ABSTRACT

Title of Thesis: EVALUATING GUTTER FILTER PERFORMANCE AFTER 10 YEARS OPERATION

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Urban stormwater runoff contains various pollutants that degrade downstream water quality. Gutter filters, below-grade filtration devices that capture sheet flow, are an ideal stormwater control measure for urban retrofits because of their small footprint. A 10-year-old gutter filter system in Mt. Rainier, MD was monitored for 18 storm events over 13 months for total suspended solids, nitrogen, phosphorus, and copper, zinc, and lead in the downstream stormwater. The filters had received no maintenance since their construction. The stormwater quality was compared to studies conducted prior to installation and immediately after installation of the filters. Total Kjeldahl Nitrogen concentrations displayed a statistically significant increase since installation. All other pollutants did not show a significant change over the 10 years. Nonetheless, overall runoff water quality was not good. Event mean concentrations are comparable to highway runoff and annual pollutant loadings are comparable to untreated runoff from other urban drainage areas in the region.

EVALUATING GUTTER FILTER PERFORMANCE AFTER 10 YEARS OPERATION

by

Madeleine Greenfield

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Chapter 1: Introduction

1.1 - Background

Urbanization has led to increased pollution of waterways through land use changes and stormwater runoff. Increases in impervious land cover reduce the area available to infiltrate rainwater, which can increase runoff volume and result in higher energy inputs to waterways (NRC, 2008). Impervious surfaces such as highways can act as concentrating factors for materials that collect on them (Opher and Friedler, 2010). Urban stormwater runoff carries various pollutants that further the decline of receiving surface water quality (NRC, 2008). Common pollutants in urban highway runoff are suspended solids, nutrients, and heavy metals (Kayhanian et al., 2003).

The NRC (2008) identified urban stormwater as the main source of impairment for 13 percent of rivers and 32 percent of estuaries in the U.S. In 2010, the US EPA established a total maximum daily load (TMDL) for the Chesapeake Bay, the largest estuary in the United States. The Chesapeake Bay watershed exhibited significant urbanization between 1990 and 2000, with the impervious surface area increasing by 41% (Jantz et al., 2005). The TMDL was prompted by continued poor water quality in the Bay and its tributaries. The TMDL sets limits for the total mass of phosphorus, nitrogen, and sediment supplied to the Bay. Phosphorus and nitrogen are the main contributors to eutrophication. The necessary reductions to meet the TMDL limits are spread across six states, including Maryland. The sources and concentrations of the Bay TMDL pollutants and select heavy metals in urban runoff are discussed below.

1.2 – Sediment measured as Total Suspended Solids

Total suspended solids (TSS) are defined as the particulates captured by a 0.45 μm pore size glass fiber filter (APHA *et al.*, 1995). Average TSS concentrations in highway runoff have been found to range between 110 mg/L and 420 mg/L (Caltrans, 2003; Flint and Davis, 2007). Pavement and vehicle part abrasion contribute particulates along with street maintenance activities and atmospheric deposition (Sansalone and Buchberger, 1997; Irish et al., 1998). Particles also have the capacity to bind with heavy metals and introduce them to receiving waters (Sansalone and Buchberger, 1997). Suspended solids can negatively impact aquatic life in numerous ways. High concentrations of particles can block sunlight from reaching aquatic vegetation, clog fish gills, and clog filtering mechanics of benthic organisms (TMDL TSS Anacostia River Basin, 2007).

1.3 - Nutrients

Phosphorus, an essential nutrient for plant growth, enters runoff through fertilizers and the deterioration of vegetation (Davis and McCuen, 2005; Davis et al., 2006). Phosphorus occurs in multiple forms in stormwater: particulate phosphorus, orthophosphate, and dissolved organic phosphorus (LeFevre et al., 2015), but is often reported as total phosphorus (TP). Average TP concentrations for urban highways have been reported between 0.08 mg/L and 0.37 mg/L (Wu et al., 1998). Excess phosphorus can result in eutrophication, which is detrimental to water quality and aquatic life (Dodds et al., 2009). The U.S. EPA (2002) recommends a TP concentration of 0.0365 mg/L for streams in Ecoregion IX, which includes Washington, D.C. and parts of Maryland and Virginia.

Nitrogen is present in numerous forms in urban runoff, mainly as the dissolved forms ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) (Taylor et al., 2005). Nitrogen enters the environment through the breakdown of vegetation, atmospheric deposition, and fertilizer application (Galloway et al., 2003; Davis and McCuen, 2005). Nitrogen is often applied in fertilizer as ammonia (NH_3) but may leach into water where it is converted to its conjugate acid ammonium. Ammonium is then commonly transformed to nitrate with nitrite as an intermediate through the nitrification process. The ammonia limit for chronic exposure in freshwater is 1.9 mg/L to protect sensitive invertebrates (EPA, 2013). Nitrogen concentrations are often reported as Total Kjeldahl Nitrogen (TKN) which is the sum of organic nitrogen and ammonium. TKN concentrations in urban runoff have been found to range from 0.87 mg/L to 2.4 mg/L (Opher and Friedler, 2010; Wu et al., 1998). Total nitrogen concentrations in Ecoregion IX streams are recommended not to exceed 0.69 mg/L (EPA, 2002). Excess nitrogen can contribute to eutrophication, particularly in the form of nitrate because it is readily used by plants (Davis and McCuen, 2005).

1.4 – Heavy Metals

Heavy metals are a concern in stormwater because they are persistent and cannot be degraded or destroyed. Many heavy metals pose a hazard to human health and aquatic life. Lead is known to be toxic to humans and can have developmental impacts on children (EPA, 2009). The maximum contaminant level in drinking water is set by the U.S. EPA as 0.015 mg/L (EPA, 2009). Lead had been a component of gasoline and paint but was banned in 1973 and 1978, respectively (EPA, 1973; CPSC, 1977). Total lead concentrations in runoff have been reported between 6.0 μg/L and 525 μg/L (Wu et al., 1998; Driscoll et al., 1990). Current sources to runoff include siding on older buildings and tire wear (Davis et al., 2001; McKenzie et al., 2009). The lead limit for aquatic life chronic exposure in freshwater has been set at 2.5 μg/L (COMAR, 2016).

Copper is a heavy metal that can be toxic to aquatic life at low concentrations. The state of Maryland has set an acute exposure limit of 13 μg/L and a chronic exposure limit of 9 μg/L for surface fresh waters (COMAR, 2016). Copper in runoff has been attributed to the wearing of automobile brakes (Davis et al., 2001; McKenzie et al., 2009). Building siding was also identified as a major contributor of copper by Davis et al. (2001) with tire wear contributing a small portion; McKenzie (2009) correlated copper to brake wear in simulated runoff. Total copper concentrations in highway runoff are reported between 2.5 μg/L and 325 μg/L (Sansalone and Buchberger, 1997; Wu et al., 1998).

Zinc is introduced to the environment mainly by siding, similar to lead (Davis et al., 2001). Tire wear has also been shown to be a major source of zinc in urban runoff (Irish et al., 1998; Davis et al., 2001; McKenzie et al., 2009). The U.S. EPA and Maryland have set acute and chronic exposure limits of 120 μg/L for surface fresh waters. Reported zinc concentrations in highway runoff have far surpassed that limit, with values ranging from 195 μg/L to 15,244 μg/L (Sansalone and Buchberger, 1997; Caltrans, 2002).

1.5 – Stormwater Management

Conventional stormwater management practices have focused on end-of-pipe treatments, such as constructed ponds and wetlands, that have the primary goal of peak flow reduction (Persson et al., 1999; Walsh et al., 2005). These treatments often have significant footprints and large drainage areas and may be able to provide recreational and landscape amenities on account of their size (Persson et al., 1999). The stormwater is treated primarily through sedimentation, which can reduce effluent TSS concentrations as well as the amounts of pollutants that bind to particles, such as heavy metals (Karlsson et al., 2010). These facilities can attenuate peak flows for larger storms, which is a common development requirement, however they can pass smaller, more frequent events due to oversized outlet structures meant to prevent clogging (NRC, 2008). These more frequent events may actually be a more significant cause of channel erosion typical of urban streams than the larger storms (Walsh et al., 2005).

Because urban sites do not have the space to allow for traditional stormwater practices, low impact development (LID) has become a popular alternative over the past couple of decades (LeFevre et al., 2015). LID aims to develop in a manner that preserves many of the hydrologic qualities of the original site such as infiltration and runoff volume while providing stormwater management in a more dispersed fashion (NRC, 2008). LID can include development practices as well as structural stormwater management. Development practices range from reducing the amount of impervious surface to minimizing earthwork and erosion and sediment control during construction (NRC, 2008). Control measures are placed closer to the source of runoff which reduces the connection between impervious surfaces and receiving streams, thus limiting flashy flows characteristic of traditional direct connections (Walsh et al., 2005). Infiltration practices provide runoff volume reduction, allow for groundwater recharge, and remove pollutants. Vegetated infiltration practices such as bioretention and vegetated swales can reduce pollutant concentrations through filtration and by trapping pollutants in the organic portion of the soil layer (NRC, 2008). Filtration practices such as sand filters remove pollutants primarily through filtration but lack volume control (Urbonas, 1999). Infiltration practices are more easily incorporated into new development because they require larger footprints, whereas filtration practices are appealing options for retrofits in urban areas because of they require small amounts of space and fit well within traditional drainage systems (NRC, 2008). As LID structural practices become more commonly used to meet stormwater requirements it is important to have an understanding of how they function over their lifespans.

1.6 - Long-Term Performance of Stormwater Management

Studies on the long-term functionality of bioretention have focused on pollutant accumulation in the media in terms of the potential for leaching and toxicity, which is a potential undesirable effect of pollutant accumulation (Komlos and Traver, 2012; Jones and Davis, 2013; Johnson and Hunt, 2016). High metal concentrations have been found to be isolated to the top 5 cm in a 4-year-old cell (Jones and Davis, 2013) and high phosphorus concentrations have been reported in the top 10 cm in a 9-year old cell (Komlos and Traver, 2012), with the capacity for decades of additional accumulation estimated in both. Stormwater control measures are dynamic systems that require periodic maintenance to ensure they are functioning as designed, however specific maintenance protocols may not be established (NRC, 2008). The primary maintenance concerns for bioretention are vegetation upkeep and avoiding surface clogging (Blecken et al., 2017), though Wardynski and Hunt (2012) fount that even when clogging was visually identified in about 44% of cells only 5% of cells demonstrated poor permeability. This finding indicates that surface clogging may not impact the permeability of bioretention media. Nonetheless, maintaining proper vegetation can help keep adequate porosity in the media and prevent clogging (Le Coustumer et al., 2007).

Research on the extended performance of sand filters has been conducted by Urbonas (1999) and Barrett (2003). Urbonas (1999) determined that the performance of a sand filter was dependent on the design configuration, all of which included upstream storage to equalize runoff flows and reduce the TSS loads to the filter. Barrett (2003) evaluated sand filter retrofits for a range of pollutants in urban runoff. Both recommended routine maintenance of scraping the first few cm of media off of the filters to ensure functionality and optimal pollutant removal. Hatt et al. (2008) conducted column studies that showed that sand filters and bioretention display a similar pollutant distribution, with heavy metals trapped in the top few centimeters. Sand filters differed from bioretention cells in that the phosphorus accumulation throughout the sand filter column did not vary significantly (Hatt et al., 2008). Factors that contribute to the clogging of permeable pavers can be extended to sand filters, particularly ones located in trafficked areas. These factors include overhanging vegetation, being exposed to dirty vehicles, and nearby soil disturbance (Blecken et al., 2017). Proper maintenance is necessary to keep the filters operational, with the first few maintenance cycles simply involving scarifying the filter surface, but subsequent cycles requiring removal of the top layer and ultimately the entire filter requiring replacement (Urbonas, 1999). Hatt et al. (2008) considered these recommendations along with the column studies and concluded that removing the first 2-5 cm of media every other year would allow the filter to function for at least 10 years.

1.7 – Project Objectives

This project aims to evaluate the performance of a set of gutter filters that were installed in Maryland 10 years ago to address untreated stormwater runoff. The filters are located along the eastbound side of an urban highway that was identified as a suitable area for LID retrofits in late 2000 (Davis et al., 2006). Prior to installation, a stormwater monitoring program was conducted to collect background data at the site. 32 storm events were collected between June 2002 and October 2003, which is referred to as Phase 1 (Flint and Davis, 2007). The filters were constructed in Fall 2003. They span 43.28 meters following an upstream collection chamber and contain three different media sections separated by baffles (Figure 1.7.2). The eastern end of the filters uses pool filter sand, followed by concrete sand, and the third section is a mixed media that contains perlite, zeolite, and granular activated carbon layered. Following construction, 17 storm events were monitored between November 2003 and October 2004 which is referred to as Phase 2. The filters are located within a parking lane and under many trees. Since construction the filters have received no maintenance and are visibly clogged. The objectives of this study are to (1) evaluate the performance of the 10-year-old unmaintained gutter filter through a stormwater monitoring program and compare to results from Phases 1 and 2; and (2) determine pollutant build-up over the course of ten years by analyzing the filter media. To meet these objectives a sampling program was conducted at the same site and 18 events were collected and characterized between March 2017 and March 2018.


Figure 1.7.1: Gutter filters.

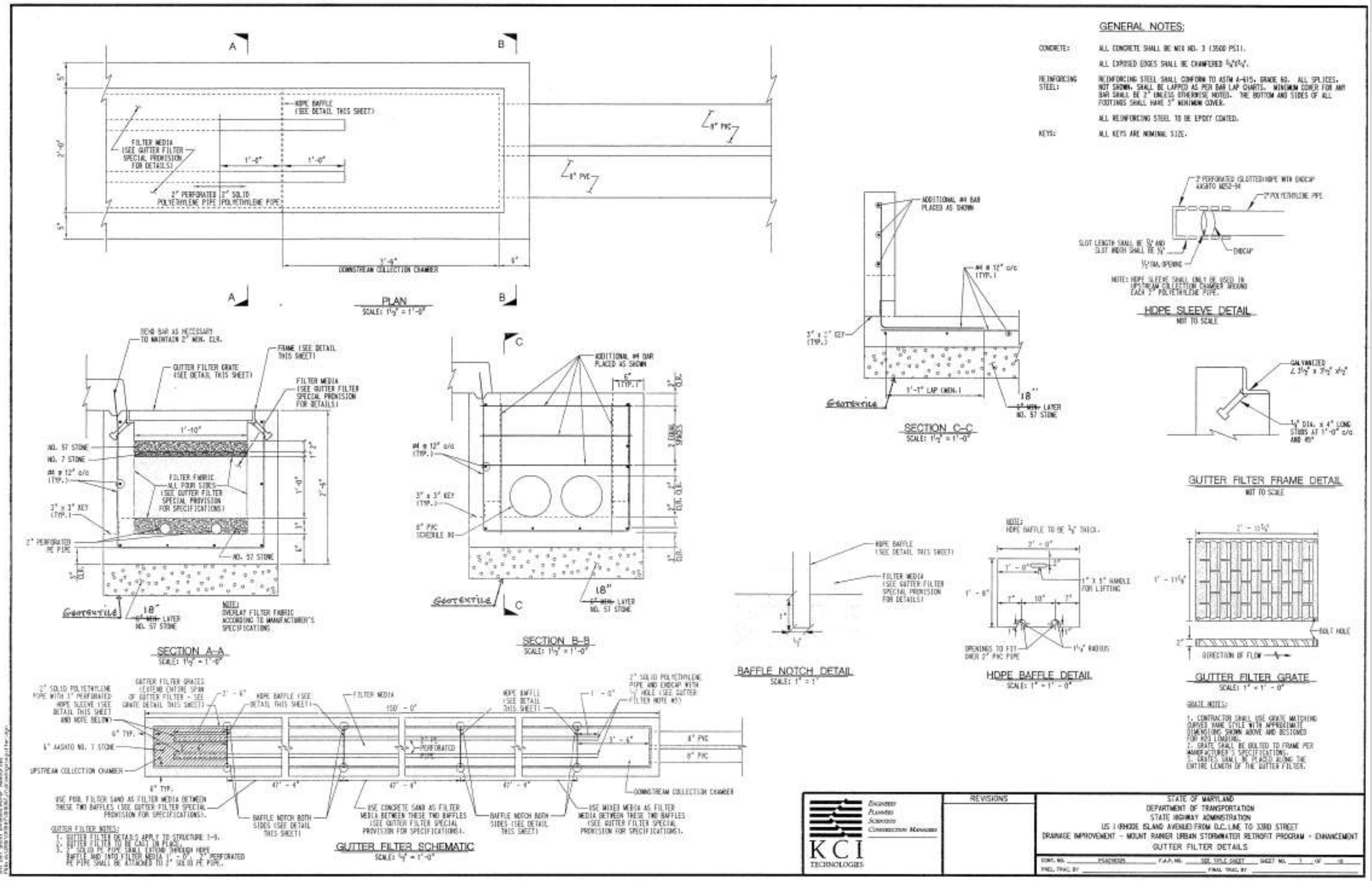


Figure 1.7.2: Gutter filter design plan.

Chapter 2: Methods

2.1 – Site Description

The monitoring site is located in Mount Rainier, Maryland at the intersection of US Route 1 and 33rd Street (38.935975, -76.961980) (Figure 2.2.1). The site is highly urban and is mainly consists of Route 1 and low-rise commercial buildings. Route 1 has an average daily traffic count of 21,721 (MD SHA, 2018). The gutter filters are located on the eastbound side of Route 1, seen in Figure 2.2.2 in blue, and have a drainage area of 2610 m^2. The flow treated by the filters is piped across the road to an inlet at the intersection where it combines with untreated flow from the westbound side of Route 1. The combined flow then enters a flume located below grade just north of the inlet, identified by the red circle in Figure 2.2.2. The site drainage patterns are shown in Figure 2.2.3. The total drainage area to the monitoring point is 5573 m^2.

The drainage area is assumed to have not undergone major changes over the past 10 years. This assumption is based on the fact that the footprint of the roadway and parking areas has not changed and the buildings within the drainage have not been significantly modified.

The project is constrained by the characteristics of the site. The sampling location is such that only slightly less than half of the total drainage area is being treated by the filters and the rest of the flow is untreated. Therefore, even if the filters are able to remove 100% of pollutants the entire site, and thus the sampling, will have only about 50% removal.

2.2 – Monitoring Equipment

The flume is a Tracom 24” Palmer-Bowlus that was left in place from the previous project (Flint, 2004; Pradhan, 2006). An ISCO 6712 Portable Sampler with a bubble flow meter was installed adjacent to the flume (Figure 2.2.4). The bubble flow meter monitored the water level in the flume and was used to calculate flow rates. The flume has a flow range of 8.312 L/second to 268 L/second. The sampler contained 24 one-liter polyethylene bottles that were acid washed prior to being placed in the sampler. Sampling was programmed to begin when the water level in the flume reached 1.52 cm (0.05 ft). 12 samples were collected per storm event with two bottles being filled per sample. Sample timing focused on the early portion of the storm event as seen in Table 2.2.1. The first nine samples were taken at 20 minute intervals and the last three samples taken each hour.

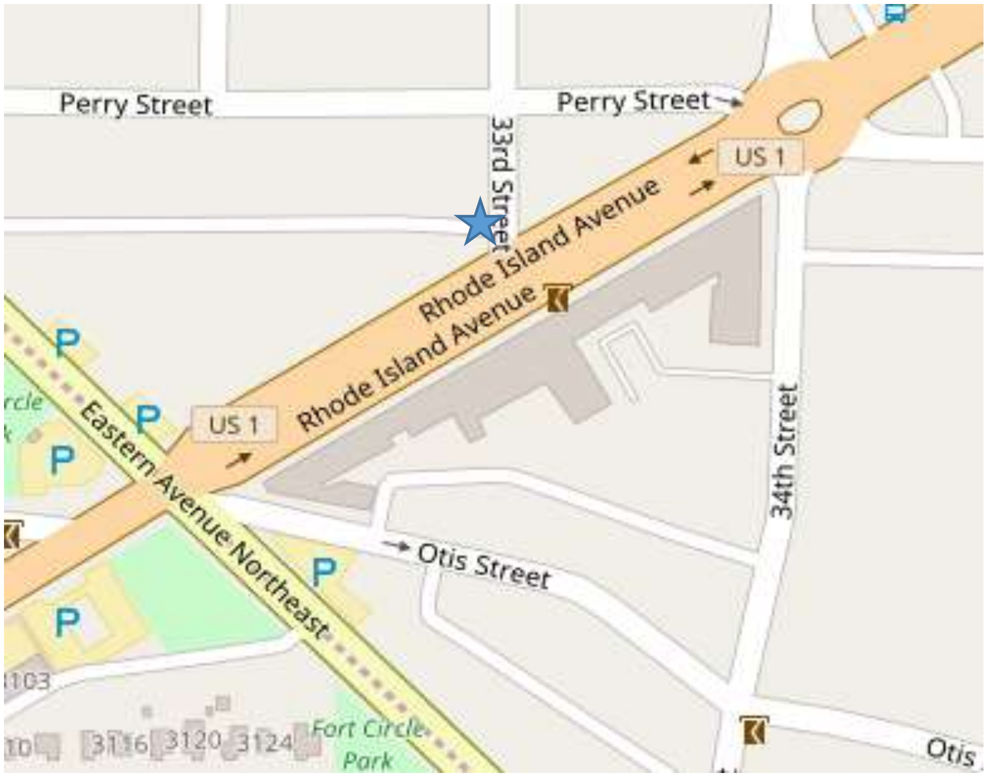


Figure 2.2.1: Monitoring site identified by blue star (MapQuest, accessed January 2017)

Figure 2.2.2: Satellite image of monitoring site (Google Maps, accessed December 2017). Blue rectangle: gutter filters. Red circle: sampling manholes. Green circle: former bioinlet.

Figure 2.2.3: Satellite image of monitoring site (Google Earth, accessed November 2018). Site drainage patterns. Flow treated by the gutter filters is outlined by the blue lines and untreated flow is outlined by the red lines. Treated flow is piped under Route 1 as shown by the blue arrow and combines with the untreated flow before entering the sampling manhole outlined by the red circle.

Figure 2.2.4: Sampler and flume manhole positions

Table 2.2.1: Sampling Times for Automated Collection Program

Sample Number	Time	Sample Number	Time
1	0 minutes	7	2 hours
2	20 minutes	8	2 hr, 20 min
3	40 minutes	9	2 hr, 40 min
4	1 hour	10	3 hr, 40 min
5	1 hr, 20 min	11	4 hr, 40 min
6	1 hr, 40 min	12	5 hr, 40 min

An ISCO 674 Rain Gauge was installed 6.46 km away from the site at the Eppley Recreation Center on the University of Maryland, College Park campus. The rain gauge collected rainfall data at five minute increments during storm events and had a sensitivity of 0.01 in (0.254 mm).

2.3 – Sample Preparation

Samples were retrieved within 24 hours after the end of an event, placed in a cooler, and transported to the Environmental Engineering Laboratory at the University of Maryland, College Park. At the laboratory, approximately 125 mL of sample was filtered through a 0.22 µm filter and frozen for subsequent analysis; 250 mL of unfiltered sample was frozen. Additionally, 100 mL of unfiltered sample was preserved for metal analyses with 2.67 mL of 70% trace metal grade nitric acid (Fischer Chemical certified). Pollutants monitored in stormwater samples included total suspended solids, total phosphorus, total dissolved phosphorus, soluble reactive phosphorus, total nitrogen, nitrate, total copper, total lead, and total zinc as well as pH and conductivity. Pollutant concentrations were determined based on *Standard Methods* (APHA *et al.* 1995) as presented in Table 2.3.1.

Table 2.3.1: Analytical Methods for Analysis of Stormwater

Parameter	Method	Standard Method	Detection Limit	Accuracy	Standards
pH	pH probe & meter	4500-H+B	pH range 2-11	0.01 unit	pH 4.00, 7.00, 10.00, Fisher Scientific
Conductivity	Conductivity probe & meter	2510-B	0-3000 mS/cm	0.001 µS/cm	
Total Suspended Solids	Gravimetric	2540-D	1 mg/L	1 mg/L	
Total Phosphorus	Digestion and spectrophotometry	4500-P B.5 4500-P E	0.01 mg/L as P	0.01 mg/L as P	1000 mg/L as P, Fisher Scientific
Total Dissolved Phosphorus	Digestion and spectrophotometry	4500-P B.5 4500-P E	0.01 mg/L as P	0.01 mg/L as P	1000 mg/L as P, Fisher Scientific
Soluble Reactive Phosphorus	Spectrophotometry	4500-P E	0.01 mg/L as P	0.01 mg/L as P	1000 mg/L as P, Fisher Scientific
Total Nitrogen	Digestion and spectrophotometry	4500-N C 4500-NO_3^-B	0.02 mg/L as N	0.01 mg/L as N	1000 mg/L as N, Fisher Scientific
Nitrate	Ion chromatography	4500-NO_3^-B 4110-B	0.1 mg/L as N	0.1 mg/L as N	1000 mg/L as N, Fisher Scientific
Ammonium	Spectrophotometry	4500-NH_3 F	0.05 mg/L as N	0.05 mg/L as N	Ammonium chloride, pure, Fisher Scientific
Copper, Lead, Zinc	ICP	3030-E ICPE-9000, SHIMADZU	1 µg/L	1 µg/L	10 mg/L Cu, Pb, Zn, Inorganic Ventures

2.4 – Media Sampling

Gutter filter media sampling was conducted on April 14, 2017. The filters were visibly clogged with sediment up to the grate, though the design specifies a gap of 6 in from the top of the filter to the top of the grate. Several sections of the filters had vegetation growing and numerous had trash. Samples were taken from the gutter filters using a 2-cm diameter corer at the middle of each of the three media sections: pool filter sand, concrete sand, and mixed media. The cores were taken at a depth of approximately 38 cm which corresponds to the granular activated carbon (GAC) layer in the mixed media section. Multiple cores were taken from the same grate to ensure adequate mass for analysis, shown in Figure 2.4.1. Sampling locations are shown in Figure 2.4.2. Additionally, cores were taken from the upstream collection chamber. At the laboratory, samples from each media section were combined into one sample and frozen.

Figure 2.4.1: Sample core location

Figure 2.4.2: Media sampling locations (Google Maps, accessed December 2017). From left to right: upstream chamber, mixed media, concrete sand, pool filter sand.

2.5 – Media Analysis

Metals were extracted according to EPA Standard Method 3050B and then analyzed using the same method for stormwater samples. Phosphorus was extracted from the media samples using a Mehlich 3 extracting solution (Mehlich, 2008). The media was oven-dried and sieved through a 2-mm opening sieve. 2.5 grams of dry media were added to a centrifuge tube along with 25 mL of extracting solution and the samples were end-to-end tumbled for 20 minutes at 75 rpm. The extract was analyzed for Mehlich 3 extractable phosphorus on an inductively coupled plasma (ICP) atomic emission spectrometer as done in Sikora et al. (2005), Pittman et al. (2005), and Adesanwo et al. (2013).

Dissolved organic nitrogen was extracted from the media samples using a 2 M KCl solution following the procedure outlined in Jones and Willet (2006). 5 grams of oven-dried, sieved media were added to a centrifuge tube along with 50 mL of solution. The samples were end-to-end tumbled for 20 minutes at 75 rpm and then centrifuged at 3000 rpm for 10 minutes. The extract was analyzed using the same method as for Total Nitrogen.

2.6 – Data Handling and Statistics

For each storm event a capped bottle was left in the manhole to serve as a field blank and upon sample collection it was filled with deionized water and brought back to the lab and analyzed along with the other samples. For nitrate, total nitrogen, and heavy metals analysis, standard checks were run every 10 to 15 samples. If the measured concentration differed by more than 15% the test was re-run. For phosphorus and ammonium, one sample was chosen each event to be run in duplicate. Calibration curves were required to have R^2 values greater than 0.999 and a minimum of five points.

Event mean concentrations (EMCs) were calculated using Equation 2.6.1 and integration by trapezoids to compare pollutant concentrations between different events.

$$EMC = \frac{\int_0^T CQdt}{\int_0^T Qdt} \tag{2.6.1}$$

T represents the event duration or sampling duration, whichever was shorter. C is the pollutant concentration for each sample. Q is the stormwater flowrate and the time between samples is dt. When a sample concentration was below the detection limit, a value equal to half of the detection limit was used when calculating the EMC. If the EMC was below the detection limit, the EMC was reported as half of the detection limit. If a sample was missed or adequate volume was not collected due to a sampling error, an average concentration of the sample before and after the missed sample was used to calculate the EMC. Flow rates were not averaged. If the missed sample was the first or last sample it was not included in the EMC calculation.

Various pollutant species were not directly measured and were calculated as follows. Particulate phosphorus (PP) was calculated by subtracting the total dissolved phosphorus (TDP) concentration from the total phosphorus (TP) concentration.

$$PP = (TP - TDP) \tag{2.6.2}$$

The dissolved organic phosphorus (DOP) concentration was determined by subtracting the soluble reactive phosphorus (SRP) concentration from the TDP concentration.

$$\text{DOP} = (\text{TDP} - \text{SRP}) \qquad (2.6.3)$$

Total Kjeldahl nitrogen (TKN) is the sum of nitrogen bound in organic substances and ammonium. It was estimated by subtracting nitrate from TN, assuming that the majority of total dissolved nitrogen is in the form of nitrate and ammonium.

$$\text{TKN} \approx (\text{TN} - NO_3^-) \qquad (2.6.4)$$

EMCs are presented on exceedance probability plots, which were developed by ranking the values as done in Davis (2007) and plotting as described in Li and Davis (2009).

The Mann-Whitney U test was used to determine statistically significant differences in pollutant concentrations between phases. The null hypothesis was that the population mean of either Phase 1 or Phase 2 was equal to the population mean from the current phase; the alternate hypothesis was that the population mean from Phase 1 or Phase 2 was greater than the population mean from the current phase. Rejecting the null hypothesis indicates the two populations are significantly different. A 5% significance level was chosen to match the analysis by Pradhan (2006).

Annual pollutant loadings were estimated using equation 2.6.5.

$$L = \frac{MP}{AD} \qquad (2.6.5)$$

L is the annual pollutant mass loading in (kg/ha-year). M is the total pollutant mass measured during the study (kg), P is the average annual precipitation (113 cm/year at Reagan National Airport), A is the drainage area in hectares, and D is the total rainfall depth measured during sampling.

Chapter 3: Results

3.1 – Current Water Quality

3.1.1 – Total Suspended Solids

TSS concentrations were measured for a total of 18 storm events between March 2017 and April 2018. The event mean concentrations (EMCs) ranged from 9 mg/L to 271 mg/L with a mean of 110 mg/L and a median of 85 mg/L The exceedance probability plot provides a visual representation of the concentrations measured during the storm events in the current phase (Figure 3.1.1). The TSS water quality goal of 25 mg/L, shown in Table 3.1.1, is identified by the green dashed line. The current study has an 85% probability of exceeding this goal, indicating that the quality of the runoff is not good.

Table 3.1.1: Water quality criteria used in this study

Pollutant	Water Quality Criteria	Source
TSS (mg/L)	25	Davis and McCuen (2005)
TP (mg/L)	0.037	US EPA (2002)
NO_3^- - N (mg/L)	<0.20	Davis and McCuen (2005)
Cu (ug/L)	13	COMAR (2016)
Pb (ug/L)	65	COMAR (2016)
Zn (mg/L)	0.12	COMAR (2016)

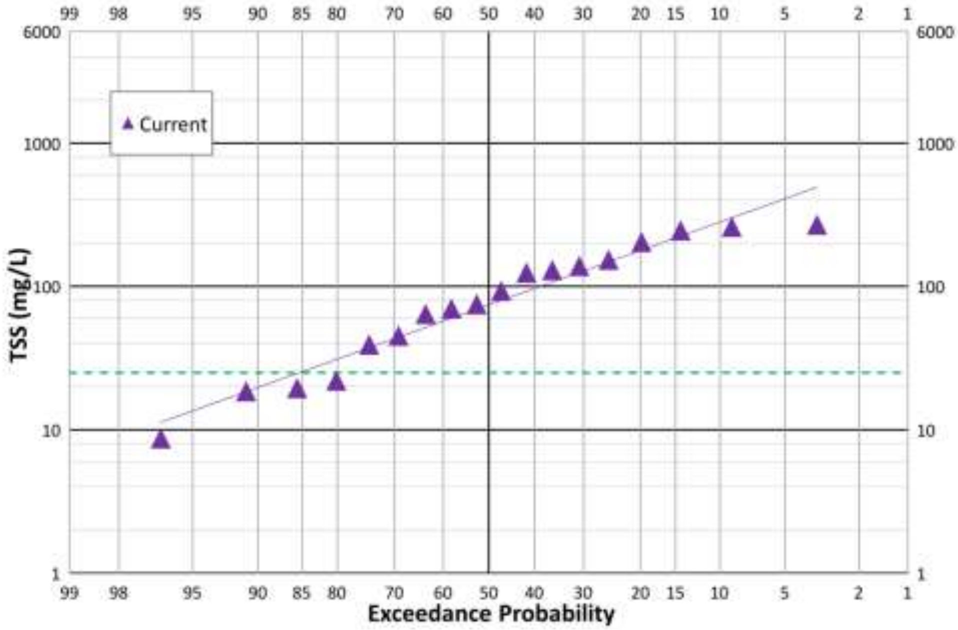


Figure 3.1.1: Probability that a given TSS event mean concentration would be exceeded for the current phase.

3.1.2 – Phosphorus

Total phosphorus, total dissolved phosphorus, and soluble reactive phosphorus concentrations were measured for a total of 18 storm events between March 2017 and April 2018. One event EMC was below the detection limit for total phosphorus and total dissolved phosphorus.

The EMCs for TP ranged from below the detection limit (0.10 mg/L) to 1.28 mg/L with a mean of 0.453 mg/L and a median of 0.368 mg/L. The exceedance probability plot shows the distribution of the storm EMCs in the current phase (Figure 3.1.2). For the current phase, the probability that the TP concentration would exceed 0.4 mg/L is approximately 52%. The water quality goal of 0.037 mg/L, shown in Table 3.1.3, is identified by the green dashed line. The current study consistently exceeds this goal, indicating that the quality of the runoff is poor.

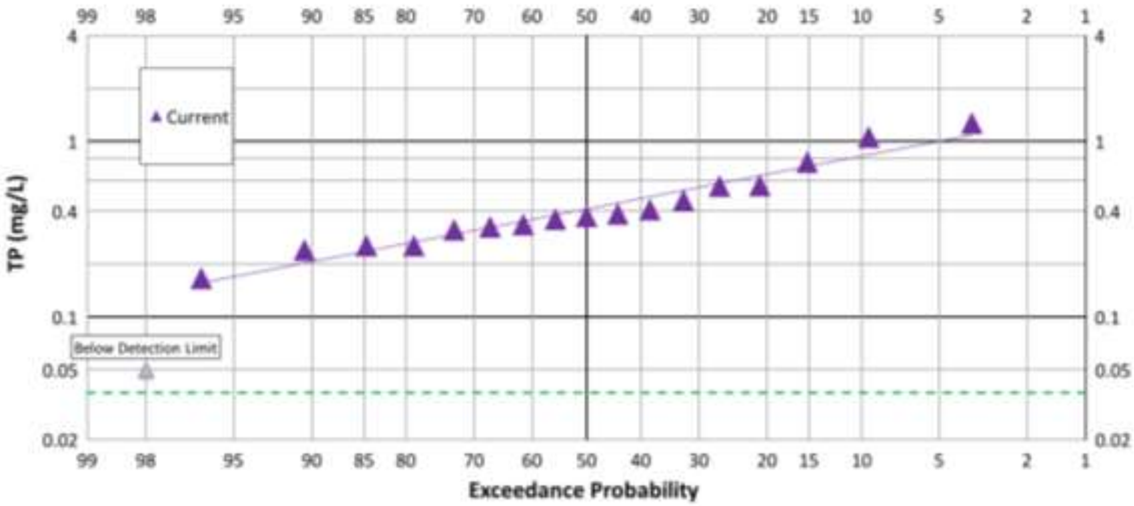


Figure 3.1.2: Probability that a given TP event mean concentration would be exceeded for each of the current phase.

The EMCs for particulate phosphorus (PP) ranged from 0.01 mg/L to 1.28 mg/L with a mean of 0.28 mg/L and a median of 0.23 mg/L. On average, 52% of TP was present as PP. The EMCs for soluble reactive phosphorus (SRP) ranged from 0.02 mg/L to 0.44 mg/L with a mean of 0.12 mg/L and a median of 0.10 mg/L. On average, 24% of TP was present as SRP. The EMCs for dissolved organic phosphorus (DOP) ranged from 0.02 mg/L to 0.50 mg/L with a mean of 0.13 mg/L and a median of 0.06 mg/L. On average, 24% of TP was present as DOP. The exceedance probability plot for PP, SRP, and DOP in the current study is shown in Figure 3.1.3. Phase 1 and Phase 2 did not characterize PP, SRP, and DOP. The percentage of TP present as PP is comparable to that previously found for untreated runoff, which may indicate limited treatment at Mount Rainier. Liu and Davis (2014) found that in untreated runoff 69% of TP was present as PP and after the runoff had been treated by a bioretention cell that percentage dropped to 33%. Selbig (2016) discovered that PP contributions ranged from 50-58% in the spring and summer.

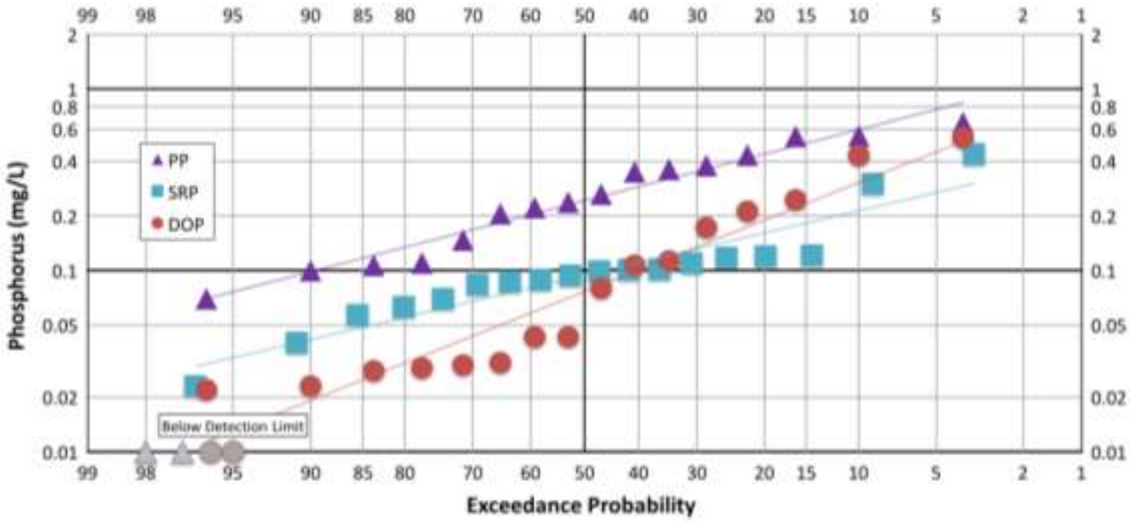


Figure 3.1.3: Probability that a given PP, SRP, and DOP event mean concentration would be exceeded in the current phase.

3.1.3 – Nitrogen

Total nitrogen and nitrate concentrations were measured for a total of 18 storm events and ammonium was measured for 17 storm events between March 2017 and April 2018. For the current study, TKN was calculated as discussed in Section 2.6.

The EMCs for TKN ranged from 0.65 mg/L to 9.00 mg/L with a mean of 3.06 mg/L and a median of 1.93 mg/L. The exceedance probability plot shows the distribution of the storm events in the current phase (Figure 3.1.4). For the current phase, the probability that the TKN concentration would exceed 2 mg/L increased to approximately 58%.

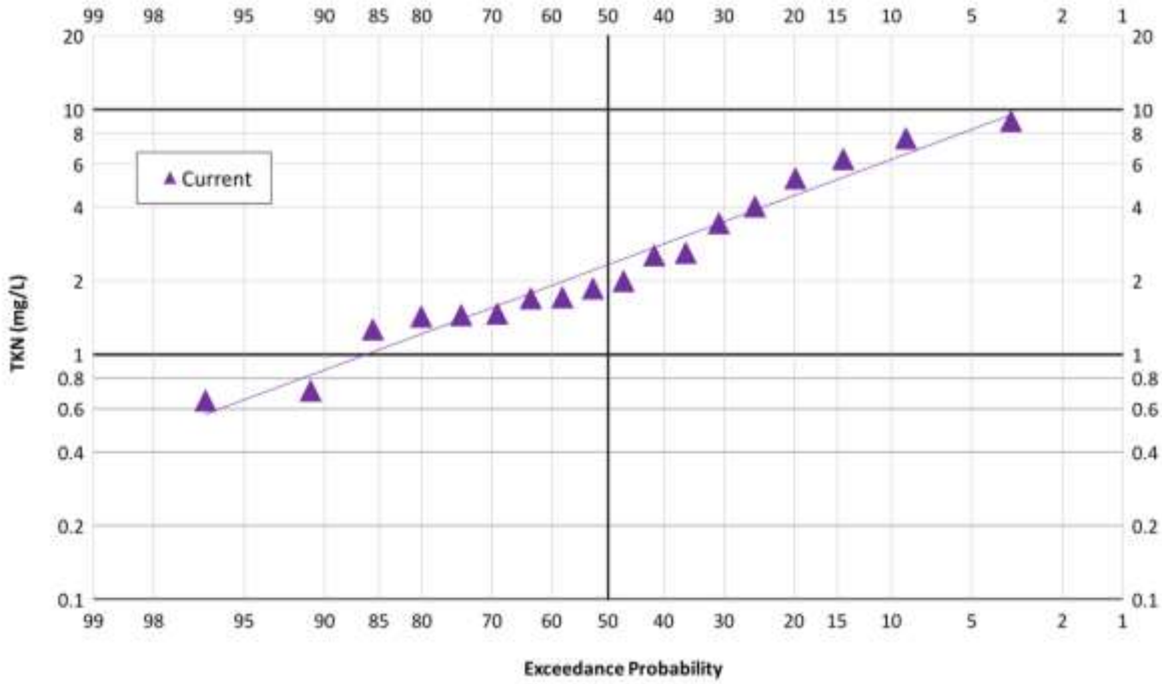


Figure 3.1.4: Probability that a given TKN event mean concentration would be exceeded for the current phase.

The EMCs for nitrate (NO_3^-) ranged from 0.08 mg/L to 3.64 mg/L with a mean of 0.83 mg/L and a median of 0.66 mg/L. The exceedance probability plot displays the differences between the EMCs of the current phase (Figure 3.1.5). The probability that a sample taken during the current study would have a nitrate concentration greater than 0.4 mg/L was about 67%. The water quality goal of 0.20 mg/L, shown in Table 3.1.3, is identified by the green dashed line. The current study has a 90% probability of exceeding this goal, indicating that the runoff quality is poor.

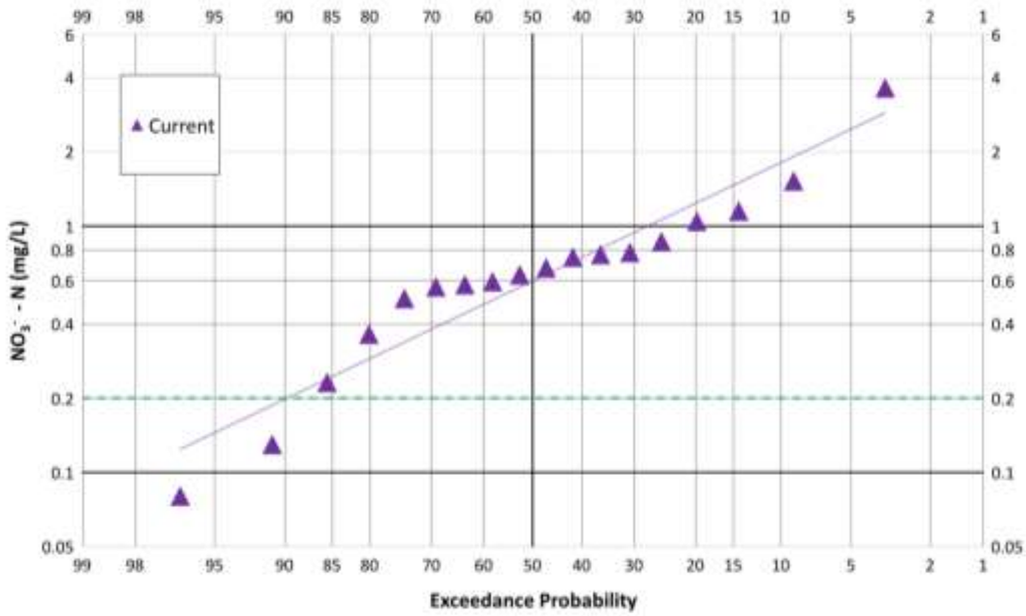


Figure 3.1.5: Probability that a given nitrate event mean concentration would be exceeded for the current phase.

The EMCs for ammonium (NH_4^+) ranged from below the detection limit (0.05 mg/L) to 1.66 mg/L with a mean of 0.602 mg/L and a median of 0.635 mg/L. The exceedance probability plot for ammonium is shown in Figure 3.1.6.

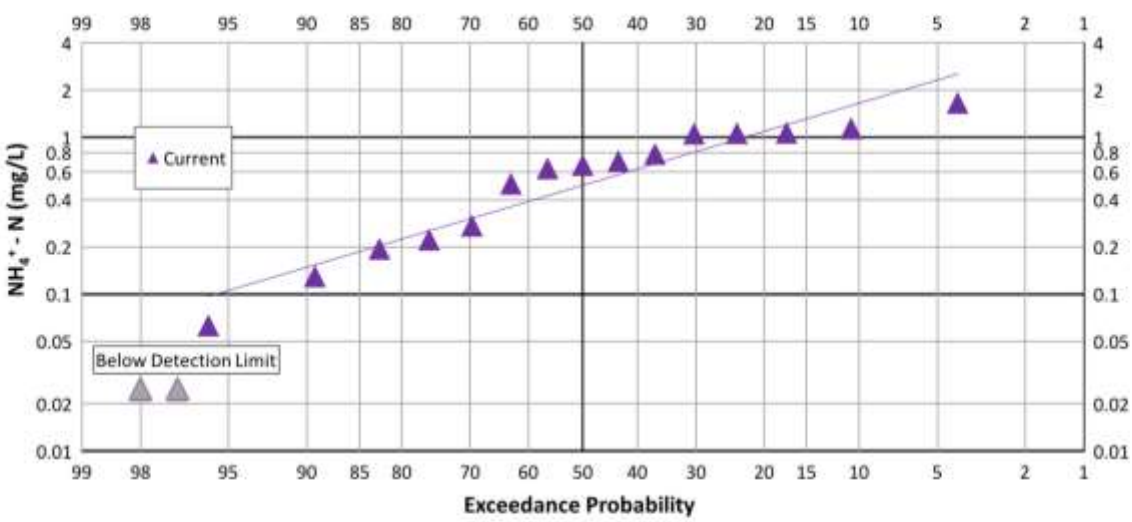


Figure 3.1.6: Probability that a given ammonium event mean concentration would be exceeded for the current phase.

3.1.4 – Heavy Metals

Total copper and total zinc concentrations were measured for 17 storm events and total lead was measured for 5 storm events between April 2017 and April 2018. The EMCs for copper ranged from below the detection limit (25 µg/L) to 391 µg/L with a mean of 105 µg/L and a median of 92 µg/L. The exceedance probability plot shows the storms of the current phase (Figure 3.1.7). The probability that a sample taken during the current phase would have a copper concentration greater than 60 µg/L is about 76%. The water quality limit of 13 µg/L, shown in Table 3.1.3, is identified by the green dashed line. Copper concentrations recorded during the current study consistently exceeds this goal, indicating that the quality of the runoff is hazardous to aquatic life.

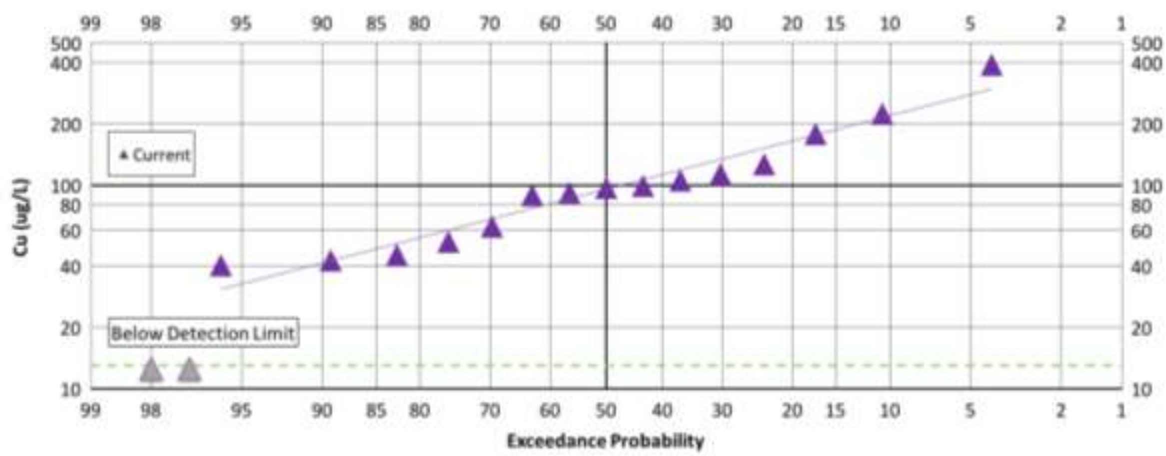


Figure 3.1.7: Probability that a given copper event mean concentration would be exceeded for the current phase.

The EMCs for zinc ranged from below the detection limit (25 µg/L) to 617 µg/L with a mean of 273 µg/L and a median of 300 µg/L. The exceedance probability plot shows the EMCs of the current phase (Figure 3.1.8). The current phase has a 24%

probability of exceeding 400 µg/L. The water quality limit of 120 µg/L, shown in Table 3.1.3, is identified by the green dashed line. The current study has an 87% probability of exceeding this goal which indicates that the quality of the runoff can be hazardous to aquatic life.

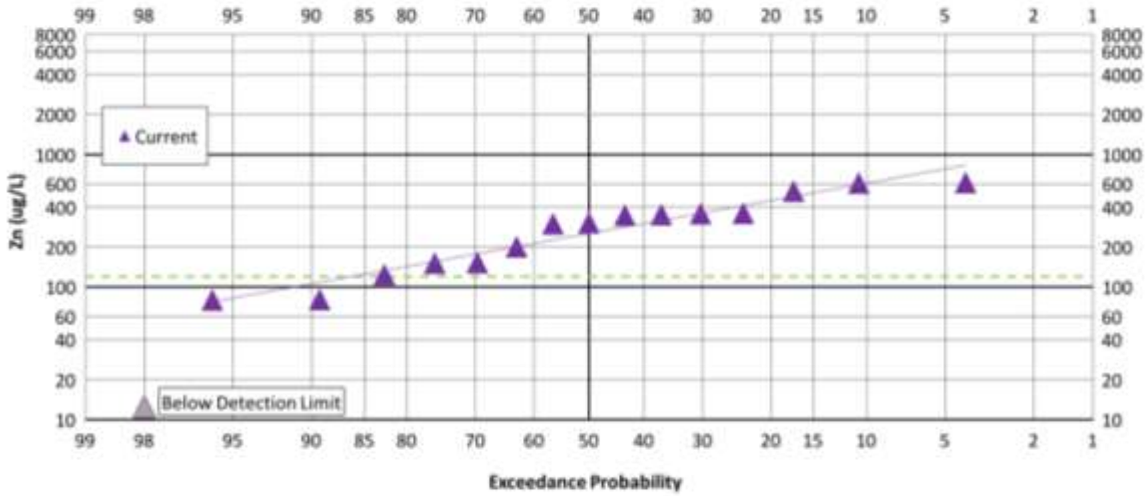


Figure 3.1.8: Probability that a given zinc event mean concentration would be exceeded for each of the current phase.

The EMCs for lead ranged from 11 µg/L to 41 µg/L with a mean of 24 µg/L and a median of 24 µg/L. The exceedance probability plot shows the differences between the storm events in the current phase (Figure 3.1.9). The current phase has a 60% probability of exceeding 20 µg/L. The water quality limit of 65 µg/L, shown in Table 3.1.3, is identified by the green dashed line. The current study did not exceed this goal which indicates that the quality of the runoff is acceptable for aquatic life.

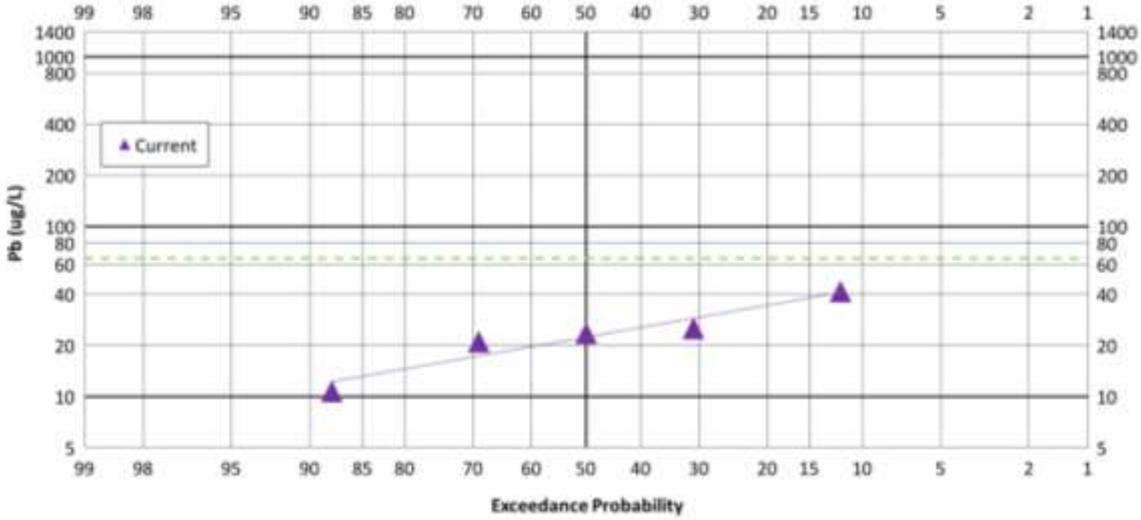


Figure 3.1.9: Probability that a given lead event mean concentration would be exceeded for each of the current phase.

3.2 – Comparison to Highway EMCs

The EMCs for the current phase agree well with previously reported values for runoff from untreated urban highways, presented in Table 3.2.1. Driscoll et al. (1990) and Caltrans (2003) are both large studies that considered data from multiple sites, with Driscoll et al. (1990) analyzing urban highways across the United States and Caltrans (2003) analyzing urban highways in California. Irish et al. (1995) and Wu et al. (1998) are smaller studies that were conducted in Austin, Texas and Charlotte, North Carolina respectively.

The Mount Rainier site and the West 35th site in Austin, Texas have similar drainage areas and runoff coefficients and they both drain curbed roadways (Barrett et al., 1998). However, the TSS median EMC for the current phase is 54% of the median for the West 35th street site and similarly the nitrate median EMC is 66% of its respective median EMC. The copper and lead median values in the current study are 19% of that from the West 35th street site. TP and zinc median EMCs agree well with the respective median values. Assuming no treatment at Mount Rainier, the difference in TSS, nitrate, copper, and lead could be due to the fact that the West 35th site has an average daily traffic (ADT) three times larger than Mount Rainier. Highways with lower traffic densities have been shown to have significantly lower pollutant concentrations than those with ADTs greater than 30,000 (Driscoll et al., 1990).

The median concentration and the concentration range at Mount Rainier are closest to the values at Site II from Wu et al. (1998). TSS, TP, and ammonium EMCs are similar to Site II, whereas the current TKN mean EMC is over twice that from Site II. The current copper mean is over an order of magnitude greater than that of Site II and lead mean EMC is 76% higher. The Mount Rainier drainage area is over twice the size of that of Site II and Site II has more contributing pervious area, but the ADT counts are similar.

Overall, the current pollutant EMC statistics at Mount Rainier fit within the previously reported values for untreated highways, with the exception of TKN and copper which appear to be higher. This similarity indicates that the runoff at Mount Rainier may not be receiving treatment from the gutter filters.

Table 3.2.1: Comparison of current phase EMC statistics with untreated highway studies. All values in mg/L.

Pollutant	Study	Current Phase	Driscoll et al., 1990	Irish et al., 1995		Wu et al., 1998		Caltrans, 2003
				West 35th	Convict Hill	Site I	Site II	
TSS	Mean	110				283	93	112
	Median	85	142	157	83	215	88	59
	Range	9 - 271		40 - 914	0 - 512	32 - 771	9 - 221	1 – 2,988
TP	Mean	0.45				0.43	0.52	0.29
	Median	0.37	0.40	0.41	0.08	0.20	0.37	0.18
	Range	<0.10 – 1.28		0.12 - 1.09	0.005 – 0.38	0.04 - 1.54	0.07 - 1.27	0.03 - 4.69
TKN	Mean	3.06				1.42	1.18	2.06
	Median	1.93	1.83			1.00	0.95	1.40
	Range	0.65 – 9.00				0.68 - 2.45	0.67 - 2.02	0.1 - 17.7
NO_3^- as N	Mean	0.82						1.07
	Median	0.66		1.0	0.73			0.60
	Range	0.08 – 3.64		0.00 – 0.36	0.21 - 1.80			0.11 - 48
NH_4^+ as N	Mean	0.60				0.83	0.76	1.08
	Median	0.64				0.66	0.62	0.77
	Range	<0.05 – 1.66				0.50 - 1.74	0.46 - 1.11	0.33 - 3.9

	Mean	0.105				0.0242	0.0115	0.0335
Cu	Median	0.092	.054	0.49	0.006	0.015	0.012	0.0211
	Range	<0.025 – 0.391		0.01 – 0.12	0.001 – 0. 32	<0.0005 – 0.052	<0.0005 – 0.021	0.0012 – 0.270
	Mean	0.024				0.015	0.0139	0.0478
Pb	Median	0.024	.400	0.123	0.016	0.021	0.013	0.0127
	Range	0.010– 0.041		0.02 – 0.44	0.007 - 0.223	<0.0005 – 0.056	<0.0005 - 0.035	0.001 – 2.60
	Mean	0.273						0.1871
Zn	Median	0.300	.329	0.263	0.053			0.1112
	Range	<0.025 – 0.617		0.06 – 0.59	0.010 – 0.310			0.0055 – 1.68

3.3 – Comparison to Bioretention and Sand Filter Performance

The Mount Rainier concentrations agree well with values for untreated runoff and the mean concentrations are much higher than those in stormwater treated by bioretention systems and sand filters. Comparisons to concentrations for bioretention and sand filter studies are shown in Table 3.3.1. If the gutter filters are still effective, the current pollutant mean EMCs should be similar to the treated concentrations from bioretention and sand filter studies. The current phase mean concentrations are similar to the untreated concentration in Li and Davis (2014), but are distinctly larger than the treated concentrations in all of the studies. Similar patterns are seen in the comparison to sand filter studies, in which the current phase concentrations align with the untreated concentrations of Barrett (2003) but are much higher than all of the treated concentrations.

Direct comparisons to treated concentrations should consider that the sampling in the current phase was conducted downstream of the gutter filter outlet. The treated runoff combining with untreated runoff prior to sampling may explain the difference between the current phase and treated concentrations. The filters receive 47% of the total drainage area to the sampling point. However, based on the EMCs from other studies the filters are not providing the expected benefits.

Table 3.3.1: Comparison of current phase pollutant EMCs with concentrations from bioretention and sand filter studies. All values in mg/L.`

Pollutant	Study	Current Phase	Keblin et al., 1998	Urbonas, 1999[a]	Barrett, 2003	Kandasamy et al., 2008	Hunt et al., 2008	Li and Davis, 2009		Li and Davis, 2014	Liu and Davis, 2014
								CP	SS		
	Practice	Gutter Filter	Sand Filter	Sand Filter	Sand Filter	Sand Filter	Bioretention	Bioretention		Bioretention	Bioretention
TSS	Untreated	110	204	160	90	14	50	66	17	100	97
	Treated		4	16	9	3 - 10	20	6	4	7	6
TP	Untreated	0.48	0.356	0.52	0.41	0.21	0.19	0.1	<0.1		0.300
	Treated		0.126	0.11	0.25	0.12 – 0.13	0.13	0.35	<0.1		0.111
TKN	Untreated	3.06	1.59	3.8	3.02	1.1	1.26	1.2	0.5		
	Treated		0.591	1.1	1.48	0.33	0.70	1.1	0.6		
NO_3^- as N	Untreated	0.83	1.24		0.63			0.36	0.34	0.28	
	Treated		0.74		1.10			1.0	0.05	0.65	
NH_4^+ as N	Untreated	0.60					0.34			0.15	
	Treated						0.10			<0.05	
Cu	Untreated	0.105		0.06	0.021		0.0128	0.019	0.013		
	Treated			0.025	0.010		0.0059	0.016	0.009		

Pb	Untreated	0.024			0.021		0.00485	0.006 <.002		
	Treated				0.003		0.0033	0.003 <.002		
Zn	Untreated	0.273	0.143	0.20	0.236	0.028	0.072	0.071 0.015		
	Treated		0.008	0.033	0.048	0.05 - 0.06	0.017	0.012 0.003		

a: Average pollutant concentration, not an EMC.

3.4 – Annual Pollutant Loading Comparison

The annual pollutant loadings for the drainage area were calculated using Equation 2.6.5 and are shown in Table 3.4.1 along with annual untreated and treated loadings from bioretention drainage areas in the region. The TSS, TP, and nitrate annual loadings for the current phase are similar to the untreated loading of the CP site from Li and Davis (2009) and Liu and Davis (2014). The TSS current loading is over two orders of magnitude larger than the treated loadings from bioretention cells. TKN, copper, lead, and zinc are all much greater than the untreated and treated bioretention loadings. Some of the load reduction seen for bioretention comes from volume reduction through infiltration, which is not present in the gutter filters. Similarity to the untreated loadings indicates that the water quality of the Mt. Rainier site is similar to that of other untreated drainage areas, suggesting minimal benefit from the gutter filters.

Table 3.4.1: Comparison of annual pollutant loadings with previous studies All values in (kg/ha-yr).

Pollutant	Study	Current Phase	Li and Davis, 2009		Li and Davis, 2014	Liu and Davis, 2014
			CP	SS		
TSS	Untreated	1,212	1,190	570	960	1,090
	Treated		37	38	39	47
TP	Untreated	4.20	3.6	0.9		3.0
	Treated		0.72	0.38		0.48
TKN	Untreated	28.5	15	6.0		
	Treated		4.1	3.6		
NO_3^- as N	Untreated	6.67	12	3.7	2.4	
	Treated		2.5	0.19	3.5	
Cu	Untreated	1.09	0.26	0.12		
	Treated		0.73	0.045		
Pb	Untreated	0.78	0.09	.003		
	Treated		0.013	~0.005		
Zn	Untreated	2.79	1.0	0.36		
	Treated		0.063	0.017		

3.5 - Water Quality Comparison of Current Phase to Phase 1 and Phase 2

3.5.1 – Total Suspended Solids

Table 3.5.1 provides a comparison of the current phase TSS EMCs with those from Phase 1, before gutter filter construction, and Phase 2, after construction. The results suggest that the gutter filters are still providing a reduction in TSS as the current mean concentration is 26% of the mean prior to construction of the gutter filters and the current median concentration is 23% of the median of Phase 1, seen in Table 3.5.1. To determine whether the concentrations were statistically different, the Mann-Whitney U Test was employed. A 5% significance level was chosen to match the analysis by Pradhan (2006). The null hypothesis was that the population of either Phase 1 or Phase 2 was equal to the population from the current phase and the alternate hypothesis was that the population from Phase 1 or Phase 2 was greater than the population from the current phase. Rejecting the null hypothesis indicates the two populations are significantly different. Table 3.5.2 shows the test statistics from both tests and the conclusions. The Mann-Whitney U Test confirmed that the populations of Phase 1 and the current phase were significantly different.

The results also imply that there has been a large improvement between Phase 2, after gutter filter construction, and the current condition as the mean TSS concentration has decreased by 70% as seen in Table 3.5.1. However, the ratio of the median concentrations suggests an increase of 50% between the Phase 2 and the current phase. The Mann-Whitney U Test indicated no statistically significant difference between Phase 2 and the current phase despite large differences in concentration indicated by the median ratio and mean ratio, respectively.

Table 3.5.1: Comparison of TSS EMCs before gutter filter construction, after construction, and current state.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)				
41 - 1600	428	373	7 – 4539	364	55	9 – 271	110	85	0.26	0.23	0.30	1.5

Table 3.5.2: Mann-Whitney U Test statistics and results for TSS.

Test	$z_{computed}$	$z_{0.05}$	Populations significantly different?
Phase 1 > Current?	3.748	1.645	Yes
Phase 2 < Current?	-0.966	-1.645	No

The exceedance probability plot provides a visual representation of the differences in the populations of the three phases (Figure 3.5.1). Phase 1 has noticeably greater concentrations than Phase 2 and the current phase. Phase 2 and the current phase intersect which makes it unlikely that they would be statistically different, which is typical of samples from the same population. The probability that a sample taken during Phase 1 would have a TSS concentration greater than 100 mg/L was approximately 86%, whereas in Phase 2 that probability dropped to about 39%. The highest point in Phase 2 was identified as an outlier by Pradhan (2006). The distribution with this point removed is shown by the blue dashed line in Figure 3.5.1. Without the outlier, Phase 2 and the current phase do not intersect but there is still no statistically significant difference between the phases. Based on the data collected, the filters are not providing the expected TSS reduction.

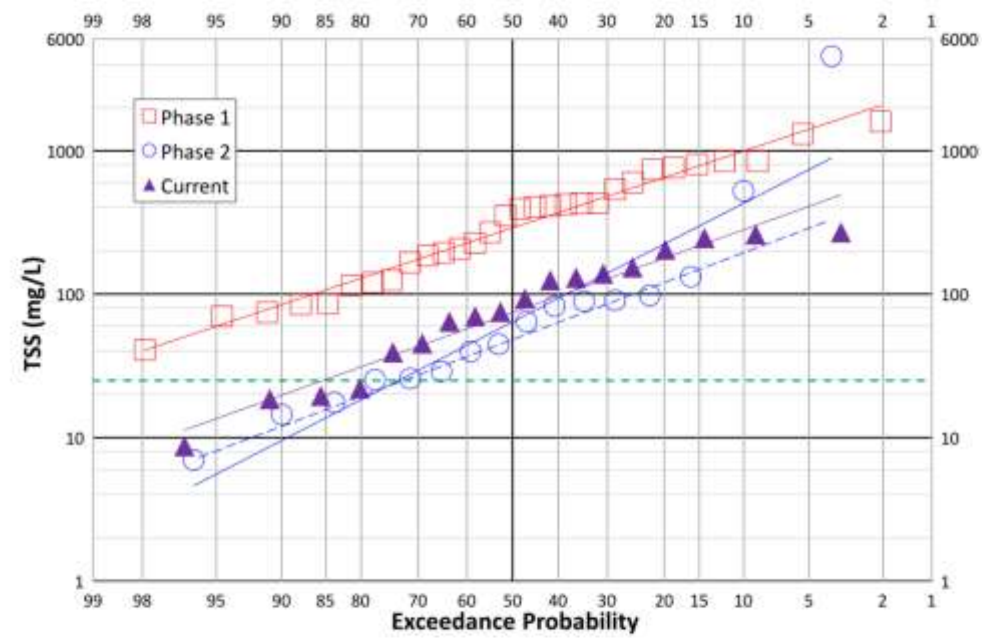


Figure 3.5.1: Probability that a given TSS event mean concentration would be exceeded for each of the three study phases.

3.5.2 – Total Phosphorus

Table 3.5.3 provides a comparison of the EMCs for TP with those from Phase 1, before gutter filter construction, and Phase 2, after construction. The results suggest that the gutter filters are still providing a moderate reduction in TP as the current mean concentration is 20% lower than the mean prior to construction of the gutter filters and the current median concentration is 22% lower than the median of Phase 1, seen in Table 3.5.3. Table 3.5.4 shows the test statistics from the hypothesis test between Phase 1 and the current study and Phase 2 and the current study as well as the conclusions. The Mann-Whitney U Test did not find that the populations of Phase 1 and the current phase and Phase 2 and the current study were significantly different.

Table 3.5.3: Comparison of TP EMCs before gutter filter construction, after construction, and current state. BDL: below detection limit.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)				
0.129 – 1.92	0.564	0.472	0.2 – 1.46	0.68	0.588	BDL – 1.28	0.53	0.58	0.80	0.78	0.67	0.63

Table 3.5.4: Mann-Whitney U Test statistics and results for TP.

Test	$z_{computed}$	$z_{0.05}$	Populations significantly different?
Phase 1 > Current?	0.937	1.645	No
Phase 2 > Current?	1.410	1.645	No

The exceedance probability plot shows the minimal differences in the populations of the three phases (Figure 3.5.2). All three phases have similar TP concentrations. The probability that a sample taken during Phase 1 would have a TP concentration greater than 0.4 mg/L was about 60%, whereas in Phase 2 that probability increased to 70%. For the current phase, the probability that the TP concentration would exceed 0.4 mg/L is approximately 52%. Based on the data collected, the filters are not providing a reduction in TP.

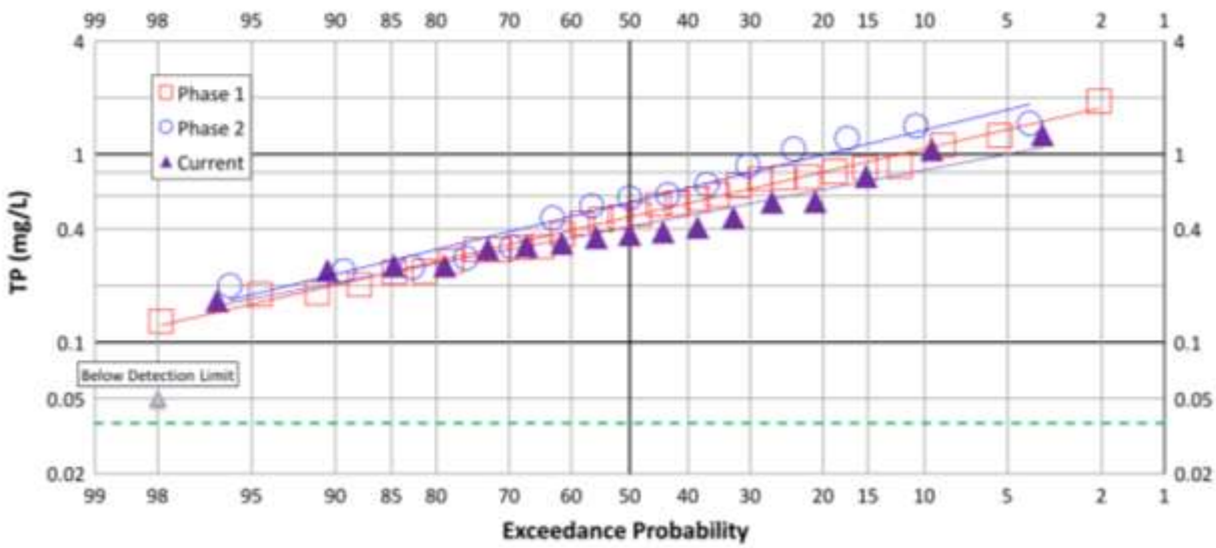


Figure 3.5.2: Probability that a given TP event mean concentration would be exceeded for each of the three study phases.

3.5.3 – Nitrogen

Phase 1 and Phase 2 directly measured total Kjeldahl nitrogen (TKN) and nitrate. For the current study, TKN was calculated as the difference between total N and oxidized N, as discussed in Section 2.6. Table 3.5.5 provides a comparison of the current TKN

EMCs with those from Phase 1, before gutter filter construction, and Phase 2, after construction.

The results suggest that the gutter filters are providing a slight reduction in TKN as the current mean concentration is 10% lower than the mean before construction and the current median concentration is 14% lower than the median of Phase 1, seen in Table 3.5.5. The Mann-Whitney U Test did not find that the populations of Phase 1 and the current phase were significantly different. The results imply that there has been a decline in function between Phase 2, after gutter filter construction, and the current condition as the mean and median TKN concentrations have increased by 63% as seen in Table 3.5.5. The Mann-Whitney U Test determined that Phase 2 and the current phase were statistically different.

Table 3.5.5: Comparison of TKN EMCs before gutter filter construction, after construction, and current state.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)				
0.82 – 10.2	3.42	2.53	0.32 – 7.03	1.88	1.19	0.65 – 9.00	3.06	1.93	0.90	0.76	1.63	1.63

Table 3.5.6: Mann-Whitney U Test statistics and results for TKN.

Test	$z_{computed}$	$z_{0.05}$	Populations significantly different?
Phase 1 > Current?	0.933	1.645	No
Phase 2 < Current?	-1.952	-1.645	Yes

The exceedance probability plot shows the differences between the EMCs of the three phases (Figure 3.5.3). Phase 1 and the current phase appear to have similar concentrations, but the current phase clearly has higher concentrations than Phase 2. The probability that a sample taken during Phase 1 would have a TKN concentration greater than 2 mg/L was about 70%, whereas in Phase 2 that probability dropped to 33%. Based on the data collected, the filters are not providing the expected TKN reduction.

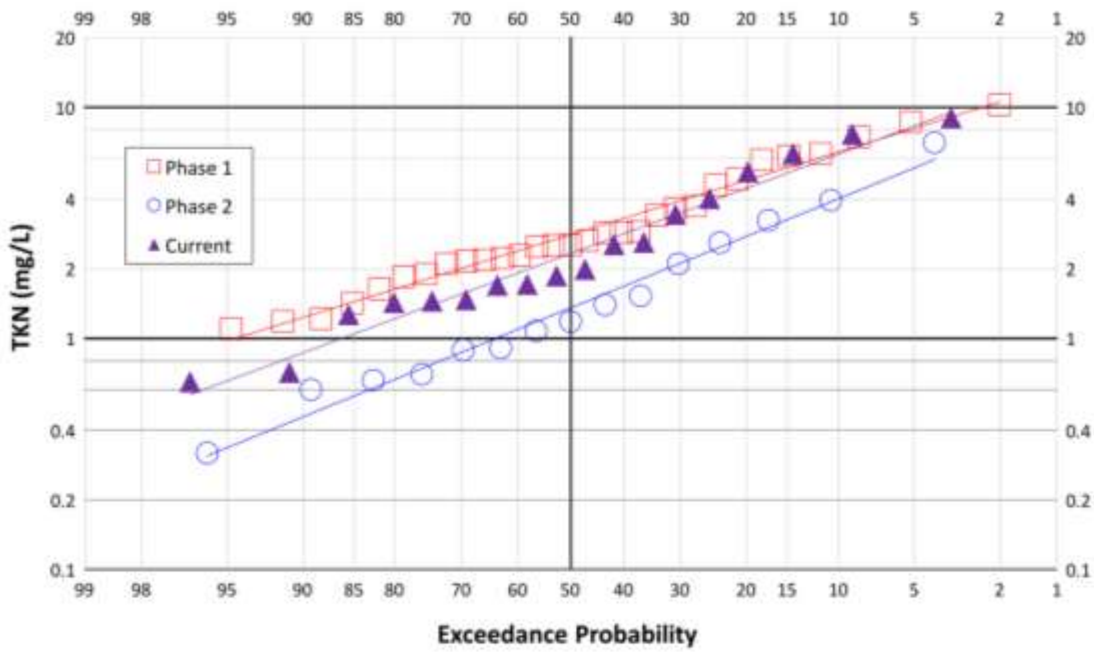


Figure 3.5.3: Probability that a given TKN event mean concentration would be exceeded for each of the three study phases.

Table 3.5.7 provides a comparison of the current phase nitrate EMCs with those from Phase 1, before gutter filter construction, and Phase 2, after construction. The mean ratio suggests that the gutter filters are not providing a reduction in nitrate as the current mean concentration is 3% lower than the mean before construction, but the median ratio suggests that there is a 27% increase in nitrate. The Mann-Whitney U Test did not find a statistically significant difference between Phase 1 and the current phase. The results imply a reduction in nitrate between Phase 2, after gutter filter construction, and the current condition as the mean concentration has decreased by 32%, however the median concentration has increased by 9% as seen in Table 3.5.7. The Mann-Whitney U Test was not applied to Phase 1 and Phase 2, or Phase 2 and the current phase due to the small sample size of Phase 2.

Table 3.5.7: Comparison of nitrate as N EMCs before gutter filter construction, after construction, and current state.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)	Range (mg/L)	Mean (mg/L)	Median (mg/L)				
0.141 – 4.27	0.852	0.515	0.15 – 3.49	1.21	0.599	0.08 – 3.64	0.83	.66	0.97	1.27	0.68	1.09

Table 3.5.8: Mann-Whitney U Test statistics and results for nitrate.

Test	$z_{computed}$	$z_{0.05}$	Populations significantly different?
Phase 1 > Current?	-0.542	1.645	No
Phase 2 > Current?	N/A	N/A	N/A

The exceedance probability plot displays the differences between the EMCs of the three phases (Figure 3.5.4). Phase 1 and the current phase appear to have similar concentrations, and their regression lines are almost identical. The slope of the current phase best fit line is 2% smaller than the Phase 1 line and the intercept is 8% smaller than that of Phase 1. The probability that a sample taken during Phase 1 would have a nitrate concentration greater than 0.4 mg/L was about 65%, and in Phase 2 that probability was similar at 62%, as well as for the current study at 67%.

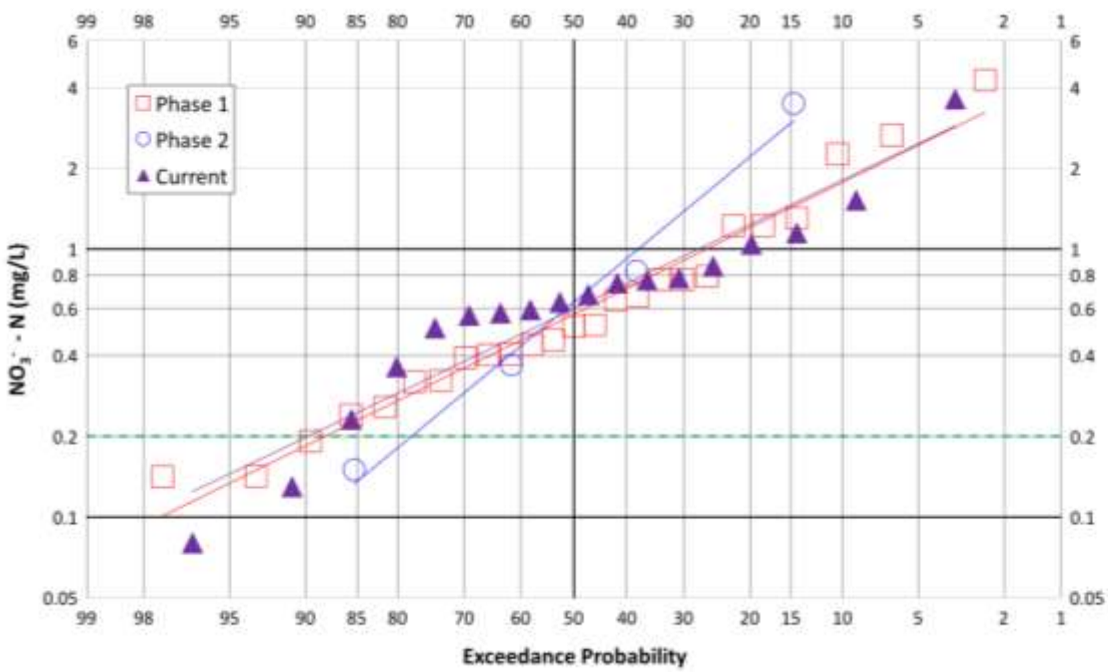


Figure 3.5.4: Probability that a given nitrate event mean concentration would be exceeded for each of the three study phases.

3.1.4 – Heavy Metals

Table 3.5.9 provides a comparison of current copper EMCs with those from Phase 1, before gutter filter construction, and Phase 2, after construction. Approximately half of the copper in stormwater has been shown to be present in the particulate phase (Dean et. al., 2005). Therefore, if the gutter filters are still providing treatment current copper EMCs would be expected to be lower than Phase 1. The results suggest that the gutter filters are not providing treatment for copper as the current mean concentration is only 2% lower than the mean prior to construction of the gutter filters and the current median concentration is 3% higher than the median of Phase 1, seen in Table 3.5.9. Table 3.5.10 shows the test statistics from the hypothesis test between Phase 1 and the current study and Phase 2 and the current study as well as the conclusions. The Mann-Whitney U Test did not find that the populations of Phase 1 and the current phase and Phase 2 and the current study were significantly different.

Table 3.5.9: Comparison of copper EMCs before gutter filter construction, after construction, and current state. BDL: below detection limit.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (µg/L)	Mean (µg/L)	Median (µg/L)	Range (µg/L)	Mean (µg/L)	Median (µg/L)	Range (µg/L)	Mean (µg/L)	Median (µg/L)				
24 – 290	108	89	18 – 150	64	55	BDL – 391	105	92	0.98	1.03	1.63	1.67

Table 3.5.10: Mann-Whitney U Test statistics and results for copper.

Test	$z_{computed}$	$z_{0.05}$	Populations significantly different?
Phase 1 > Current?	-0.651	1.645	No
Phase 2 < Current?	-1.551	-1.645	No

The exceedance probability plot shows the differences between the EMCs of the three phases (Figure 3.5.5). Phase 1 and the current phase seem to have comparable concentrations, but the current phase clearly has higher concentrations than Phase 2. The probability that a sample taken during Phase 1 and the current phase would have a copper concentration greater than 60 µg/L is about 76%, whereas in Phase 2 that probability decreased to 45%. Based on the data collected, the filters are not providing the expected reduction in copper.

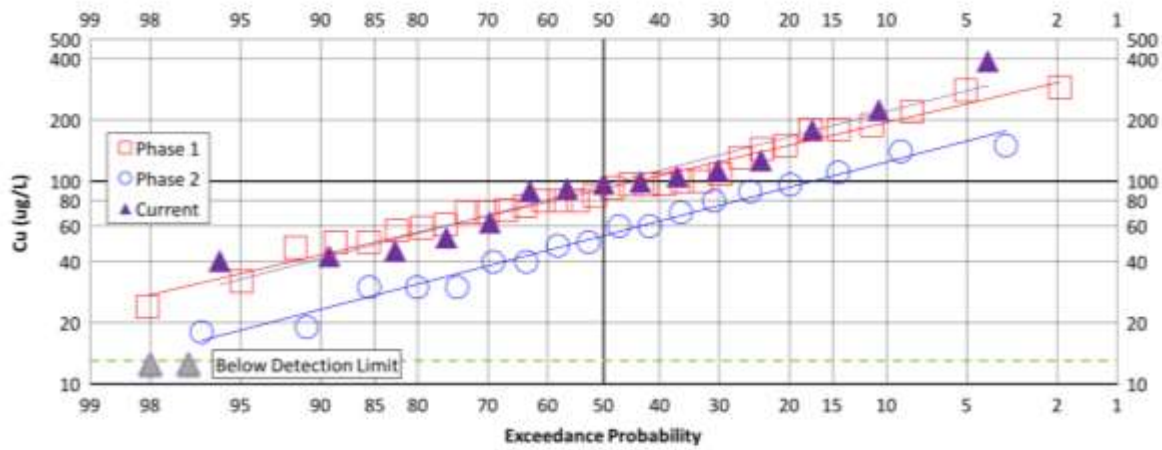


Figure 3.5.5: Probability that a given copper event mean concentration would be exceeded for each of the three study phases.

Table 3.5.11 provides a comparison of the current zinc values with those from Phase 1, before gutter filter construction, and Phase 2, after construction. The results suggest that the gutter filters are still providing a reduction in zinc as the current mean concentration is 23% of the mean prior to construction of the gutter filters and the current median concentration is 37% of the median of Phase 1, seen in Table 3.5.11. The current mean concentration is also 33% lower than that of Phase 2 and the current median concentration is 14% lower. Table 3.5.12 shows the test statistics from the hypothesis test between Phase 1 and the current study and Phase 2 and the current study as well as the conclusions. The Mann-Whitney U Test found a statistically significant difference between Phase 1 and the current phase but no significant difference between Phase 2 and the current phase.

Table 3.5.11: Comparison of zinc EMCs before gutter filter construction, after construction, and current state. BDL: below detection limit.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (µg/L)	Mean (µg/L)	Median (µg/L)	Range (µg/L)	Mean (µg/L)	Median (µg/L)	Range (µg/L)	Mean (µg/L)	Median (µg/L)				
182 – 6030	1182	813	50 – 760	352	347	BDL – 617	273	300	0.23	0.37	0.77	0.86

Table 3.5.12: Mann-Whitney U Test statistics and results for zinc.

Test	$z_{computed}$	$z_{0.05}$	Populations significantly different?
Phase 1 > Current?	4.893	1.645	Yes
Phase 2 > Current?	1.367	1.645	No

The exceedance probability plot shows the differences between the EMCs of the three phases (Figure 3.5.6). Zinc has been shown to be more prominent in the particulate phase in high flow rate events, which would allow the filters to be more effective in removing zinc (Dean et. al., 2005). This removal is seen between Phase 1 and Phase 2. Phase 1 has larger concentrations than both Phase 2 and the current phase, which appear to have similar concentrations. The probability that a sample taken during Phase 1 would have a zinc concentration greater than 400 µg/L was 85%, whereas in Phase 2 that probability decreased to about 33%. Based on the data collected, the filters may still be providing a reduction in zinc.

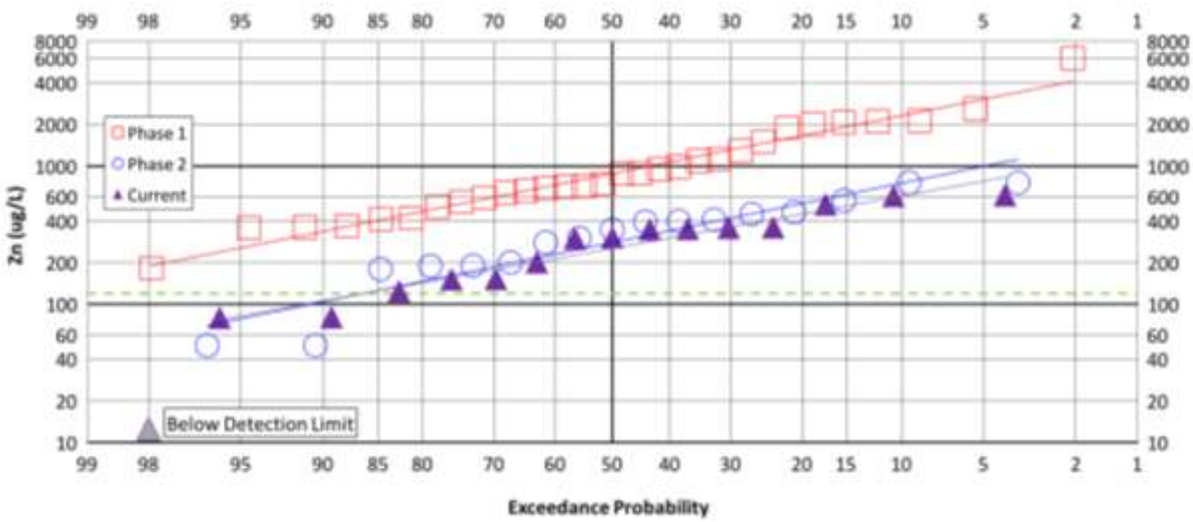


Figure 3.5.6: Probability that a given zinc event mean concentration would be exceeded for each of the three study phases.

Table 3.5.13 provides a comparison of the current lead EMCs with those from Phase 1, before gutter filter construction, and Phase 2, after construction. Lead is predominantly particulate-bound and thus the current lead EMCs would be expected to be lower than Phase 1 if the filters are still functioning (Dean et. al., 2005). The results suggest that the gutter filters are still providing a reduction in lead as the current mean concentration is 11% of the mean prior to construction of the gutter filters and the current median concentration is 24% of the median of Phase 1, seen in Table 3.15.13. The current mean concentration is also 77% lower than that of Phase 2 and the current median concentration is 59% lower. Due to the small sample size of the current study, the Mann-Whitney U test could not be applied to identify significant differences between the current phase and Phases 1 and 2.

Table 3.1.13 Comparison of lead EMCs before gutter filter construction, after construction, and current state.

Phase 1			Phase 2			Current			Ratio of Mean $\frac{Current}{Phase\ 1}$	Ratio of Median $\frac{Current}{Phase\ 1}$	Ratio of Mean $\frac{Current}{Phase\ 2}$	Ratio of Median $\frac{Current}{Phase\ 2}$
Range (µg/L)	Mean (µg/L)	Median (µg/L)	Range (µg/L)	Mean (µg/L)	Median (µg/L)	Range (µg/L)	Mean (µg/L)	Median (µg/L)				
10 – 1220	223	98.5	10 – 910	107	58.3	11 – 41	24	24	0.11	0.24	0.23	0.41

The exceedance probability plot shows the differences between the EMCs of the three phases (Figure 3.5.7). Phase 1 has larger concentrations than both Phase 2 and the current phase. The current phase appears to have lower concentrations than Phase 2 but also has a limited data set. Phase 1 would consistently have a lead concentration greater than 20 µg/L, whereas Phase 2 has a 76% probability of exceeding that concentration. Based on the data collected, the filters may still be providing a reduction in lead. However lead has been phased out of materials over the past few decades. The U.S. EPA began the phase-out of lead in gasoline in 1976 and completed it in 1996. The sale of residential lead-based paint was banned in 1978. Therefore, the decreased lead concentrations could be due to the overall decrease in the use of lead in the drainage area and not the direct result of the filters.

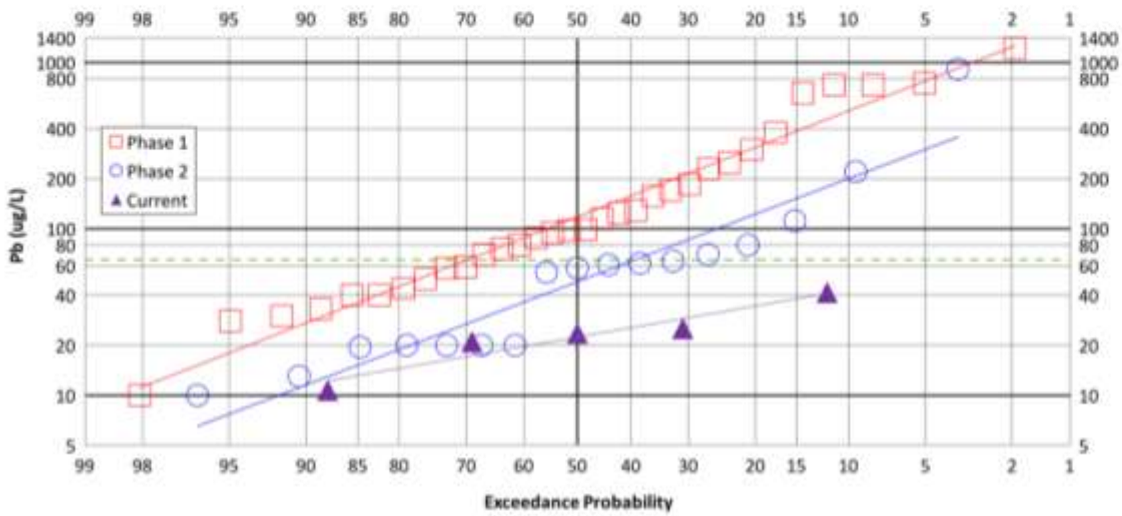


Figure 3.5.7: Probability that a given lead event mean concentration would be exceeded for each of the three study phases.

3.6 – First Flush

The presence of a first flush phenomenon for all pollutants was evaluated using the criteria set by Wanielista and Yousef (1993), which states that 50% of the total pollutant mass must runoff within the first 25% of the runoff volume. Table 3.6.1 summarizes the events that exhibited a first flush for each pollutant. Based on the data, the drainage area did not consistently exhibit a first flush for any of the measured pollutants.

Table 3.6.1: Presence of a first flush for each pollutant.

Pollutant	Storm events exhibiting a first flush	Mass-volume relationship
TSS	6/19/17 and 2/22/18	Figure 3.6.1
TP	5/11/17 and 6/19/17	Figure 3.6.2
TKN	7/28/17	Figure 3.6.3
NO_3^- as N	6/19/17 and 2/10/18	Figure 3.6.4
NH_4^+ as N	6/19/17 and 8/27/17	Figure 3.6.5
Zn	6/19/17, 7/28/17, and 2/10/18	Figure 3.6.6
Cu	6/19/17 and 2/10/18	Figure 3.6.7
Pb	None	Figure 3.6.8

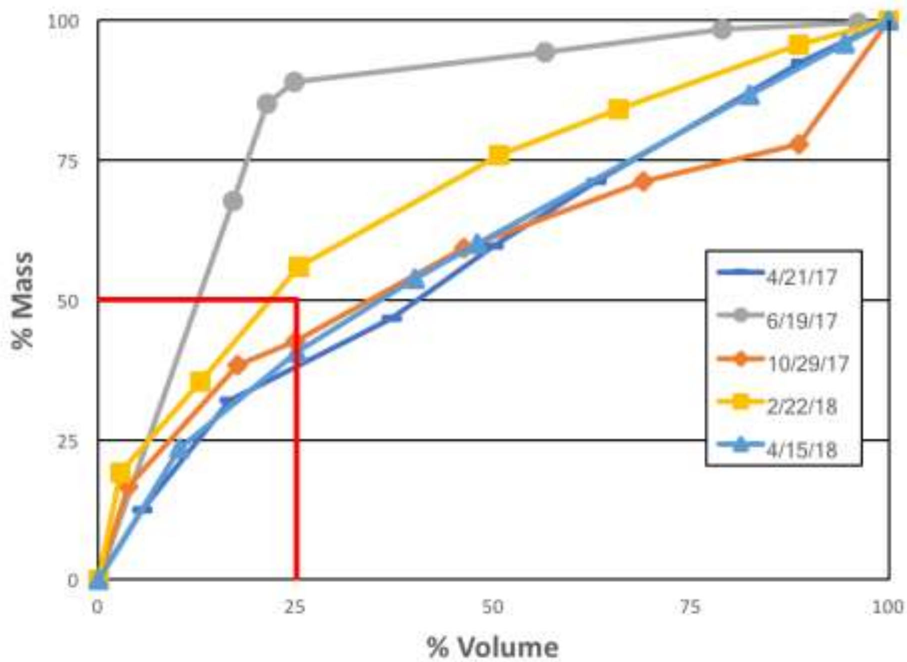


Figure 3.6.1: Percentage of total TSS mass loading versus runoff volume for five selected events.

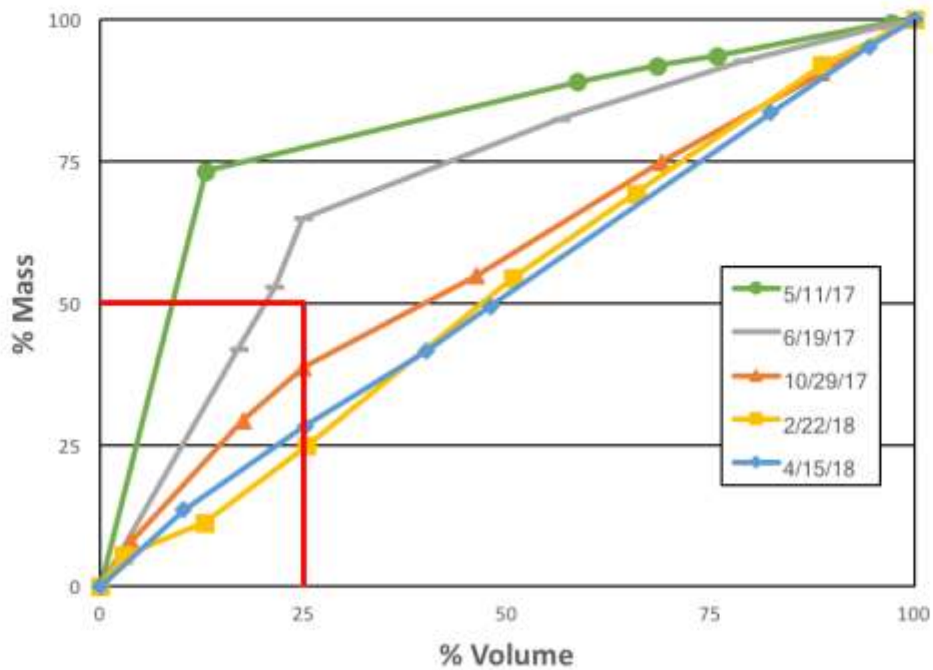


Figure 3.6.2: Percentage of total TP mass loading versus runoff volume for five selected events.

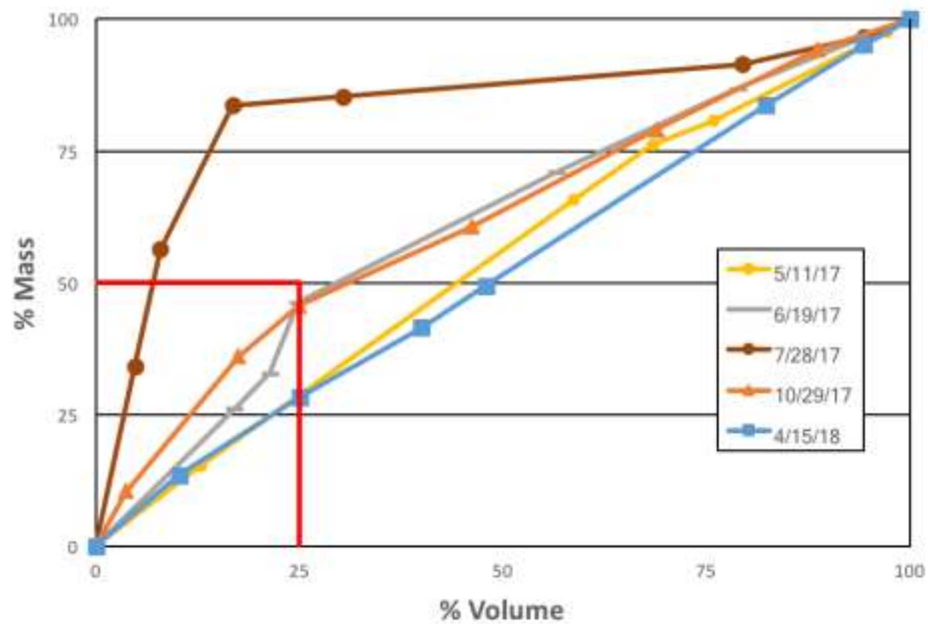


Figure 3.6.3: Percentage of total TKN mass loading versus runoff volume for five selected events.

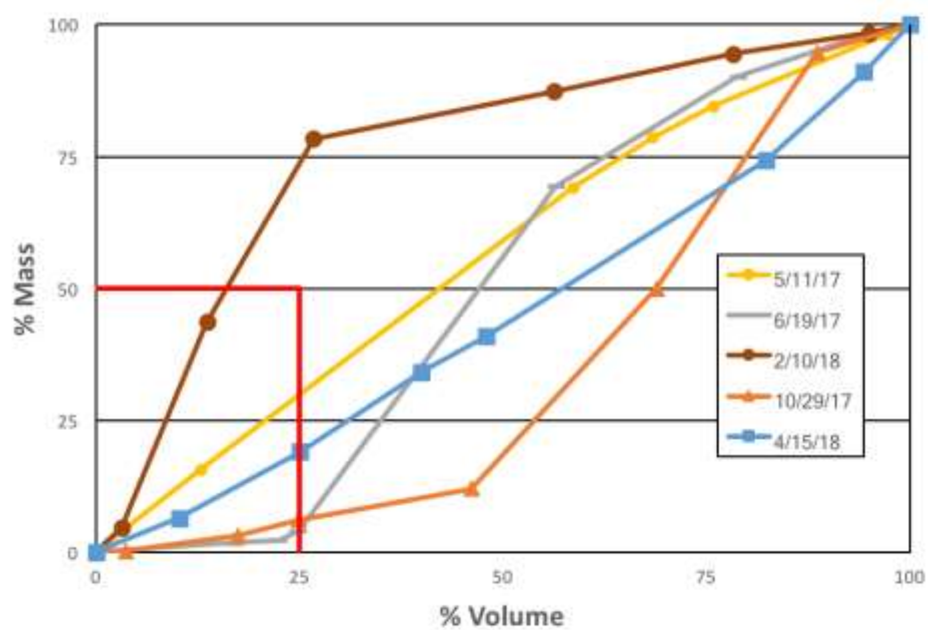


Figure 3.6.4: Percentage of total nitrate mass loading versus runoff volume for five selected events.

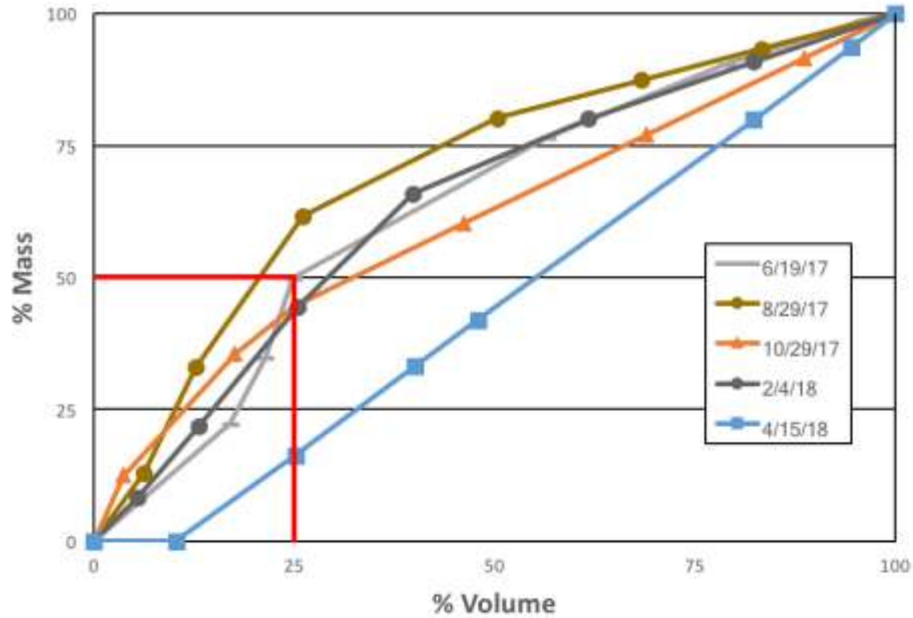


Figure 3.6.5: Percentage of total ammonium mass loading versus runoff volume for five selected events.

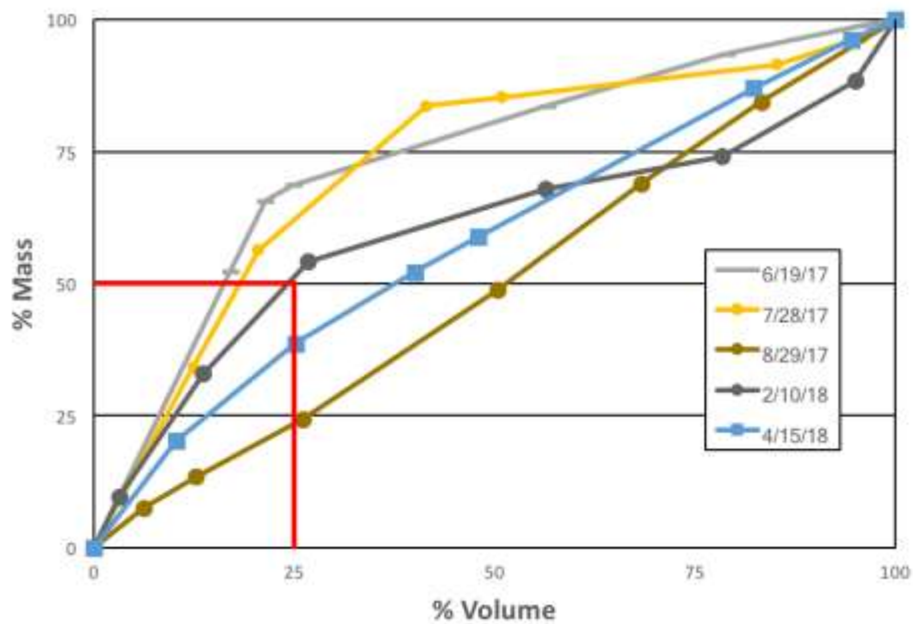


Figure 3.6.6: Percentage of total zinc mass loading versus runoff volume for five selected events.

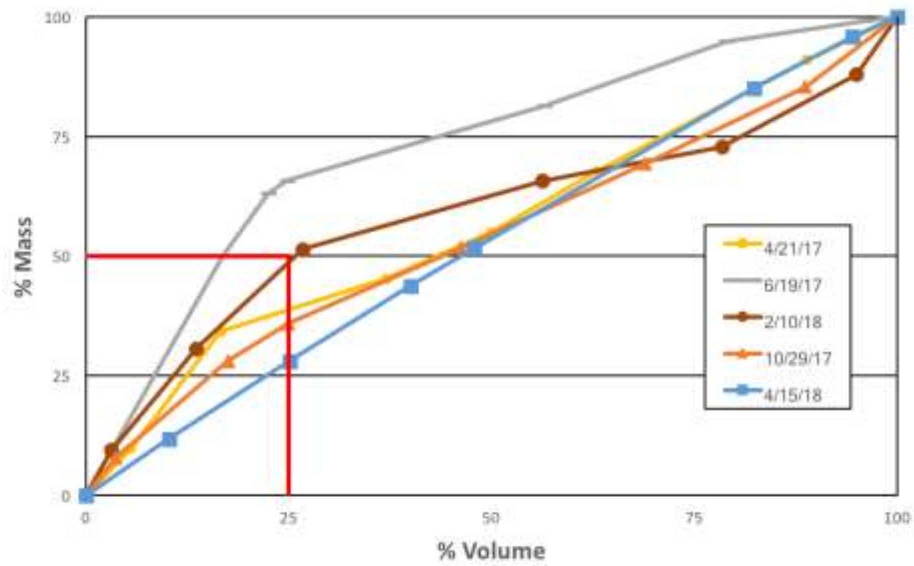


Figure 3.6.7: Percentage of total copper mass loading versus runoff volume for five selected events.

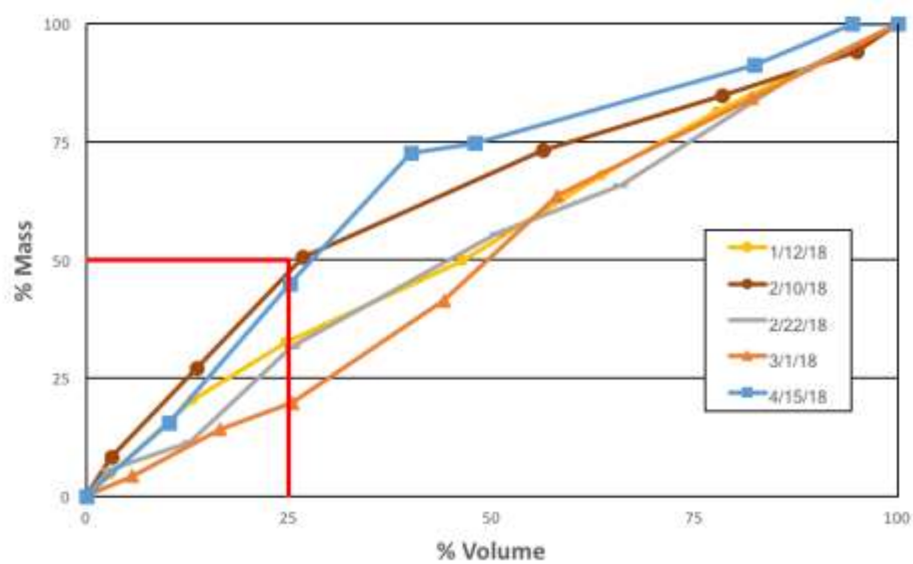


Figure 3.6.8: Percentage of total lead mass loading versus runoff volume for five selected events.

3.7 – Media Extractions

Media samples were collected and analyzed as discussed in Section 2.4. The first two media sections of the gutter filter system were designed to function similarly to sand filters – the primary pollutant removal mechanism is filtration. Filtration should be able to remove the larger particulate phosphorus; however, it is not effective for removing dissolved phosphorus. The GAC in the mixed media allows for both filtration of particulate phosphorus and chemical sorption of dissolved phosphorus. Pool filter sand has a maximum aggregate size around 1 mm whereas concrete sand has a maximum aggregate size of 4.75 mm (Special Provision 300 – Gutter Filters). Thus, the pool filter sand would offer greater filtration efficiency and be expected to result in a larger quantity of trapped phosphorus. Samples were extracted and analyzed for phosphorus, nitrogen, copper, zinc, and lead. Total lead was below the detection limit (25 μg/L) for all samples which corresponds to a media concentration of 2.5 mg/kg. Comparisons to other long-term studies are shown in Table 3.7.1. All studies were sampled between 30 and 40 cm except for Johnson and Hunt (2016) which was sampled at the surface. The surface sampling could account for the large concentration range in that study.

Table 3.7.1: Mehlich 3 extractable phosphorus compared to other long-term studies. PS: pool sand, CS: concrete sand, MM: mixed media.

Study	Current			Johnson and Hunt, 2016	Muerdter et al., 2016	Kandel et al., 2017			
Facility	Gutter filter			Bioretention	Bioretention	Bioretention			
	PS	CS	MM			ECP	GHS	GLA	SR
M3 extractable P (mg/kg)	22 +/- 3.3	16 +/- 1.8	32 +/- 1.4	5.1 – 173.3	15 – 25	6 +/- 0.4	16 +/- 5	26 +/- 8	7.5 +/- 1

The Mehlich 3 extractable phosphorus concentrations are presented in Figure 3.7.1. Note that the error bars for upstream chamber, pool filter sand, and concrete sand are all fairly large which could indicate that the samples were not completely homogenized prior to analysis. The phosphorus concentrations in the current study seem to align well with other studies, but are on the higher end. The mixed media samples may have a higher total phosphorus accumulation due to the potential for both filtration and chemical sorption of phosphorus. The differences in the phosphorus concentrations could be due to the different particle sizes of the filter media.

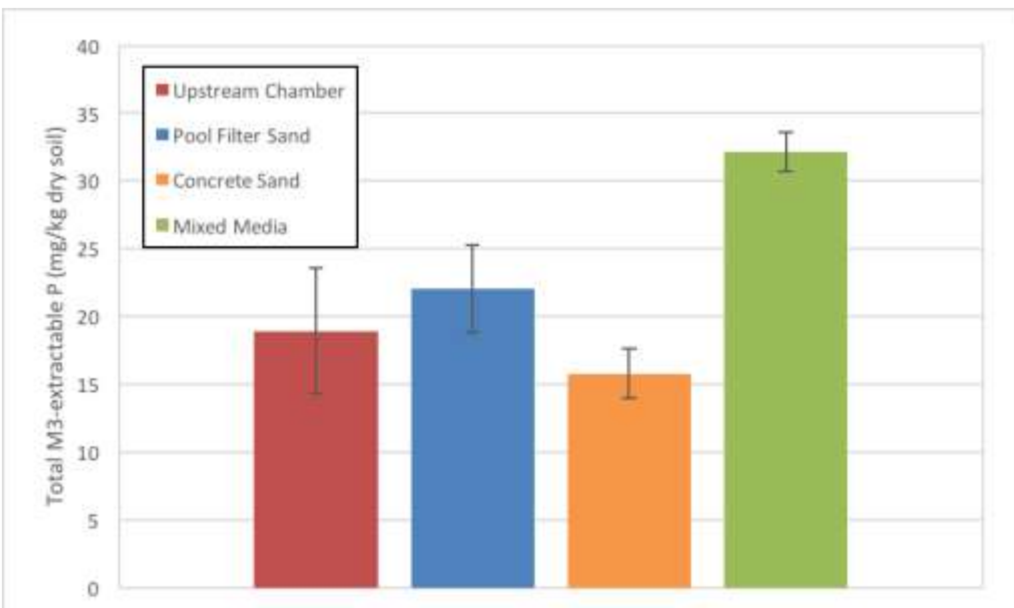


Figure 3.7.1: Mehlich 3 extractable phosphorus concentrations from media samples.

The total potassium chloride extractable nitrogen concentrations are presented in Figure 3.7.2. Not enough sample of the mixed media remained to perform the extraction. Interestingly, the sand trend seen in the phosphorus accumulation was reversed for nitrogen. The larger aggregate sand, concrete sand, had more nitrogen accumulation than the smaller pool filter sand. The upstream chamber likely had much higher nitrogen concentrations because it was empty when constructed and over the past decade filled with sediment and detritus, which can be expected to have a high nitrogen content.

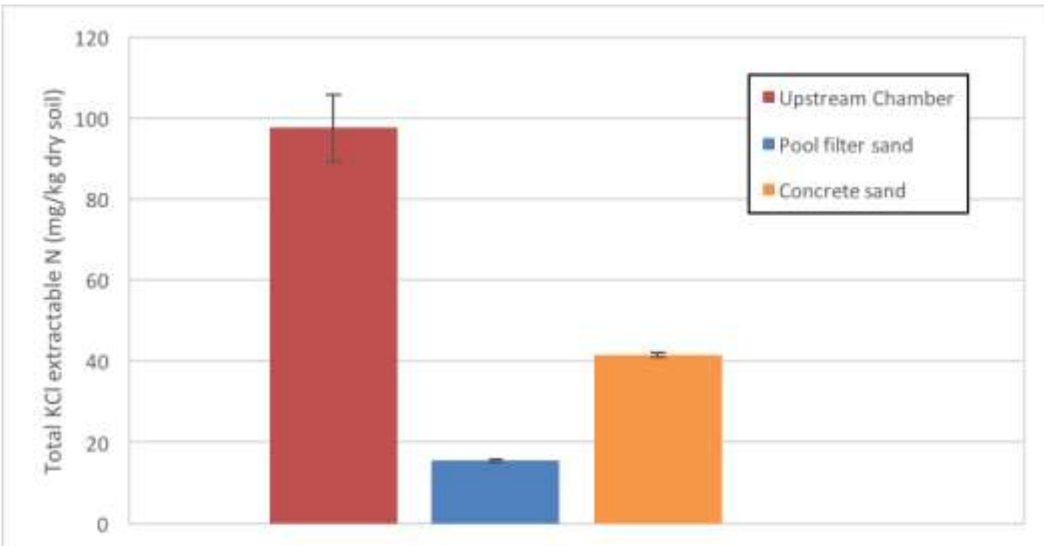


Figure 3.7.2: Total potassium chloride extractable nitrogen concentrations from media samples.

The total copper concentrations are presented in Figure 3.7.3. The trends mimic those seen for nitrogen, with the pool filter sand having the lowest concentrations and the upstream chamber having the highest concentrations. With the exception of pool filter sand, the total copper concentrations are higher than those seen for a 4-year-old bioretention cell sampled between 30 and 40 cm, in which concentrations ranged between 5 and 10 mg/kg soil (Jones and Davis, 2013). The concentrations are also higher than those from an 11-year-old bioretention cell sampled at 20 cm, in which all concentrations were below 10 mg/kg soil (Johnson and Hunt, 2016). These results indicate that the filters may have successfully removed copper through filtration over their lifespan.

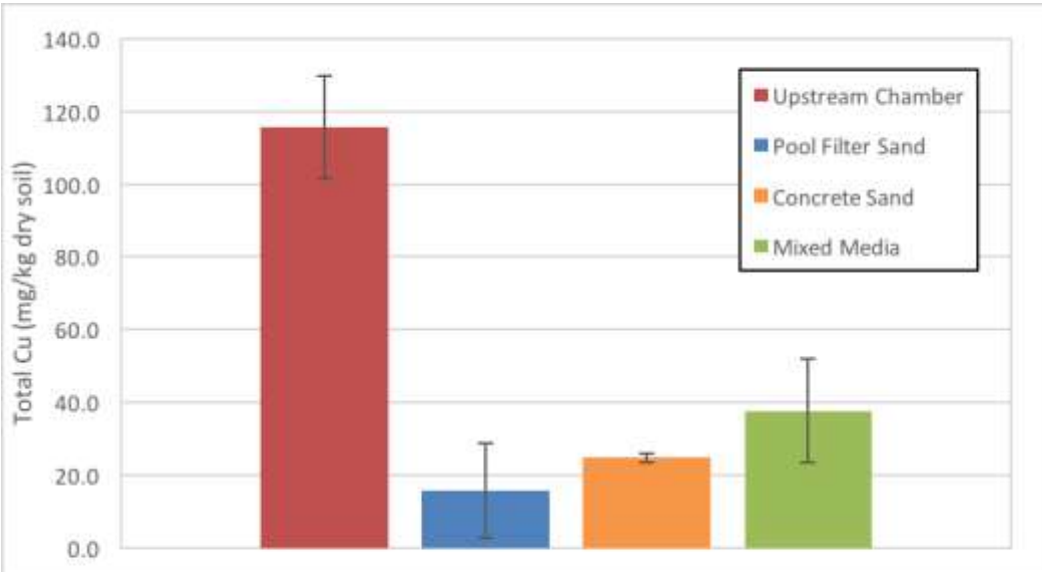


Figure 3.7.3: Total copper concentrations from media samples.

The total zinc concentrations are presented in Figure 3.7.4. Note that the error bars for upstream chamber, pool filter sand, and mixed media are all fairly large which could indicate that the samples were not completely homogenized prior to analysis. The concrete sand exhibited higher concentrations of zinc than the pool filter sand which is the opposite of what was seen with the copper concentrations. However, the copper concentration of the pool filter sand is not the most reliable because of the large amount of error. Again, the upstream collection chamber had the largest concentration. With the exception of pool filter sand, zinc concentrations were above the 10 to 25 mg/kg soil range for the 4-year-old bioretention (Jones and Davis, 2013). The concentrations were also higher than the 11-year old bioretention which were below 25 mg/kg soil (Johnson and Hunt, 2016). The high zinc concentrations are unexpected considering that zinc is primarily present in the dissolved form in stormwater. This indicates that there may be a source of zinc to the filters other than stormwater.

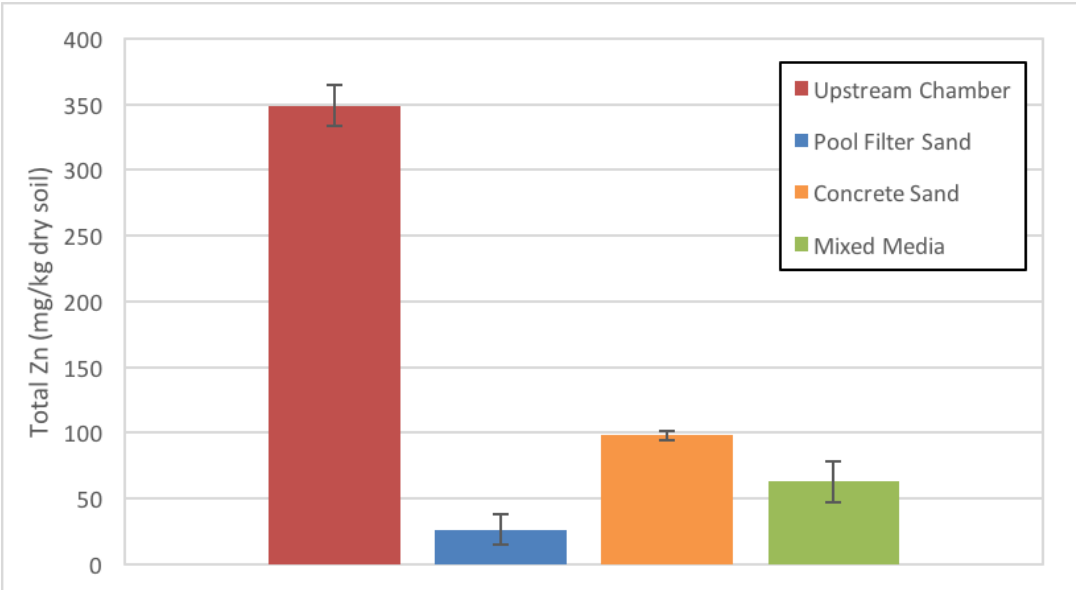


Figure 3.7.4: Total zinc concentrations from media samples.

Chapter 4: Conclusions

4.1 - Conclusions

A stormwater sampling program was conducted to evaluate the performance of gutter filters that were installed in 2006 in Mount Rainier, Maryland. The filters have seen minimal maintenance since installation and are visibly clogged. 18 storm events were collected and analyzed for TSS, nitrogen, phosphorus, copper, lead, and zinc between March 2017 and April 2018. Results were compared to sampling conducted prior to filter construction, Phase 1, and after construction, Phase 2.

TKN was the only pollutant that showed a statistically significant increase from Phase 2. All other pollutants were not statistically different from Phase 2. TP, nitrate, TKN, and copper were not statistically different from Phase 1. TSS, TKN, copper, lead, and zinc showed statistically significant decreases between Phase 1 and Phase 2. Similarity to Phase 1 for TP, nitrate, and copper, and the increase since Phase 2 for TKN indicates that the filters are not providing treatment for these pollutants. TSS and zinc still showed a statistically significant decrease from Phase 1. Based on the parameters measured, the current stormwater quality is poor, with the exception of lead.

Current pollutant EMCs are comparable to those from untreated highway runoff. The current TSS median concentration of 85 mg/L falls within the reported EMC range of 59 to 215 mg/L (Wu et al., 1998; Caltrans, 2003). Pollutant concentrations were generally much greater than those treated by sand filters and bioretention. Annual pollutant loadings are similar to those of untreated urban drainage areas and are much greater than treated loadings from bioretention cells. The current TSS annual loading of 1,212 kg/ha-year fits is similar to the range of reported loadings from untreated drainage areas, 570 to 1,190 kg/ha-year (Li and Davis, 2009). However, the TSS annual loading is much larger than the reported treated loadings ranging from 37 to 47 kg/ha-year (Li and Davis, 2009; Liu and Davis, 2014). Similarity to untreated runoff and untreated drainage areas implies that the filters are not functional. A first flush phenomenon was not consistently present for the drainage area.

Media pollutant accumulations were measured and phosphorus accumulation in the filter media is comparable to 7 to 11-year-old bioretention cells (Johnson and Hunt, 2016; Muerdter et al., 2016). Copper and zinc accumulation are greater than a 4 and 11-year-old bioretention cell (Jones and Davis, 2014; Johnson and Hunt, 2016).

4.2 – Recommendations for Gutter Filters

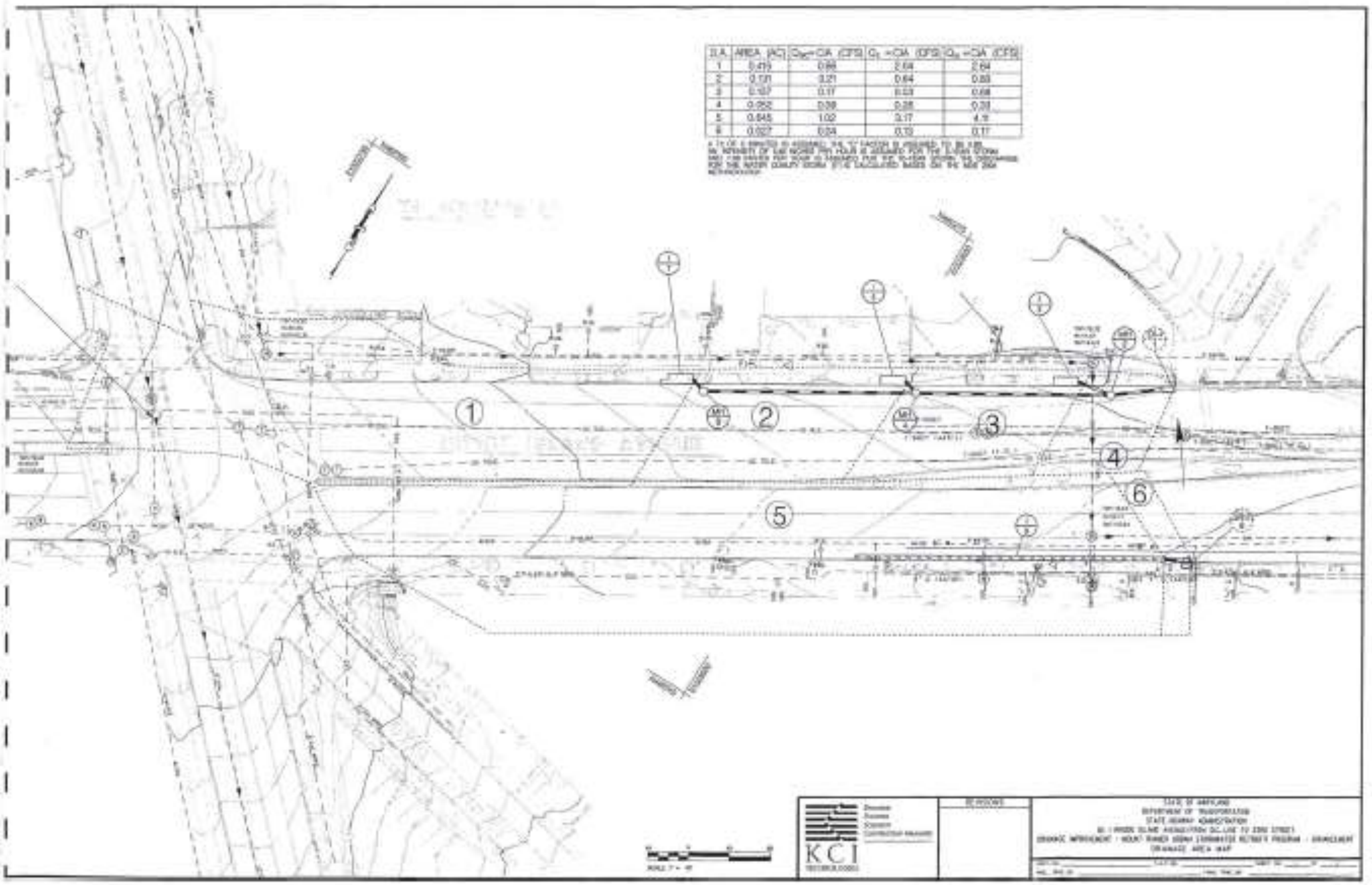
The current water quality mirrors that of untreated stormwater indicting that the filters are either not or minimally functional. It is recommended that the filters at Mount Rainier have the top portion of sediment removed and the upstream and downstream collection chambers cleaned out to expose the underdrains. Afterwards, they should receive a maintenance cycle similar to what was recommended by Urbonas (1999) and Barrett (2003), which involves scraping off the first 5 to 7 cm of media every two years until the media is reduced to a depth of 0.3 m at which time it should be replaced. If gutter filters are to be used in a future retrofit, an upstream detention chamber is recommended to reduce the amount of sediment directly delivered to the filters.

4.3 – Recommendations for Future Research

Gutter filters are an attractive option for urban stormwater retrofits. There are multiple research options that could be explored at the Mount Rainier site to better understand gutter filters.

1. Prior to sediment removal, the infiltration rate should be measured to quantitatively determine if runoff is entering the filter or bypassing the system.
2. A sampling program could be conducted on the westbound lanes of Route 1 to characterize the untreated stormwater. These concentrations could be compared to this study to confirm if the current water quality is the result of lack of treatment.
3. After the filters receive maintenance, collecting untreated and treated first flush samples from just the filters would help inform the current treatment capabilities of the filters

APPENDIX A: Site Information


D.A.
AREA (AC)
1
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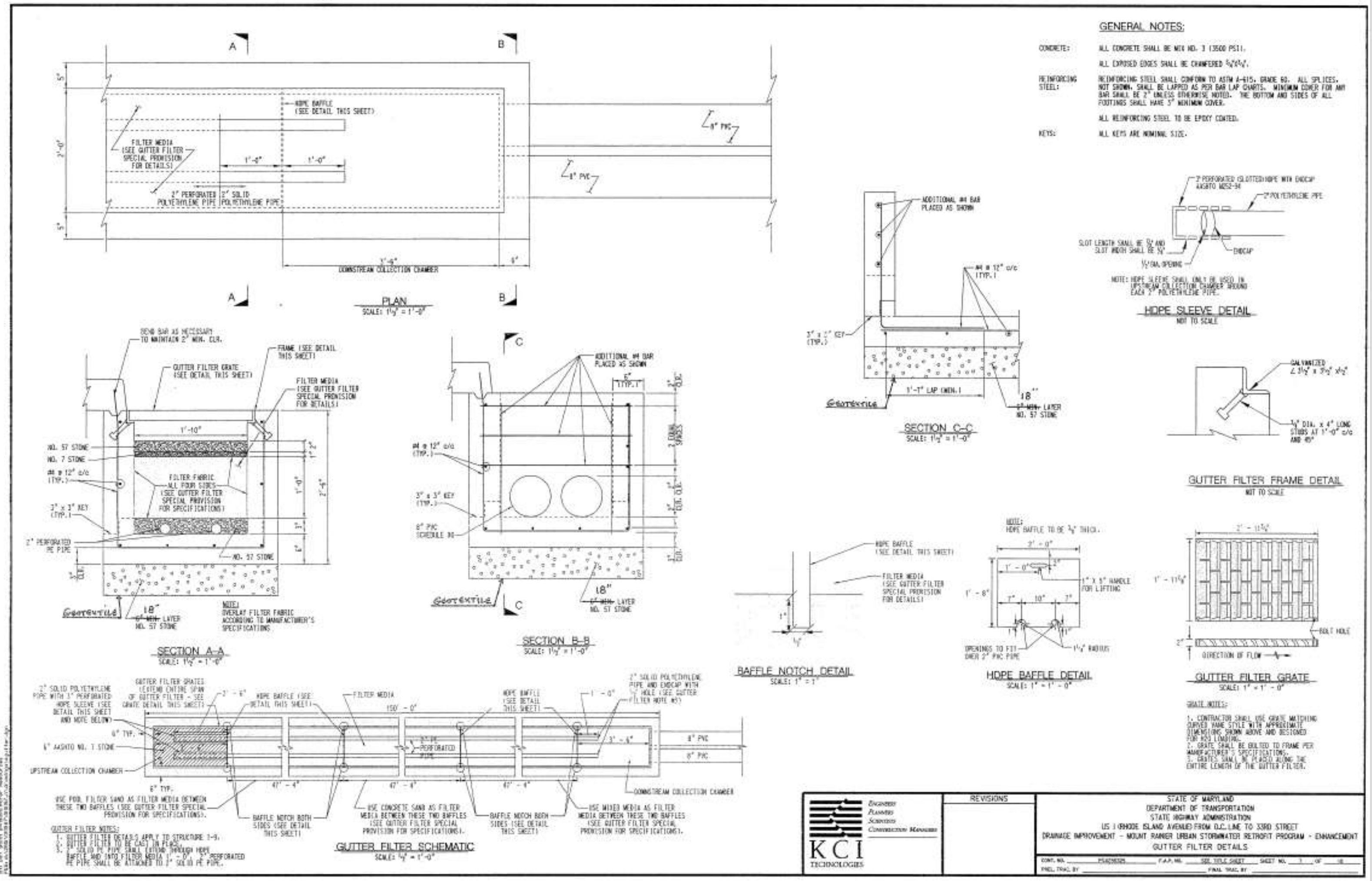
KCI


GENERAL NOTES:
CONCRETE: ALL CONCRETE SHALL BE MIX NO. 3 (3500 PSI).
ALL EXPOSED EDGES SHALL BE CHAMFERED ¾"X¾".
REINFORCING STEEL: REINFORCING STEEL SHALL CONFORM TO ASTM A-615, GRADE 60. ALL SPLICES, NOT SHOWN, SHALL BE LAPPED AS PER BAR LAP CHARTS. MINIMUM COVER FOR ANY BAR SHALL BE 2" UNLESS OTHERWISE NOTED. THE BOTTOM AND SIDES OF ALL FOOTINGS SHALL HAVE 3" MINIMUM COVER.
ALL REINFORCING STEEL TO BE EPOXY COATED.
KEYS: ALL KEYS ARE NOMINAL SIZE.
PLAN
SECTION A-A
SECTION B-B
SECTION C-C
BAFFLE NOTCH DETAIL
HDPE BAFFLE DETAIL
HDPE SLEEVE DETAIL
GUTTER FILTER FRAME DETAIL
GUTTER FILTER GRATE
GUTTER FILTER SCHEMATIC
GRATE NOTES:
1. CONTRACTOR SHALL USE GRATE MATCHING CURVED VANE STYLE WITH APPROXIMATE DIMENSIONS SHOWN ABOVE AND DESIGNED FOR H20 LOADING.
2. GRATE SHALL BE BOLTED TO FRAME PER MANUFACTURER'S SPECIFICATIONS.
3. GRATES SHALL BE PLACED ALONG THE ENTIRE LENGTH OF THE GUTTER FILTER.
KCI TECHNOLOGIES
Engineers
Planners
Scientists
Construction Managers
REVISIONS
STATE OF MARYLAND
DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION
US 1 (RHODE ISLAND AVENUE) FROM D.C. LINE TO 33RD STREET
DRAINAGE IMPROVEMENT - MOUNT RAINIER URBAN STORMWATER RETROFIT PROGRAM - ENHANCEMENT
GUTTER FILTER DETAILS

APPENDIX B: EMC Calculations

Bibliography

Adesanwo, O. O., Ige, D. V., Thibault, L., Flaten, D., & Akinremi, W. (2013). Comparison of Colorimetric and ICP Methods of Phosphorus Determination in Soil Extracts. *Communications in Soil Science and Plant Analysis*, *44*(21), 3061–3075.

American Public Health Association; American Water Works Association; and Water Pollution Control Federation (1995) Standard Methods for the Examination of Water and Wastewater. 17[TH] Ed. Washington, D.C.

Barrett, M. E. (2003). Performance, Cost, and Maintenance Requirements of Austin Sand Filters. *Journal of Water Resources Planning and Management*, *129*(3), 234–242.

Blecken, G.-T., Hunt, W. F., Al-Rubaei, A. M., Viklander, M., & Lord, W. G. (2017). Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. *Urban Water Journal*, *14*(3), 278–290.

Caltrans, C. D. of T. (2003). *Discharge Characterization Study Report* (CTSW-RT-03-065.51.42).

Code of Maryland Regulations (COMAR) 26.08.02.03-2. (2016). Retrieved from http://www.dsd.state.md.us/comar/comarhtml/26/26.08.02.03-2.htm

Davis, A. P. (2007). Field Performance of Bioretention: Water Quality. *Environmental Engineering Science*, *24*(8), 1048–1064.

Davis, A. P., Shokouhian, M., & Ni, S. (2001). Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere*, *44*(5), 997–1009.

Davis, A. P., & McCuen, R. H. (2005). *Stormwater Management for Smart Growth*. New York, New York: Springer Science+Business Media Inc.

Davis, A. P., Shokouhian, M., Sharma, H., & Minami, C. (2006). Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal. *Water Environment Research*, *78*(3), 284–293.

Dean C. M., Sansalone J. J., Cartledge F. K., & Pardue John H. (2005). Influence of Hydrology on Rainfall-Runoff Metal Element Speciation. *Journal of Environmental Engineering*, *131*(4), 632–642.

Driscoll, E. D., Shelley, P. E., & Strecker, E. W. (1990). *Pollutant Loadings and Impacts From Highway Stormwater Runoff* (No. FHWA-RD-88-008).

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., … Thornbrugh, D. J. (2008). Eutrophication of U.S. Freshwaters: Analysis of Potential Economic Damages. *Environmental Science & Technology*, *43*(1), 12–19.

Flint, K., & Davis, A. P. (2007). Pollutant Mass Flushing Characterization of Highway Stormwater Runoff from an Ultra-Urban Area. *Journal of Environmental Engineering*, *133*(6).

Galloway, J. N., Aber, J. D., Erisman, J. W., Seitzinger, S. P., Howarth, R. W., Cowling, E. B., & Cosby, B. J. (2003). The Nitrogen Cascade. *BioScience*, *53*(4), 341–356.

Hatt, B. E., Fletcher, T. D., & Deletic, A. (2008). Hydraulic and Pollutant Removal Performance of Fine Media Stormwater Filtration Systems. *Environmental Science & Technology*, *42*(7), 2535–2541.

Hunt W. F., Smith J. T., Jadlocki S. J., Hathaway J. M., & Eubanks P. R. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C. *Journal of Environmental Engineering*, *134*(5), 403–408.

Irish, L. B., Lesso, W. G., Barrett, M. E., Malina, J. F., Charbeneau, R. J., & Ward, G. H. (1995). *An evaluation of the factors affecting the quality of highway runoff in Austin, Texas area* (No. Technical Report CRWR 264). Center for Research in Water Resources: University of Texas at Austin.

Irish, L. B., Barrett, M. E., Malina, J. F., & Charbeneau, R. J. (1998). Use of Regression Models for Analyzing Highway Storm-Water Loads. *Journal of Environmental Engineering*, *124*(10), 987–993.

Jantz, P., Goetz, S., & Jantz, C. (2005). Urbanization and the Loss of Resource Lands in the Chesapeake Bay Watershed. *Environmental Management*, *36*(6), 808–825.

Johnson, J. P., & Hunt, W. F. (2016). Evaluating the spatial distribution of pollutants and associated maintenance requirements in an 11 year-old bioretention cell in urban Charlotte, NC. *Journal of Environmental Management*, *184, Part 2*, 363–370.

Jones, D. L., & Willett, V. B. (2006). Experimental evaluation of methods to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil. *Soil Biology and Biochemistry*, *38*(5), 991–999.

Jones, P. S., & Davis, A. P. (2013). Spatial Accumulation and Strength of Affiliation of Heavy Metals in Bioretention Media. *Journal of Environmental Engineering*, *139*(4), 479–487.

Kandasamy, J., Beecham, S., & Dunphy, A. (2008). Stormwater sand filters in water-sensitive urban design. *Proceedings of the Institution of Civil Engineers - Water Management*, *161*(2), 55–64.

Kandel, S., Vogel, J., Penn, C., & Brown, G. (2017). Phosphorus Retention by Fly Ash Amended Filter Media in Aged Bioretention Cells. *Water*, *9*(10), 746.

Karlsson, K., Viklander, M., Scholes, L., & Revitt, M. (2010). Heavy metal concentrations and toxicity in water and sediment from stormwater ponds and sedimentation tanks. *Journal of Hazardous Materials*, *178*(1), 612–618.

Kayhanian, M., Singh, A., Suverkropp, C., & Borroum, S. (2003). Impact of Annual Average Daily Traffic on Highway Runoff Pollutant Concentrations. *Journal of Environmental Engineering*, *129*(11), 975–990.

Keblin, M. V., Barrett, M. E., Malina, J. F., & Charbeneau, R. J. (1997). *The Effectiveness of Permanent Highway Runoff Controls: Sedimentation/Filtration Systems* (No. 97–4). Center for Research in Water Resources: University of Texas at Austin.

Komlos, J., & Traver, R. G. (2012). Long-Term Orthophosphate Removal in a Field-Scale Storm-Water Bioinfiltration Rain Garden. *Journal of Environmental Engineering*, *138*(10), 991–998.

Le Coustumer, S., Fletcher, T. D., Deletic, A., & Barraud, S. (2007). Hydraulic performance of biofilters for stormwater management: first lessons from both laboratory and field studies. *Water Science and Technology*, *56*(10), 93–100.

LeFevre, G. H., Paus, K. H., Natarajan, P., Gulliver, J. S., Novak, P. J., & Hozalski, R. M. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells. *Journal of Environmental Engineering*, *141*(1), 4014050.

Li, H., & Davis, A. P. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. *Journal of Environmental Engineering*, *135*(8), 567–576.

Li, L., & Davis, A. P. (2014). Urban Stormwater Runoff Nitrogen Composition and Fate in Bioretention Systems. *Environmental Science & Technology*, *48*(6), 3403–3410.

Liu, J., & Davis, A. P. (2014). Phosphorus Speciation and Treatment Using Enhanced Phosphorus Removal Bioretention. *Environmental Science & Technology*, *48*(1), 607–614.

Maryland Department of the Environment, & District of Columbia Department of the Environment - Natural Resources Administration. (2007). *Total Maximum Daily Loads of Sediment/Total Suspended Solids for the Anacostia River Basin, Montgomery and Prince George's Counties, Maryland and The District of Columbia*.

McKenzie, E. R., Money, J. E., Green, P. G., & Young, T. M. (2009). Metals associated with stormwater-relevant brake and tire samples. *Science of The Total Environment*, *407*(22), 5855–5860.

Muerdter, C., Özkök, E., Li, L., & Davis, A. P. (2016). Vegetation and Media Characteristics of an Effective Bioretention Cell. *Journal of Sustainable Water in the Built Environment*, *2*(1), 4015008.

National Resource Council. (2008). *Urban Stormwater Management in the United States*.

Opher, T., & Friedler, E. (2010). Factors affecting highway runoff quality. *Urban Water Journal*, *7*(3), 155–172.

Persson, J., Somes, N. L. G., & Wong, T. H. F. (1999). Hydraulics Efficiency of Constructed Wetlands and Ponds. *Water Science and Technology*, *40*(3), 291–300.

Pittman, J. J., Zhang, H., Schroder, J. L., & Payton, M. E. (2005). Differences of Phosphorus in Mehlich 3 Extracts Determined by Colorimetric and Spectroscopic Methods. *Communications in Soil Science and Plant Analysis*, *36*(11–12), 1641–1659.

Pradhan, A.U. (2006). "Field Evaluation of Low Impact Development Practices for Treatment of Highway Runoff in an Ultra Urban Area." Master's Thesis. University of Maryland, College Park.

Sansalone, J. J., & Buchberger, S. G. (1997). Partitioning and First Flush of Metals in Urban Roadway Storm Water. *Journal of Environmental Engineering*, *123*(2), 134–143.

Selbig, W. R. (2016). Evaluation of leaf removal as a means to reduce nutrient concentrations and loads in urban stormwater. *Science of The Total Environment*, *571*, 124–133.

Sikora, F. J., Howe, P. S., Hill, L. E., Reid, D. C., & Harover, D. E. (2005). Comparison of Colorimetric and ICP Determination of Phosphorus in Mehlich3 Soil Extracts. *Communications in Soil Science and Plant Analysis*, *36*(7–8), 875–887.

Taylor, G. D., Fletcher, T. D., Wong, T. H. F., Breen, P. F., & Duncan, H. P. (2005). Nitrogen composition in urban runoff—implications for stormwater management. *Water Research*, *39*(10), 1982–1989.

Urbonas, B. R. (1999). Design of a Sand Filter for Stormwater Quality Enhancement. *Water Environment Research*, *71*(1), 102–113.

U.S. CPSC. (1977). *CPSC Announces Final Ban On Lead-Containing Paint* (No. 77–096).

U.S. EPA. (1973). EPA Requires Phase-Out of Lead in All Grades of Gasoline [Reports and Assessments].

US EPA. (2002). *Summary Table for the Nutrient Criteria Documents*.

U.S. EPA. (2009). National Primary Drink Water Regulations.

U.S. EPA. (2013). *Aquatic Life Ambient Water Quality Criteria For Ammonia - Freshwater* (No. EPA-822-R-13-001).

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. *Journal of the North American Benthological Society*, *24*(3), 706–723.

Wanielista, M. P., and Yousef, Y. A. 1993. Stormwater Management. John Wiley & Sons, Inc., New York, N.Y., 1-579.

Wardynski, B. J., & Hunt, W. F. (2012). Are Bioretention Cells Being Installed Per Design Standards in North Carolina? A Field Study. *Journal of Environmental Engineering*, *138*(12), 1210–1217.

Wu, J. S., Allan, C. J., Saunders, W. L., & Evett, J. B. (1998). Characterization and Pollutant Loading Estimation for Highway Runoff. *Journal of Environmental Engineering*, *124*(7), 584–592.