FILTERRA®: ANALYSIS OF LONG-TERM PERFORMANCE

Prepared by

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ABSTRACT

In situ performance of conventional, slow-flow bioretention and high rate biofiltration systems is typically characterized via load and concentration reduction performance over a typical water year. However, long-term performance monitoring is also beneficial, since bioretention soil media is expected to have a useful life measured in decades without the need for replacement.

This report aims to advance our knowledge of biofiltration longevity through research that assesses the ability of high rate biofiltration systems (designed at infiltration rates of 100 inches per hour or greater) to provide consistent water quality and hydraulic performance at the decadal time scale with standard maintenance.

Since 2007, Contech Engineered Solutions LLC has continuously evaluated water quality performance at three different high rate biofiltration sites in the Mid-Atlantic via third-party field sampling and laboratory analysis. All sites utilize Filterra®, a proprietary biofilter that shares primary pollutant removal processes with conventional bioretention but has a much higher design infiltration rate and a footprint that is typically less than 10% the size of conventional bioretention systems. The study sites represent different sizes, ages, and land uses. All sites received regular maintenance. Monitoring duration varied by site, ranging upwards to 13 years.

Hydraulic testing was conducted in a saturated and unsaturated condition to assess changes in hydraulic capacity over time, for which suggested research methods and results are presented. Media profile composition and plant growth progression are studied to understand changes in system dynamics.

Based on available data, Filterra continues to meet or exceed performance expectations, suggesting that routine maintenance is adequate to maintain design functionality long-term without replacement of the bioretention soil media. Filterra performance continues to be similar or better than conventional bioretention performance for TSS, nutrients and metals. Sampling methods and results are presented for parameters of interest including TSS, nutrients, metals, oil and grease, pH and temperature. Recommendations are made for ensuring long-term water quality compliance, with a focus on providing proper and timely maintenance.

BACKGROUND

Conventional bioretention systems have been used to reduce stormwater runoff volume and rate, and to improve the quality of stormwater discharge for over two decades. Design characteristics vary regionally, but typically include a vegetated media bed of at least 18 inches in depth comprised of a blend of sand and compost or topsoil. Typical design infiltration rates range up to 12 inches per hour with resultant ratios of bioretention area to contributing effective impervious area of less than 10%. Where the long term reliable native soil infiltration rate is high enough to infiltrate the entire design storm, bioretention systems are often designed without an underdrain and effectively have no downstream discharge in routine storm events. Where native soil infiltration rates are insufficient to eliminate runoff during the design storm, an underdrain is typically installed within a gravel drainage layer below the bioretention soil. In this configuration, a portion of the design storm is treated and released downstream, and the effluent quality of the system must be considered. Although terminology varies regionally, with terms like bioretention, rain garden and biofiltration often used interchangeably, for the purposes of this report, the term bioretention refers to those systems that retain the design storm via infiltration after filtration through vegetated soil media. The term biofiltration refers to those systems that release all or a portion of the design storm through an underdrain after filtration through vegetated soil media.

The Filterra system was developed as a compact, high-performance alternative to conventional bioretention and biofiltration and can be designed to retain and infiltrate all or a portion of the design storm. Like conventional systems, it includes vegetation, a mulch layer for pretreatment and moisture retention, engineered soil media and an underdrain that discharges treated stormwater. Unlike conventional systems, the design infiltration rate of the filtration media ranges from 50 to 175 inches per hour depending on local approvals. This significantly higher infiltration rate is made possible by stringent quality control practices that ensure media consistency, and by standardized design, construction, activation and maintenance practices. Due to the smaller size of the Filterra system, the media experiences a higher pollutant load per area and volume. However, the mulch layer over the top of the media is designed to protect the media from degradation over time.

Filterra systems have been tested extensively following peer reviewed testing protocols including the TAPE protocol (Ecology 2018). These studies have all been conducted on systems less than 5 years old and over a duration of 1 to 3 years. These tests have demonstrated that the pollutant removal capabilities of the Filterra system meet or exceed the performance goals set by the Washington State Department of Ecology TAPE program which is the premier field-based stormwater control measure performance verification program in the United States. This study was initiated to assess the ability of Filterra systems to remove common pollutants over time as the system ages.

The International Stormwater BMP (Best Management Practice) Database is a clearinghouse for test results from stormwater BMP field performance studies. In 2020, a performance summary was released summarizing water quality performance of 14 types of stormwater control measures for common pollutants (Clary et al. 2020). Included in the summary report is performance data for Bioretention (BR) and High Rate Biofiltration (HRBF) which are defined as follows:

> “Bioretention - Shallow, vegetated basins with a variety of planting/filtration media and often including underdrains. Also called rain gardens and biofiltration”
>
> “High Rate Biofiltration - Manufactured devices with high-rate filtration media that support plants.”

Although there are several types of proprietary biofiltration systems commercially available, the data for HRBF in the summary report is entirely comprised of results from 6 Filterra sites, since that was the only proprietary biofilter data in the database at the time of the report. The BR data includes influent data from 43 studies and effluent from 41 studies.

The 2020 summary report concludes that both BR and HRBF provide significant removal of TSS. HRBF also provides significant reduction in total phosphorus concentration, but runoff treated by BR shows a significant increase in total phosphorus (Table 1).

Table 1. Bioretention and high rate biofiltration performance for TSS and total phosphorus from the 2020 Summary Statistics Report by the International Stormwater BMP Database

Parameter		TSS		Total Phosphorus	
Units		(mg/L)		(mg/L)	
Stormwater Control Measure		BR	HRBF	BR	HRBF
Median Value	Influent	44	30.8	0.19	0.099
	Effluent	10	3.8	0.24	0.05
Significant Median Value Reduction (Mann Whitney P-value 0.05)		Yes	Yes	Significant export	Yes

HRBF provided a significant reduction in total and dissolved copper and zinc. BR provided significant reduction of total and dissolved zinc and total copper but reduction in dissolved copper was insignificant (Table 2).

Table 2. Bioretention and high rate biofiltration performance for zinc and copper from the 2020 Summary Statistics Report by the International Stormwater BMP Database

Parameter		Total Copper		Total Zinc		Dissolved Copper		Dissolved Zinc	
Units		(µg/L)		(µg/L)		(µg/L)		(µg/L)	
Stormwater Control Measure		BR	HRBF	BR	HRBF	BR	HRBF	BR	HRBF
Median Value	Influent	13.1	7.95	62	178	6.85	4.5	20.8	189
	Effluent	7.13	3.75	12.8	60.6	7.54	3.4	12.5	79
Significant Median Value Reduction (Mann Whitney P-value 0.05)		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

This report will compare the performance of Filterra systems over time to Filterra results from short-term (1-3 years) testing under the TAPE protocol and other similar protocols from the 2020 Stormwater BMP Database Report. Changes over time in factors contributing to water quality performance, including the saturated and unsaturated infiltration rate of the Filterra media, media composition and plant growth will be investigated as well.

Long-term performance monitoring is helpful since bioretention soil media is expected to have a useful life measured in decades without the need for replacement. This report aims to advance our knowledge of biofiltration longevity through research that assesses the ability of high rate biofiltration to provide consistent water quality and hydraulic performance at the decadal time scale with standard maintenance.

Three Filterra study sites ranging in system age, size and land use were monitored in Maryland and Virginia for various pollutants of concern to verify consistency in long-term performance (Figure 1(a)(b), Figure 2(a)(b), Figure 3(a)(b)). Monitoring duration varied by study site ranging from 3 to 13 years and covered system ages from 1 to 13 years since activation. Activation is defined as when Filterra begins treating runoff after removal of flow barriers to protect the system from construction-phase runoff and installation of vegetation, mulch, and dissipation stone. Pollutant removal efficiency was evaluated via third-party field sampling and laboratory analysis procedures. Pollutants monitored varied by site, including total suspended solids (TSS), phosphorus, nitrogen, heavy metals, and oil and grease. Study test site descriptions are provided in Table 3 below. Photos taken throughout the study period are provided for each study site in Appendix A: **Photo Log**

Table 3. Filterra study test sites

Study Site ID	A	B	C
Land Use	Restaurant Commercial Parking Lot	Oil Service Station Commercial Parking Lot	Gas Station Retail Area
Location	Virginia Beach, VA	Baltimore, MD	Hampton, VA
System Size (ft.)	6x4	6x6	6x8
Plant Type	Nellie Stevens Holly	Northern Bayberry	Redtwig Dogwood, Foster Holly
Activation Date	4/13/2007	6/1/2005	5/27/2005
Age at Time of Monitoring (yrs.)	1 - 11	3 - 6	0 - 13
Time Monitored (yrs.)	10	3	13

(a)

(b)

Figure 1(a)(b). Study site A 2014

(a)

(b)

Figure 2(a)(b). Study site B 2009

(a) **(b)**

Figure 3(a)(b). Study site C 2014

The three test systems were sized according to Filterra regulatory approvals at the time of plan approval. Systems were sized to treat design storms of ½ inch and 1 inch in Virginia and Maryland, respectively, at the then current state-approved design infiltration rate of 100 inches/hr (~ 1 gpm/sqft) based on test data available at the time of the approvals. Sizing criteria was historically established following the rainfall distribution and frequency data from the mid-Atlantic region to ensure 90% treatment of the total annual rainfall volume.

METHODS

Sampling

Grab samples were collected following EPA sampling guidance (1992) over a 30-minute duration at 10-minute intervals. Influent and effluent sampling were paced 5 minutes apart to allow for proper detention time. Samples were collected near the beginning of the storm to capture the pollutant first flush. Acceptable storm event criteria included (1) antecedent conditions of at least 6 hours of no greater than trace precipitation and (2) more than 0.1 inch of total rainfall depth.

Sample information at collection included sample name, lab sample ID, date, sample times, sample collection type, sampler name, parameters collected, sample container type, preservation, and any unusual circumstances that may impact sample results. Samples were collected in preserved bottles as appropriate, placed on ice and transferred to the appropriate analytical laboratory with a complete chain of custody.

Influent sample collection occurred at the Filterra throat opening just before runoff entered the system and effluent sample collection occurred at the Filterra outlet pipe invert into the downstream catch basin. Sample collection and analysis was performed by Universal Laboratories at study sites A and C and Microbac Laboratories at study site B. Laboratory contact information is found below.

Universal Laboratories

Project Manager: Dan Thornton, Project Supervisor

20 Research Drive

Hampton, VA 23666

(800) 695-2162

Microbac Laboratories, Inc.
Project Manager: Michael Arbaugh Sr., Division Manager

2101 Van Deman St.

Baltimore, MD 21224

(410) 633-1800

Reporting limits and analytical methods for water quality parameters are shown in Table 4.

Table 4. Water quality parameter reporting limits and analytical methods.

Parameter	Method	Reporting Limit (mg/L) (Universal)	Reporting Limit (mg/L) (Microbac)
Total Suspended Solids (TSS)	SM 2540 D	1.0	<10.0, 1.0
Total Phosphorus	EPA 365.1	0.02	0.01
Dissolved Phosphorus	SM 4500 P/B/E	0.02	0.01
Total Copper	EPA 200.7	0.001, 0.005	0.005
Total Zinc	EPA 200.7	0.005	0.005
Oil & Grease	EPA 1664A	5.0	5.0

The required analytical container, sample handling, preservative and maximum allowable holding time limits for each parameter are shown in Table 5.

Table 5. Water quality parameter sample handling requirements

Parameter	Container	Preservative	Max. Allowable Hold Time
Total Suspended Solids (TSS)	1000 mL HDPE	<6°C	7 days
Total Phosphorus	250 mL glass	H_2SO_4 to pH<2/<6°C	28 days
Dissolved Phosphorus	250 mL glass	filtration/ H_2SO_4 to pH<2/<6°C	28 days
Total Copper	250/500 mL plastic	HNO_3 to pH<2/<6°C	6 months
Total Zinc	250/500 mL plastic	HNO_3 to pH<2/<6°C	6 months
Oil & Grease	1000 mL glass	HCl to pH<2/<6°C	28 days

Hydraulic Evaluation

Field hydraulic evaluation was performed in July 2021 on the 14-year-old Filterra system at study site A to correlate flow and quality performance. Hydraulic evaluation was not performed at the other two study sites due to an oil spill at the oil service station at study site B that required full remediation and lack of accessibility due to decommissioning of the Filterra system for site reconstruction at study site C.

Source Water and Flow Control

A fire hydrant, in combination with a rented city meter, was used as the influent supply for the field test system (Figure 4). Source water from the hydrant was controlled manually with a ball valve on the hydrant meter and directed to a flow meter via a combination of 2-inch flexible fire hose and 2-inch PVC pipe. Flow was measured by a factory-calibrated Seametrics EX810 electromagnetic flowmeter and logged at a minimum of 1 minute intervals. The logged flow data was used to verify that testing was conducted at the target flow rates. Influent water was conveyed into 2-inch PVC piping connected to an upright-positioned factory-calibrated rotameter (by King Instrument Company, manufacturer number 7205026163W). The influent flow rate was regulated via a 2-inch globe valve on the discharge of the rotameter and adjusted for the appropriate flow rate following the protocol. Water from the valve was directed into a section of 2-inch fire hose that discharged water into the gutter, mimicking real-world conditions for runoff. The flow rate was held steady during the test at ±10% of the target value. The flow meters were calibrated together at the test's start via time-bucket method, where water was introduced into a gradated tank and timed. A ruler was secured to the inside of the tree grate frame to monitor fluctuations in the water surface level in the head space of the Filterra system (Hills 2021).

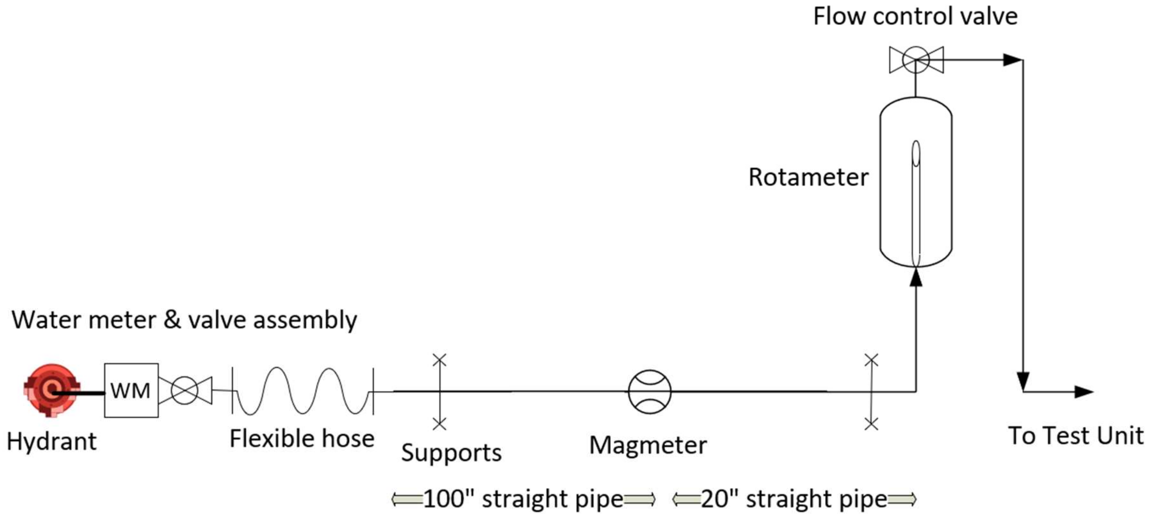


Figure 4. Field equipment flow diagram

Protocol

The field hydraulic evaluation was based on a prior protocol developed in consultation with Geosyntec Consultants for the Filterra system. Protocol revisions were made to allow for automatic data collection and data verification (Hills 2021). The general protocol included initiating hydraulic flow rate based on the Filterra media surface area. Monitored media surface area, media depth and ponding depth allow for the conversion between media flow rate (infiltration rate) and saturated hydraulic conductivity (Ksat) via Darcy's Law. The infiltration rate is the rate at which water passes through the Filterra media, and may be a function of media depth, hydraulic head, and moisture conditions among other factors (Geosyntec 2008).

Testing was performed in two phases: an unsaturated phase, followed by a saturation phase. The first test allowed for observation of the system flow rate under (typical) dry conditions with less available water content in the media, while the second test allowed for observation of the flow rate under (atypical, worst case) saturated conditions. It is assumed the Filterra media is unsaturated at the beginning of the initial test phase. The purpose of the unsaturated test was to bring the system to bypass and saturate the media, followed by a draindown period to bring the media to field capacity. Flow was initially introduced near design flow rate and increased incrementally by 20% until bypass was achieved. Flow rates were recorded with each adjustment along with the accumulated water depth or water surface level (WSL) and elapsed time per Thomas Scientific 1235C26 traceable stopwatches from the prior flow rate adjustment. Once bypass was achieved, constant head conditions were maintained for five minutes to ensure saturation. Bypass is defined as water exiting the system and traveling downstream of the system in an offline application. Inflow was terminated after five minutes of bypass conditions and the rate of drawdown or falling head was measured by recording the WSL with time over the media surface.

After a twenty-minute rest period passed since ceasing the initial unsaturated test, the saturation test began with flow introduced near design flow rate and increased incrementally. Flow rates were again recorded with each flow adjustment along with the WSL and elapsed time from the prior flow rate adjustment until the system reached and maintained a steady WSL just below the bypass depth. Once an approximate steady-state flow rate had been found, the flow rate and the WSL were noted, and the flow rate was applied for five minutes. After these conditions were met, inflow was terminated, and the WSL was noted. The rate of drawdown was then measured by recording the WSL with time over the media surface (Geosyntec 2008; Hills 2009).

Biofiltration Media Composition Sampling and Analysis Techniques

To evaluate media characteristics, the mulch was scraped back in several locations within the system following hydraulic testing. Media samples were collected at various depths throughout the media profile and placed in properly labeled sample bags. Samples were analyzed for particle size analysis via following ASTM F1632-03 (ASTM 2018) and organic content via loss on ignition following ASTM F-1647 (ASTM 2011), respectively.

RESULTS

Summary statistics for sediment, nutrients, metals, oil & grease, temperature and pH are provided in Table 6 below. Water quality performance data analysis is presented by pollutant and represents combined data sets across all three study sites over the three-to-thirteen-year monitoring duration. Reporting of descriptive statistics generally follows the format used in the International Stormwater BMP Database Summary Statistics report (2020). Data include sample counts, interquartile ranges of 25th and 75th percentiles, and median influent, effluent, and removal efficiencies with 95% confidence intervals. Data was analyzed in this manner to avoid outliers or concentrations below detection limits that may impact results. Where non-detect concentrations were observed, concentration values equal to half the detection limit were used for statistical analysis (Croghan and Egeghy 2003). Statistically significant differences between influent and effluent median concentrations for each parameter were identified using the non-parametric Mann-Whitney rank sum hypothesis test comparing the P-value to a significance value of 0.05.

Influent and effluent concentrations were used to generate side-by-side box and whisker plots for each pollutant. Data are presented on a log-scale where necessary to provide visual resolution on the y-axis. The 25th and 75th percentiles for each pollutant data set are represented by the bottom and top of the box, respectively, and listed in Table 6 below. The middle line of the box represents the 50th percentile median for each pollutant. The notches at the median represent the 95% confidence internal around the median and are also displayed in Table 6. The whiskers represent the furthest observation within 1.5 times the interquartile range (IQR) from the quartiles. Near outliers displayed as orange plus symbols represent observations further than 1.5 x IQR from the quartiles, and far outliers displayed as red asterisk symbols represent observations further than 3.0 x IQR from the quartiles.

Regression analyses comparing effluent concentration versus time were conducted to understand pollutant removal performance longevity. Confidence intervals were applied to the regression line to show the 95% probability of the true regression line of the data set. R-squared values are also displayed on each scatter plot figure as a measure of how well the regression model describes the data. Line plots comparing influent versus effluent concentration by pollutant were also created to visually track the impact of time on fluctuations in performance. Line plots were completed by study site for clarity and comparison purposes.

Table 6. Water quality performance summary for all Filterra study sites

Parameter	Sample count		IQR 25th-75th percentiles		Median (95% confidence interval)			IN vs. EFF significant diference P < 0.05 (Y/N)
	Influent (IN)	Effluent (EFF)	IN Conc. (mg/l)	EFF Conc. (mg/l)	IN Conc. (mg/l)	EFF Conc. (mg/l)	Removal (%)	
Sediment								
TSS	88	88	13 - 57.25	1.6 - 7.45	31.2 (21, 37)	3.6 (2.5, 5)	88.7 (84, 90.5)	Y
TSS-TAPEa	56	56	32.8 - 89.5	2.73 - 8.13	47.7 (36, 59.3)	5 (3.7, 6)	90.1 (88.9, 92.4)	Y
Nutrients								
TP	218	218	0.06 - 0.208	0.04 - 0.09	0.1 (0.09, 0.12)	0.05 (0.05, 0.06)	48.6 (40, 50)	Y
TP-TAPEb	111	111	0.13 - 0.395	0.05 - 0.16	0.2 (0.18, 0.26)	0.09 (0.07, 0.11)	60 (41.7, 63.3)	Y
DP	190	190	0.03 - 0.12	0.02 - 0.07	0.06 (0.05, 0.07)	0.04 (0.03, 0.04)	35 (30.6, 45.5)	Y
OP	172	172	0.03 - 0.103	0.01 - 0.07	0.053 (0.05, 0.07)	0.03 (0.03, 0.04)	50 (40, 50)	Y
TN	89	89	0.7 - 3.2	0.5 - 2	1.4 (1, 2.03)	1 (0.8, 1.25)	31.9 (22.2, 38.5)	Y
$NO_{2,3}$-N	57	57	0.1 - 0.53	0.15 - 0.6	0.22 (0.13, 0.34)	0.32 (0.2, 0.44)	-9.52 (-78.6, 0)	N
TKN	74	74	0.655 - 3	0.405 - 1.45	1.4 (0.84, 2.01)	0.655 (0.5, 1)	42 (33.3, 55.6)	Y
NH_4	16	16	0.288 - 0.56	0.1 - 0.26	0.34 (0.29, 0.52)	0.1 (0.1, 0.26)	64.9 (58.3, 67.5)	Y
Metals								
Total Zn	58	58	0.083 - 0.305	0.033 - 0.08	0.14 (0.109, 0.188)	0.0455 (0.038, 0.07)	63 (53.1, 71.4)	Y
Total Cu	56	56	0.011 - 0.071	0.006 - 0.019	0.029 (0.017, 0.43)	0.01 (0.008, 0.014)	57.3 (40, 72.9)	Y
Total Cd	13	13	0.001 - 0.001	0 - 0.001	0.0084 (0.001, 0.001)	0.00059 (0, 0.001)	27.3 (-172, 68.8)	N
Total Cr	14	14	0.002 - 0.006	0.001 - 0.001	0.0042 (0.002, 0.007)	0.0008 (0.001, 0.002)	76.5 (52.2, 87.5)	Y
Total Pb	15	15	0.008 - 0.028	0.003 - 0.005	0.0147 (0.008, 0.028)	0.0025 (0.003, 0.005)	68.8 (0, 83)	Y
Total Ni	9	9	0.016 - 0.025	0.005 - 0.012	0.018 (0.01, 0.034)	0.005 (0.005, 0.063)	64.3 (-152, 72.2)	Y
Oil & Grease								
O&G	25	25	5.6 - 11	2.5 - 5.7	7.2 (6, 9.2)	2.5 (2.5, 5.6)	58.3 (48.2,66.1)	Y
TPH	4	4	8.975 - 11	2.5 - 2.5	10.2 (8, 11)	2.5 (2.5, 2.5)	75.2 (68.8, 77.3)	Y
Other								
pH	57	57	6.6 - 7.34	6.3 - 6.9	7 (6.8,7.3)	6.6 (6.5, 6.7)	N/A	N/A
Temperature	35	35	14.3 - 25.9	14.3 - 25.4	16.5 (14.5, 25.3)	16.7 (14.8, 25)	N/A	N/A

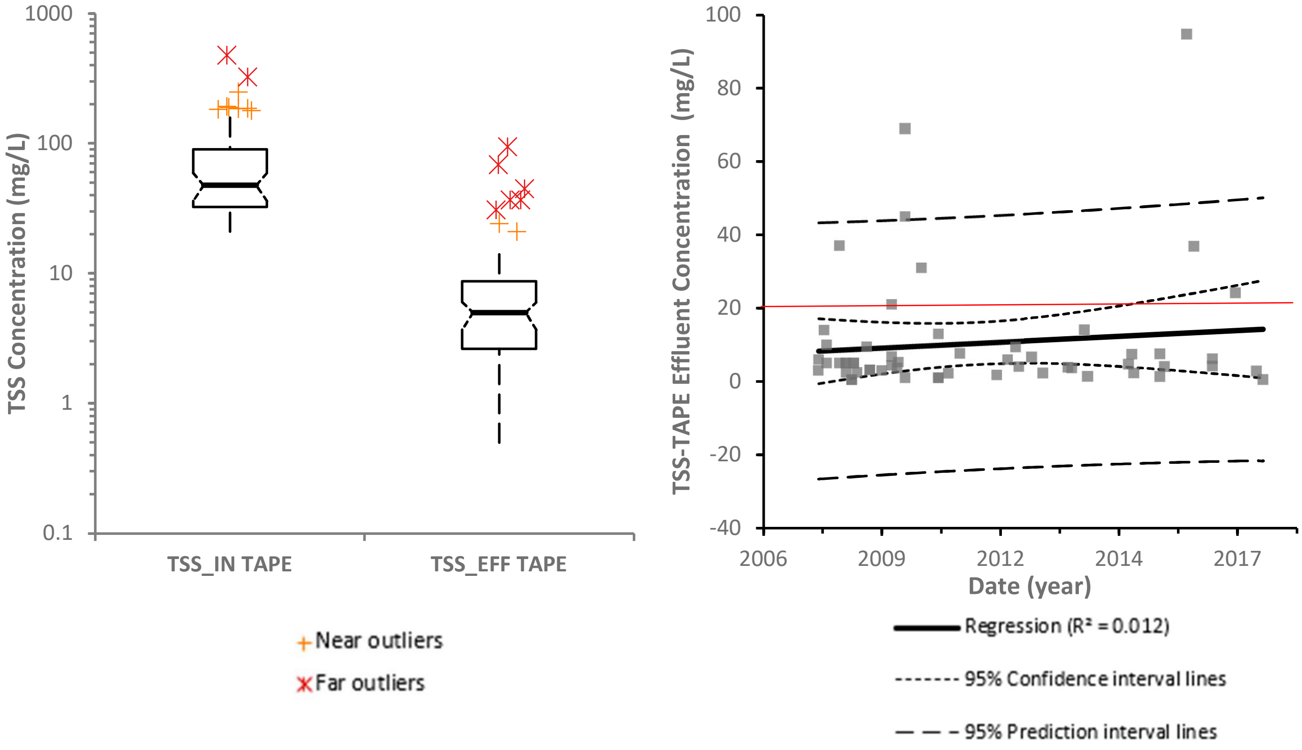
a TAPE influent range of interest limited to ≥20 mg/L. Influent concentrations capped at 200 mg/L for removal efficiency calculation per TAPE guidelines.

b TAPE influent range of interest set at 0.1 to 0.5 mg/L. Influent concentrations capped at 0.5 mg/L for removal efficiency calculation per TAPE guidelines.

Sediment

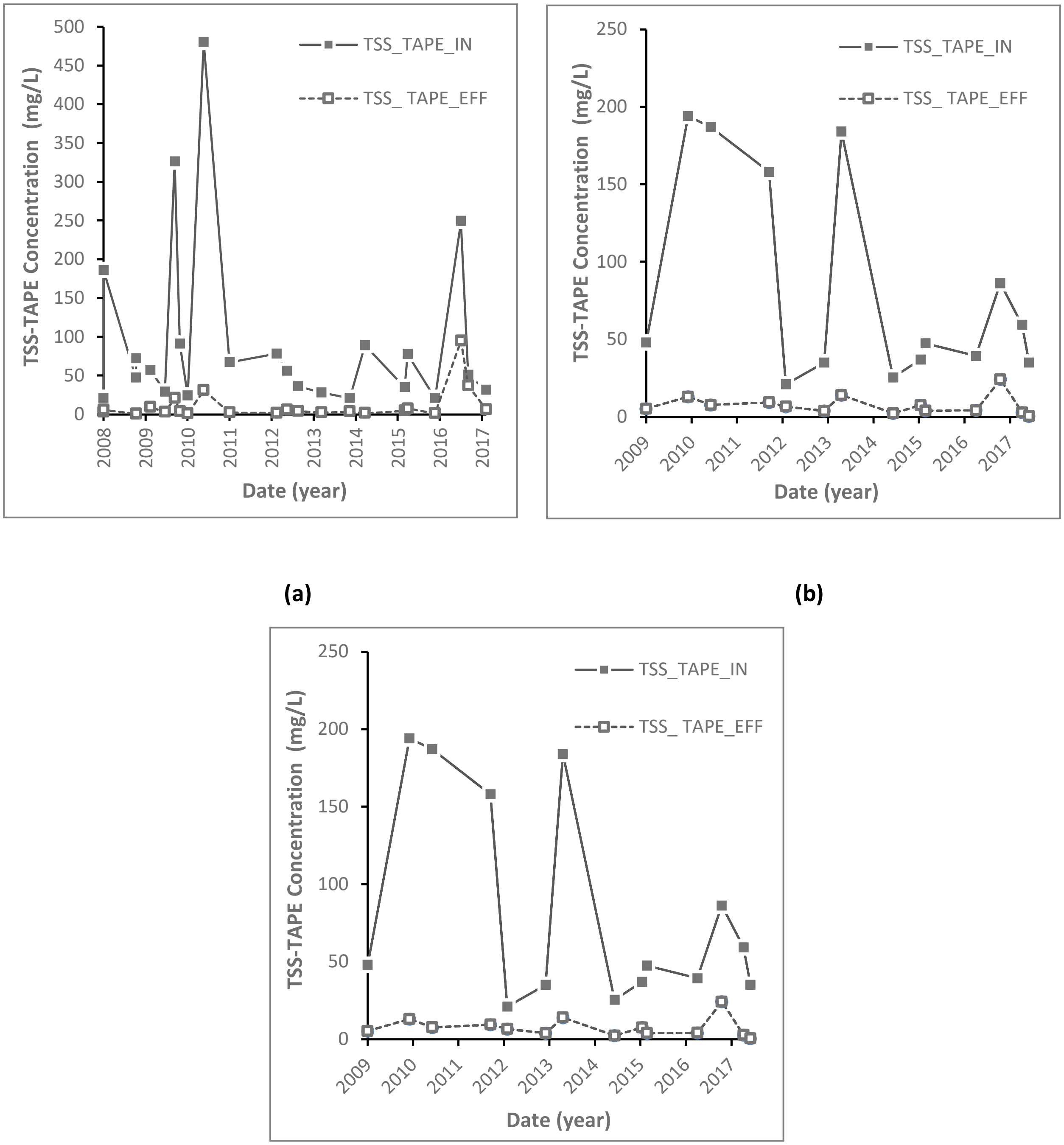
A statistical evaluation of 88 TSS sampling events demonstrated 88.7% median removal efficiency for median influent and effluent concentrations of 31.2 mg/L and 3.6 mg/L, respectively. Influent concentration range criteria set forth in the Technology Assessment Protocol - Ecology (TAPE) technical guidance manual were applied to the TSS influent concentrations to exclude runoff events with very low concentrations, resulting in 56 qualified events (Ecology 2018) that were above the lower 20 mg/L threshold set by TAPE for TSS performance evaluation. For those events greater than 200 mg/L, the influent concentration was capped at 200 mg/L in accordance with TAPE procedures. Applying TAPE criteria to TSS influent concentrations increased median removal efficiency to 90% for median influent and effluent concentrations of 47.7 mg/L and 5 mg/L, respectively. For both TSS and TSS-TAPE, median influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

TSS box and regression plots (Figure 5) show the entire data distribution, excluding events with TSS influent concentrations less than 20 mg/L per TAPE guidance. The box and regression plots show significant TSS removal and no correlation between effluent concentration and time with the TAPE criteria applied for the concentration range evaluated. Effluent concentrations fall consistently below the TAPE treatment goal of 20 mg/L indicated by the red threshold line within the regression plot. This correlation is further supported via line plot analysis in Figure 6 showing consistently low effluent concentrations over time given variation in influent concentrations at all study sites.



(a) **(b)**

Figure 5. TSS descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**

(c)

Figure 6. TSS line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

Nutrients

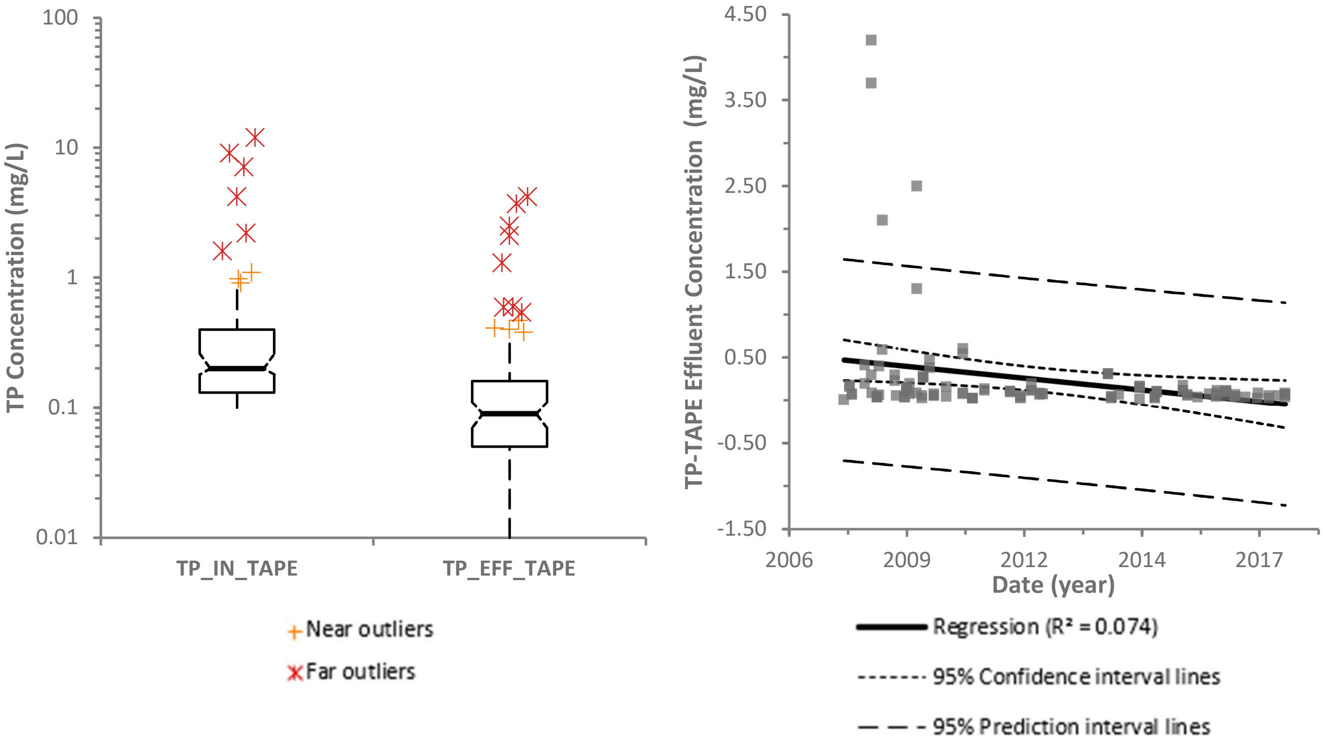
Box and regression plots for all nutrient forms monitored, with the exception of nitrite/nitrate nitrogen, show statistically significant differences between influent and effluent median concentrations using the non-parametric Mann-Whitney rank sum hypothesis test comparing the P-value to a significance value of 0.05.

Regression plots for all nutrient forms show no correlation between effluent concentration and time. Higher nutrient effluent concentrations observed from 2008 through 2010 represent atypically high influent concentrations at study site B. Line plot analysis for total phosphorus demonstrates low effluent concentrations over time given variation in influent concentrations at all study sites. Other nutrient forms including total dissolved phosphorus, orthophosphate, total nitrogen, total Kjeldahl nitrogen, and ammonium, show greater correlation between influent and effluent concentrations in comparison to other contaminants, with higher influent concentrations producing higher effluent concentrations.

Total Phosphorus

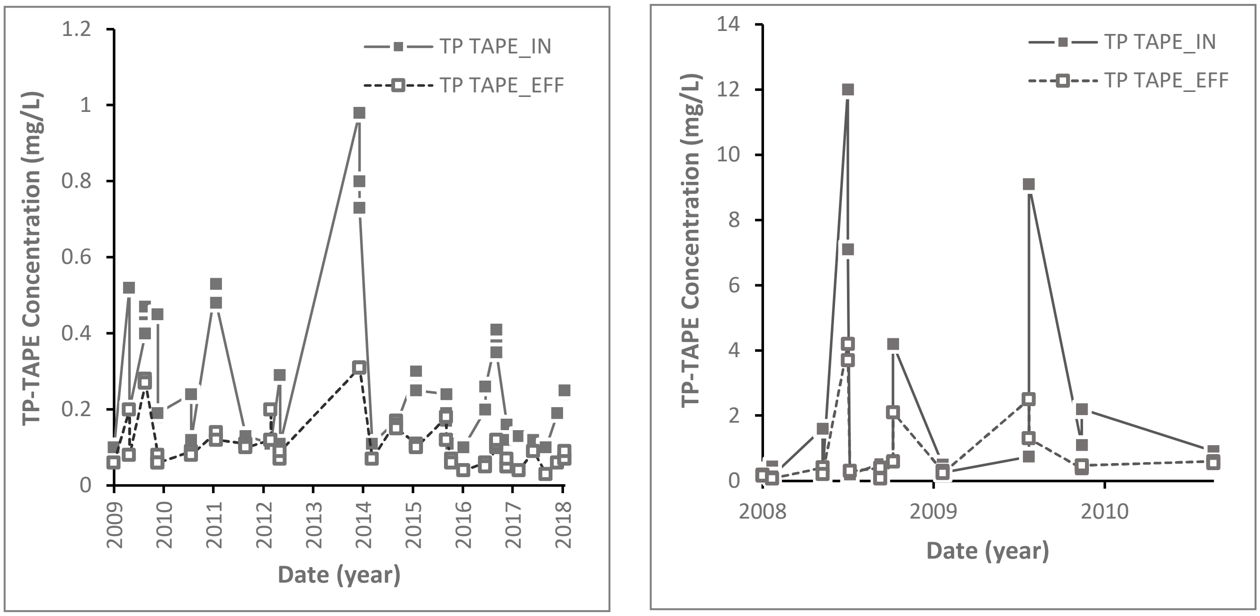
A statistical evaluation of 218 total phosphorus (TP) sampling events demonstrated 48.6% median removal efficiency for median influent and effluent concentrations of 0.1 mg/L and 0.05 mg/L, respectively. Influent concentration range criteria set forth in the Technology Assessment Protocol - Ecology (TAPE) technical guidance manual were applied to the TP influent concentrations to exclude very low concentration runoff events, resulting in 111 qualified events (Ecology September 2018) that were above the 0.1 mg/L TAPE influent TP concentration threshold. For those events greater than 0.5 mg/L, the influent concentration is capped at 0.5 mg/L according to TAPE procedures. Applying TAPE criteria to TP influent concentrations increased median removal efficiency to 60% for median influent and effluent concentrations of 0.2 mg/L and 0.09 mg/L, respectively. For both TP and TP-TAPE, median influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

TP box and regression plots (Figure 7) show the entire data distribution excluding events with TP influent concentrations less than 0.1 mg/L per TAPE guidance. The box and regression plots show significant TP removal and no correlation between effluent concentration and time with the TAPE criteria applied for the concentration range evaluated. This correlation is further supported via line plot analysis in Figure 8 showing consistently low effluent concentrations over time given variation in influent concentrations at all study sites.

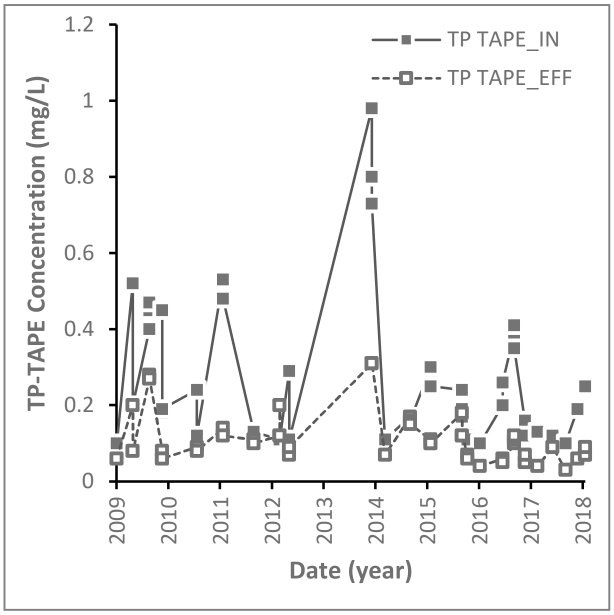


(a) **(b)**

Figure 7. TP descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**

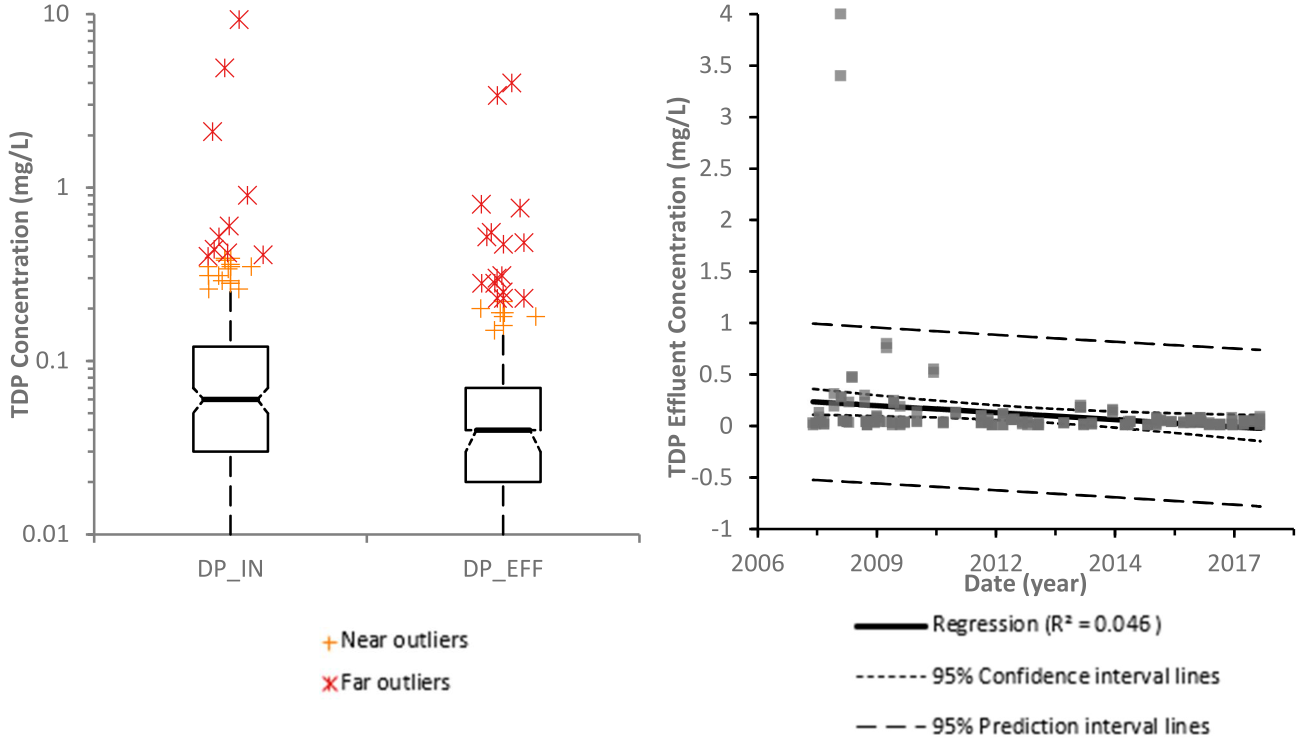


(c)

Figure 8. TP line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

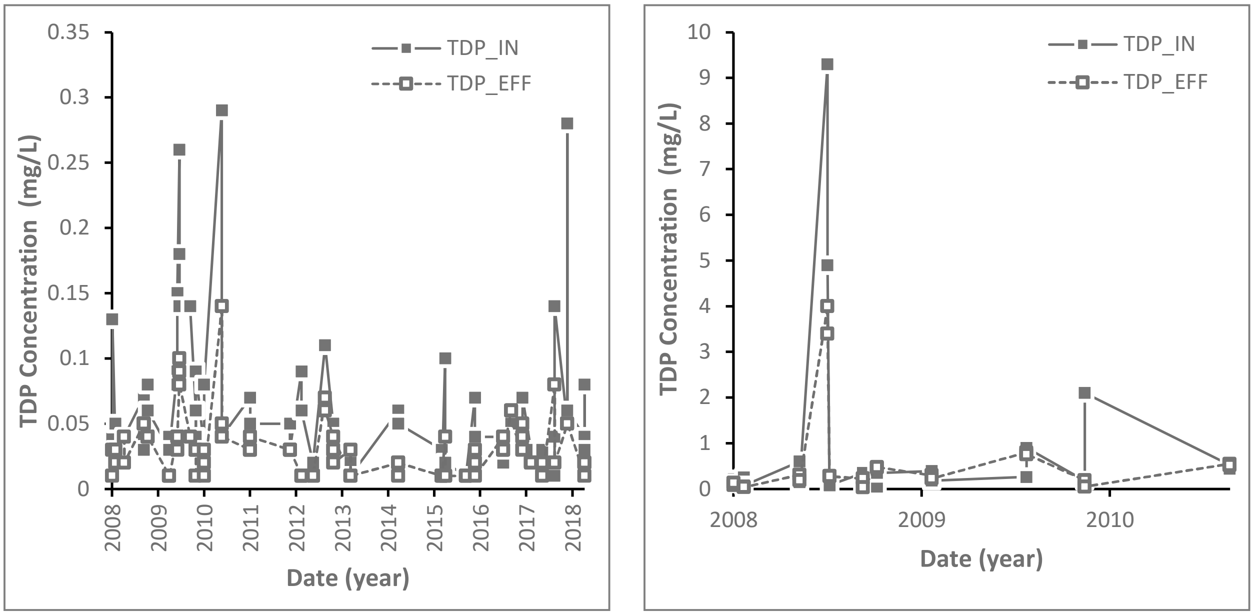
Total Dissolved Phosphorus

A statistical evaluation of 190 total dissolved phosphorus (TDP) sampling events demonstrated 35% median removal efficiency for median influent and effluent concentrations of 0.06 mg/L and 0.04 mg/L, respectively. Median TDP influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001. TDP box and regression plots (Figure 9) show significant TDP removal and no correlation between effluent concentration and time. Line plot analyses in Figure 10 show correlation between influent and effluent concentrations, with higher influent concentrations producing higher effluent concentrations.

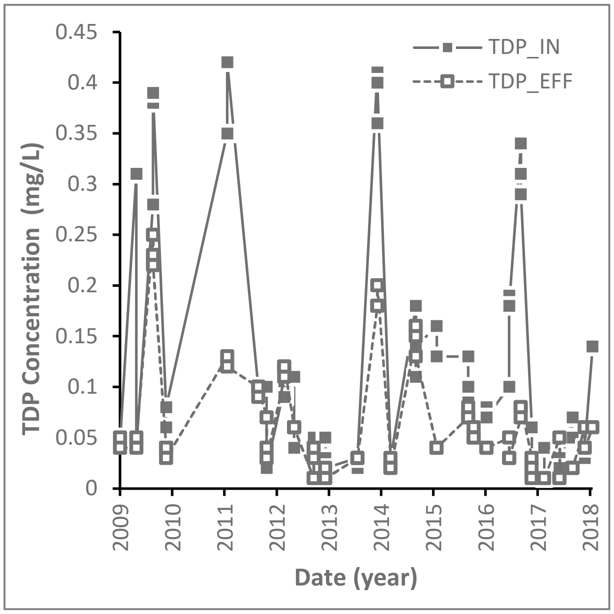


(a) **(b)**

Figure 9. TDP descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**



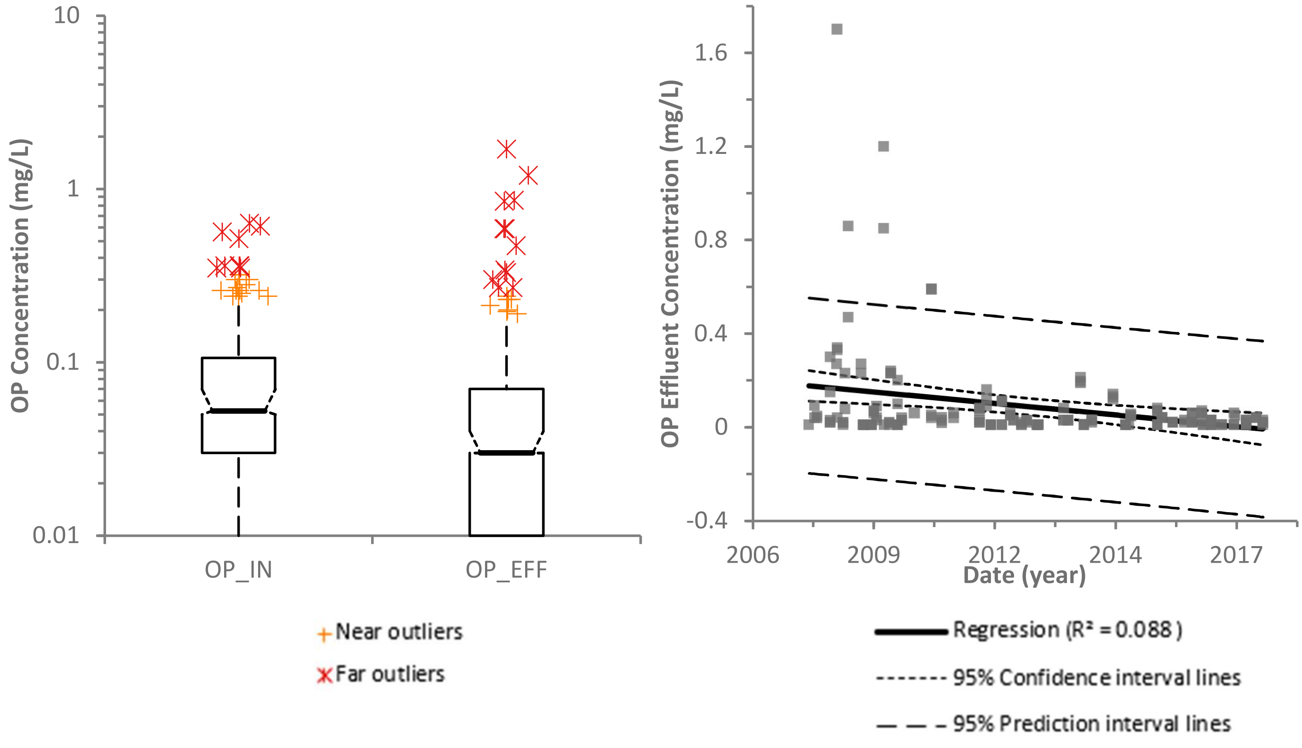
(c)

Figure 10. TDP line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

Orthophosphate

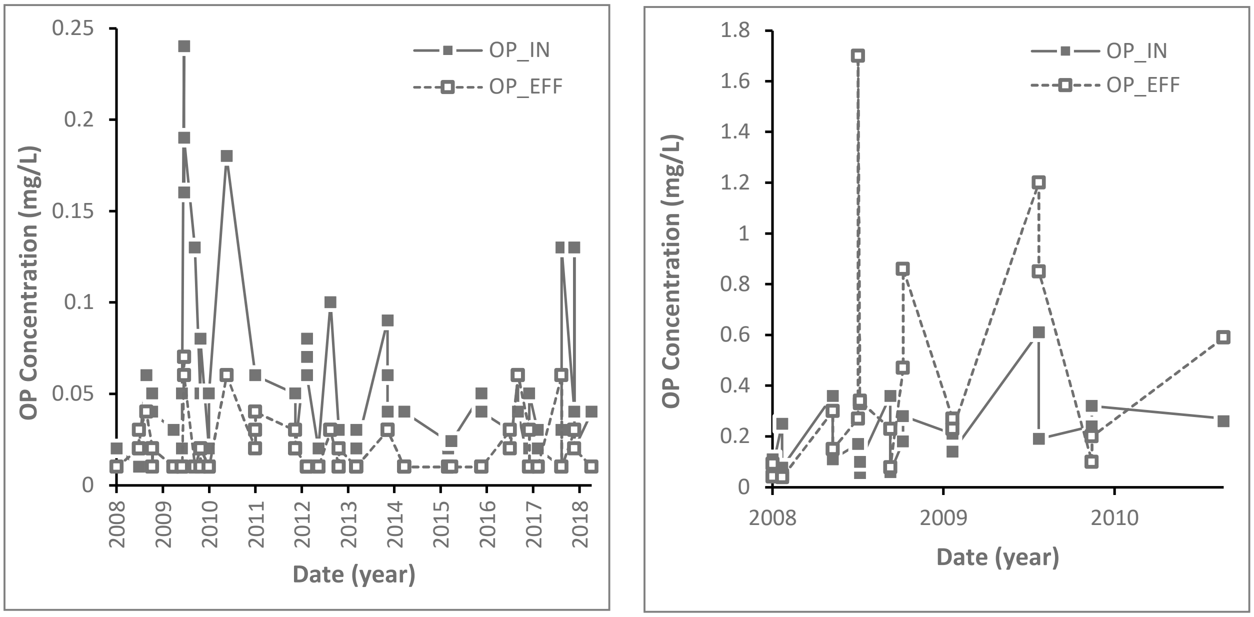
A statistical evaluation of 172 orthophosphate (OP) sampling events demonstrated 50% median removal efficiency for median influent and effluent concentrations of 0.053 mg/L and 0.030 mg/L, respectively. Median OP influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

OP box and regression plots (Figure 11) show significant OP removal and no correlation between effluent concentration and time. Line plot analyses in Figure 12 show correlation between influent and effluent concentrations, with higher influent concentrations producing higher effluent concentrations.

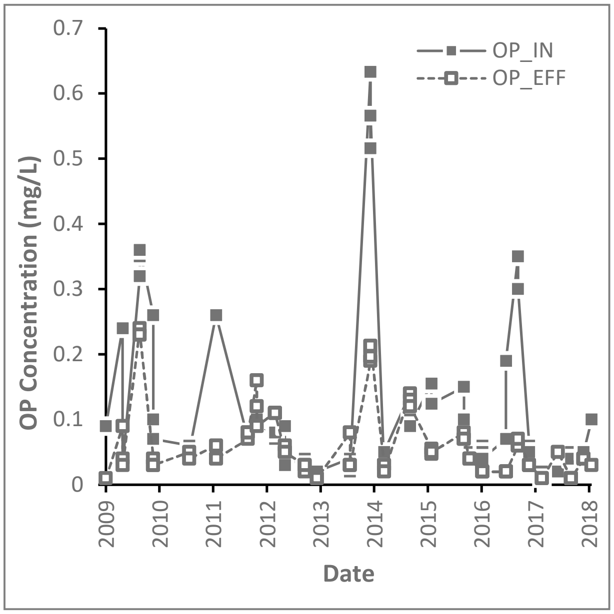


(a) **(b)**

Figure 11. OP descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**



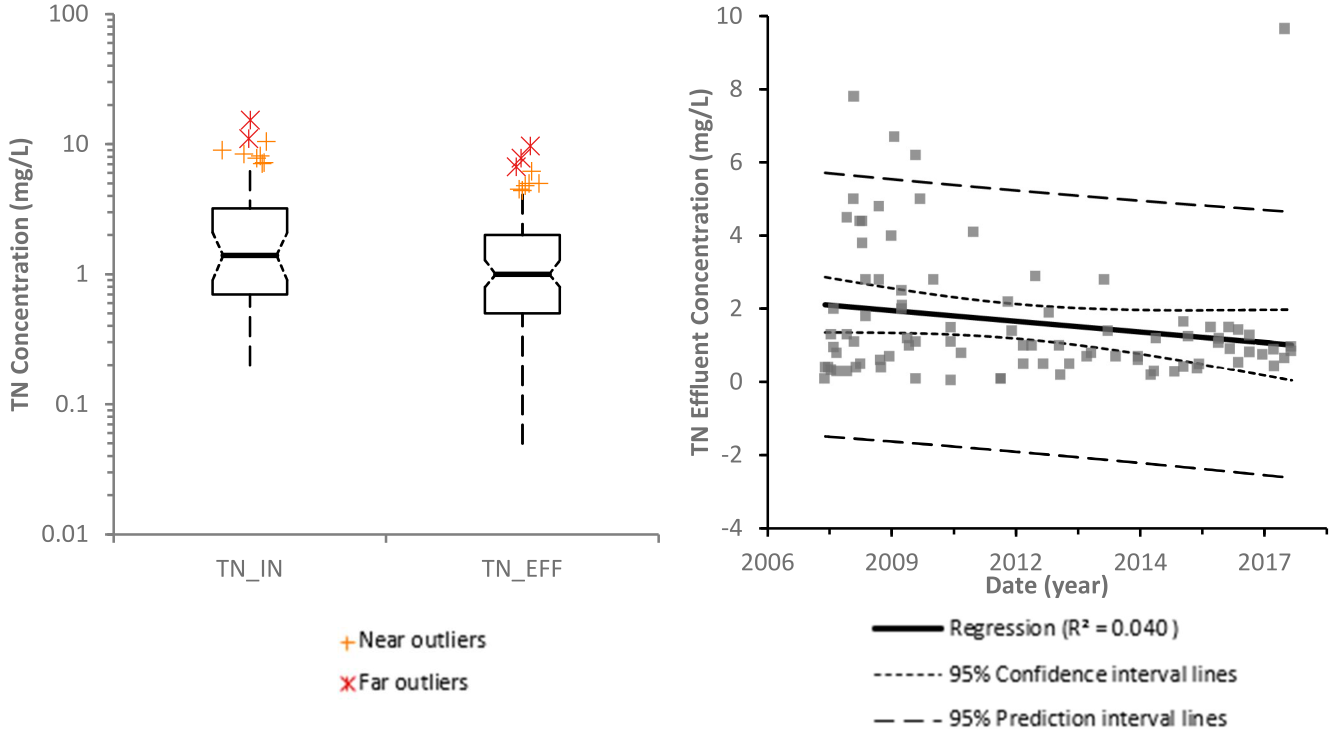
(c)

Figure 12. OP line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

Total Nitrogen

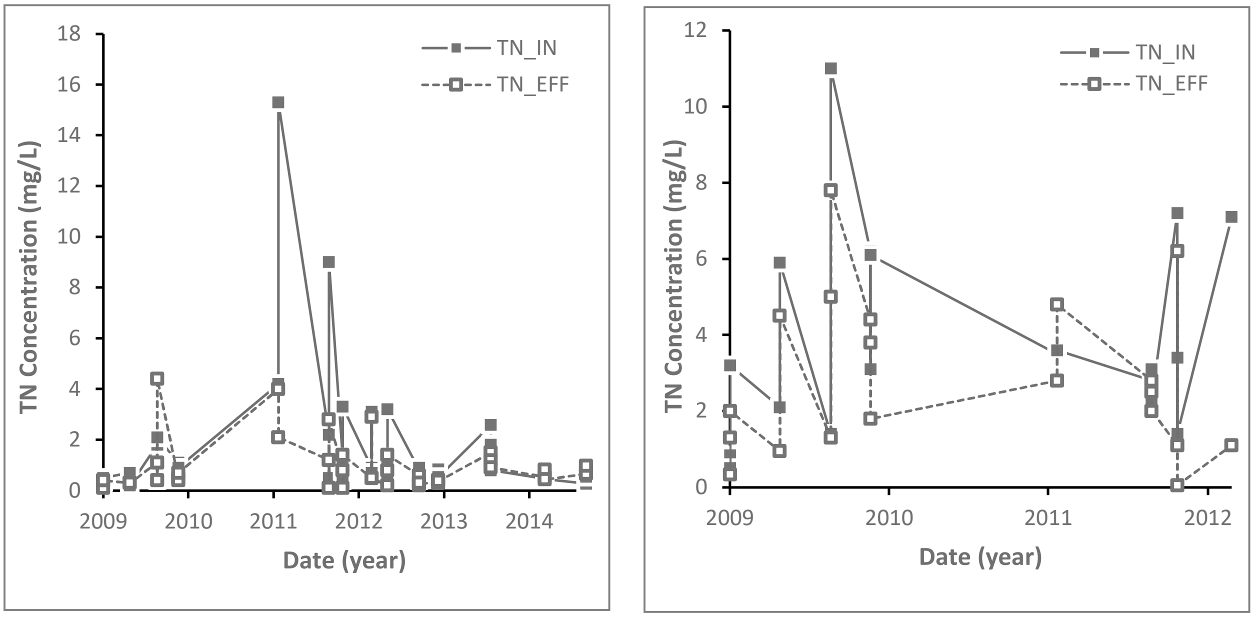
A statistical evaluation of 89 total nitrogen (TN) sampling events demonstrated 31.9% median removal efficiency for median influent and effluent concentrations of 1.4 mg/L and 1.0 mg/L, respectively. Median TN influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

TN box and regression plots (Figure 13) show significant TN removal and no correlation between effluent concentration and time. Line plot analyses in Figure 14 show correlation between influent and effluent concentrations, with higher influent concentrations producing higher effluent concentrations.

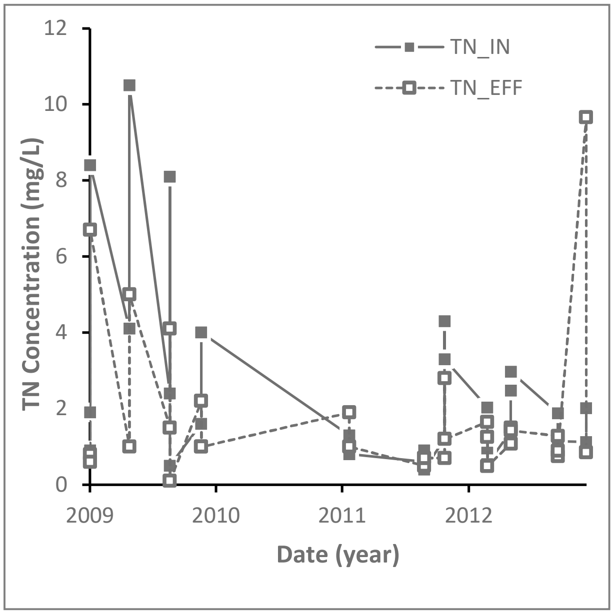


(a) **(b)**

Figure 13. TN descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**



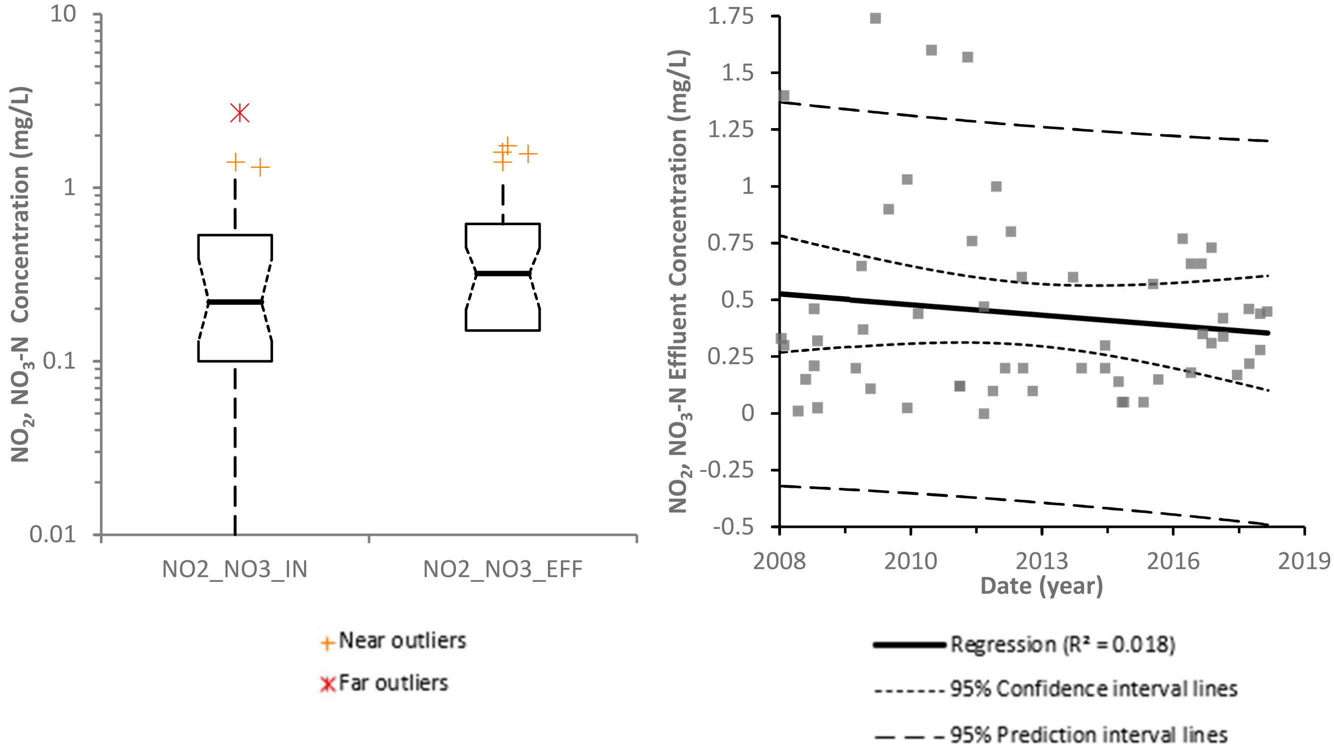
(c)

Figure 14. TN line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

Nitrite/Nitrate-Nitrogen

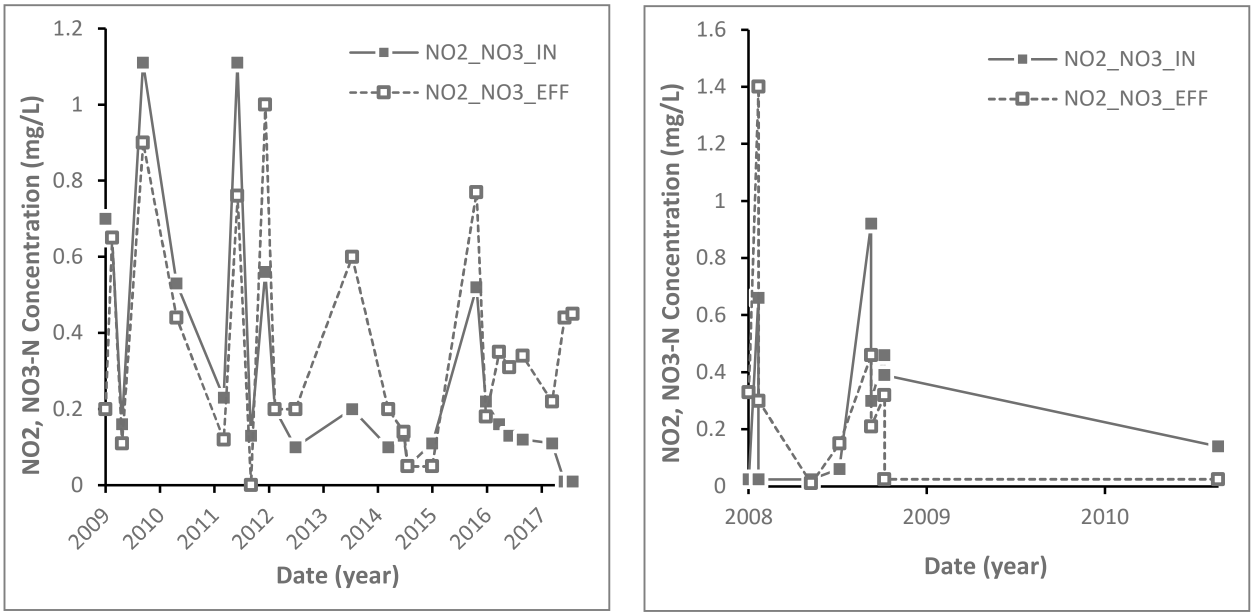
A statistical evaluation of 57 Nitrite/Nitrate-Nitrogen (NO_2, NO_3-N) sampling events demonstrated -9.52% median removal efficiency for median influent and effluent concentrations of 0.22 mg/L and 0.33 mg/L, respectively. Median NO_2, NO_3-N influent and effluent concentrations were not statistically different with a P-value of 0.202. NO_2, NO_3-N is highly soluble in soils, and export is common in bioretention media due to nitrification of ammonium to nitrite and nitrate.

NO_2, NO_3-N box and regression plots (Figure 15) show no significant NO_2, NO_3-N removal and no correlation between effluent concentration and time. Line plot analyses in Figure 16 show correlation between influent and effluent concentrations, with higher influent concentrations producing higher effluent concentrations.

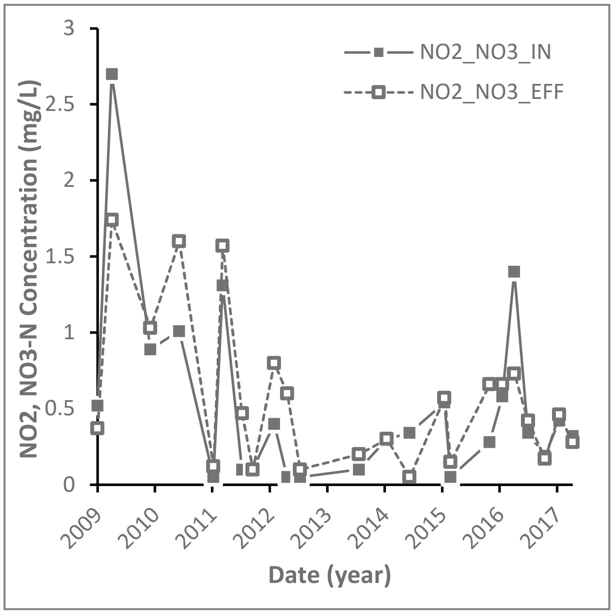


(a) **(b)**

Figure 15. NO2, NO3-N descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**



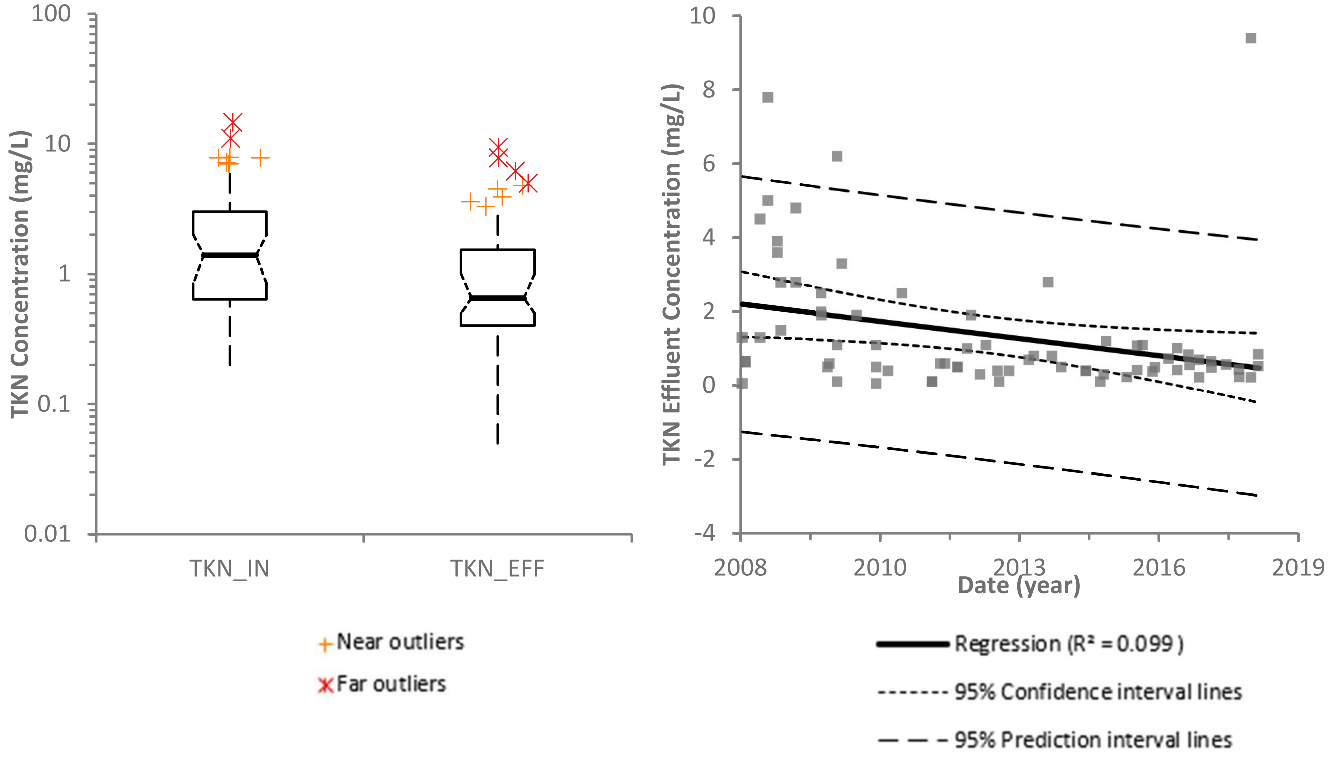
(c)

Figure 16. NO2, NO3-N line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

Total Kjeldahl Nitrogen

A statistical evaluation of 74 total Kjeldahl nitrogen (TKN) sampling events demonstrated 42% median removal efficiency for median influent and effluent concentrations of 1.4 mg/L and 0.655 mg/L, respectively. Median TKN influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

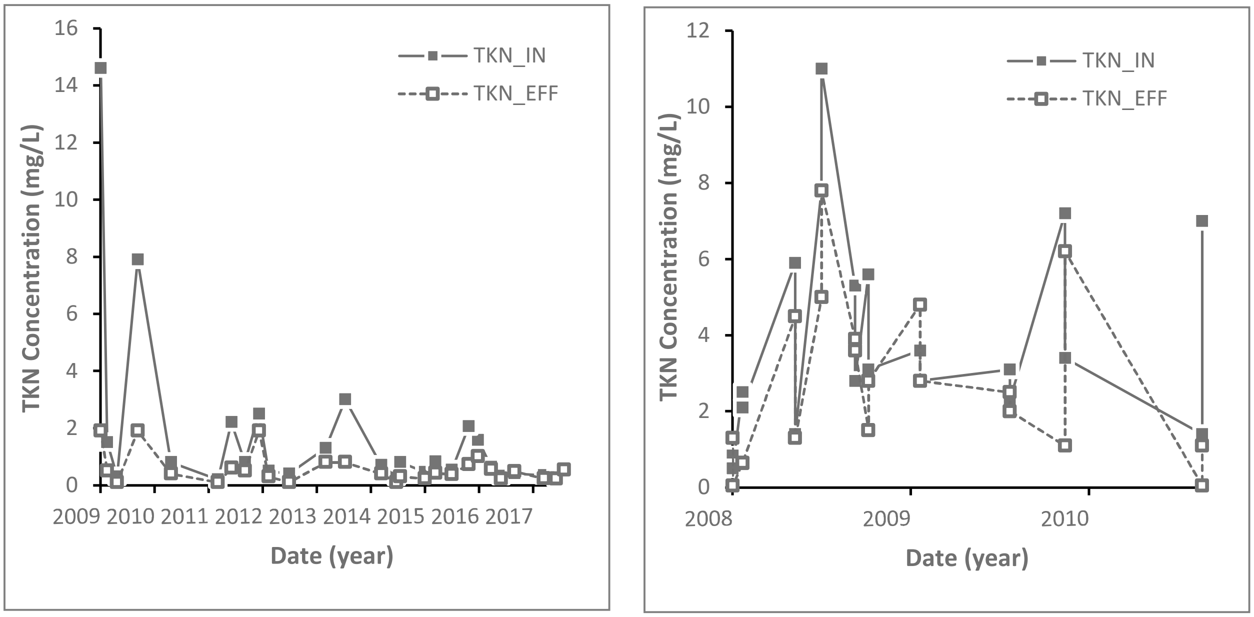
TKN box and regression plots (Figure 17) show significant TKN removal and no correlation between effluent concentration and time. Line plot analyses in Figure 18 show correlation between influent and effluent concentrations, with higher influent concentrations producing higher effluent concentrations.



(a)

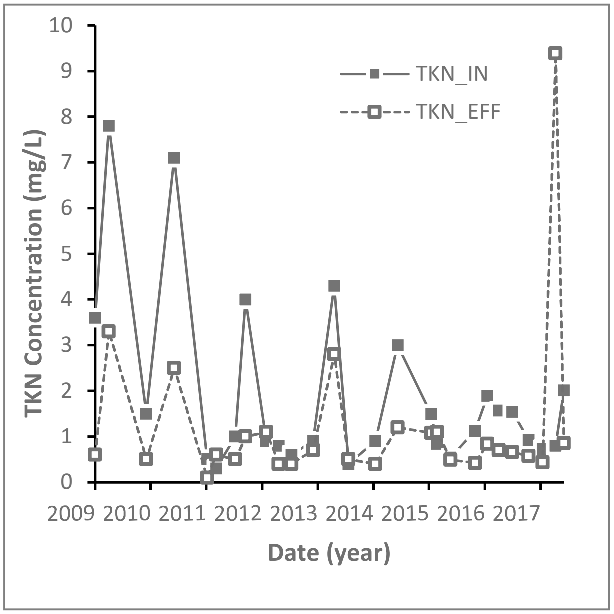
(b)

Figure 17. TKN descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a)

(b)



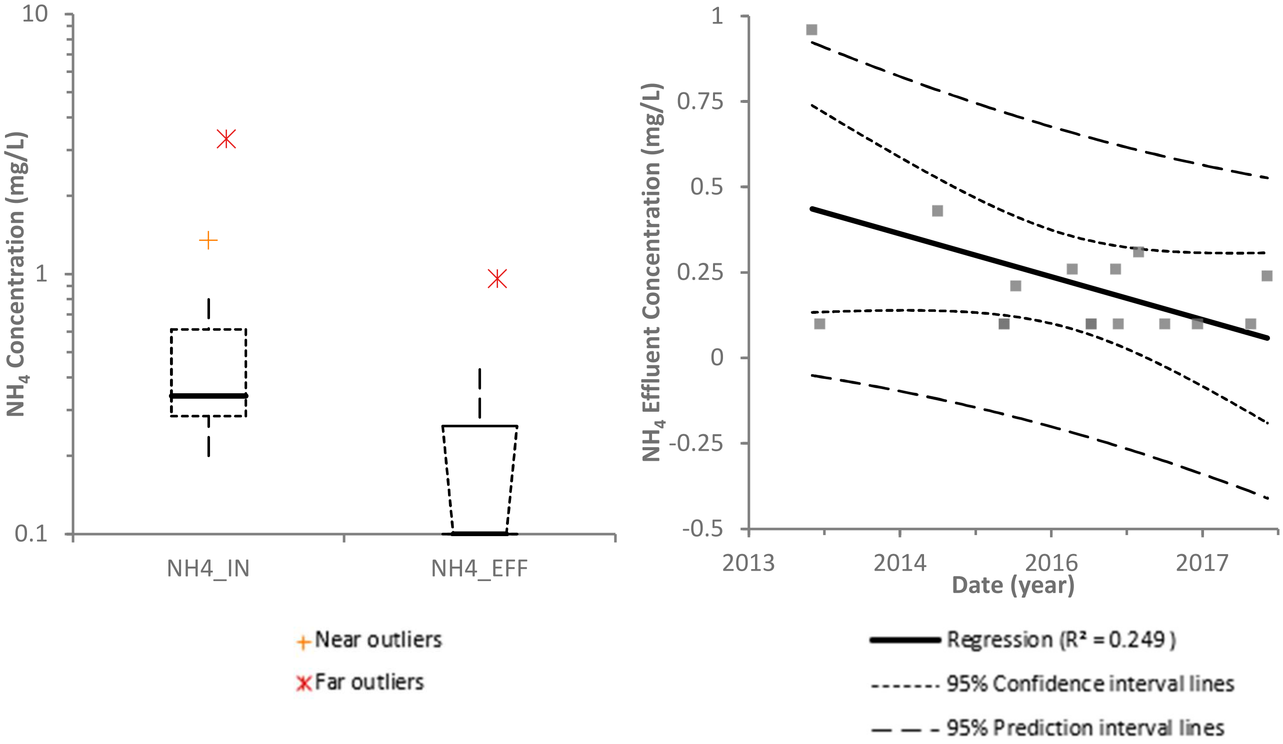
(c)

Figure 18. TKN line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site B **(c)** Study site C

Ammonium

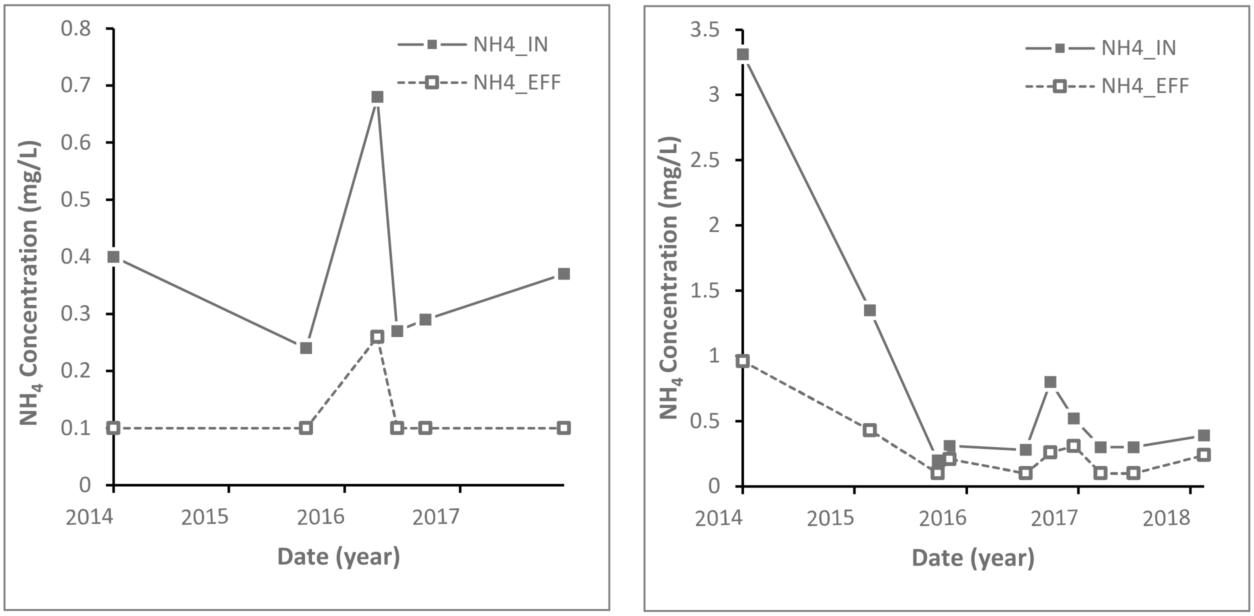
A statistical evaluation of 16 ammonium (NH_4) sampling events demonstrated 64.9% median removal efficiency for median influent and effluent concentrations of 0.34 mg/L and 0.1 mg/L, respectively. Median NH_4 influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001. NH_4 was not monitored at study site B.

NH_4 box and regression plots (Figure 19) show significant NH_4 removal and no correlation between effluent concentration and time. Line plot analyses in Figure 20 show correlation between influent and effluent concentrations, with higher influent concentrations producing higher effluent concentrations.



(a) **(b)**

Figure 19. NH$_4$ descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**

Figure 20. NH$_4$ line plot analysis comparing influent and effluent concentrations **(a)** Study site A **(b)** Study site C

Metals

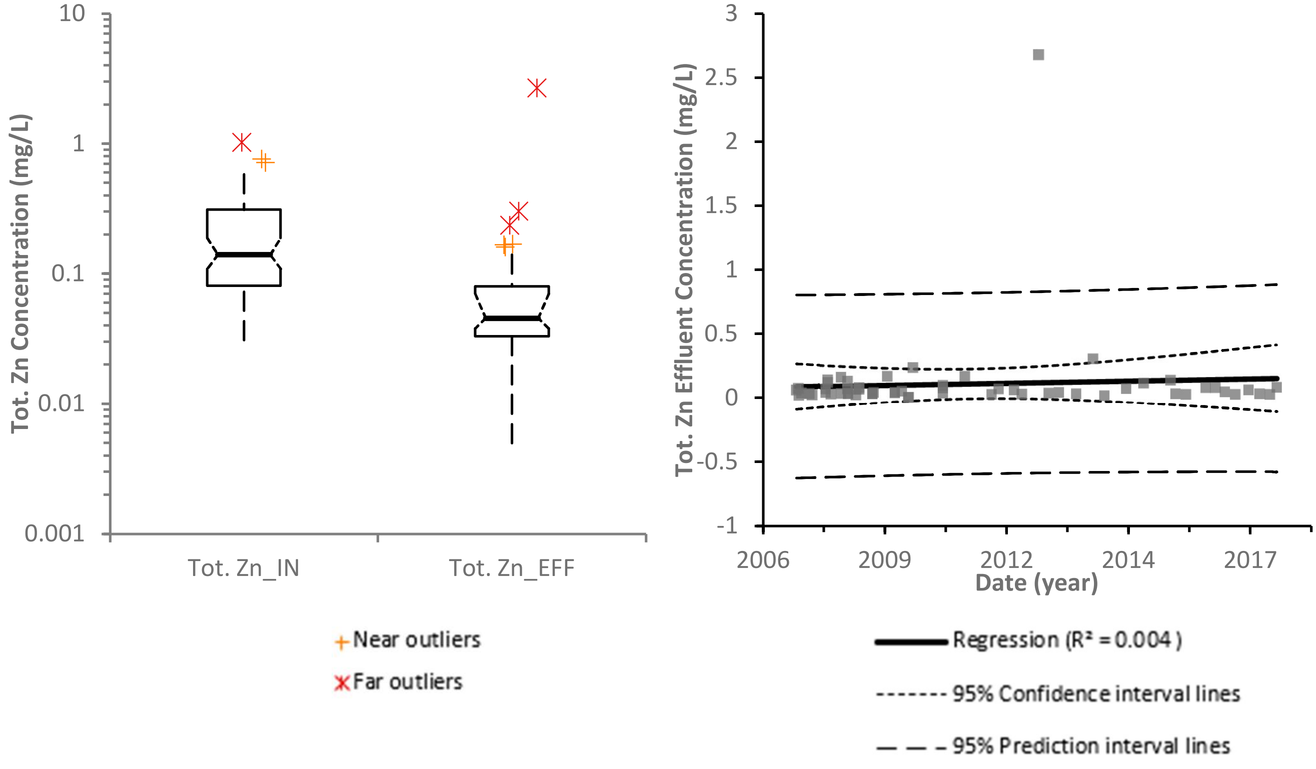
Box and regression plots for all metals monitored, with the exception of cadmium which was likely influenced by influent concentrations near the detection limit, show statistically significant differences between influent and effluent median concentrations using the non-parametric Mann-Whitney rank sum hypothesis test comparing the P-value to a significance value of 0.05.

Regression plots for all metals show no correlation between effluent concentration and time. Line plot analysis for all metals generally demonstrate low effluent concentrations over time given variation in influent concentrations at all study sites.

Total Zinc

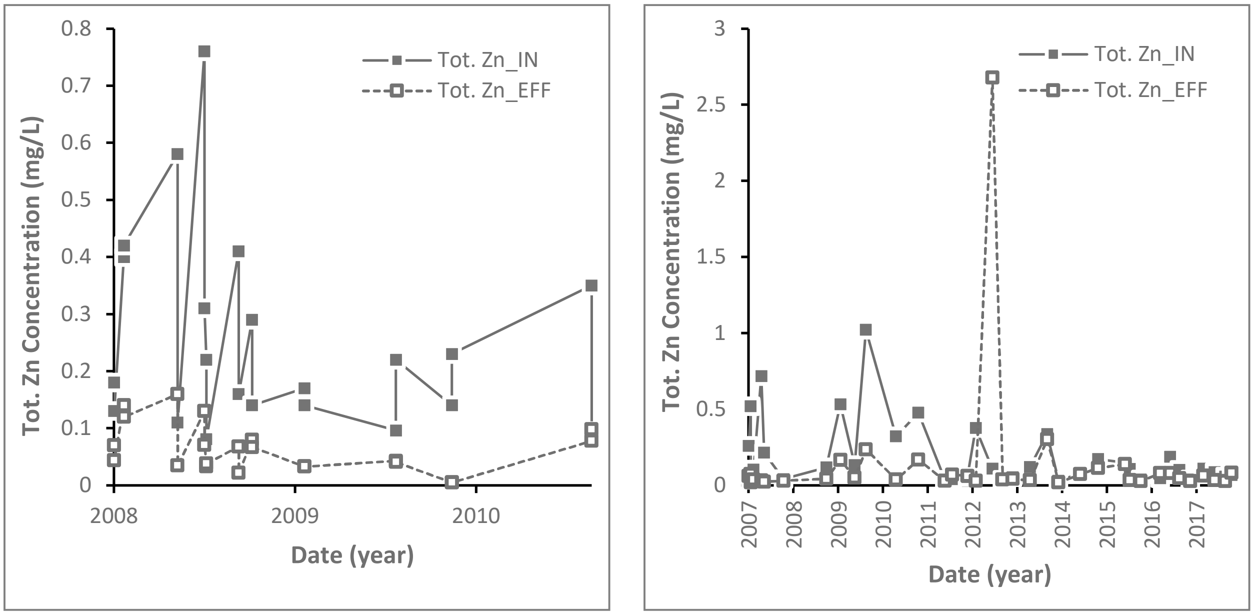
A statistical evaluation of 58 total zinc (Tot. Zn) sampling events demonstrated 63% median removal efficiency for median influent and effluent concentrations of 0.14 mg/L and 0.0455 mg/L, respectively. Median Tot. Zn influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

Tot. Zn box and regression plots (Figure 21) show significant Tot. Zn removal and no correlation between effluent concentration and time. This correlation is further supported via line plot analysis in Figure 22 for study sites where Tot. Zn was monitored, showing consistently low effluent concentrations over time given variation in influent concentrations.



(a) **(b)**

Figure 21. Tot. Zn descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



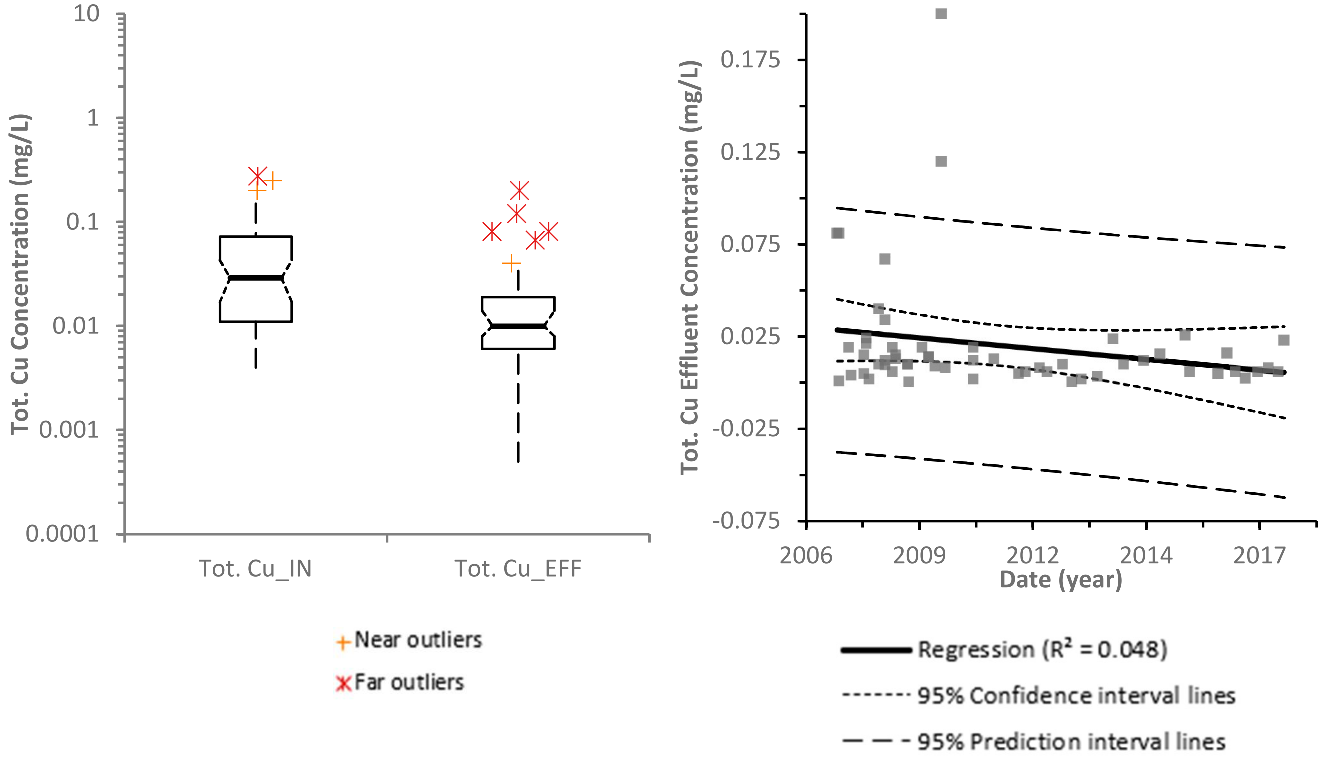
(a) **(b)**

Figure 22. Tot. Zn line plot analysis comparing influent and effluent concentrations **(a)** Study site B **(b)** Study site C

Total Copper

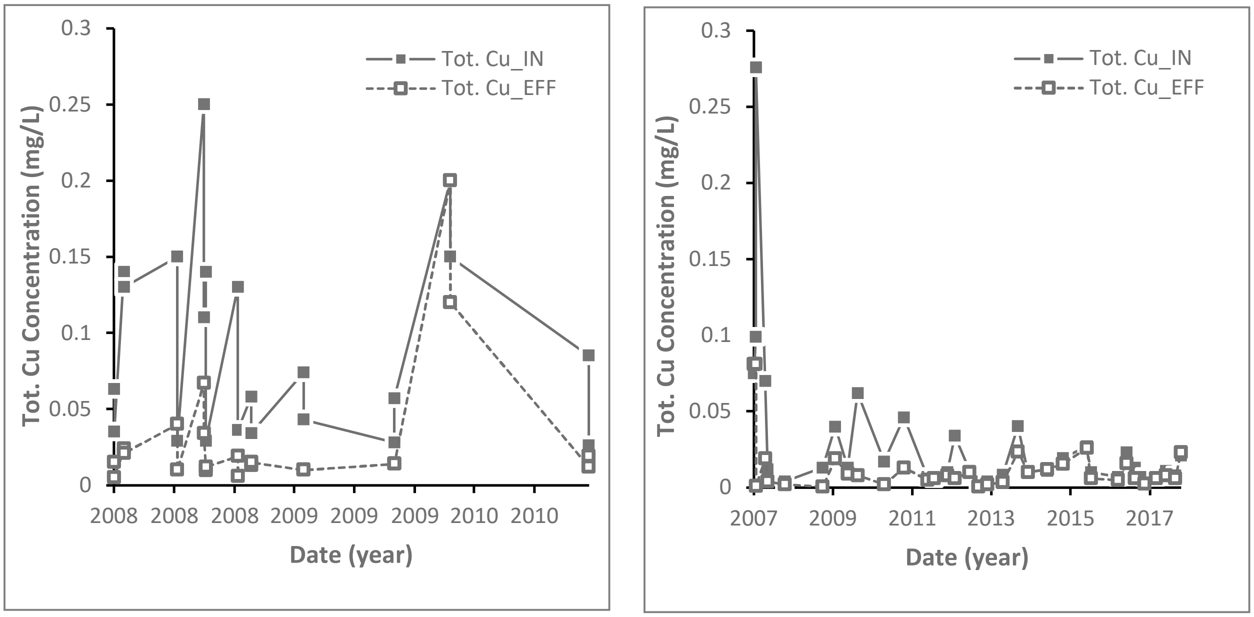
A statistical evaluation of 56 total copper (Tot. Cu) sampling events demonstrated 57.3% median removal efficiency for median influent and effluent concentrations of 0.029 mg/L and 0.01 mg/L, respectively. Median Tot. Cu influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

Tot. Cu box and regression plots (Figure 23) show significant Tot. Cu removal and no correlation between effluent concentration and time. This correlation is further supported via line plot analysis in Figure 24 for study sites where Tot. Cu was monitored, showing consistently low effluent concentrations over time given variation in influent concentrations.



(a) **(b)**

Figure 23. Tot. Cu descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



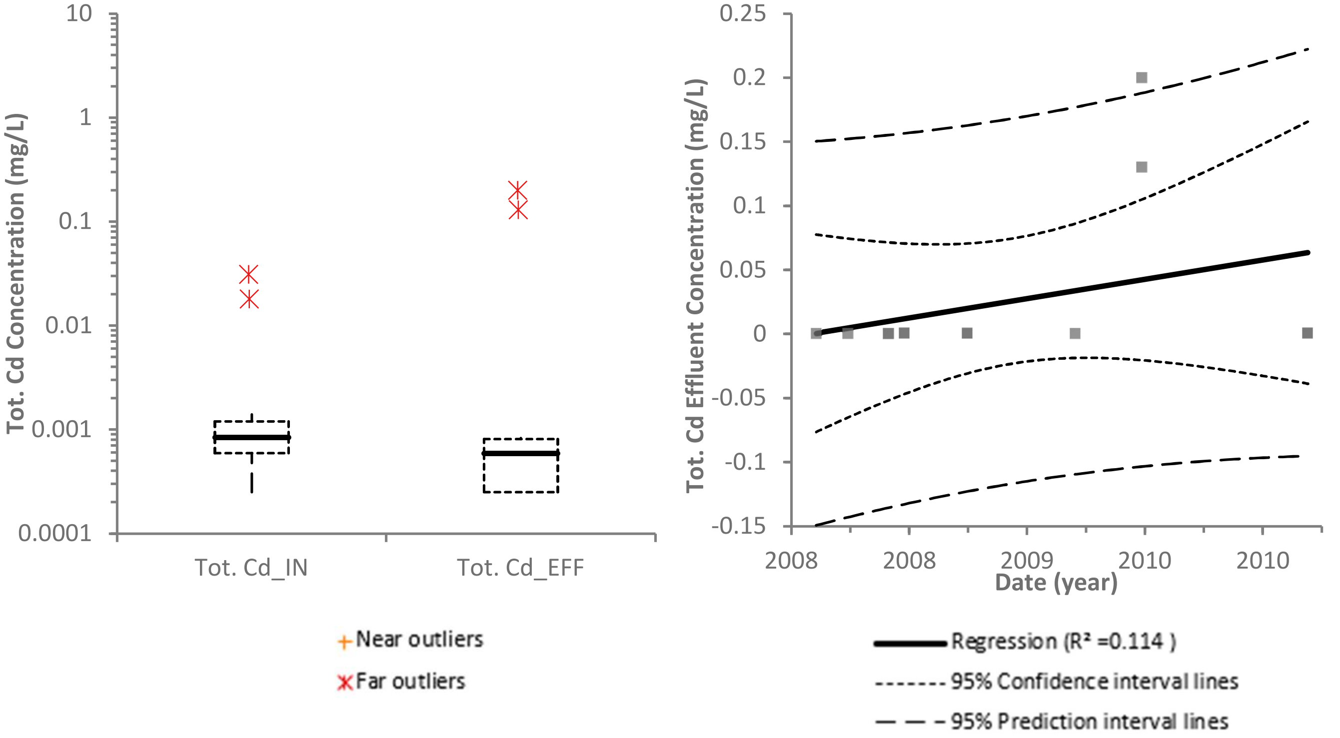
(a) **(b)**

Figure 24. Tot. Cu line plot analysis comparing influent and effluent concentrations **(a)** Study site B **(b)** Study site C

Total Cadmium

A statistical evaluation of 13 total cadmium (Tot. Cd) sampling events demonstrated 27.3% median removal efficiency for median influent and effluent concentrations of 0.0.0084 mg/L and 0.00059 mg/L, respectively. Median Tot. Cd influent and effluent concentrations were not statistically different with a P-value of 0.110. The lack of statistical difference between median influent and effluent concentrations is likely influenced by influent concentrations near the detection limit of 0.005 mg/L.

Tot. Cd box and regression plots (Figure 25) show no significant Tot. Cd removal and no correlation between effluent concentration and time. Low influent and effluent concentrations for most storm events make any correlation between influent and effluent concentration difficult to evaluate in the line plot analyses in Figure 26 for study site B where Tot. Cd was monitored.



(a) (b)

Figure 25. Tot. Cd descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time

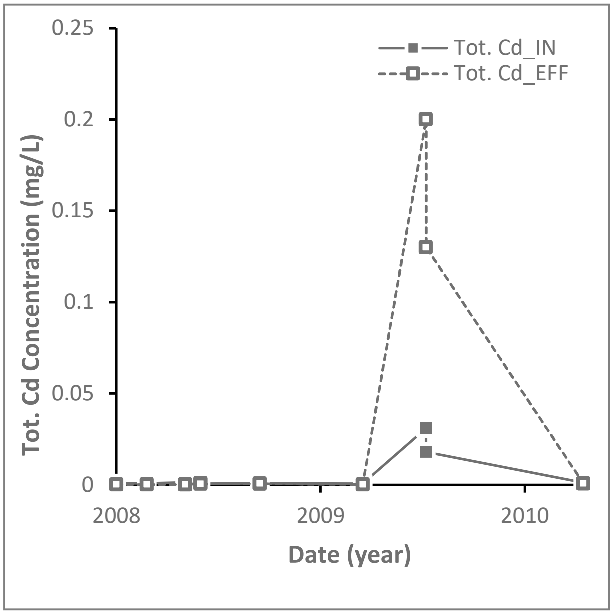
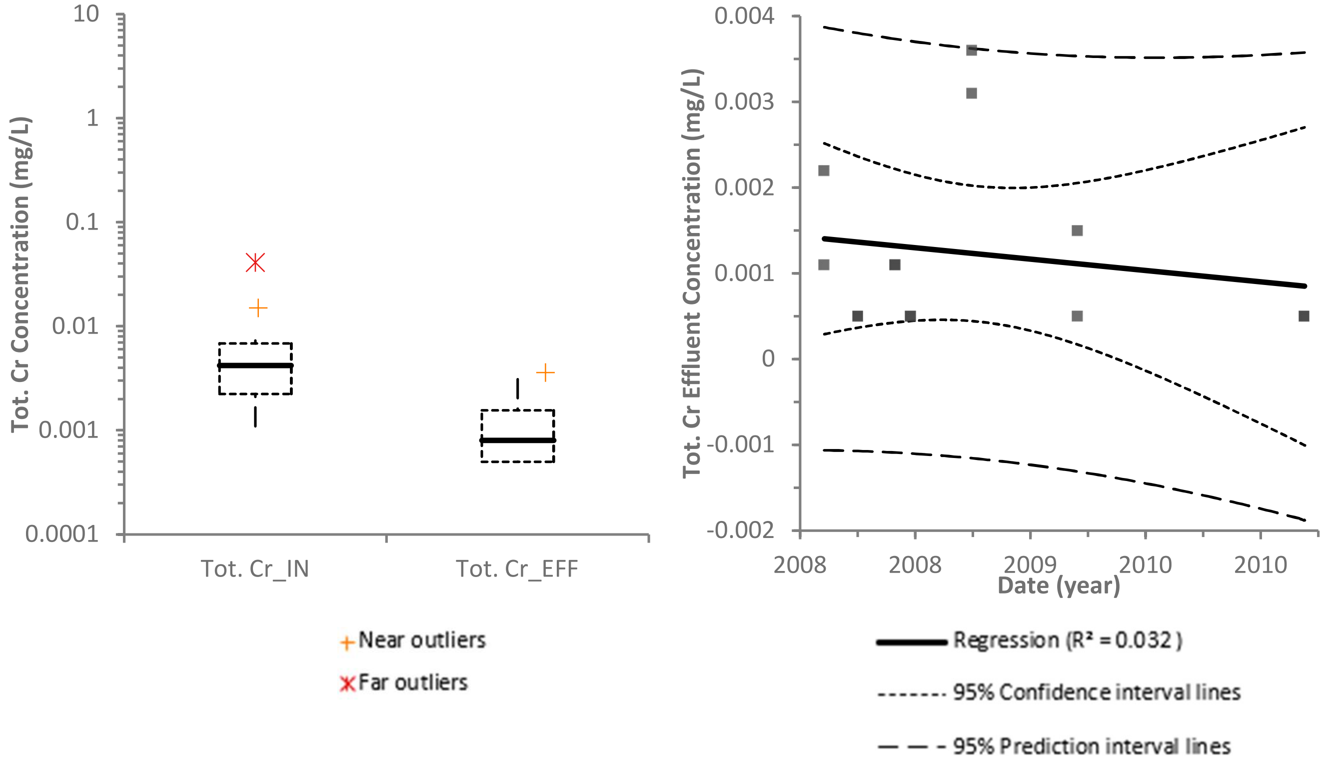


Figure 26. Tot. Cd line plot analysis comparing influent and effluent concentrations at Study site B

Total Chromium

A statistical evaluation of 14 total chromium (Tot. Cr) sampling events demonstrated 76.5% median removal efficiency for median influent and effluent concentrations of 0.0042 mg/L and 0.0008 mg/L, respectively. Median Tot. Cr influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

Tot. Cr box and regression plots (Figure 27) show significant Tot. Cr removal and no correlation between effluent concentration and time. This correlation is further supported via line plot analysis in Figure 28 for study site B where Tot. Cr was monitored, showing consistently low effluent concentrations over time given variation in influent concentrations.



(a) (b)

Figure 27. Tot. Cr descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time

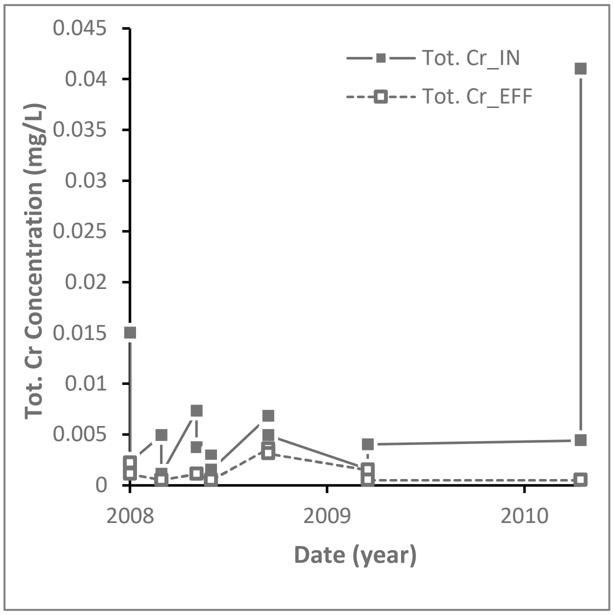
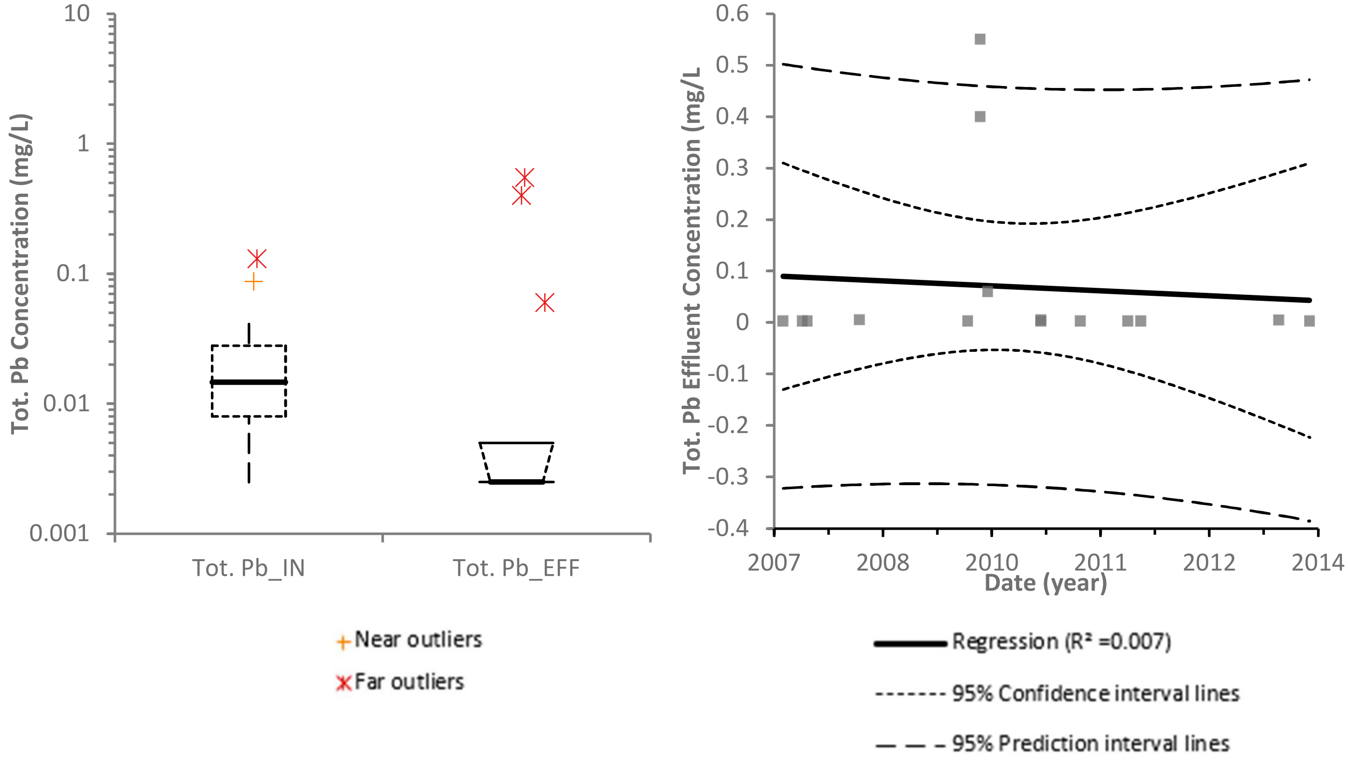


Figure 28. Tot. Cr line plot analysis comparing influent and effluent concentrations at Study site B

Total Lead

A statistical evaluation of 15 total lead (Tot. Pb) sampling events demonstrated 68.8% median removal efficiency for median influent and effluent concentrations of 0.0147 mg/L and 0.0025 mg/L, respectively. Median Tot. Pb influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value of 0.022.

Tot. Pb box and regression plots (Figure 29) show significant Tot. Pb removal and no correlation between effluent concentration and time. This correlation is further supported via line plot analysis in Figure 30 where Tot. Pb was monitored, generally showing low effluent concentrations over time given variation in influent concentrations. Export instances occurred in 3 of the 15 sampling events, which may be due to heavier lead loading at the gas and oil service station study sites in a prior storm event resulting in residual concentration influencing these sampling events.



(a) **(b)**

Figure 29. Tot. Pb descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time

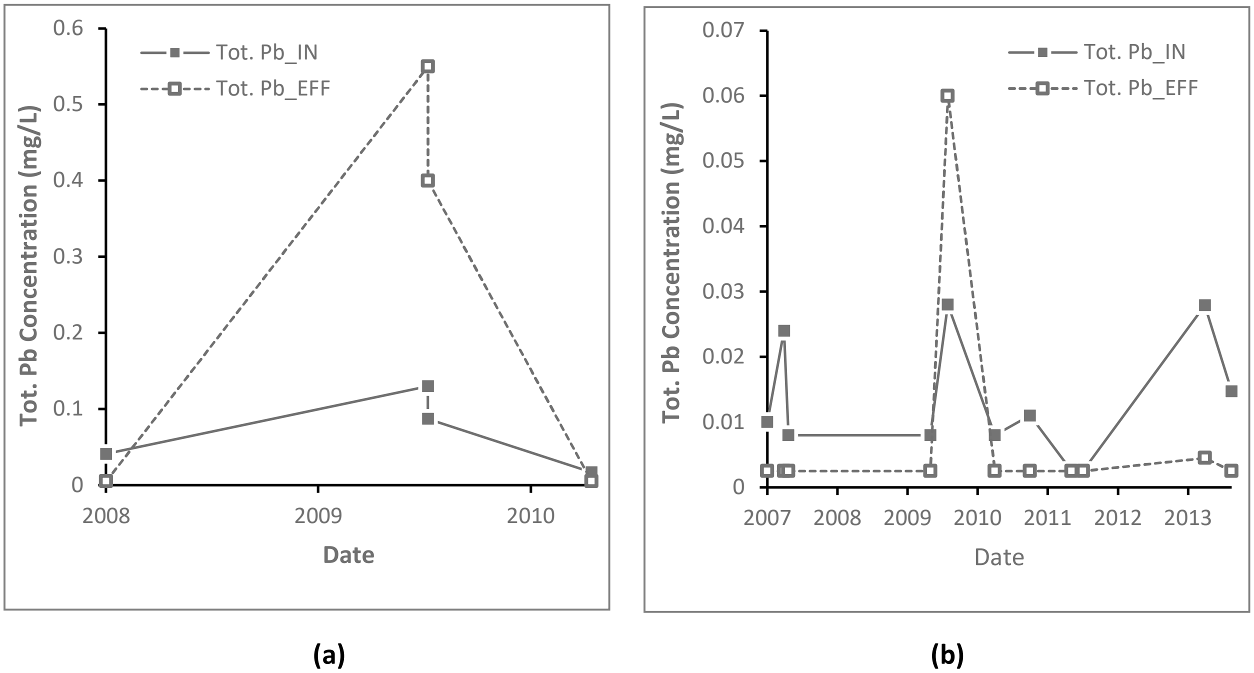
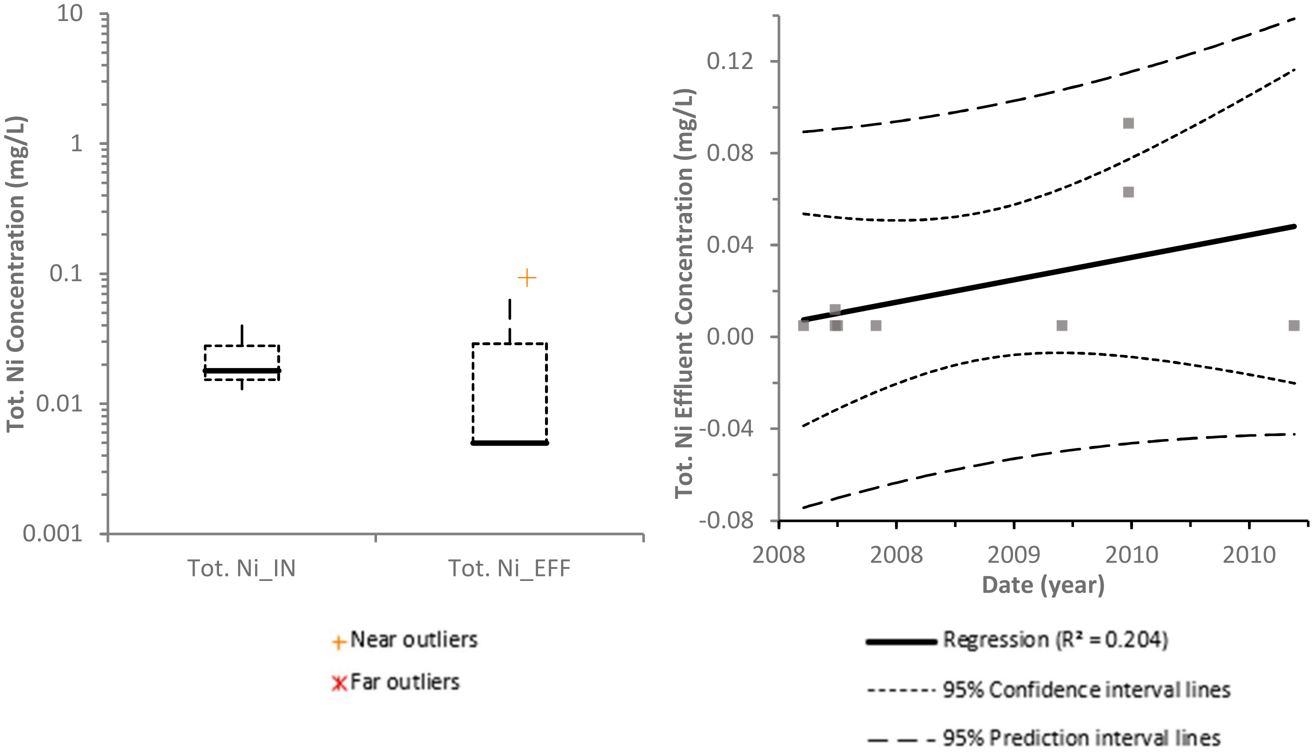


Figure 30. Tot. Pb line plot analysis comparing influent and effluent concentrations **(a)** Study site B **(b)** Study site C

Total Nickel

A statistical evaluation of 9 total nickel (Tot. Ni) sampling events demonstrated 64.3% median removal efficiency for median influent and effluent concentrations of 0.018 mg/L and 0.005 mg/L, respectively. Median Tot. Ni influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value of 0.048.

Tot. Ni box and regression plots (Figure 31) show significant Tot. Ni removal and no correlation between effluent concentration and time. This correlation is further supported via line plot analysis in Figure 32 for study site B where Tot. Ni was monitored, generally showing low effluent concentrations over time given variation in influent concentrations.



(a) **(b)**

Figure 31. Tot. Ni descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time

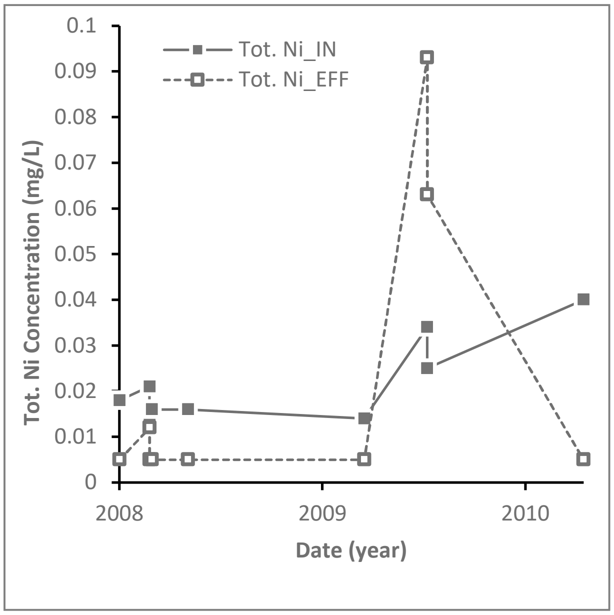
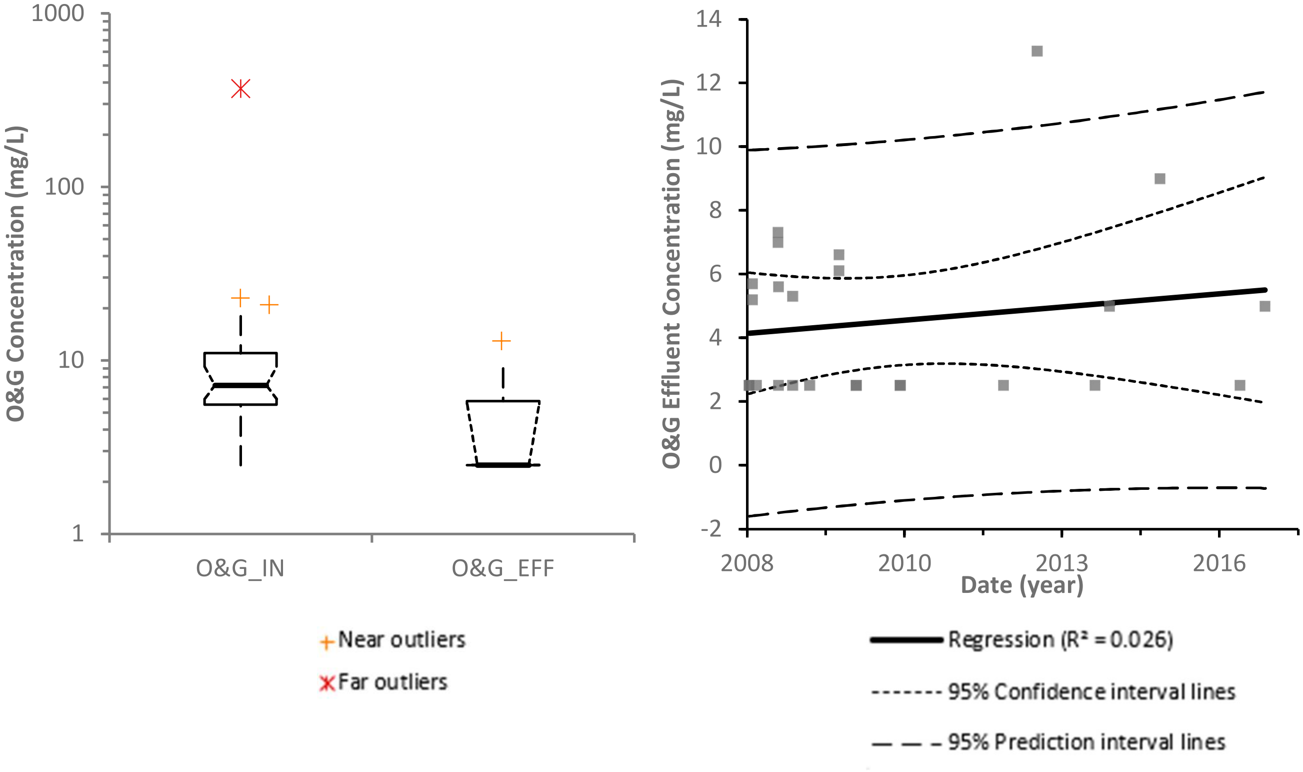


Figure 32. Tot. Ni line plot analysis comparing influent and effluent concentrations at Study site B

Oil & Grease

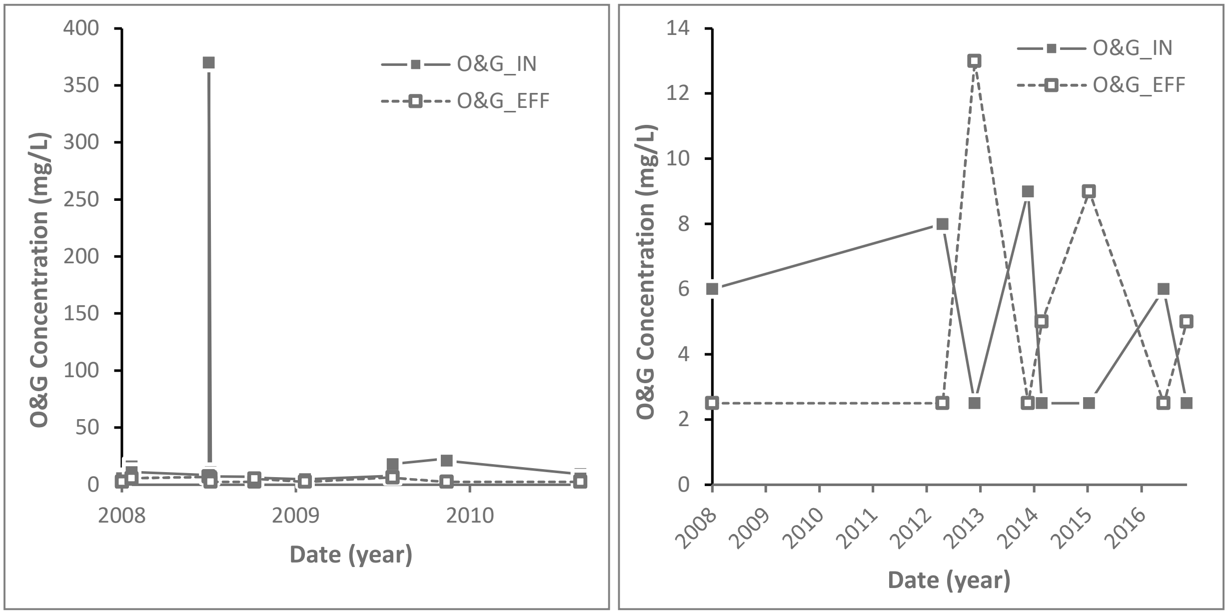
A statistical evaluation of 25 oil and grease (O&G) sampling events demonstrated 58.3% median removal efficiency for median influent and effluent concentrations of 7.2 mg/L and 2.5 mg/L, respectively. Median O&G influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value < 0.001.

O&G box and regression plots (Figure 33) show significant O&G removal and no correlation between effluent concentration and time. Line plot analyses in Figure 34 show no correlation between influent and effluent concentration over time.



(a) **(b)**

Figure 33. O&G descriptive statistical analysis **(a)** box and whisker plots of influent and effluent concentrations **(b)** regression scatter plot of effluent concentrations and time



(a) **(b)**

Figure 34. O&G line plot analysis comparing influent and effluent concentrations **(a)** Study site B **(b)** Study site C

Total Petroleum Hydrocarbons

A statistical evaluation of 4 total petroleum hydrocarbon (TPH) sampling events demonstrated 75.2% median removal efficiency for median influent and effluent concentrations of 10.2 mg/L and 2.5 mg/L, respectively. Median TPH influent and effluent concentrations were statistically different with very low effluent concentrations and a P-value of 0.029.

The TPH box plot (Figure 35) shows significant TPH removal. Sample size was not adequate for proper regression analysis to demonstrate whether correlation exists between effluent concentration and time. Line plot analysis in Figure 36 for study site B where TPH was monitored shows low effluent concentrations over time given variation in influent concentrations

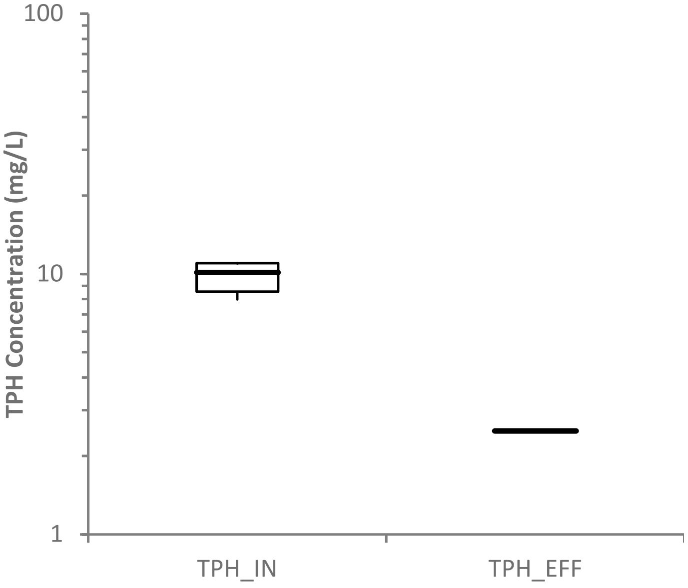


Figure 35. TPH descriptive statistical analysis box and whisker plots of influent and effluent concentrations

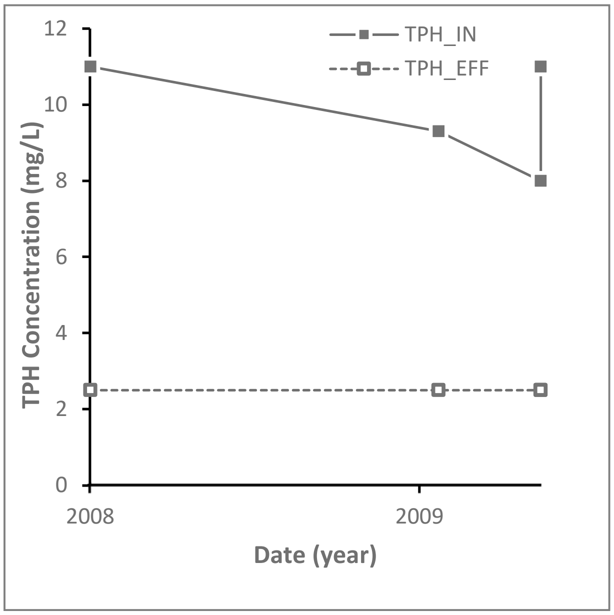


Figure 36. TPH line plot analysis comparing influent and effluent concentrations at Study site B

Temperature and pH

An evaluation of 35 temperature sampling events demonstrated no statistical difference between median influent and effluent temperatures of 16.5 mg/L and 16.7 degrees C, respectively. An evaluation of 57 pH sampling events demonstrated no statistical difference between median influent and effluent pH of 7 and 6.6, respectively.

Hydraulic Capacity

Separate analyses were completed in 2021 at study site A, after the water quality sampling phase, to evaluate Filterra hydraulic conductivity in unsaturated and saturation conditions. Following procedures performed in the Filterra Field Flow Rate Evaluation Report (Geosyntec 2008), hydraulic evaluation was conducted in three distinct phases described below with results displayed in Table 7. The Filterra media hydraulic evaluation demonstrated a typical condition median infiltration rate of 177 in/hr, in line with Filterra's Washington Department of Ecology General Use Level Designation approved infiltration rate of 175 in/hr. The Filterra media saturated, atypical operating conditions displayed a median infiltration rate of 107 in/hr.

> *Steady Flow Rate, Rising Head* – The initial unsaturated and saturation tests included a period when steady inflow was maintained above the hydraulic capacity of the Filterra system and water accumulated in the system causing the water surface level (WSL) to rise. The duration of the rising water level, inflow rate, change in accumulated head and average WSL during the period or rising head was used to calculate an infiltration rate.
>
> *Modulated Flow Rate, Constant Head* – During the saturation test, an inflow rate that allowed constant accumulated head for five minutes was determined. The constant head data was calculated similarly to the Steady Flow Rate, Rising Head data, however changes to WSL was set to zero.
>
> *No Inflow, Falling Head* – The ponded water receded after inflow ceased in both the initial unsaturated and saturation tests and rate of fall was recorded. Analysis was calculated similar to those calculations in the Steady Flow Rate, Rising Head test described above.

Table 7. Study site A hydraulic evaluation summary

Test ID	Steady Flow, Rising Head	Modulated Flow, Constant Head	Falling Head	Method Average	Method Median
Unsaturated Infiltration (in/hr)	191	N/A	163	177	177
Saturated Infiltration (in/hr)	107	109	75	97	107

N/A: constant head is not held during unsaturated test.

Biofiltration Media Composition

Particle size analysis demonstrates average gravel, sand, and silt and clay percentages vary by less than 3.4% among all profile depths when compared to a media depth of 12 inches (Table 8). The profile depth of 12 inches was selected as the reference for comparison because historic depth profile analysis demonstrates Filterra media generally meets specification at this depth and is not altered over time.

Table 8. Aggregate classification profile comparison

Depth Comparison	Gravel (>2mm) Difference (%)	Sand (>53µm, <2mm) Difference (%)	Silt and Clay (<53µm) Difference (%)
3" vs. 12"	-3.37	0.21	3.20
6" vs. 12"	-1.02	-0.42	1.50
9" vs. 12"	1.76	-2.33	0.60
Average:	-0.88	-0.85	1.77
Median:	-1.02	-0.42	1.50

Organic content analysis demonstrates the average organic content varies by 0.44% among all profile depths, and by 0.03% when the 3-inch media bed depth is excluded (Table 9). The data was analyzed with the 3-inch bed depth organic difference excluded since the surface layer contained significantly higher organic content in comparison to the other depths sampled.

Table 9. Organic content profile comparison

Depth Comparison	Organic Difference (%)
3" vs. 12"	1.27
6" vs. 12"	0.02
9" vs. 12"	0.04
Average (all):	0.44
Median (all):	0.04
Avg. (excluding 3"):	0.03
Med. (excluding 3"):	0.03

Plant Growth Progression

Activation and maintenance records are provided in Tables 11 –13 in Appendix B for each study site. Plant height and width measurements were recorded during most maintenance events. Stem diameter was also recorded in some instances. Results indicate plant growth progression over time at all study sites. Reduction in plant height or width from the prior measurement at maintenance is due to plant pruning. Table 10 shows plant height and width for study sites A through C increased 1.3 to 2.4 fold and 1.7 to 3.2 fold, respectively, over the different monitoring periods. The amount of waste removed, defined as sediment, trash, debris, etc., was also recorded, with the largest waste retrieval summing 49 cubic feet at study site A per Table 12. Waste removed is a conservative value since the mulch volume placed at the prior maintenance was subtracted from the waste volume removed at the following maintenance, which would have degraded some since the prior maintenance.

Table 10. Plant growth progression

	Fold Change from Initial Measurement		
Study Site	[a]Plant Height (ft.)	[a]Plant Width (ft.)	Duration (yrs.)
A	2.4	2.1	9.0
B	1.5	3.2	4.5
[b]C-1	2.6	3.0	5.0
[b]C-2	1.3	1.7	3.0

[a]Pruning occurred at maintenance throughout the plant measurement period resulting in occasional reduction in plant height and width.

[b]C-1 represents Redtwig Dogwood at activation and C-2 represents later replacement with Foster Holly due to plant injury.

DISCUSSION AND CONCLUSION

Biofiltration treatment mechanisms rely on a synergistic community of living organisms such as plants, microorganisms and organic media to ensure long-term sustainable quality and hydraulic performance. Plants and organics facilitate a sustainable biological cycle through regeneration of hydraulic function and pollutant removal capacity through decomposition, degradation and uptake of captured pollutants. Organic matter within the engineered soil media is sustained overtime to replenish adsorption capacity through influx of organic material in stormwater runoff, plant root die off, and mulch degradation and replacement at maintenance. Microbes support nutrient cycling through organic matter and compound decomposition and biodegrade pollutants into less toxic forms. These biofiltration components support the hydraulic and water quality performance longevity evidenced in the long-term data collection at the different Filterra study sites up to 13 years with routine maintenance.

Organic Matter

As a biofiltration surface layer, mulch is the first line of defense for treatment via physical filtration and chemical complexing, but also protects the underlying treatment media from scour and occlusion. The media stays protected and infiltration rates are maintained while most of the sedimentation occurs on the surface of the mulch within a biofiltration practice. The consistent water quality and hydraulic performance longevity demonstrated by Filterra is likely due in part to regular maintenance which includes removal and replacement of the mulch layer. In addition to trapping particulate matter that could migrate into the media bed, it also provides many benefits thought to improve long-term functionality. For example, supporting the biological community by providing organic replenishment to the media, pollutant treatment, adsorption site regeneration, and moderating temperature and moisture within the media bed. Ongoing maintenance will reduce the likelihood of needing to replace the media over the long term.

Organic, wood-sourced mulch should be used due to its metals adsorption capacity and intrinsic properties including humic compounds consisting of carboxyl and hydroxyl functional groups, cation exchange capacity, surface area and pH. Wood mulch is known to capture oil and grease among other organic compounds. Wood mulch is also a host for microbial and macro-organism activity which supports plant health and pollutant degradation. Organic matter within the soil media retains moisture, provides carbon to the microbial community, supports vegetative growth, and enhances pollutant removal. These components are critical to long-term success by supporting inert and reactive filtration during storm events as well as the biological transformations and sequestration that occur between storm events.

Vegetation

Vegetation is key to sustainability by supporting microbiological activity and maintaining an assimilative capacity. Captured pollutants are biodegraded by microorganisms into forms available for plant uptake via phytoremediation. As vegetation biomass increases, as observed in the growth progression data in Table 10, so does Filterra's ability to capture and process more pollutants. Plants regenerate the Filterra media pollutant removal capacity by making the media adsorption sites available for the next storm event. Vegetation improves sustainability of the Filterra system by enhancing pollutant removal and uptake as well as maintaining design hydraulic flow rates through root expansion, penetration, exudate production and die-off. Roots shrink and swell during wetting and drying cycles keeping preferential pathways within the filtration media open. Plant roots and associated microbiological growth provide exudates which build and maintain soil structure. This increases macropore development for maintaining infiltration rates.

When healthy vegetation is part of the living ecosystem that makes up a biofilter, media porosity is increased, soil structure is improved, and compaction is reduced. Plant roots continuously penetrate filter media as the plant grows and the roots themselves die and regrow forming micro channels. This prevents media compaction and increases porosity, maintaining aeration and hydraulic rates. Infiltration rates observed during hydraulic field evaluation at study site A under typical operating conditions demonstrate the Filterra system sustained hydraulic capacity after 14 years with routine maintenance and supporting vegetation. At the surface, plant movement by wind or activity of birds, rodents and insects which associate with the plants can increase hydraulic rates by breaking apart the sedimentation crust that occludes the surface. Plants also enhance volume reduction through evapotranspiration.

Root-zone Macro- and Microorganisms

Biofilters with plants and organic media have more microbial density and diversity than non-vegetated, non-organic media filters and therefore have more ability to transform and uptake pollutants (Hills et al. 2017). Microorganisms degrade and transfer pollutants into less toxic forms through nutrient cycling. Nutrient cycling can include chelation for plant uptake, and sequestration of pollutants through carbon and nutrient assimilation (Coyne 1999). Microorganisms alter the soil chemistry in the rhizosphere that enhances pollutant removal efficiency. Plants increase organic matter in the soil through decomposition of biomass, including the roots themselves, known as cell sloughing, which provides a carbon source to the microorganisms in the media (Tugel 2000).

Additionally, mycorrhizae fungi create a symbiotic relationship with plant roots whereby plant roots excrete sugars for the fungi while the fungi provide "pollutants" to the plants in the form of nutrients for further biomass production. Mycorrhizae fungi increase the surface area of plant roots, which enhances absorption of phosphorus, nitrogen, and metals, which are all macro and micro plant nutrients vital for plant growth and reproduction (Lewis and Lowenfels 2010).

Macroorganisms, like earthworms, live symbiotically with microorganisms. Earthworms increase organic content in media by burying and consuming organic material deposited on the surface. Earthworms also support continued hydraulic and pollutant biodegradation by increasing microbial activity, recycling nutrients and altering soil structure through cast production. Earthworms also increase infiltration by improving porosity and drainage with burrow creation. Earthworms are an indicator of healthy soils, as evidenced during the hydraulic field evaluation at study site A (Figure 84) (Tugel 2000).

Media QA/QC

Filterra's history of performance success is predicated on a robust media QA/QC program. There is oversight beginning with the raw materials through the commercially produced Filterra media blend. Standards of practice have been developed utilizing rigorous verification testing for qualifying, sourcing, verifying, producing, storing, and handling Filterra media. Media certification is based on a controlled manufacturing process with post-production media validation required to ensure that the blend meets specification. QA/QC procedures are critical to ensuring media consistency and function per design specification (Hills et al. 2016).

Routine Maintenance

Contech recommends annual to semi-annual maintenance depending on the site location. As demonstrated in the maintenance records in Table 12 through Table 14, routine maintenance is recommended for quality and hydraulic design sustainability. Not following a regular maintenance schedule may result in enduring later expensive restorative costs. Prior hydraulic evaluation on older Filterra systems with large gaps in maintenance history demonstrated slower hydraulic capacity, supporting the importance of keeping a regular maintenance schedule (Hills 2009).

Filterra maintenance requires removing degraded mulch along with sediment, trash and debris and replacing with new mulch. Proper vegetative pruning should also occur as necessary not only for aesthetic value but to preserve access for sediment, debris and spent mulch removal during future maintenance visits. The mulch is typically the only component of the system that needs to be replaced regularly due to decomposition. Mulch replacement will extend the service life of the soil media indefinitely. Organic mulch replacement is necessary to support the chemical and biological processes with the ecosystem, microbial activity, media regeneration and preservation, and water holding capacity. Additionally, maintenance permanently removes contaminants associated with mulch and accumulated sediment (Herrera and Geosyntec 2010).

For bioretention practices, degraded mulch looks much like a layer of soil overtime, and these smaller soil particles and captured pollutants begin to migrate into the media bed, causing flow restriction. Longer than recommended maintenance intervals may require removal of the first few inches of media to restore hydraulic capacity. Therefore, new mulch cannot simply be placed overtop of old mulch; spent mulch removal and replacement is required. A technical memorandum on bioretention maintenance produced by the EPA suggests surface layer media replacement may also rejuvenate water quality performance based on research by University of Maryland demonstrating sedimentation and heavy metal accumulation in the top 2 to 4 inches of media (EPA 2016).

Performance Comparison to High Rate Biofiltration

Water quality results for the three Filterra long-term performance study sites were very similar to the 2020 International Stormwater BMP Database Summary Report (Table 11)(Clary et al. 2020) results for High Rate Biofiltration (HRBF). The median influent and effluent TSS and total phosphorus concentrations were nearly identical for both data sets. Median total zinc influent concentration was lower at the Filterra long-term performance study sites as compared to the HRBF results from the BMP Database at 140 µg/L and 178 µg/L, respectively. Median effluent zinc concentration was also lower at the Filterra long-term performance study sites as compared to the HRBF BMP Database results at 46 µg/L vs 60.6 µg/L, respectively. Median influent total copper concentration was higher at the Filterra long-term performance study sites at 29 µg/L vs 8 µg/L. Median effluent total copper concentration was also higher at the Filterra long-term performance study sites at 10 µg/L vs 4 µg/L. Removal efficiency was significant for all parameters. These are the only parameters with data from both sources for both types of BMPs.

Table 11. Filterra long-term performance versus high rate biofiltration performance as reported in the 2020 Summary Statistics Report by the International Stormwater BMP Database

Parameter		**TSS**		**Total Phosphorus**		**Total Copper**		**Total Zinc**	
Units		(mg/L)		(mg/L)		(µg/L)		(µg/L)	
Stormwater Control Measure		High Rate Biofiltration	Filterra Long-term Performance	High Rate Biofiltration	Filterra Long-term Performance	High Rate Biofiltration	Filterra Long-term Performance	High Rate Biofiltration	Filterra Long-term Performance
Median Value	Influent	30.8	31.2	0.099	0.1	7.95	29	178	140
	Effluent	3.8	3.6	0.05	0.05	3.75	10	60.6	46
Significant Median Value Reduction (Mann Whitney P-value 0.05)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

As noted previously, the HRBF category in the 2020 International Stormwater BMP database summary report is comprised entirely of six Filterra field studies, conducted over a period of one to three years and all initiated within a few years of installation. None of the long-term performance study sites are included in the International Stormwater BMP Database. Therefore, the nearly identical data sets from both sources indicate that Filterra long-term performance is similar to initial Filterra performance for these parameters.

The synthesis of similar long-term performance data for conventional bioretention systems was beyond the scope of this study. Some evidence suggests that conventional bioretention performance may improve over time, particularly as labile nutrients and dissolved metals originating from the media itself are flushed and vegetation matures (Herrera 2016). Further research is recommended at multiple sites to assess changes in long-term performance for conventional bioretention systems.

Hydraulic Performance

Pollutant load reduction provided by biofilters is a function of concentration reduction, runoff reduction (via infiltration and evapotranspiration) and capture efficiency (the proportion of average annual flow that is treated). This research demonstrates that Filterra systems continue to provide consistently high concentration reduction for typical stormwater pollutants over time. Filterra capture efficiency depends on the ratio of the system to its contributing drainage area, which is dictated by local regulations, and any changes in hydraulic capacity over time. It was infeasible to conduct hydraulic testing repeatedly over the life of each system. Instead, the media flow rate was tested after completion of the pollutant removal testing to establish a worst-case scenario for final flow rate. This proved to be difficult for Site B and Site C, as impacts on both sites prevented the final flow test. Site B experienced an oil spill in 2011 resulting in a full remediation of the Filterra system media. Replacing the media with new media rendered any future flow data irrelevant when compared with the pollutant removal testing. Site C was razed in late 2018 and fenced off preventing any additional testing or maintenance. Site A was therefore the only site remaining at the time of the final flow test.

Given that all 3 systems were originally designed based on a media flow rate of 100”/hr, the unsaturated median rate of 177”/hr proves that the system continues to outperform expectations even after 14 years. The saturated median media flow rate of 107”/hr also meets the original design flow rate.

A decrease in infiltration rate was observed from the unsaturated test to the saturated test. The unsaturated flow rate is a measurement of the flow through the system when water begins to enter the system up to the point that the media is fully saturated. Preferential flow paths and moisture deficit can draw the water into the media at a higher rate than under saturated processes via matric potential or suction head that draws water into unsaturated soils. The unsaturated flow rate would represent the flow rate that would be seen in a Filterra system in the field without an antecedent rain event (i.e. storms within a few hours). On the other hand, the saturated flow rate is a conservative measurement of flow through the media after the media has been fully saturated. Antecedent moisture conditions are more uniform where saturated flow processes dominate. Saturation of the media can impact flow because water droplets occupy media void space and organic particles within the media can absorb water and change shape, modifying preferential flow paths. Therefore, the saturated media flow rate represents the flow rate that would be seen in a Filterra system with a large antecedent rain event.

The time between maintenance events at Site A was longer than the recommended 6 to 12 months on several occasions throughout the monitoring period, which may have contributed to increased fines in the first several inches of media. Per the organic content and silt and clay analysis, the results are outside of the media specification in the first 3 inches of media, as demonstrated in Table 8 and Table 9, which likely reduced the potential 175 inch/hour infiltration rate recognized by many localities. Replacement of the first several inches of media may be necessary after 10 to 15 years to restore the original system flow rate.

Biofiltration Media Composition Correlation to Performance

Particle size analysis demonstrated less than 3% differences in the average gravel, sand, and silt and clay percentages among all media profile depths. The particle size analysis data collected remained within the Filterra media specification after 14 years of operation, supporting the quality and hydraulic performance observed over the monitoring life of the system. The particle size and organic content analysis data showed the media is preserved, sustaining pollutant removal and hydraulic function.

Organic content analysis demonstrated the average organic content varied more in the media surface layer in comparison to the other profile depths due to increased organic material (Figure 37). Moving upwards from a 12-inch media bed depth to 9 and 6 inches showed no significant difference in organic content (≤ 0.04%), however a higher percent difference of 1.27% was observed in the 0 to 3-inch media surface layer (Table 9). Additionally, slightly elevated levels of silt and clay were present in the top 3 inches of media (Figure 38), which is to be expected after 14 years of operation with several missed or extended maintenance periods. Moving upward from a 12-inch media bed depth to 9- and 6-inch depths showed a gradual increase in silt and clay, with the highest percent difference of 3.2% observed in the surface media layer (Table 8). While the system still maintained expected quality and hydraulic performance, the data suggests that replacement of the first several inches of media after 10 years may be beneficial. Media surface layer replacement ensures hydraulic function is not compromised as the surface layer may become richer in organic material over time due to natural degradation processes.

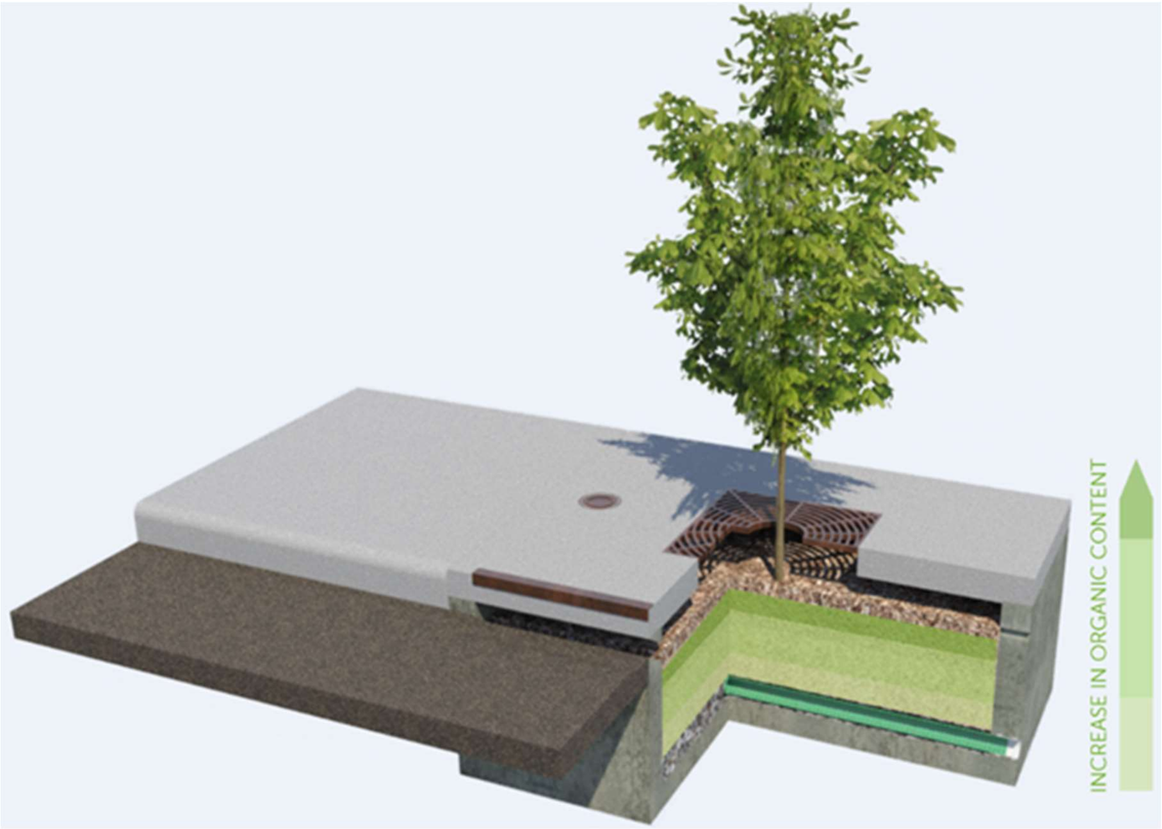


Figure 37. Study site A Filterra media profile composition analysis of organic content after 14 years in operation

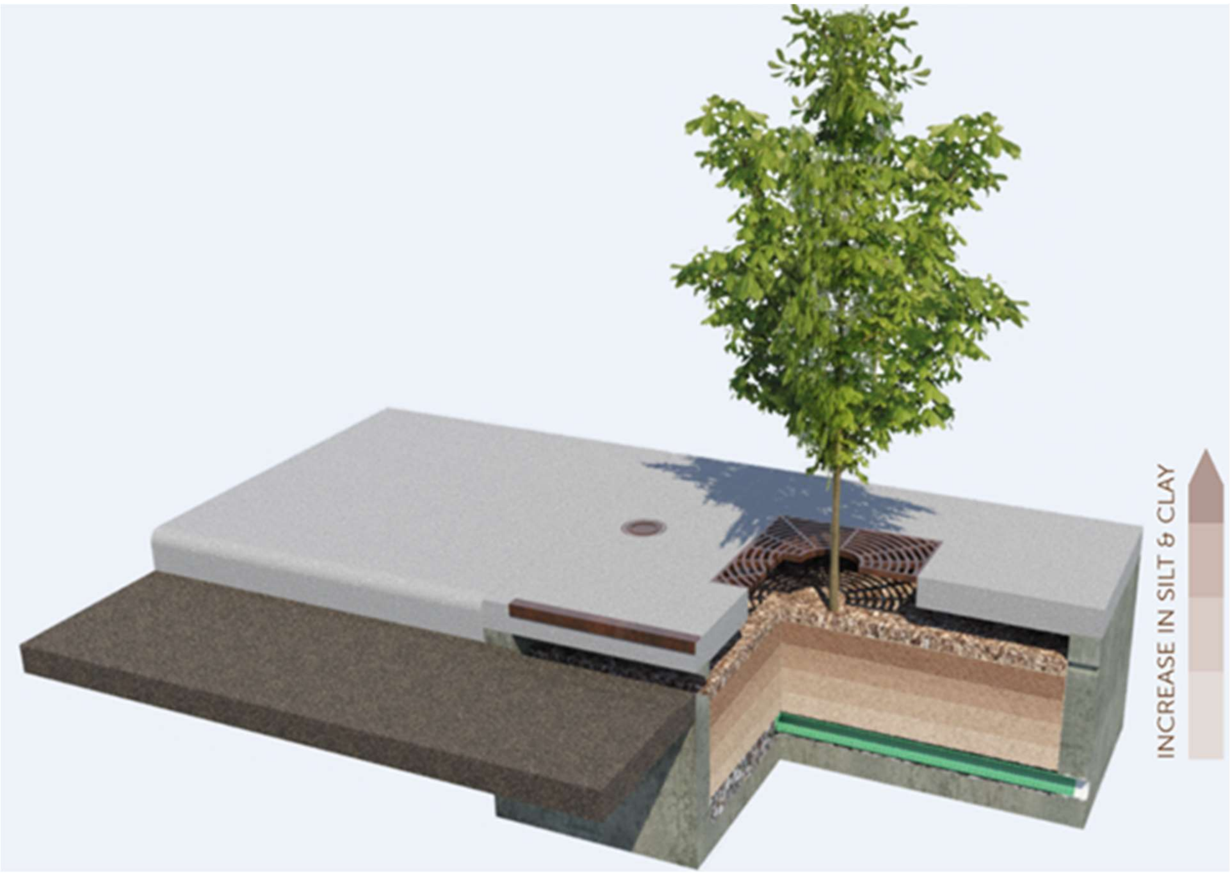


Figure 38. Study site A Filterra media profile composition analysis of silt and clay content after 14 years in operation

CONCLUSION

Filterra long-term performance is similar to short-term (1-3 year), third-party verified Filterra field studies for TSS, phosphorus, copper and zinc per the 2020 International BMP Database. Filterra long-term performance meets or exceeds conventional bioretention performance with each system type providing significant reduction in TSS, total and dissolved zinc, and total copper. Filterra also demonstrated significant total phosphorus and dissolved copper reduction while conventional bioretention showed insignificant dissolved copper removal and a net export of phosphorus (Clary et al. 2020).

Biofiltration systems with plants and organic media support the hydraulic and water quality performance longevity evidenced in the long-term data collection. Filterra performance should remain consistent over time with routine maintenance based on long-term quality and hydraulic performance, and media composition analysis. Annual to semi-annual maintenance depending on the site location is recommended for quality and hydraulic design sustainability and avoiding restorative costs. Maintenance requires removing degraded mulch along with sediment, trash and debris, replacing it with new mulch, and vegetative pruning as needed.

Additional long-term emerging contaminant studies and a better understanding of vegetation’s role in contaminant reduction are needed. Long-term performance and comparison information provided in this report, along with future research needs, will help design engineers and approval entities make more informed decisions on selecting stormwater control measures as sustainable solutions.

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APPENDIX A: PHOTO LOG

Filterra Plant Progression Photos

Figure 39. Study site A plant progression 2008

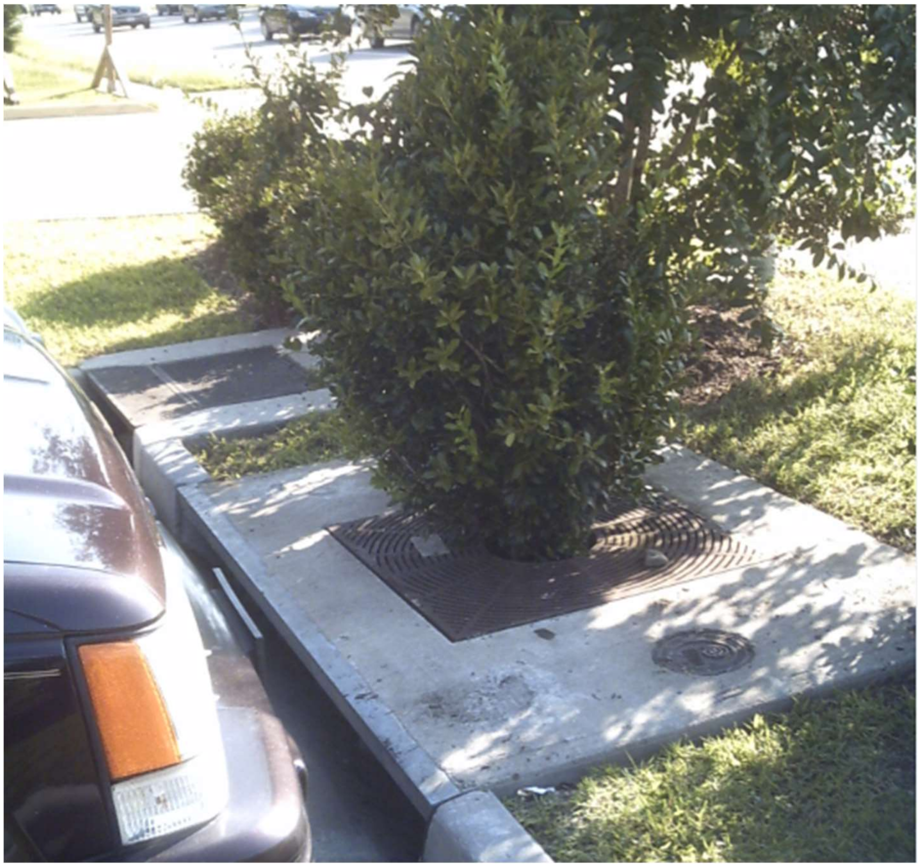

Figure 40. Study site A plant progression 2010

Figure 41. Study site A plant progression 2012

Figure 42. Study site A plant progression 2014

Figure 43. Study site A plant progression 2015

Figure 44. Study site A plant progression 2018

Figure 45. Study site A plant progression 2019

Figure 46. Study site A plant progression 2019, cut to single stem

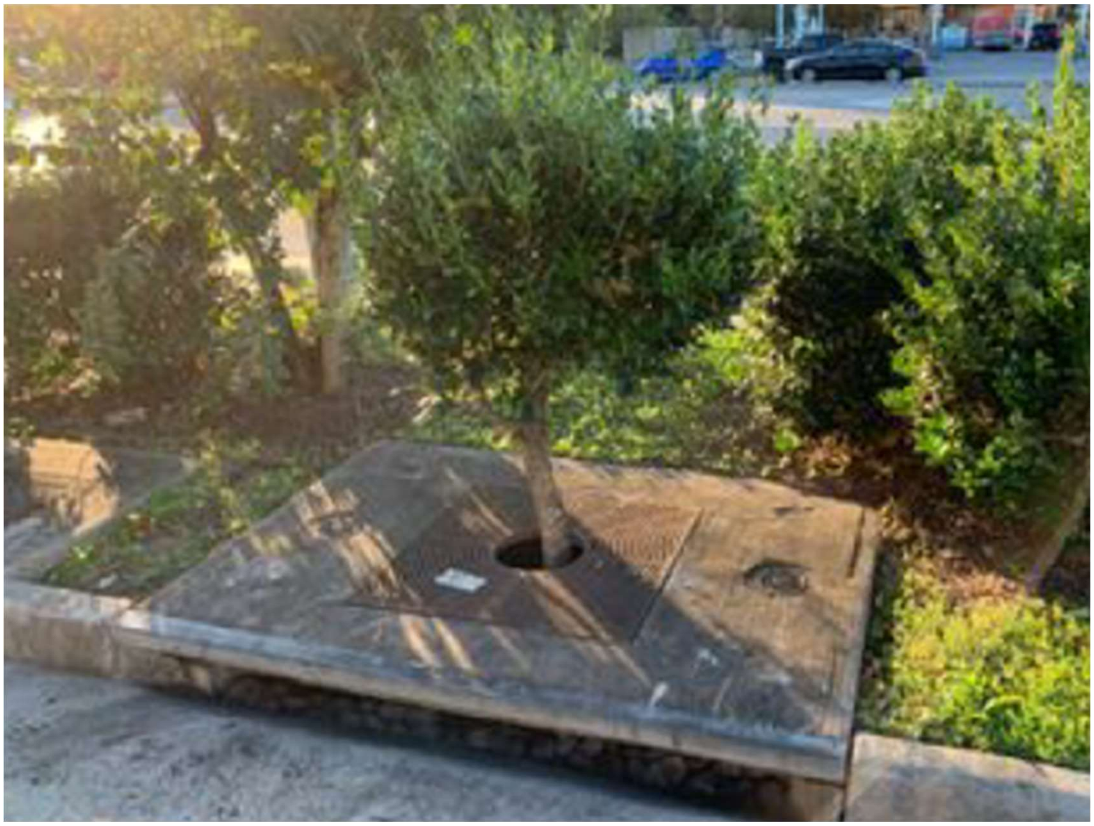

Figure 47. Study site A plant progression 2020

Figure 48. Study site A plant progression 2021

Figure 49. Study site B activation 2005

Figure 50. Study site B motor oil from oil service station caked on mulch surface in 2005

Figure 51. Study site B plant replacement with Northern Bayberry from heavy motor oil contamination in 2005

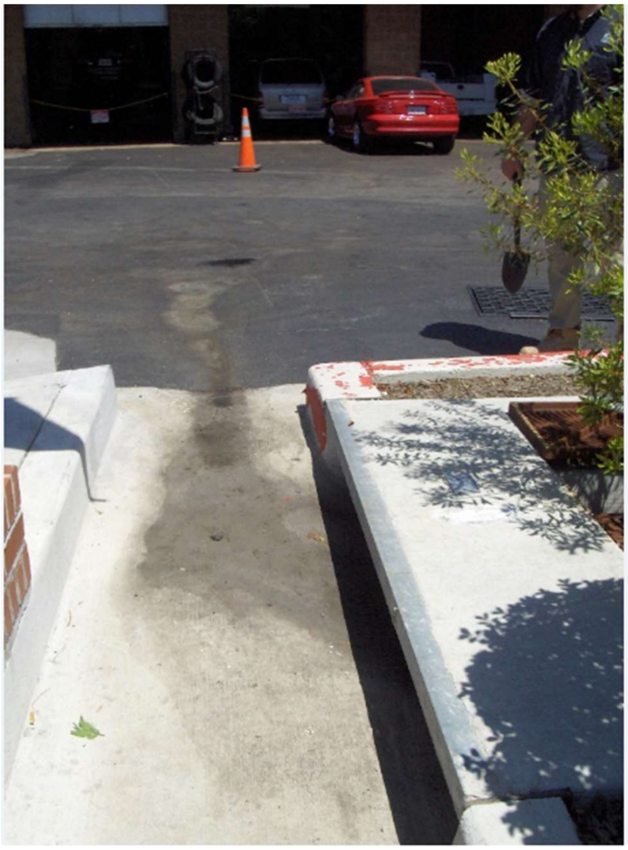

Figure 52. Study site B motor oil residue evident in drainage area feeding Filterra system 2006

Figure 53. Study site B plant progression 2006


[redacted]

Figure 54. Study site B plant progression 2008

Figure 55. Study site B plant progression 2009

Figure 56. Study site B plant progression 2009

Figure 57. Study site B plant progression 2009

Figure 58. Study site B continual motor oil contamination to Filterra system; monitoring discontinued

Figure 59. Study site C plant progression 2005

Figure 60. Study site C plant progression 2007

Figure 61. Study site C plant progression 2008

Figure 62. Study site C plant progression 2008

Figure 63. Study site C plant progression 2009

Figure 64. Study site C plant progression 2010

Figure 65. Study site C plant progression 2011

Figure 66. Study site C plant replacement 2012 with Foster Holly; photo taken 2013

Figure 67. Study site C plant progression 2014

Figure 68. Study site C plant progression 2015

Figure 69. Study site C plant progression 2016

Figure 70. Study site C plant progression 2017

Figure 71. Study site C plant progression 2018

Figure 72. Study site C decommissioning

Filterra Maintenance Photos

(a) **(b)**

Figure 73 (a)(b). Study site A pre-maintenance **(a)** and healthy roots evident post- maintenance prior to mulch replacement **(b)** 2017

Figure 74. Study site A pre-maintenance 2019

Figure 75. Study site A healthy roots evident post maintenance prior to mulch replacement 2019

(a) (b)

Figure 76 (a)(b). Study site C pre-maintenance **(a)** and post-maintenance **(b)** 2016

(a) (b)

Figure 77 (a)(b). Study site C pre-maintenance **(a)** and healthy roots evident post-maintenance prior to mulch replacement **(b)** 2017

Hydraulic Evaluation Photos

Figure 78. Study site A Filterra system hydraulically tested 2021

Figure 79. Hydrant and meter set up

Figure 80. Flow monitoring equipment set up

Figure 81. Curb influent flow

Figure 82. Initial flow during unsaturated test phase

Figure 83. Head development during unsaturated test phase

Figure 84. Worms present during hydraulic evaluation

APPENDIX B: ACTIVATION AND MAINTENANCE RECORDS

Table 12. Study site A activation and maintenance record

Date	Plant Height (ft.)	Plant Width (ft.)	Stem Diameter (in.)	Waste (cuft.)
[b]4/13/2007		[a]N/A		
12/11/2007	2.5	2.3	[a]N/A	0.0
5/11/2008	2.0	1.0	[a]N/A	0.0
2/25/2009		[a]N/A		
1/26/2010		[a]N/A		
8/30/2010	6.8	4.3	[a]N/A	4.7
7/25/2011		[a]N/A		
1/23/2012	4.3	2.8	2.0	0.7
9/13/2012	4.5	3.0	4.0	1.4
3/28/2013	4.8	3.2	2.0	3.4
10/14/2013	4.3	3.8	2.0	2.7
4/23/2014	5.5	4.4	2.5	3.4
4/3/2015	5.3	4.3	2.5	0.7
10/26/2015	4 - 5	3 - 4	2 - 3	0.0
4/6/2016	5 - 6	4 - 6	2 - 3	2.7
10/11/2016	3 - 4	2 - 3	1 - 2	0.0
4/28/2017	5.5	3.0	5.0	0.0
10/9/2017	4 - 5	3 - 4	2 - 3	8.0
4/19/2018	5 - 7	3 - 4	3 - 4	1.4
10/11/2018	5 - 7	3 - 4	3 - 4	1.4
4/8/2019	4 - 5	3 - 4	2 - 3	4.7
10/24/2019	4 - 5	2 - 3	3 - 4	2.0
4/8/2020	4 - 5	1 - 2	3 - 4	3.4
11/5/2020	4 - 5	3 - 4	3 - 4	3.4
4/14/2021	5 - 7	3 - 4	3 - 4	5.4
Sum				49.1

[a] N/A

[b] Activation, planted Nellie Stevens Holly

Table 13. Study site B activation and maintenance record

Date	Plant Height (ft.)	Plant Width (ft.)	Waste (cuft.)
[b]12/1/2004		[a]N/A	
[c]6/17/2005	4.7	2.7	2.4
11/1/2005	6.6	5.3	1.4
5/3/2006		[a]N/A	
[d]4/17/2007	5.2	5.6	
1/14/2008	5.5	6.2	3.4
6/22/2008		[a]N/A	
4/30/2009	7.1	5.0	1.4
11/4/2009		[a]N/A	
[e]9/13/2010	6.3	8.6	3.4
[f]2/17/2011			
Sum			11.9

[a] N/A

[b] activation, planted Foster Holly

[c] Dead plant, heavy silt/oil on system surface, replaced w/ Northern Bayberry

[d] Motor oil on system surface

[e] Dead plant, motor oil on system surface

[f] Oil spill, maintenance and monitoring terminated

Table 14. Study site C activation and maintenance record

Date	Plant Height (ft.)	Plant Width (ft.)	Stem Diameter (in.)	Waste Removed (cuft.)
[b]5/27/2005			[a]N/A	
11/3/2005	4.0	3.0		5.4
4/11/2006			[a]N/A	
5/1/2007	5.8	8.0		0.0
1/29/2008	7.8	9.0		1.4
4/29/2008			[a]N/A	
12/17/2008			[a]N/A	
9/11/2009			[a]N/A	
8/30/2010	10.3	7.3	3.0	4.0
7/25/2011	8.0	9.0		0.0
1/25/2012	7.2	6.6	2.0	4.0
[c]9/13/2012	4.5	2.3	2.0	2.7
6/17/2013	5.3	2.8	1.5	2.0
11/11/2013	4.5	3.3	2.0	0.0
6/25/2014	4.8	2.7	1.0	0.7
12/16/2014	4.5	3.0	1.0	0.0
6/23/2015	5.4	3.9	1.0	3.4
12/29/2015	5 - 7	3 - 4	1 - 2	N/A[1]
6/13/2016	4 - 5	0 - 1	1 - 2	2.7
12/7/2016	4 - 5	2 - 3	1 - 2	6.0
6/6/2017	5 - 7	2 - 3	1 - 2	6.0
12/13/2017	4 - 5	2 - 3	1 - 2	2.0
6/6/2018	5 - 7	3 - 4	1 - 2	2.0
Sum				42.5

[a]N/A: Maintenance occurred but record not available

[b]Activation, planted Redtwig Dogwood

[c]Replaced Dogwood with Foster Holly