A meta-analysis of North Shore streams: maximizing the effect of installed rain gardens through strategic placement

by

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Abstract

A meta-analysis using pre-existing data was done for streams in the North Shore of Vancouver, British Columbia. Parameters considered were chemical concentrations from stormwater input including: heavy metals concentrations (Copper (Cu), Zinc (Zn), Cadmium (Cd), Lead (Pb)) and nutrient concentrations (Nitrate ($N0^{3-}$) and Orthophosphate ($P04^{3-}$)). Chronic toxicity guideline exceedance based on the British Columbia Approved Water Quality Guidelines was found in all 94% of stream systems for Cu and 44% of stream systems for Zn. Heavy metal concentrations were found to be positively correlated with percent impervious surface cover in the watershed, with the strength of the correlation being metal-dependent. Three sites within the study had the highest levels of both Cu and Zn. These watersheds (Upper Keith Creek, Maplewood Creek, and Mackay Creek) were prioritized for rain garden installation. Rain garden building specifications to remediate for Zn and Cu were recommended and included addition of mulch layer, minimum depth of topsoil (30 cm), and vegetating with plants with high potential for biofiltration and/or phytoremediation.

Keywords: Stormwater; rain garden; green infrastructure; heavy metal analysis; impervious surface cover

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Glossary

Green Infrastructure (GI)	An approach to development that protects, restores, or mimics natural processes. GI can have many varying benefits and objectives including water management, carbon sequestration, improving air quality, and wildlife value.
Stormwater	Surface water in abnormal quantity resulting from precipitation event, usually containing contaminants associated with human development
Urban Runoff	Surface runoff created by urbanization, specifically the hardening of surfaces, usually containing contaminants associated with human development
Infiltration Gallery	Basin with perforated conduits in gravels to intercept stormwater runoff
Rain Garden	A planted depression or basin that intercepts, filters, and infiltrates stormwater runoff from impervious surfaces.
Green Stormwater Infrastructure (GSI)	An approach to managing wet weather impacts that aims to reduce and treat stormwater at it's source while providing other environmental, social, and economic benefits.
Low Impact Development (LID)	A land planning and engineering design approach to manage stormwater runoff as part of green infrastructure.
Grey Infrastructure	Tradition stormwater management methods, including storm drains, pipes, pumps, and outfalls.
British Columbia Approved Water Quality Guidelines for Aquatic Life (BCAWQG)	British Columbia's water quality guidelines developed to promote healthy ecosystems. These are science-based levels of physical, biological, and chemical parameters for the protection of water uses such as aquatic life, wildlife, agriculture, drinking water and recreation.
Urban Stream Syndrome (USS)	Symptoms of the urban stream syndrome as defined by Walsh et al. (2005) include a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology, and reduced biotic richness, with increased dominance of tolerant species.
LD_{50}	Lethal Dose 50. The dose of a substance that kills 50% of a test sample.
The North Shore Rain Garden Project (NSRGP)	A partnership between SFU's Faculty of the Environment and the Pacific Water Research Institute aiming to expand the green infrastructure network on the North Shore through providing citizen and student outreach and research opportunities

Chapter 1. Introduction

In 2005, Walsh et al. classified a set of characteristics commonly seen in urban aquatic environments as the Urban Stream Syndrome (USS). The consistent symptoms of these streams include flashy hydrographs, elevated concentrations of nutrients and contaminants, altered channel morphology and stability, reduced biotic richness, and increased dominance of pollutant-tolerant species (Walsh et al. 2005). This is caused by a shift to runoff dominance in the hydrologic cycle of urban environments, leading to an excess of surface water runoff (Walsh et al. 2005). This runoff also often contains contaminants contingent with human development (Walsh et al. 2005)(Mayer et al. 2012)(McIntyre et al. 2015).

In undisturbed states, ecosystems provide essential ecosystem services such as water filtration, infiltration, and flood mitigation, among many others (Ehrlich and Ehrlich 1981). However, encroachment on these systems from urban development and the associated hardening of surfaces has limited these natural system's abilities to provide these services (Mayer et al. 2012). This led to a rise in engineered solutions (Mayer et al. 2012). Traditionally, stormwater management has used Grey Infrastructure, a system of pipes, storm drains, and outfalls to convey excess surface water running off impervious surfaces to aquatic water bodies but, these strategies have unintended, detrimental effects to receiving systems (McIntyre et al. 2015). Recently, practitioners have been seeking alternative methods of stormwater management to minimize these detrimental effects. One set of methods is inclusively called Green Stormwater Infrastructure (GSI) and includes many different subsets of technology including rain gardens, the focus of this work.

1.1. Urban Stormwater Runoff

Stormwater runoff is a common pollutant to urban, aquatic ecosystems (McIntyre et al. 2015). It can affect water quality and quantity in surface water, interflow, and groundwater (Gobel et al. 2007). As levels of urban development increase, land is converted from natural, pervious systems, to impervious surfaces such as roads, sidewalks, and parking lots (Mayer et al. 2012). As rainwater flows over impervious surfaces, it picks up pollutants deposited onto these surfaces from various human activities (Gobel et al. 2007). Now contaminated, this urban runoff is then conveyed through grey infrastructure directly to adjacent aquatic systems, where contaminants may concentrate, directly and indirectly affecting the aquatic biota (McIntyre et al. 2015).

The most common contaminants in stormwater are heavy metals (Copper (Cu), Cadmium (Cd), Nickel (Ni), Lead (Pb), Zinc (Zn)), polycyclic aromatic hydrocarbons (PAHs), mineral oil hydrocarbons (MOHs), readily soluble salts, nutrients (nitrates and phosphates), and fecal bacteria (Gobel et al. 2007)(McIntyre et al. 2015). The presence and concentration of these contaminants depends on land use, traffic intensity, local industry, and percentage of impervious surface cover in the watershed (Gobel et al. 2007)(Mayer et al. 2012)(Zhang et al. 2013).

The negative effects of contaminants into receiving aquatic systems will vary based on water chemistry and stormwater toxicity, as well as the physical nature of the receiving system (McIntyre et al. 2014). The effects may be acute or chronic and may affect the systems over short or long timeframes (Lijklema et al. 1993). Acute impacts are usually caused by toxic concentrations of ammonia or heavy metals (Lijklema et al. 1993). Whereas long-term impacts include increased biological oxygen demands (BOD) or chemical oxygen demand (COD), high flows that make the environment physically unsuitable (Walsh et al. 2005), bacterial contamination (Gobel et al. 2007), and cumulative toxic impacts from metals and trace organic contaminants (TOCs)(Lijklema et al. 1993). The frequency and intensity of these impacts will depend greatly on climate, geography of the area, current stormwater infrastructure, and land use (Mayer et al. 2012).

Stormwater contaminants can be toxic to fish, invertebrates, and aquatic vegetation (Kayhanian et al. 2008)(McIntyre et al. 2015). Stormwater has been isolated as the cause of pre-spawn die-off of adult coho (*Oncorhynchus kisutch*)(Scholz et al. 2011), reductions in reproductive success in female coho (*O. kisutch*), and acute lethality in juveniles (*O. kisutch*)(McIntyre et al 2015). Stormwater inputs during storm events can quickly increase surface flow through urban aquatic systems, which further degrades aquatic environments through bank erosion, flooding, bed armouring and removal of spawning gravel for salmonids (Walsh et al. 2005)(Kominkova et al. 2016).

1.2. Rain Gardens

Green stormwater infrastructure (GSI) is a set of ever-evolving technologies aiming to achieve low-impact development (LID) that imitates the infiltrative and hydrologic characteristics of undeveloped landscapes (McIntyre et al. 2015). GSI includes a spectrum of technologies that imitate the functions of specific ecosystem water management services, including evapotranspiration, filtration, infiltration, flood protection, and erosion control (McIntyre et al. 2015). Traditional stormwater infrastructure, grey infrastructure, has a high initial investment cost as well as upkeep, and increasingly, concerns about it's unintended impacts to the natural environment have been acknowledged (Booth and Jackson 1997)(Walsh et al. 2005)(Asleson et al. 2009). These factors have led to the development of green technologies, such as green roofs, porous pavement, rain gardens, infiltration galleries, bioretention ponds, and rain barrels (Mayer et al. 2012). This research deals specifically with one sub-category of GSI; rain gardens.

Rain gardens are vegetated basins or depressions that fill with stormwater during storm events. These basins have soil with intentionally high permeability, so water is infiltrated into the soil, eventually moving as lateral flow or groundwater towards aquatic systems. Rain gardens improve stormwater quality by removing contaminants, mediating flooding, and reducing flashy surface flows to local aquatic systems during precipitation events (DeBusk et al. 2011)(McIntyre et al. 2015). Rain gardens remove contaminants through a diversity of mechanisms including filtration, adsorption and bio-chemical transformation (McIntyre et al. 2015). These systems can transform stormwater from a substance toxic to fish and invertebrates to a chemically non-harmful substance (McIntyre et al. 2015). McIntyre et al. (2015) determined bio-indicator levels in the gills of fish in rain garden-treated stormwater were similar to fish unexposed to stormwater. Treatment through bioretention cells, in-lab rain garden columns, can eliminate the mortality of macroinvertebrate species (Mayflies and Cladocerns) seen in untreated stormwater (Corsi et al. 2010). It was also shown to reverse the reproductive impairment of *Ceriodaphnia dubia*, a sensitive sublethal indicator of stormwater quality (McIntyre et al. 2015). Studies comparing treated to untreated stormwater found an overwhelming positive effect on water quality and contaminant levels, inferring a strong viability for rain gardens to act as treatment cells for stormwater (Corsi et al. 2010)(McIntyre et al. 2015).

Since a single rain garden can only intake and treat a certain portion of local stormwater, it is important to build rain gardens in clusters or networks to have measurable effects on local systems (Mayer et al. 2012). Aging grey infrastructure and the cost to replace it has led to a rise in the popularity of GSI as well as the potential for community-wide installations to decrease demands for costly grey infrastructure updates (Thurston et al. 2003). Since cost per volume stormwater managed can be halved by using a green infrastructure approach, green infrastructure represents a viable economic and environmental improvement to current stormwater management practices (Thurston et al. 2003). Future climatic models suggest that flood events and unpredictable, extreme weather systems will become increasingly common, making updates to current stormwater infrastructure not only necessary but also costly (Mayer et al. 2012)(Matsubara 2018). As such, GSI has been in the spotlight as a functional tool to minimize costly updates, while simultaneously reducing deleterious effects on urban aquatic systems.

Individual contaminants are conveyed, treated, and stored differently in GSI systems. The fate of contaminants in rain gardens depends on the chemical nature of the contaminant in question as well as the physical, chemical, and biological processes within the rain garden. Mechanisms for contaminant removal include: sorption, ion exchange, formation of complexes, solubility, precipitation and co-precipitation, volatilization, oxidation-reduction, hydrolysis, photolysis, photo-transformation, and microbial degradation (Davis et al. 2009)(ESSPD 2013). The processes of importance to a specific contaminant will vary, and understanding the processes affecting each contaminant is crucial to successful contaminant removal (ESSPD 2013). The removal processes will affect the availability, toxicity, persistence, and eventual fate of the contaminants in rain gardens and their receiving water bodies (ESSPD 2013). A review of contaminants as well as their fate in rain gardens follows.

1.3. Contaminants of Concern

1.3.1. Heavy Metals

Almost all stormwater contains metals (Pitt et al. 1995). The primary metals of concern are Cd, Cu, Pb, and Zn because of their frequency and possible toxicity to receiving aquatic systems (Weiss et al. 2006)(Nieber et al. 2014). In some studies, aluminium and nickel were also included, although nickel is often overlooked due to it's low mobility (Mayer et al. 2012). For this study, I will focus on the first four Cd, Cu, Pb, and Zn, based on a review of stormwater chemical parameters of concern (Gobel et al. 2007).

Metals in stormwater are present in both dissolved phases as well as bound to SS thus, concentrations may also depend on other parameters, such as turbidity (Gobel et al. 2007). Particulate metals are usually removed via physical straining through root and soil matrix, while dissolved metals are most often removed via adsorption to soil particles in the soil media (Nieber et al. 2014). Depending on the metal, dissolved metals can be removed from stormwater by several mechanisms: adsorption to soil particles, precipitation, occlusion with precipitates, diffusion into solid particles, and biological uptake in plants (Nieber et al. 2014). Because there are different removal pathways, rain garden building specifications can be tailored based on the stormwater contaminants of concern in any given watershed. For heavy metal removal mechanisms, removal rates, and remediation methods in a rain garden, see Table 1.

Metals are introduced to stormwater from many different sources. The sources for specific contaminants will vary based on land use, materials present and in use in a specific area, as well as the chemical nature of rainwater (Gobel et al. 2007). Sources of metals are diverse and widespread, but some examples include: roofing material (Cu, Al, Zn), vehicle-related inputs (Cu, Cd, Pb, Zn, Ni, As), industrial and commercial use of specific metals, and the galvanization process (Zn)(Gobel et al. 2007).

Table 1: Summary of removal mechanisms, removal efficiencies, and most effective filter medias in rain gardens for four heavy metals (Cu, Pb, Cd, Zn) common to stormwater runoff

Contaminant	Removal Mechanisms	Removal Efficiency in Rain Gardens	Effective Filter Media
Copper	Sorption, complex ion formation, ion exchange (Pitt et al. 1996)	98% (Sun and Davis 2007)	Addition of mulch layer to media (Dietz and Clausen 2006)
Lead	Sorption, ion exchange, precipitation (Pitt et al. 1995)	80-98% (Davis et al. 2003)	Sand media more effective than mulch (Davis et al. 2003)
Cadmium	Sorption, ion exchange, precipitation (Pitt et al. 1996)	Up to 95% (Sun and Davis 2007)	Look up media in Sun and Davis 2007
Zinc	Precipitation, sorption, ion exchange (Pitt et al. 2996)	50% to 70% (Davis 2007)	Addition of mulch layer to media (Dietz and Clausen 2006)

1.3.2. Nutrients

The two most widespread and influential forms of nutrient pollution are phosphorus and nitrogen. Although both are essential and naturally present in aquatic ecosystems, in excess these nutrients can cause eutrophication and potentially detrimental algal blooms, as well as acute toxicity in high concentrations for certain nutrients such as nitrate and ammonia (BCAWQG 2016)(Nieber et al. 2014). Nitrogen enters aquatic systems in several forms. Nitrite, nitrate, and ammonia are the forms readily available to aquatic organisms (U.S. EPA 1999). Common sources to stormwater runoff include animal waste, septic leakage, fertilizers, and atmospheric deposition (U.S. EPA 1999).

Concentrations of nitrogen vary seasonally and with land use, although correlations are weak due to the complexity of systems and non-point source pollutions (Nieber et al. 2014).

Phosphorus occurs in several different forms and is introduced through animal waste, plant material, fertilizers, and motor oil, where it aids in preventing wearing of metal parts (Nieber et al. 2014). Concentrations of phosphorus increase logarithmically with impervious surface area in areas using curb-and-gutter style infrastructure (Dietz and Clausen 2008), but will vary depending on watershed land use, rainfall intensity, traffic intensity, and time since last rain event (Nieber et al. 2014).

Rain gardens remove nutrients by different mechanisms. See Table 2 for removal mechanisms, rates, and remediation methods. PO_4^{3-} removal through precipitation or chemical adsorption is dependent on reactions with iron, calcium, or aluminium (Pitt et al. 1999). Under low pH conditions, iron and aluminum phosphate formation is predominant and under high pH conditions, calcium phosphate formation is predominant (Pitt et al. 1999). Rates of phosphorus retention vary widely due to variability in phosphorus inputs from breakdown in plant materials, variability in media composition, and incorporation into biofilms and plants (Nieber et al. 2014). Addition of elemental iron to filter sand media has been found to increase removal rates of dissolved phosphorus (Erickson et al. 2007). Adding 5% by weight iron to sand mixture has been found to remove 90% of dissolved phosphorus entering the filter medium (Erickson et al. 2007).

Nitrate concentrations in urban runoff are usually low (Pitt et al. 1996) but can be high in areas with high fertilizer use (Carlson et al. 2011). Davis et al. 2001 found that filtration through columnar infiltration galleries could reduce ammonia by 60-80% but nitrate concentrations in the media and effluent increased due to biological activity. The simple addition of newspaper clippings to the media creates anaerobic layers, increasing biological reduction of nitrate through denitrification (Kim et al. 2003). Using this method, nitrite-nitrate retention can be improved to 70-80% (Kim et al. 2003). Field studies of rain gardens suggest a nitrogen removal of less than 10% (Hsiesh and Davis 2005). On the other hand, other field studies suggest adding a saturated mulch layer will significantly reduce nitrate and ammonia effluent concentrations (Dietz and Clausen 2006).

Table 2: List of nutrient, and solid contaminants in rain gardens, and their specific removal mechanisms, removal efficiencies and effective filter mediums in rain gardens

Contaminant	Removal Mechanisms	Removal Efficiency in Rain Gardens	Effective Filter Media
Nitrate	Plant uptake, anaerobic denitrification (Kim et al. 2003)	60-80% (Davis et al. 2001)	Addition of newspaper and/or saturated mulch layer to create anaerobic zone (Dietz and Clausen 2006)
Orthophosphate	Precipitation, chemical adsorption with iron, calcium, aluminium (Pitt et al. 1999)	Variable (Negative to 100%) (Dietz and Clausen 2006)(Neiber et al. 2014)	Addition of elemental iron to filter sand media (Erikson et al. 2007)
Suspended Solids (SS)	Physical filtration, sedimentation (Nieber et al. 2014)	77-99% (Hunt et al. 2006)(Davis 2007)	Increase interaction time with filter media (increase depth of filter media & size of rain garden)

1.3.3. Suspended Solids

Suspended solids (SS) are the most common stormwater contaminants and can degrade water quality for both human consumption and aquatic life (U.S. EPA 1999).

Metals, pesticides, and hydrocarbons will often be adsorbed to particles, further increasing the toxicity of stormwater to receiving systems (U.S. EPA 1999)(Nieber et al. 2014).

The primary removal mechanisms for SS are physical filtration and sedimentation (Nieber et al. 2014)(Table 2). Field study removal rates range from 77% to 99% (Hsieh and Davis 2005), but other studies show a wide variation in rates from negative removal rates to study highs of 47% (Hunt et al. 2006)(Davis 2007). For this study, SS will not be focused on as sources for SS can be varied and are not specific to stormwater, as excess surface flow from stormwater inputs can cause erosion throughout the stream system (Walsh et al. 2005). On the other hand, SS levels are important to note as contaminants are often SS-associated and removal of SS removes a significant portion of their associated contaminants (Gobel et al. 2007)

1.4. Project Rationale and Objectives

To reduce the deleterious effects of stormwater inputs to urban aquatic environments, urban restoration and installation of GSI have become increasingly common (McIntyre et al. 2015). These efforts, although well-intentioned, are often fragmented and site-specific (Neeson et al. 2014). This may be one of possible reasons behind the negligible effects of GSI implementation observed in several measured parameters, along with the legacy effects of many contaminants and the length of the study period (Mayer et al. 2012).

This study aims to pinpoint specific aquatic systems within a landscape that have high loading of stormwater contaminants, so to install GSI in a more targeted way. The North Shore Rain Garden Project (NSRGP), a partnership between SFU's Faculty of the Environment and the Pacific Water Research Institute, currently has the backing to install three demonstration gardens, one in each of the North Shore municipalities. The rationale behind the landscape-wide analysis was to pinpoint areas within the North Shore where the NSRGP installations could target the most depreciated watersheds.

Certain building techniques can be used to deal with specific contaminants and this work suggests areas and buildings strategies to reduce inputs of targeted contaminants to urban aquatic systems using the rain gardens to be installed by the NSRGP.

The following objectives will be addressed to inform these strategies:

I. Identify 'streams of concerns' within the North Shore of Vancouver B.C. through a meta-analysis of pre-existing water quality data

   a. Based on the number of parameters above BCAWQG for: heavy metals (Cd, Cu, Pb, Zn) and nutrients ($N0^{3-}$, PO_4^{3-})

II. Identify contaminants within 'streams of concern' that are present in the most elevated concentrations

III. Observe patterns between contaminant concentrations and impervious surface cover to further pinpoint mechanisms for contaminant concentrations

IV. Design a monitoring protocol to assess:

   a. Quantity of stormwater treated by each installation

   b. Quality of stormwater before and after rain garden treatment

   c. Statistical differences between traditional, non-targeted methods of implementation with methods of implementation proposed in this work

Chapter 2. Methods

2.1. Study Site

The North Shore of Vancouver, B.C. encompasses three municipalities: District of West Vancouver, District of North Vancouver, and the City of North Vancouver. It is constrained in the north by the North Shore Mountains. The North Shore mountains are a typical coast range of mainland British Columbia with elevations ranging between sea level and 1500m (Jakob and Weatherly 2003). Annual precipitation is high and varies with elevation, ranging from 1300mm/year near at sea level to 4000mm/year at summit elevations (Jakob and Weatherly 2003). It lies in the Coastal Douglas Fir Biogeoclimatic Zone (Jakob and Weatherly 2003).

Since the 1860's, the North Shore has undergone extensive deforestation, and over the past century, increasing levels of urban development (Sommer 2007). These combined stressors have changed the hydrologic cycles within certain urban watersheds to runoff dominant, putting them at risk for the deleterious effects of stormwater inputs (Mayer et al. 2012). Increasing levels of development paired with high precipitation and the sensitivity of receiving aquatic systems and their biota make the area an ideal location for GSI development and study (Matsubara 2018).

2.2. Data Compilation

The most recent data from stream systems within the District of North Vancouver, District of West Vancouver, and City of North Vancouver was compiled into a single database. Data collection focused mainly on raw data from documents created through the Integrated Stormwater Management Process (ISMP) of each municipality. These documents are recent (2007-2016) and cover a variety of water quality parameters (NSSK 2009)(ODK 2013)(KWL 2016)(G3 2016).

Parameters of interest were the matrix of known contaminants found in urban stormwater (Gobel et al. 2007). The parameters were further reduced to those sampled most consistently in the ISMP documents. Water quality parameters (DO, pH, temperature, conductivity, and turbidity) were noted, but since these parameters can be affected by other aspects of the watershed their consideration was limited, unless they were at levels considered to be acutely toxic to aquatic life (CWGAL 1999)(BCAWQG 2017).

The parameters of key interest were: nutrient concentrations ($N0^{3-}$ and $P04^{3-}$), heavy metal concentrations (Cd, Cu, Pb, and Zn), and pH and hardness, for heavy metal toxicity guideline calculations (BCAQG 2017).

Impervious surface cover percentages were also taken from ISMP documents wherever possible (NSSK 2009)(ODK 2013)(KWL 2016)(G3 2016). When percent impervious surface cover was not available, the corresponding contaminant concentrations were exempted from the analysis. $P0^{4-}$ concentrations were also exempted as values were consistently below detection limits in most watersheds.

2.3. Identifying Streams and Contaminants of Concern

The concentrations of individual contaminants at each site were graphed against the guideline values from the British Columbia Approved Water Quality Guidelines: Aquatic Life (BCAWQG 2017). Both long-term chronic toxicity guideline values and short-term acute toxicity guideline values were graphed against specific site concentrations. Sites with the highest levels of each contaminant were noted, especially if these values fell above water quality guideline standards. Three locations within the North Shore that had the highest guideline exceedance levels for the most contaminants were selected as the streams of concern.

Contaminants of concern were determined as the contaminants within the study data base that were most commonly found to exceed the toxicity guideline values based on the British Columbia Approved Water Quality Guidelines (BCAWQG 2017).

2.4. Statistical Analysis

Contaminant concentrations (Cd, Cu, Pb, Zn, $N0^{3-}$) within each watershed were plotted against percent impervious surface cover of the watershed. Data sets were tested for normality using a Shapiro-Wilk (S-W) test. Cu, $N0^{3-}$ and percent impervious surface cover passed the S-W test for normality. Zn and Pb were $\log_{10}$ transformed to meet assumptions of normality. Cd had two outliers at detection limit removed and then was

$\log_{10}$ transformed to meet assumptions of normality. A regression analysis was carried out for non-transformed and transformed heavy metal and nutrient concentration data to determine whether heavy metals and nutrients concentrations within the North Shore were correlated with percent impervious surface cover of the watershed.

2.5. Rain Garden Building Specifications

Rain garden building specifications were suggested to remediate for the contaminants most commonly in exceedance of BCAWQG in the watersheds of concern. The rain garden building specifications were pulled from recent literature and tailored for the contaminants in exceedance of the BCAWQG.

Chapter 3. Results

3.1. Heavy Metal Analysis

Heavy metal concentrations were compared with guidelines calculated from the British Columbia Approved Water Quality Guide for Aquatic Life (Figure 1-6). Toxicity guideline values vary with hardness (mg/L $CaCO_3$) for Cd, Cu, and Pb, where as Zn toxicity guideline values were constant at hardness below a certain level (BCAWQG 2017).

Exceedance of Cu chronic toxicity guidelines occurred in 67% of all sites and acute toxicity guideline exceedance was found in two sites (0.05%), an outfall to Capilano Flats and the Third Avenue sample site of Mackay Creek (Figure 1)(Figure 2). When looking exclusively at creek sample sites, all exceeded Cu chronic toxicity guidelines except for one Mackay Creek site which had values below detection limits (Figure 1).

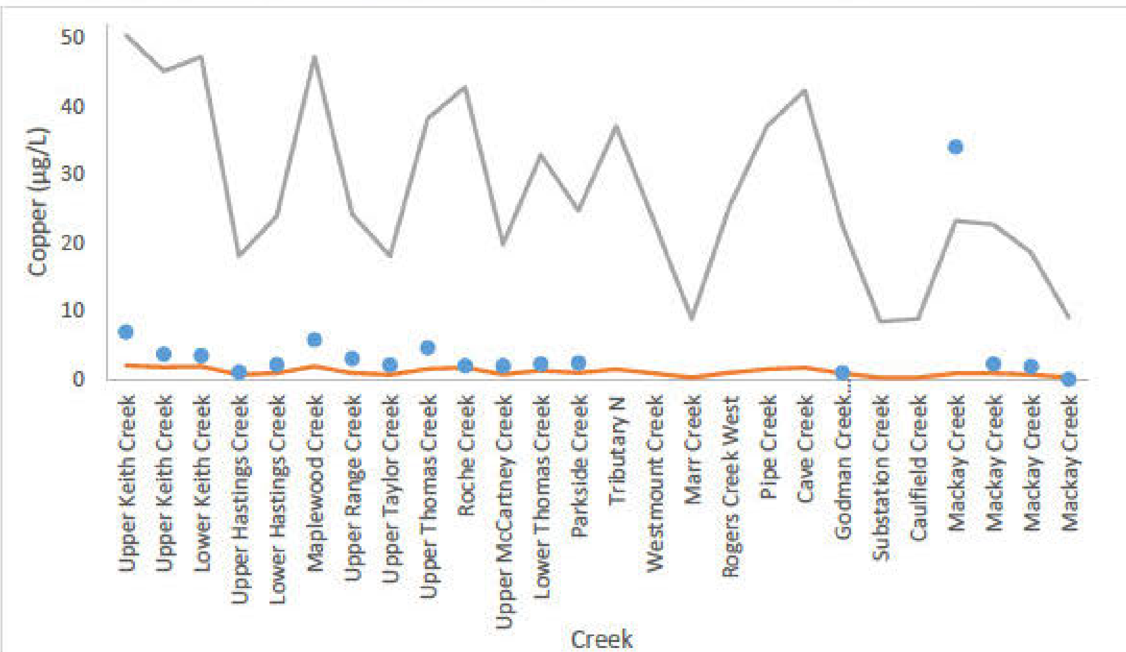

Figure 1: Copper concentrations (µg/L) in creek sites throughout the North Shore of British Columbia. Blue dots represent specific site concentrations. The orange line is the threshold for long-term chronic toxicity guidelines taken from the BCAWQG and calibrated for hardness ([$CaCO_3$]) and the grey line is the threshold for short-term acute toxicity guidelines taken from the BCAWQG.

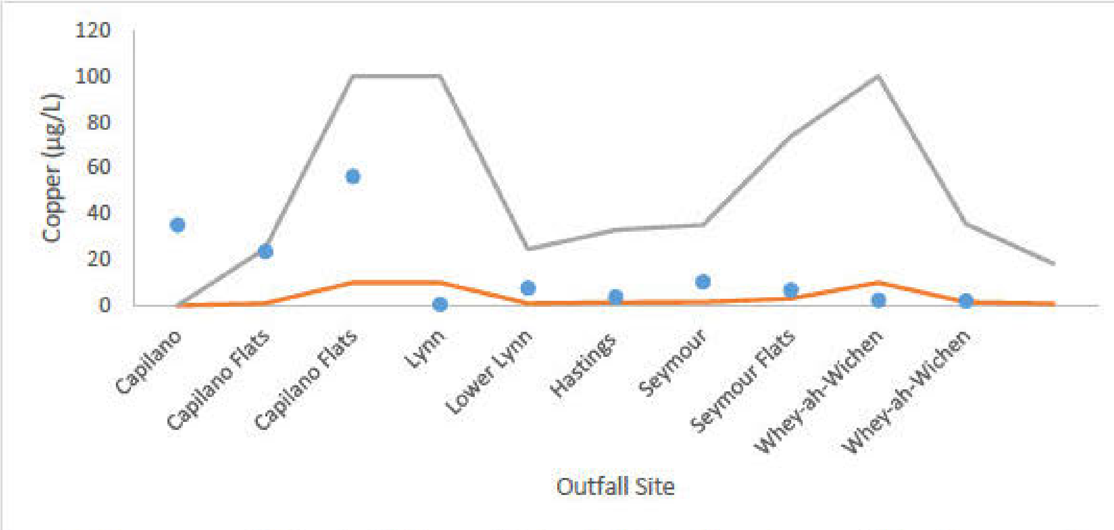

Figure 2: Copper concentrations (μg/L) for specific in outfall sites. Site values are in blue. The orange line indicates long-term chronic toxicity guidelines calculated for water hardness from the BCAWQG and the grey line indicates short-term acute toxicity guidelines, also from BCAWQG.

Cd chronic toxicity guideline exceedance was only found in two outfalls, both in the Capilano watershed (Capilano and Capilano Flats 2) but, did not occur in any of the creek systems (Figure 3). One site (Capilano Flats 1) had hardness values outside the range of the short-term acute toxicity guideline equation, so values calculated for this site are not conclusive. 3 sites had hardness values (Capilano Flats 1 and 2, and Seymour Flats) outside the range of the long-term chronic toxicity guideline equation so these values for these sites are also not conclusive. For sites in exceedance of equation

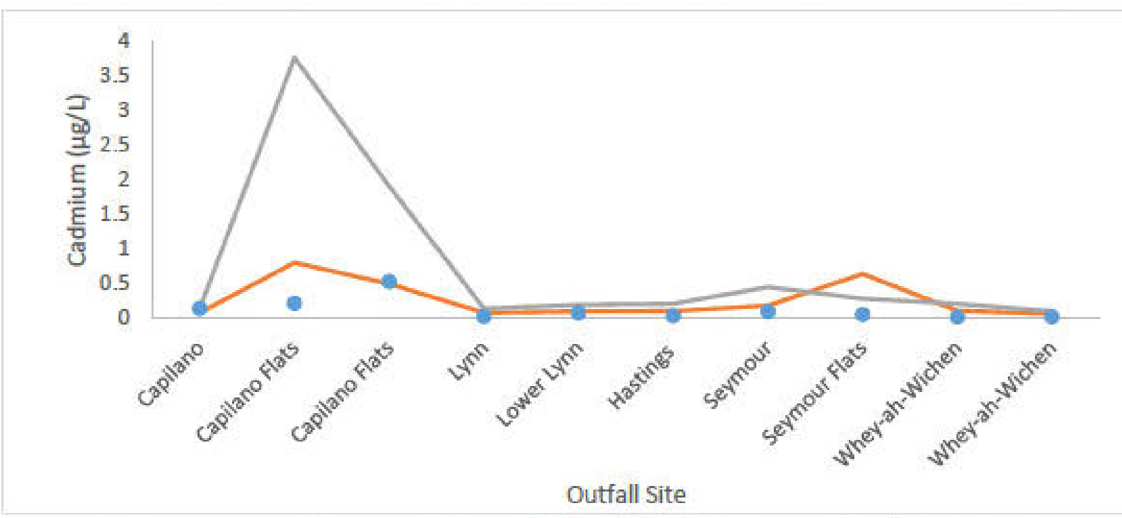

Figure 3: Cadmium concentrations (μg/L) for outfall sites in the North Shore of British Columbia. Long-term chronic toxicity guideline values, based on hardness, are shown in orange and short-term acute toxicity guideline values are shown in grey (BCAWQG 2017)

limits, toxicity guideline values would have to be based on site-specific assessments (BCAWQG 2017).

Pb chronic toxicity guideline exceedance was uncommon and only detected in one outfall sample, Capilano outfall from Fullerton Ave (Figure 4). The rest of the creek and outfall values fell below both acute and chronic toxicity guideline values. Two sites had hardness values above the constraints of the toxicity value calculation and therefore, toxicity guideline values of Pb in these systems must be determined with specific site assessment (BCAWQG 2017).

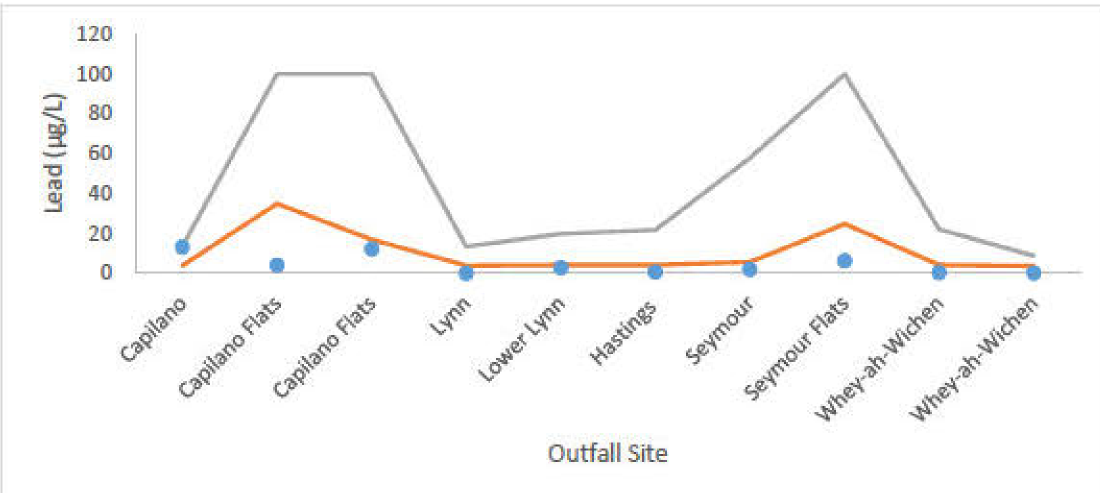

Figure 4: Lead concentrations (µg/L) for individual sites in the North Shore of British Columbia. Long-term chronic toxicity guideline values, based on water hardness, are shown in orange and short-term acute toxicity guideline values are shown in grey (BCAWQG 2017).

Zn chronic toxicity guideline exceedance was found in 37% of all samples (Figure 5). Zn acute toxicity guideline exceedance was found in 3 outfall samples (1, 2, 12). When looking at only creek samples, Zn chronic toxicity guideline exceedance occurred in 44% of all creeks (Figure 6).

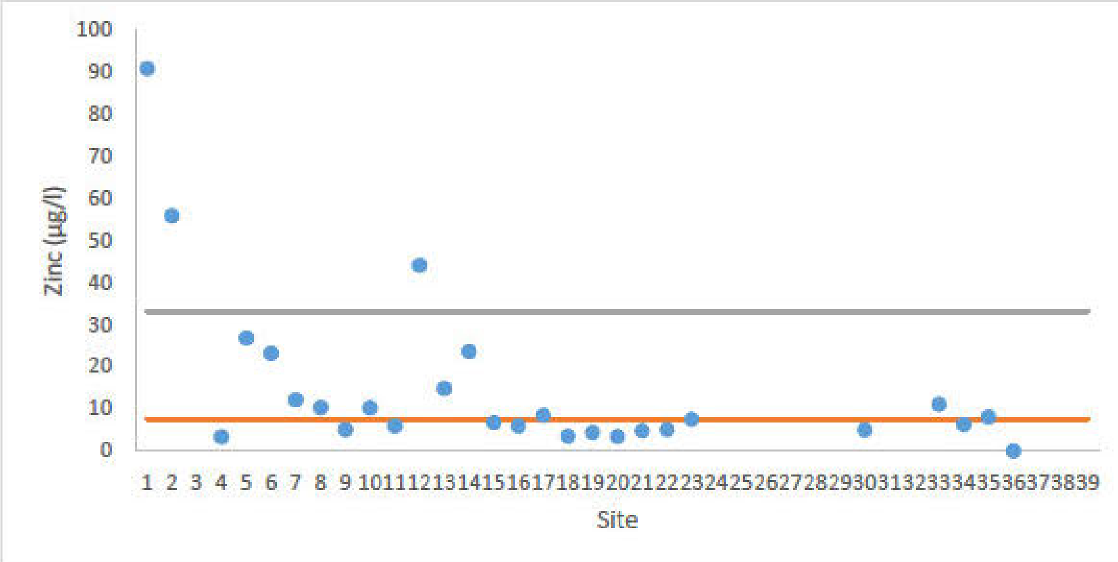

Figure 5: Zinc concentrations (µg/L) for individual sites in the North Shore of British Columbia. Long-term chronic toxicity guideline values are shown in orange and short-term acute toxicity guideline values are shown in grey (BCAWQG 2017).

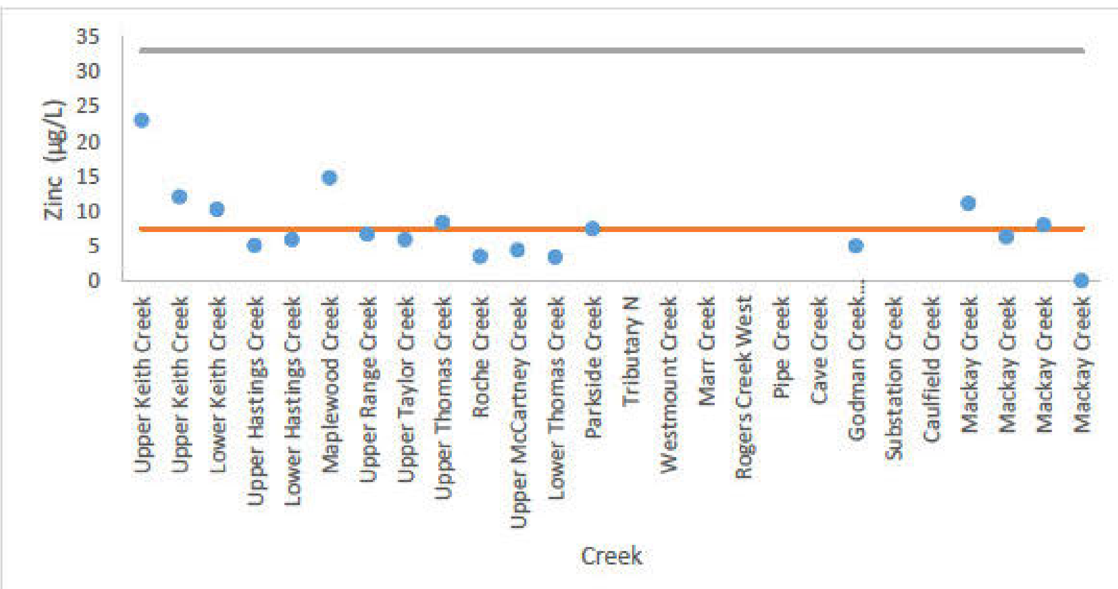

Figure 6: Zinc concentrations (µg/L) for specific in creek sites. Site concentration values are in blue. The orange line indicates long-term chronic toxicity guideline values from the BCAWQG and the grey line indicates short-term acute toxicity guideline values, also from BCAWQG.

3.2. Nutrient Analysis

Nitrate was below long-term chronic toxicity levels at all sites (Figure 7).

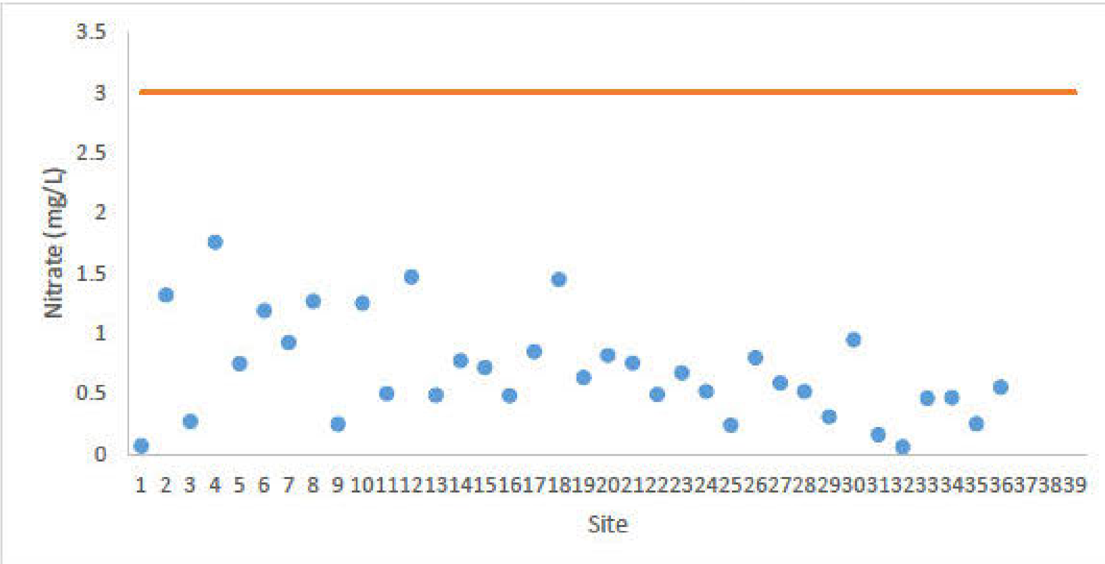

Figure 7: Nitrate concentrations (mg/L) for individual sites. Orange line is the long-term toxicity guideline value (BCAPQG 2017).

Orthophosphate levels were almost all below detection limits, except for several creek sites that had levels well below any toxicity limits.

3.3. Contaminants and Impervious Surface Cover

Relationships between impervious surface cover and metal concentrations were metal dependent and differed in strength. Relationships as determined by R^2 were 0.42, 0.32, 0.59, and 0.39 for Cu, Cd, Pb, and Zn respectively (Figure 8)(Figure 9). All relationships were significant at $P<0.05$. P-values for Cu, Cd, Pb, and Zn were 0.024, 0.014, 0.038, 0.023, respectively.

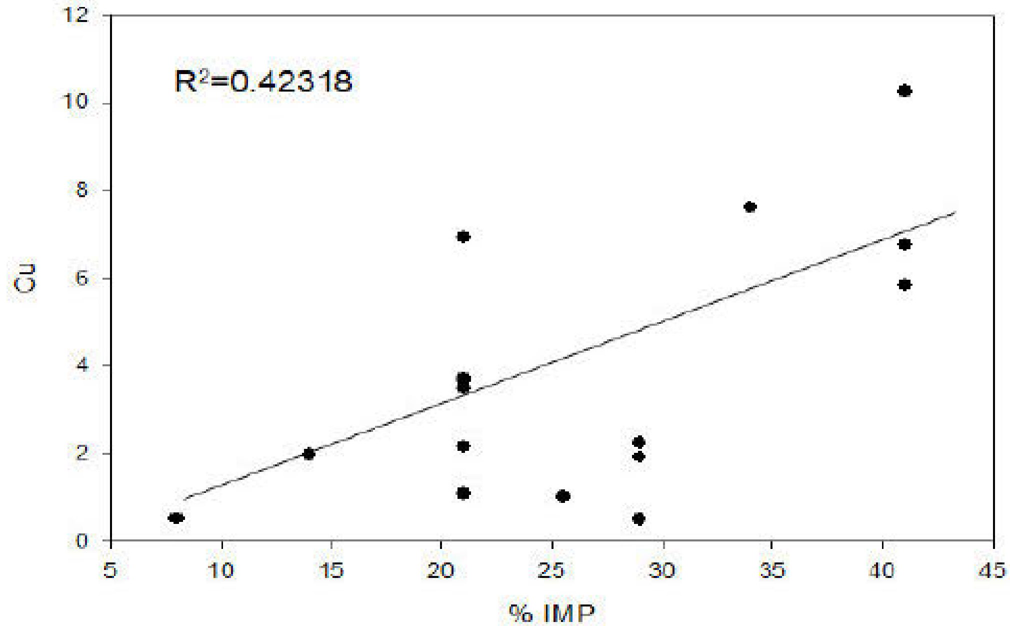

Figure 8: Regression plots of each individual heavy metal concentration (y-axis) and percent impervious surface cover in each watershed (x-axis).

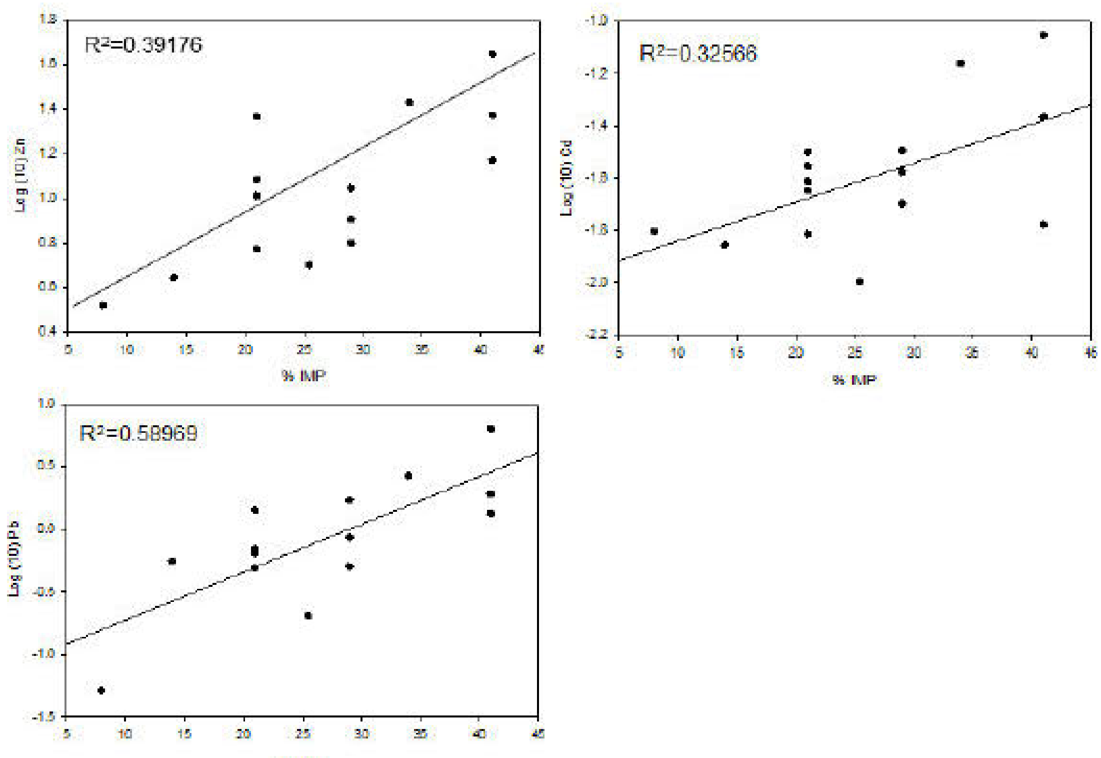

Figure 9: Regression plots with percent impervious surface cover in the watershed (x-axis) versus log(10) transformed heavy metal concentrations (y-axis).

3.4. Watershed and Contaminants of Concern

When considering only creeks systems, the only heavy metals that were present in exceedance of chronically or acutely toxic water quality guidelines were Cu and Zn. Since these were the problematic contaminants, these were the parameters used to select the key sites for rain garden installation. Those sites are highlighted in Figure 9 and are Upper Keith Creek, Maplewood Creek, and Mackay Creek at Third Avenue. All three of these sites were highest for both Zn and Cu.

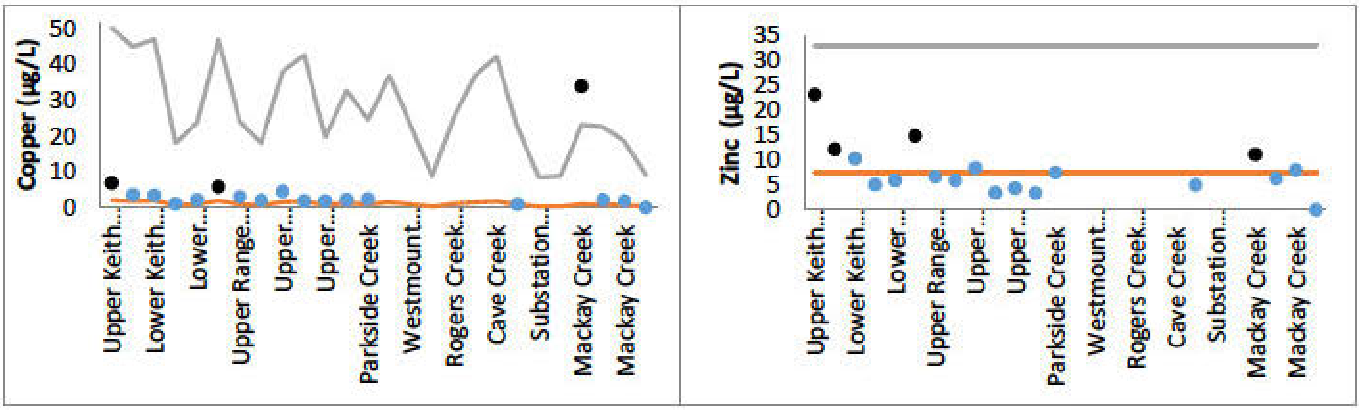

Figure 10: Copper and Zinc concentrations (µg/L) at each creek site. Shown in black are the selected sites. Values for selected sites were highest for both copper and zinc.

Chapter 4. Discussion

4.1. Heavy Metal Analysis

Of the four heavy metals introduced from stormwater runoff, the metals of most concern are Zn and Cu.

All creek sites, save one, were in exceedance of chronic long-term toxicity guideline values for Cu. Cu toxicity guideline values were dependent on site-specific water hardness so the guideline values varied between sites. Sites with high water hardness ([$CaC0_3$]) have higher toxicity thresholds than sites with low water hardness (ESSPD 2013) because Cu's ionic form is very toxic, but when copper forms metal-carbonates or calcium antagonism, as it does in hard waters, it is substantially less toxic (ESSPD 2013). At constant hardness, occurrence of toxic forms of Cu increase at lower pHs (Sprague 1985). This is important to consider when looking at stormwater runoff because major ions from combustion (SO_x, NO_x, and Cl) generate acids that will further lower pH of rainwater, increasing the proportion of dissolved metals in stormwater runoff (Gobel et al. 2007). Since dissolved forms of metals have higher toxicity, these other major ions (SO_x, NO_x, and Cl) will affect the toxicity of metals in stormwater (Gobel et al. 2007).

Cu originates from several different sources. Major sources include: copper brake pad abrasion, tire abrasion, and erosion of copper roof surfaces (Muschak 1989)(Gobel et al. 2007)(Zhang et al. 2013). Dust associated with abrasion products will be deposited onto impervious surfaces and be taken up by stormwater during the first flush of storm events (Gobel et al. 2007). Erosion of copper roof surfaces will result in a high portion of dissolved Cu in stormwater, with erosion rates being dependent on rainwater pH (Gobel et al. 2007).

Zn was also found to be in exceedance of chronically toxic long-term water quality guidelines in creek sites on the North Shore, with 44% of the creeks in the data set exceeding guidelines for chronic toxicity (BCAQWG 2017). Zn toxicity is dependent on Zn availability and on sorption or binding of available Zn to biological tissues, making soluble forms of Zn the most toxic (ESSPD 2013). Since Zn is typically present in runoff in a higher dissolved portion than other metals, it presents a potentially high risk to biota in receiving systems (Gobel et al. 2007).

Zn is derived from several sources. It is used as a rust-resistant coating for iron and steel, and in the manufacture of many products (glass, screens, batteries, electrical apparatus, hardeners, adhesives, etc.). It is also used a filler in automotive tires, so heavy vehicle traffic will deposit Zn onto impervious surfaces (Zhang et al. 2013). Areas with high concentrations of Zn roofs or Zn-lined gutters have associated stormwater with dissolved Zn concentrations higher than that of roads or highways (Gobel et al. 2007).

The other stormwater-related heavy metals were not found to be of concern in the ambient creek water, although some outfall measurements were above toxicity levels for Pb and Cd.

The heavy metal concentrations found in this meta-analysis are concerning as they exceed water quality guidelines, based on LD_{50} and EC_{50}, set out for sensitive species, including salmonids at their most sensitive life stages (spawning, over-wintering, and alevin life stages), which are present in some of creek sites in question (NSSK 2009)(ESSPD 2013). Common reference species for the BCAWQG include zooplankton (*Daphia magna, Daphnia pulex*, or *Ceriodaphnia dubia*), amphipods (*Gammarus* sp.), fathead minnows (*Pimephales promelas*), and salmonids (*Oncorhynchus* sp. or *Salmo* sp.)(ESSPD 2013). Bioitic factors can vary the toxicity of contaminants, so toxicity of contaminants will vary based on species, life stage, size, nutritional status, general health, and acclimatization to environmental conditions or a particular pollutant (Sprague 1985). The concentrations considered in this study are for wet season averages. Wet season spans from October to March, encompassing the time in which some salmonids spawn, and the time in which the eggs and alevins are present in the streams (ESSPD 2013).

The BCAWQG represent guidelines for healthy aquatic life, both long-term and short-term, for single contaminant exposures (ESSPD 2013). Many of the species within these urban systems are dealing with the compounding effects of being exposed to a suite of contaminants found in stormwater, and other sources, over their life history (Gobel et al. 2007). Very few studies have looked at species being exposed simultaneously to a suite of contaminants, so the potential compounding effects of these exposures is unknown

(McIntyre et al. 2015). This is one of the limiting factors of both my data set and most toxicology studies in general, as they measure the effect of single contaminants for lethal and sub-lethal effects. Future studies looking into the effects of a suite of stormwater contaminants on sensitive species in local systems would greatly help to inform future remediation and restoration efforts.

It is also important to note that the exceedance of BCAWQG is not indicative of absolute toxicity but rather an exceedance of values recommended for long-term, healthy aquatic biota. Toxicity of stormwater in local environments to species in question must be determined in a site-specific assessment (ESSPD 2013). Conclusive heavy metal toxicity must be determined using a site-specific analysis of multiple life history parameters (ESSPD 2013).

4.2. Nutrient Analysis

Both orthophosphate and nitrate were analyzed for all sample sites. No exceedance of BCAWQG were found for either nutrient. Nitrate acute toxicity guideline values are based on LD_{50}, although nitrate can have indirect effects on stream ecosystems, such as eutrophication, which can also be toxic (BCAWQG 2017). Indirect toxicity cannot be gauged used BCAWQG and needs to be assessed based on site-specific conditions (ESSPD 2013). Nitrate values, although below any toxicity guidelines, were quite high, about 4x that of an average, undisturbed lotic system in British Columbia (BCAWQG 2017). Orthophosphate values were not graphed as only several values were found to be above detection levels. This is likely due to the very quick uptake and retention of orthophosphate in the aquatic environment (ESSPD 2013).

4.3. Contaminants and impervious surface cover

All metals were found to correlate positively with increasing impervious surface cover of the watershed. Nitrate values showed a negligible relationship to impervious surface cover percentage (R_2=0.0187, p-value=0.004). Mayer et al. 2012 found that heavy metals concentrations tend to increase with increasing hardening of the landscape. As well, heavy metal concentrations were found to increase with increasing traffic intensity (Gobel et al 2007). Zn and Cu concentrations in stormwater are much higher in areas with Cu and Zn roofing since low pH rainwater tends to erode roofing material, increasing the dissolved proportions of both Zn and Cu (Gobel et al. 2007). Zhang et al. (2013) found that Cd concentrations tended to be irregularly distributed in the landscape, and associated with a specific source, where as Cu, Pb, and Zn tended to decrease from high to low traffic intensity areas. This study also corroborates these findings, as Cd had the lowest R^2 value and Pb and Cu had the highest.

The particulate portion of stormwater heavy metals are dependant on the amount of SS in runoff (Gobel et al. 2007). SS in runoff has been found to be positively correlated to both impervious surface cover and traffic intensity (Hermann et al. 1998)(Shinya et al. 2000). Pb and Cu are found predominantly sorbed to SS particles, and therefore with increasing impervious surface cover and therefore SS, increasing Pb and Cu are common (Hermann et al.1998)(Gobel et al. 2007). This study found similar results, with Pb and Cu showing the highest correlation to impervious surface cover of the watershed. These findings highlight the importance of locating stormwater treatment basins in areas where impervious surface cover and traffic intensity are both high, rather than placing rain gardens in easy-to-implement areas.

4.4. Site Selection for rain garden application

Cu and Zn, the two metals that were consistently exceeding BCAWQG in North Shore systems, were used to choose the three sites of focus for rain garden installation. These sites were Upper Keith Creek, Maplewood Creek, and one reach of Mackay Creek (at 3rd Ave.). These sites had long-term chronic toxicity guideline exceedance for both metals and had elevated levels of other heavy metals as well.

4.5. Rain Garden Build Specifications

Since Cu and Zn are the two contaminants with the highest concentrations in North Shore systems, rain garden building specifications were tailored to remediate for these two metals.

Cu is removed from stormwater in rain gardens through three main mechanisms: sorption, complex ion formation, and ion exchange (Pitt et al. 1996). Removal efficiencies by current practices are high (88-93%)(Sun and Davis 2007), but these can be further improved (>98%) by amending the soil with a mulch layer, within which 98% of influent copper was found to be retained (Dietz and Clausen 2006). Rycewicz-Borecki et al. (2016) found that 92% of heavy metal uptake in bioretention systems occurs within the first 27 cm of the soil media, underlying the importance of maintaining a minimum depth of soil depth. Since the majority of soil metal removal occurs in this first foot, ensuring this as a minimum soil depth will help maximize in-soil Cu retention and minimize possible leaching into lateral flow or groundwater (Zimmerman et al. 2005). Furthermore, planting a suite of plants that accumulate metals will help reduce the soil burden, increasing availability of soil sorption sites (Read et al. 2008). Soils in rain garden systems will eventually lose their ability to uptake metals as sorption capacity decreases over time (Read et al. 2008). Uptake from plants can help lessen this burden as plants can be much more easily harvested, than soils can be remediated. Hyper-accumulator plants can be used, although few, if any, of these species are native to the Pacific Northwest (PNW)(Fritoff and Greger 2003). Several species are much more effective at heavy metal uptake, but are not native to the PNW and some, not suitable for growth in a rain garden environment (Fritoff and Greger 2003). If remediation of the soils is necessary, re-planting with non-native, high accumulator, high-biomass species such as canola (*Brassica napus*) or common sunflower (*Helianthus annuus*), may be useful for several seasons to increase the soils ability to filter metals (Solhi et al. 2005).

The removal mechanisms for Zn are precipitation, sorption, and ion exchange (Pitt et al. 1996). Removal rates are comparatively lower than other heavy metals in rain gardens (50-70%) with most of the Zn being stored in the sediment (Davis 2007). Installing a mulch layer can help increase the Zn uptake, and one study showed the mulch layer uptake accounting for 16% of the total Zn removed (Dietz and Clausen 2006). The building specifications for the removal of Zn are very similar to the recommendations for Cu: mulch addition and soil depth of at least 30 cm.

There are some native plant species that uptake Zn at a higher rate than other rain garden species. These species may be useful to increase uptake within each individual rain garden, although the information available for the specific geographic area in question is limited (Fritioff and Gregor 2003)(Davis et al. 2009). *Juncus effusus* has a relatively high uptake of zinc in the tissues, with a concentration of Zn in the roots triple that of the soil media (Fritioff and Greger 2003). Some plants (*Carex* sp. and *Juncus* spp.) have been found to be particularly effective at reducing concentrations of pollutants through biofiltration of the root media (Read et al. 2008). *Carex praegracilis* has been shown to do well in the unique conditions of a rain garden environment which includes variable hydraulic regimes, high nutrient-, and high metal-loading (Rycewicz-Borecki et al. 2016). As plants vary in their ability to remove different pollutants, a suite of different species may be most suitable to maximize the spectrum of contaminants removed (Read et al. 2008).

Due to the lack of local knowledge about metal-accumulating, native plant species, further research into native species' ability to phytoremediate is recommended. Soil remediation within rain gardens is one of the key maintenance concerns and costs, so finding effective methods to increase lifespan of rain garden soils is important (Lilley 2018)(Matsubara 2018). Furthermore, reducing soil metal uptake is key to limit metal leaching into lateral flow and potentially groundwater so, finding methods to reduce this risk can improve social and stakeholder buy-in, and limit potential environmental and human health risks (Zimmermann et al. 2005). Since heavy metal accumulation by PNW native species in rain gardens is poorly understood, future work by the NSRGP will aim to test stormwater-associated metal accumulation in a variety of different native plant species in rain garden environments.

4.6. Conclusion

Based on the data collected, the contaminants of most concern within the North Shore of British Columbia are Cu and Zn. These two contaminants were consistently found to be above long-term chronic toxicity guideline values proposed by the British Columbia Approved Water Quality Guides. The sites with the highest values of these two parameters were Upper Keith Creek, Maplewood Creek, and a specific site of Mackay Creek. Heavy metal values within the systems were found to be positively correlated to impervious surface cover in the watershed where as other parameters, such as nutrients, were not. The strength of the correlation varied between metals, with Pb and Cu, SS-associated contaminants, having the highest R^2 values. For the sites of concern (Upper Keith, Maplewood, and Mackay Creek), proposed rain garden building techniques were tailored to remediate for Cu and Zn. The techniques included fortifying the soil with a mulch layer, using a minimum of 30 cm soil depth, and planting several different native plant species that have been found to uptake metals (*Juncus effusus*) and/or have a high biofiltrating-capacity of the root system (*Carex* sp.).

Chapter 5. Monitoring Plan

5.1. Introduction

In any restoration work, monitoring is an essential part of determining whether restoration objectives were achieved and whether restoration methods can be improved upon. This monitoring plan aims to measure differences between traditional methods of locating and installing rain gardens versus the methods proposed in this paper. This will be done by comparing several different parameters of individual rain gardens, some of which were installed with traditional methods and some of which will be installed based on considerations from this work. Measured parameters will be compared statistically to determine if the proposed method of installation improves the ability of rain gardens to treat stormwater to mitigate the negative effects of stormwater on receiving systems.

This monitoring protocol will also measure the efficacy of installed rain gardens as local case studies of rain garden functionality. Local case studies can help inform policy decision, risk management, and best management practices (BMPs)(Lilley 2018)(Matsubara 2018). Understanding how these systems function locally can help us tailor BMPs to our landscape so the assumptions of BMPs are accurately grounded in the working environment. The monitoring protocol will also be designed to measure rain garden efficacy over time as well as the overall abilities of rain gardens to treat urban stormwater within the North Shore of Vancouver, B.C.

5.2. Objectives

To achieve these monitoring goals, the following will be addressed:

1. Ensure initial functionality of each rain garden

    1.1. Ensure stormwater is infiltrating

        1.1.1. Ensure overflow function, no flooding in large storm events, and erosion control

    1.2. Monitor plant survival over time

1.2.1. Note which plants have highest survival

1.2.2. Replant with plants with high survival, where necessary

2. Monitor overall functionality over time for individual rain gardens

2.1. Calculate infiltrative capacity, total rainfall managed, and percent efficacy

2.1.1. Compare values between years to determine any changes in infiltrative capacity, rainfall managed, or efficacy over time

3. Compare previous rain garden installation functionality with proposed installations

3.1. Compare rainfall volume managed between previous and proposed installations

3.2. Measure incoming and outgoing water quality between previous and proposed installations

3.2.1. Measure heavy metal concentrations (Cu, Cd, Pb, and Zn)

3.2.1.1. Calculate percent removal efficiency for heavy metals

3.2.2. Measure nutrient concentrations ($N0^{3-}$, $P0_4^{3-}$)

3.2.2.1. Calculate percent removal efficiency for nutrients

4. Perform statistical analysis to detect variation among parameters in each rain garden and differences among parameters among rain garden installation types

5.3. Methods

5.3.1. Functionality Monitoring

After rain garden installation, it's important to ensure proper functioning. There are four main parameters of importance: infiltration capacity, erosion control, overflow functionality, and plant survival (Campbell et al. 2013). These parameters are important to monitor and control as they pose threats to functionality and some are threats to human safety (flooding) (Campbell et al. 2013). While plants are establishing, mulch can be added to reduce erosion. Some watering may be necessary, depending on weather conditions while plants establish, to increase survival. Apply spot watering as necessary.

Infiltration capacity is the rate at which water is infiltrated into the soil. This can be measured by either the rate at which a certain volume is removed from a system or the length of time it takes a storm flow to go from peak to base values. This will give you a rate in volume/hour. See figure 11, where infiltration rate is the rate at which the volume is reduced from the peak to the base flow. From here you can calculate how much volume can be managed by: (pervious area(m^2))(ponding volume(m^3))(infiltration rate(m/hr)) (Campbell et al. 2013)(Matsubara and Gerwin 2017).

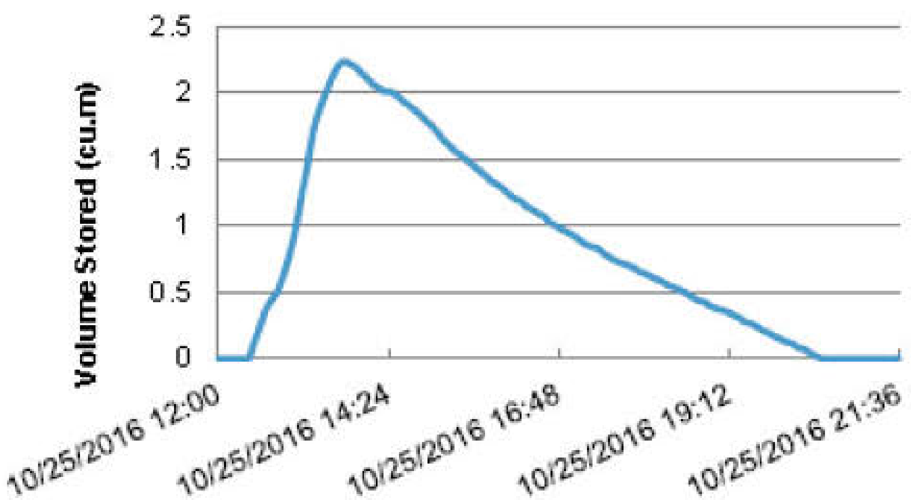

Figure 11: The volume (cu.m) stormwater managed by a single rain garden during a small stormwater event. Source: Matsubara and Gerwin 2017.

Erosion will be monitored weekly where possible. This will be done visually. Mulch will be added in areas where soil is exposed to limit erosion.

The overflow grate will be tested after initial installation by flooding the rain garden to ensure overflow redirects excess water to storm drains. Subsequent monitoring, to observe for any potential street flooding, will occur after the first three storm events, reducing frequency to once every wet season, after a storm event, after initial clearance.

5.3.2. Rain Garden Comparison Measurements

To compare water treatment capacity of individual rain gardens and to compare among rain gardens, in-going and out-going water quality will be monitored for common stormwater parameters (SS, Cd, Cu, Pb, Zn, $N0^{3-}$, $P0_4^{3-}$). A piezometer will be installed directly downhill from the rain garden to measure out-going water quality and in-going water quality will be collected from inflow. Optimally, these measurements will be taken at first flush, the initial precipitation event after at least a 3-day dry period (Gobel et al. 2007). By measuring percent efficiency removal of metal and nutrient concentrations, variability between in-going stormwater quality will be taken into account.

5.4. Statistical Analysis

Statistical analysis will be used to measure trends in individual rain gardens over time. The parameters of concern will be percent efficiency for metal and nutrient removal and infiltration rates over time. These measurements will allow us to measure the effectiveness of each individual rain garden over time and to plan for any decreases in stormwater filtration capacity as the rain garden ages. This will help effectively plan for any remediation or maintenance efforts necessary, as well as to provide a better understanding of rain garden life cycle in a local context.

Statistical analysis will be done between rain gardens installed using proposed methods and rain gardens installed in traditional methods to compare percent efficiency of heavy metal and nutrient removal. This will allow comparison between proposed methods and current rain garden installation methods. The comparison will be done between rain gardens installed within the same season, some of which would be installed using methods proposed in this paper and some of which would be installed using the common practices of the given municipalities.

5.5. Outcomes

The outcomes of the monitoring plan will be:

1. Calculation of key rain garden functionality parameters

    1.1. Infiltration rate, volume stormwater managed, percent efficiency metal removal

2. Statistical analysis of functionality over time

    2.1. Comparing the infiltration capacity, nutrient and heavy metal removal efficiencies within each rain garden

3. Statistical comparison of removal efficiencies between rain gardens

    3.1. Comparing percent efficiency metal removal between proposed installation methods and traditional installation methods

5.6. Conclusions

In a recent green infrastructure workshop, many barriers to green infrastructure implementation were acknowledged (Lilley 2017). One of these barriers was a lack of local research on rain garden installations within the Lower Mainland (Lilley 2017). Studies such as the one proposed in this monitoring plan can help demonstrate just how these technologies act in local environments and how they can be tailored to local conditions (Asleson et al. 2009). There is currently a research gap as to which native plants not only have high survival rates in these systems, but also can aid in remediating the heavy metal soil burden. Several different plants were proposed in this study, but a more thorough investigation of local plants with phytoremediating capabilities would prove beneficial to the local advancement of these technologies.

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Appendix A.

Supplementary Information

Additional Stormwater Contaminants

Organic Compounds

Organic compounds can be naturally occurring, but the ones focused on in this study are anthropogenically deposited petroleum hydrocarbons and rubber particles. Sources of petroleum hydrocarbons include leaky storage tanks, parking lot and roadway runoff, automotive emission, dumping, and chemical spills (U.S. EPA 1999). The fate of hydrocarbons in rain gardens is determined by their type, with mineral oil hydrocarbons (MOHs) being captured and degraded more readily than polycyclic aromatic hydrocarbons (PAHs) (Nieber et al. 2014). One study found that most hydrocarbons are removed in the soil layer or vadose zone of rain gardens but some compounds have been measured as groundwater contaminants near infiltration basins (Nieber et al. 2014). Rain gardens with a sandy/sandy-loam media were found to remove 96% of oils and grease in a laboratory setting while the field component had 99% to 100% removal (Hsieh and Davis 2005). Vegetation was found to increase removal rates of naphthalene from 73% in non-vegetated cells to 93% in vegetation cells because of adsorption, mineralization, and plant uptake (LeFevre et al. 2012) (McIntyre et al. 2015). LeFevre et al. 2012 also found that rain garden soils contained more petroleum hydrocarbons than upland soils but that these values were still far below regulatory limits.

Pathogens

Bacteria and viruses can be present in high concentrations in stormwater and easily leak through rain garden systems into groundwater (Pitt et al. 1999). The highest concentrations of bacteria and viruses are found in areas where the water table is very near or at the surface (Pitt et al. 1999). Bacteria is removed from runoff by straining through the soil media and sorption onto particles (Nieber et al. 2014). These removed bacteria may continue to survive within the soil for two to three months if the environment remains suitable, although much longer times have been noted (Pitt et al. 1999)(Nieber et al. 2014). Soils with a low pH and high organic matter have been found to sustain bacteria for longer periods (Nieber et al. 2014). *E. coli* and *enterococci* concentrations were reduced when infiltrated through a sand filter but levels were not reduced below detection limits, indicated a level of leakiness. Removal efficiencies were with a 100% sand media were 0-88% for *E. coli* and 16-89% for *enterococci*. A mixed sand-peat media removed 35-96% of *E.coli* and 0-94% of *enterococci* (Clark 2000). In one study fecal coliforms median concentrations were reduced by 98.6% ((Dietz and Clausen 2005).

Chloride

Chloride is soluble, readily transported, and not easily filtered or readily sorbed to soil media, and can reach concentrations in aquatic systems that threated aquatic biota (Kaushal et al. 2005). It's use as a de-icing agent means it can be present in high concentrations on impervious surfaces and will be readily dissolved and transported come first flush (Nieber et al. 2014). Chloride has been found to significantly increase chloride concentrations in lakes (Novotny et al. 2008). This concentration increase can also lead to the release of phosphorous and metals sorbed onto sediments as increasing chloride concentrations deplete oxygen levels (Novotny et al. 2008). Kelly et al. 2008 found that 91% of sodium chloride inputs into a creek were from de-icing salt and only 2% was from natural atmospheric deposition and rock weathering. Chloride is only minimally absorbed or adsorbed, and plant uptake is low, making it of risk through infiltration practices to both aquatic and human life through the contamination of ground and surface waters (Neiber et al. 2014)

Primary removal mechanisms for nickel are surface adsorption, ion exchange, and chelation (Pitt et al. 1996). Although found on impervious surfaces, nickel is usually in low concentrations in stormwater and compared to other metals, as it is much less mobile (Pitt et al. 1995). Nickel removal is relatively low, with observed rates of 11% to 23% (Mohammed et al. 2012).

Soil Remediation

In areas with high concentrations of particulate metals, estimates suggest that soils may need to be remediated, as they could exceed safe levels in 20 years (Davis et al. 2003). This period can be more accurately estimated with a soil metal concentration equation (Marsalek et al. 2001).

Leaching of metals from rain garden soils may occur, but this can be remediated by adding soil amendments (Harden and Pitt 2011). Gypsum soil softener was found to reduce leaching of chromium and arsenic by over 70% (Harden and Pitt 2011). Some metals may also accumulate into plant biomass, and uptake rates are dependent on plant species (Nieber et al. 2014). Plants with a high uptake rate and a high metal tolerance are ideal for planting in areas where heavy metal concentrations are of concern (Nieber et al. 2014).