R. Pitt
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Long-Term Performance of Biofilter, Media Filter and Treatment Train Stormwater Controls at a Historical Industrial Site in Southern California

Pitt, R., M. Otto, A. Questad, R. Gearheart, J. Jones, M. Josselyn, M. Stenstrom, and B. Steets

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Abstract

Introduction

There have been a very large number of monitoring projects investigating the performance of stormwater controls, with much recent interest focusing on biofilters/bioretention systems. Most of these investigations were only conducted for relatively short (1 or 2 years) periods of time, with minimal data concerning long-term performance and maintenance issues, of great interest to stormwater managers.

The International BMP Database (http://bmpdatabase.org/) includes water quality performance data for over 700 studies. The 2016 Summary Statistics report (Clary, *et al.* 2017) describes the evolution of this database over the past 20 years. Even with this large number of performance investigations, only 9 biofilters, bioretention, or rain garden sites have been monitored for at least 3 years (maximum of 6 years). Another large-scale review of multiple stormwater control installations was conducted by Taylor, *et al.* (2014) for the Transportation Research Board, mostly based on stormwater controls at highway sites included in the International BMP Database. As part of this investigation, they reviewed long-term Department of Transportation performance studies at 6 vegetated sites having more than 4 years of data (one ecology embankment for four years in Washington, one swale for five years in Texas, and four strips for 5 to 7 years in California) to determine if performance changed over time. Also examined were three sand filter installations in California (monitored for 4 to 6 years) and one permeable friction course overlay study in Texas (monitored for 5 years). They were not able to identify any changes in performance based on these limited data.

The purpose of this paper is to expand this data set of long-term water quality performance of biofilters and media filter stormwater controls with monitoring data collected at several stormwater control installations at the Santa Susana Field Laboratory (SSFL) in Southern California. The SSFL is a 1,120 ha (2,800 ac) former federal government rocket engine testing and energy research facility located in the Santa Susana Mountains of eastern Ventura County that is currently owned by The Boeing Company and the U.S. Government. Activities at the site are now limited to demolition, remediation, and restoration. Much of the site is open space. Stormwater discharges from the site are regulated by the Los Angeles Regional Water Quality Control Board (LARWQCB) through an individual industrial NPDES permit that includes Water Quality Based Effluent Limits (WQBELs) for many constituents, including metals, organic solvents, dioxins, and radionuclides, at multiple outfalls.

As part of the initial stormwater control design activities, Boeing partnered with the University of Alabama and Penn State Harrisburg to conduct laboratory performance studies to identify and evaluate stormwater treatment media filter mixtures. Bench-scale tests using stormwater included clogging, breakthrough, and removal; contact time and media depth; media capacity and kinetics; and aerobic/anaerobic effects. Results indicated that of the ten media mixes evaluated, a blend of rhyolite sand, surface modified zeolite (SMZ), and granular activated carbon (GAC) was a top ranked performer for the removal of a broad range of the contaminants of concern at reasonable flow rates and with minimal clogging. This media mix was implemented at stormwater control systems constructed at the SSFL.

Due to severe site constraints at two of the compliance monitoring “outfalls” (i.e., natural drainages located near the property boundary), “end-of-pipe” stormwater controls are not feasible. Therefore, a watershed-based, distributed stormwater control approach has been implemented, with numerous applications of advanced treatment trains incorporating sedimentation and flow equalization followed by flow-through media filters (or “biofilters” when vegetated).

Description of Stormwater Controls and Monitoring Efforts

As part of the distributed stormwater control approach, numerous locations have been monitored during all runoff producing rains. Figure 1 shows 68 potential stormwater control monitoring locations downstream of historical industrial activities, known impacted surface soils, and/or significant developed areas (such as buildings and/or paved surfaces) along with 16 background monitoring locations and two NPDES outfall monitoring locations. Performance monitoring was also conducted at the constructed stormwater controls.

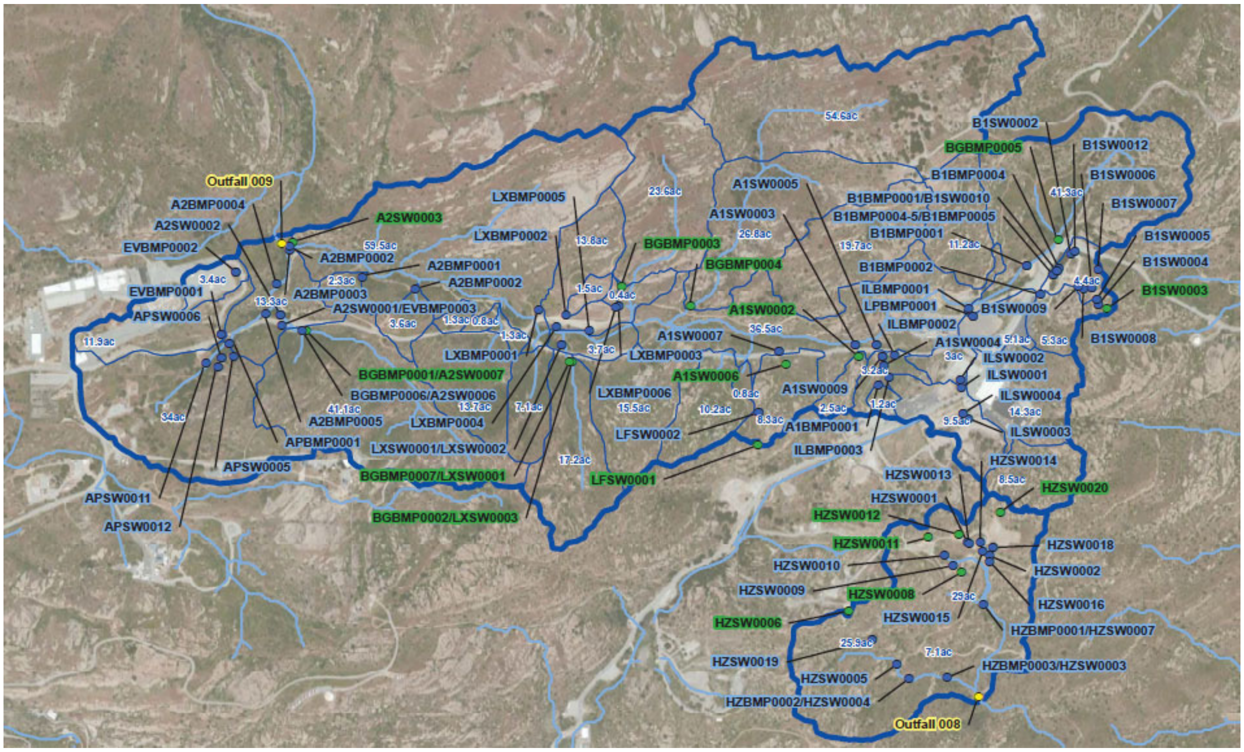


Figure 1. Source area monitoring locations (Blue at potential stormwater control monitoring locations, green: 16 at background monitoring locations, and yellow at NPDES outfall monitoring locations.

Every year, the source area monitoring data are evaluated, and the locations ranked according to procedures considering concentrations above the outfall NPDES benchmarks and/or limits and the number of samples available. The top ranked locations are then examined in detail and suitable stormwater controls evaluated, designed, and constructed. Performance monitoring is also conducted at these stormwater controls to verify the procedure and their performance. As of 2018, numerous stormwater controls have been used at the SSFL, as shown on Figure 2. Detailed site descriptions and historical activities are available at web sites of Boeing and various state agencies. The annual reports (including the monitoring data and evaluations) are also publicly available on web sites.

"Culvert modifications" (CMs) were installed early in the process in 2009 and 2010 before statistically sufficient amounts of data were collected as these could be installed quickly and at relatively low cost. These create impoundments at road crossing culverts with the impounded water directed through a horseshoe shape mound of the media mixture which is then collected with underdrains. Twelve culvert modifications have been installed at SSFL.

Table 1 lists ten stormwater controls examined in this paper, representing the types of controls at the SSFL and a range of drainage area characteristics. All of these controls were designed to hydraulically handle the 1-yr, 24-hr rain, which is 2.5 inches in depth (the peak flow rates depend on the drainage area times of concentration).

Table 1. Characteristics of Stormwater Controls Examined at SSFL

Stormwater Control	Footprint of Stormwater Control	Residence time in Filter Media (minutes)	Drainage Area (ha and acres)	Approximate Impervious Cover in Drainage Area (pavement, roofs, and massive rock outcrops) (%)	Percentage of Annual Flow Treated (%)	Treatment Area (sedimentation plus media filter) to Drainage Area Ratio (m^2/ha and %)
CM-1	Media filter area: 3 m^2	XXX	17 to 21 ha (43 to 53 ac)	6.5 to 22%	29%	0.14 to 0.18 (0.001 to 0.002%)
CM-8; Background location (no known historical industrial activity)	XXX	XXX	1 ha (2.6 ac)	36%	XXX	XXX
CM-9	Media filter area: 3 m^2	XXX	4.1 ha (10.2 ac)	48%	33%	0.73 (0.007%)
CM-11; Background location (no known historical industrial activity)	XXX	XXX	2.3 ha (5.7 ac)	26%	XXX	XXX
B-1 Media Filter	Biofilter area: 19 m^2	XXX	1.8 ha (4.4 ac)	53%	51%	10.6 (0.1%)
ELV Treatment Train	Sediment tank area: 42 m^2 Media filter area: 21 m^2	XXX	2.6 to 6.2 ha (6.6 to 15.6 ac)	26 to 37%	96%	10.2 to 24.2 (0.1 to 0.2%)
Northern Detention Bioswale	XXX	XXX	1.0 ha (2.6 ac)	50%	XXX	XXX
Southern Detention Bioswale	XXX	XXX	5.7 ha (14.2 ac)	50%	XXX	XXX
Lower Lot Biofilter	Sedimentation area: 300 m^2 Biofilter area: 300 m^2	XXX	12 ha (29.9 ac)	53%	79%	50 (0.5%)
Upper Lot Media Filter	XXX	XXX	2.0 ha (5.1 ac)	35%	XXX	XXX

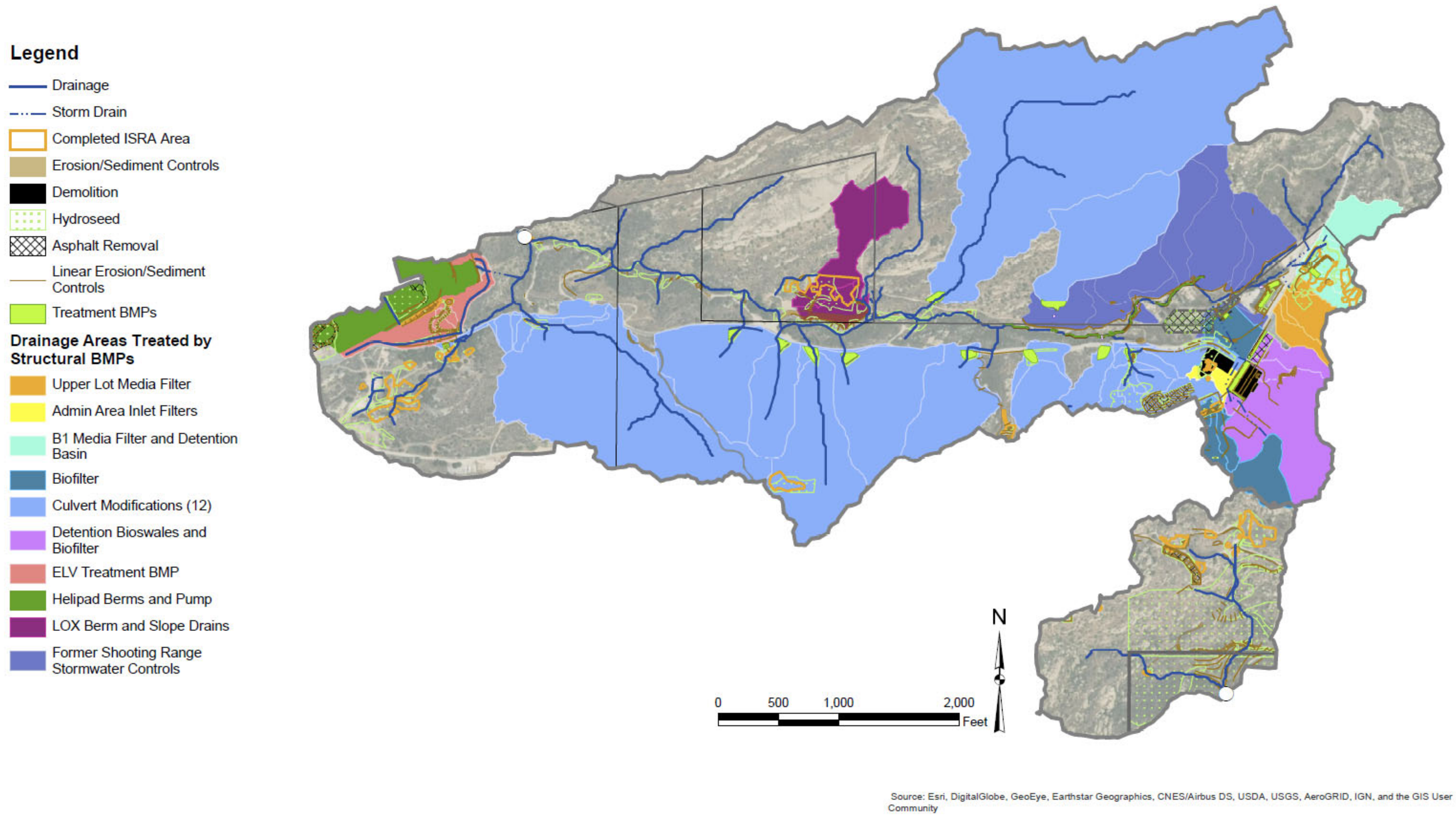


Figure 2. Locations of structural and non-structural stormwater controls at SSFL, along with the drainage areas treated.

The performance of the stormwater controls is dependent on many site and design factors. Generally, the best performance is expected for large stormwater controls and small drainage areas, for long contact times with the treatment media, and large fractions of the annual flows treated by the stormwater control (with the excess flows bypassing complete treatment). The effluent quality is better when the influent quality is better, while the percentage reductions are better if the influent concentrations are high.

Besides the stormwater controls listed on Table 1, Figure 1 indicates many other distributed controls on the site. The culvert modifications treat about half of the site area in these two subdrainages, while erosion controls have also been established on much of the site. The main drainage (the Northern drainage) has constantly undergone restoration and stabilization. Many minor controls are also on the site, including some inlet filters and diversions. At the Helipad large paved area, berms are established and much of the flows from that area are pumped to a sophisticated stormwater treatment system using chemical controls in an adjacent subdrainage area. In addition, Interim Source Remediation Action (ISRA) excavations have been conducted to remove contaminated soil from hotspots. A shooting range also was on the site and special soil excavation and stormwater controls have also been used to remove lead material from the site. Finally, demolition and removal of buildings and asphalt, and other site industrial structures has helped restore the natural hydrological response of the site. Final site restoration, including removal of additional soil contaminated by the site rocket testing and energy research activities, is still in state agency review. The stormwater and erosion controls established on the site will be kept in operation and maintained until these final activities are completed and the agencies approve the final site cleanup.

Unfortunately, the devastating Woolsey Fire in November 2018 covered about 80% of the SSFL area. There was only minor damage to site structures or stormwater controls by the fire, but massive amounts of natural and re-established vegetation were destroyed. The site owners and operators (The Boeing Company and the federal government, along with their contractors) immediately started emergency erosion controls and repairs to the site facilities. The source area monitoring had been tapering off in recent years as the critical subdrainage areas were addressed by stormwater controls that were established based on the site ranking system. However, after the fire, the sampling effort is being increased to identify any new potential critical areas needed stormwater control. The SSFL site was also affected by a fire in 2005 after which extensive erosion and other controls were used to control the movement of denuded soil from the site during rains. An on-site nursery was also used to produce many specimens of native plants which were re-planted in burnt and other areas.

The following describe the stormwater controls that are evaluated in this paper.

B1 Media Filter and Detention Basin (2012)

Upstream of the existing B-1 culvert, a media filter with sediment forebays was installed to capture stormwater from the hillside and roadway. Two gabion check structures (filled with 10 – 20 cm rock) were placed on either end of the existing depression next to the road, to separate the media bed from the forebay, in order to promote settling and therefore preserve the life of the media. The media filter consists of a 10 cm layer of gravel on the surface, underlaid by 45 cm filter media (sand, GAC, zeolite), which sits on top of a 10 cm perforated pipe set in gravel. The perforated underdrains convey the treated media to a riser overflow structure where it is discharged to the Northern Drainage. Additional curb cuts along Facility Road were installed to direct roadway stormwater to a series of check dams and riprap, which ultimately drain to the forebay and media filter. Finally, a detention basin was installed upstream to provide additional settling and pretreatment of hillside flows prior to entering the media bed.

Figure 3. B-1 Sedimentation Basin and Media Filter

Detention Bioswales (2014)

Two detention bioswales consisting of vegetated swales with underlying storage chambers (Contech ChamberMaxx®), surrounded by stone bedding, pretreat the stormwater from the upper lot paved and surrounding areas before discharging to the lower lot biofilter system. These detention bioswales detain the drainage water for treatment in the lower lot biofilter after the initial lower lot flows are treated. Excess water that is not further treated by the biofilter is discharged to the Northern Drainage. Each unit drains through an outlet pipe, controlled by two orifices sized to drain the system within 72 hours. The vegetation mixture is comprised of Mugwort, Dwarf Coyote Bush, Tufted Hairgrass, Creeping Wildrye, California Fuchsia, Red Fescue, Baja Bush Snap Dragon, and Sticky Monkeyflower.

Figure 4. B1436 Detention Bioswales

Lower Lot Sediment Pond and Biofilter (2013)

A collection trench drain conveys stormwater from the lower paved lot to an 85 m^3 cistern, which is then pumped to a 650 m^3 dry sediment basin. The sediment basin drains to the biofilter, which discharges back to the Northern Drainage. The sediment basin includes an orifice plate designed to drain 1/2 the volume in 12 hours and the remaining volume in 28 hours (total of 40 hours). The biofilter includes an outlet structure with orifices sized to limit the flow through the media, resulting in a minimum contact time of 2.1 hours. A 50 cm weir plate was originally installed, but replaced by a 10 cm weir plate, which is expected to result in an increase from 53% to 95% diversion of flows to the biofilter during the design storm. The biofilter cross-section includes: 10 cm layer topsoil/compost vegetative support layer, 46 cm layer of treatment media (fine filter sand, GAC, zeolite), 30 cm gravel layer with 150 cm PVC well screen laterals that drain through 200 cm underdrain. A plant growth pilot study was performed to confirm growth of plants in the treatment media and under alternating submerged and dry conditions. Additional vegetation studies were also conducted to select native vegetation found throughout SSFL and also to emphasize pollinators (Pollinator Partnership). Plants include Coastal Deerweed, Rose Snapdragon, Big Berry Manzanita, California Sagebrush, Narrow Leaf Milkweed, Coyote Brush, Island False Bindweed, Creeping Wildrye, California Encelia, Leafy Fleabane, California Buckwheat, Golden Yarrow, Toyon, Heart Leaved Penstamon, Chaparral Bush Mallow, California Melic, Sticky Monkey Flower, Wild Peony, Holly Leaved Cherry, Coast Live Oak, Lemonade Berry, White Chaparral Currant, Chaparral Currant, Purple Sage, Black Sage, Blue Elderberry, Indian Pink, Purple Needlegrass, Mugwort, Mulefat, California Fuchsia, Bricklebush, Sedge, Saltgrass, and Common Rush.

Figure 5. Lower Parking Lot Sedimentation Basin and Biofilter

Upper Lot Media Filter (2017)

An existing shotcrete sump that collected water from a small portion of the upper paved lot was used as the base of this media filter which was filled with media, gravel, and pipe to create the flow-through components. The stormwater percolates through a 50 cm media layer (GAC, Zeolite, Sand) and into a roughly 30 cm drainage layer, which collects the water in a 150 cm PVC underdrain that discharges into a riser overflow structure. The media filter was designed to provide 100% capture of the 1-yr, 24-hr, design storm (with no outlet controls) and the outlet structure overflow was designed to provide equal or greater conveyance capacity compared to the existing outlet pipe in the sump that drains to the Northern Drainage.

Figure 6. Upper Parking Lot Media Filter

NASA ELV Stormwater Treatment Train (2013)

The ELV channel conveys runoff from the hillside below the paved helipad to a 30 m^3 concrete sump, which also collects runoff from Helipad Road. The stormwater captured in the sump (up to the design storm) is pumped into two 70 m^3 open top portable sediment tanks equipped with floating tube settlers to provide greater effective surface area for particle settling. The sediment basins drain by gravity to an additional 70 m^3 open top portable media filter tank, which percolates water through 45 cm of media (sand, zeolite, GAC) and into a PVC well screen pipe controlled by an outlet orifice plate. The concrete sump includes an overflow that discharges high flows through a weir into the ELV culvert. Flows in excess of the sediment tank capacity overflow through a weir and discharge to the filtration tank.

Figure 7. ELV Treatment Train

Culvert Modifications (2009)

Prior to the installation of the CMs, stormwater from the hillside and adjacent roadways drained into small drainage ways and through under-road culverts, which discharged into the Northern Drainage. The CMs are retrofits of the existing culverts and include fiber-reinforced plastic headwalls with removable weir boards that span the entrance to each culvert. The stormwater is forced to pond in front of the weir boards and is directed through a 60 cm (minimum) mound of filter media (GAC, zeolite, sand) that is collected by 100 cm perforated pipe lateral underdrains. Once the stormwater filters through the media and through the laterals, the water is conveyed behind the weir boards and through the existing culvert, where it discharges into the Northern Drainage. During large storms, the water can overtop the weir boards and overflow into the existing culvert, thus bypassing treatment through the media mounds. No emphasis on vegetation at the CMs; however, existing vegetation was re-planted.

Figure 8. Culvert Modifications

Sampling Effort and Rainfall

Influent and effluent results for each stormwater control for the same storm event were compared to evaluate concentration reductions. Although split samples were periodically collected and used for QA/QC purposes, only the primary samples were used in these analyses.

For each of the five CM sites (constructed in 2009) discussed herein, the number of paired samples per CM ranges from 10 to 29 pairs for TSS and 0 to 29 pairs for dioxins, copper, and lead for 2011/2012 through 2017/2018. Influent grab samples are collected from the flowing surface water upstream of the maximum extent of ponding at each CM as observed before that date. All sampled CMs include a media filter and a slipline HDPE lining through existing galvanized corrugated metal culvert pipes with the exception of B-1, which is a media bed with no slipline element. Effluent grab samples at CM-1, CM-9, and B-1 are collected from the underdrain outlet (beginning in October 2011, rather than the culvert outlet), while other CM effluent grab samples are collected at the culvert outlets on the downstream side of the road, where the culvert pipes discharge to the Northern Drainage. Flows from the culvert outlets may represent treated runoff (via sedimentation and media filtration) and partially treated runoff (flowing through or over the weir boards).

Performance data for the lower lot biofilter (construction of which was completed in 2013) were collected from three locations within the system (influent, effluent, and a mid-point sample at the sedimentation basin outlet before the media filter inlet). There are 24 total sample pairs associated with the lower lot biofilter system location to date.

The ELV treatment train, constructed during the 2013/2014 reporting year, includes paired data from 10 events. The media bed for this system appears to have been flushing fines during the first sampling event in 2013/2014. During this event, the ELV treatment train was also heavily loaded by sediments eroded from the denuded ELV channel prior to implementation of subsequent erosion control improvements.

The B1436 detention bioswales, which were constructed in December 2014, were sampled for the first time during the 2015/2016 reporting year. Samples were collected at three locations at the southern detention bioswale: two influent locations (results from both locations were flow-weighted based on drainage area size and estimated imperviousness to determine the influent concentrations) and the effluent. Paired influent and effluent performance data were collected during 16 events at the southern detention bioswale. Samples were also collected at both the influent and effluent locations of the northern detention bioswale during eight events during the 2015/2016 and 2016/2017 reporting years.

The upper lot media filter was completed on May 16, 2017. Eight samples were collected during the 2016/2017 reporting year, but only at the influent location. Paired samples were collected for the first time at the upper lot media filter during 2017/2018 (for two events).

Table 2 shows the amount of rainfall and numbers of rain events and samples collected since the initial CM controls were constructed in 2009. Note the highly variable rainfall amount per year (6.1 to 23 inches and 4 to 14 rain events per year) and the sample numbers (17 to 150 per year). The average annual rainfall during the 8 years with samples was 13.1 inches, compared to the long-term average rainfall of 16.8 inches. Overall, more than 500 samples were collected at the stormwater control locations and other subareas.

Table 2. Rainfall Amounts, Rain Events, and Sample Numbers

reporting year (June 1 to May 31)	on-site measured total rainfall (inches)	number of rain events per year (>0.1 inches in 24 hr period with at least 72 hrs of preceding dry weather)	number of samples at stormwater control locations and other subareas (observable flows)
2009/2010	19.39	11	0
2010/2011	23.39	14	67
2011/2012	11.33	11	88
2012/2013	8.10	9	29
2013/2014	6.07	5	27
2014/2015	11.22	9	17
2015/2016	11.97	13	113
2016/2017	23.35	14	150
2017/2018	9.75	4	36
Total for 9 years	124.57		527
average	13.84 inches/year		
long-term (1958/1958 to 2017/2018): 16.80 inches per year			

Analyses and Findings

The regulated NPDES outfalls on the SSFL site are monitored for many constituents for each flow-producing event, including solids and particle sizes, heavy metals, organic solvents, radionuclides, and many major ions and other organic compounds. In recent years, the outfall stormwater water quality has improved (based on decreasing violations in numeric effluent limits). However, periodic exceedances occur for dioxin (TCDD, TEQ no DNQ, Tetrachlorodibenzo-*p*-dioxin, toxicity equivalence, and detected not quantifiable excluded) and total lead. Rare benchmark exceedances of iron and pH have also been noted in recent years. The performance monitoring at the stormwater control locations focus on a shorter list of constituents, including TSS, TCDD, total and filtered copper, total and filtered lead, total and filtered cadmium, total and filtered mercury, particle size distribution, conductivity, pH, temperature, and turbidity. These are evaluated in this paper, especially examining any potential trends in removal and effluent quality during the several years of operation of these stormwater controls. Influent and effluent samples were manually collected during all events that had observed flows at influent and effluent locations, totaling 225 total events for the ten locations combined.

The general data analyses (mostly conducted using Microsoft Excel, SigmaPlot version 14, and Minitab version 18) described in this section include the following:

- Basic statistical summaries of influent and effluent concentrations, concentration reductions, filterable fraction of the metals, and particulate strengths of the metals and dioxin, buy control measure.
- Comparisons of influent concentrations and statistical groupings between locations (Kruskal-Wallis One Way Analysis of Variance on Ranks, all Pairwise Multiple Comparison Procedures using Dunn's method, and associated grouped box and whisker plots).
- Full factorial analyses of influent concentrations for selected control locations to identify significant factors and interactions of rain characteristics affecting TSS concentrations.
- Grouped log-normal probability plots of influent and effluent concentrations, using Anderson-Darling test statistics for normalcy, for grouped stormwater control types.
- Line plots illustrating concentration trends between unit processes in treatment systems.
- Comparisons of paired influent vs. effluent concentrations using the Wilcoxon Signed Rank test to identify which constituents and control types resulted in significant differences between influent and effluent concentrations.
- Analyses of paired influent and effluent concentrations (found to have significant differences) to identify significant regression coefficients and models (using ANOVA) to calculate effluent concentrations for given influent concentrations.
- Standard residual analyses of significant regression equations to identify differences between stormwater controls within a grouped set, and to identify residual trends with time.
- Evaluation of influent concentrations with time using time-series scatterplots and regression with ANOVA to identify significant concentration trends with time.
- Calculations of accumulative sediment in stormwater controls with time.

Stormwater Characteristics

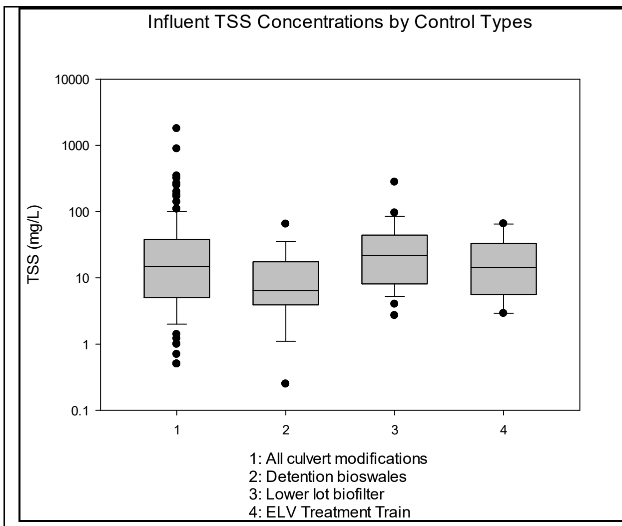
Table 3 summarizes concentrations for these ten stormwater controls combined for an overall indication of the water quality at the SSFL at the locations where source area controls have been located. For comparison, industrial stormwater data contained in the National Stormwater Quality Database (NSQD), version 4.02 are also shown for a few of the constituents. The NSQD industrial data are for light and medium industrial activity. Even so, the NSQD median concentrations are about 2 to 5 times the SSFL influent concentrations for TSS, total and filtered Cu, and total Pb. The total Cd values for both sets of data are mostly non-detected, while the SSFL pH median values are about 1 pH unit less than the NSQD pH values. Also shown on this table are summary stormwater concentrations from medium to heavy industrial sites as presented by Clark and Pitt (2018). These data are from sites monitored by those authors along with selected data from the International BMP Database. Effluent concentrations of industrial stormwater controls are also summarized (sedimentation, filtration, and treatment trains). The medium and heavy industry stormwater concentrations are all much greater than the SSFL concentrations (about 4 times for TSS, about 9 times for Cu, about 20 times for Pb, while the filtered concentrations were closer). Because the influent concentrations were less for the SSFL locations, their corresponding effluent concentrations are also lower than for the medium and heavy industrial stormwater treatment effluent values. In contrast, the percentage reductions in concentrations are greater for the medium and heavy industrial controls than for SSFL locations. SSFL constituents that were mostly not detected (52 to 95% not detected) included: filtered Pb, total and filtered Cd, and total and filtered Hg. Appendix A contains influent and effluent concentration (and % reduction) summaries for each of these four groups, along with the background CM-8 and CM-11 control locations, for all of the monitored constituents.

Table 3. SSFL Influent and Effluent Stormwater Concentrations

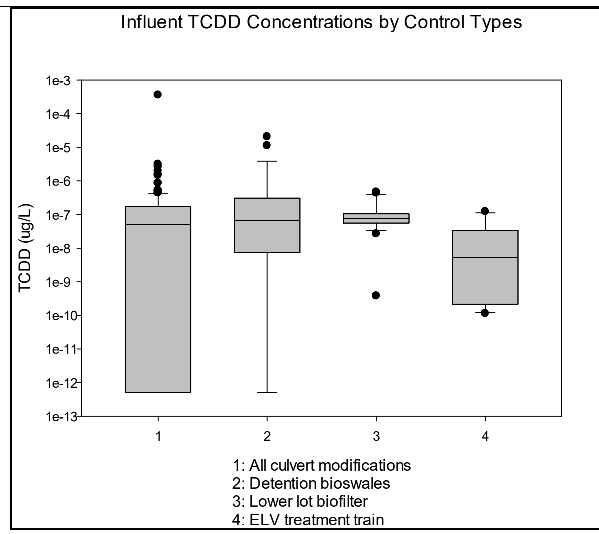
	SSFL count	Light to medium indus count (NSQD)	Medium to heavy indus count (Clark and Pitt 2018)	SSFL % non-detects	Light to medium indus % non-detects (NSQD)	Medium to heavy indus % non-detects (Clark and Pitt 2018)	SSFL min	SSFL max	SSFL median	Light to medium indus median (NSQD)	Medium to heavy indus median (Clark and Pitt 2018)	SSFL COV	Light to medium indus COV (NSQD)	Medium to heavy indus COV (Clark and Pitt 2018)
Sample Date	225						12/11/2009	3/22/2018						
TSS inf mg/L	199	967	217	6.0	0.6	1.8	1	1,800	16	74	60	3.0	1.0	2.7
TSS efl mg/L	184		215	7.1		4.2	1	610	11		22	2.4		2.1
TCDD inf µg/L	183			18.6			1.00E-12	3.60E-04	5.60E-08			11.6		
TCDD efl µg/L	167			34.7			1.00E-12	4.33E-06	2.10E-10			5.4		
Cu inf µg/L	158	3,090	203	1.9	14.5	1.5	0.1	44.9	6.9	12	60	0.8	2.0	1.6
Cu efl µg/L	134		206	3.7		2.4	0.1	53.0	6.5		21	0.9		1.9
filt Cu inf µg/L	148	104	185	0.0	15.4	9.2	0.7	164	4.2	8	12	2.1	0.9	3.8
filt Cu efl µg/L	117		188	0.0		12.2	0.9	47.0	5.1		8	1.0		2.7
Pb inf µg/L	187	2,497	167	8.0	29.5	3.6	0.1	55.0	2.8	7	61	1.7	2.6	1.2
Pb efl µg/L	172		171	7.0		4.7	0.1	39.0	1.6		24	1.7		1.7
filt Pb inf µg/L	148	28	150	52.0	n/a	69.3	0.1	26.4	0.5	5	0.5	2.5	1.6	3.0
filt Pb efl µg/L	117		153	57.3		73.9	0.1	5.0	0.5		0.5	1.0		3.5
Cd inf µg/L	161	2,561		62.1	58.8		0.10	6.21	0.25	0.25		1.5	4.0	
Cd efl µg/L	139			91.4			0.10	1.30	0.25			0.6		
filt Cd inf µg/L	148	23		80.4	n/a		0.10	4.94	0.25	0.60		1.6	1.1	
filt Cd efl µg/L	117			95.7			0.10	2.50	0.25			1.1		
Hg inf µg/L	162	27		95.1	n/a		0.05	0.98	0.10	0.2		0.7	2.7	
Hg efl µg/L	139			92.8			0.05	1.70	0.10			1.3		
filt Hg inf µg/L	145			97.2			0.05	0.49	0.10			0.5		
filt Hg efl µg/L	116			94.8			0.05	0.12	0.10			0.2		
Cond inf mS	178			0.0	n/a		0.005	1.80	0.075	0.135		1.5	2.2	
Cond efl mS	166	129		0.0			0.001	1.33	0.104			1.2		
Grain size inf µm	42			0.0			1	347	17			1.42		
Grain size efl µm	28			0.0			0	71	10			1.16		
pH inf	181	902		0.0	0.1		3.83	7.98	6.61	7.5		0.1	0.1	
pH efl	167			0.0			4.62	8.23	6.71			0.1		
Temp inf °F	171			0.0			6.5	21.3	11.6			0.2		
Temp efl °F	153			0.0			5.9	23.5	11.8			0.2		
Turb inf NTU	175	38		0.0	n/a		0.2	900	36	17		1.6	1.8	
Turb efl NTU	160			0.0			0.1	961	40			1.6		

Influent Concentration Differences by Location

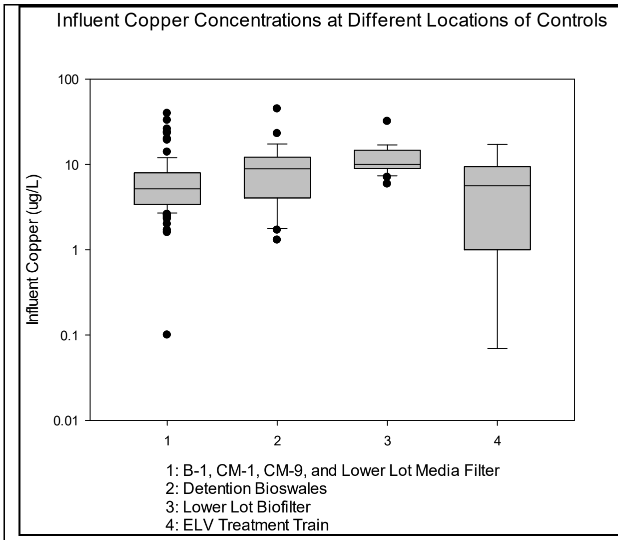
Comparison analyses of SSFL influent stormwater concentrations for the different control locations were also conducted to identify logical groupings of the data for the performance calculations. Similar influent concentrations at all the control types would reduce their effect on differences of the treatment performance. Figure 9 shows box and whisker plots for TSS, TCDD TEQ no DNQ, Cu, and Pb for four groups of controls: 1) B-1, CM-1, CM-9 and upper lot media filter, 2) Southern and Northern detention bioswales, 3) Lower lot biofilter with sedimentation, and 4) ELV treatment train. Of the four main constituents shown here, only copper indicated significant differences, using the Kruskal-Wallis one way analysis of variance on ranks test, between at least one control type and the others. The ELV treatment train influent copper concentrations appear to be relatively low while the lower lot biofilter influent copper concentrations appear to be relatively high. The other constituent influent concentrations had more over-lapping concentration ranges with higher Kruskal-Wallis p values what were not significant.



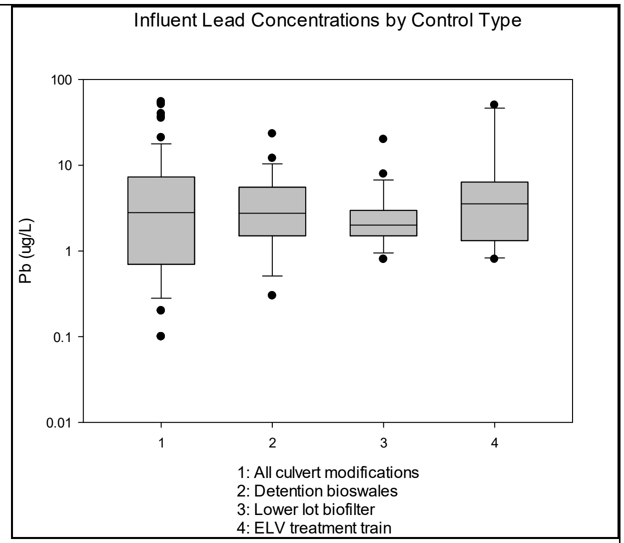
Kruskal-Wallis One Way Analysis of Variance on Ranks P = 0.13



Kruskal-Wallis One Way Analysis of Variance on Ranks P = 0.13



Kruskal-Wallis One Way Analysis of Variance on Ranks P = <0.001



Kruskal-Wallis One Way Analysis of Variance on Ranks P = 0.076

Figure 9. Box and whisker plots of influent concentrations for different stormwater control types.

Filterable Fraction

The filterable fraction of the constituents affects their removal by most stormwater controls. Constituents having large portions of their mass associated with particulates are more effectively removed by conventional sedimentation and filtering processes. Constituents having large amounts of filterable components usually require chemical unit processes (such as chemically-active filtration media). Generally, the effluent filterable fraction is less than the influent filterable fraction indicating the preferential removal of the particulate bound pollutants.

The filterable fraction information is also needed to calculate the particulate strengths of the constituents, as shown in the following subsection.

Table 4 presents the filterable fraction of the influent and effluent stormwater constituents for the stormwater controls located in watersheds affected by historical industrial activities or having large amounts of buildings and roads. Very few effluent cadmium and influent and effluent mercury values were detected, with most of the data being available for copper, lead, and influent cadmium.

Table 4. Filterable Fraction of Influent and Effluent Stormwater from SSFL Stormwater Controls

Influent Location	Percent filterable	Cu inf % filt	Cu efl % filt	Pb inf % filt	Pb efl % filt	Cd inf % filt	Cd efl % filt	Hg inf % filt	Hg efl % filt
B-1 Media Filter	count	21	19	21	19	6		1	6
	min	29.5	33.8	3.5	7.1	48.1		86.7	41.7
	max	88.8	337.5	98.0	96.2	91.7			83.3
	median	68.4	70.6	12.5	22.2	77.4			60.7
	COV	0.31	0.75	1.11	0.74	0.20			0.23
CM-1	count	21	5	26	10	7	1	1	
	min	7.5	22.4	0.8	6.4	13.7	45.5	66.7	
	max	117.6	100.0	100.0	100.0	125.0			
	median	70.0	72.1	12.6	14.4	50.0			

	COV	0.49	0.42	1.15	1.19	0.61			
CM-9	count	29	12	29	12	13	1	1	
	min	11.9	30.0	0.6	5.8	9.1	86.7	76.9	
	max	131.0	107.7	141.4	100.0	112.0			
	median	82.4	88.9	22.4	55.4	77.7			
	COV	0.39	0.27	1.22	0.55	0.49			
Upper Lot Media Filter	count	10	2	10	2				
	min	41.8	86.1	9.0	45.5				
	max	100.0	87.6	100.0	87.7				
	median	71.7	86.9	47.8	66.6				
	COV	0.32	0.01	0.59	0.45				
Southern Detention Bioswale	count	17	18	17	18	18			
	min	31.6	63.6	5.5	16.7	33.6			
	max	93.8	114.1	31.6	100.0	130.0			
	median	61.7	87.6	10.0	46.1	57.2			
	COV	0.26	0.15	0.50	0.55	0.37			
Northern Detention Bioswale	count	7	18	8	15				1
	min	19.3	18.1	19.2	20.0				41.7
	max	176.9	184.6	100.0	138.9				
	median	62.5	88.1	66.3	58.8				
	COV	0.71	0.44	0.46	0.52				
LLBF	count	24	25	24	25				
	min	34.4	26.2	7.3	9.8				
	max	113.6	100.0	227.3	86.2				
	median	83.4	69.3	25.0	26.5				
	COV	0.28	0.28	1.27	0.63				
ELV	count	7	7	10	13				
	min	50.8	52.8	1.3	12.7				
	max	158.2	110.4	28.6	35.6				
	median	75.3	69.8	18.3	24.3				
	COV	0.43	0.25	0.50	0.26				

Table 5 compares the approximate of the SSFL filterable fractions for Cd, Cu, and Pb with results from a few other stormwater studies. The SSFL Cd filterable fraction is larger than for the other locations, as with most of the SSFL Cu filterable fraction values, although not as distinctly. The Pb filterable fraction is generally quite low, as most of the SSFL data indicates, while some of the SSFL locations had much greater filterable fractions of Pb than typical. The upper lot biofilter and the Northern detention bioswale, which both drain a large paved area, have the largest Pb filterable fraction values, while the other locations, including the Southern detention bioswale that drains the same general area, are within the range of the other observed filterable fractions.

Table 5. Filterable Fraction Compared to SSFL Values

	SSFL influent	Morquecho (2005), summary of NSQD ver 1	House, Waschbusch, and Hughes 1993 (WI pond influent from commercial area, about 60 samples)	Pitt, et al. (1998) 550 nationwide samples	Pitt, Lantrip, Harrison, Henry, and Hue. 1999 (87 source area samples, Bham)
Cd	50 to 80%	30%			1 to 36%
Cu	60 to 80%	35%	13%	33%	2 to 86%
Pb	10 to 65%	20%	4%	21%	3 to 7%

Particulate Strength

Pollutant strengths are the contaminant concentrations associated with the particulate matter in the stormwater. Constituents having large particulate strengths, especially for large particle sizes, are more effectively retained by most stormwater controls. Also, the effluent particulate strengths are usually larger than the influent particulate strengths due to the typical great particulate strengths associated with the harder to control smaller particle sizes. These values can also be compared to particulate strengths of potential source area particulates, such as eroding soil, atmospheric deposition, and pavement particulates ("street dirt") to help identify the sources of the contaminants in the stormwater.

Particulate strengths are determined by calculating the pollutant concentrations only associated with the particulates (measured as TSS or SSC) in the stormwater. They are calculated by the following equation:

$$\frac{(total\ conc. - filterable\ conc.)}{particulate\ solids\ conc.}$$

As an example, if the total copper concentration was 50 µg/L, the filterable ("dissolved") copper concentration was 10 µg/L, and the TSS concentration was 150 mg/L, the particulate strength for this sample would be:

$$\frac{\left(50\ \mu\frac{gCu}{L} - 10\mu\frac{gCu}{L}\right)}{150\ mg/L} = 0.26\ \mu\frac{gCu}{mg\ solids} = 260\ \mu g\ Cu/g\ solids =$$

260 mg Cu/kg solids (also = 260 ppm)

Table 6 shows the calculated particulate strengths for the influent and effluent stormwater at the different SSFL stormwater controls. The TCDD TEQ no DNG values were calculated assuming these compounds were all particulate bound, with very low filterable fractions. Few filtered concentrations were available for Hg and effluent Cd, as noted previously, so few particulate strength data are available for these constituents.

Table 6. Particulate Strengths for Influent and Effluent Stormwater Samples for SSFL Stormwater Controls

Influent Location	Effluent Location	TCDD inf part strgth mg/kg	TCDD efl part strgth mg/kg	Cu inf part strgth mg/kg	Cu efl part strgth mg/kg	Pb inf part strgth mg/kg	Pb efl part strgth mg/kg	Cd inf part strgth mg/kg	Cd efl part strgth mg/kg	Hg inf part strgth mg/kg	Hg efl part strgth mg/kg
CM-8	count						10				
	min						20.0				
	max						310				
	median						210				
	COV						0.47				
CM-11	count	12	12								
	min	5.26E-11	1.11E-10								
	max	1.95E-08	1.50E-07								
	median	4.17E-10	1.00E-09								
	COV	1.70	2.84								
B-1 Media Filter	count	21	22	21	16	21	23	6			6
	min	1.08E-10	1.85E-10	19.5	12.5	3.2	3.7	0.2			1.0
	max	2.45E-02	1.08E-05	171	408	462	192	2.2			6.5
	median	7.34E-06	2.25E-06	64.5	60.0	101	66.7	0.5			2.1
	COV	4.55	0.92	0.63	1.15	0.83	0.60	0.88			0.79
CM-1	count	42	34	20	5	24	33	7	1	1	
	min	6.12E-11	5.71E-12	3.6	45.2	31.2	9.9	-1.1	12.0	3.8	
	max	5.53E-05	2.46E-04	314	827	664	1,300	8.6			
	median	1.02E-06	2.28E-07	81.1	100	92.7	245	2.3			
	COV	2.15	3.28	0.77	1.16	1.03	0.95	1.18			
CM-9	count	38	23	37	25	26	27	23	10	1	
	min	6.67E-11	1.00E-10	12.7	23.1	0.0	16.2	0.1	0.9	3.4	
	max	2.40E-05	7.13E-06	5,500	4,300	1,022	1,000	290	160		
	median	4.50E-07	1.06E-08	134	200	138	120	10.0	7.8		
	COV	1.86	2.23	2.22	1.88	1.14	1.19	1.87	1.91		

Influent Location	Effluent Location	TCDD inf part strgth mg/kg	TCDD efl part strgth mg/kg	Cu inf part strgth mg/kg	Cu efl part strgth mg/kg	Pb inf part strgth mg/kg	Pb efl part strgth mg/kg	Cd inf part strgth mg/kg	Cd efl part strgth mg/kg	Hg inf part strgth mg/kg	Hg efl part strgth mg/kg
Upper Lot Media Filter	count	10	2	9	2	10	2				
	min	2.11E-06	3.21E-08	15.8	85.7	0.0	12.1				
	max	8.13E-05	1.32E-05	217	86.2	106	42.9				
	median	1.41E-05	6.61E-06	142	86.0	56.8	27.5				
	COV	1.08	1.41	0.42	0.00	0.63	0.79				
Southern Detention Bioswale	count	17	18	16	15	16	16	16			
	min	4.88E-07	1.08E-10	18.2	55.6	32.7	0.0	2.4			
	max	9.45E-04	7.85E-06	168	1,200	245	259	16.8			
	median	3.71E-06	5.95E-08	110	200	108	83.9	10.1			
	COV	3.01	2.05	0.45	1.11	0.48	0.82	0.40			
Northern Detention Bioswale	count	8	18	6	12	6	13				2
	min	2.00E-10	3.70E-11	31.3	83.3	14.6	11.4				0.0
	max	1.77E-06	1.12E-06	2,132	9,053	453	579				40.0
	median	2.47E-08	2.82E-10	166	1,062	53.1	90.0				20.0
	COV	1.87	4.05	1.71	1.33	1.48	1.07				1.41
LLBF	count	24	25	20	24	23	25				
	min	4.5E-08	9.1E-12	56.3	47.0	44.1	15.4				
	max	2.8E-05	6.6E-06	370.4	465.1	153.8	432.0				
	median	4.1E-06	1.3E-08	101.9	143.3	75.0	90.9				
	COV	1.06	3.12	0.66	0.69	0.38	0.83				
ELV	count	10	13	6	7	9	13				
	min	2.0E-08	2.6E-11	21.1	4.0	60.5	16.7				
	max	5.6E-06	1.2E-06	253.1	48.8	287.6	133.2				
	median	2.8E-07	3.3E-09	113.2	21.4	168.1	47.2				
	COV	1.58	3.38	0.69	0.69	0.34	0.55				

As noted, the effluent stormwater generally has higher particulate strengths, but not for all control locations and constituents. As an example, the upper lot media filter and ELV treatment train show decreased particulate strengths for TCDD, Cu, and Pb. Table 7 lists some historical industrial area particulate strength data for Cu and Pb. As typical for stormwater, there are substantial variations in particulate strengths, usually depending on the source of the particulates. As noted previously, the special studies on-going at SSFL involve collecting and analyzing particulate samples from several locations on and off the site for comparison to the stormwater particulate strengths to indicate potential major sources of the stormwater pollutants.

Table 7. Industrial Area Samples Particulate Strengths

	Copper (mg Cu/kg SS)	Lead (mg Pb/kg SS)
Industrial streets (Pitt 2004 WI and MN sheetflow)	74 (0.4)*	100 (0.3)
Industrial parking (Pitt 2004 WI and MN sheetflow)	83 (0.5)	180 (0.5)
Industrial pvd path (Pitt and McLean 1986, Toronto, Ontario 125μm)	280	460
Industrial NSQD outfalls	281 (0.6)	664 (0.9)
Industrial street dirt (Pitt and McLean 1986, Toronto, Ontario <125 μm)	360	900
Industrial pvd parking (Pitt and McLean 1986, Toronto, Ontario 125μm)	1110	650
Industrial unpvd parking (Pitt and McLean 1986, Toronto, Ontario 125μm)	1120	2050
Industrial roofs (Pitt 2004 WI and MN sheetflow)	n/a	220 (1.1)

* Average and coefficient of variation values (where available).

Treatment Performance

Permit Limit Exceedances

Appendix A contains the summary influent and effluent concentrations for the stormwater control groups and associated reductions. The outfall 008 and 009 watersheds, where the controls described in this paper are located, used multiple tools to reduce the outfall stormwater concentrations, including:

- Source controls
    - Interim soil remediation action (ISRA) soil removal
    - Pavement and building removal
- Erosion and sediment controls and restoration
    - Hydroseeding, mulching, and plantings of native vegetation
    - Dirt road controls
    - Northern channel stabilization controls
- Treatment controls
    - Flow-through media filters (culvert modifications, upper lot media filter, sedimentation basin and biofilter, ELV treatment train, and administration area inlet filters)
    - Detention bioswales with gravel filters
    - Temporary sedimentation areas (at LOX and helipad areas)

The primary purpose of the stormwater controls is to reduce the occurrence of exceedances of NPDES permit limits at the regulated outfalls. Since 2009, many site activities and improvements have resulted in the general reduction of these exceedances. Figure 10 shows how the SSFL outfall permit limit exceedances have substantially reduced over time with the use of stormwater controls and other site improvements. The 2017 – 2018 rain year had the least number of exceedances on record, while the rain total was generally similar to the prior years 2011 through 2016, which all had many more exceedances. The 2016 – 2017 rain year had more exceedances than the 2011 to 2016 rain years, likely due to much greater rainfall. However, when compared to the 2010 – 2011 rain year which had similar rain amounts, the later period had less than half of the former period exceedances.

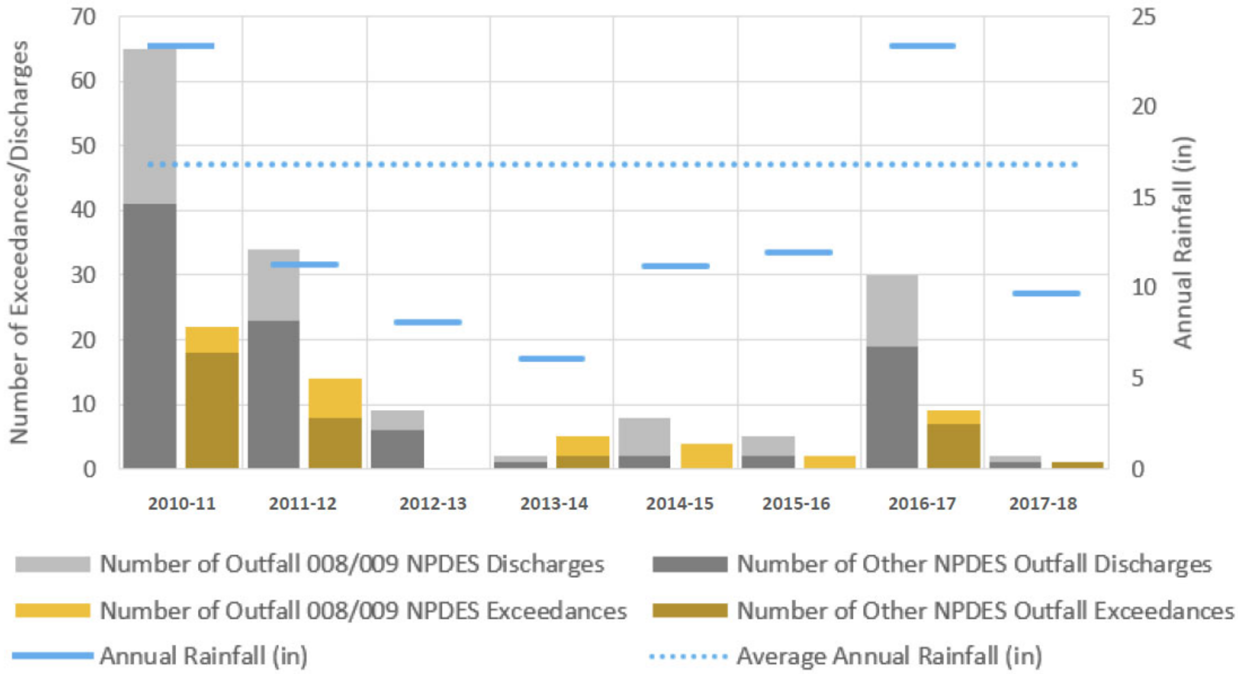


Figure 10. Historical overview of NPDES outfall permit limit exceedances.

Table 8 shows the percentage of influent and effluent samples for several controls that exceeded the permit limit values, along with the ratios of the concentrations to the permit limit values, for all monitoring data from 2009 through 2018. In all cases, the exceedance percentages were all much less for the effluent samples than for the influent samples, while most of the controls also indicate smaller average concentration ratios for the effluent samples compared to the influent samples (except for B-1 Pb and CM-1 TCDD). During the most recent monitoring year having samples (2016 – 2017, which had the largest site rainfall during this period), no effluent sample concentrations exceeded the permit limit values. However, a small number of TCDD values at CM-1 and northern detention bioswale exceeded the permit limit value, but no outfall samples at 009 exceeded the permit limit. Therefore, the site water quality is improving with time and the stormwater controls, and other site improvements, have reduced the permit exceedances to very low numbers.

Table 8. Influent and Effluent Concentrations Compared to Permit Limits

2009 to 2018					
Stormwater Control	Parameter	% of Samples Greater than Permit Limits (5.2 ug/L for Pb and 2.80 x 10^{-8} ug/L for Dioxin)		Average Exceedance Ratio (Exceeding Result to Permit Limit ratio)	
		Influent	Effluent	Influent	Effluent
B-1	Lead	35	9	1.3	1.5
	TCDD TEQ no DNQ	85	68	770	3.9
CM-1	Lead	42	24	4.3	3.1

	TCDD TEQ no DNQ	77	60	13	18
CM-9	Lead	39	28	4.3	2.9
	TCDD TEQ no DNQ	47	26	9.1	3.2
Upper Lot Media Filter	Lead	10	0	1.1	no exceedances
	TCDD TEQ no DNQ	90	50	5.4	2.7
Lower Lot Biofilter	Lead	13	4	2.1	1.1
	TCDD TEQ no DNQ	92	8	4.4	3.9
ELV Treatment Train	Lead	20	0	5.9	no exceedances
	TCDD TEQ no DNQ	30	8	2.3	1.6
Detention Bioswales	Lead	31	0	1.9	no exceedances
	TCDD TEQ no DNQ	73	14	67	2.9

Unfortunately, the November 2018 Woolsey fire covered most of the SSFL site and it is expected that there will be some degradation in the stormwater quality until the site vegetation is restored. All of the SSFL stormwater and critical erosion controls were put back in operation before the first rains which occurred less than a week after the fire. Increased monitoring is now on-going and the results will be used to direct continued site restoration and stormwater control efforts, as it had after the prior 2005 fire that also covered most of the SSFL site.

Line Performance Plots

Appendix B contains grouped line plots for the primary constituents: TSS, TCDD, total and filtered Cu, total and filtered Pb, conductivity, median particle size (few samples), pH, temperature, and turbidity. The stormwater controls were grouped: background culvert modifications, prior industrial area culvert modifications, detention bioswales with gravel filters, lower lot detention and biofilter, and ETV treatment train. These plots link the concentrations for the influent and effluent sampling locations. The lower lot and ELV systems also have an intermediate sampling location between the sedimentation pond or tank and the biofilter or media filter.

Figure 11 is a copy of the line plot for TCDD. Observing the trend lines indicate how effective and consistent these controls are for varying influent concentrations, and also visually separate the performance of the unit processes in the multiple unit controls (low lot detention/biofilter and the ELV treatment train). The summary tables in Appendix A also include the Wilcoxon Signed Rank test p value indicating the statistical significance of the differences in the influent and effluent concentrations, for reference. The background area culvert modifications do not indicate and obvious or consistent reductions, and the Wilcoxon Signed Rank p value is a high 0.45. In contrast the many samples available for the culvert modifications located in prior industrial areas show many downward trends, but large number of over-lapping data lines hinder a clear observation. The Wilcoxon Signed Rank p value is a very significant <0.001 indicating significant differences in the influent and effluent concentrations. The detention bioswale plots more clearly indicate concentration reductions, and the p values is also significant at <0.001. The lower lot and ETV systems also have p values <0.05 also indicating significant differences in concentrations (<0.001 and 0.004, respectively). These plots also indicate that the greatest reductions occur when the influent concentrations are the highest, while little differences are seen when the influent concentrations are low (but in most cases, they are already lower than the permit limit values).

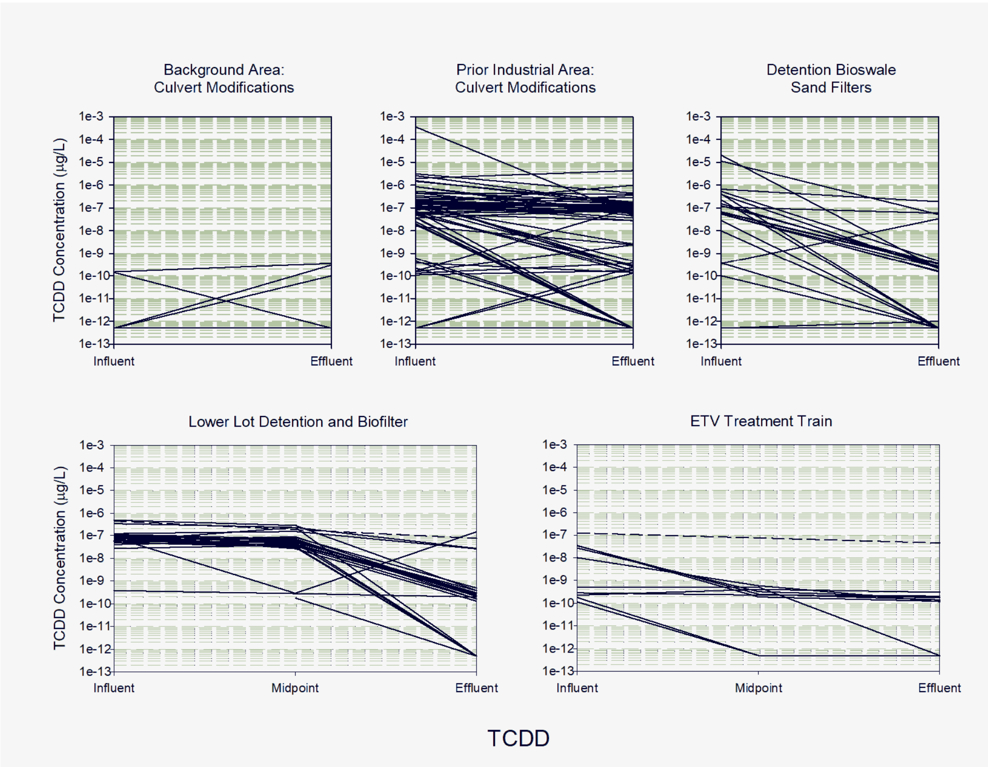


Figure 11. Performance line figures for TCDD.

Most importantly, these plots also provide a visual comparison of the consistency and magnitude of reductions of the concentrations for the different control types. Table 9 shows the Wilcoxon Signed Rank p values along with some notes on the visual consistency of any trends. Although the culvert modifications were shown to have significant TCDD concentration differences, the changes are not very consistent, with trend lines both increasing and decreasing. This is likely due to the very small footprints of these controls compared to the drainage areas, with associated very short contact times of the stormwater with the media. The significant p results are also affected by the large number of observations for these culvert modifications. In contrast, the detention bioswales are very large compared to their drainage areas, with much greater contact times to provide sedimentation of silt-sized stormwater particulates in the crushed stone material under the swales. The slow infiltration of the stormwater through the surface soils also provides for the capture of stormwater pollutants, compared to under-sized systems, although the longer contact times appear to have resulted in increases in copper, pH, and temperature.

Table 9. Wilcoxon Signed Rank p Values and Comments on Treatment Trends

	background culvert modifications (CM8 and CM11)	prior industrial area culvert modifications (B1, CM1, CM9, and ULBF)	detention bioswales with gravel filters	lower lot detention and biofilter	ETV treatment train

TSS	0.09; inf low (all <100)	**<0.001; high inf; many overlapping trends**	**<0.001; apparent consistent decrease**	0.55; inf low (most <100)	0.074; if low (all <100); consistent reduc in sed tank, but consistent flush out in media
TCDD TEQ no DNQ	0.45; all very low inf	**<0.001; hgh inf conc; appears consistent decrease**	**<0.001; high inf; consistent decrease**	**<0.001; high inf; no change in dry pond, consistent decrease in biofilter**	**0.004; apparent consistent decrease, esp in sed tanks**
Total Cu	n/a	**<0.001; all trends in consistent range**	**0.007; consistent INCREASE**	0.12; all trends in narrow range, apparent slight trend	**0.031; consistent decrease, esp in sed tanks**
filtered Cu	n/a	**<0.001; all trends in narrow range, slight consistent trend**	**0.004; mostly consistent INCREASE**	**0.003; narrow range, slight trend**	**0.014; consistent trend, esp in sed tank**
Total Pb	>0.5; few samples and low concentrations	**<0.001; wide range of overlapping trends**	**<0.001; consistent trend**	0.88; slight trend in dry pond	**0.008; consistent decrease in sed tank. Possible loss in media (but overall reduc)**
filtered Pb	n/a	**<0.001; overlapping trends, apparent trend**	0.063; few obs, inconsistent trends, but high inf large decreases	1.0; apparent decrease in dry sed pond, then increase in biofilter	0.084; consistent but small trend overall
conductivity	0.21; no apparent trends	**0.006; wide band of overlapping trends**	0.053; inconsistent trends	0.086; inconsistent trend in dry pond, consistent INCREASE in biofilter	**0.031; no apparent change in sed tank; consistent INCREASE in media (overall increase)**
median particle size	n/a	0.27; few data, but apparent decrease	0.12; few data, but apparent decrease	0.30; few data, but apparent decrease in biofilter	n/a
pH	0.31; consistent no trend	0.29; many overlapping trends	**<0.001; consistent INCREASE in pH**	0.90; no consistent pattern	0.69; few data, no consistent pattern
temperature	0.47; no consistent trend	0.73; many overlapping trends	**0.008; slight consistent INCREASE**	0.87; apparent decrease in dry pond, possible increase in biofilter	0.94; few data, no apparent trend
turbidity	0.59; no consistent trend	0.46; many overlapping trends	0.11; some increase and some decrease	**0.03; apparent decrease in dry pond, consistent INCREASE in biofilter**	0.30; few data, apparent INCREASES in dry tank and more so in media

The most consistent and lowest stormwater effluent concentrations are associated with properly sized stormwater controls that are able to treat most of the annual flows with minimal bypassing of treatment. Multiple-stage unit process treatment systems can also provide the most consistent levels of treatment for a broad range of constituents having large influent concentration ranges.

Paired Probability Plots

Figure 12 is an example paired probability plot prepared using MiniTab (version 18) that indicates the concentration distributions for influent and effluent (and mid point) for four sets of SSFL stormwater controls. All of the culvert modification data were combined (instead of keeping the background locations separate) as the treatment processes are all the same and combining the background data with the industrial locations expanded the range of influent concentrations. Appendix C includes similar sets of plots for the same four stormwater control groups, for: TSS, TCDD, total and filtered Cu, total and filtered Pb, total and filtered Cd, filtered Hg, conductivity, median particle size, pH, temperature, and turbidity. These plots indicate the relative differences between the influent and effluent concentrations and show the best fit probability line and 95% confidence limits for each distribution. All of these are plotted as log-probability plots, except for pH (which is already a log scale). Also noted on these plots are the Anderson-Darling test statistic and corresponding p value. If the p values are smaller than 0.05, the distribution can be considered to be significantly different from a log-normal distribution (a straight line on these plots). Most of the statistical tests conducted using these data are non-parametric and are less sensitive to the distribution types than parametric tests.

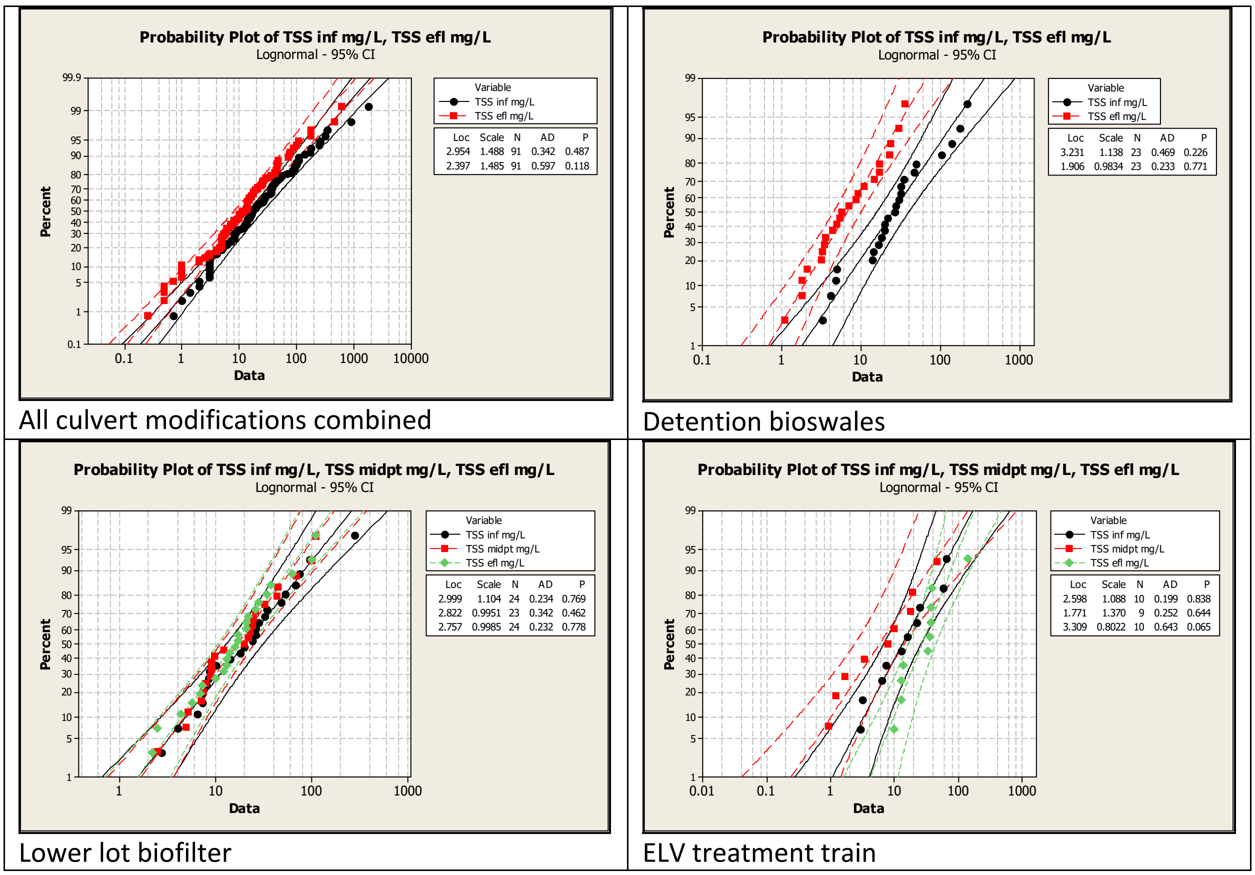


Figure 12. Paired probability plots for TSS for SSFL stormwater control types

Table 10 summarizes the characteristics of the probability plots, indicating the amount of overlapping confidence limits of the probability distributions, the consistency of the concentration patterns, and the Anderson-Darling test results. Generally, the culvert modifications had the narrowest separations (except for filtered Pb and total and filtered Cd), while the detention bioswales had the widest separations (but with increases in Cu concentrations, conductivity, and pH, with treatment).

Table 10. Probability Plot Characteristics

	Culvert Modifications	Detention Bioswales	Lower Lot Biofilter	ELV Treatment Train
TSS	Small separation, log-normal distributions	Wide separation, log-normal distribution	Much overlap, efl lower conc for high inf conditions, log-normal distributions	Some overlap, midpoint consistently lowest concentrations, log-normal distributions
TCDD	Much overlap, failed AD test	Wide separation, failed AD test	Very wide separation, failed AD test	Overlapping distributions, but inf highest conc; failed AD test
Total Cu	Small separation, mixed AD results	Wide separation, but effluent consistently higher, mixed AD results	Much overlapping, but efl consistently lowest conc; log-normal distributions	Wide separations between efl/mid vs inf, and midpoint and efl consistently lower conc than inf; log-normal distributions
filtered Cu	Small separation, efl mostly lower than inf; log-normal distributions	Wide separation, but effluent consistently higher than influent; log-normal distributions	Much overlapping, and efl consistently lower than mid and inf; mixed AD test results	Efl and mid-point similar to each other and wide separation from inf; log-normal distribution
Total Pb	Small but consistent separation; log-normal distributions	Wide separation with efl always less than inf; log-normal distributions	Much overlapping, with midpoint values mostly the lowest; log-normal distribution	Wide separation with mid and efl similar and always less than efl; log-normal distributions
filtered Pb	Wide separations with consistently lower efl; mixed AD test results	Wide separation with efl narrow conc range close to ND; mixed AD results	Few data and large overlaps; log-normal distributions	Much overlapping, with efl generally lowest; log-normal distributions
Total Cd	Wide separations with efl consistently lower; mixed AD test results	Wide separation with efl narrow conc range close to ND; mixed AD results	Few data and large overlaps, efl lowest; log-normal distributions	Only two pairs of data observed; efl both ND
filtered Cd	Wide separations with efl consistently lower; mixed AD test results	Wide separation with efl narrow conc range close to ND; failed AD test	Few data, but efl lowest conc; log-normal distributions	Only two pair of data
Total Hg	Mostly overlapping, but most efl lower than inf; mixed AD results	n/a	n/a	n/a
filtered Hg	Only two pair of data, efl less than inf for both	n/a	n/a	n/a
conductivity	All overlapping; failed AD test	Consistent separation with efl greater then inf; mixed AD results	Mostly all overlapping; log-normal distributions	Inf and mid overlapping and lower than widely separated higher efl concentration; log-normal distributions
median particle size	Mostly separated with efl smaller than inf; log-normal distributions	Mostly separated with efl smaller than inf; log-normal distributions	Efl small thatn similar inf and mid; log-normal distributions	n/a
pH	All overlapping; failed AD tests	Widely separated with inf lower pH than efl pH; normal distribution	All overlapping; mixed AD test results	All overlapping; log-normal distributions
temperature	All overlapping and narrow; log-normal distributions	All overlapping; log-normal distributions	All overlapping; mixed AD test results	All overlapping; mixed AD test results
turbidity	All overlapping and narrow; failed AD test	Overlapping distributions but efl consistently less than inf; mixed AD test results	Overlapping distributions, but efl consistently higher than inf and mid; log-normal distributions	Overlapping distributions; mixed AD test results

Effluent Concentration Equations

Table 11 summarizes the results of the statistical analyses examining the relationships between the influent and effluent concentrations. Three sets of observations were noted, as described below.

1) The constituents having statistically significant removals based on the Wilcoxon Signed Rank Test ($p<0.05$) were further examined using regression analyses (first-order polynomials), with ANOVA and residual analyses (using combinations of Microsoft Excel, Minitab ver 18 and SigmaPlot ver 14). The resulting equation coefficients were examined by ANOVA to determine the significance of the coefficients and the overall equation. If the intercept term was not significant ($p > 0.05$), it was removed from the equation which was then re-evaluated, forcing the regression through the origin. In this case, the percentage reduction is the same for all influent concentrations. With a significant intercept term, low influent concentrations have lower percentage removals than high influent concentrations.

   If the final equation was significant based on ANOVA, residuals were calculated and examined. Equations were examined using $\log_{10}$ transformed influent and effluent concentrations and non-transformed concentration data. The non-transformed equations were used if the residuals met the basic residual requirements (especially an even distribution of the independent variable over the range of concentrations). Other residual analyses tested for the overall random distribution of the residual values, random distribution of residuals vs. time order, and random distribution of residuals vs. calculated effluent concentrations).

   The residuals vs. control type were also examined for the stormwater control types that had multiple examples combined (the culvert modifications and the detention bioswales). The residuals were desired to have consistent behavior with time and for different controls which indicated little likelihood of different individual controls having fundamentally different performance relationships. Direct paired statistical comparisons of the effluent concentrations could be affected by different ranges of influent concentrations for the different controls. Comparing performance equation residuals would identify separate behavior patterns more accurately. Also, consistent residual behavior with time indicated consistent performance with minimal effects associated with accumulation of captured material or consuming the chemical capacity of the media. In all cases, these residual plots did not indicate any performance differences for different individual controls they were grouped with, or with time.

2) The second scenario is when the influent vs. effluent scatterplot indicated a relative constant effluent concentration (also confirmed by the grouped probability plot), and if the paired Wilcoxon Signed Rank test indicated significant differences between influent and effluent concentrations ($p<0.05$). This scenario occurred when the slope coefficient and overall equation were not significant using ANOVA. Under this condition, the effluent is assumed to be the average of all observed effluent concentrations, with no change associated with influent concentrations. The variation of these data are represented by the COV values.

3) The third scenario is when the Wilcoxon Signed Rank test had a large p value (>0.05) indicating that the differences between the influent and effluent concentrations could not be distinguished based on the number of data observations available. In these cases, the table shows the efl = inf.

The detention bioswale equations are all in the second category above, with the average and COV values shown, except for temperature. If the COV is large, the variation of the resulting effluent concentration is also large. The TCDD results have the largest COV values, while the pH values have the smallest COV values (if present, as most of the pH relationships did not indicate any significant differences between the influent and effluent pH values).

Table 11. Equations to Predict Effluent Concentrations for Different Stormwater Controls at SSFL

		TSS	**TCDD**	**Cu**	**filt Cu**	**Pb**	**filt Pb**
B1, CM1, CM9, ULBF, CM8, and CM11 combined	Wilcoxon Signed Rank Test P, inf = efl	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	number of pairs	91	59	55	38	81	18
	ANOVA P for selected equation	<0.001		<0.001	<0.001	<0.001	<0.001
	selected efl equation or values	log TSS efl = 0.791 log TSS inf	1.07E-07 (4.31)*	Cu efl = 1.95 + 0.427 Cu inf	filt Cu efl = 1.89 + 0.348 filt Cu inf	Pb efl = 0.473 Pb inf	filt Pb efl = 0.303 + 0.229 filt Pb inf

		TSS	**TCDD**	**Cu**	**filt Cu**	**Pb**	**filt Pb**
South and North Detention Bioswales combined	Wilcoxon Signed Rank Test P, inf = efl	<0.001	<0.001	0.007	0.004	<0.001	0.063
	number of pairs	23	21	24	24	22	5
	ANOVA P for selected equation						
	selected efl equation or values	9 (0.94)	1.15E-08 (3.08)	18.1 (0.59)	16.0 (0.65)	1.38 (0.51)	1.02 (0.98)

		TSS	**TCDD**	**Cu**	**filt Cu**	**Pb**	**filt Pb**
Lower Lot Biofilter	Wilcoxon Signed Rank Test P, inf = efl	0.550	<0.001	0.120	0.003	0.880	1.000
	number of pairs	24	24	24	24	24	3
	ANOVA P for selected equation				0.004		
	selected efl equation or values	efl = inf	1.11E-08 (2.92) with many NDs	efl = inf	filt Cu efl = 2.83 + 0.469 filt Cu inf	efl = inf	efl = inf

		TSS	**TCDD**	**Cu**	**filt Cu**	**Pb**	**filt Pb**
ELV Treatment Train	Wilcoxon Signed Rank Test P, inf = efl	0.074	0.004	0.031	0.014	0.008	0.084
	number of pairs	10	10	7	10	10	10
	ANOVA P for selected equation	<0.001		<0.001	0.028	0.023 (efl = inf mostly, except for high efl values)	0.001
	selected efl equation or values	log TSS efl = 0.745 log TSS inf	3.51E-09 (3.50) with many NDs	Cu efl = 0.863 + 0.301 Cu inf	filt Cu efl = 1.56 + 0.167 filt Cu inf	log Pb efl = 0.269 log Pb inf	filt Pb efl = 0.840 filt Pb inf

*Average and (COV))

Table 11. Equations to Predict Effluent Concentrations for Different Stormwater Controls at SSFL (continued)

		Cd	filt Cd	Cond	pH	Temp	Turb
B1, CM1, CM9, ULBF, CM8, and CM11 combined	Wilcoxon Signed Rank Test P, inf = efl	<0.001	0.004	0.003	0.290	0.540	0.530
	number of pairs	27	9	87	91	86	84
	ANOVA P for selected equation			<0.001			
	selected efl equation or values	0.19 (0.49) with many NDs	mostly NDs	log cond efl = - 0.320 + 0.773 log cond inf	efl = inf	efl = inf	efl = inf

		Cd	filt Cd	Cond	pH	Temp	Turb
South and North Detention Bioswales combined	Wilcoxon Signed Rank Test P, inf = efl	<0.001	0.042	0.053	<0.001	0.008	0.110
	number of pairs	16	11	20	20	15	20
	ANOVA P for selected equation					<0.001 (efl = inf for most)	
	selected efl equation or values	0.32 (0.60) and many ND	0.47 (1.08) with many NDs	0.29 (0.94)	6.5 (0.09)	Temp efl = 1.06 Temp inf	efl = inf

		Cd	filt Cd	Cond	pH	Temp	Turb
Lower Lot Biofilter	Wilcoxon Signed Rank Test P, inf = efl	0.250	0.500	0.086	0.900	0.870	0.030
	number of pairs	3	2	23	23	22	23
	ANOVA P for selected equation			<0.001 efl = inf with scatter)			
	selected efl equation or values	efl = inf	efl = inf	cond efl = 1.15 cond inf	efl = inf	efl = inf	log turb efl = 0.887 + 0.588 log turb inf

		Cd	filt Cd	Cond	pH	Temp	Turb
ELV Treatment Train	Wilcoxon Signed Rank Test P, inf = efl	0.500	1.000	0.031	0.690	0.940	0.300
	number of pairs	2	2	6	7	7	7
	ANOVA P for selected equation			0.011			
	selected efl equation or values	efl = inf	efl = inf	cond efl = 2.30 cond inf	efl = inf	efl = inf	efl = inf

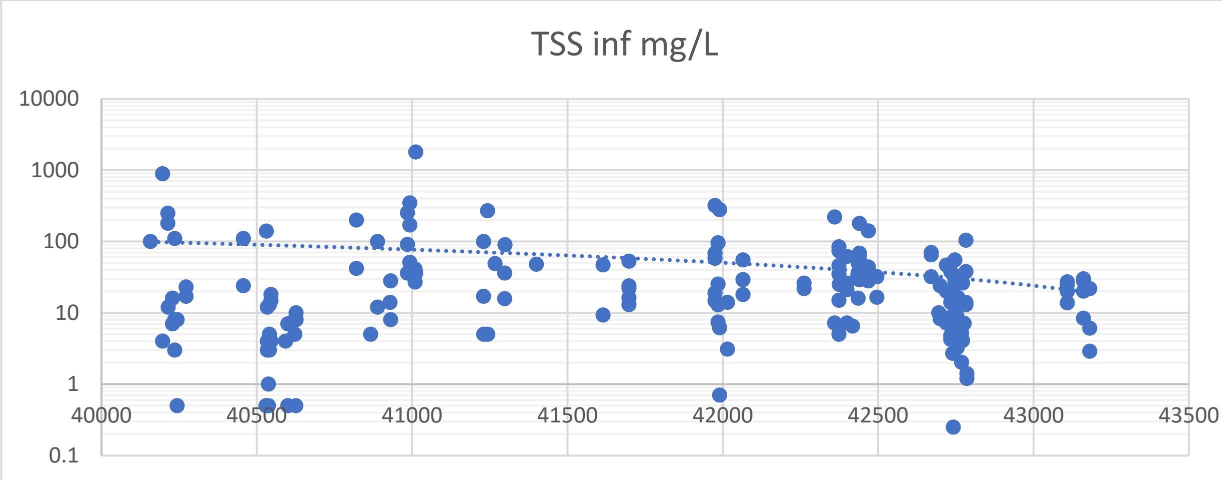
Influent and Effluent Concentration Trends with Time

Effluent concentrations are dependent on influent concentrations, so identification of changes in effluent conditions with time due to degradation of the stormwater controls cannot be directly detected without also considering possible changes in influent concentrations. Therefore, all of the influent data from locations having historical industrial activity (or significant pavement or buildings) were combined and plotted with time (CM-8 and CM-11 background data were not used). Regression analyses with ANOVA was conducted to see if the slope of the trend line was significant, as a quick check to identify possible changes of influent concentrations since the SSFL controls were established. Figure 13 is the plot for TSS, while Appendix D contains similar plots for the other constituents analyzed. The horizontal scale is the days (Julian) while the vertical scales are the concentrations. Significant slope terms in the equations ($p < 0.05$) are noted on the figures. The slope term is significant for TSS ($p = 0.033$), with an overall average decreasing concentration of 0.026 mg/day over the 9 years of monitoring. During this period, the TSS decreased by an overall average of about 85 mg/L due to changes in site conditions. Treatment by the stormwater controls further decreased the effluent concentrations.

Table 12. Observed Concentration Trends in Influent Samples

Constituent	Significance of Trend	Slope Factor, if Significant (all decreases)	Average Overall Concentration Change over 9 Years
TSS	0.033	0.026 mg/day	85 mg/L decrease
TCDD	0.93		
Total Cu	0.78		
Filtered Cu	0.35		
Total Pb	0.025	0.002 µg/day	6.6 µg/L decrease
Filtered Pb	0.42		
Total Cd	0.35		
Conductivity	<0.001	7×10^{-5} mS/day	0.23 mS decrease
Median particle size	0.41		
pH	<0.001	0.00035 pH units/day	1.1 pH units decrease
Temperature	0.054 (marginal)	0.00048 degrees F/day	1.6^{o}F decrease
Turbidity	0.070 (marginal)	0.016 NTU/day	53 NTU decrease

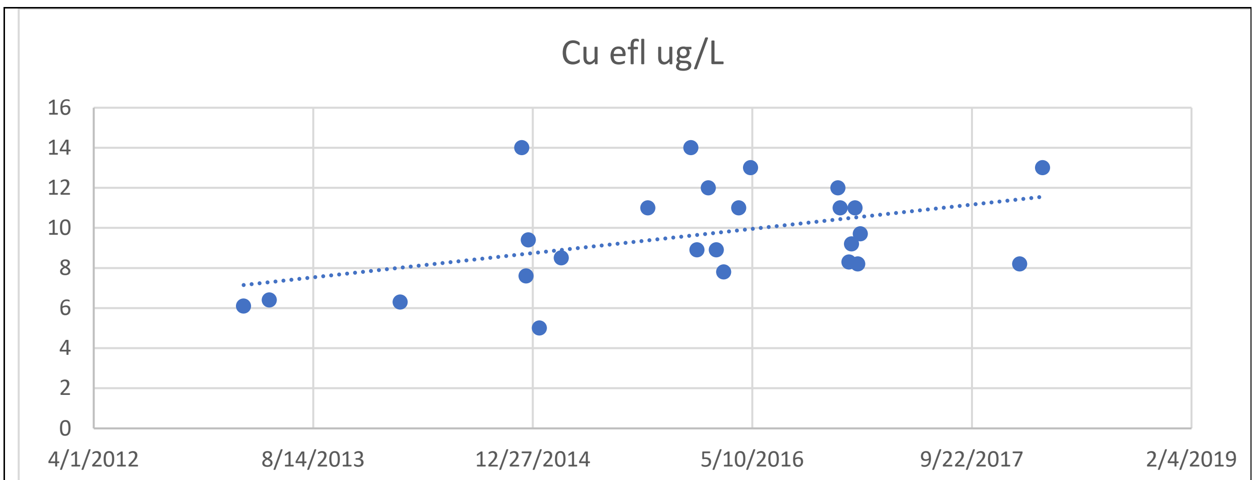
The TSS and turbidity trends may be related to improved erosion control and vegetation re-establishment with time. The TSS and turbidity time series plots show an apparent increase during the first four years of monitoring and then a slower decrease during the remaining five years, mainly with some lower values with the data spread over a wider range compared to a narrower range in the later years.



significant slope with time (-0.026 mg/day; p = 0.033)

Figure 13. Time series plot of all influent TSS data.

Effluent concentration trends were examined for the four treatment groups separately for those constituents that did not have significant influent concentration trends. However, several of the constituents (filtered Pb, total Cd, and median particle size) had too few data observations for these analyses. Therefore, TCDD, along with total and filtered Cu, were analyzed for effluent concentration trends for culvert modifications (having historical industrial activity), the detention bioswales, the lower lot biofilter, and the ELV treatment train. Figure 14 is a time series plot of the effluent concentrations of total copper for the lower lot biofilter, showing a significant increasing concentration trend with time. Additional effluent concentration time series plots are also included in Appendix D.



significant increasing slope with time (p = 0.023); 0.0024 ug/day increase

Figure 14. Time series plot of lower lot biofilter Cu.

Table 13 summarizes the significant effluent concentration trends observed for these four control groups and the constituents that did not have any observed influent calculation trends. Filtered Pb, total Cd, and median particle size had too few effluent concentration observations for effluent trend analyses for each control type, although they indicated no significant trends for influent concentrations for all sites combined. The culvert modifications and the detention bioswales had no observed significant effluent concentration trends. The lower lot biofilter system indicated significant increasing total and filtered Cu effluent concentrations with time. The ELV treatment train indicated significant decreasing concentration trends for all three of these constituents with time. It is not known why the lower lot biofilter is indicating increasing trends in effluent copper concentrations with time, especially as the influent concentrations (site wide) were not increasing.

Table 13 Observed Concentration Trends in Effluent Samples

Constituent having no significant influent trends	Significance of Trend	Slope Factor, if Significant (all decreases)	Average Overall Concentration Change over data period
Culvert modifications: TCDD	0.70		
Culvert modifications: total Cu	0.17		
Culvert modifications: filtered Cu	0.74		
Detention bioswales: TCDD	0.21		
Detention bioswales: total Cu	0.72		
Detention bioswales: filtered Cu	0.71		
Lower lot biofilter: TCDD	0.41		
Lower lot biofilter: total Cu	0.024 (significant increasing trend)	0.0024 ug/day increase	4.4 ug/L increase over 5 years
Lower lot biofilter: filtered Cu	<0.001 (significant increasing trend)	0.0046 ug/day increase	8.4 ug/L increase over 5 years
ELV treatment train: TCDD	0.034 (significant decreasing trend)	1.8×10^{-11} ug/day decrease	2.4×10^{-8} ug/L decrease after 4 years
ELV treatment train: total Cu	0.020 (significant decreasing trend)	0.0028 ug/day decrease	4.1 ug/L decrease after 4 years
ELV treatment train: filtered Cu	0.015 (significant decreasing trend)	0.0011 ug/day decrease	1.6 ug/L decrease after 4 years

It is not known why the lower lot biofilter indicated increasing trends in effluent copper concentrations with time, especially as the influent concentrations (site wide) were not increasing. Figure 15 is a plot of the lower lot biofilter influent trends alone, compared to the effluent trends. The influent total Cu did not indicate any significant trend ($p = 0.24$), while the effluent total Cu has a significant increasing trend ($p = 0.024$). This figure indicates much scatter for the influent trends (as typical for stormwater), but with less scatter for the effluent trends (as expected for a well-operating stormwater control). The decreased scatter in the effluent concentration time series allows a greater confidence in the trend compared to the influent time series that has greater scatter.

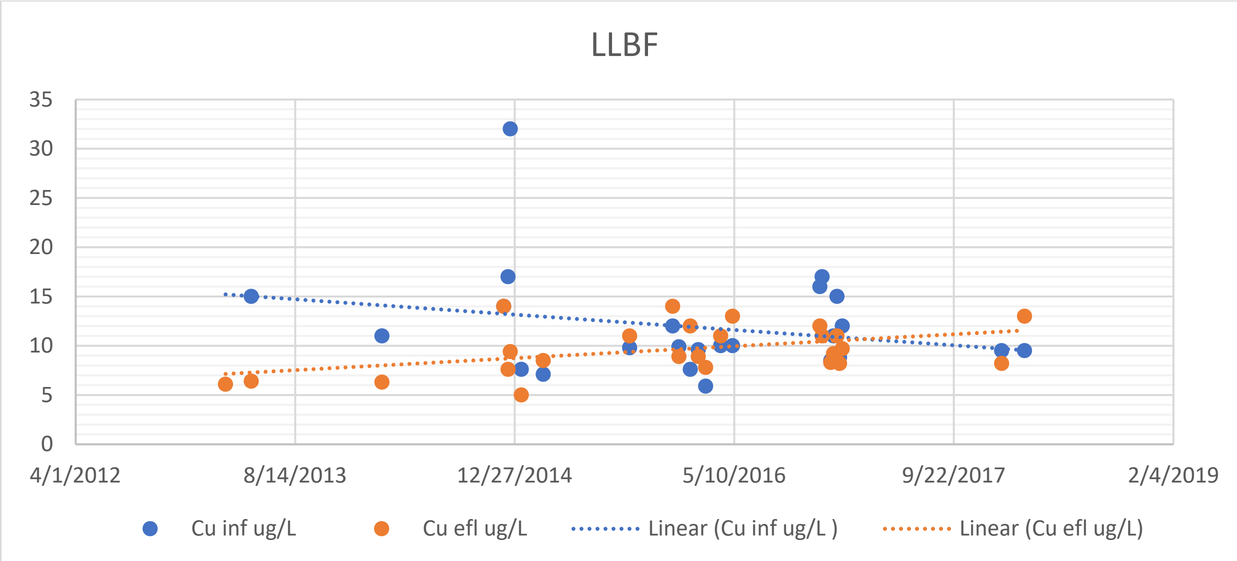
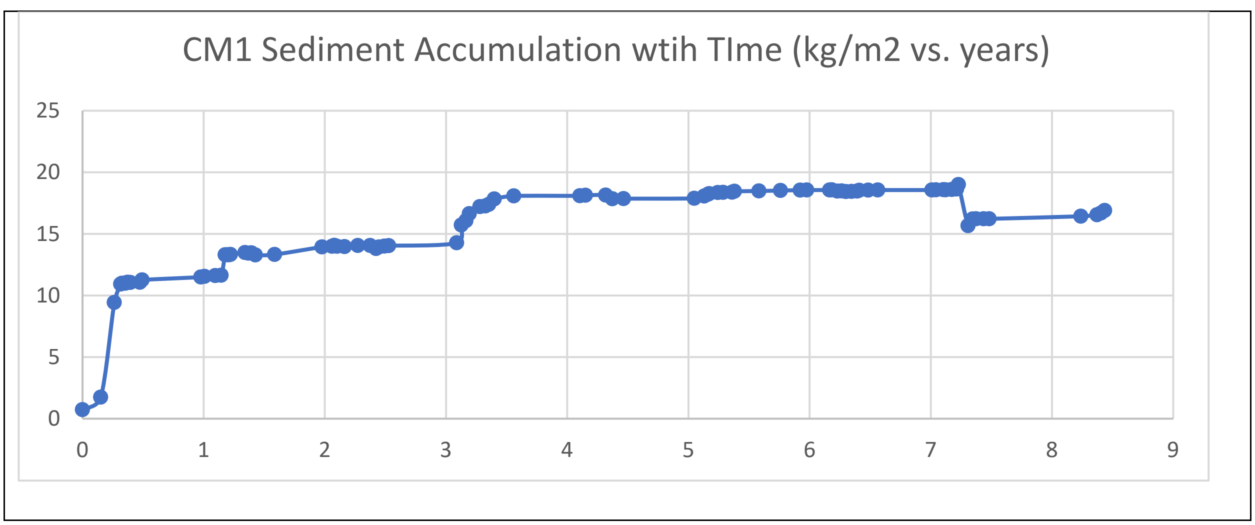
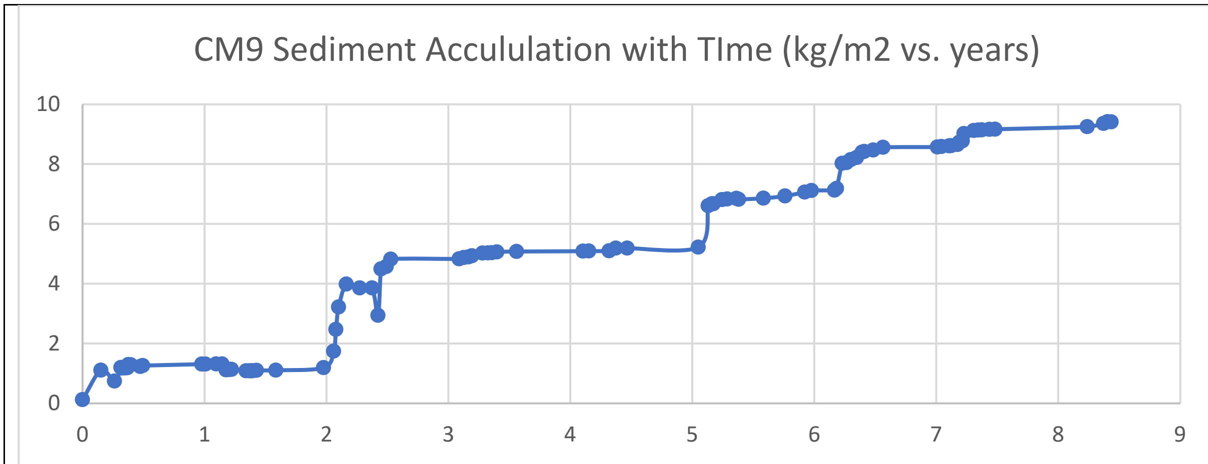


Figure 15. Influent and effluent concentration time series for total copper at the lower lot biofilter system.

Sediment Accumulation with Time

Time series plots of accumulated sediment in several of the stormwater controls were also prepared. SWMM was calibrated for the SSFL 009 watershed outfall data, which was then used to calculate the annual stormwater flow quantity to each of these stormwater controls. SWMM was also used to calculate the fraction of the flow that was treated by the controls, and how much was bypassed during high flow periods. The sediment retention was calculated based on the difference between the influent and effluent concentrations TSS concentrations for each event. This TSS concentration retention was calculated for each event. These were then multiplied by the treated flow volume to obtain the mass TSS retained for each event. These were then used to calculate the accumulative sediment load retained for each control device and plotted as time series, as shown in Figures 16 and 17.





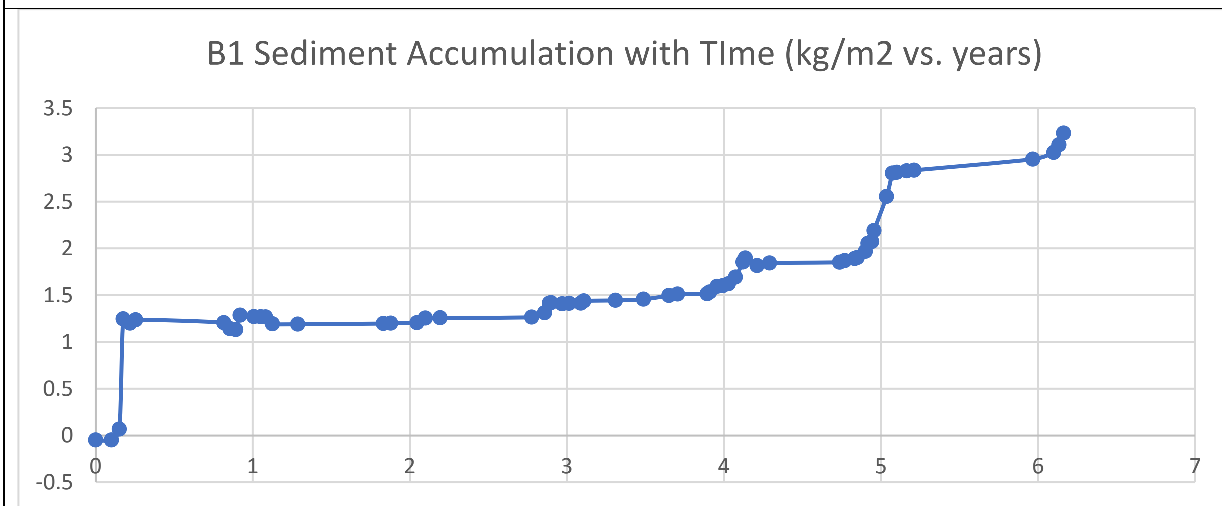
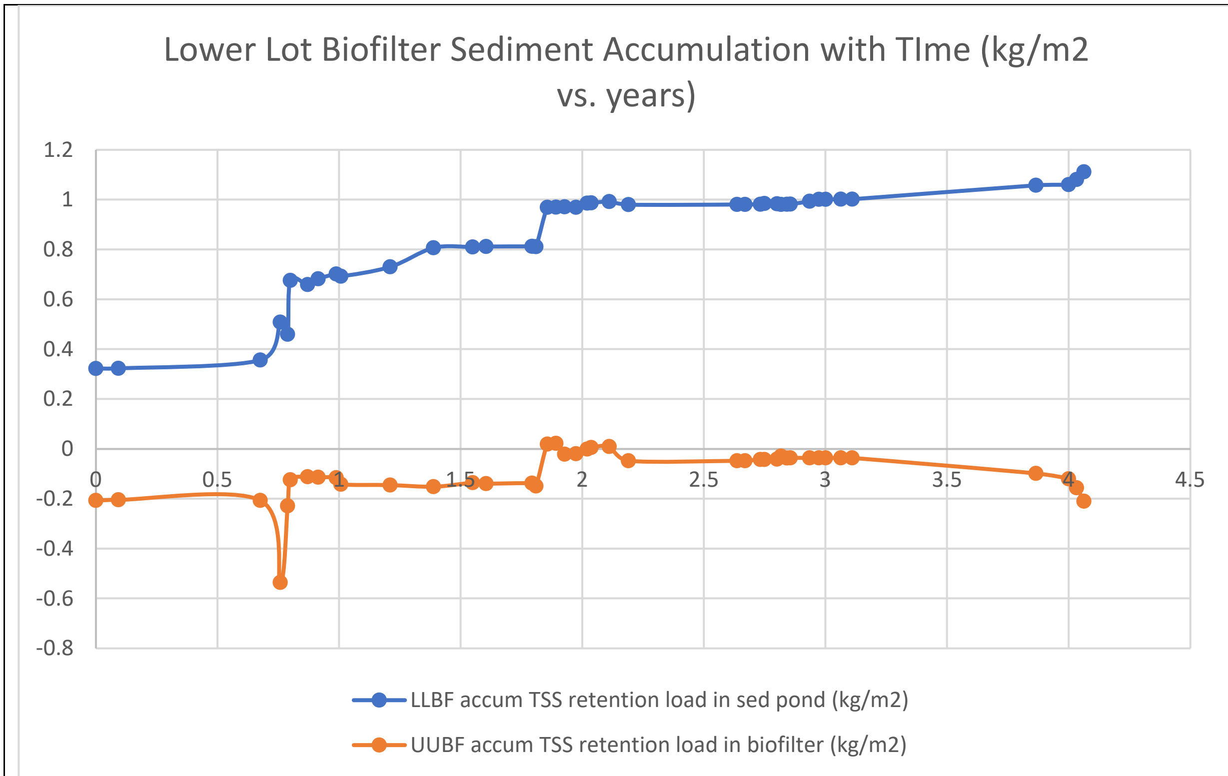


Figure 16. Time series of sediment retention in SSFL culvert modification stormwater controls.



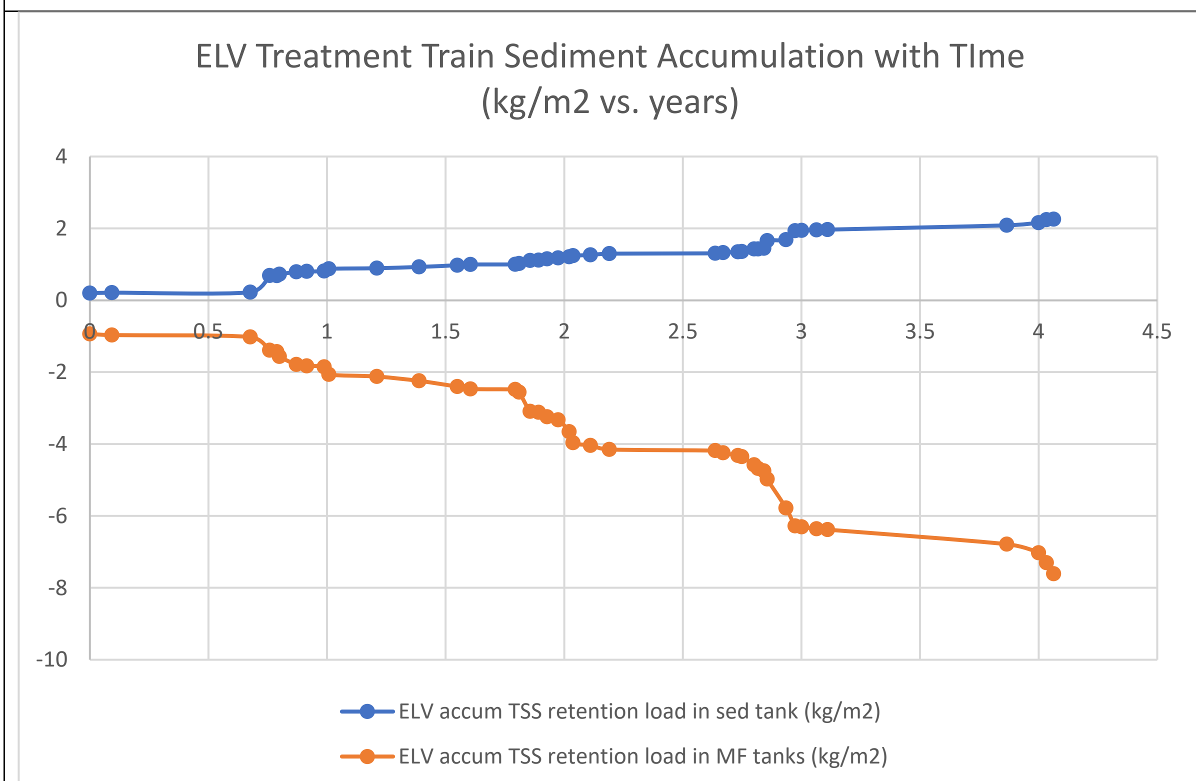


Figure 17. Time series of sediment retention in SSFL lower lot biofilter system and ELV treatment train stormwater controls.

The sediment accumulation for CM-1 shown in Figure 16 indicates a large accumulation of material during the first year of operation. The accumulation then increases until about the fourth year of operation where it levels off, with possible scour of material occurring during the 7th year. The apparent total sediment accumulation capacity for this stormwater control appears to be about 20 kg/m^2 of media surface area. The sediment accumulations at the CM-9 and B-1 locations are also seen to have periodic short periods of large accumulations of sediment, again during the first year of operation at B-1. Both of these culvert modifications appear to be continuing to collect material after 8 years of operation, with total accumulation amounts in CM-9 of about 10 kg/m^2 and 3 kg/m^2 at B-1. With an assumed total capacity of 20 kg/m^2, B-9 may have about another 8 years of operation before needing replacement, while B-1 may have another 30+ years of operation before replacement.

The sediment accumulation time series for the lower lot biofilter system and at the ELV treatment train are shown in Figure 17. These plots show accumulations for the sediment and the biofilter/filter sections of the treatment systems separately as these controls also included a sampling port between the two unit processes. In both cases, the sediment accumulations in the sediment pond/tank sections are only about 1 or 2 kg/m^2 over the four years of operation. The lower lot biofilter shows only small net accumulation changes with time in the biofilter, while the ELV shows large losses of sediment material from the filter, likely due to washout of fines from the media mixture.

The November 2018 Woolsey fire is expected to cause additional mobilization of sediment to the stormwater controls at SSFL until the area becomes well stabilized and re-vegetated. Continued monitoring will indicate any changes in accumulation of material and increased maintenance or replacement of the controls.

As noted previously, the residual analyses for the constituent time series equations did not indicate any break-through of monitored constituents during the monitoring period. One of the features of the media testing and selection was that the sediment accumulation would cause clogging well before break-through of the constituents of concern.

Conclusions

Stormwater biofilters and bioretention controls have been extensively studied and are accepted

Maintenance

Table XX. Stormwater Control Maintenance Schedule

BMPs Implemented	Quantity Implemented	Routine Maintenance	Repair/ Upgrade
Mechanical/Chemical Treatment Systems	2	After major storm events	Annually as needed
Structural BMPs	5	After major storm events	Annually as needed
Structural BMPs with Advanced Media	16	After major storm events	Annually as needed
Fiber Rolls and Silt Fencing	~19 Linear Miles	Annually as needed	Annually as needed
Rolling Dips and Water Gravel Bars	~1400 Linear Feet	Annually as needed	Annually as needed
Check Dams	~1000 Linear Feet	Annually as needed	Annually as needed
Erosion Control, Hydroseed, and Jute Straw Mat	~760 Acres	Annually as needed	Annually as needed

- Expected years to needed media replacement (based on total suspended solids loading) is evaluated annually for each media filter
- Inspections are also conducted 72-hours after each rain event to make note of extended ponding
- CM-1 media replacement is currently recommended per the TSS loading estimate and ponding observations; CM-1 to be reconstructed later this summer
- Other media filters are estimated to have 2 to 30+ years of useful media life remaining

Acknowledgements

References

Additional Information (e.g., NPDES Permit, Panel Presentations, and Technical Reports):
www.boeing.com/principles/environment/santa_susana

Appendix A: Stormwater Characteristics and Treatment Performance

Control Location		Sample Date	TSS inf mg/L	TSS efl mg/L	TSS % reduc	TCDD inf ug/L	TCDD efl ug/L	TCDD % reduc	Cu inf ug/L	Cu efl ug/L	Cu % reduc	filt Cu inf ug/L	filt Cu efl ug/L	filt Cu % reduc
CM8 and CM11	count	22	22	22	18	12	12	2	0	0	0	0	0	0
	% ND		14	23		75	75							
	min	1/20/2010	1	1		1.0E-12	1.0E-12							
	max	3/21/2011	82	33		3.7E-10	3.5E-10							
	median		3	3		1.0E-12	1.0E-12							
	COV		1.57	1.22		2.04	1.99							
	Wilcoxon Signed Rank Test				0.090			0.450						
B1, CM1, CM9, and ULBF	count	126	118	88	74	111	81	56	99	62	56	88	43	38
	% ND		7	9		20	26		1	3		0	0	
	min	12/11/2009	1	1		1.0E-12	1.0E-12		0.1	0.1		1.0	0.9	
	max	3/22/2018	1,800	610		3.6E-04	4.3E-06		39.7	22.0		20.0	8.5	
	median		16	13	37.3	5.9E-08	2.6E-09	73.4	5.2	4.1	20.8	3.2	3.2	19.4
	COV		3.02	2.38		9.91	4.01		0.89	0.68		0.76	0.55	
	Wilcoxon Signed Rank Test				<0.001			<0.001			<0.001			<0.001
Southern and Northern bioswales	count	38	25	36	23	26	36	20	26	36	24	26	36	24
	% ND		4	0		12	44		0	0		0	0	
	min	5/15/2015	1	1		1.0E-12	1.0E-12		1.3	5.8		0.7	3.8	
	max	3/2/2018	220	36		2.1E-05	1.9E-07		44.9	53.0		164.1	47.0	
	median		27	6	62.5	6.6E-08	1.6E-10	99.7	8.9	16.0	-42.5	5.2	12.0	-87.4
	COV		1.24	0.94		3.31	3.08		0.91	0.59		2.50	0.65	
	Wilcoxon Signed Rank Test				<0.001			<0.001			0.007			0.004
Lower Lot Biofilter	count	25	24	25	24	24	25	24	24	25	24	24	25	24
	% ND		0	0		0	28		0	0		0	0	
	min	3/8/2013	3	2		3.8E-10	1.0E-12		5.9	5.0		3.8	1.6	
	max	3/2/2018	280	110		4.7E-07	1.5E-07		32.0	14.0		15.0	12.0	
	median		22	17		7.6E-08	2.2E-10	99.6	10.0	9.2		8.4	7.2	23.3
	COV		1.52	1.08		1.07	2.92		0.45	0.26		0.35	0.40	
	Wilcoxon Signed Rank Test				0.550			<0.001			0.120			0.003
ELV Treatment Train	count	13	10	13	10	10	13	9	9	11	7	10	13	10
	% ND		0	0		0	38		22	27		0	0	
	min	2/28/2014	3	7		1.1E-10	1.0E-12		0.1	0.1		1.6	1.3	
	max	3/22/2018	66	144		1.2E-07	4.4E-08		17.2	5.3		10.1	3.7	
	median		15	15		5.3E-09	1.2E-10	99.3	5.6	2.4	56.4	4.2	2.1	42.8
	COV		1.02	1.13		1.66	3.50		0.88	0.72		0.64	0.30	
	Wilcoxon Signed Rank Test				0.074			0.004			0.031			0.014

Control Location		Pb inf ug/L	Pb efl ug/L	Pb % reduc	filt Pb inf ug/L	filt Pb efl ug/L	filt Pb % reduc	Cd inf ug/L	Cd efl ug/L	Cd % reduc	filt Cd inf ug/L	filt Cd efl ug/L	filt Cd % reduc
CM8 and CM11	count	10	10	9	0	0	0	0	0	0	0	0	0
	% ND	10	20										
	min	0.2	0.2										
	max	11.0	7.0										
	median	0.6	0.3										
	COV	1.39	1.36										
	Wilcoxon Signed Rank Test			>0.5									
B1, CM1, CM9, and ULBF	count	117	88	70	88	43	19	101	65	28	88	43	7
	% ND	10	8		41	56		61	83		85	98	
	min	0.1	0.1		0.1	0.1		0.1	0.1		0.1	0.1	
	max	55.0	39.0		12.0	0.8		1.1	0.5		0.5	0.3	
	median	3.0	1.8	39.2	0.5	0.5	45.9	0.3	0.2	31.9	0.2	0.3	18.2
	COV	1.67	1.63		1.64	0.40		0.69	0.49		0.43	0.35	
	Wilcoxon Signed Rank Test			<0.001			<0.001			<0.001			0.004
Southern and Northern bioswales	count	26	36	22	26	36	5	26	36	17	26	36	11
	% ND	8	14		77	86		31	100		54	94	
	min	0.5	0.5		0.5	0.5		0.3	0.3		0.3	0.3	
	max	23.3	3.0		26.4	5.0		6.2	1.3		4.9	2.5	
	median	2.8	1.3	62.0	0.5	0.5		0.5	0.3	65.9	0.3	0.3	17.9
	COV	1.06	0.51		3.01	0.98		1.43	0.60		1.67	1.08	
	Wilcoxon Signed Rank Test			<0.001			0.063			<0.001			0.042
Lower Lot Biofilter	count	24	25	24	24	25	3	24	25	3	24	25	2
	% ND	0	0		88	48		88	100		92	96	
	min	0.8	0.7		0.3	0.4		0.3	0.1		0.3	0.1	
	max	20.0	5.6		2.5	2.5		0.8	0.5		1.3	1.3	
	median	2.0	2.6		0.5	0.5		0.3	0.3		0.3	0.3	
	COV	1.22	0.54		0.80	0.63		0.42	0.27		0.72	0.76	
	Wilcoxon Signed Rank Test			0.880			1.000			0.250			0.500
ELV Treatment Train	count	10	13	10	10	13	10	10	13	2	10	13	2
	% ND	0	0		0	8		80	92		80	92	
	min	0.8	0.6		0.2	0.1		0.1	0.1		0.1	0.1	
	max	50.2	3.7		1.0	1.3		0.3	0.3		0.6	0.5	
	median	3.6	1.3	34.4	0.5	0.4		0.1	0.1		0.1	0.1	
	COV	1.81	0.58		0.47	0.78		0.34	0.25		0.78	0.61	
	Wilcoxon Signed Rank Test			0.008			0.084			0.500			1.000

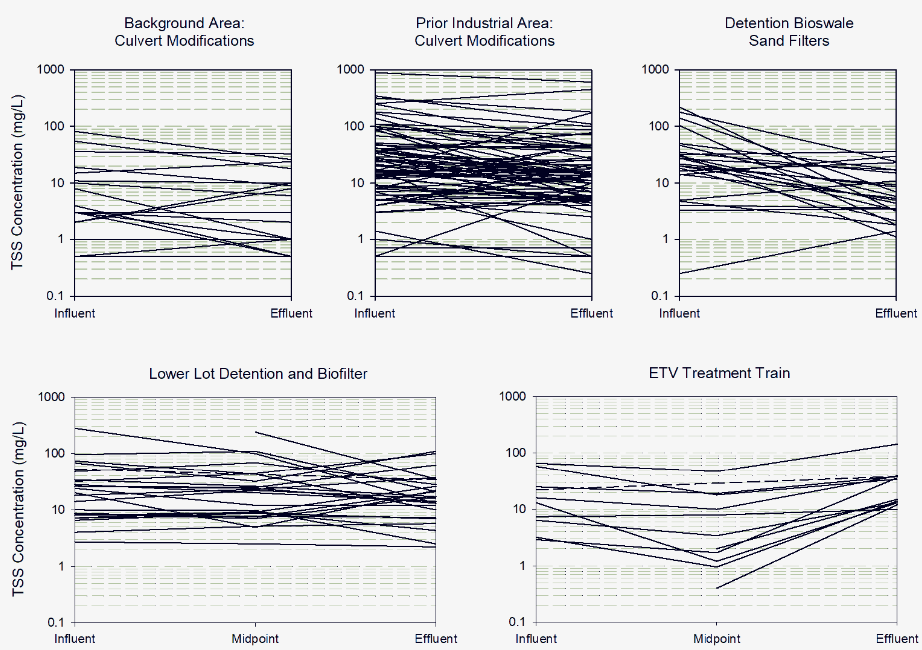
Control Location			Hg inf ug/L	Hg efl ug/L	Hg % reduc	filt Hg inf ug/L	filt Hg efl ug/L	filt Hg % reduc	Cond inf mS	Cond efl mS	Cond % reduc	Grain size inf um	Grain size efl um	Grain size % reduc
CM8 and CM11	count		0	0	0	0	0	0	20	20	19	0	0	0
	% ND								0	0				
	min								0.006	0.001				
	max								0.300	0.133				
	median								0.077	0.078				
	COV								0.73	0.53				
	Wilcoxon Signed Rank Test										0.210			
B1, CM1, CM9, and ULBF	count		102	65	6	87	43	2	105	82	70	16	7	7
	% ND		93	89		95	95		0	0		0	0	
	min		0.05	0.05		0.05	0.05		0.010	0.014		7.1	6.7	
	max		0.98	1.70		0.49	0.10		1.800	0.757		100.7	71.1	
	median		0.10	0.10		0.10	0.10		0.074	0.078	15.4	31.6	10.0	
	COV		0.86	1.57		0.58	0.18		1.52	1.19		0.66	1.08	
	Wilcoxon Signed Rank Test				0.44			0.50			0.006			0.270
Southern and Northern bioswales	count		26	36	0	26	36	0	23	34	19	17	12	9
	% ND		100	94		100	94		0	0		0	0	
	min		0.10	0.10		0.10	0.10		0.005	0.008		7.9	4.9	
	max		0.11	0.24		0.11	0.12		0.913	1.330		347.1	24.6	
	median		0.10	0.10		0.10	0.10		0.064	0.223		15.1	14.5	
	COV		0.02	0.22		0.01	0.05		1.56	0.94		1.59	0.41	
	Wilcoxon Signed Rank Test										0.053			0.120
Lower Lot Biofilter	count		24	25	1	24	25		24	24	23	9	9	8
	% ND		96	100		100	100		0	0		0	0	
	min		0.10	0.10		0.10	0.10		0.006	0.056		1.0	0.0	
	max		0.20	0.10		0.10	0.10		0.400	0.799		16.2	47.7	
	median		0.10	0.10		0.10	0.10		0.110	0.155		13.4	2.9	
	COV		0.26	0.00		0.00	0.00		0.76	0.85		0.37	1.90	
	Wilcoxon Signed Rank Test										0.086			0.300
ELV Treatment Train	count		10	13		8	12		7	7	7			
	% ND		100	92		100	92		0	0				
	min		0.05	0.05		0.05	0.05		0.020	0.042				
	max		0.10	0.10		0.10	0.10		0.053	0.129				
	median		0.05	0.05		0.05	0.05		0.030	0.076	-194.1			
	COV		0.34	0.36		0.37	0.31		0.38	0.40				

	Wilcoxon Signed Rank Test									0.031			

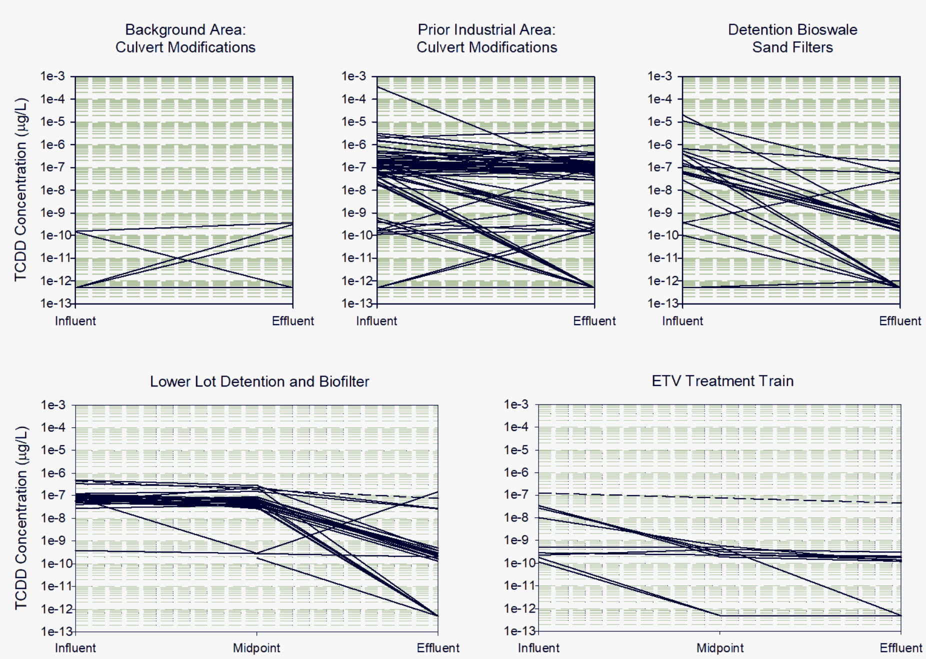
Control Location			pH inf	pH efl	pH % reduc	Temp inf oF	Temp efl oF	Temp % reduc	Turb inf NTU	Turb efl NTU	Turb % reduc
CM8 and CM11	count		20	20	19	18	18	17	17	18	13
	% ND		0	0		0	0		0	0	
	min		5.8	5.9		9.8	9.3		0.5	2.0	
	max		7.7	7.4		17.7	15.4		111.0	112.0	
	median		6.8	6.8		10.9	11.0		13.0	25.1	
	COV		0.07	0.06		0.18	0.15		1.17	0.92	
	Wilcoxon Signed Rank Test				0.310			0.470			0.590
B1, CM1, CM9, and ULBF	count		107	82	72	102	79	69	104	77	68
	% ND		0	0		0	0		0	0	
	min		4.2	4.6		6.5	5.9		0.2	0.2	
	max		7.9	7.9		20.0	21.1		777.0	961.0	
	median		6.6	6.6		11.4	11.6		37.5	47.5	
	COV		0.13	0.11		0.22	0.20		1.44	1.80	
	Wilcoxon Signed Rank Test				0.290			0.730			0.460
Southern and Northern bioswales	count		23	34	20	21	26	17	23	34	20
	% ND		0	0		0	0		0	0	
	min		3.8	5.2		7.0	7.7		2.1	0.1	
	max		7.3	7.9		21.3	23.5		151.9	139.0	
	median		5.2	6.5	-25.1	11.7	12.5	-3.4	44.6	17.6	
	COV		0.17	0.09		0.29	0.31		0.74	1.06	
	Wilcoxon Signed Rank Test				<0.001			0.008			0.110
Lower Lot Biofilter	count		24	24	23	23	23	22	24	24	23
	% ND		0	0		0	0		0	0	
	min		5.4	5.8		7.5	8.0		5.9	11.0	
	max		8.0	8.0		21.3	22.1		900.0	311.0	
	median		7.0	6.9		13.0	13.2		35.2	85.3	-75.6
	COV		0.12	0.08		0.22	0.21		1.87	0.79	
	Wilcoxon Signed Rank Test				0.900			0.870			0.030
ELV Treatment Train	count		7	7	7	7	7	7	7	7	7
	% ND		0	0		0	0		0	0	
	min		6.3	6.1		6.7	6.8		2.3	35.0	
	max		7.7	8.2		13.4	13.0		250.0	191.0	
	median		7.3	7.2		12.2	12.0		72.6	95.2	
	COV		0.07	0.10		0.25	0.21		1.08	0.61	

	Wilcoxon Signed Rank Test			0.690			0.940			0.300

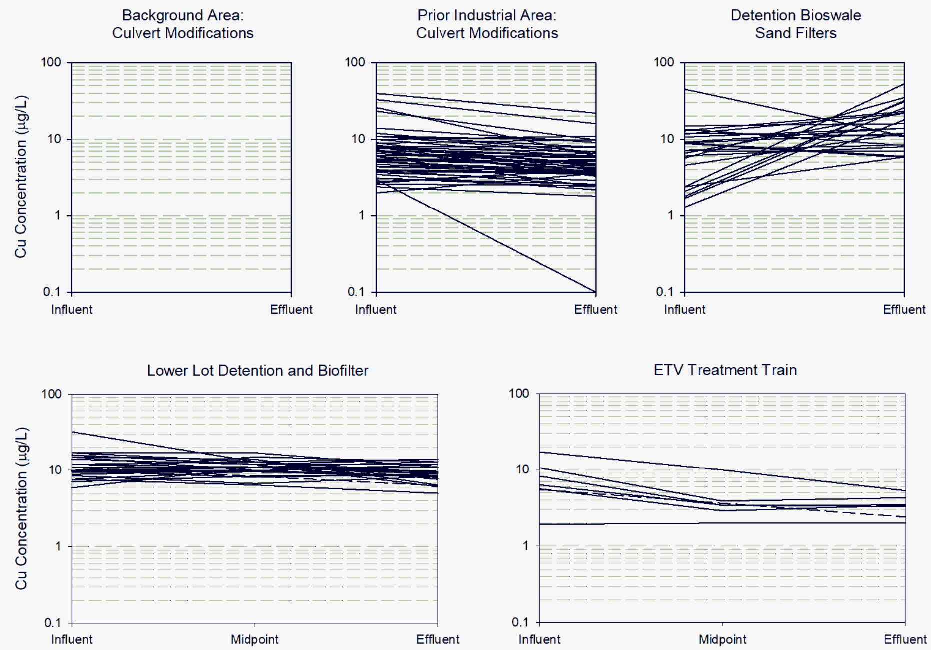
Appendix B: Line Performance Plots



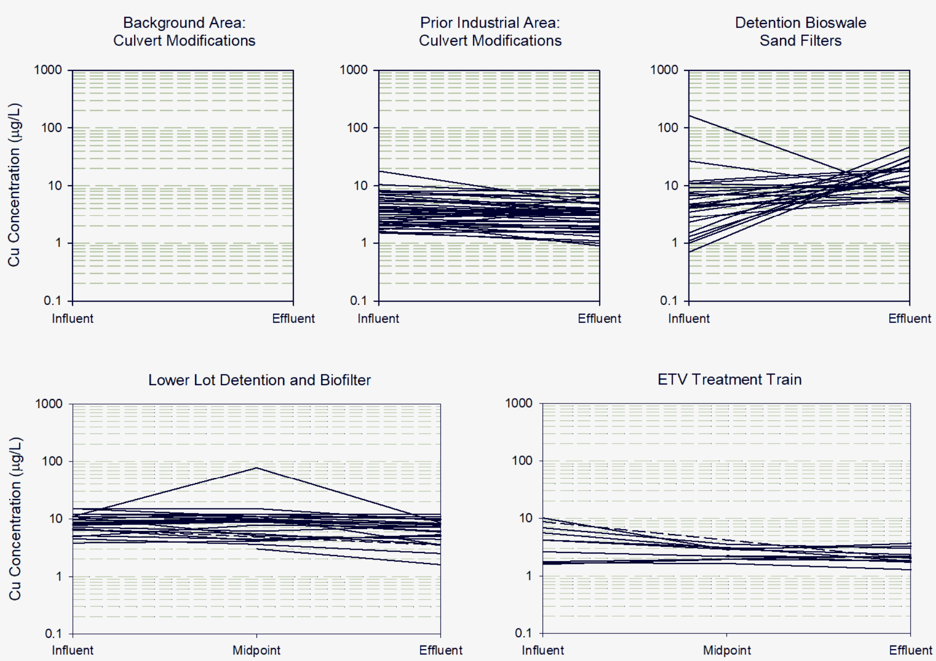
TOTAL SUSPENDED SOLIDS



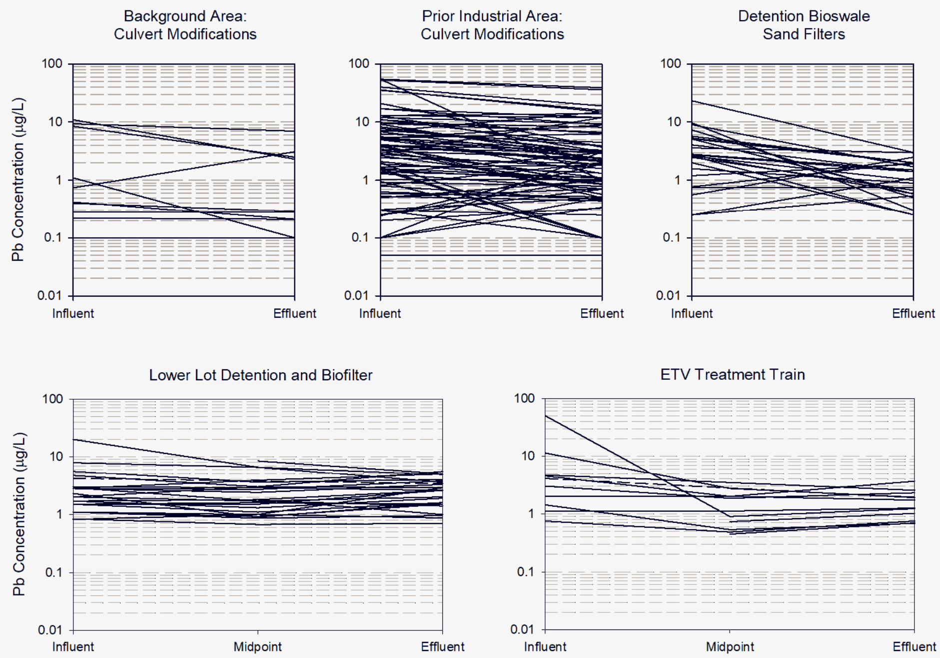
TCDD



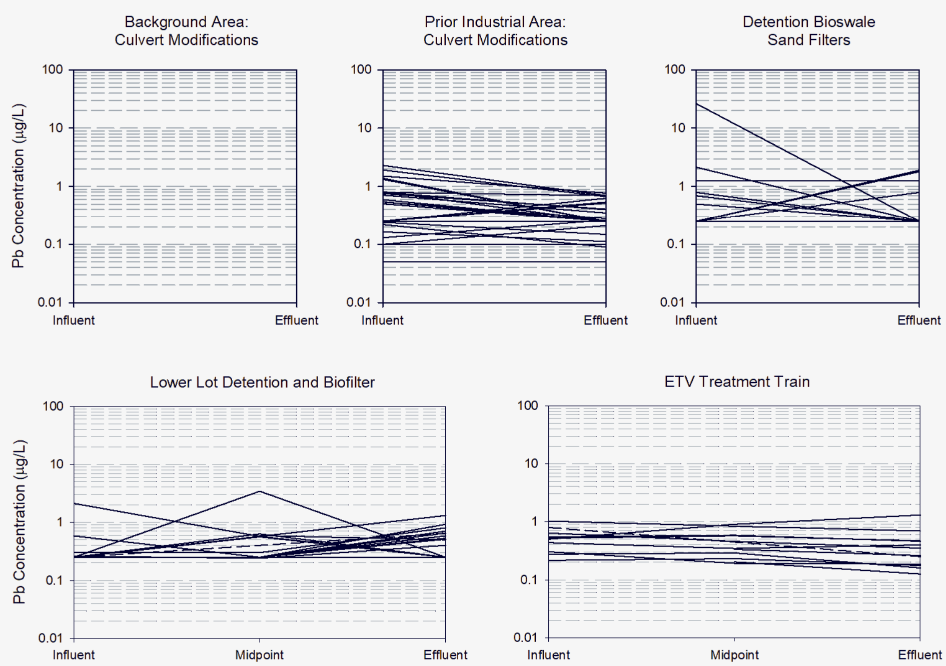
COPPER, TOTAL



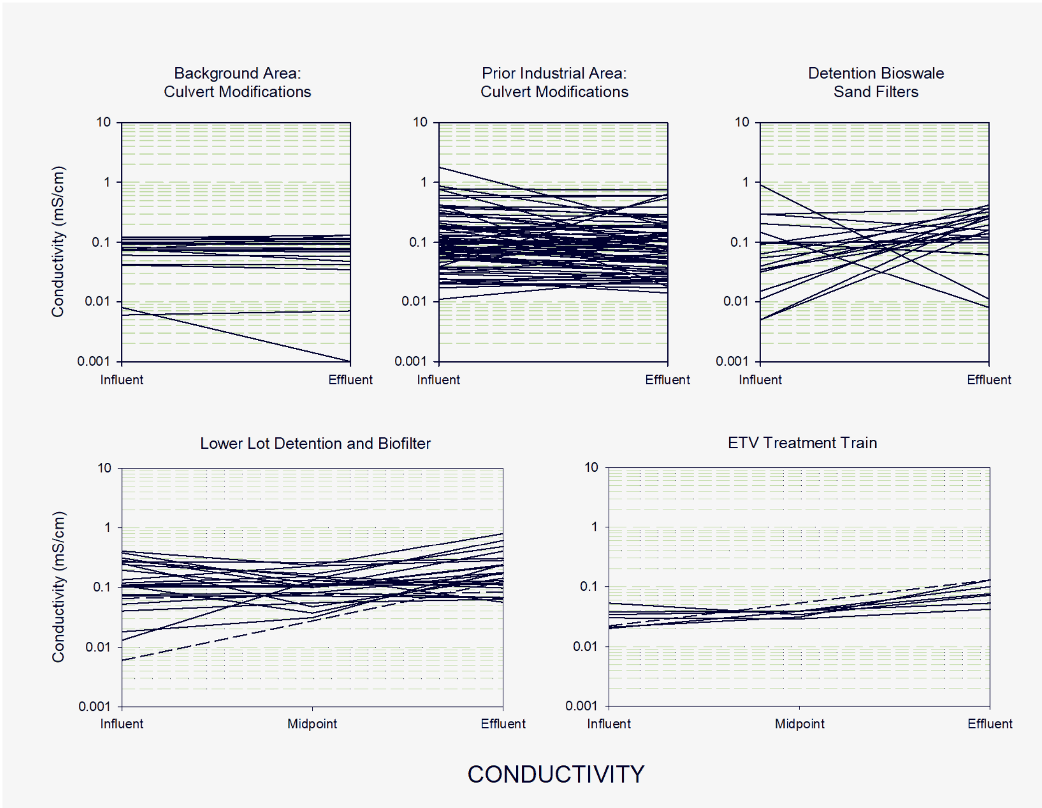
COPPER, FILTERED



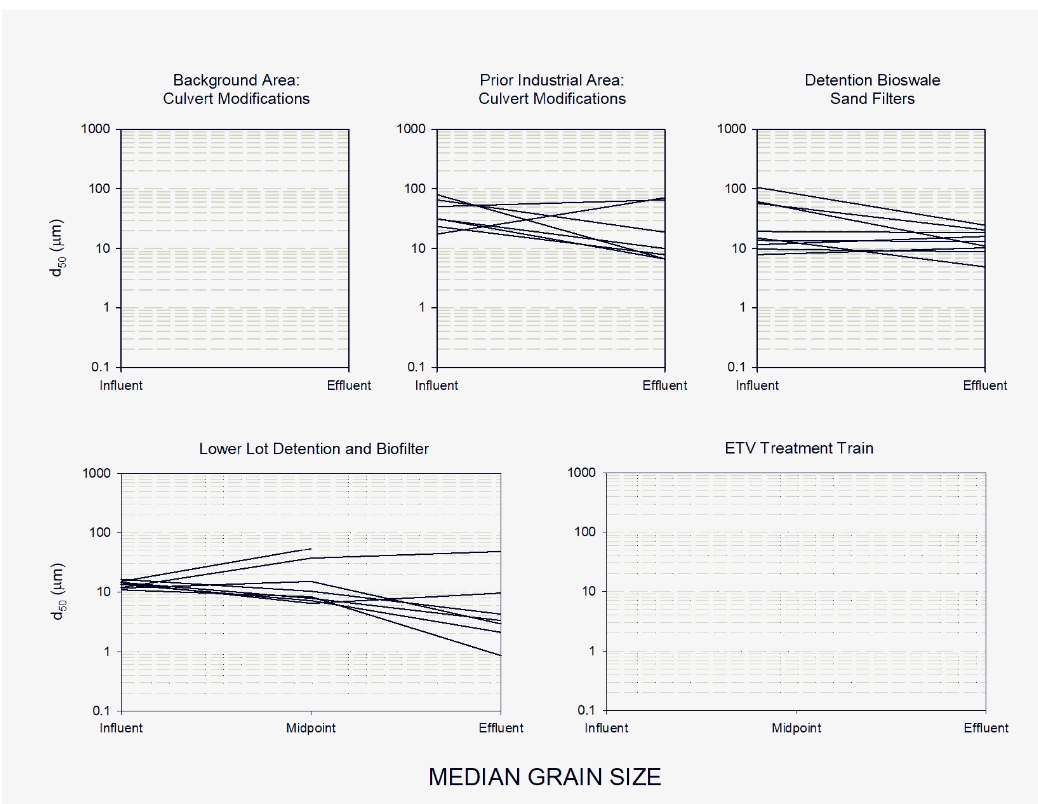
LEAD, TOTAL



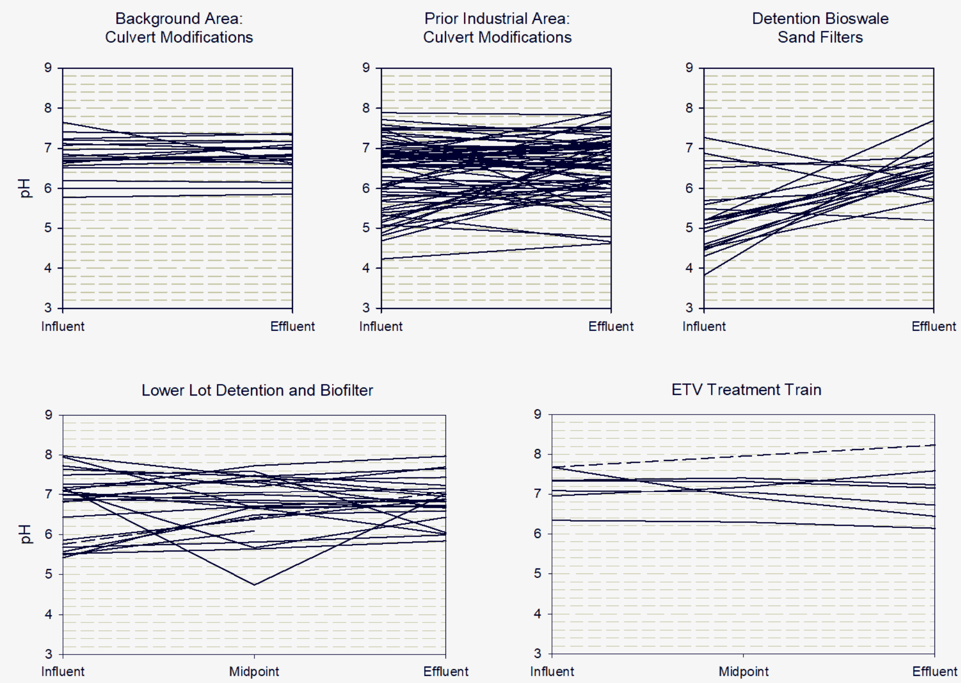
LEAD, FILTERED



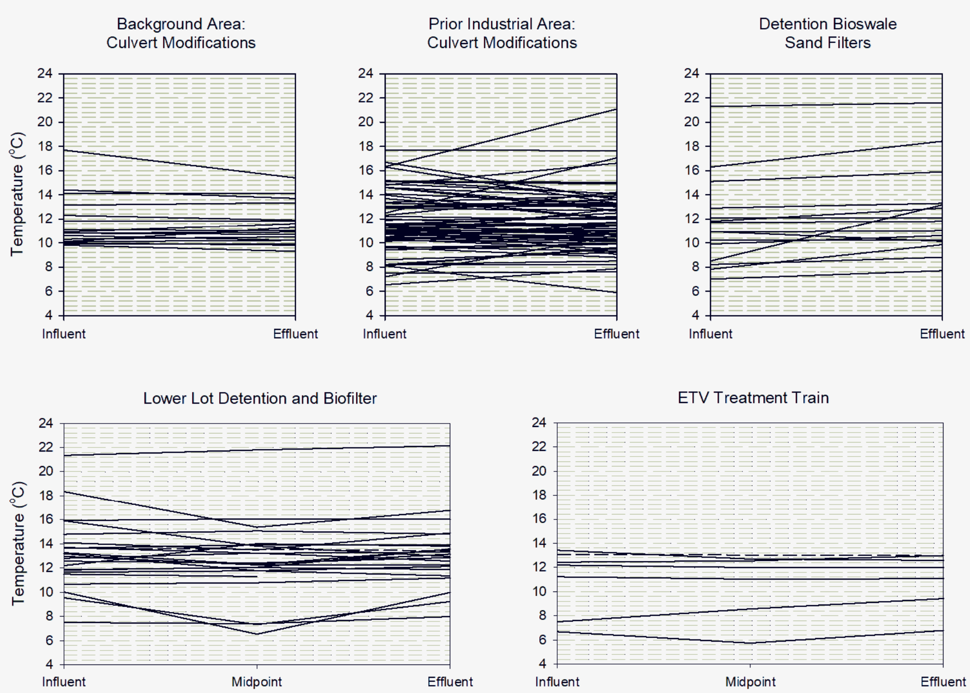
Background Area: Culvert Modifications
Prior Industrial Area: Culvert Modifications
Detention Bioswale Sand Filters
Lower Lot Detention and Biofilter
ETV Treatment Train
Conductivity (mS/cm)
10
1
0.1
0.01
0.001
Influent
Midpoint
Effluent
CONDUCTIVITY



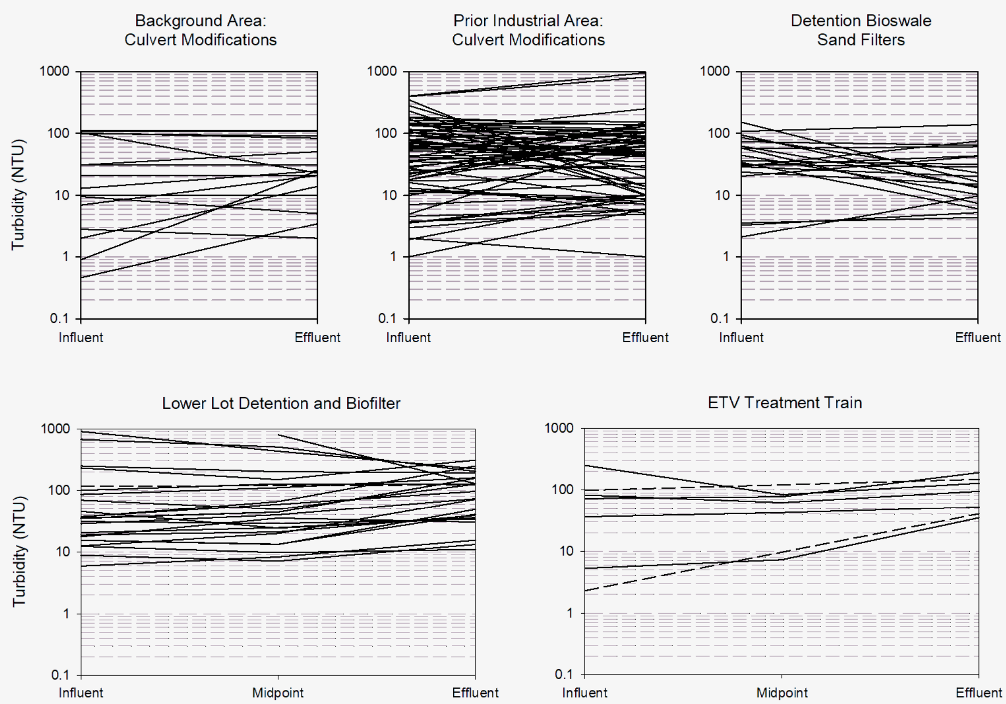
Background Area: Culvert Modifications
Prior Industrial Area: Culvert Modifications
Detention Bioswale Sand Filters
Lower Lot Detention and Biofilter
ETV Treatment Train
d_{50} (µm)
1000
100
10
1
0.1
Influent
Midpoint
Effluent
MEDIAN GRAIN SIZE



pH

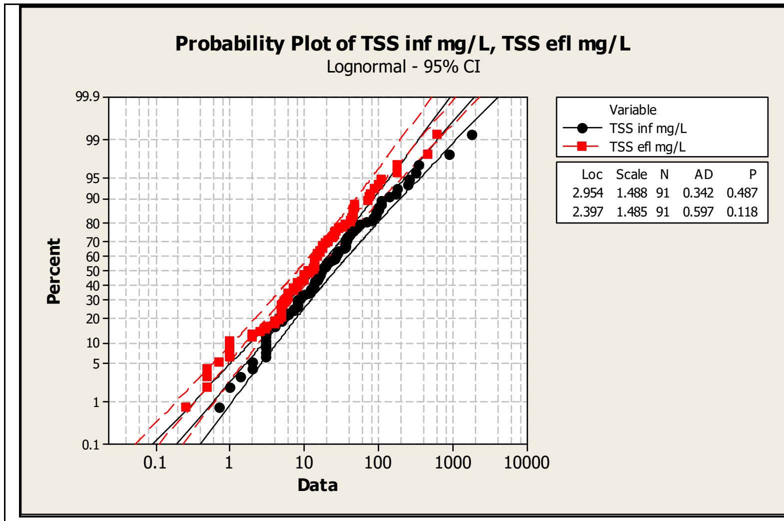


TEMPERATURE

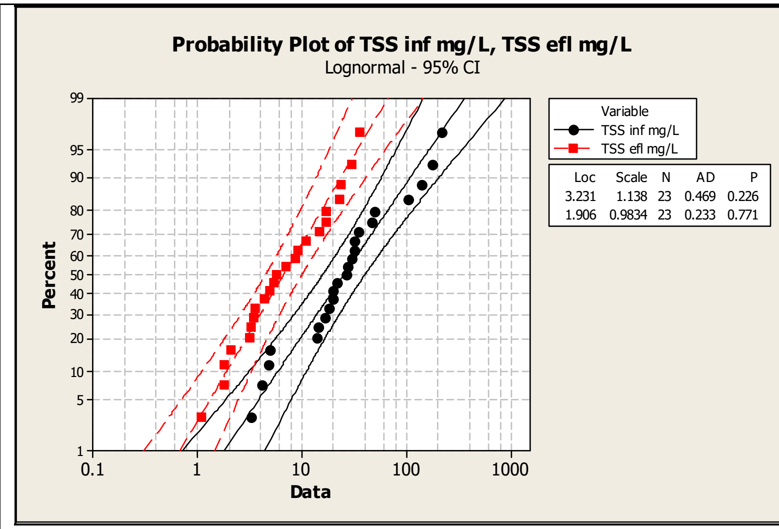

Background Area:
Culvert Modifications
Prior Industrial Area:
Culvert Modifications
Detention Bioswale
Sand Filters
Lower Lot Detention and Biofilter
ETV Treatment Train
Turbidity (NTU)
1000
100
10
1
0.1
Influent
Midpoint
Effluent

TURBIDITY

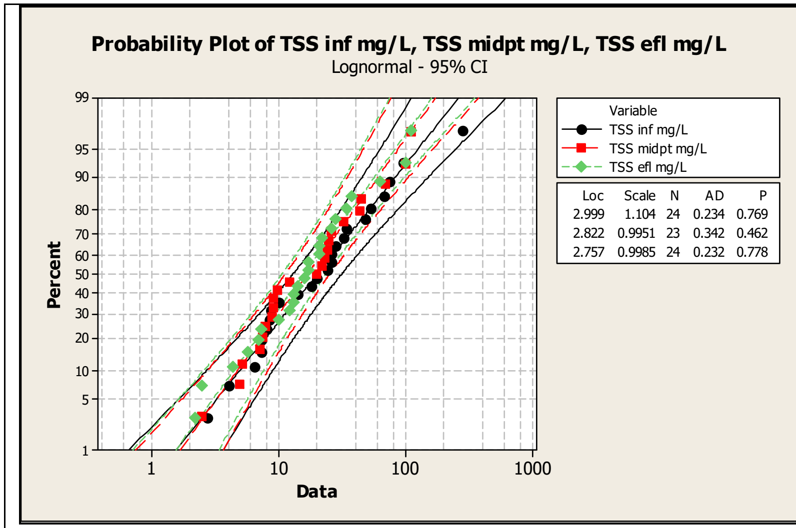
Appendix C: Influent and Effluent Concentration Probability Plots



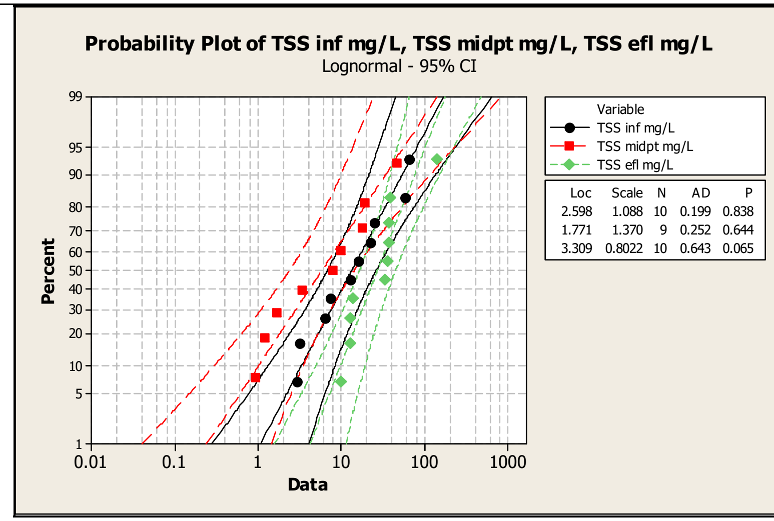
All culvert modifications combined



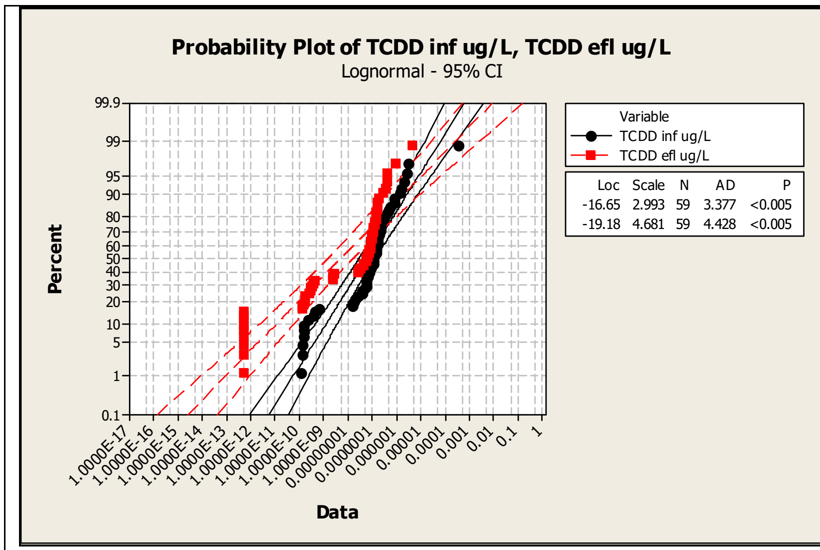
Detention bioswales



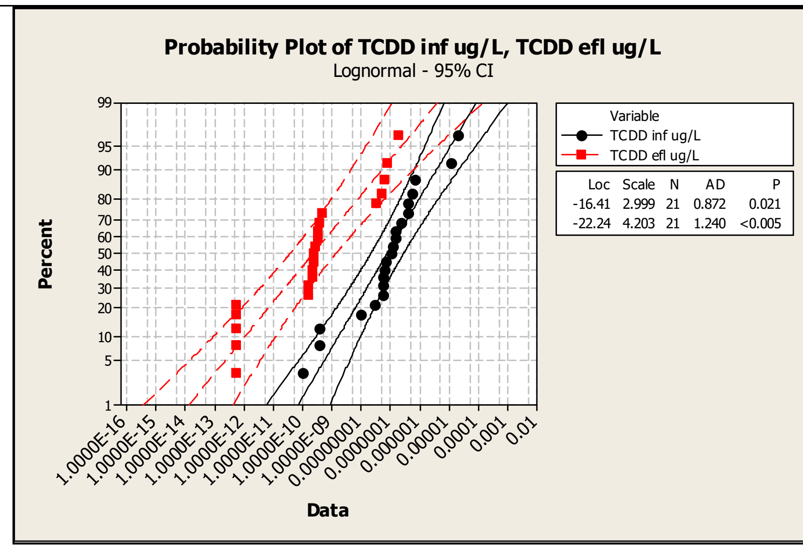
Lower lot biofilter



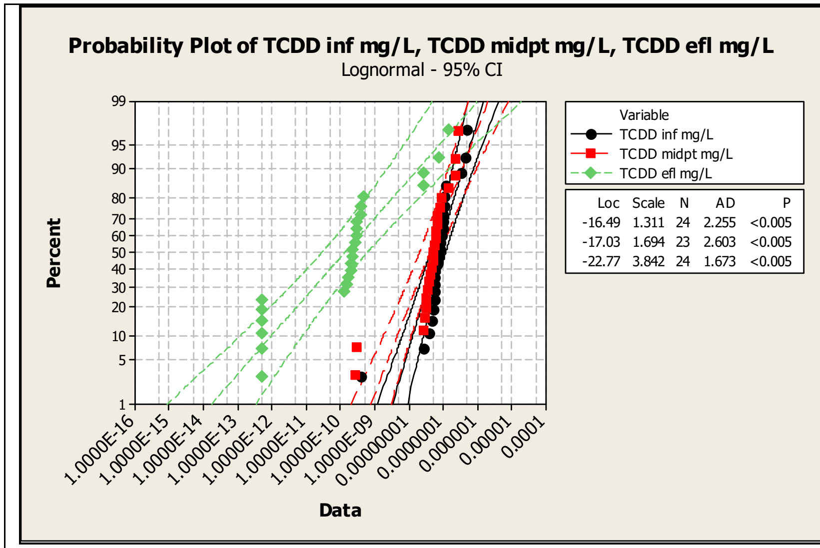
ELV treatment train



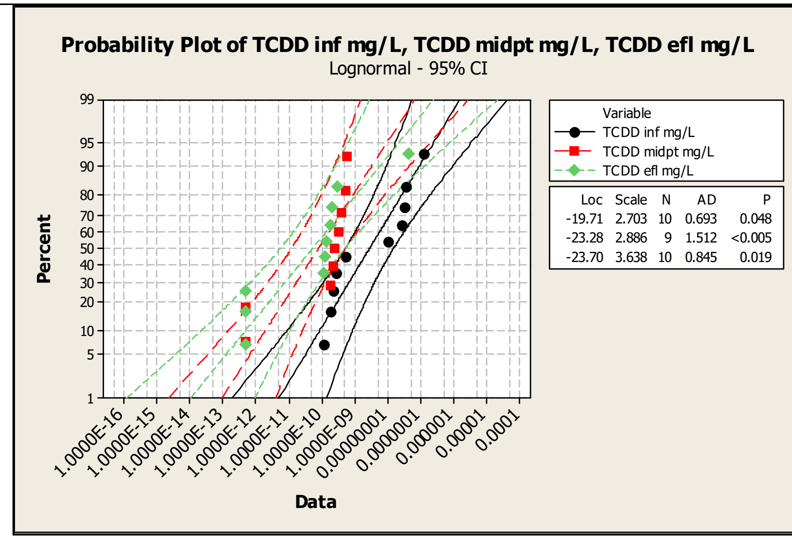
All culvert modifications combined



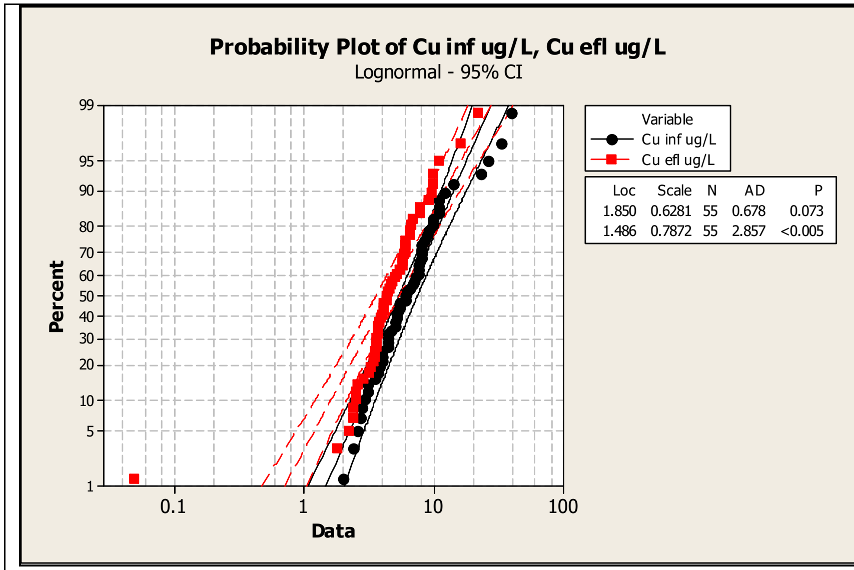
Detention bioswales



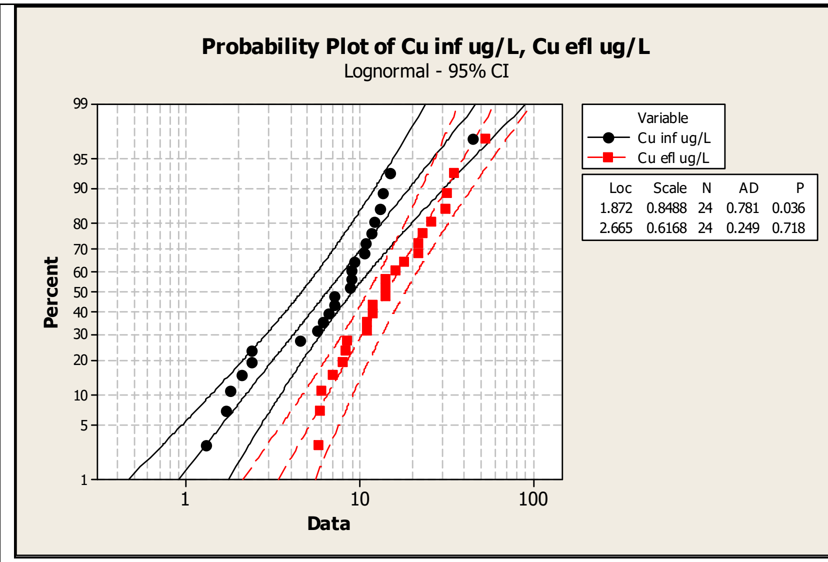
Lower Lot biofilter



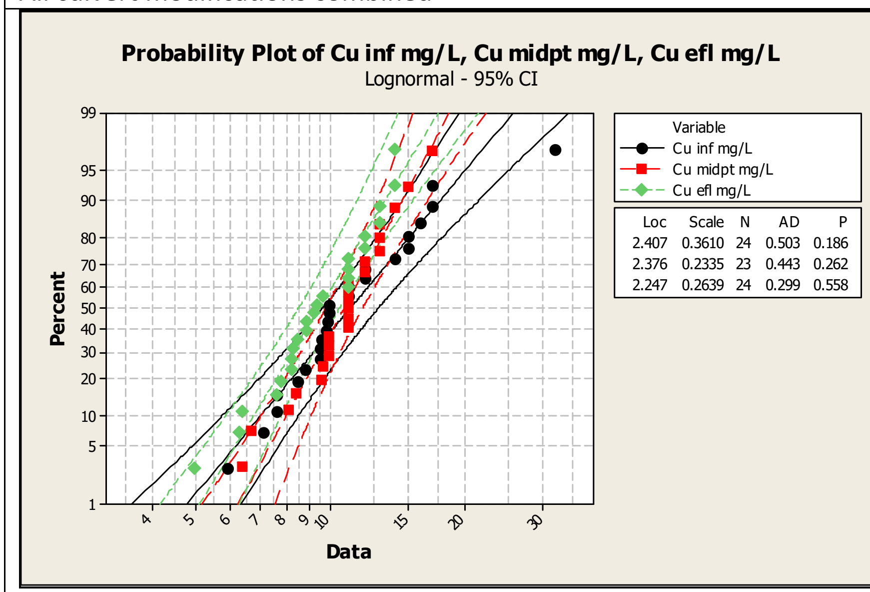
ELV treatment train



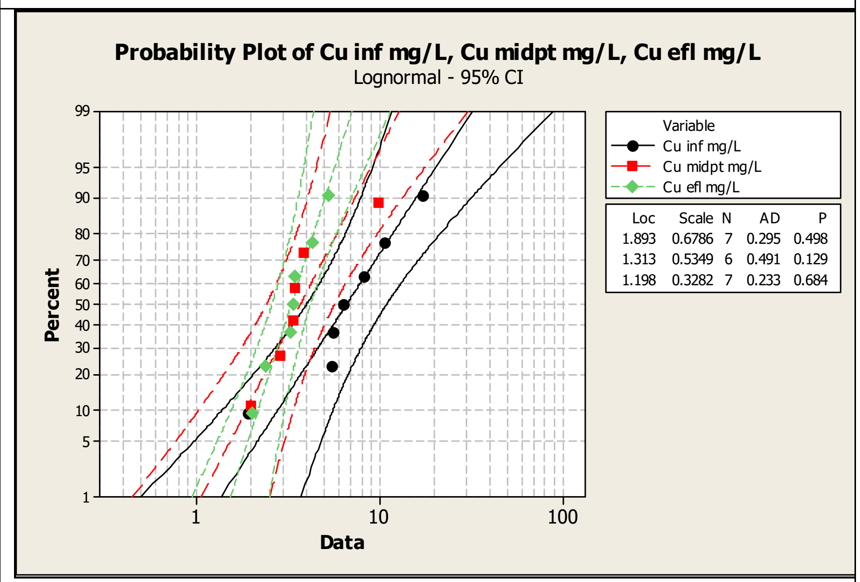
All culvert modifications combined



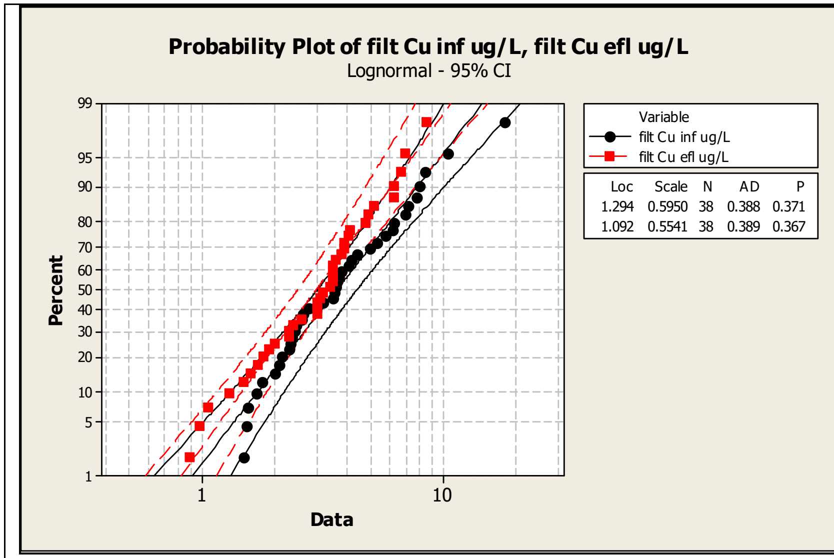
Detention bioswale



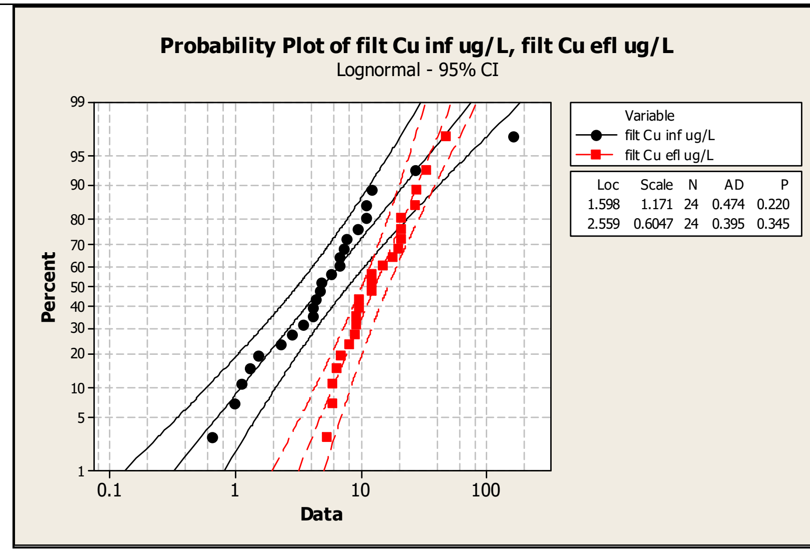
Lower Lot biofilter



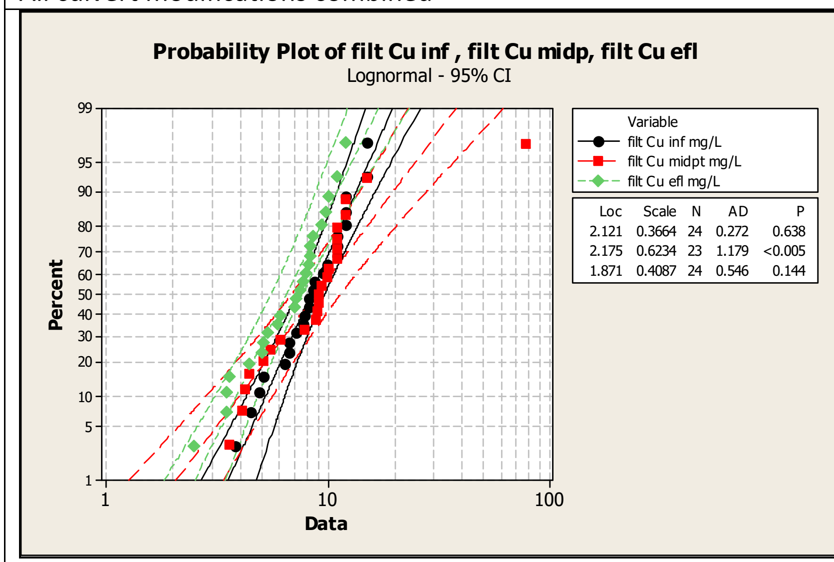
ELV treatment train



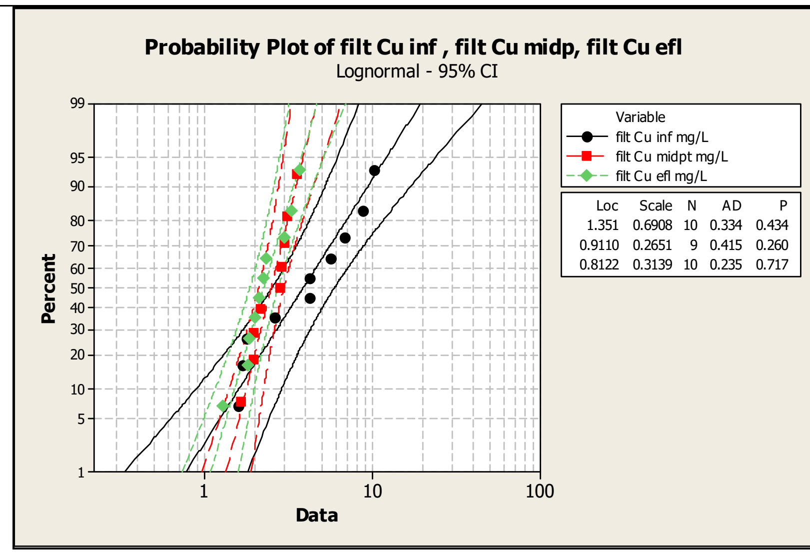
All culvert modifications combined



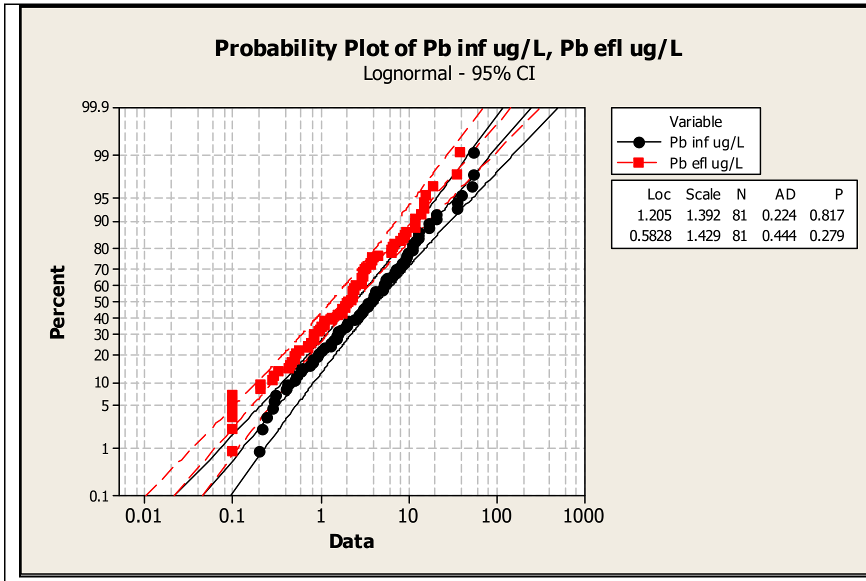
Detention bioswales



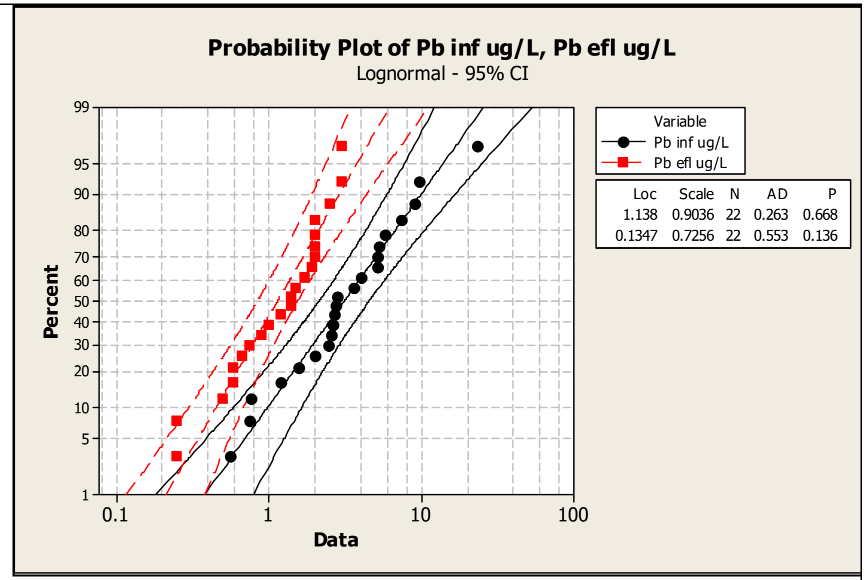
Lower Lot biofilter



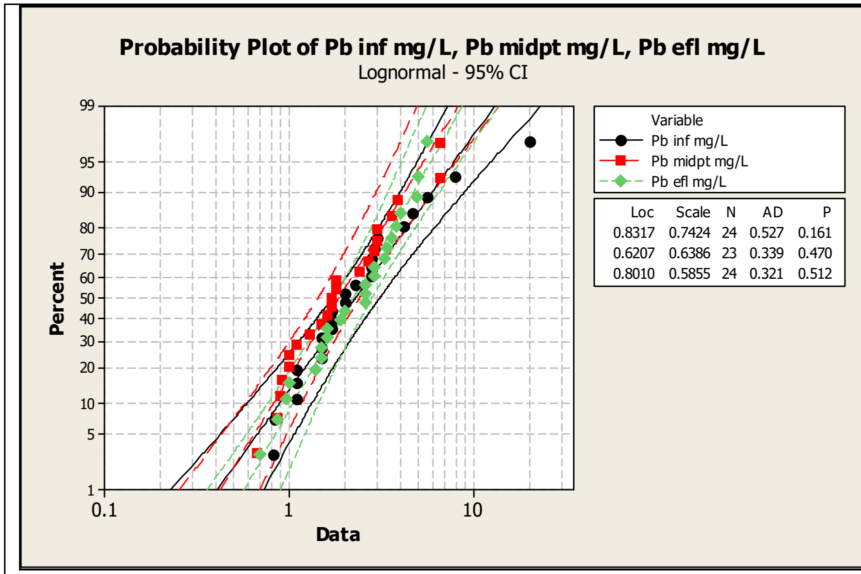
ELV treatment train



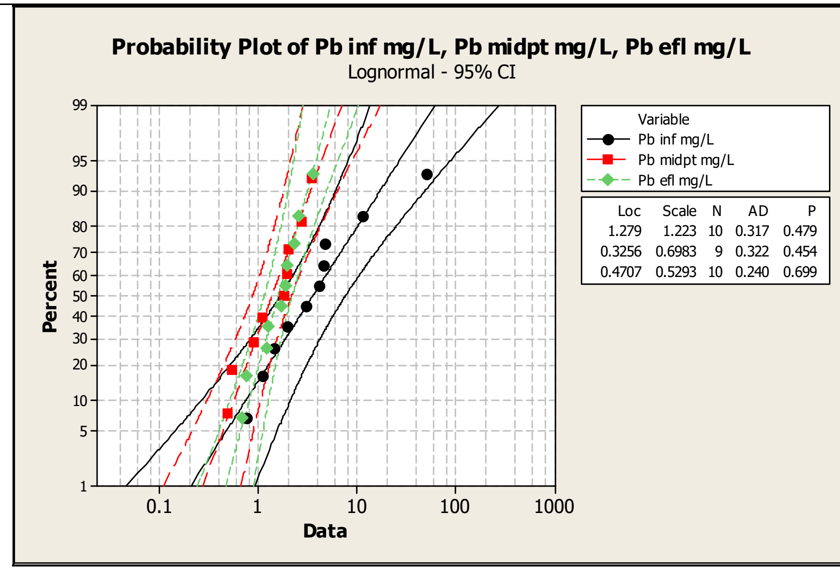
All culvert modifications combined



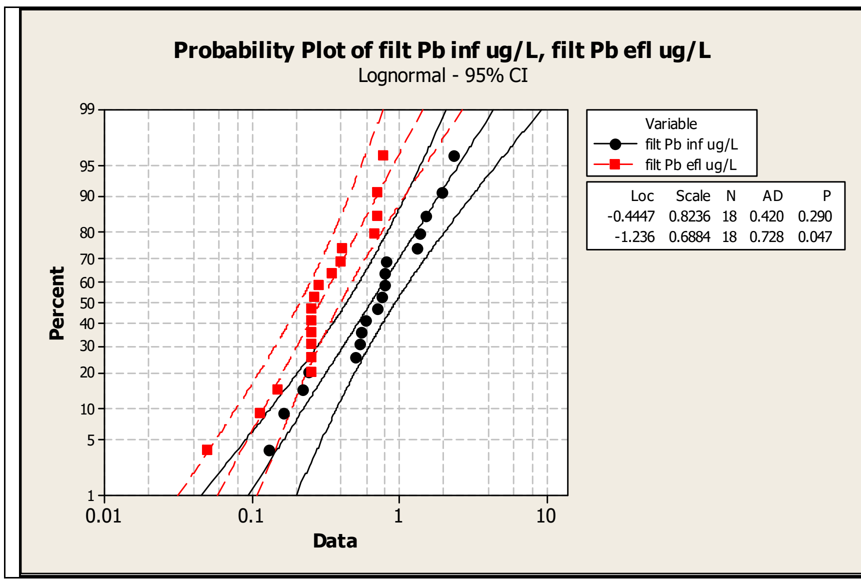
Detention bioswales

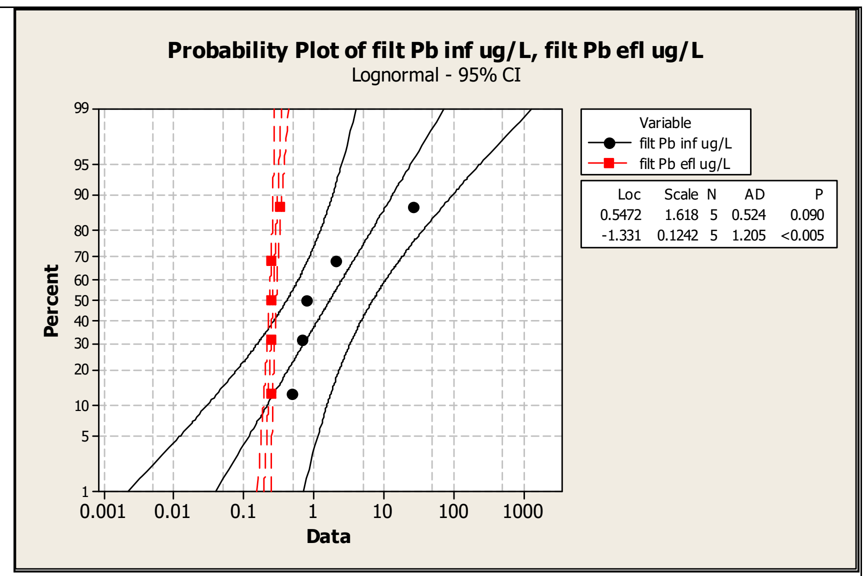


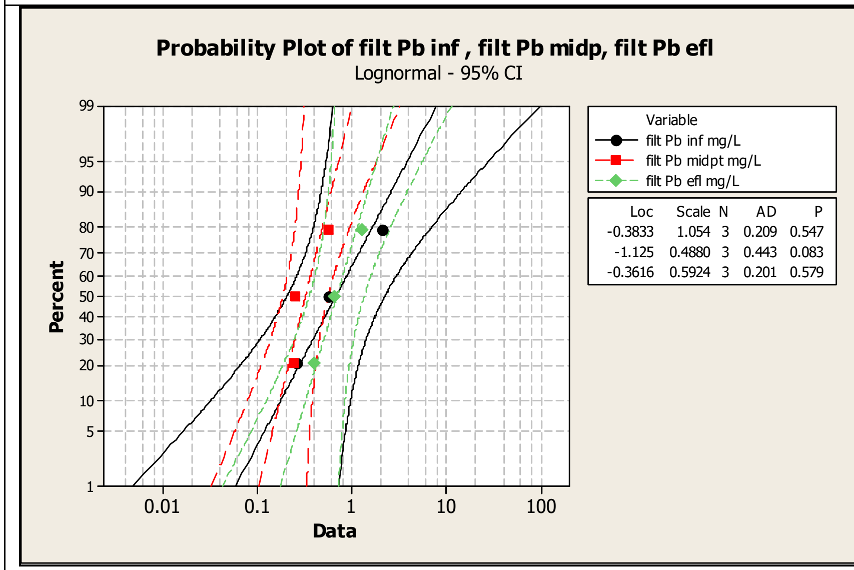
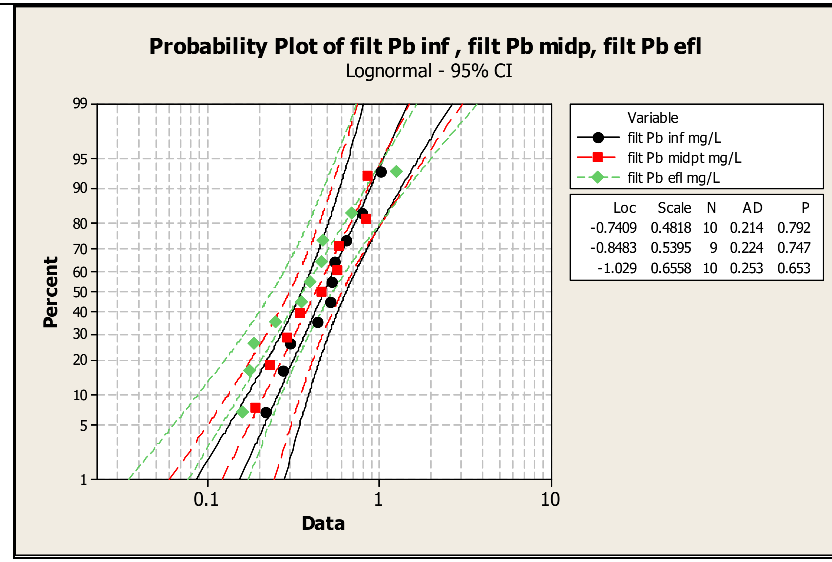
Lower Lot biofilter

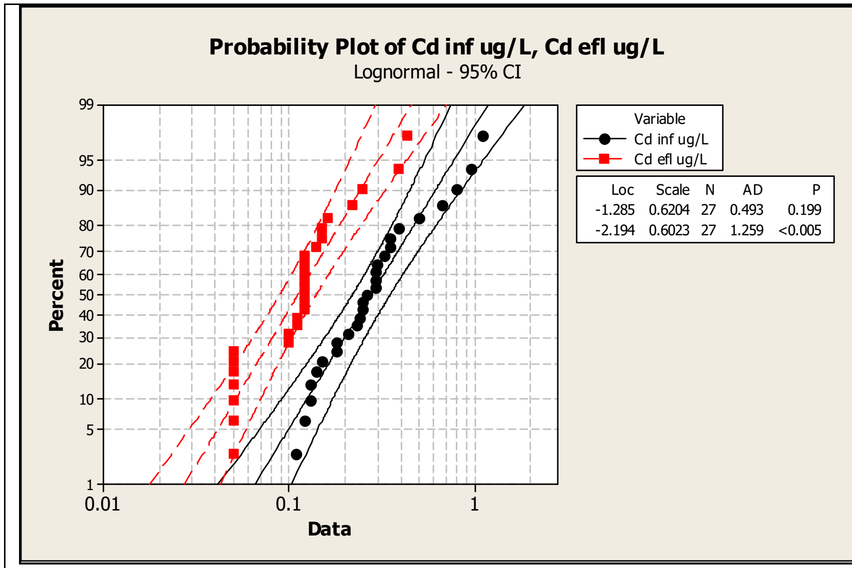


ELV treatment train

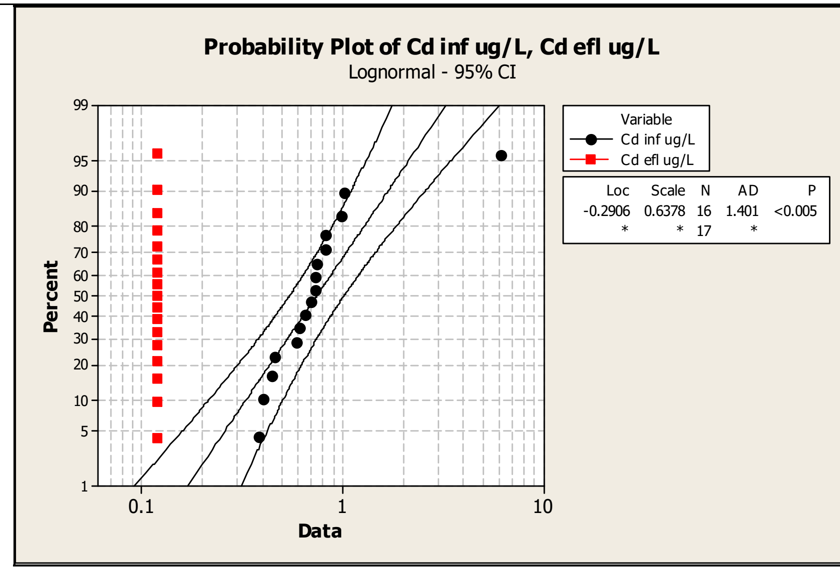




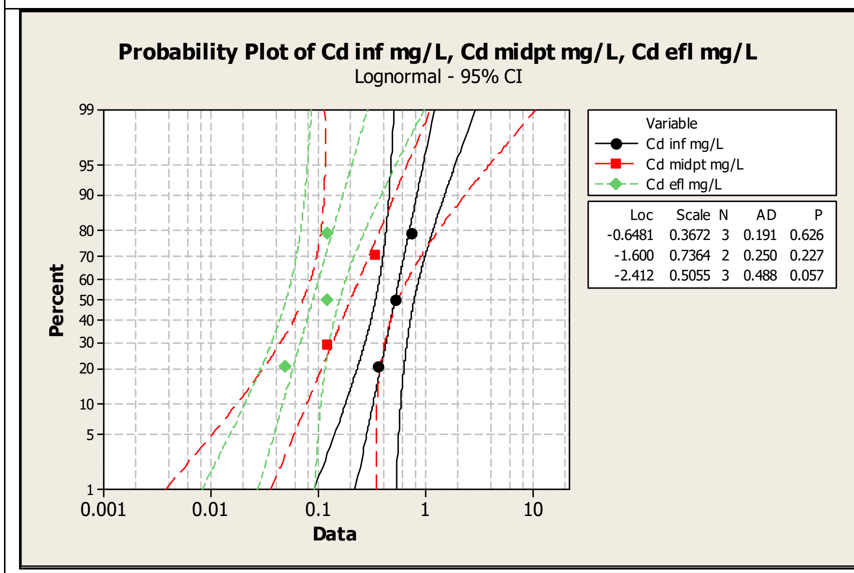
All culvert modifications combined	Detention bioswales
	
Lower Lot biofilter	ELV treatment train



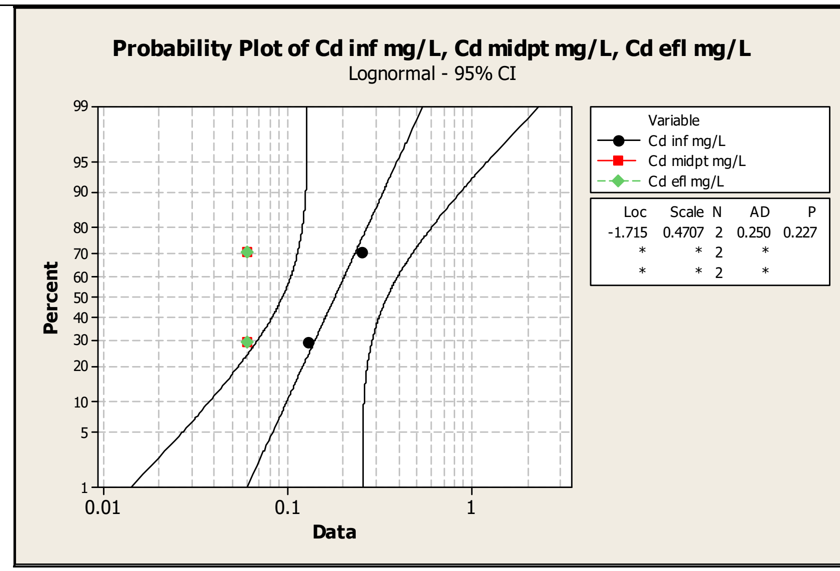
All culvert modifications combined



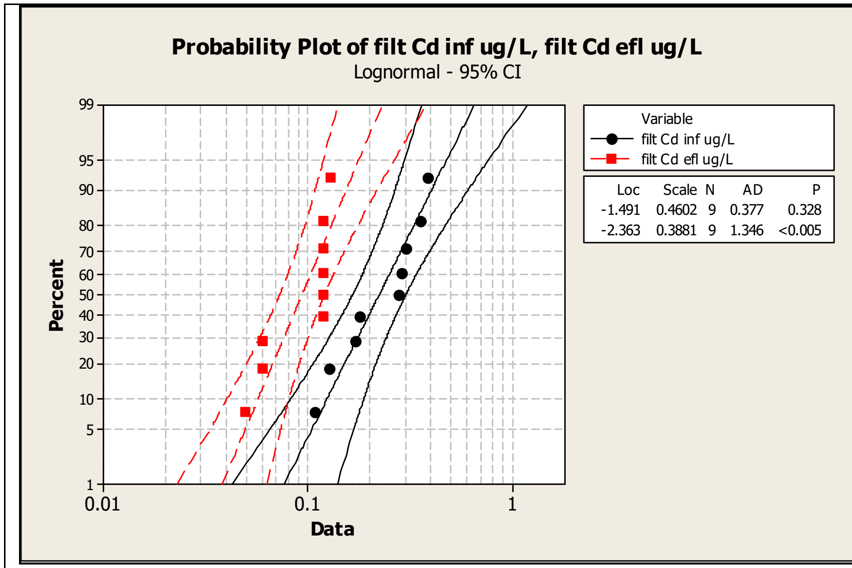
Detention bioswales



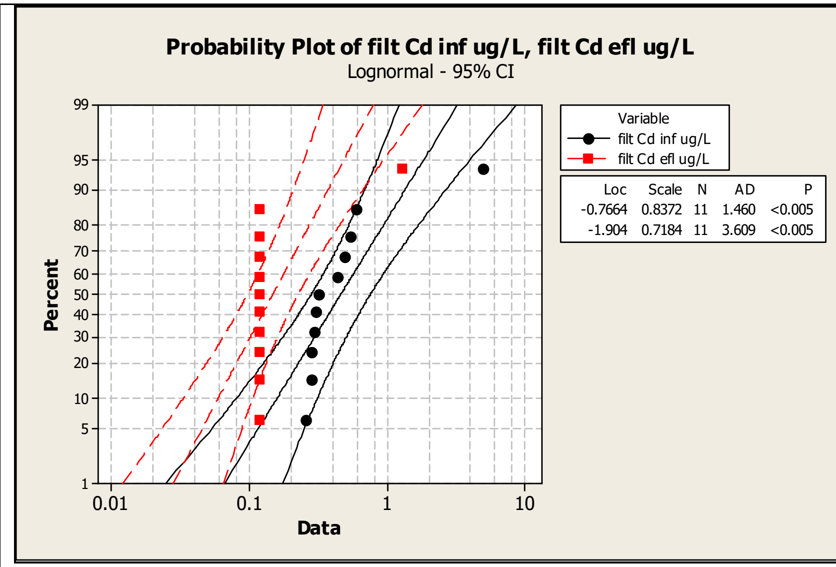
Lower Lot biofilter



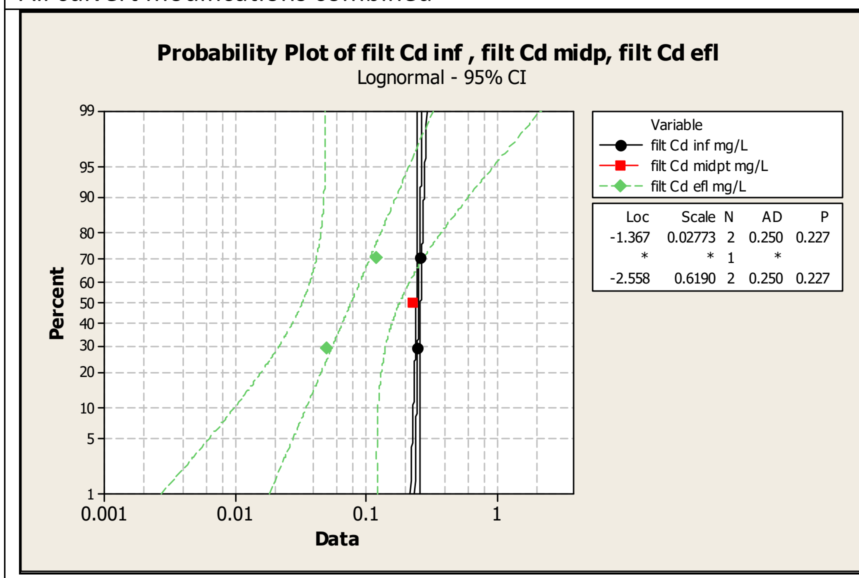
ELV treatment train



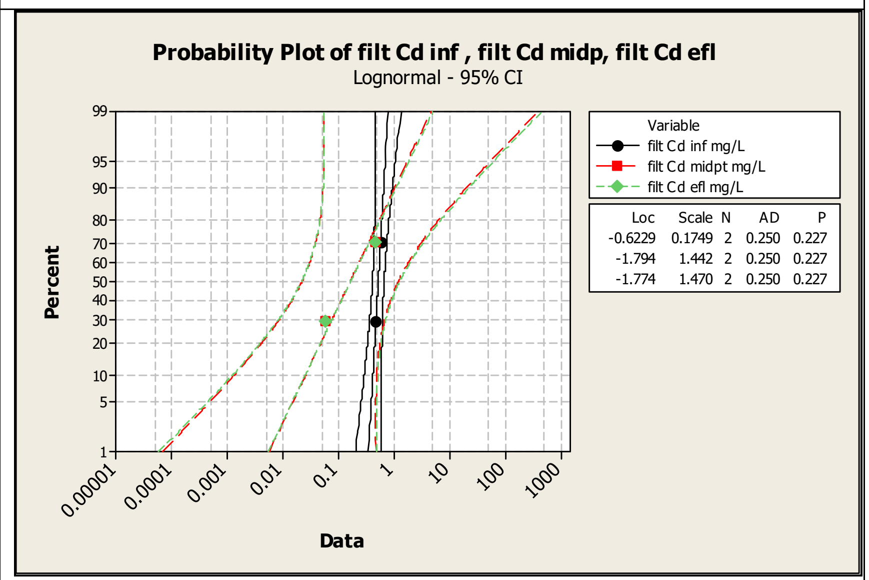
All culvert modifications combined



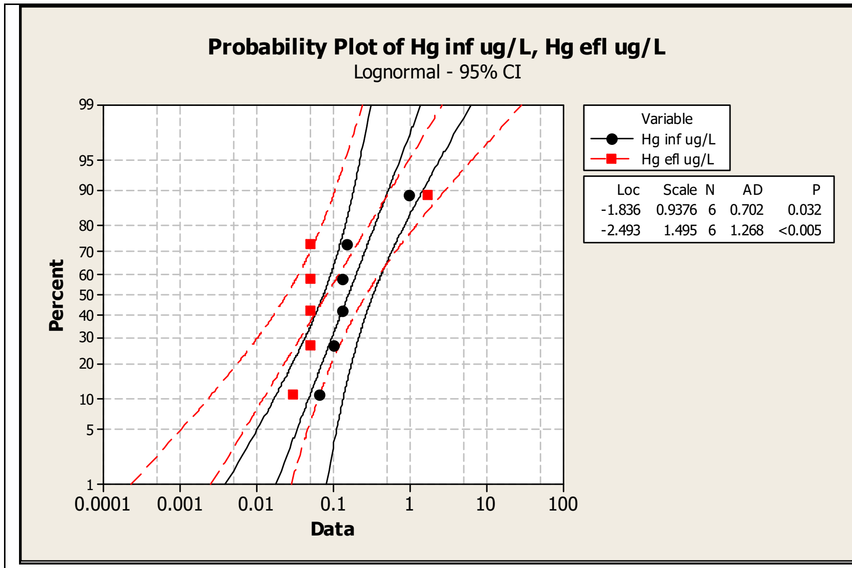
Detention bioswales



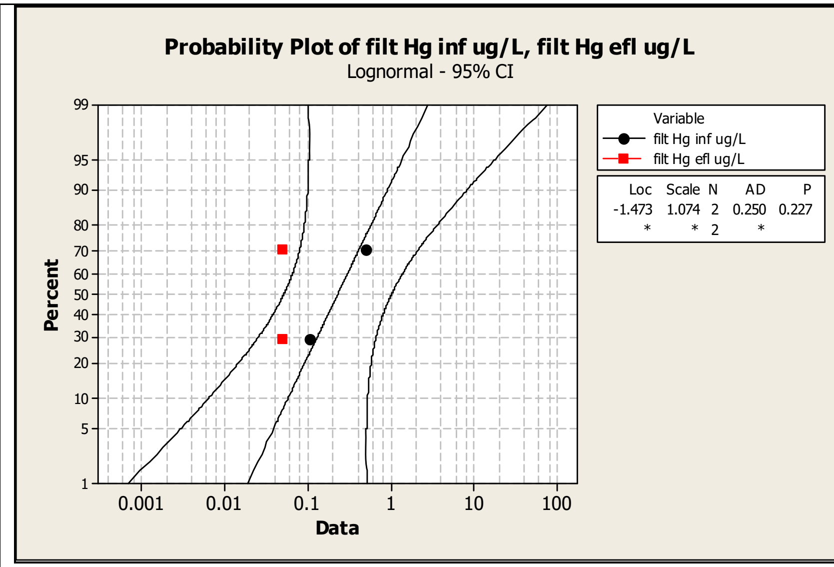
Lower Lot biofilter



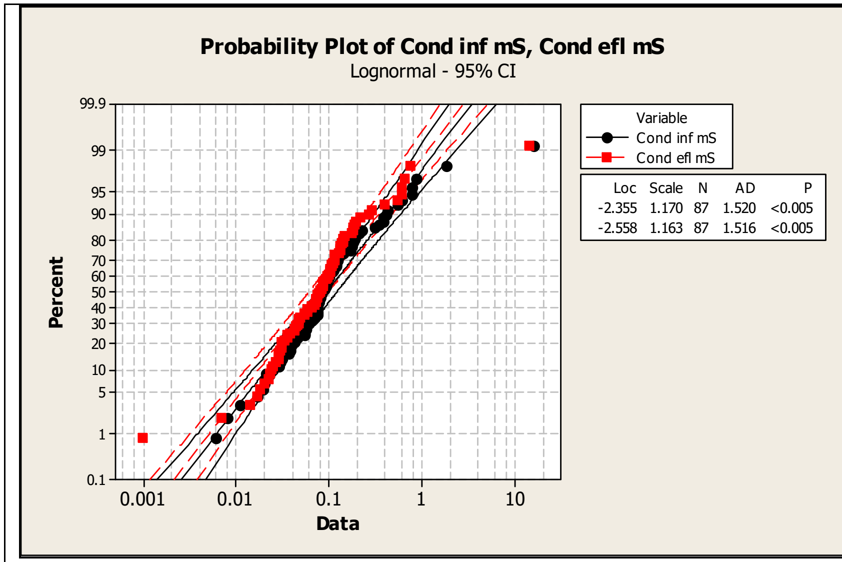
ELV treatment train



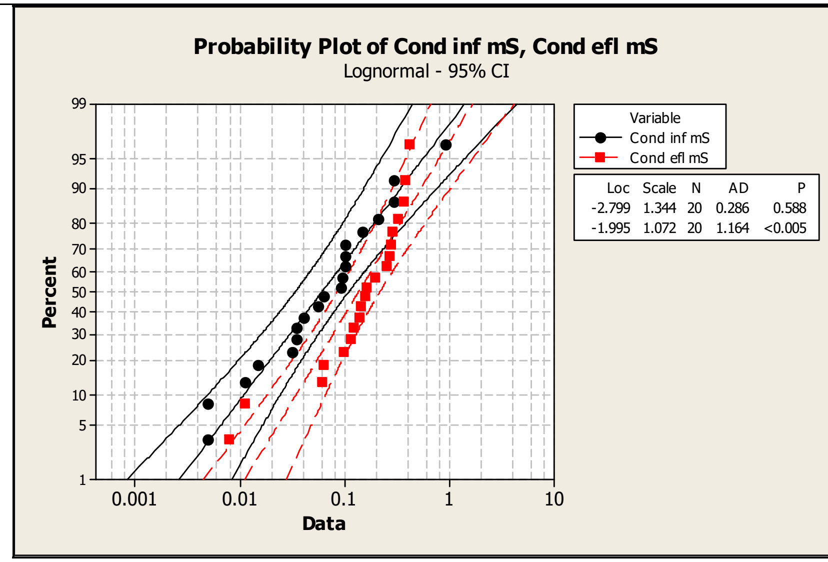
All culvert modifications combined



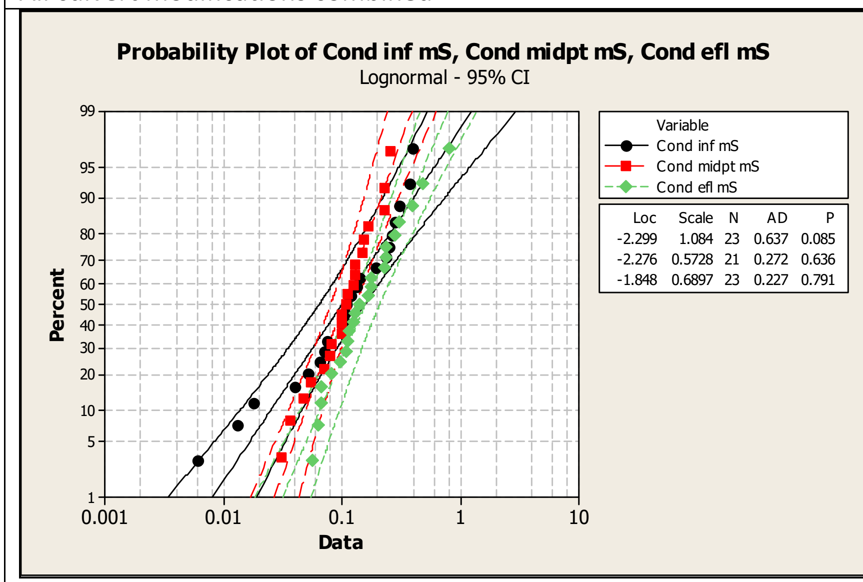
All culvert modifications combined



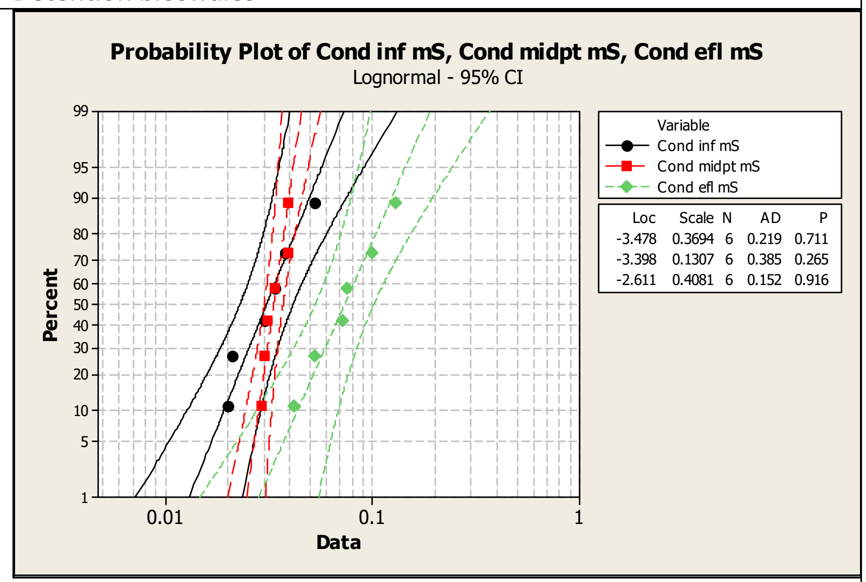
All culvert modifications combined



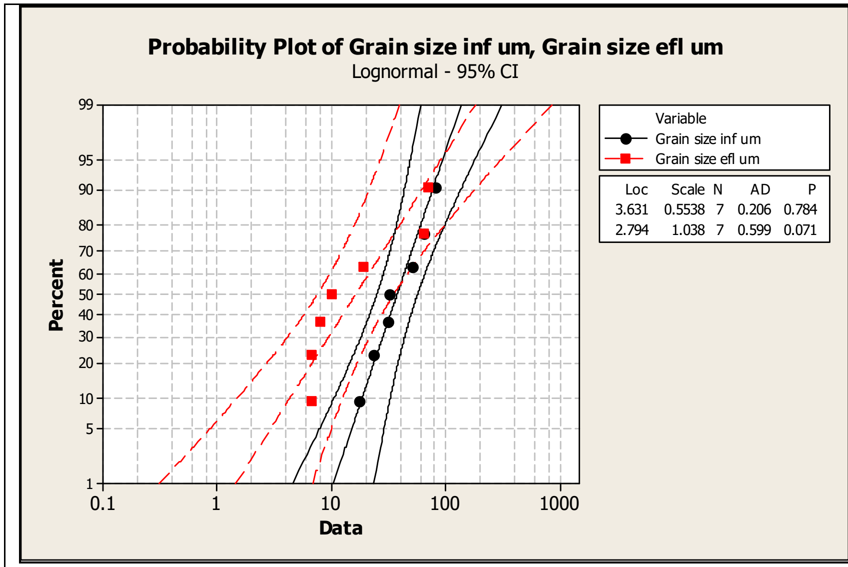
Detention bioswales



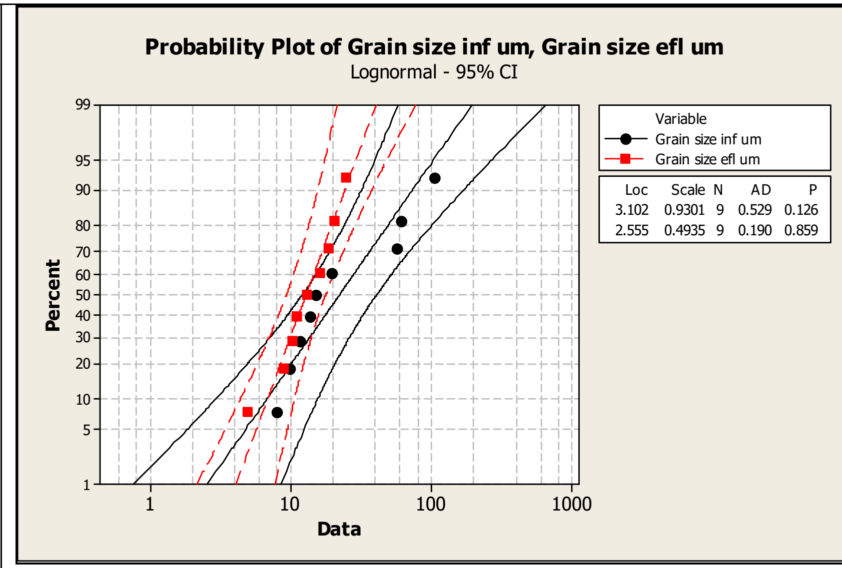
Lower Lot biofilter



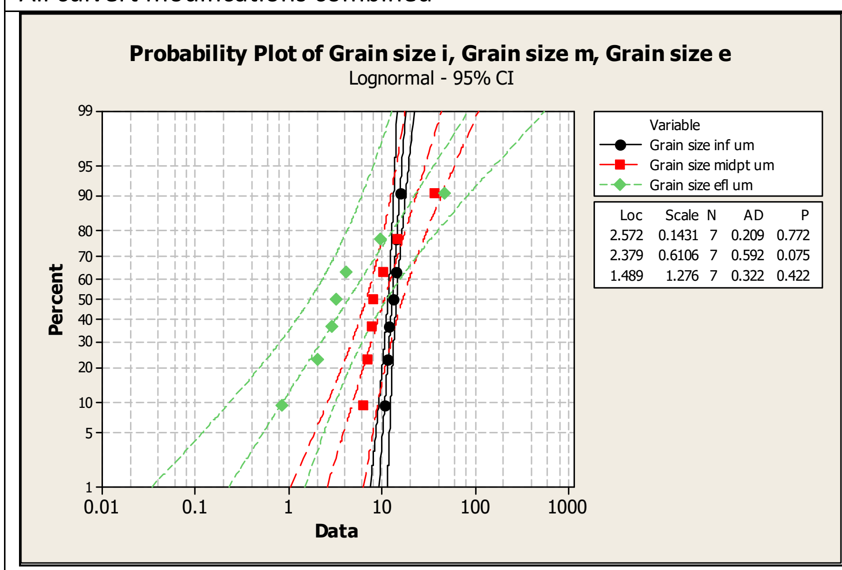
ELV treatment train



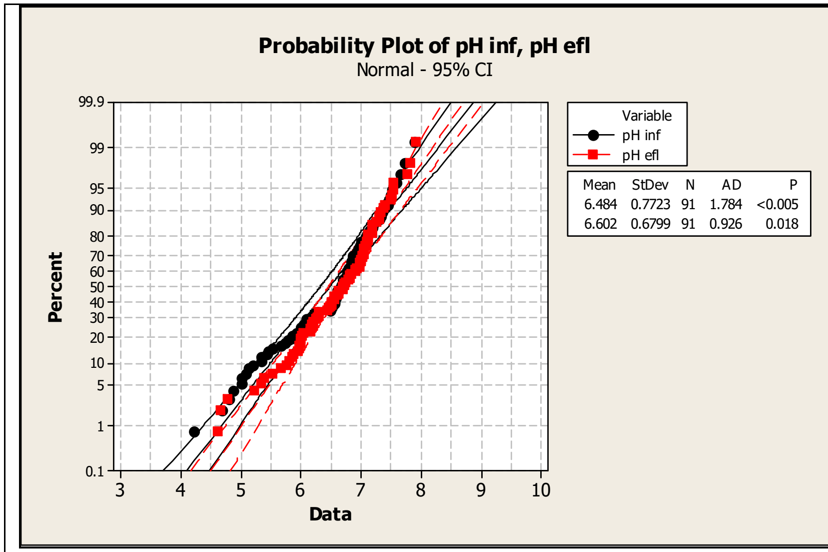
All culvert modifications combined



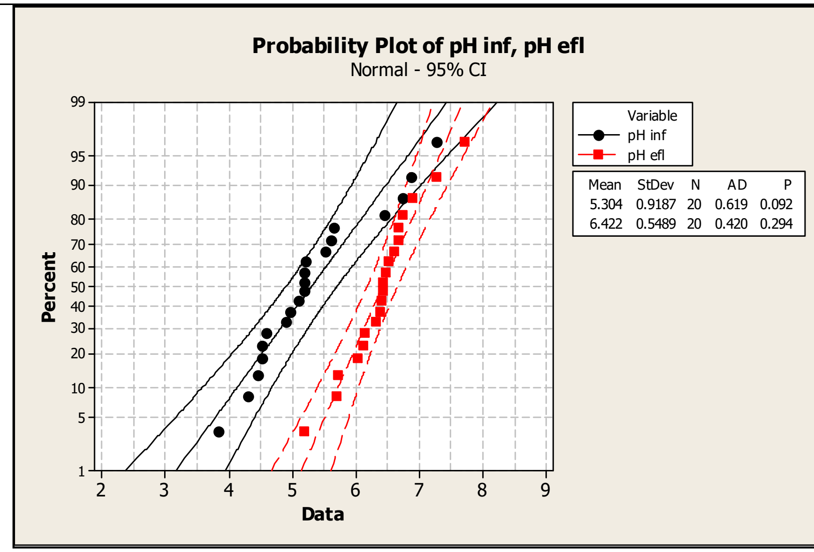
Detention bioswales



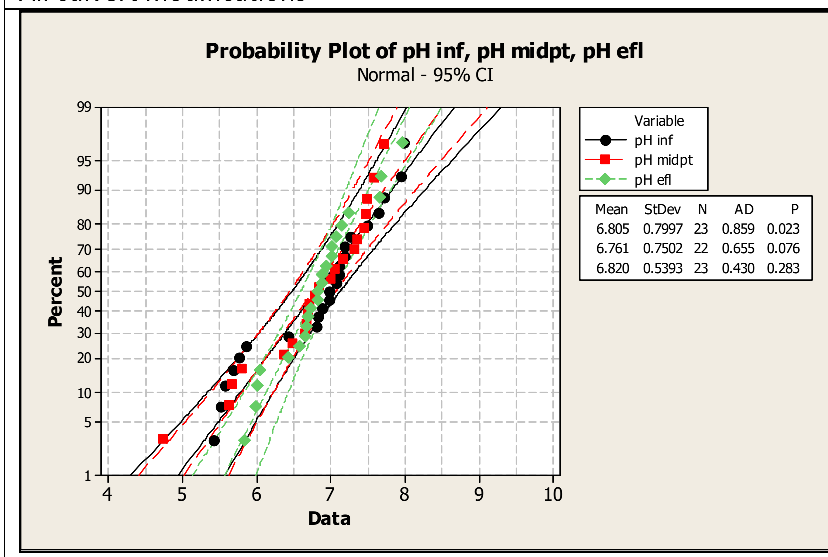
Lower Lot biofilter



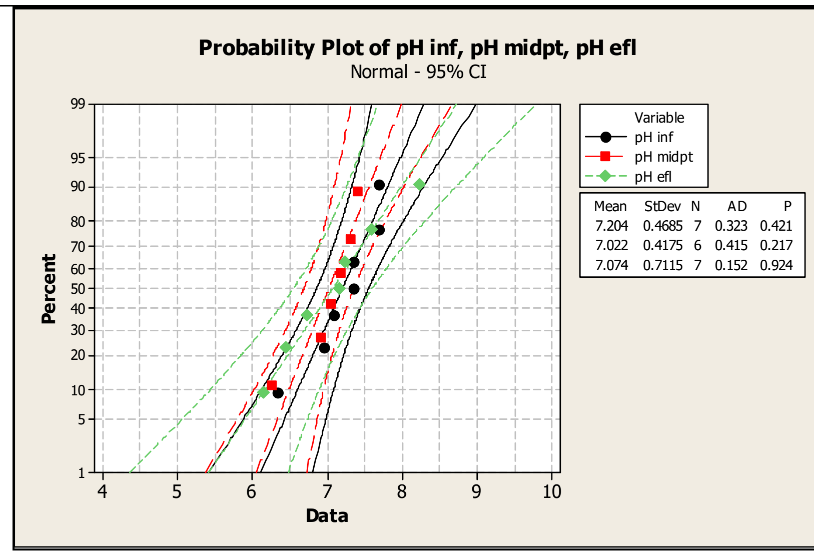
All culvert modifications



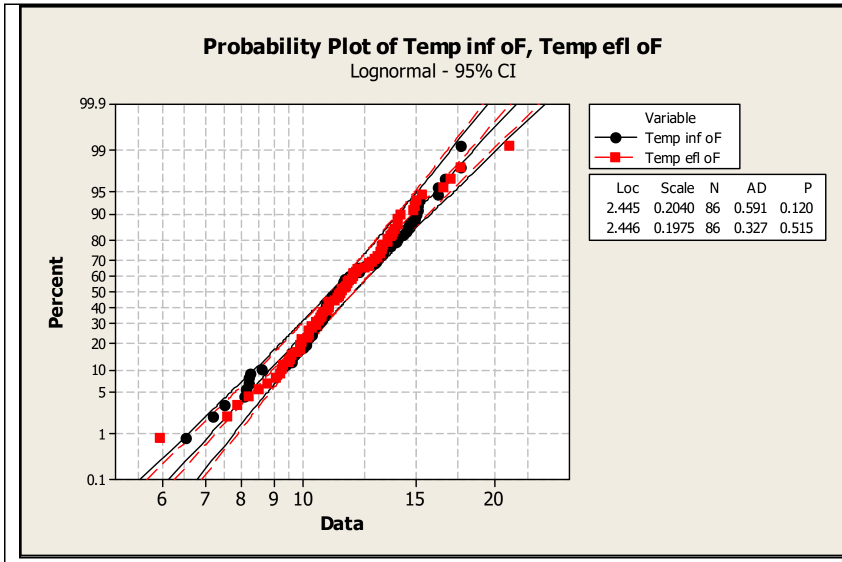
Detention bioswales



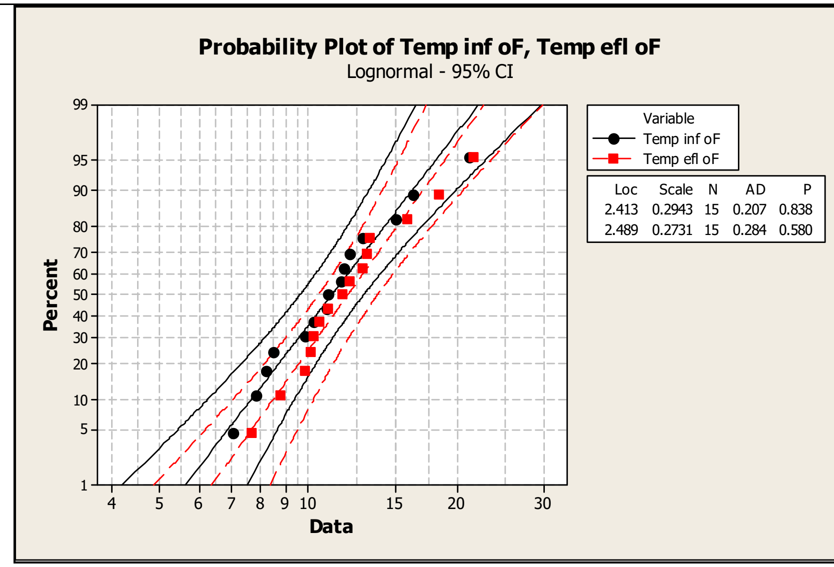
Lower Lot biofilter



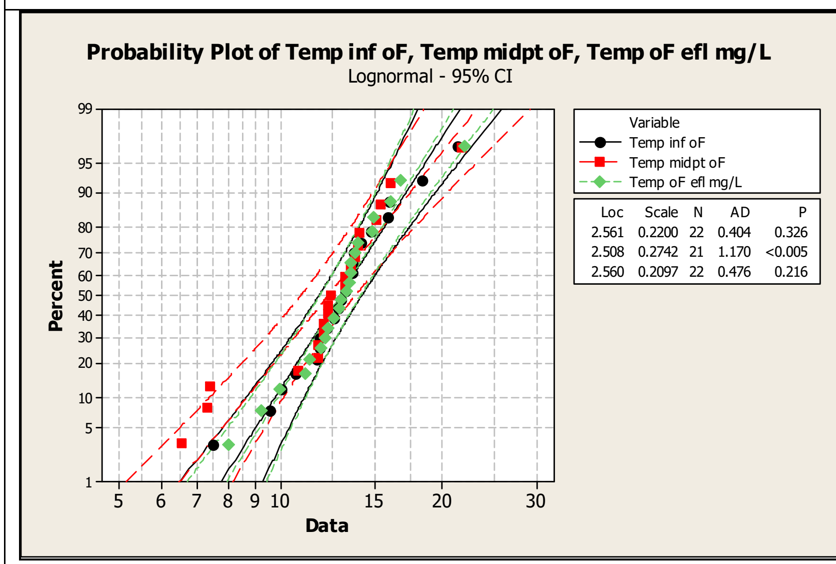
ELV treatment train



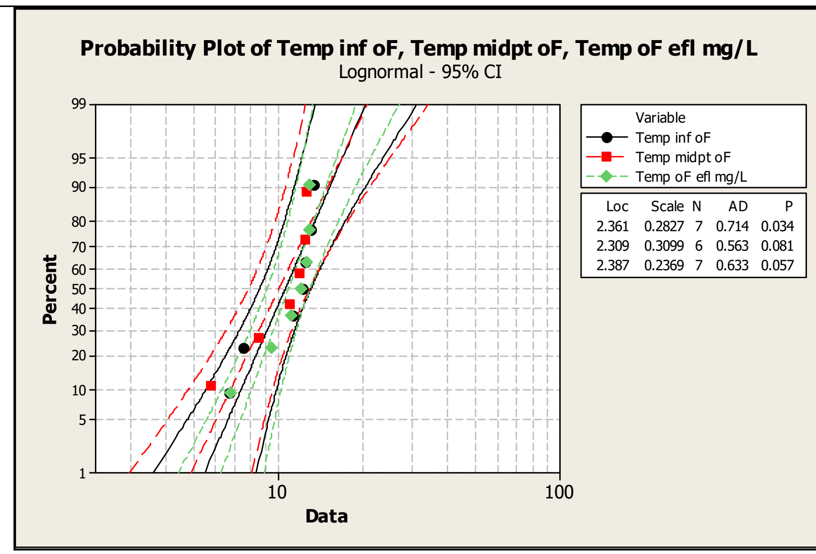
All culvert modifications combined



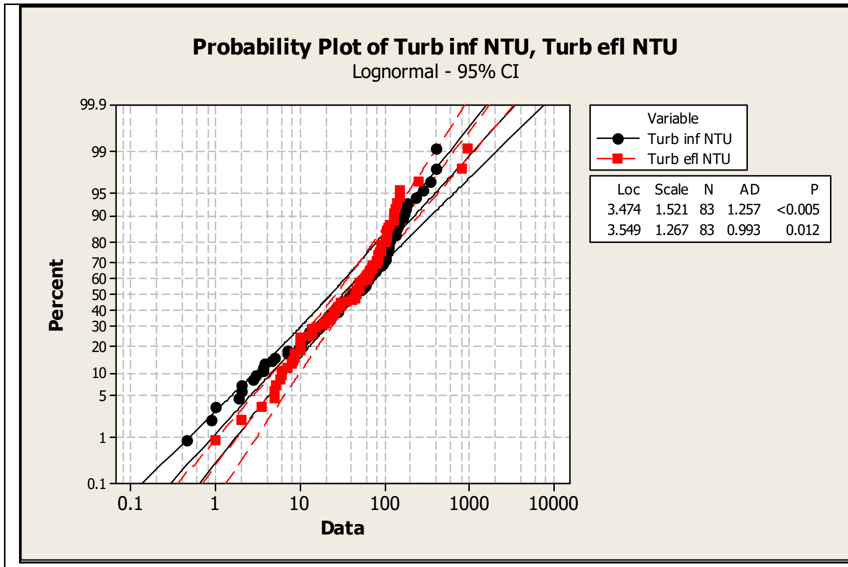
Detention bioswales



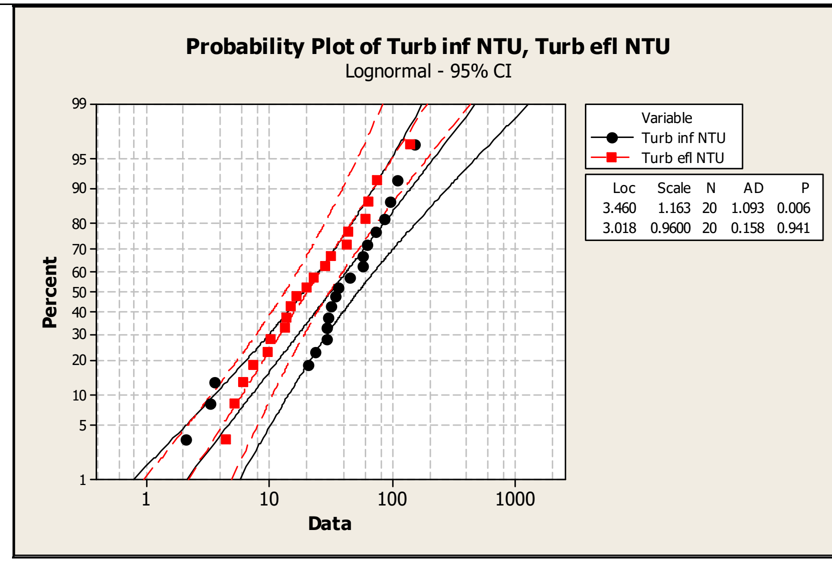
Lower Lot biofilter



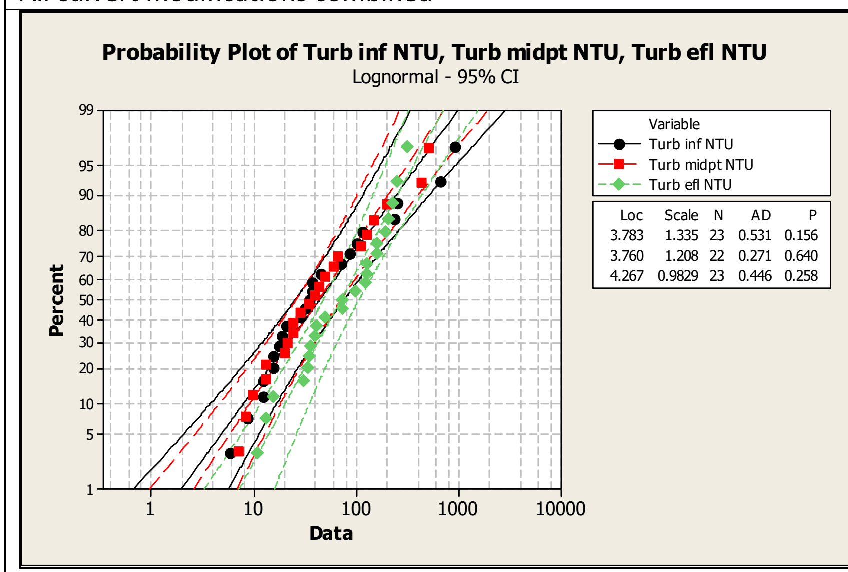
ELV treatment train



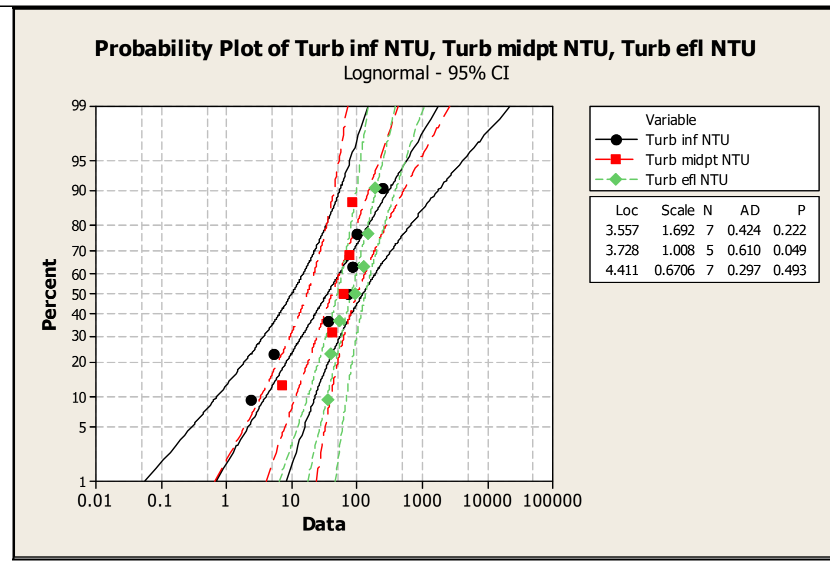
All culvert modifications combined



Detention bioswales



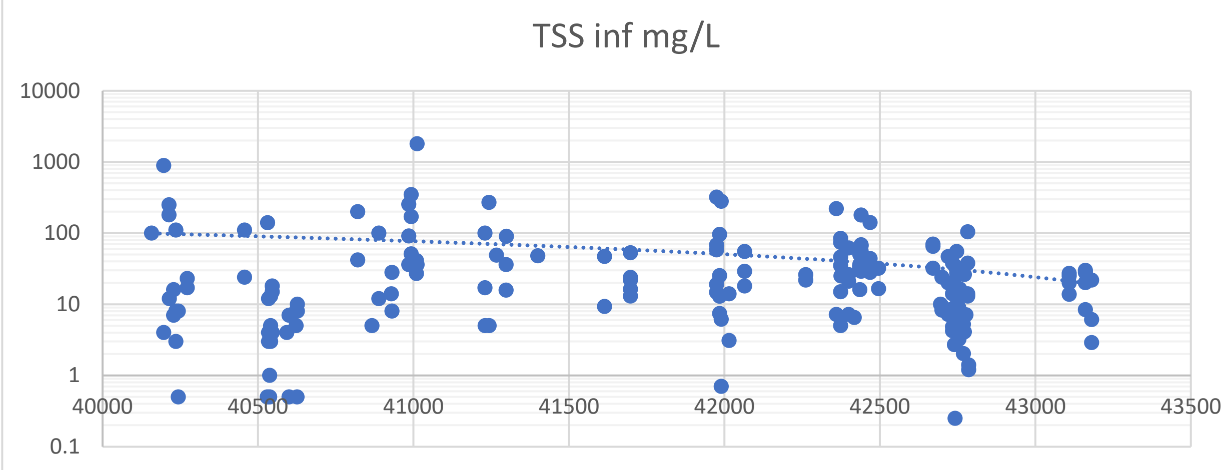
Lower Lot biofilter



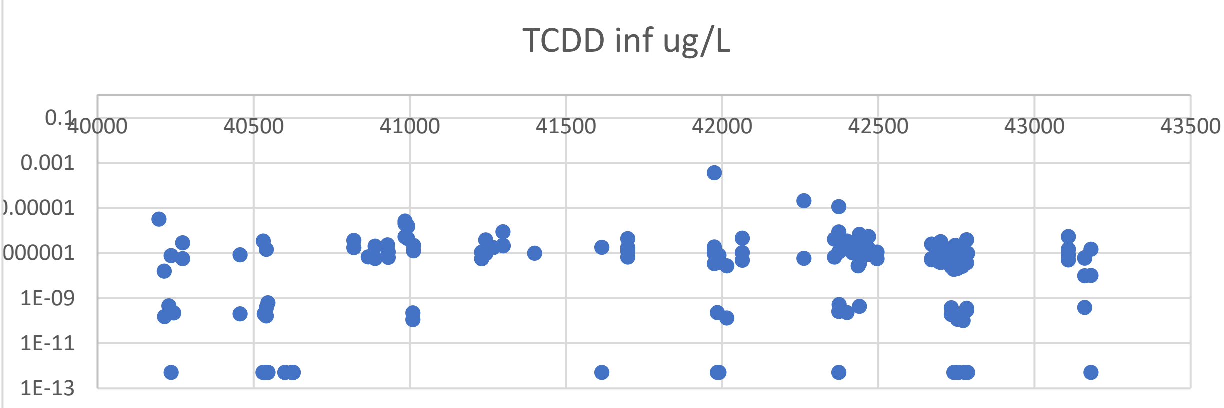
ELV treatment train

Appendix D: Influent and Effluent Concentration Trends with Time

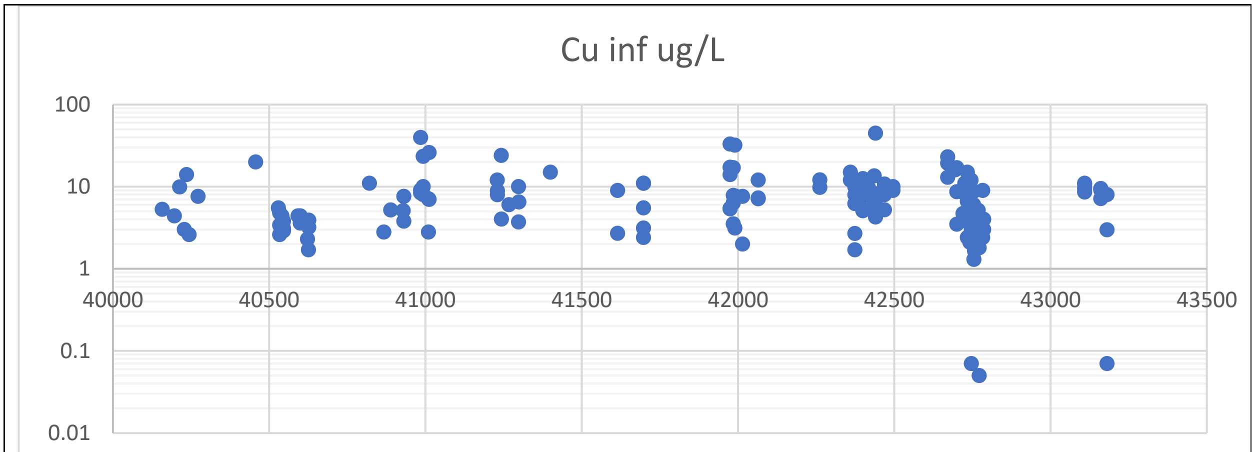
All sites combined, except for background sites (CM-8 and CM-11) removed



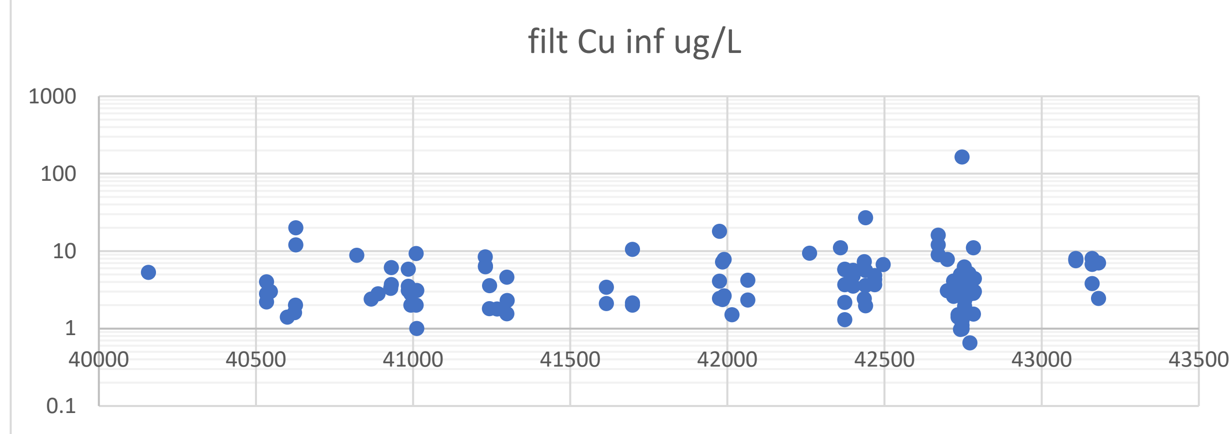
significant slope with time (-0.026 mg/day; p = 0.033)



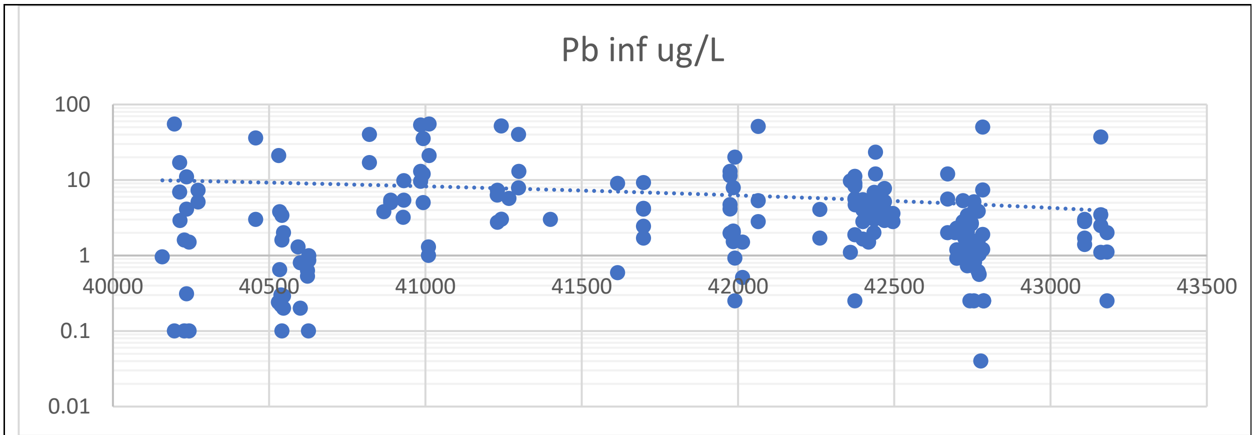
no significant slope with time (p = 0.93)



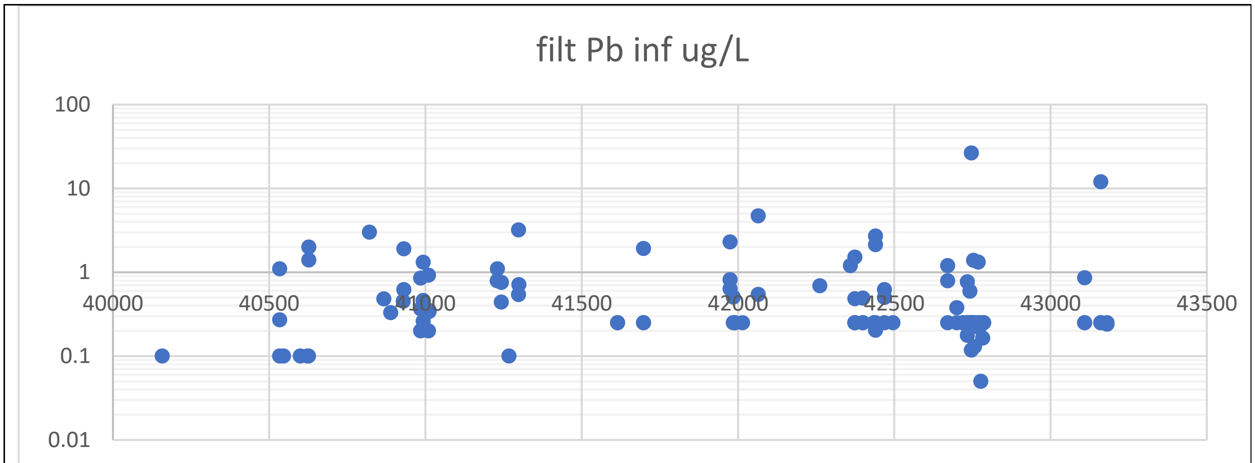
no significant slope with time (p = 0.78)



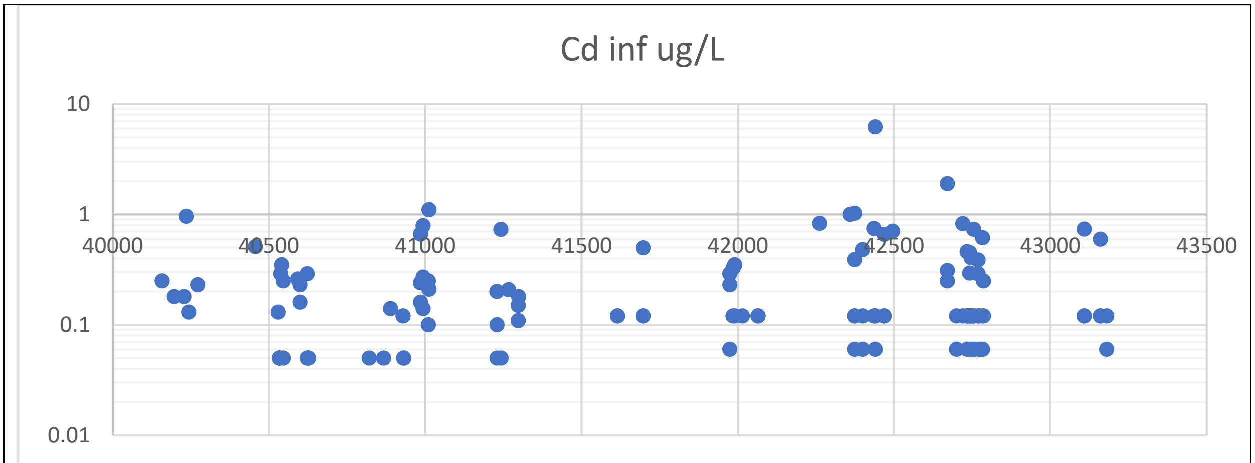
no significant sloe with time (p = 0.35)



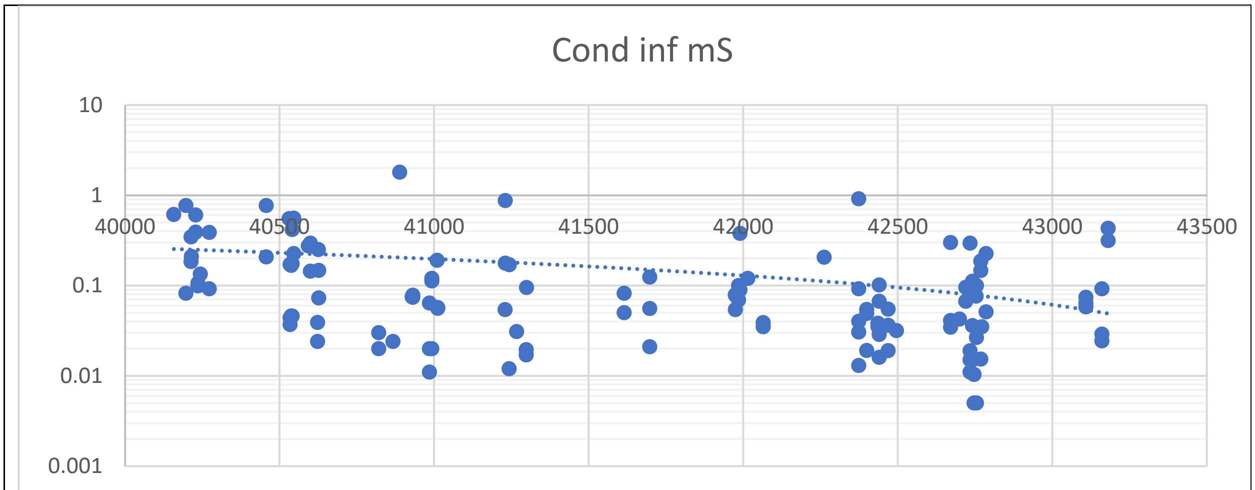
significant slope with time (-0.002ug/day; p = 0.025)



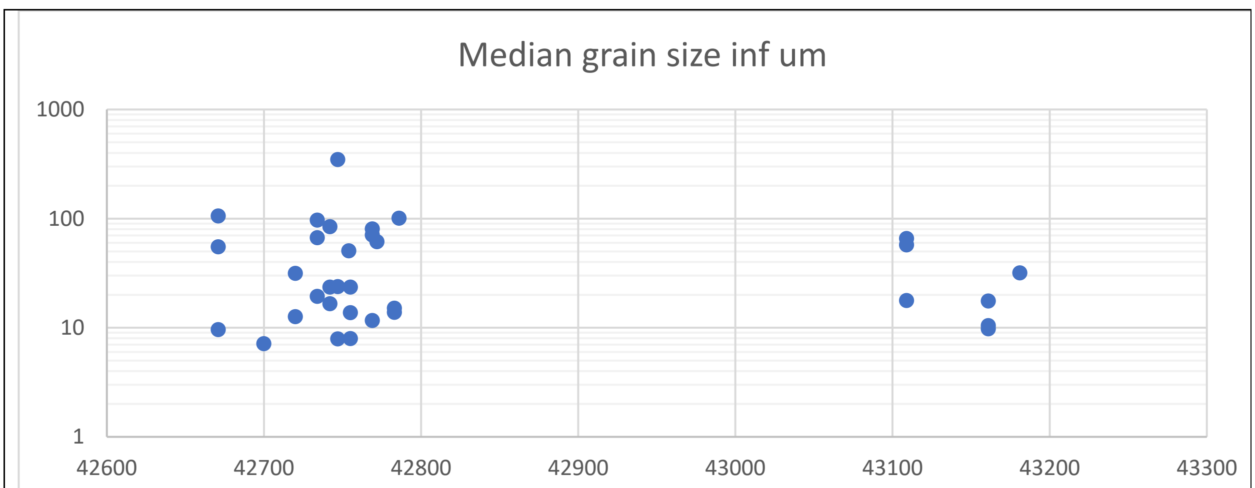
no significant slope with time (p = 0.42)



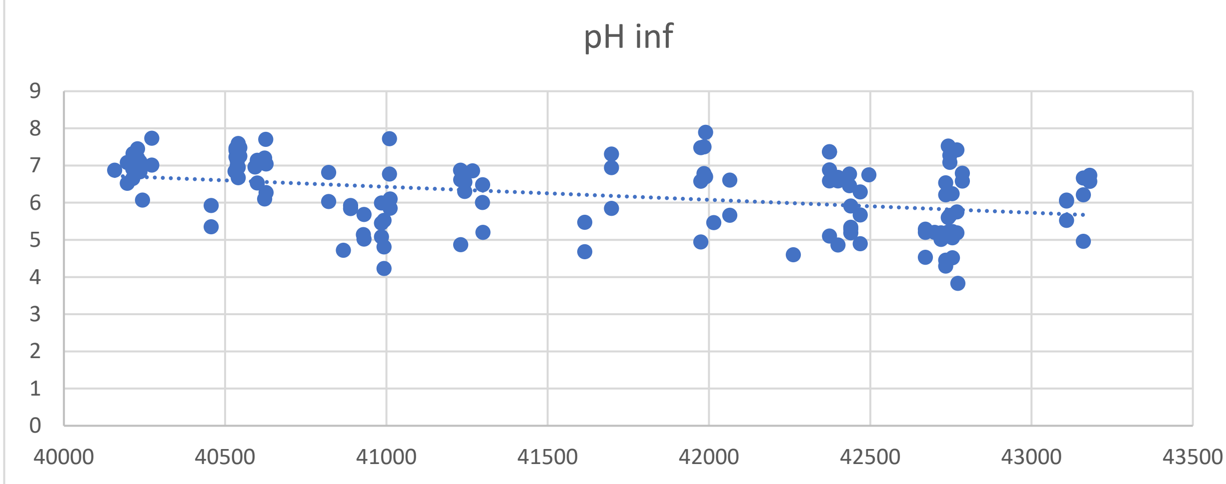
no significant slope with time (p = 0.35)



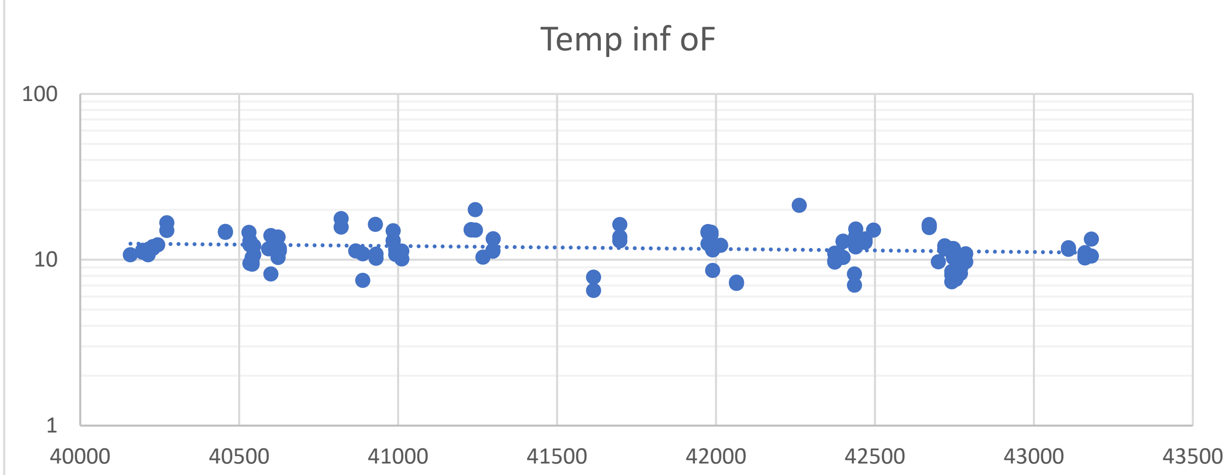
significant slope with time (-7E-05 mS/day; p = 0.0009)



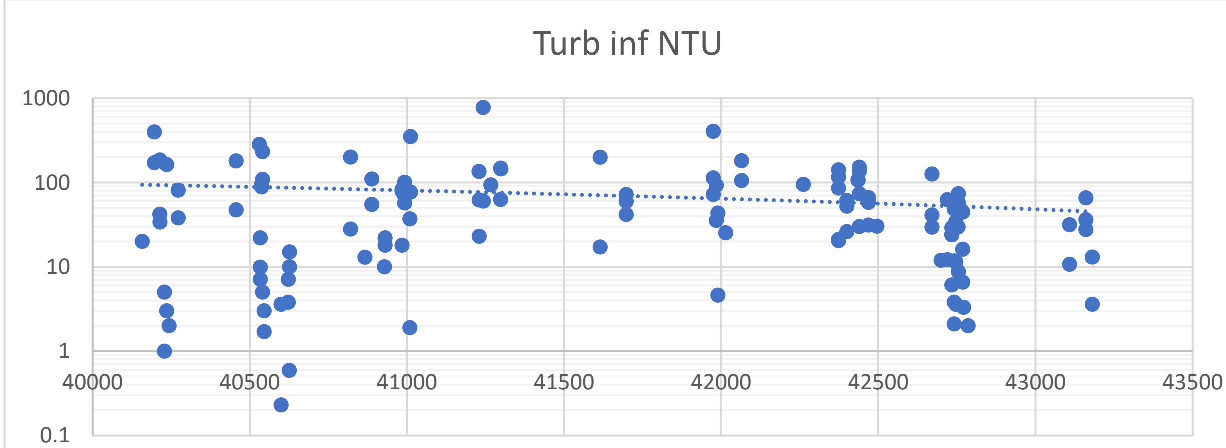
no significant slope with time (p = 0.41)



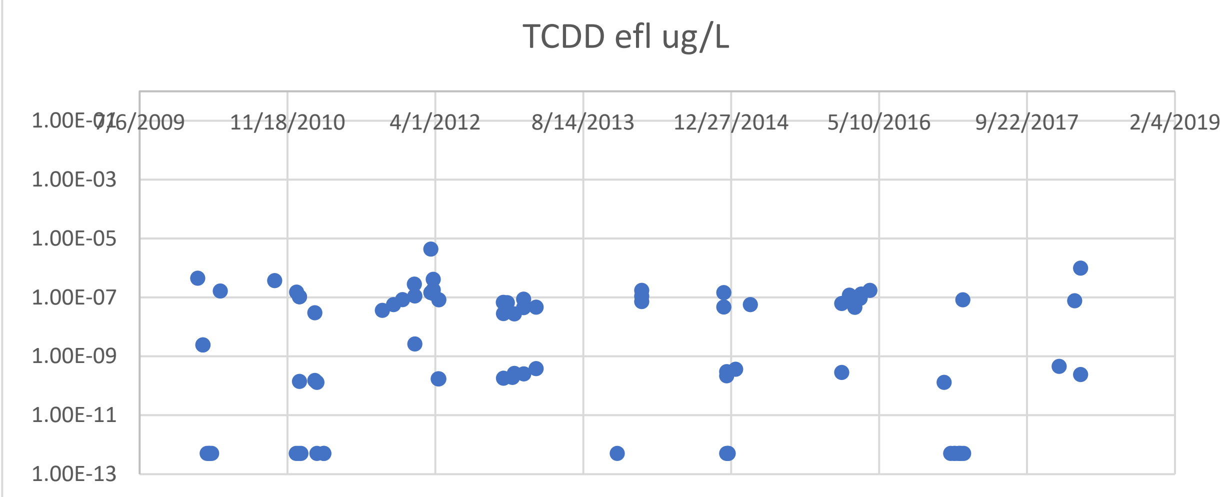
significant slope with time (-0.00035pH units/day; p = <0.0001)



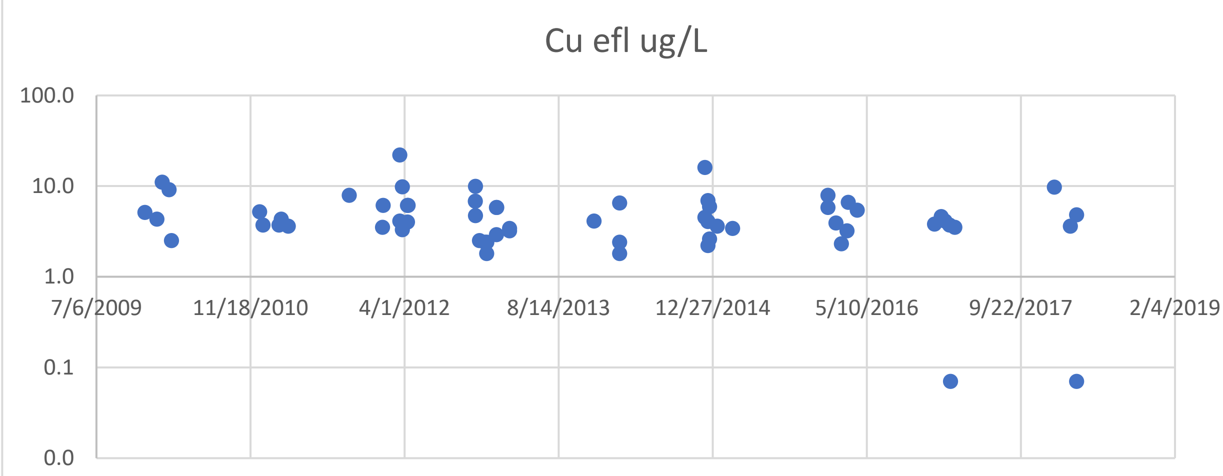
marginal significant slope with time (-0.00048degF/day; p = 0.054)



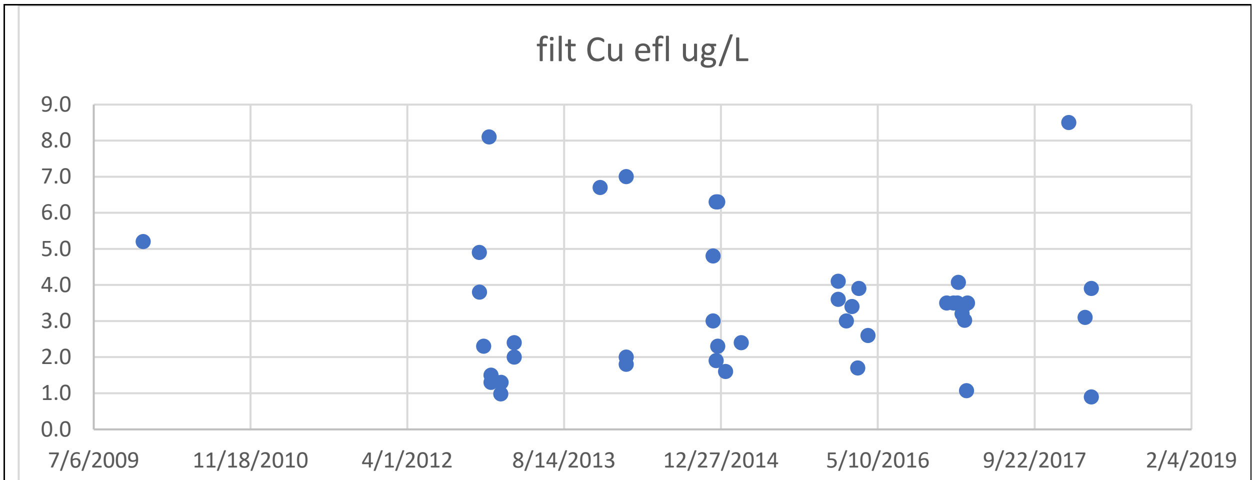
marginal significant slope with time (-0.016NTU/day; p = 0.070)



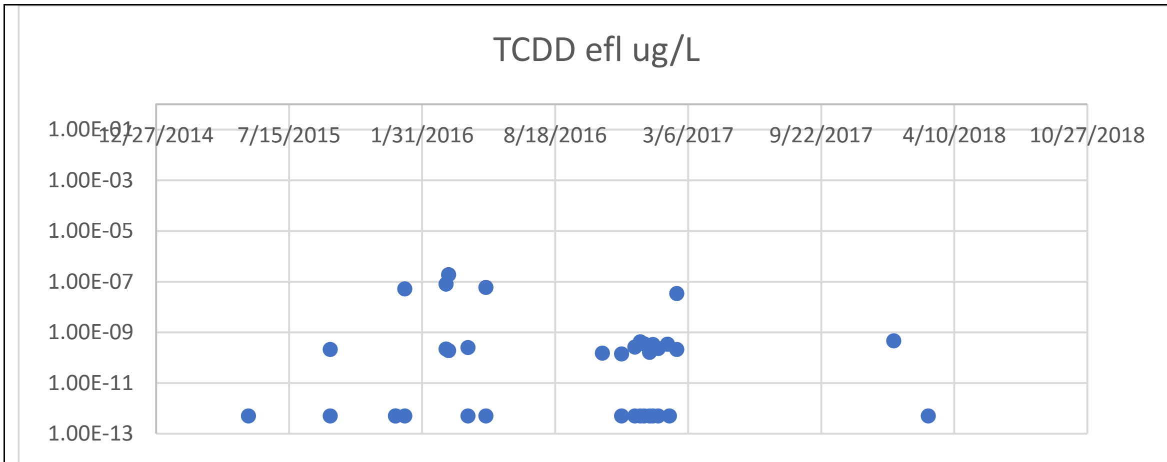
All culvert modifications combined (no background sites); No significant slope with time (p = 0.70)



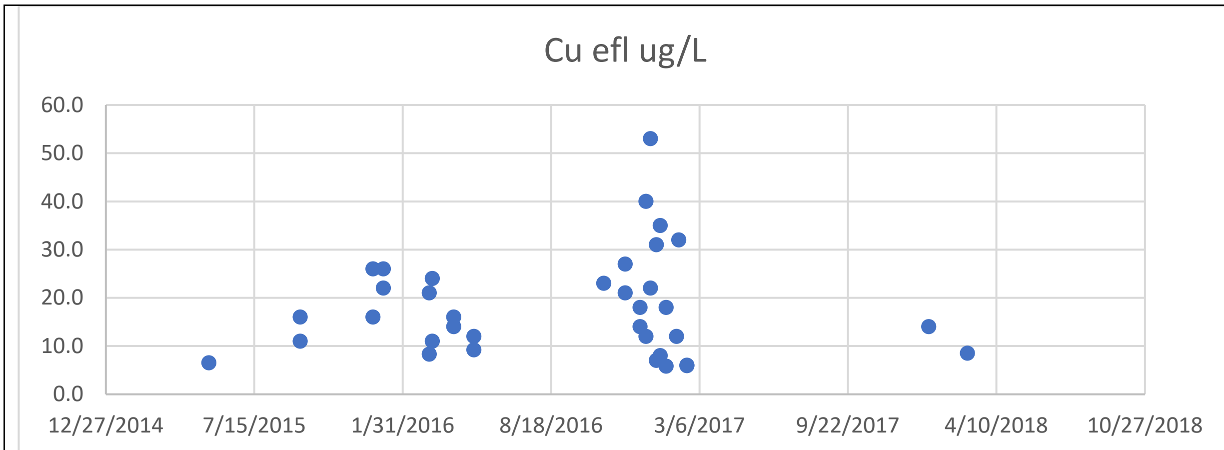
All culvert modifications combined (no background sites); No significant slope with time (p = 0.17)



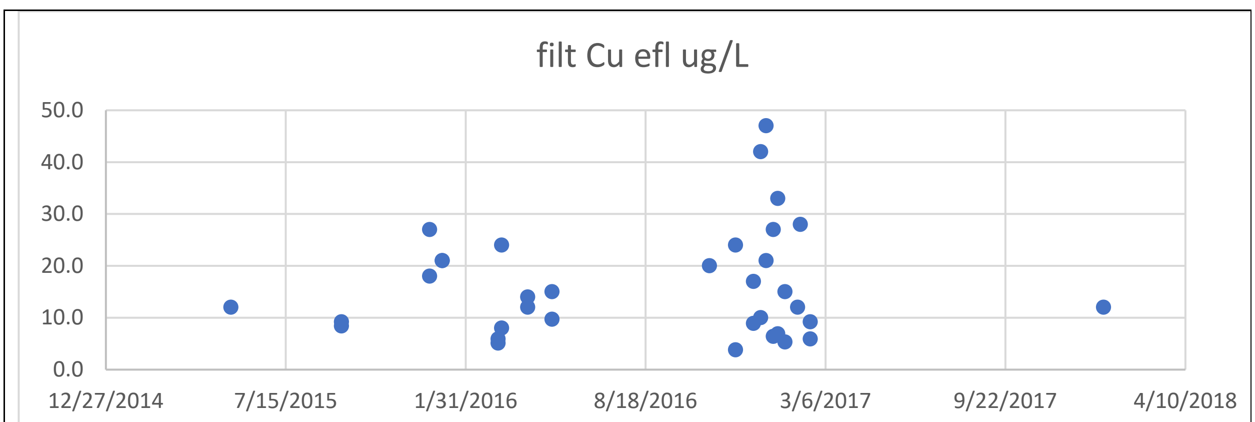
All culvert modifications combined (no background sites); No significant slope with time (p = 0.94)



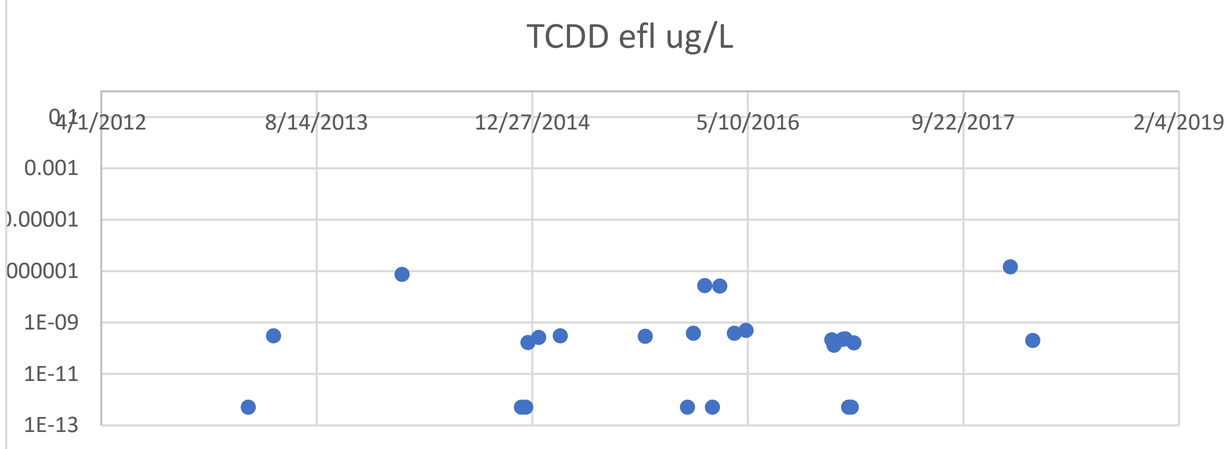
Northern and southern detention bioswales combined; No significant slope with time ($p = 0.21$)



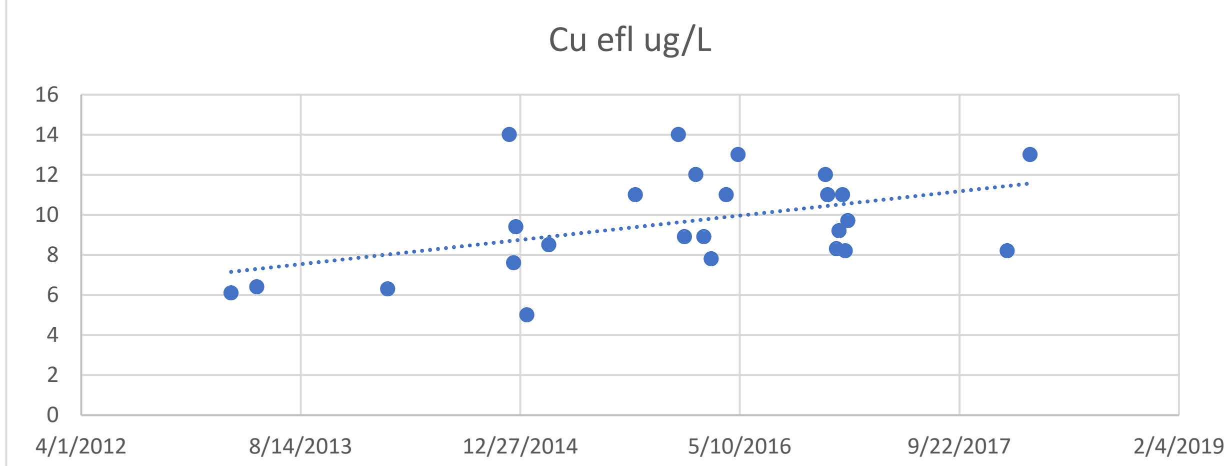
Northern and southern detention bioswales combined; No significant slope with time ($p = 0.72$)



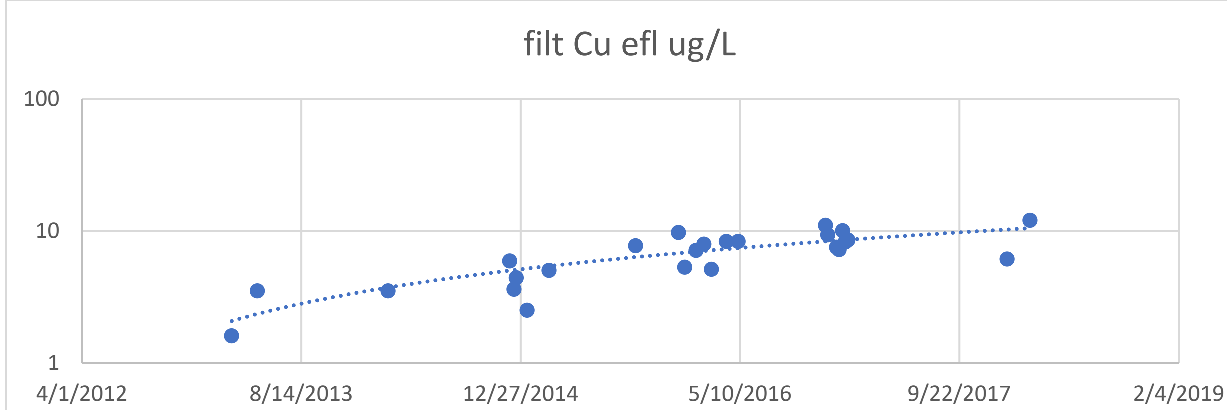
Northern and southern detention bioswales combined; No significant slope with time ($p = 0.71$)



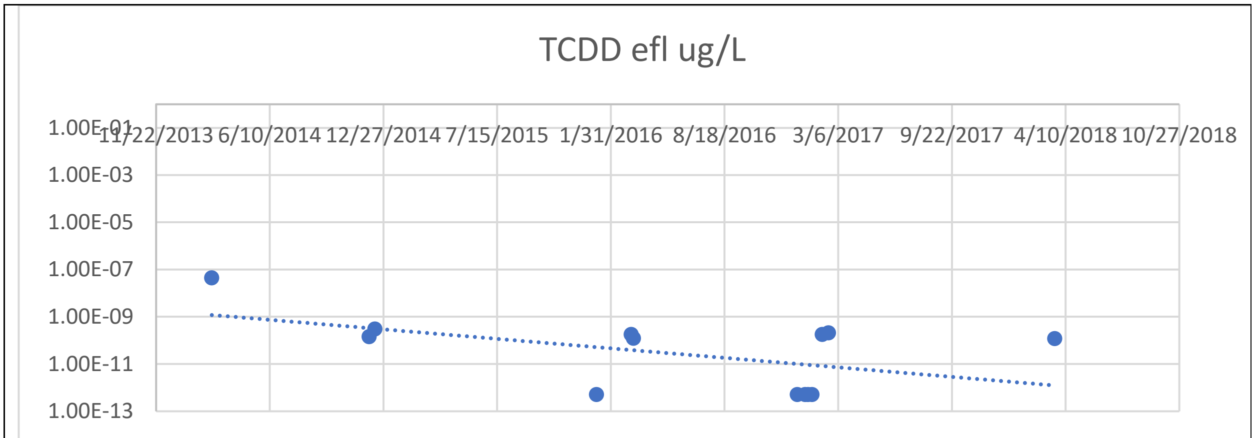
Lower lot biofilter; No significant slope with time (p = 0.41)



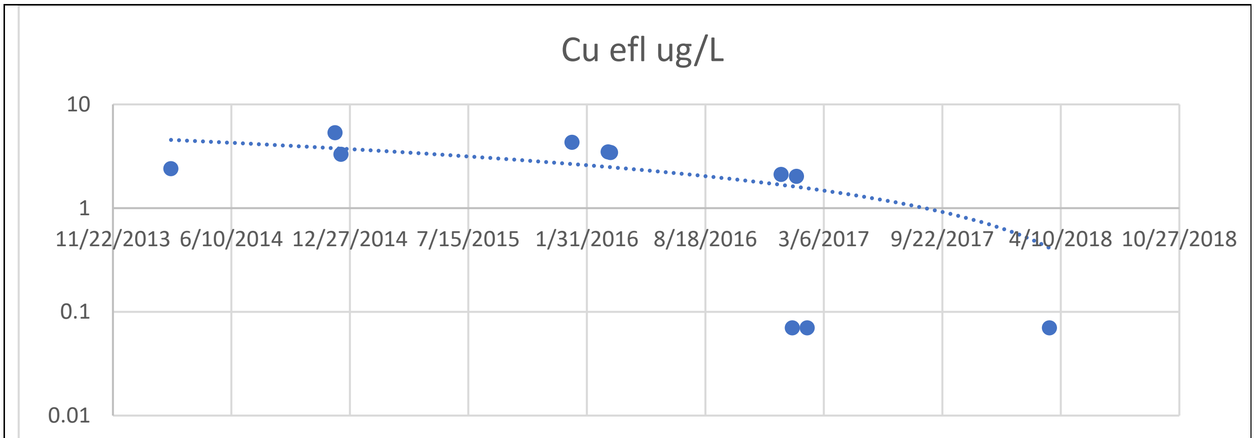
Lower lot biofilter; significant increasing slope with time (p = 0.023); 0.0024 ug/day increase



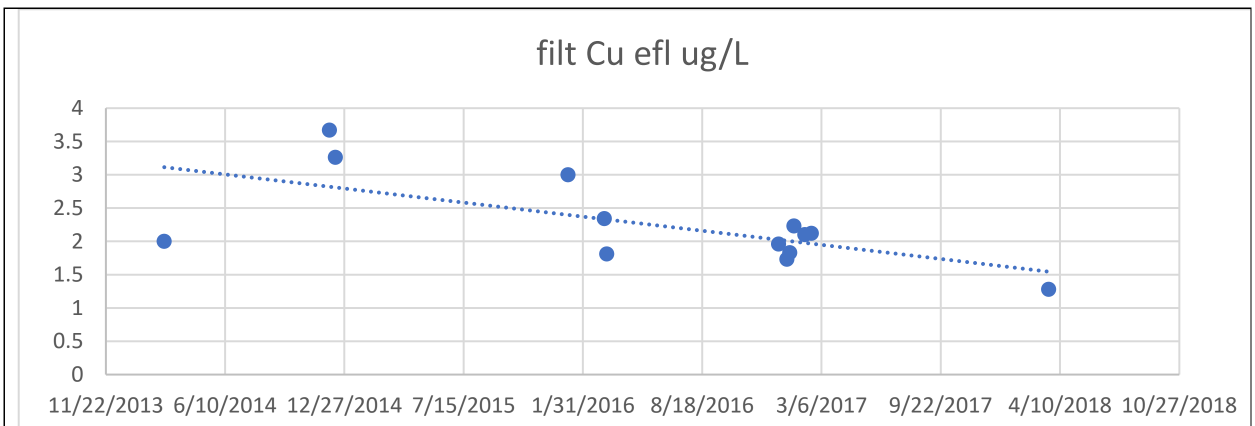
Lower lot biofilter; significant increasing slope with time (p = <0.001); 0.0046 ug/day increase



ELV treatment train; significant decreasing slope with time (p = 0.034); 1.7E-11 ug/day decrease



ELV treatment train; significant decreasing slope with time (p = 0.020); 0.0028 ug/day decrease



ELV treatment train; significant decreasing slope with time (p = 0.015); 0.0011 ug/day decrease