 or 11%. Up to this publication, design guidelines for the subsurface gravel wetland specifications (UNHSC, 2009) identified that the ISR be 0.26 WQV (26% of the WQV).
    - Water Quality Volume (WQV) is the amount of stormwater runoff that should be captured and treated to remove the bulk of the stormwater pollutants on an average annual basis. For New Hampshire the recommended WQV is the volume of runoff associated with the first 1-inch of rainfall (NHDES Stormwater Manual, 2008).

$$WQV = P * Rv * A$$

        - WQV = Water Quality Volume (acre-inch)
        - P = 1” of Rainfall (in)
        - Rv = unitless runoff coefficient = 0.05 + 0.9*I
        - I = percent impervious cover draining to structure in decimal form
        - A = total site area draining to structure (acre)

- All SCMs demonstrate small footprints; SGWSC-1 has a footprint of 480 ft^2, IBSC-2 has a footprint of 142 ft^2, and IBSC-3 has a footprint of 800 ft^2. All systems are urban/sub-urban retrofits and were designed to be installed into existing urban/sub-urban environments and were designed to be as large as possible without significant disruption to the existing infrastructure.
- The SCMs have a physical storage capacity of 0.1 to 0.3 inches of runoff from the contributing watershed impervious cover. See also “Detailed System Specifications” section for specific design details.

Table 2: Particle size distribution and testing tolerances for wetland humus for the subsurface gravel wetland system

US Standard Sieve Size in/mm	Percent Passing	Percent Passing Testing Tolerances
0.5/12.5	100	± 10.0
#10/2.00	90 - 75	± 5.0
#100/0.15	40-50	± 5.0
#200/0.75	25-50	± 5.0

Detailed System Specifications

Oyster River Road – Subsurface Gravel Wetland

Figure 6: Oyster River Road SGWSC during second growing season.

The ORR SGW System (SGWSC-1) watershed area is approximately 261,690 ft^2 (6.01 acres) of residential land use that is 33% impervious. The time of concentration is approximately 17.4 minutes as determined by the NRCS method, with variable slopes. There are two high flow bypasses designed within the system. The first high flow bypass is provided by a 6” diameter riser connected to the primary outlet control just downstream of the 1” orifice plate. There is also an emergency spillway provided by a 2’ rectangular elevation control in the back of the system armored with 6”-8’ stone. The result of this configuration is that the vast majority of all flows are monitored. Even in the rare occurrence that the emergency spillway conveyed bypass flows the monitoring location in the 6” outlet was continually monitored and passed both primary system flows and secondary bypass flows.

The climatology of the area is consistent with the Durham testing location and characterized as a coastal, cool temperate forest. Average annual precipitation is 44 inches that is nearly uniformly distributed throughout the year, with average monthly precipitation of 3.7 inches ±0.5 inches. The mean annual temperature is 48°F, with the average low in January at 15.8°F, and the average high in July at 82°F.

The SGWSC-1 in contrast to the dynamically sized IBSC-2 was sized statically, storing 5% of the water quality volume (WQV) above ground in the basin geometry. The primary outlet structure and its hydraulic rating curve are based on a calculated release rate by orifice control to drain the stored design WQV in 24-48 hrs. It should be noted that the design treatment volume is statically drained through the outlet control structure through a simple orifice equation defined as follows:

$$Q = CdA\sqrt{2gh}$$

- Q = Flow Rate (cfs)
- C_d = Coefficient of Discharge (typ. 0.62)
- A = Area of Orifice (ft^2)
- g = Gravitational Acceleration (ft/sec^2)
- h = Depth of water from center of orifice (ft)

The target residence time should be at minimum 24 hours. Column studies conducted by UNHSC concluded that the most important factor in N removal is the retention time in the saturated, anaerobic zone. A prolonged residence time in the system allows for longer time of contact of the stormwater with the denitrification bacteria, which results in better nitrogen removals. At this point, differentiation needs to be made between the drainage time of the stormwater and the residence time of stormwater in the system. Since subsurface gravel wetlands are plug flow type systems, the drainage time is very close to the duration of runoff (old water moves out as new water moves in). The residence time is the time between the storm events. The final steps in the denitrification process, the transformation of NO_3 and NO_2 to N_2 or N_2O, take place mostly in between the storm events. Figure 7 summarizes the results of the column study indicating the improved performance associated with larger ISR design capacities and longer retention times. The control column was constructed without an anaerobic zone therefore results represent removals by the media in the column only.

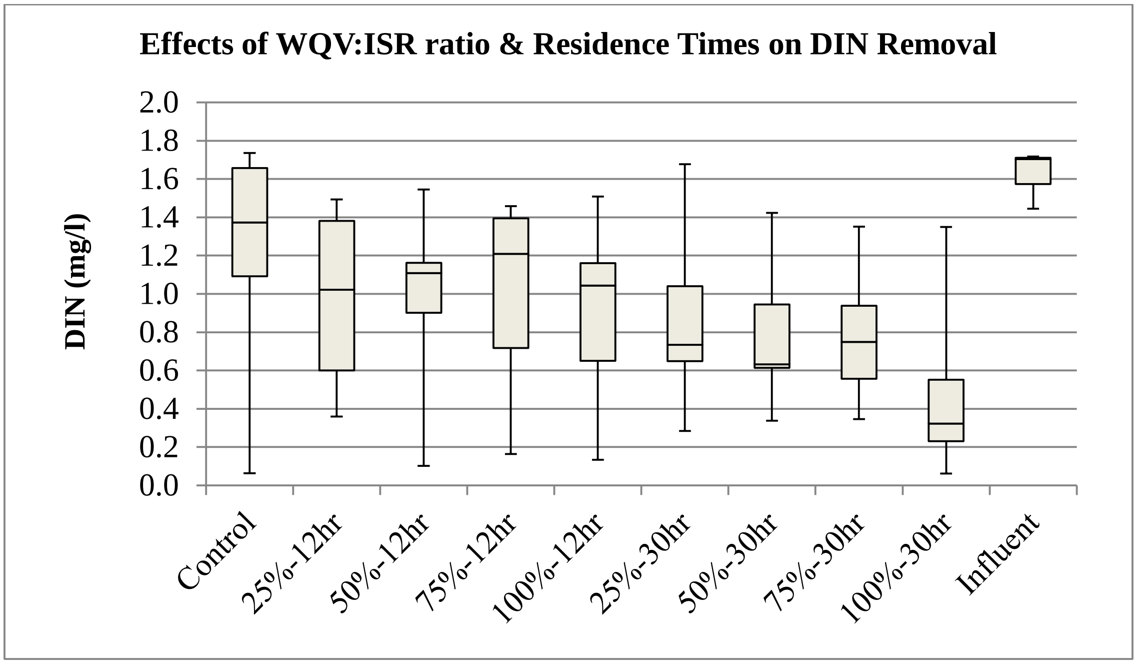

Figure 7: Box and Whisker plots of column study results for influent and effluent DIN concentrations for various WQV:ISR ratios and various resident times.

Table 3: Watershed characteristics for SGWSC-1

Input Table	
Watershed Area (sf)	261,796
Watershed Area (acres)	6.01
Percent Impervious Cover	0.33

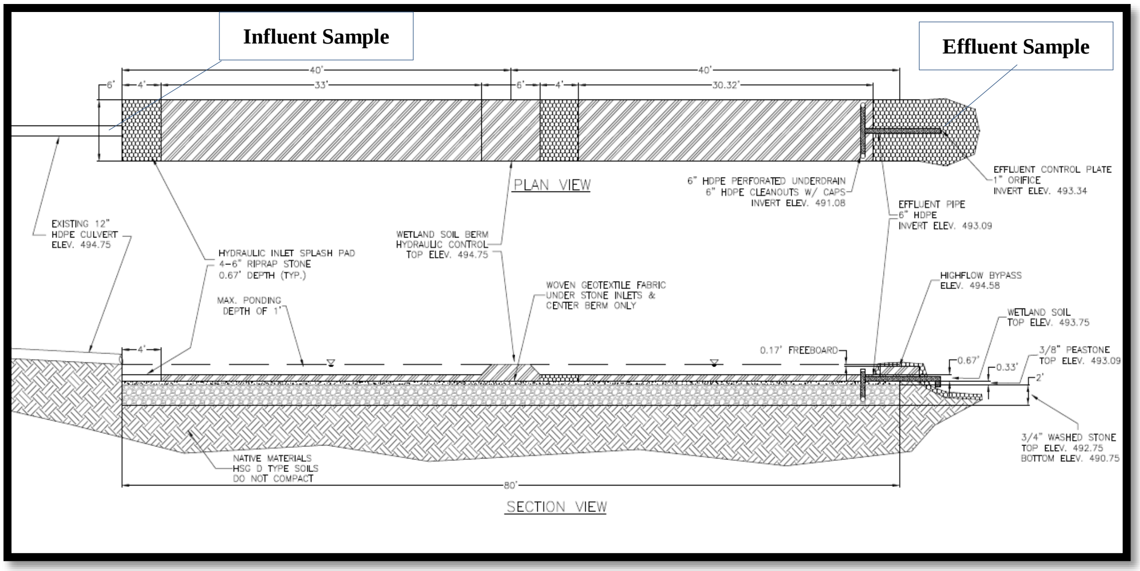

Figure 8: Plan and profile view of Oyster River Road SGWSC.

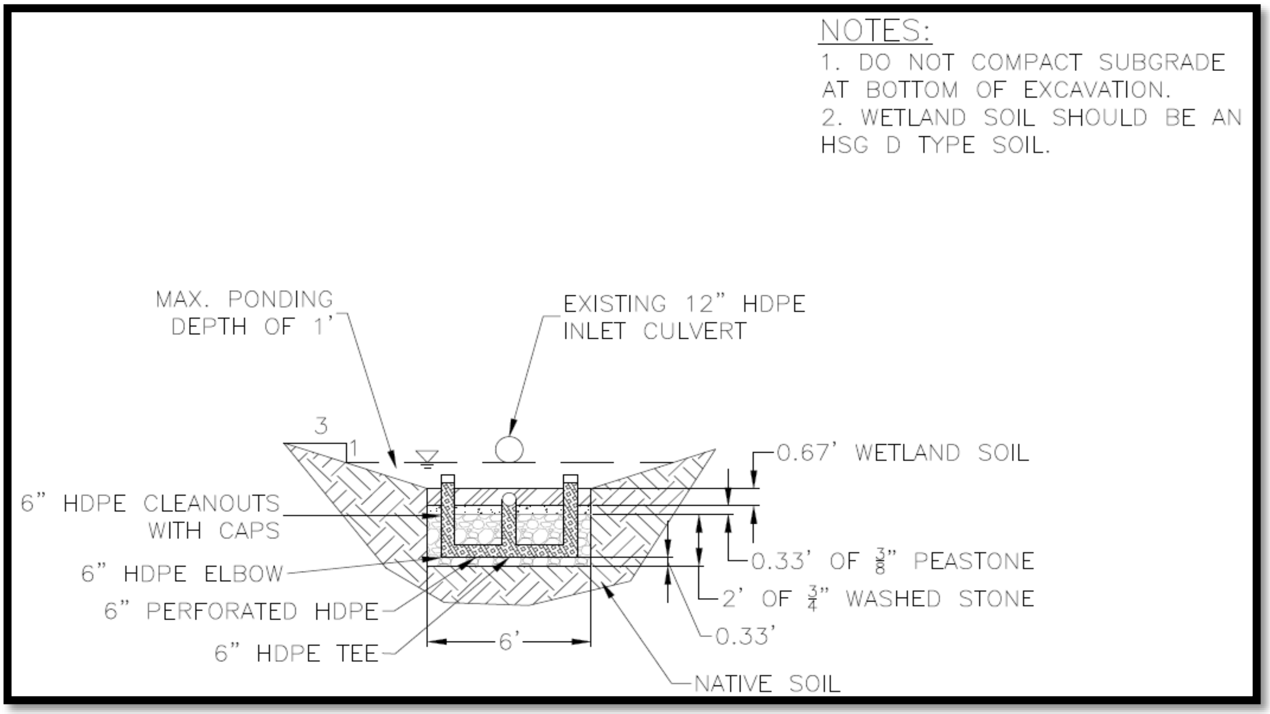

Figure 9: Cross-section view of Oyster River Road SGWSC

Municipal Parking Lot, Durham NH – Innovative Bioretention Stormwater Control

Construction and planting of the Durham bioretention system was completed late in the growing season, August 2011. This installation was followed by a monitoring period plagued with insufficient vegetation establishment and lack of a sufficient system ripening phase (preferably a minimum of 3 months).

Figure 10: Innovative Bioretention Stormwater Control in Durham, NH

The Durham Bioretention (IBSC-2) watershed area is approximately 17,200 ft^2 (0.4 acre) of commercial land use that is nearly entirely impervious. The time of concentration is approximately 6 minutes as determined by the NRCS method, with slopes ranging from 2.0-3.2%. The climatology of the area is consistent with the Durham testing location and characterized as a coastal, cool temperate forest. Average annual precipitation is 44 inches that is nearly uniformly distributed throughout the year, with average monthly precipitation of 3.7 inches ±0.5 inches. The mean annual temperature is 48°F, with the average low in January at 15.8°F, and the average high in July at 82°F.

The Durham Bioretention System (IBSC-2) was designed based on the dynamic sizing equation which assumes that water continually infiltrates the bioretention soil media as the basin fills during a rain event. The biofiltration area (A_f) is thus sized based on principles of Darcy's Law, where:

$$Af = Vwq * \frac{df}{(i(hf + df)tf)}$$

- A_f = surface area of filter bed (square feet)
- d_f = filter bed depth (feet)
- i = the infiltration capacity of the filter media divided by a safety factor (2 to 3) (feet per day)
- Vwq = the water quality volume resulting from one inch of precipitation (ft^3)
- h_f = average height of water above filter bed (feet)
- t_f = design filter bed drain time (days)

There are different ways to size bioretention areas dictated by local stormwater management goals. Two additional methods worthy of mention are: 1) the static sizing method where the storage volume of the SCM is set equal to the runoff volume from the contributing impervious drainage area - typically the WQV; and 2) the percent watershed sizing method where the filter area is required to be a certain percentage (typically 3-5%) of the contributing drainage area.

Table 4: Watershed characteristics for IBSC-2

Input Table	
Watershed Area (sf)	17,200
Watershed Area (acres)	0.39
Percent Impervious Cover	0.98

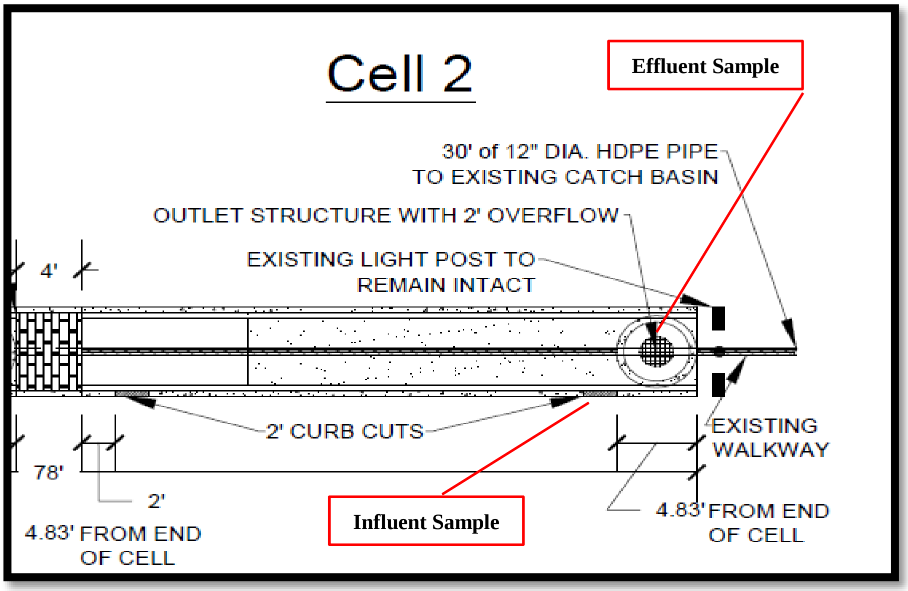

Figure 11: Plan view of Durham Innovative Bioretention Stormwater Control.

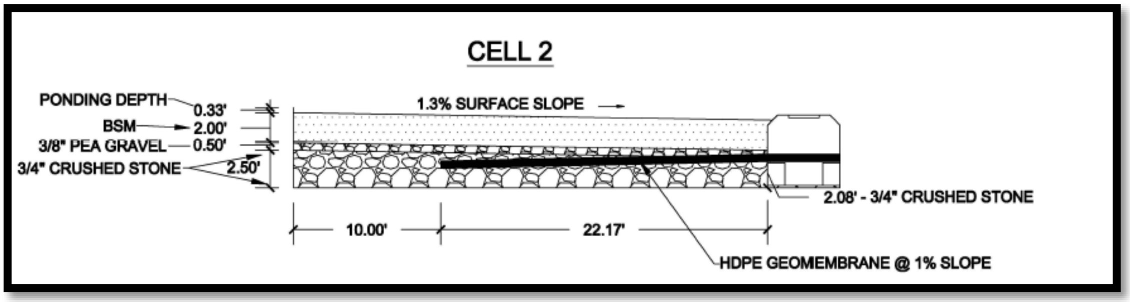

Figure 12: Profile view of Durham Innovative Bioretention Stormwater Control.

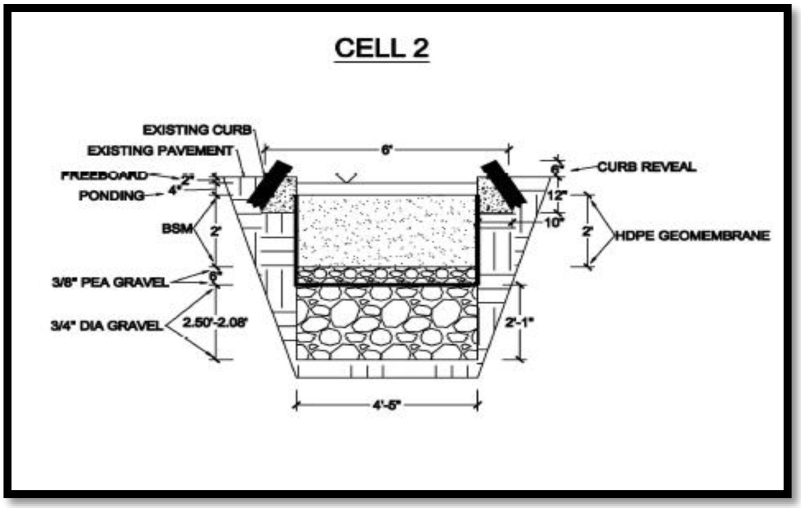

Figure 13**: Cross-Section of Durham Innovative Bioretention Stormwater Control.**

Table 5: details for each monitored system comparing conventional design approach to the actual design monitored.

System	WQV (cf)	Actual WQV(cf)	% of conventional design	Rain Event (in)	Sizing Method
SGWSC-1	7,577	720	10%	0.10	Static
IBSCS-2	1,336	310	23%	0.23	Dynamic

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.

More details on experimental design are provided in the project approved QAPP (attachment A).

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.

Precipitation and flow measurement records were maintained for all events that occurred during the study period results are provided in this report and raw values provided as (attachment B). 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 3.

Additional Analytical Procedures

Field samples were analyzed for: nitrogen species, phosphorus species, sediment, and metals (see Appendix A for the EPA approved QAPP). All water quality samples that were reported as below detection limit (BDL) from the analytical labs were used in data analysis at values half of the method detection limit (Helsel and Hirsch 2002). That is to say, when the method detection limit for orthophosphate at Aquatic Resource Associates (ARA) was 0.01 mg/L, samples that returned from the lab as BDL were entered for data analysis as 0.005 mg/L. In addition to pollutant analyses, a comparative assessment of dissolved nutrient versus particulate nutrient concentrations were conducted at a UNH run laboratory facility to determine the need to update laboratory analytical methods.

Table 6: 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 6 (Oyster River Road) and Table 7 (IBSCS-2) 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

Analytical comparison results

Samples were sent to two analytical labs as requested during initial project discussions to determine if there was any major difference for nutrient values between different laboratories. Absolute Resource Associates, Inc. (ARA) and the UNH Water Quality Analysis Laboratory (WQAL) in the UNH Department of Natural Resources and the Environment. Analysis at WQAL consisted of nutrients only while the entire suite of analyses, see Table 3, were conducted at ARA. Table 4 and Table 5 are comparison tables showing side-by-side comparison of the pollutant concentrations from each lab. It was found that the resultant average and median differences were near or below the detection limits for each analysis demonstrating consistency between the labs as well as good quality control of post-storm sample processing.

Table 7: Oyster River Road SGWSC analytical lab comparison results from Absolute Resource Associates (ARA) and Water Quality Analysis Laboratory (WQAL).

		TDN (mg/L)		NO3+NO2 (mg/L)		NH3 (mg/L)	NH4 (mg/L)	Soluble TKN (mg/L)	DON (mg/L)	TN (mg/L)		PO4 (mg/L)		TP (mg/L)	
Storm Date	Location	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL
5/27/2014	ORR-IN	3.0	1.3	0.6	0.6	< 0.5	0.08	2.4	0.6	1.6	1.7	0.04	0.03	0.10	0.03
	ORR-EFF	3.7	1.3	0.7	0.8	< 0.5	0.02	3.0	0.5	2.5	1.6	0.05	0.04	0.09	0.05
6/13/2014	ORR-IN	1.7	1.1	0.3	0.3	< 0.5	0.03	1.4	0.8	2.4	1.8	0.12	0.08	0.29	0.20
	ORR-EFF	1.6	1.3	0.4	0.5	< 0.5	0.01	1.2	0.8	2.1	1.4	0.07	0.06	0.17	0.14
6/25/2014	ORR-IN	0.9	0.9	0.2	0.3	< 0.5	0.08	0.7	0.5	1.5	1.6	0.24	0.26	0.35	0.42
	ORR-EFF	1.1	0.8	0.3	0.4	< 0.5	0.03	0.8	0.4	1.4	1.1	0.10	0.13	0.27	0.17
7/23/2014	ORR-IN	2.0	1.5	0.6	0.7	< 0.5	0.08	1.4	0.7	3.1	3.7	0.16	0.18	0.56	0.68
	ORR-EFF	1.1	0.7	0.1	0.2	< 0.5	0.04	1.0	0.4	1.1	0.9	0.03	0.04	0.09	0.10
7/27/2014	ORR-IN	1.8	1.1	0.3	0.4	< 0.5	0.07	1.5	0.6	2.8	2.3	0.18	0.15	0.36	0.52
	ORR-EFF	1.1	0.7	0.1	0.2	< 0.5	0.03	1.0	0.5	1.3	0.8	0.05	0.02	0.08	0.08
8/13/2014	ORR-IN	1.3	1.0	0.3	0.2	< 0.5	0.06	1.0	0.7	2.0	1.8	0.15	0.11	0.22	0.27
	ORR-EFF	1.5	1.1	0.3	0.3	< 0.5	0.02	1.2	0.8	1.7	1.5	0.09	0.08	0.18	0.19
9/2/2014	ORR-IN	1.1	1.1	< 0.2	0.4	< 0.5	0.13	1.1	0.6	1.6	1.7	0.19	0.30	0.32	0.34
	ORR-EFF	0.9	0.7	< 0.2	0.3	< 0.5	0.07	0.9	0.3	1.1	0.9	0.05	0.06	0.04	0.10
Median Difference		0.4		-0.1		NA		0.6		0.2		0.01		-0.01	
Average Difference		0.6		-0.1		NA		0.7		0.2		0.00		-0.01	
Detection Limit		0.5		0.2		0.5		0.5		0.5		0.01		0.01	

Table 8: Durham IBSC analytical lab comparison results from Absolute Resource Associates (ARA) and Water Quality Analysis Laboratory (WQAL).

		TDN (mg/L)		NO3+NO2 (mg/L)		NH3 (mg/L)	NH4 (mg/L)	Soluble TKN (mg/L)	DON (mg/L)	TN (mg/L)		PO4 (mg/L)		TP (mg/L)	
Storm Date	Location	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL	ARA	WQAL
10/6/2013	Bio-5 IN	-	1.3	-	0.5	< 0.5	0.6	-	0.2	3.3	1.9	0.00	0.05	0.01	0.15
	Bio-5 EFF	-	0.6	-	0.1	< 0.5	0.3	-	0.2	1.4	0.6	0.01	0.01	0.03	0.05
11/10/2013	Bio-5 IN	-	1.3	-	0.7	< 0.5	0.3	-	0.2	4.2	2.7	0.01	0.25	0.27	0.26
	Bio-5 EFF	-	0.4	-	0.1	< 0.5	0.1	-	0.2	1.0	0.5	0.02	0.00	0.03	0.04
11/17/2013	Bio-5 IN	-	0.7	-	0.2	< 0.5	0.2	-	0.3	1.8	1.0	0.05	0.06	0.07	0.05
	Bio-5 EFF	-	0.6	-	0.2	< 0.5	0.1	-	0.3	1.5	0.7	0.02	0.01	0.04	0.01
11/26/2013	Bio-5 IN	-	0.2	-	0.1	< 0.5	0.1	-	0.1	0.8	0.3	0.02	0.02	0.03	0.06
	Bio-5 EFF	-	0.3	-	0.1	< 0.5	0.0	-	0.2	0.8	0.3	0.01	0.02	0.03	0.02
6/13/2014	Bio-5 IN	0.8	0.6	< 0.2	0.1	< 0.5	0.1	0.7	0.4	1.1	1.0	0.01	0.03	0.12	0.15
	Bio-5 EFF	1.6	1.2	0.7	0.6	< 0.5	0.1	0.9	0.5	1.9	1.6	0.05	0.04	0.10	0.09
6/25/2014	Bio-5 IN	1.2	1.3	0.3	0.3	< 0.5	0.3	0.9	0.7	1.9	2.1	0.01	0.09	0.23	0.26
	Bio-5 EFF	1.1	1.0	0.5	0.5	< 0.5	0.2	0.6	0.4	1.5	1.5	0.03	0.04	0.22	0.24
7/13/2014	Bio-5 IN	2.5	1.7	0.3	0.3	< 0.5	0.5	2.2	0.9	2.7	2.4	0.03	0.13	0.18	0.19
	Bio-5 EFF	1.9	0.9	0.3	0.3	< 0.5	0.2	1.6	0.4	1.4	1.4	0.03	0.04	0.02	0.17
7/23/2014	Bio-5 IN	1.5	1.6	0.4	0.7	< 0.5	0.4	1.1	0.5	2.5	1.7	0.03	0.10	0.19	0.18
	Bio-5 EFF	2.2	1.5	1.0	1.0	< 0.5	0.4	1.2	0.1	2.5	1.8	0.04	0.05	0.12	0.11
7/27/2014	Bio-5 IN	1.2	1.0	0.3	0.3	< 0.5	0.0	0.9	0.7	1.5	1.3	0.01	0.05	0.09	0.15
	Bio-5 EFF	1.7	1.0	0.6	0.6	< 0.5	0.2	1.1	0.2	1.9	1.4	0.04	0.05	0.06	0.09
7/31/2014	Bio-5 IN	2.4	1.7	0.5	0.6	0.6	0.3	1.9	0.8	2.5	1.8	0.08	0.06	0.16	0.13
	Bio-5 EFF	1.2	0.5	0.1	0.2	0.3	0.3	1.1	0.1	1.3	0.7	0.04	0.05	0.10	0.09
9/2/2014	Bio-5 IN	1.1	0.9	< 0.2	0.3	< 0.5	0.3	1.0	0.4	1.4	1.3	0.02	0.08	0.10	0.18
	Bio-5 EFF	1.4	1.0	< 0.2	0.6	< 0.5	0.2	1.3	0.2	1.6	1.3	0.02	0.06	0.13	0.14
9/13/2014	Bio-5 IN	0.8	0.7	< 0.2	0.1	< 0.5	0.1	0.7	0.5	0.9	1.0	0.04	0.09	0.12	0.12
	Bio-5 EFF	0.7	0.5	< 0.2	0.1	< 0.5	0.1	0.6	0.3	0.8	0.7	0.03	0.03	0.05	0.08
10/1/2014	Bio-5 IN	0.6	1.0	0.3	0.3	0.8	0.2	< 0.5	0.5	1.8	1.9	0.01	0.10	0.20	0.19
	Bio-5 EFF	1.0	0.6	0.3	0.3	0.3	0.0	0.7	0.2	0.9	0.7	0.01	0.02	0.01	0.04
Median Difference		0.3		0.0		0.2		0.6		0.4		-0.02		-0.01	
Average Difference		0.3		0.0		0.3		0.7		0.4		-0.03		-0.02	
Detection Limit		0.5		0.2		0.5		0.5		0.5		0.01		0.01	

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

		RAINFALL		INFLUENT		EFFLUENT				
Storm Date	Storm Event Duration (min)	Rainfall Depth (in)	Peak Intensity (in/5-min)	Peak Flow (gpm)	Total Volume (gal)	Peak Flow (gpm)	Total Volume (gal)	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 10: Durham IBSC storm characteristics for 20 monitored events where volume balance is the percent difference between influent and effluent measured volumes.

		RAINFALL			EFFLUENT				
Storm Date	Storm Event Duration (min)	Rainfall Depth (in)	Peak Intensity (in/5-min)	Modeled Volume (gal)	Peak Flow (gpm)	Total Volume (gal)	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

Runoff volumes did not yield any discernable flow reductions for either system. The average runoff reduction calculated for the SGWCS-1 was -2% where the runoff reduction calculated from modeled influent and measured effluent for the IBSC-2 was 11%. Both these values are within the standard deviation of the dataset and therefore negligible. There is no assumed runoff reduction for either of these systems which is expected as both systems were constructed in an extremely low permeability clay soil (HSG D). For the SGWCS-1 device there is variability between influent and effluent volumes however the overall average difference is statistically zero. For the IBSC-2 system three is much greater variability between modeled results for flow and measured effluent flow but overall reductions are still negligible. There are numerous reasons for this variability. Flow is historically difficult to measure in open channel and openly drained areas. Flow is generally never directly measured in the field. Instead flow is often calculated from stage discharge relations or geometric conversions developed from weir and orifice equations. Most retrofit locations for SCMs do not lend themselves to installation of flumes and weir structures that offer more reliability and accuracy in converting depths to flow volumes. Beyond these difficulties there is also micro-topography especially in urban retrofit areas where the delineated watershed can change with respect to different storm events (sheet flow conveyance vs shallow concentrated flow conveyances) that invariably result in differences between modeled volume estimates and measured effluent flows.

Field Monitoring Results

Influent and effluent EMC and RE values are presented in Figure 14 through Figure 25 for each storm for all pollutants over the monitored storm events. These time series plots show performance for individual storm events as well as seasonal and annual trends. Table 8 and Table 9 summarize each parameter over the monitoring period using simple statistics to present performance outcomes. 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 11: 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 12: 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							

Sediment and Metal Performance

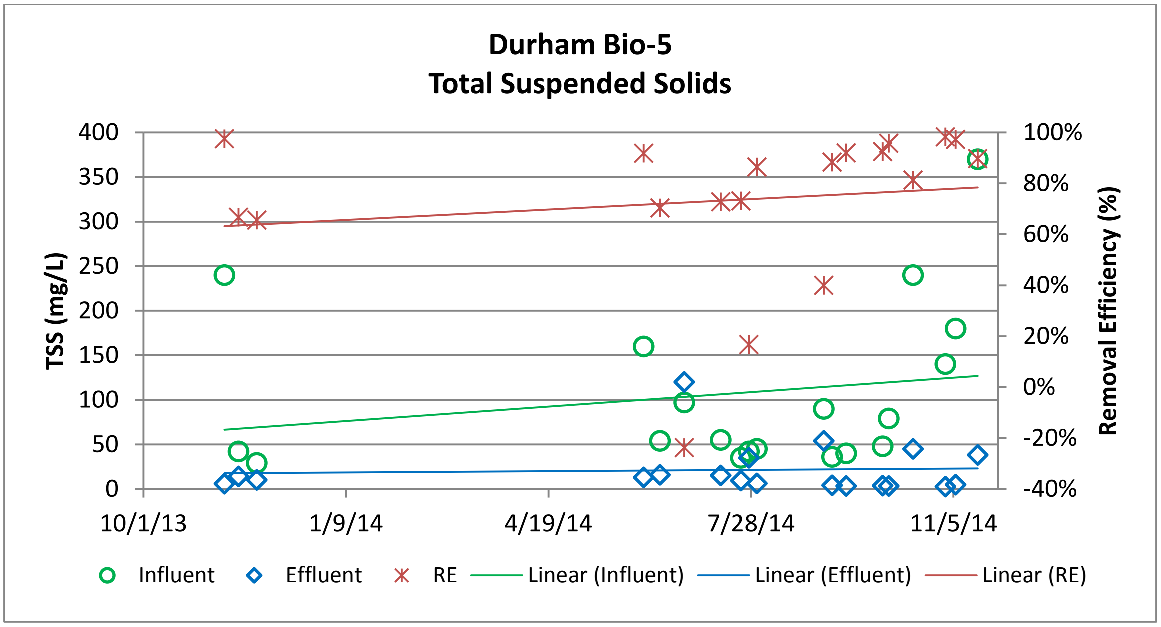

Figure 14: Durham IBSC total suspended solids event mean concentrations and removal efficiencies for each storm event.

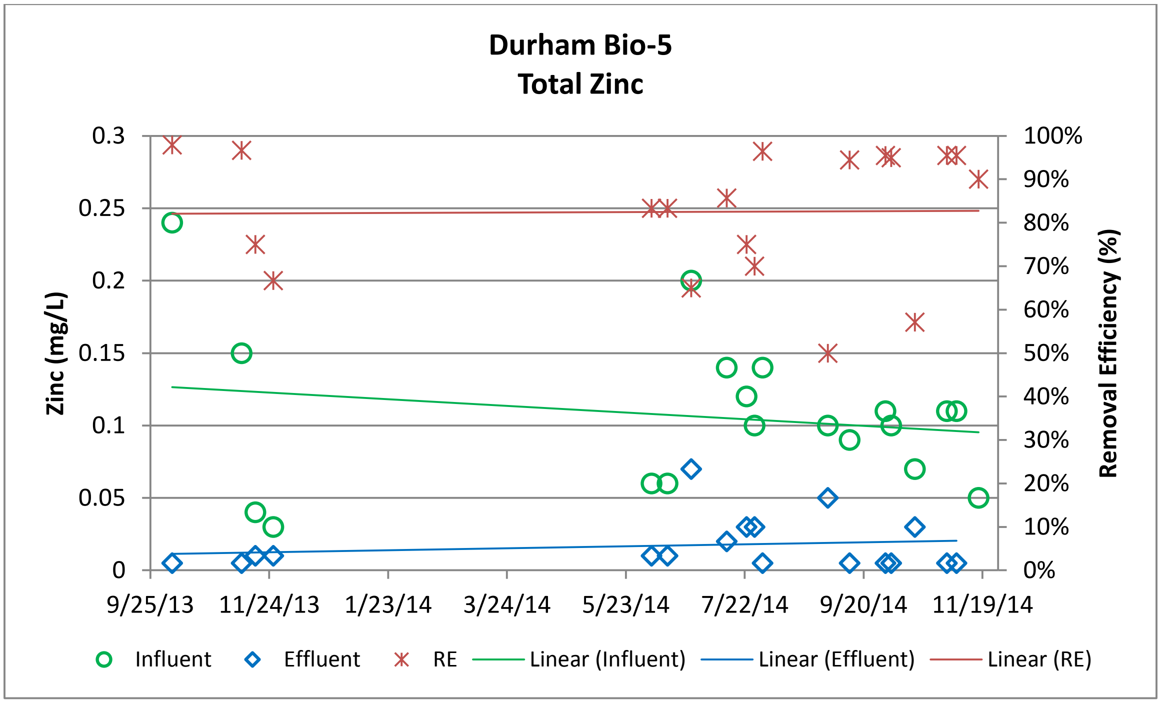

Figure 15: Durham IBSC total zinc event mean concentrations and removal efficiencies for each storm event.

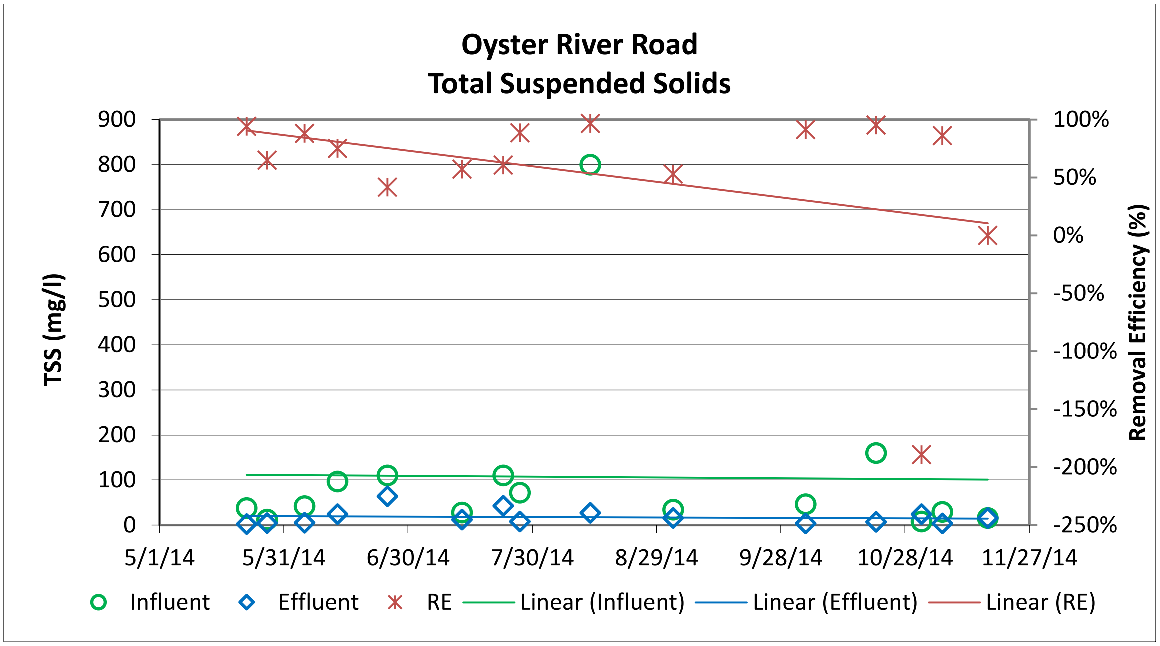

Figure 16: Oyster River Road SGWSC total suspended solids event mean concentrations and removal efficiencies for each storm event.

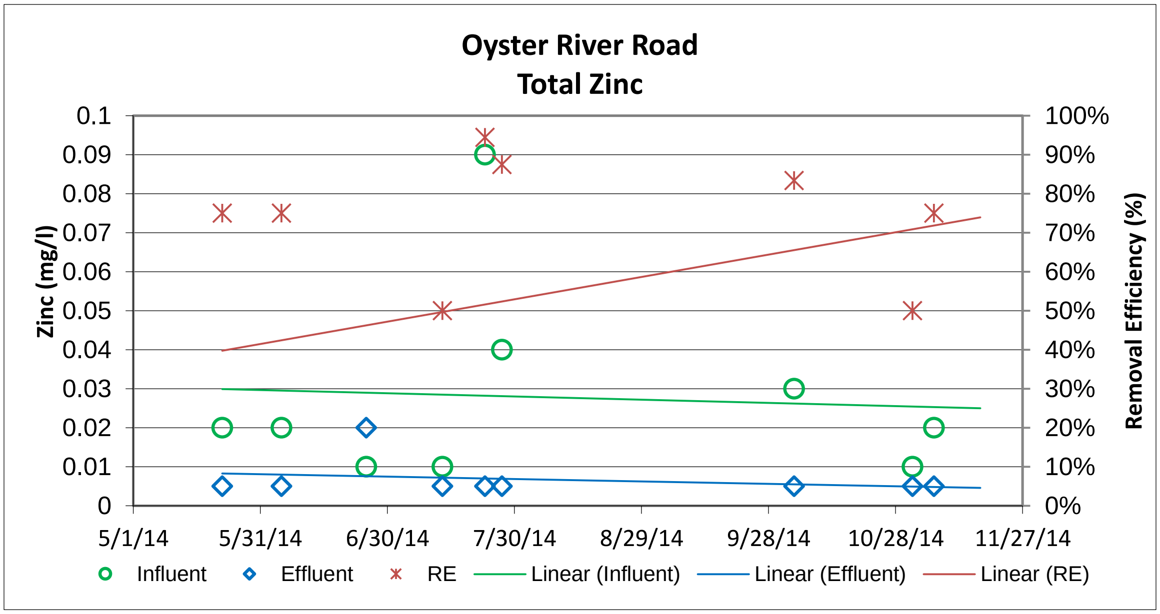

Figure 17: Oyster River Road SGWSC total zinc event mean concentrations and removal efficiencies for each storm event.

In general there is very strong performance with respect to TSS and TZn removals for both undersized systems studied. Previous UNHSC studies have shown that sediment and sediment associated pollutants such as TZn and hydrocarbons follow similar removal trends (UNHSC, 2012). More interesting is the consistent high performance level across the range of storm events including many that are above the overall design event. This underscores the fact that many conventional sizing practices may be overly conservative with respect to TSS and TZn particularly if a system is undersized by a factor of 0.6 or 0.9 achieves equal performance to a system designed to treat the full WQV. Results indicate that for sediment or sediment associated pollutants such as TZn or hydrocarbons, filtration practices are top performers regardless of any conventional sizing criteria. While results are promising, it should be noted that this study represents one full year of monitoring. Long term performance trends are necessary to determine overall functionality.

Nutrient Performance: Total Nitrogen and Total Phosphorus

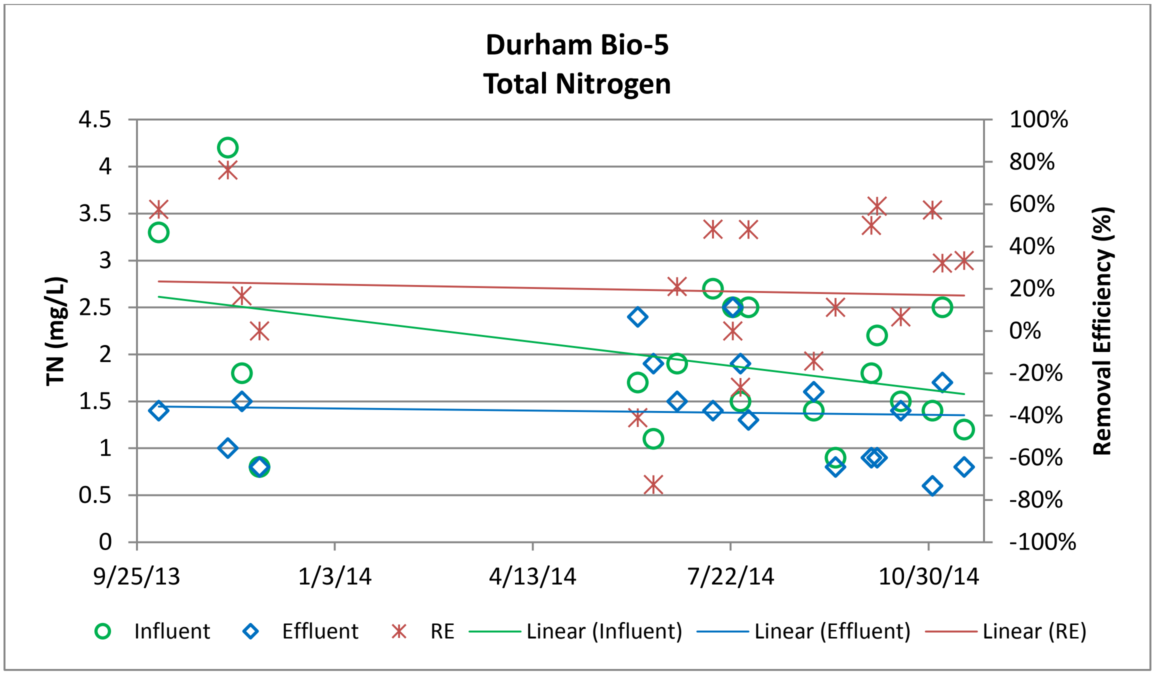

Figure 18: Durham IBSC total nitrogen event mean concentrations and removal efficiencies for each storm event.

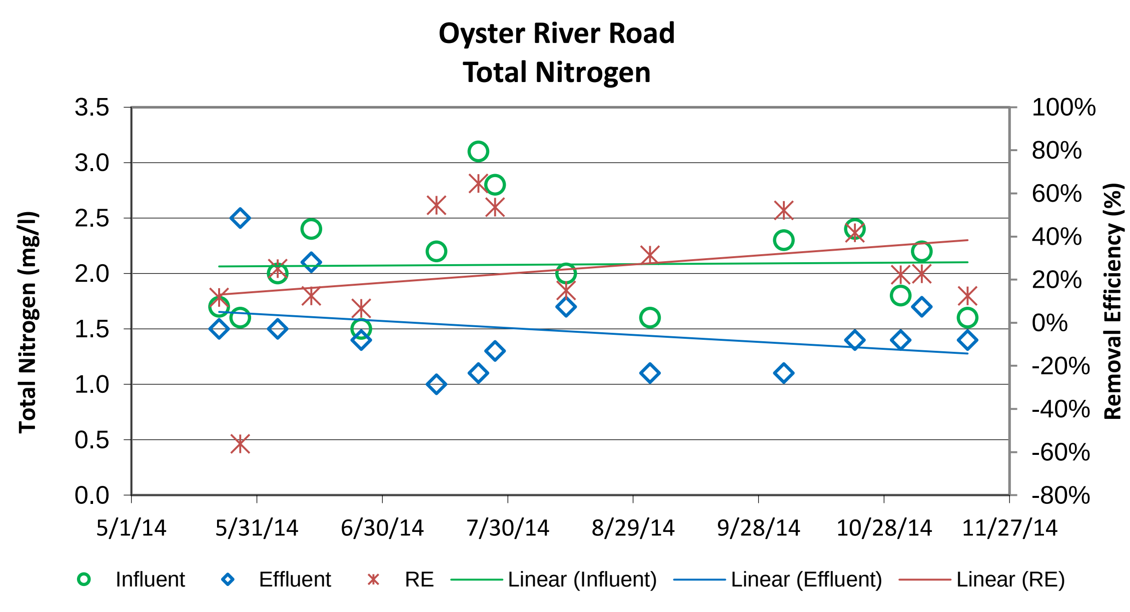

Figure 19: Oyster River Road SGWSC total nitrogen event mean concentrations and removal efficiencies for each storm event.

For TN performance, while removals appear to be low the overall data trends appear promising particularly for the SGWSC#1 which was the most undersized system. Removal efficiencies trend higher over time despite adequate time for vegetation to establish. Overall effluent concentrations remain flat or consistent despite increasing influent concentrations. The same could be concluded for the IBSC#2.

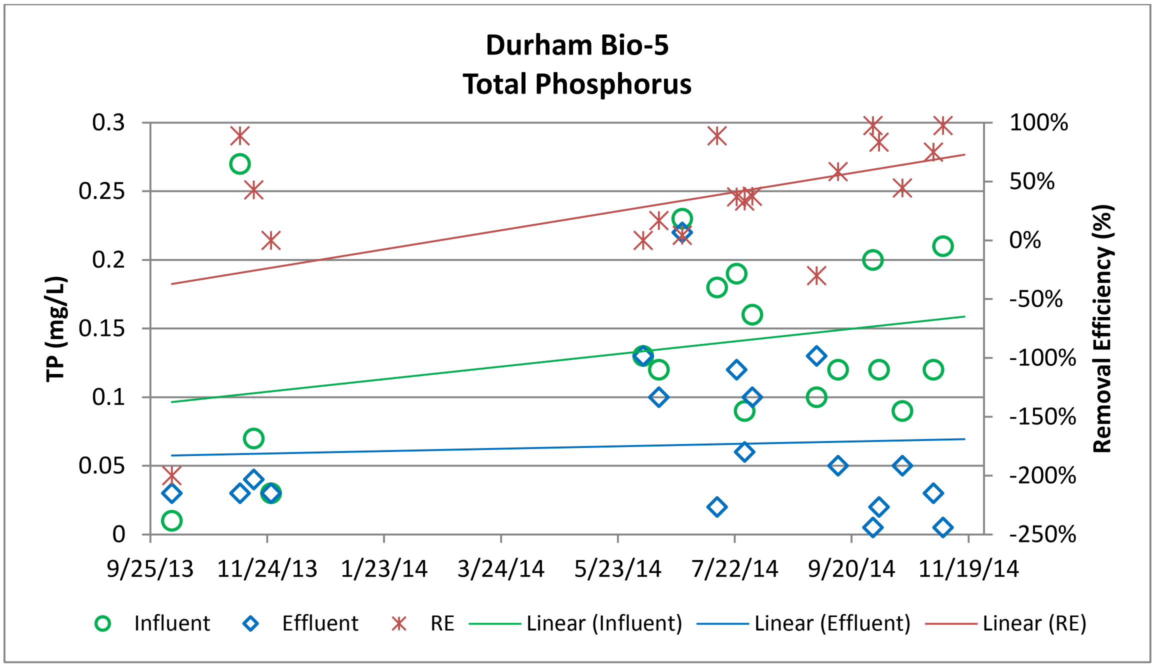

Figure 20: Durham IBSC total phosphorus event mean concentrations and removal efficiencies for each storm event.

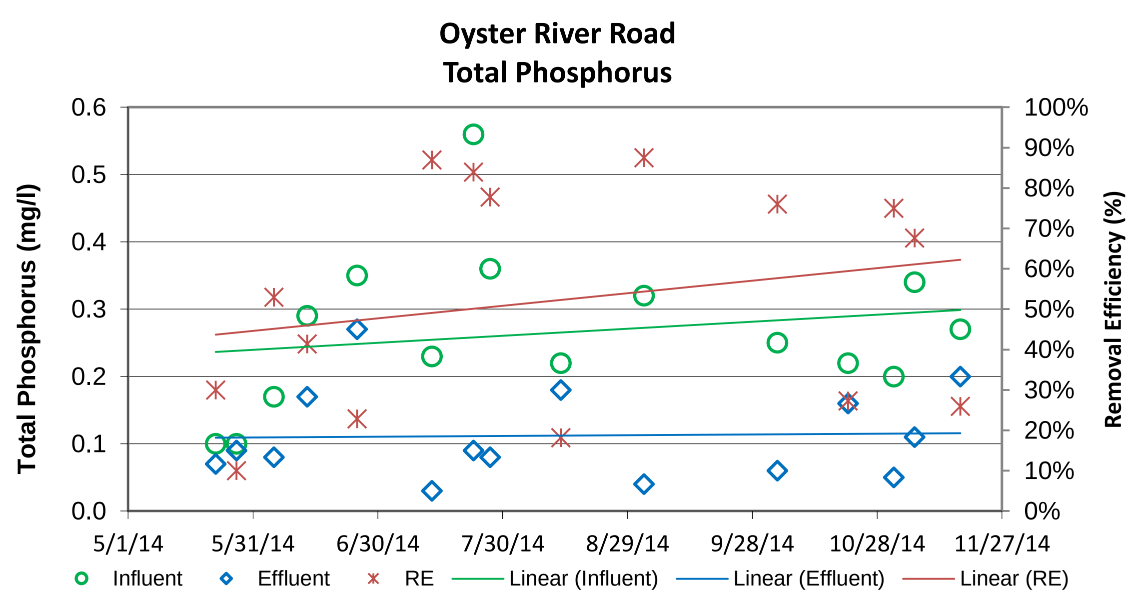

Figure 21: Oyster River Road SGWSC total phosphorus event mean concentrations and removal efficiencies for each storm event.

For TP performance results are very promising. In both instances overall removal efficiencies are not only high compared to the conventionally designed larger capacity systems but they also increase over time and approach higher RE thresholds. This indicates that these are living systems and performance may increase as the system matures and the biological components develop and integrate. This is of importance as most research projects conduct monitoring of SCM measures directly after installation. With proper maintenance and adequate growth timeframes SCM measures that employ biological unit processes should continue to get better with time. This dataset underscores that a "ripening" phase occurs with many green infrastructure systems, and this phase will vary but is associated with maturity of biological and geochemical systems. "Ripening" is a general term that attempts to explain complex biological assembly of vegetative and microbiological unit processes primarily responsible for pollutant reductions in these systems. Unlike physical unit operations such as settling or filtration biological processes are less well understood but generally require time to mature and form the interconnection within the systems necessary for optimal performance. There were attempts to accelerate this process through seeding of ISR with water from the original SGW system at the UNHSC field facility however the results of these efforts are unknown. This is an area UNHSC researchers continue to study,

Dissolved Nutrient Performance: Dissolved Inorganic Nitrogen (DIN) and Dissolved Phosphorus (ortho-Phosphate)

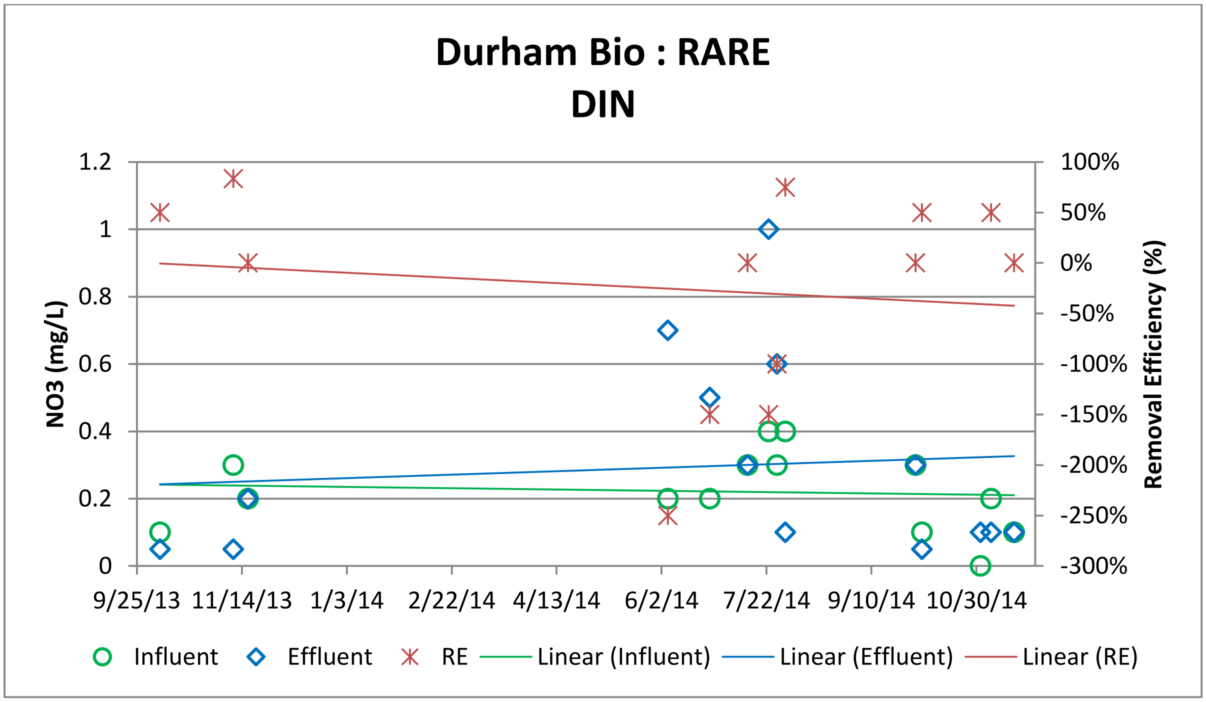

Figure 22: Durham IBSC dissolved inorganic nitrogen event mean concentrations and removal efficiencies for each storm event.

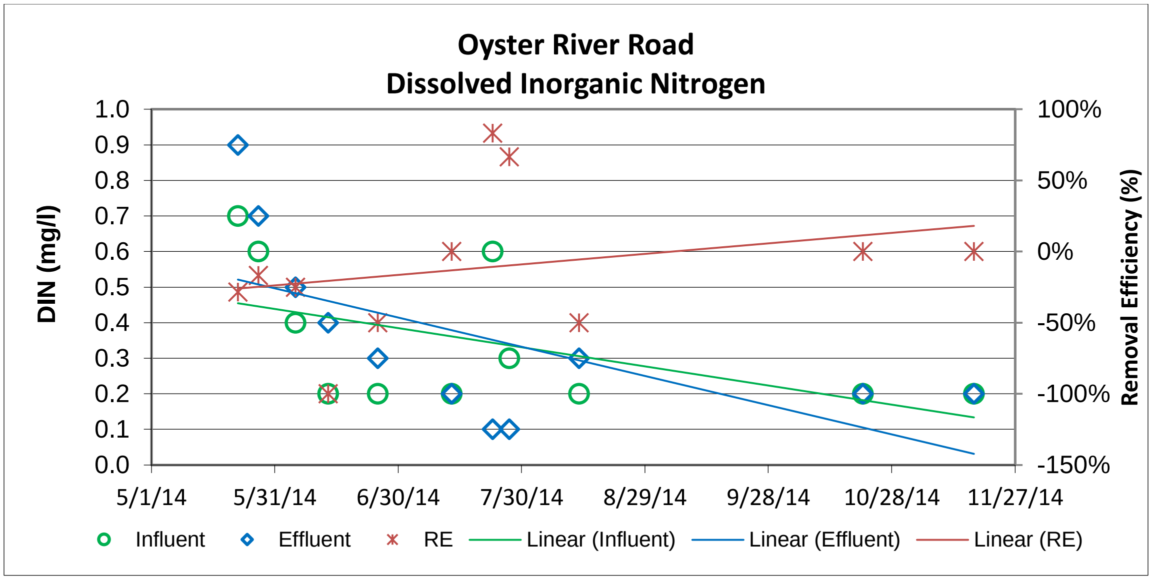

Figure 23: Oyster River Road SGWSC dissolved inorganic nitrogen event mean concentrations and removal efficiencies for each storm event.

For dissolved inorganic nitrogen (N03, N02, and NH4) reductions it is clear that there is more to learn. With respect to the Durham Bio system (IBSC#2) there was an increased DIN concentration from urban environments but no clear advantage with respect to undersized systems. It is possible that the modeling and design approaches need more refinement to address these issues. For rural residential land uses there appears to be a seasonal trend with higher DIN concentrations during spring although this finding would need to be confirmed over a multi-year monitoring period.

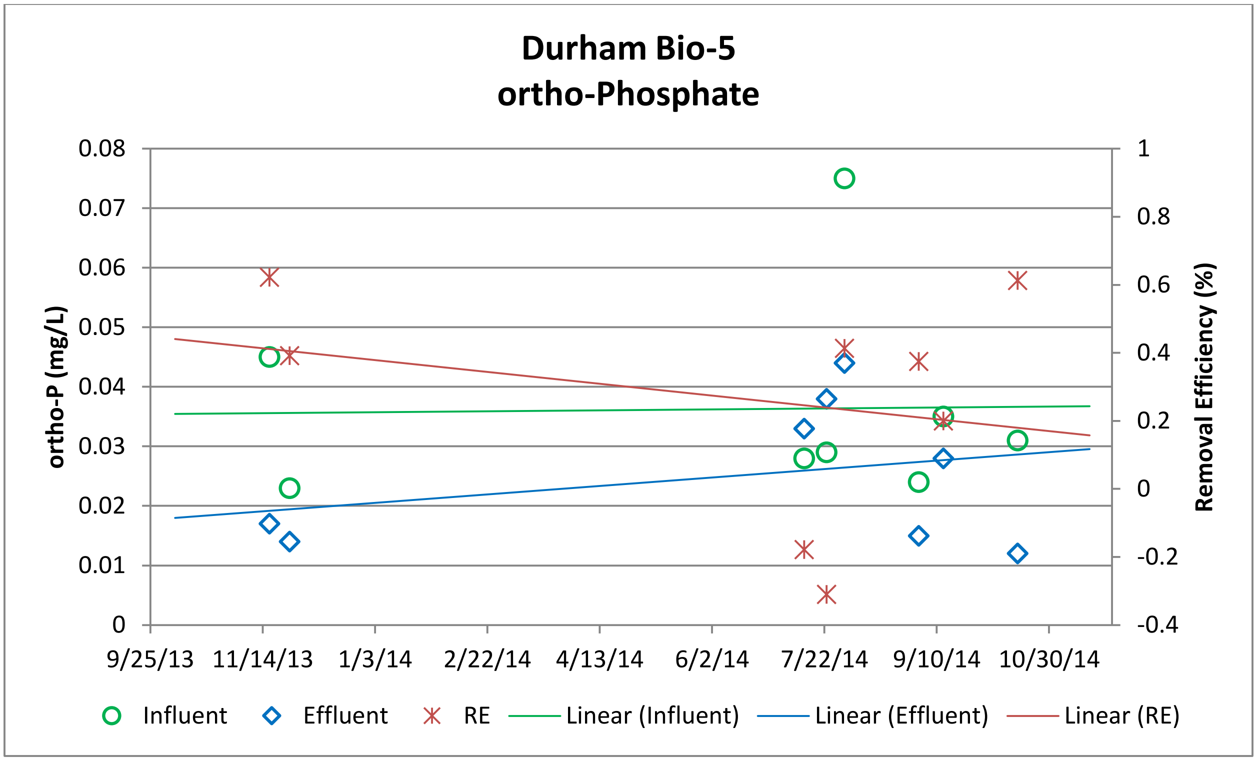

Figure 24: Durham IBSC dissolved phosphorus event mean concentrations and removal efficiencies for each storm event.

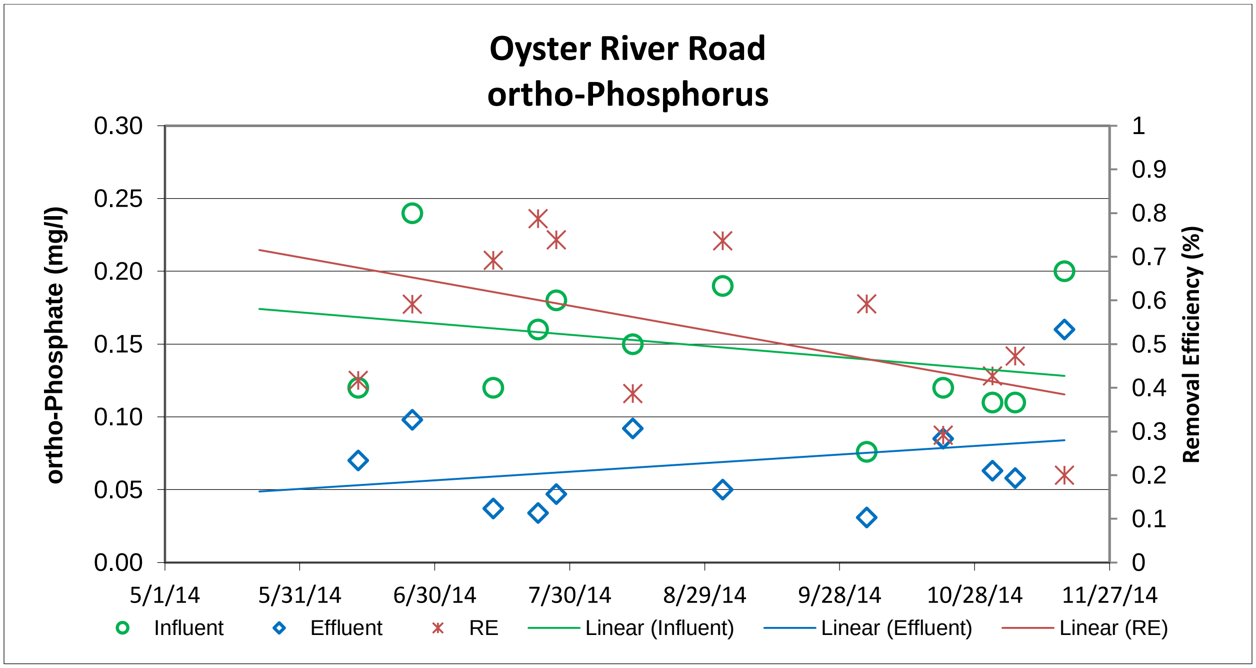

Figure 25: Oyster River Road SGWSC dissolved phosphorus event mean concentrations and removal efficiencies for each storm event.

In general phosphorus levels are higher in the residential land use and much like higher DIN values may be a consequence of fertilizer applications although this finding would need to be confirmed over a multi-year monitoring period. It is obvious that where there are higher influent concentrations there are better corresponding removal efficiencies trending toward higher removal thresholds over time. Where there is lower dissolved phosphorus concentrations such as commercial land uses there is greater variability in RE performance thresholds although overall effluent limits are well below actionable levels. The lower influent levels and attendant lower RE may reflect a type of "irreducible" concentration, which has been recognized in the treatment of wastewater (Kadlec and Knight, 1995) and therefore may be a similar phenomenon with stormwater.

Treatment Effects on Sediments and Metals

In general there are significant TSS and TZn removal efficiencies for all storms (design and non-design). This is significant as most removal efficiencies are based on a standardized design approach. For design events the effluent concentrations remained very consistent, often hovering around the method detection limits. While effluent concentrations for non-design events are more variable, removals are predominantly still positive and often approach expected performance for conventionally sized systems. Figures 26 and 27 demonstrate the performance of the systems with respect to TZN. These figures present the data summarized in Tables 8 and 9 and the attendant high removal of Zinc. In the figures, "bypass" means that water elevations exceeding the volumetric storage capacity of the system were exceeded. It should be noted that the bypass was included in the monitoring data. While different from the design storage volume the bypass events offer a hydraulic indication when the actual capacity of the system has been exceeded.

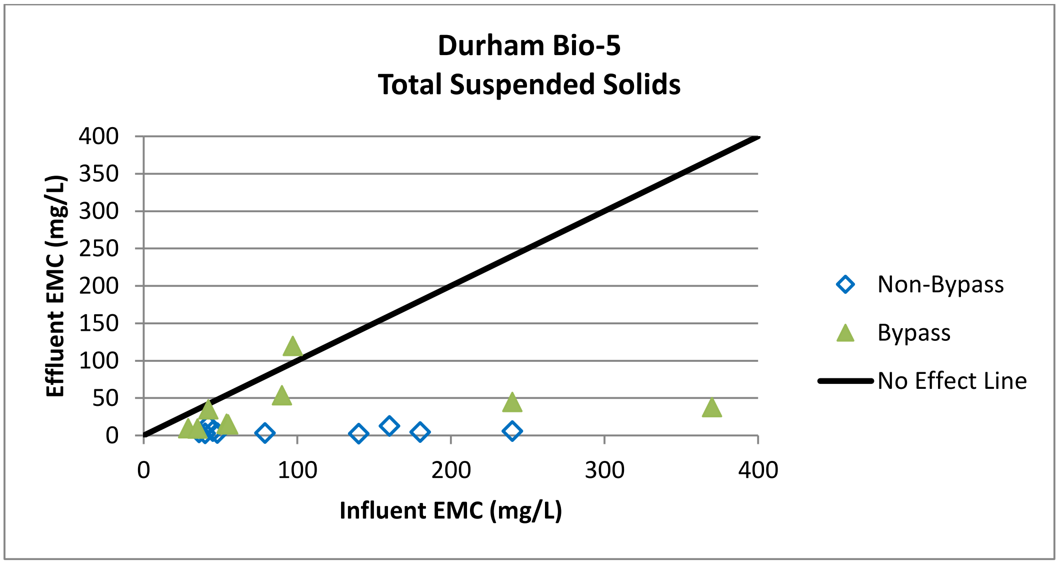

Figure 26: Durham IBSC treatment effects plot for total suspended solids.

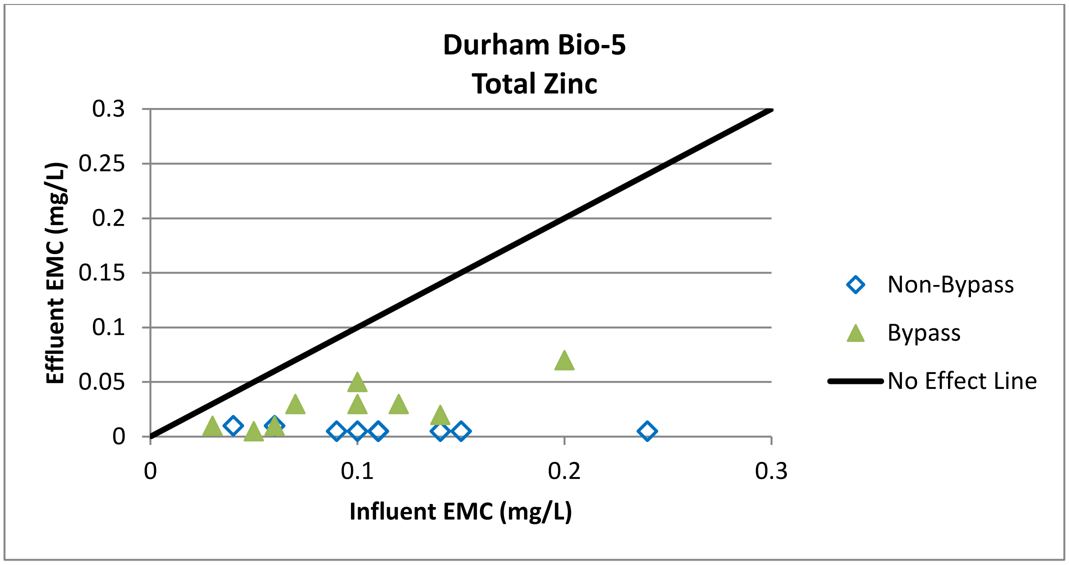

Figure 27: Durham IBSC treatment effects plot for total zinc.

Figures 28 and 29 present influent and effluent TSS EMC data that was also summarized in Tables 8 and 9. Even though these systems are considered undersized, their performance is quite impressive in TSS reduction.

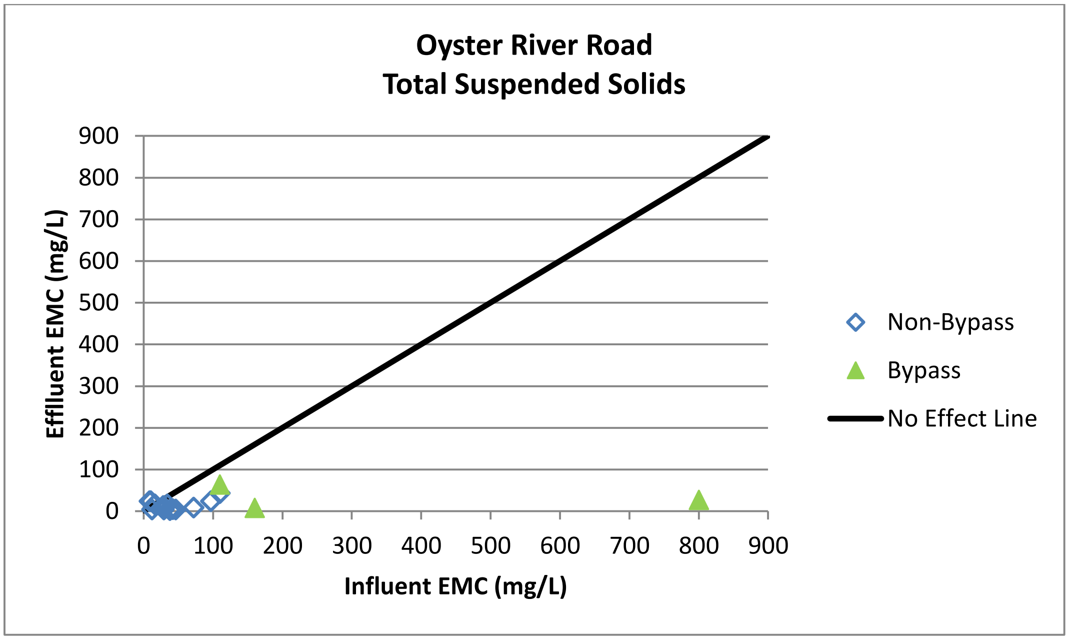

Figure 28: Oyster River Road SGWSC treatment effects plot for total suspended solids.

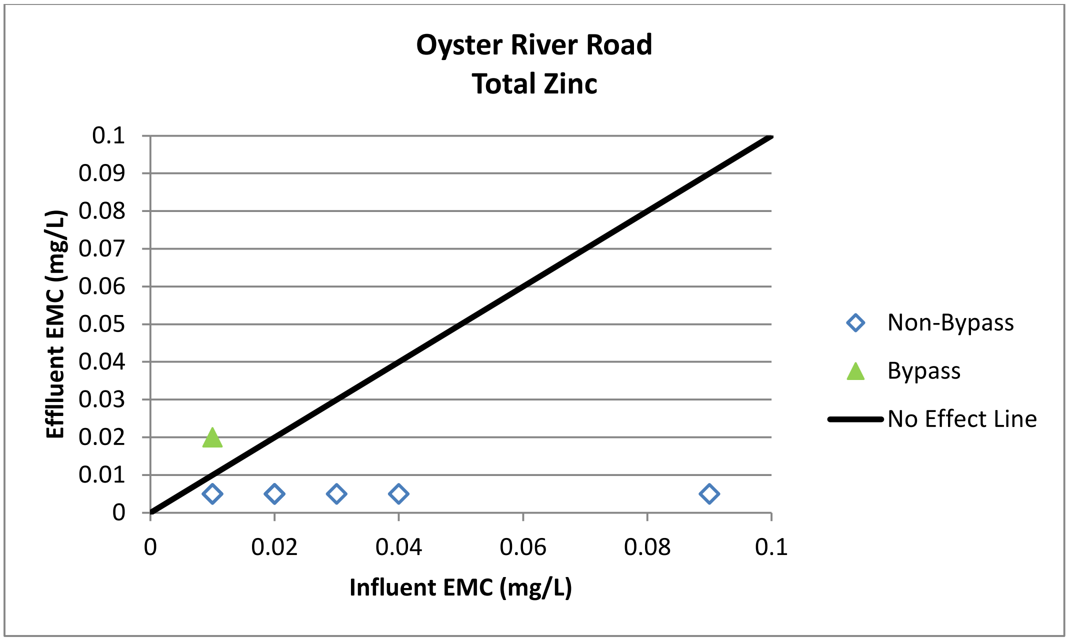

Figure 29**: Oyster River Road SGWSC treatment effects plot for total zinc.**

Treatment Effects on Nutrients (TN, TP)

The collected data confirms both that undersized systems perform well for nutrients and that use of the internal storage reservoirs for nitrogen removal is effective. Figures 30 through 33 depict the Total Nitrogen and Total Phosphorus performance of each system. The data is also summarized in Tables 8 and 9. While there is variability in effluent concentrations between bypass and non-bypass events, effluent concentrations remain more consistent with a flatter overall trend than non-bypass effluent concentrations, which trend steeper toward the no-effect line. While effluent concentrations for bypass events are more variable, removals are predominantly still positive and often approach expected performance for conventionally sized systems. This is significant in that grossly undersized systems are still performing within the expected range of "appropriately" sized systems. This would indicate that sizing methods for SCMs with respect to nutrient reductions may have room for improvement: much smaller (and therefore less expensive) SCMs may deliver almost the same nutrient reduction benefits.

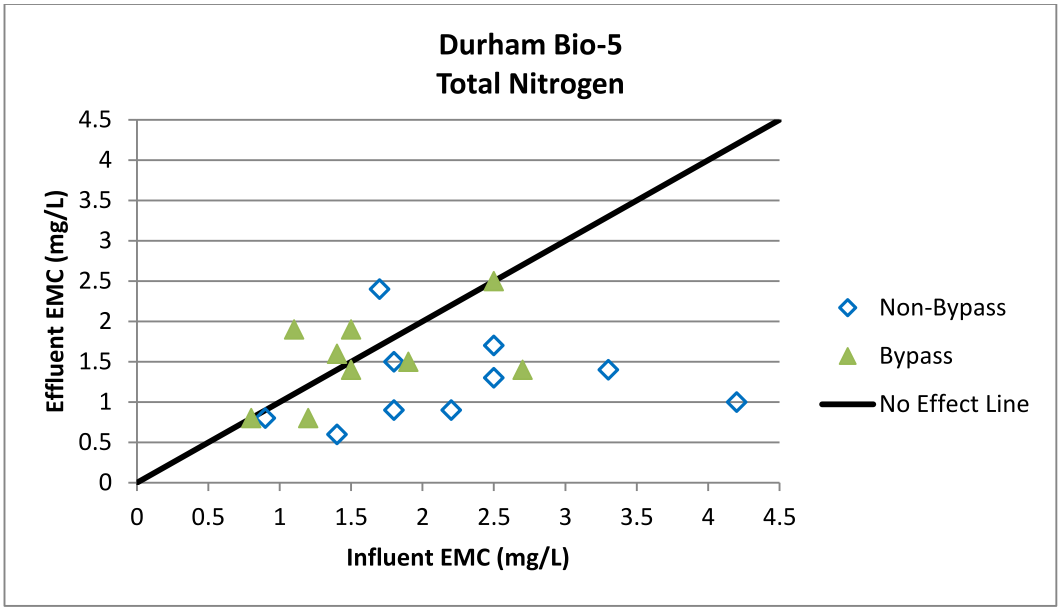

Figure 30: Durham IBSC treatment effects plot for total nitrogen.

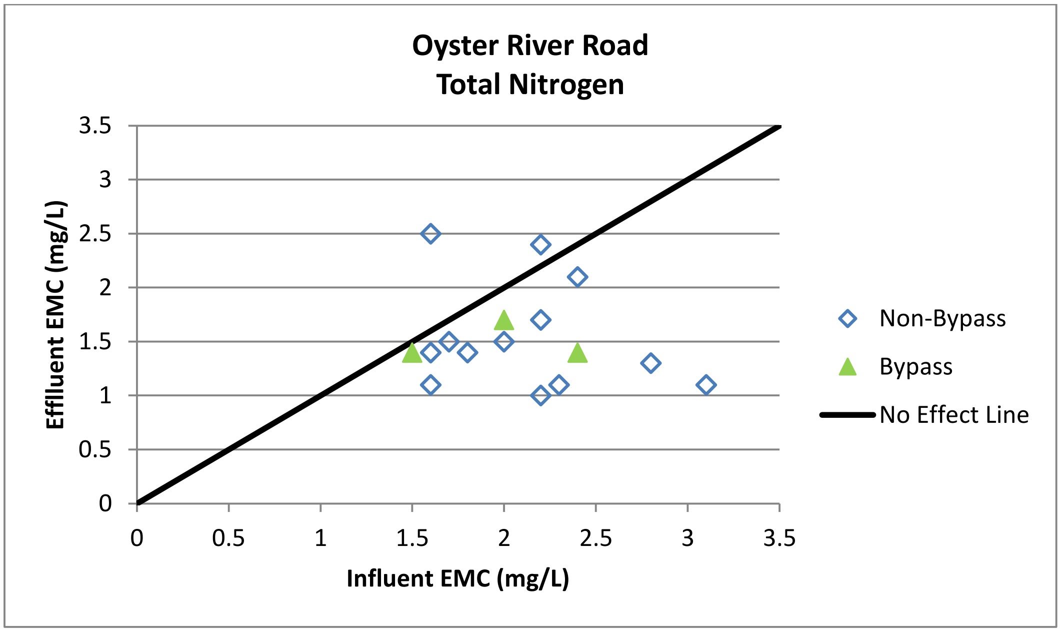

Figure 31: Oyster River Road SGWSC treatment effects plot for total nitrogen.

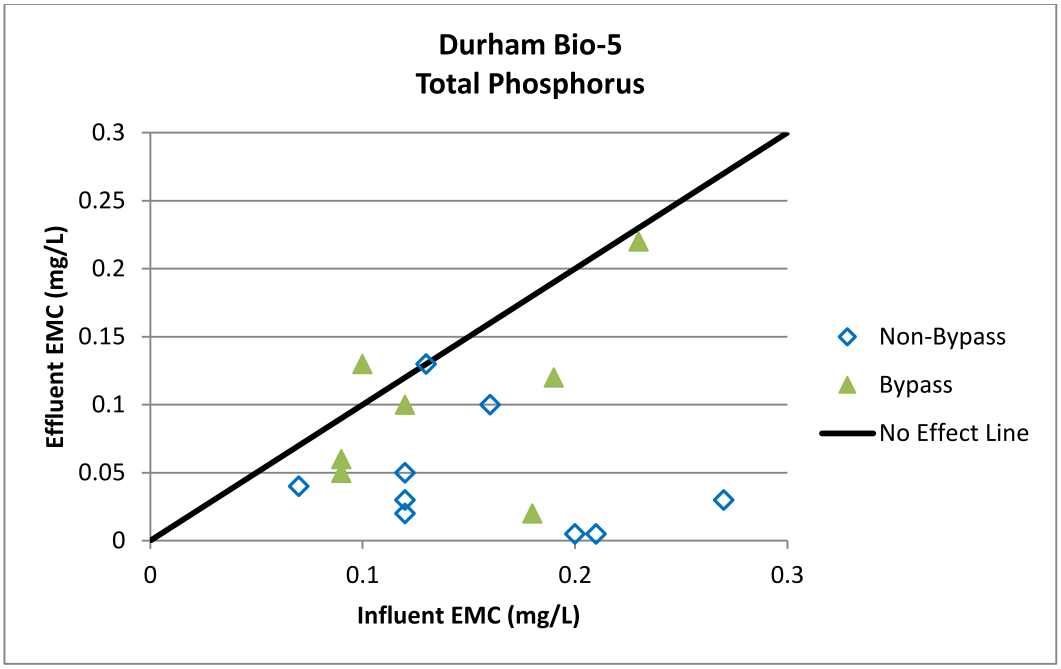

Figure 32: Durham IBSC treatment effects plot for total phosphorus.

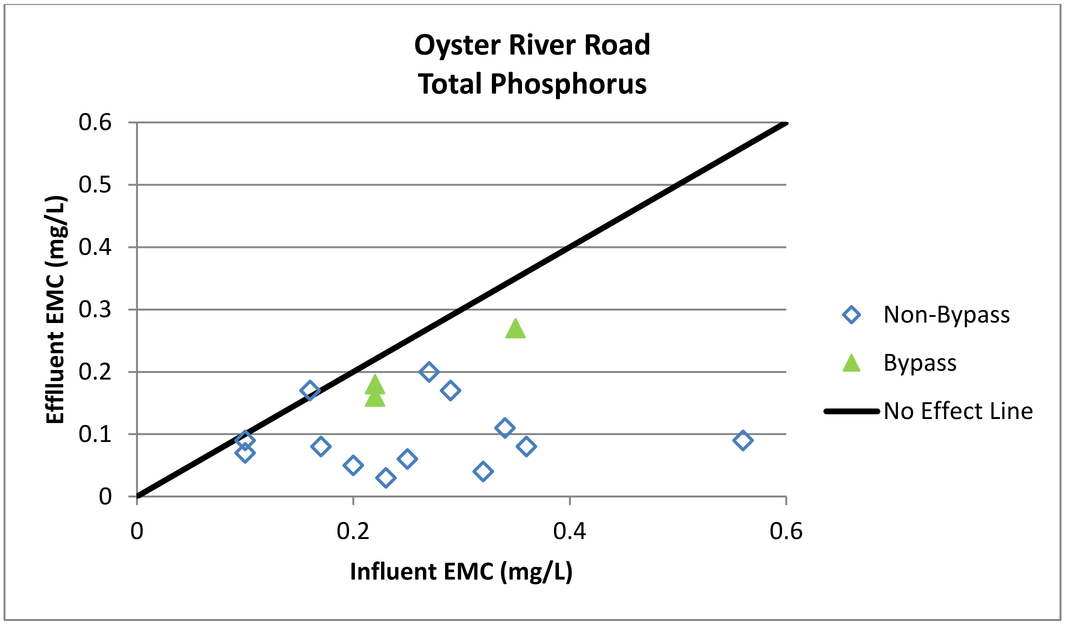

Figure 33: Oyster River Road SGWSC treatment effects plot for total phosphorus.

The nutrient removal results from these two systems are largely positive; however it underscores the need for greater residence times. The ORR SGW (SGWSC#1) was designed with a residence time of 10 hours. The Durham Bio had a resultant residence holding time of only 2.4 hours. Originally minimum orifice diameters were 1” as the convention was that anything smaller in stormwater systems had a high potential for clogging. Since the water is drained from the stone, and philosophically large particles should not be flowing out of that, there is no reason why orifice controls could not be designed to be smaller. With improvements to the design, performance may be increased, however this is an area for future research.

Treatment Effects on Dissolved Nutrients (DIN, ortho-P)

Influent and effluent EMCs for dissolved nutrient species may be found in Figures 34 through 37. The IBSC outperformed the SGWC for DIN. In fact for DIN, when viewing Figures 34 and 35 the IBSC in general showed removal whereas the SGWC did not. In future designs and specifications more attention needs to be paid to the outlet control design. Originally minimum orifice diameters were 1" as the convention was that anything smaller in stormwater systems had a high potential for clogging. Since the water is drained from the stone and philosophically large particles should not be flowing out of that, there is no reason why orifice controls could not be designed to be smaller. The lack of performance may also stem from the degree of undersizing and possibly that the anaerobic zone could not be consistently maintained in the anaerobic state (too much mixing) and it could also be due to the lack of system maturity and relatively lower concentrations of influent DIN as demonstrated in Figures 22 and 23.

Figures 36 and 37 display the influent and effluent data for ortho-phosphate. Both systems perform well and provide significant removal. In this case the SGWSC outperforms the IBSC. The influent EMC at the SGWSC is higher than at the IBSC and may illustrate the consequences of lawn fertilization.

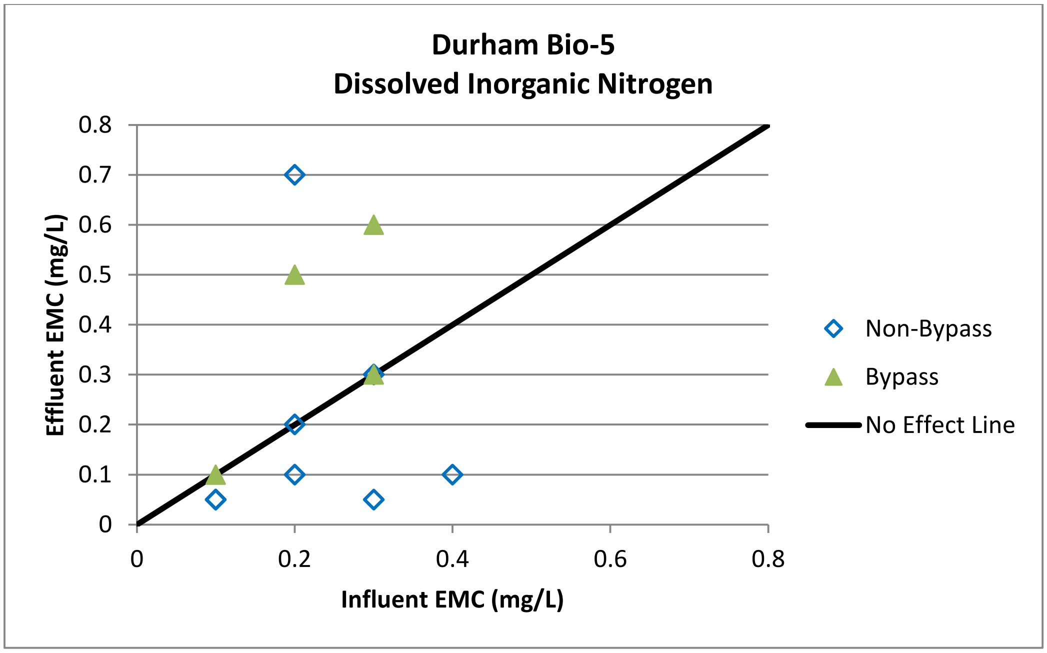

Figure 34: Durham IBSC treatment effects plot for dissolved inorganic nitrogen.

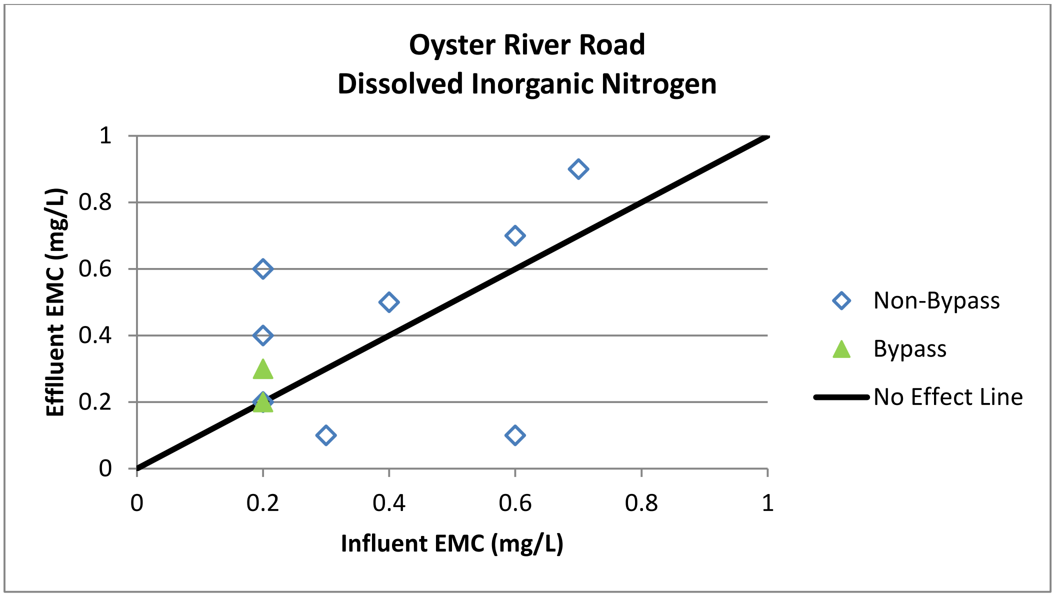

Figure 35: Oyster River Road SGWSC treatment effects plot for dissolved inorganic nitrogen.

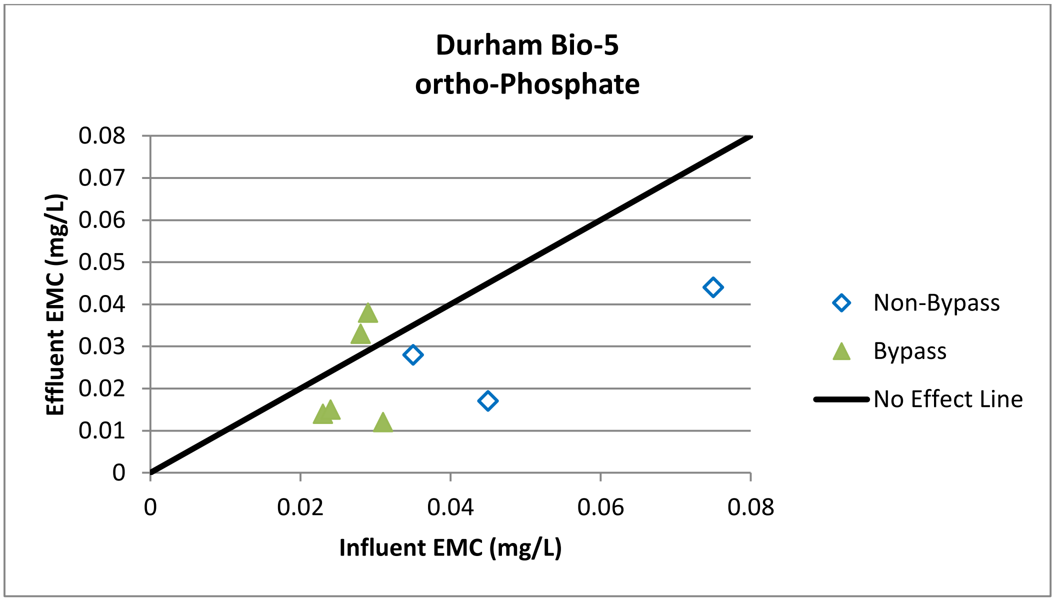

Figure 36: Durham IBSC treatment effects plot for dissolved phosphorus.

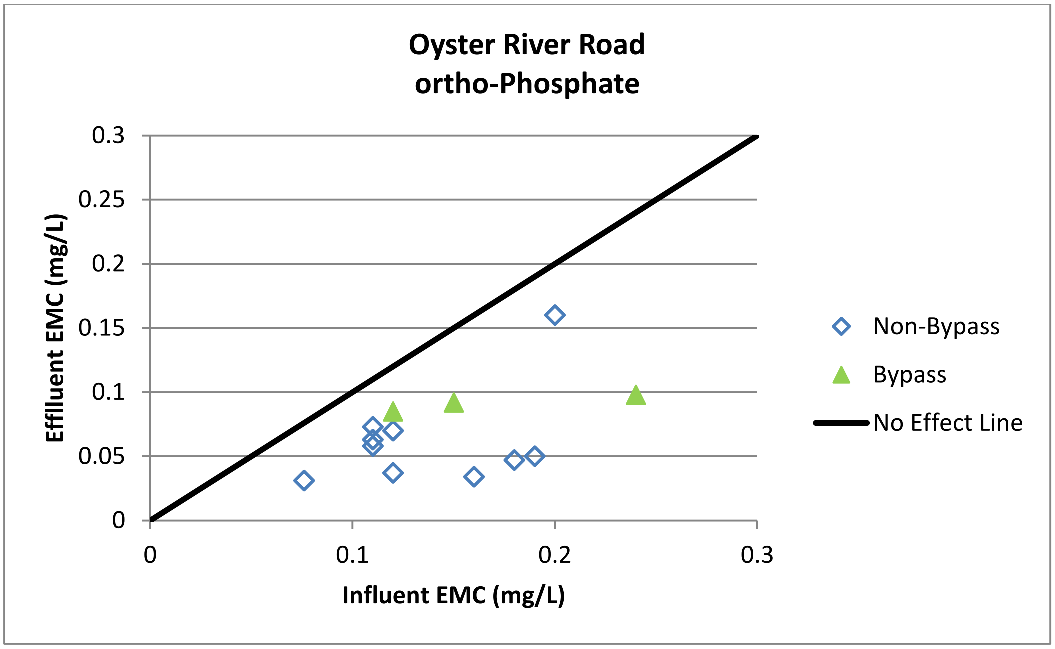

Figure 37: Oyster River Road SGWSC treatment effects plot for dissolved phosphorus.

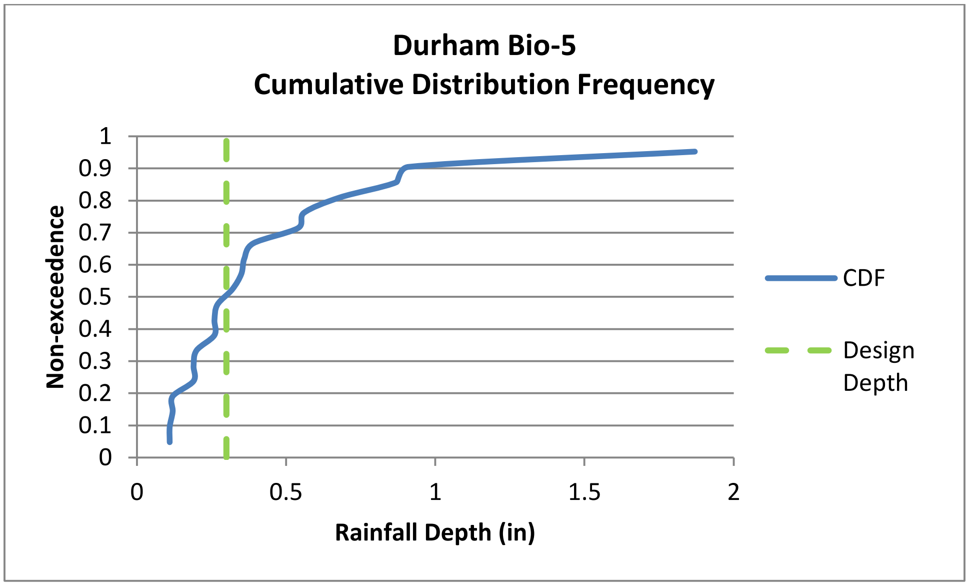

Figure 38: Durham IBSC rainfall cumulative distribution frequency plot with rainfall design depth of 0.3" for reference.

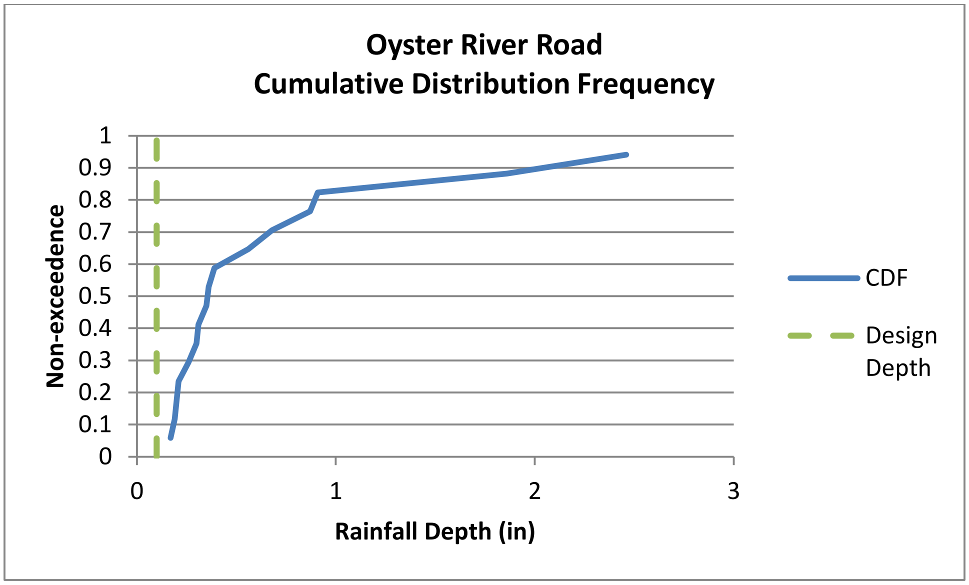

Figure 39: Oyster River Road SGWSC cumulative distribution frequency plot with rainfall design depth of 0.1" for reference.

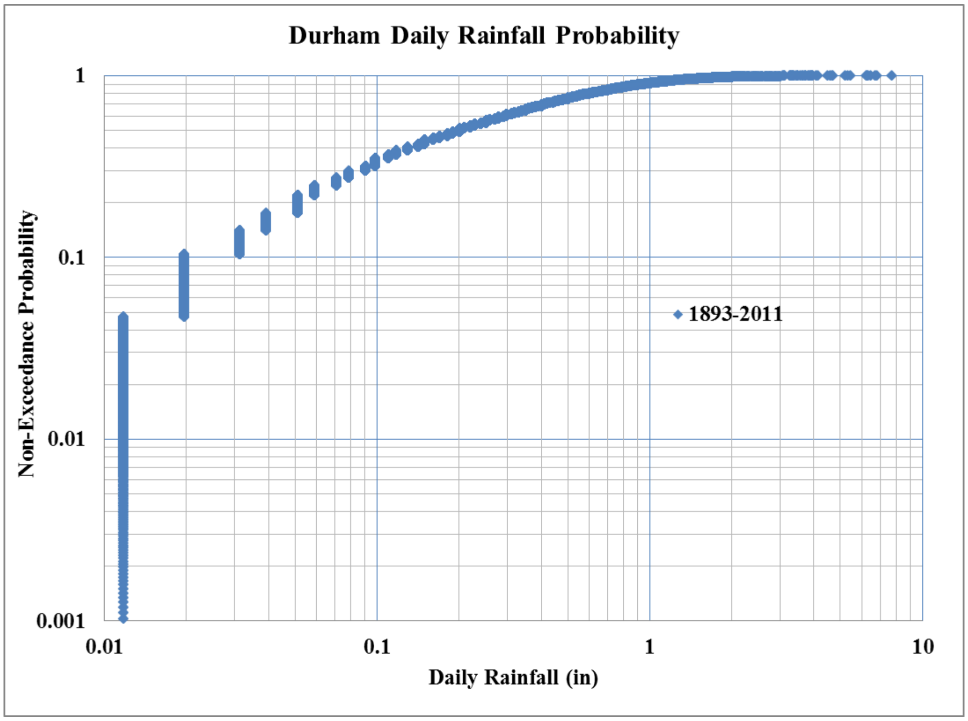

Figure 40: Cumulative non-exceedance values for rainfall depths over a 118 year rainfall record

In general, despite the overall undersized nature of the monitored systems performance was commensurate to conventionally sized systems. Based on a 118 year rainfall record at a NOAA station in Durham the following table illustrates the percentage of storms anticipated to be fully treated without more complex hydraulic routing modeling.

Table 13: The percentage of storms anticipated to be fully treated without more complex hydraulic routing modeling.

System	Design Rainfall Depth (in)	% Storms Fully Treated
SGW (SGWSC#1)	0.1	33%
Durham Bio (IBSC#2)	0.3	60%

CONCLUSIONS VOLUME REDUCTION NOTES

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 in size. 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.

For the purposes of comparison Figures 41-43 and tables 10-11 were developed to relate the empirical performance of the two small capacity urban retrofit stormwater controls to the modeled assessments conducted by EPA Region 1. With the exception of TN empirical values either generally meet or exceed modeled values providing additional confidence that at the lower end of the performance curve the values are substantiated. 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.

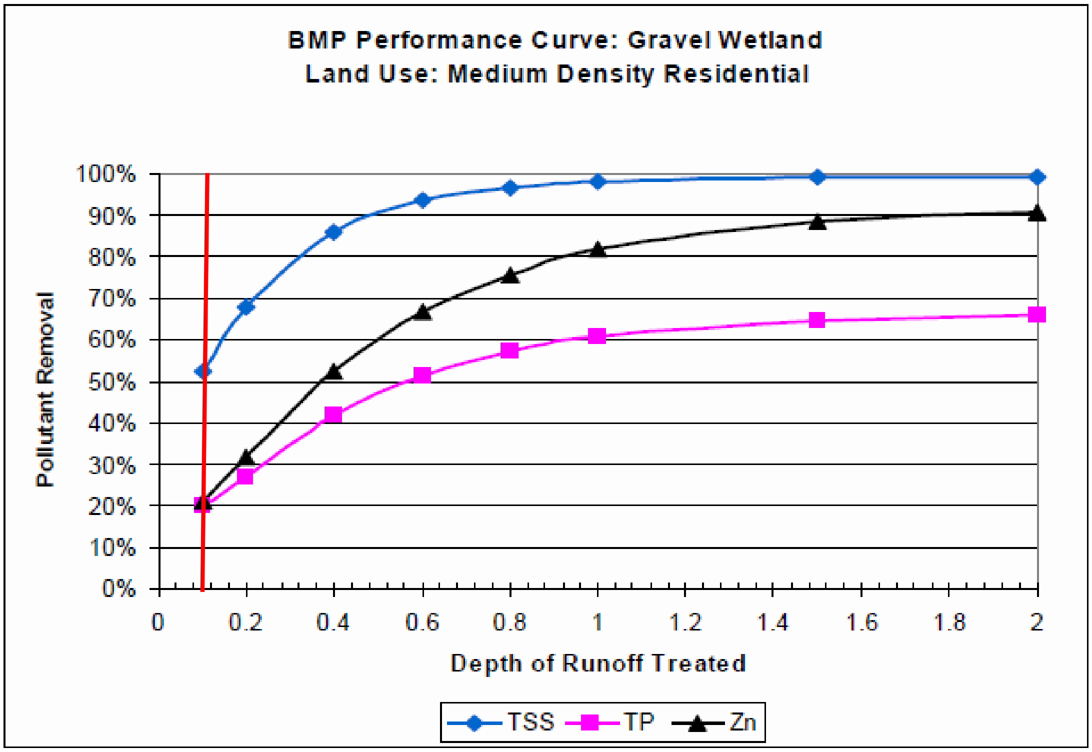

Figure 41: Cumulative performances curves with depth of runoff captured for the for the SGWCS-1 (vertical red line) in medium residential land uses (EPA, 2010)

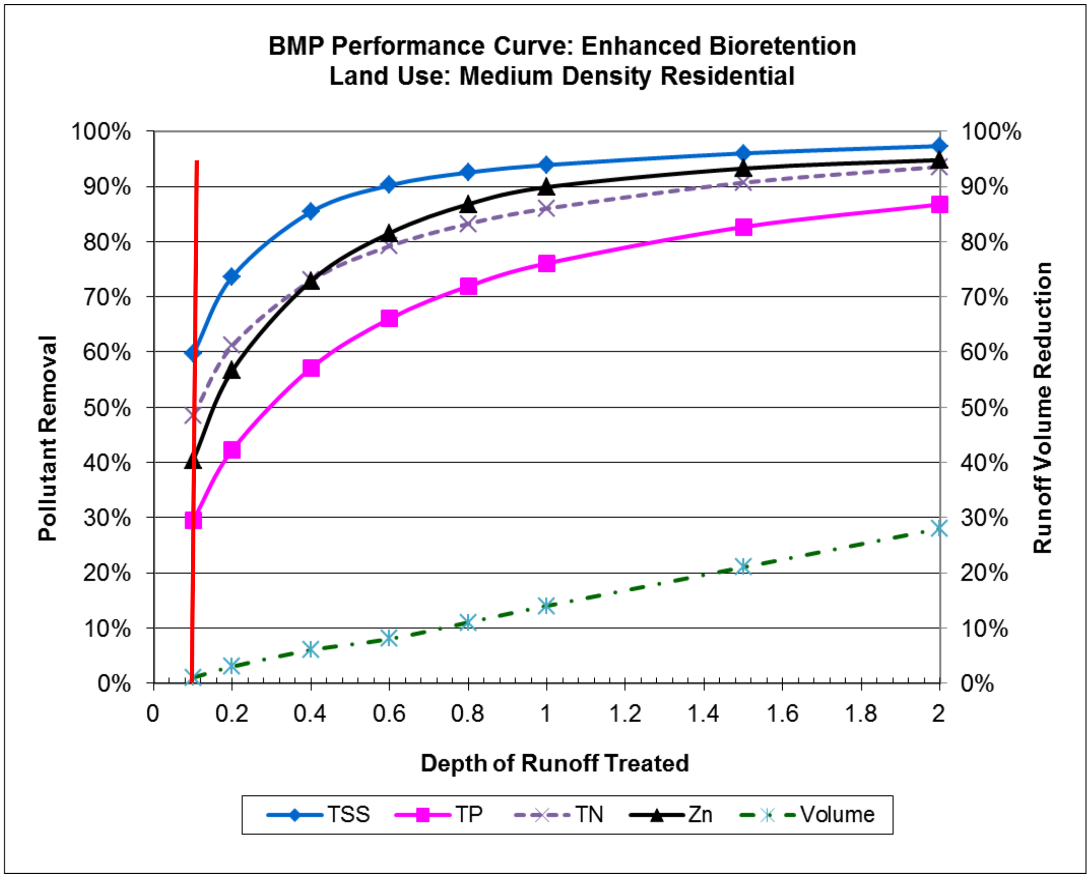

Figure 42: Cumulative performances curves and depth of runoff captured for the for the SGWCS-1 (vertical red line) for medium density residential land uses (EPA, 2012)

Table 14: Empirical versus modeled RE for SGW and IBSC systems in medium density residential land uses

Analyte	Depth of Runoff stored (in)	Modeled RE % (Enhanced Bio Curve)	Measured Median RE %
TSS	0.1	52 (60)	75
TZn	0.1	20 (40)	75
TP	0.1	20 (30)	53
TN	0.1	49	23

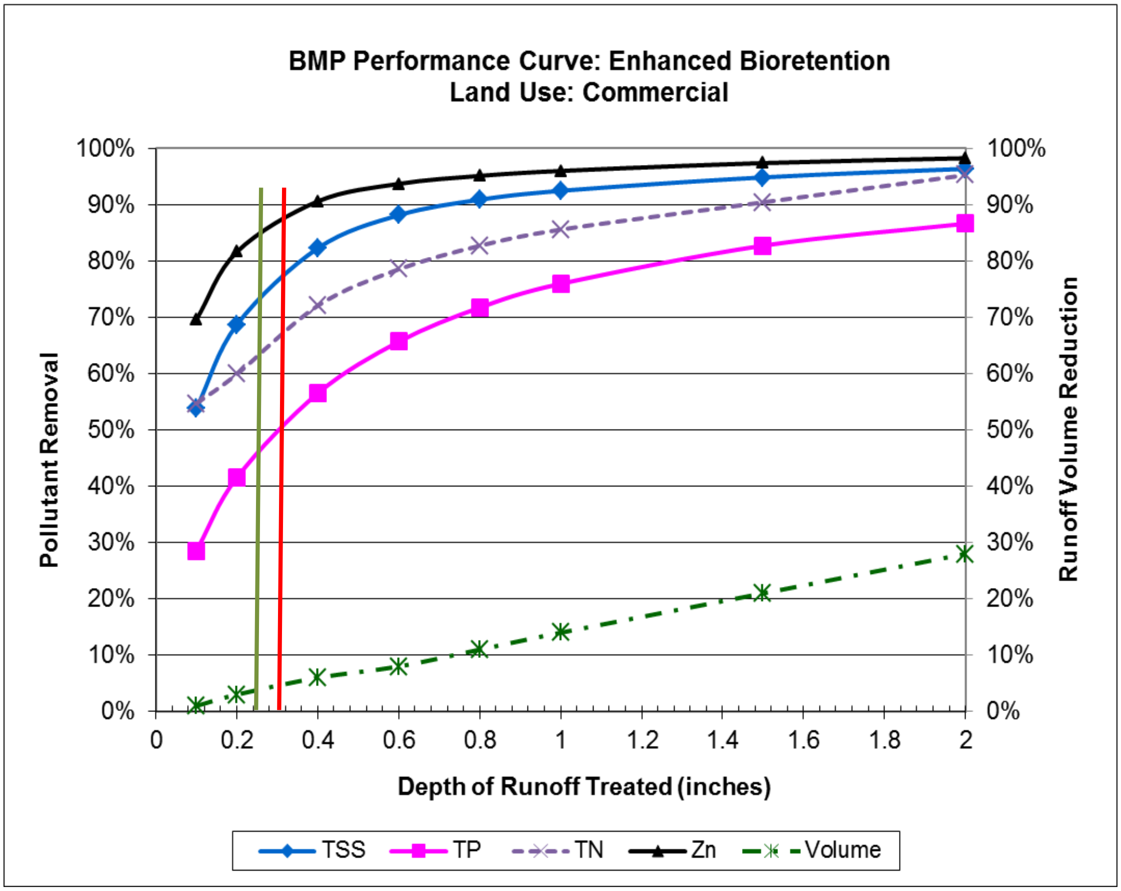

Figure 43: Cumulative performances curves and depth of runoff stored for IBSC-2 for commercial land uses (EPA, 2012).

* Note: The Green line represents runoff depth stored and redline represents runoff depth treated.

Table 15: Empirical versus modeled RE for IBSC systems in commercial land uses

Analyte	Depth of Runoff (in) (Vol Stored)	Modeled RE % (Depth Runoff Vol)	Measured Median RE %
TSS	0.3 (0.24)	78 (73)	86
TZn	0.3 (0.24)	88 (85)	86
TP	0.3 (0.24)	50 (45)	40
TN	0.3 (0.24)	68 (62)	21

Table 16: Annual pollutant load reduction estimates for each of the studied systems based on empirically derived pollutant load export rates using the simple method.

EPA REGION 1 RARE PROJECT POLLUTANT LOAD REDUCTION CALCULATIONS															
Location (Land Use)	BMP Description	Method					TSS			TP			TN		
			Drainage Area 'A' Acre	Impervious Area 'Ia' %	Runoff Coefficient 'Rv'	Annual Runoff 'R' inches	Annual Load 'L$_i$' #/year	Effluent Load 'L$_e$" #/year	Annual PL Removed #/year	Annual Load 'L$_i$' #/year	Effluent Load 'L$_e$" #/year	Annual PL Removed #/year	Annual Load 'L$_i$' #/year	Effluent Load 'L$_e$" #/year	Annual PL Removed #/year
2013-2015 Research Results															
SGWSC-1 Residential	GW	IC	6.0	0.3	0.4	15.1	2190.1	541.9	1648.2	5.44	2.56	2.88	42.65	32.95	9.69
IBSC-2 Commercial	Bio	IC	0.4	1.0	0.9	40.3	382.4	51.8	330.5	0.49	0.29	0.20	6.98	5.51	1.47
Totals			**6.4**	**1.3**	**1.3**	**55.4**	**2572.5**	**593.7**	**1978.8**	**5.93**	**2.85**	**3.08**	**49.62**	**38.46**	**11.16**

Table 17: Annual pollutant load reduction estimates for each of the studied systems based on EPA Region 1 and WISE project derived pollutant load export rates.

EPA Region 1 Draft Permit Values											
						TP			TN		
Location	DA	IA	DCIA	PLER	NLER	load	effluent	annual load removed	load	effluent	annual load removed
Durham SGW	6.0	0.3	2.0	1.96	14.10	3.92	1.84	2.08	28.19	21.79	6.41
Residential											
Durham IBSC	0.4	1.0	0.4	1.78	15.08	0.69	0.41	0.28	5.83	4.61	1.23
Commercial											

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