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Evaluation of Bioretention Performance in Northern Utah as a Function of Media, Vegetation, and Loading

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EVALUATION OF BIORETENTION PERFORMANCE IN NORTHERN UTAH AS A FUNCTION OF MEDIA, VEGETATION, AND LOADING

by

Trixie Rife

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ABSTRACT

Evaluation of Bioretention Performance in Northern Utah as a Function of Variable Media, Vegetation, and Pollutant Loading

by

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Utah State University, 2020

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The EPA has identified bioretention (BR) systems as a best management practice to mitigate pollutants in stormwater runoff. BR systems reduce pollutant loads received by surface water bodies and lower concentrations for water infiltrating into groundwater storage areas. However, further study is necessary for variable loadings, different filter media, and vegetation. This study evaluated the effectiveness of plants, specific filter media for pollutant removal, and impact of loading on removal of nitrogen, phosphorus, Cu, Zn, and Pb in a BR system at three field sites. The Salt Lake City Public Utilities site contained a BR system with Utelite™ expanded shale and pea gravel. The Green Meadows contained native soil and compost and 300 East site contained native soil. The Public Utilities site leached most pollutants and the soil at the Green Meadows site leached high concentrations of As. Water extractions were completed on the Public Utilities media, identifying the source of the leached pollutants as the expanded shale within the BR system. Two field sites were used to examine the impact of the presence of vegetation and vegetation selection on pollutant removal from stormwater runoff. The Green Meadows site was planted with four species of BR specific plant species and the

300 East site was planted with a common cabin grass mixture. Results show that vegetation improves pollutant removal compared to no vegetation and common cabin mixture grass contributes to pollutant removal from stormwater runoff. The same two field sites were used to analyze loading rates on pollutant removal. At the Green Meadows and 300 East sites pollutant loadings were not reflected in the pore water concentrations for most pollutants examined. The pollutant loadings at 300 East were assimilated for the BR system and the concentrations found in the pore water were reflective of the background concentrations of the soil media and not those found in the runoff. The selection of filter media and vegetation for BR systems is an important step in the system design process, with the appropriate design a BR system can remove a variety of pollutant loads from stormwater runoff.

(155 pages)

PUBLIC ABSTRACT

Evaluation of Bioretention Performance in Northern Utah as a Function of Variable Media, Vegetation, and Pollutant Loading

Trixie Rife

Pollutants found in stormwater runoff are a growing environmental concern. The EPA has identified bioretention (BR) systems as a best management practice for the control of pollutants in stormwater runoff. BR systems reduce pollutant loads discharged to surface water bodies and to lower pollutant concentrations of water infiltrating into underlying groundwater. However, knowledge of the performance of BR systems in semi-arid Western climates is lacking. This study was conducted at three field sites in Northern Utah to evaluate the effectiveness of various natural and engineered media and various plant species on pollutant removal subjected to a range of pollutant loadings found to represent stormwater runoff in the region. The three field sites were used to evaluate media selection for pollutant removal in a BR system. Two vegetated field sites were used to examine the impact of vegetation selection and loading rates on pollutant removal from stormwater runoff. Pollutant removal was not consistent among the three field sites due to leaching of pollutants from the media at varying rates. The vegetated BR systems improved pollutant removal when compared to unvegetated systems. Pore water concentrations were not correlated with the stormwater runoff loading rates for most pollutants examined in this study, being controlled primarily by media characteristics. Media type, vegetation species and loading are important parameters when considering bioretention design.

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CHAPTER 1

INTRODUCTION

1.1 Overview

In the semi-arid West there is a predicted change in weather patterns that will increase precipitation in the winter months as rain and increase drought in the summer months (EPA 2016a). Because of this shift, strategies are necessary to increase water availability in the summer for irrigation and consumption. Currently, most semi-arid regions in the Intermountain West depend on snowmelt to provide the necessary water in the spring and summer for crops and water needs for a growing population. Climate change models indicate that the snowpack will diminish, limiting springtime infiltration into aquifers and runoff into reservoirs and therefore, the amount of freshwater necessary for agriculture and human consumption (EPA 2016a, EPA 2017b). An effective way to capture and filter stormwater runoff is necessary to increase the water supply for future human consumption or irrigation by infiltration to groundwater.

Stormwater runoff, however, can be a source of pollutants that negatively impact a receiving water body, and some pollutants may pose a significant health risk to humans and aquatic organisms (Cohen et al. 2001; Gaffield et al. 2003). Urbanization has increased the amount of runoff by increasing the coverage of impermeable surfaces, creating a need to improve stormwater runoff quality. An increase in runoff creates an increase in pollutant loadings as the water flows over lawns, parking lots, roads, sidewalks and roofs. The pollutants found in these areas come from lawn fertilizer, pesticides, tire wear, brakes, engine lubricants, auto exhaust, etc. (Davis et al. 2001b; Charters et al. 2016). Some of the pollutants of concern in stormwater include nitrogen

(N), phosphorus (P), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn). These pollutants should be removed before water can be used for groundwater recharge or be allowed to run into surface water bodies.

By using bioretention (BR) systems for infiltration, stormwater runoff can be captured and harvested for reuse. BR systems are depressed areas that contain vegetation and filter media designed to reduce peak flows and increase infiltration into groundwater and have been a method of stormwater mitigation since the 1990s. (Prince George's County 2007; Winston et al. 2016).

The Department of Environmental Resources, Prince George's County, MD developed the practice and prepared the first instructional manual for the design and implementation of BR systems in 1993 (EPA 1999; Prince George's County 2007). BR systems are considered best management practices by the EPA for pollutant removal which occurs by settling, filtration, adsorption and/or plant uptake (EPA 1999; Prince George's County 2007; EPA 2016b). Many studies have been completed verifying the ability of BR systems to remove pollutants, including nutrients and suspended solids from stormwater runoff.

However, national design guidelines may be ineffective since regional pollutant loading, plant species, and soil type are generally not considered, and retention areas are not always modified for local conditions. Pollutant loading, media type and plant variety can all effect the efficiency of pollutant removal in a BR system. These variables should be considered in the design of BR systems in areas with different climates. Some areas have created BR system manuals to accommodate the different variables that can impact BR system performance in their specific regions (Kennedy/Jenks Consultants 2007;

Watershed Management Group 2012; ACHD 2014; City of Tucson 2015; City of Mesa 2015; Delta Institute 2017) but no guidelines or manuals have been developed for the Intermountain West.

Filtration media within a BR system plays an important role in performance. The media must allow drainage within a certain time frame, must allow for plant growth, and should aid in pollutant removal. Amendments to soil or engineered media may improve pollutant removal in BR systems. Studies have been conducted using different types of sand (Barrett et al. 2013; Ren et al. 2016; Glaister et al. 2017), naturally occurring soil (Zhang et al. 2008; Ren et al. 2016; Glaister et al. 2017), expanded shale combined with other amendments (Sloan et al. 2008; Zhang et al. 2008), and various other soil amendments to enhance pollutant removal (Zhang et al. 2008; Gilchrist et al. 2013; Lim et al. 2015; Ren et al. 2016; Afrooz et al. 2017; Shrestha et al. 2018). These studies reported variable results for pollutant removal with each media type or amendment that was added, from negligible to high removal for most pollutants. Zhang et al. (2008) and Ren et al. (2016) found that fly ash enhanced P and Pb removal when combined with sand or gravel. Expanded shale has been found to remove significant amounts of P and metals when combined with compost, soil, sphagnum peat moss, or zeolite (Zhang et al. 2008; Sloan et al. 2008). Naturally occurring soils, in most cases, perform better at pollutant removal when amendments are added (Zhang et al. 2008; Lim et al. 2015; Ren et al. 2016; Glaister et al. 2017).

Vegetation within BR systems is generally selected simply for plant survivability. However, using vegetation to enhance pollutant removal should also be considered when selecting plants for BR systems. Studies conducted on BR systems with and without vegetation have shown that vegetation improves pollutant removal, specifically N (Barrett et al. 2013; Rycewicz-Borecki et al. 2017; Glaister et al. 2017). However, studies have shown that different plant types vary in their ability to remove pollutants and these finding should be considered when choosing plants for BR systems (Bratieres et al. 2008; Read et al. 2008; Barrett et al. 2013; Payne et al. 2014; Leroy et al. 2016; Wu et al. 2017; Rycewicz-Borecki et al. 2017; Wang et al. 2017; Shrestha et al. 2018). A lack of vegetation increases clogging potential, ponding, evaporation and decreases infiltration leading to inefficient pollutant removal (Barrett et al. 2013; Rycewicz-Borecki et al. 2017).

This study, consisted of three field sites in Northern Utah and was used to 1) determine the role filter media in BR systems plays in affecting soil pore water and protecting groundwater quality and subsequent BR system pollutant removal performance evaluation, 2) evaluate the role of vegetation and vegetation type on BR systems removal of nutrients and select trace elements, and 3) document maximum loading rates that can be applied to vegetated BR systems to ensure protection of groundwater quality from nutrient and trace metal contamination from stormwater runoff.

1.2. Research Hypotheses & Objectives

The overall objective for this study was to determine how different vegetation and media types under different loading conditions reflective of stormwater runoff conditions in Northern Utah affect stormwater pollutant removal. Removing pollutants is important to protect groundwater quality and increase water resource availability. The findings from this study will help to improve design recommendations of BR systems that can effectively capture stormwater, while maintaining groundwater quality. The specific hypotheses and objectives were:

Hypothesis 1: Soil and engineered media affect the removal of stormwater pollutants in BR systems. To test this hypothesis, two engineered materials, Utelite™ expanded shale and pea gravel, used as storage and treatment media in one BR system field site in Salt Lake City, along with native soils used as fill material at two field sites in Logan, UT were analyzed for their effectiveness in pollutant removal from stormwater runoff. Runoff samples were collected and analyzed along with well and pore water samples below the sites to quantify and compare pollutant removal through the media and soil layers.

Hypothesis 2: Plant species vary in efficiency in nutrient and select trace element removal within a BR system. To test this hypothesis, a chosen set of plant species (turf grass (*Poaceae*), small wing sedge (*Carex microptera*), cattail (*Typha latifolia*), common Baltic rush (*Juncus balticus*), and sunflowers (*Helianthus maximilliana*)) were evaluated to determine their effectiveness at removal of nutrients and trace elements found in stormwater runoff. BR system pore water was sampled and analyzed to evaluate pollutant removal as a function of vegetative cover. Unvegetated treatments served as controls.

Hypothesis 3: Variable pollutant loadings impact nutrient and trace metal removal in BR systems. To test this hypothesis, nutrient (N and P) and trace metal concentrations in pore water throughout the BR system soil profiles were analyzed to determine their mobility and distribution, and to document overall pollutant removal efficiency as a function of pollutant loading. Maximum pollutant loading rates were also quantified for future BR system design.

1.3. Experimental Design

The cities of Logan, UT and Salt Lake City, UT have installed BR systems to help manage stormwater runoff. However, currently both cities have limited data related to the functionality of these BR systems. With cooperation through the Utah Water Research Laboratory (UWRL), Logan City, and Salt Lake City Public Utilities, studies were conducted at three field sites to determine the effectiveness of a range of BR types with different design parameters. Two sites were located in Logan, UT and one site was in Salt Lake City, UT, as shown in Figure 1.

Figure 1: Locations of three field sites for project

The first Logan site, the Green Meadows housing development (Logan, UT), was designed and installed by a former PhD student at the UWRL to study the impacts of various plant types on nutrient and metal uptake from urban stormwater from this development (Figure 2) (Rycewicz-Borecki 2015). Simulated storms, with three pollutant loading regimes, low, medium and high, were applied over the length of the study. Plants used for the study were *Typha latifolia* (Broadleaf cattail), *Carex micorptera* (Small wing sedge), *Heliathus maximiliani* (Maximilian Sunflower) and *Juncus balticus* (Baltic rush). Three watering regimes were used, once every 5 days, once every 11 days, and once every 23 days. Total pollutant load at the end of the study was equal among regimes, while the total amount of water applied over the course of the study varied. The study was conducted from May 2018 to September 2018.

Figure 2: Green Meadows field demonstration site, Logan, Utah

The second Logan site is a curbside bioswale, designed and constructed by Logan City Public Works Department. The bioswale is located along 300 East between 900 North and 1000 North (Figure 3) and contains turf grass and ornamental pear trees. Samples were collected and analyzed after natural storm events. Events were sampled from Spring 2016 to Fall 2018.

Figure 3: 300 E Bioswale, 900 N – 1000N, Logan, Utah

The site in Salt Lake City was constructed at the Public Utilities office building and lies at the edge of a parking lot to treat runoff from the area (Figure 4). This BR system contains two types of engineered subsurface media and top soil, and various plant species that lie outside the primary runoff infiltration area that were planted primarily for aesthetic value. The site in Salt Lake City and in the roadside bioswale in Logan were both sized using design specifications for from the United States Environmental Protection Agency (EPA) (EPA 2016b). Samples were collected and analyzed after natural storm events. Events were samples from Spring 2017 to Fall 2017.

Figure 4: BR system at Salt Lake City Public Utilities, Salt Lake City, Utah

Chapter 2

LITERATURE REVIEW

2.1 Introduction and Background

In 1999 the EPA updated the National Pollutant Discharge Elimination System (NPDES) policy limiting the amount of stormwater discharges from municipalities (municipal separate storm sewer systems, MS4), industry, and from construction sites. The NPDES permit aims to reduce sediment runoff, reduce harmful pollutant influx to surface water, and protect water resources. The initial policy was limited to cities over 100,000 in population. All other urban areas were advised that the policy would apply to other areas by 2010. In 2010 Phase II of the MS4 policy expanded the sources that were covered through the NPDES and MS4 permitting process. This included all urban areas with a population of 50,000 or more (EPA, 2017a). Both Salt Lake City (population 194,000) and Logan City (population 51,000) are now covered under parts of the MS4 permitting program and are required to manage pollutants in stormwater.

Due to increased restrictions and requirements to develop a stormwater management plan, municipalities and state agencies are examining ways to improve pollutant removal from stormwater runoff, using existing technology, specifically BR systems. Using BR systems to capture and treat stormwater runoff can decrease pollutant load input into nearby surface water or groundwater (EPA, 2017a). BR systems may contain filter media and vegetation where runoff is routed to remove pollutants including sediment, nutrients and trace metals. Different features allow for different functions of the BR system. Various vegetation types can provide enhanced nutrient and metal uptake from runoff (Davis et al. 2001a; Davis et al. 2001b; Davis et al. 2003; Sun and Davis 2007; Bratieres et al. 2008; Brisson and Chazarenc 2009; Read et al. 2010; Barrett et al 2013; Leroy et al. 2016; Nocco et al. 2016; Glaister et al. 2017; Rycewicz-Borecki et al. 2017, Turk et al. 2017; Wu et al. 2017; Cording et al. 2018; Shrestha et al. 2018; Schück and Greger 2019). Different depths of media, inlet and planting configurations and the use of features, such as an underdrain or saturated zone (SZ), allow for improved N or P removal (Davis et al. 2003; Kim et al. 2003; Forbes et al. 2005; Brisson & Chazarenc 2009; Read et al. 2010; Liu & Davis 2014; Reddy et al. 2014; Dietz 2016; Turk et al. 2016; Wu et al. 2017; Afrooz & Boehm 2017; Cording et al. 2018; Wang et al. 2018; Lopez-Ponnada 2020). Variation in BR system design can improve pollutant removal when pollutant loading, filter media, and plant variability are considered.

2.2 Bioretention Design and Function

BR systems generally consist of vegetation, for uptake of key nutrients and metals, erosion control, and increased infiltration; soil and filter media to accomplish the optimum filtration rate for pollutant removal and reduction of peak flows; and an optional underdrain system to increase holding time for runoff within the BR system, thereby increasing N and P removal (Prince George's County 2007; EPA 2016b). While BR systems have been installed nationwide, the original BR design focused on upland, forested terrestrial system (Prince George's County 2007).

BR systems remove pollutants from stormwater through physical, biological and chemical processes (EPA 2016b). Different varieties of plants and soil types within BR systems, compared to non-vegetated BR systems, deliver variable removal efficiencies for different pollutants (Lucas and Greenway 2008; Barrett et al. 2013; Li and Davis 2014; Rycewicz-Borecki et al. 2016, 2017). Vegetation increases the removal of N and P from stormwater with variation reported among different plant species (Lucas and Greenway 2008; Bratieres et al. 2008; Read et al. 2010; Barrett et al. 2013; Rycewicz-Borecki et al. 2017; Cording et al. 2018; Lopez-Ponnada 2020). Metal removal occurs through sedimentation and sorption in the upper layers of the BR system (EPA 1999) along with plant uptake. Organic amendments, such as compost or wood chips, added to a BR system increases the sorption of nutrients, metals, and organic pollutants within the system, removing them from stormwater (Davis et al. 2009). Vegetation helps to maintain long term infiltration rates within BR systems; without plants, the surface clogs quickly creating a crust through which little to no infiltration can occur (Davis et al. 2012; Rycewicz-Borecki 2015).

Vegetation and soil selection impact the effectiveness and sustainability of BR systems. Proper vegetation selection can also create landscaping that does not need irrigation; a necessity in water stressed arid areas (Houdeshel and Pomeroy 2014). Various studies have compared different vegetation types and their ability to uptake metals, nutrients and other pollutants. *Carex Apressa* (sedge) (Bratieres et al. 2008; Read et al. 2008, 2010; Barron et al. 2019), *Juniperus horizontalis* (creeping juniper) (Davis et al. 2001a; Davis et al. 2001b; Davis et al. 2003), *Buchloe dactyloides* (buffalograss), *Muhlenbergia lindheimeri* (big muhly) (Barrett et al. 2013), *Carex microptera* (small wing sedge) (Rycewicz-Borecki et al. 2016, 2017), *Helianthus maximilliana* (sunflower) (Rycewicz-Borecki et al. 2016, 2017), and *Typha latafolia* (cattail) (Houdeshel and

Pomeroy 2014; Rycewicz-Borecki et al. 2016, 2017; Schück and Greger 2019) are just a few of the plant species that have been studied in BR systems.

Media composition can affect pollutant removal within BR systems. Different studies have used Skye sand (Glaister et al. 2017), loamy sand (Glaister et al. 2017), expanded shale with amendments (Zhang et al. 2008; Sloan et al. 2008), fly ash (Zhang et al. 2008; Ren et al. 2016; Liu, et al. 2018; Jiang et al. 2019), concrete sand (Barrett et al. 2013), masonry sand (Barrett et al. 2013), SorbtiveMedia™ (Cording et al. 2018; Shresta et al. 2018), and compost (Lim et al. 2015; Cording et al. 2018) with differing volumes of each component within a system. Compost within a soil mixture may increase the amount of P in the effluent, however increased organic matter is beneficial for vegetation and for increased metal sorption capacity. When used in conjunction with an internal water storage layer, organic matter has been shown to improve the removal of copper through enhanced sorption (Bradl 2004) and total N through stimulation of denitrification (Dietz and Clausen 2006). While choice of media is important for targeting specific pollutant removal, the presence of vegetation significantly increases N and P uptake and increases the useful life of BR areas (Lucas and Greenway 2008).

2.3 Pollutant Uptake in Plants

Plants in BR systems can improve trace metal, P, and N retention over BR systems without plants. Unplanted controls consistently have decreased removal ability when compared with BR systems with vegetation for most pollutants (Lucas and Greenway 2008; Barrett et al. 2013; Rycewicz-Borecki et al. 2015, 2017; Barron et al. 2019; Luo et al. 2019).

For removal of dissolved metals in BR systems, plants are effective in removing varying amounts, depending on plant type with varying uptake ability. Rycewicz-Borecki et al. (2016) in a study conducted in Logan, UT, found that *Carex* species were able to mobilize metal in the rhizosphere and increase the amounts taken up by both the below ground and above ground plant material. With removal of above ground plant material at the end of the growing season the metals that have accumulated within the vegetation can be removed from the BR system, extending its operating life (Rycewicz-Borecki et al. 2015, Cording et al. 2018). Metal concentrations in the harvested plant material would not be expected to be at dangerous levels if harvested annually due to low annual loading of metal pollutants in urban runoff, and this harvested biomass can then be incorporated into local composting programs.

Read et al. (2010) compared different characteristics of plants in Australia with the plant's ability to remove metals from the soil. No characteristic was deterministic in a plant's ability to uptake metals, but all 20 plant species that were studied were effective in removing Cu, Pb and Zn from BR influent (Read et al. 2010). N and P removal however was correlated with root length, root mass, and high growth rate with *Carex appressa* being the most effective in nutrient removal. Schück and Greger (2019) analyzed 34 wetland species in Sweden and found that the removal of Cu, Zn and Pb was highly correlated with root/rhizome biomass and above ground biomass. They also determined that the majority of the pollutants were removed from the simulated stormwater within the first 24 hours of application, with large variability among species. Leroy et al. (2016) compared two BR systems in France, one planted with fescue (*Festuca arundinacea, Festuca rubra*) and ryegrass (*Lolium perenne)* and another planted with macrophytes, to analyze the systems' effectiveness for pollutant removal. The BR system planted with macrophytes performed better than the system planted with fescue and ryegrass for removal of trace metals. This may be due to the inability of the grass to capture soil particles as the stormwater moved through the system whereas the higher root density of the macrophytes retained particulate metals (Leroy et al. 2016). Sun and Davis (2007) analyzed three types of grass *Panicum virgatum* (switch grass), Kentucky-31, and *Bromus ciliatus* in a BR system in Maryland for their effectiveness of trace metal removal. They found that the plants only removed 0.5-3.3% of applied metals, most likely due to the low plant biomass production (Sun and Davis 2007). Muthana et al. (2007) analyzed BR systems along three roadway types in Norway. The study specifically looked at the high pollutant loads created with snow removal and the impact the salts and runoff have on BR systems in cold climates. Of the six plant species analyzed, the evergreen *Vinca minor* accumulated the largest amount of metals in the above ground plant material. However, the plant metal uptake was only between 2 and 8% of the total metal retention in the system (Muthana et al. 2007). Barron et al. (2019) saw enhanced removal of Cu from columns with layers of sand and sand with and without cedar mulch in all vegetated laboratory columns when compared to an unvegetated column, however Zn removal was consistent across all columns, regardless of the presence of vegetation. Wang et al. (2018) observed that Cu, Zn, and Pb were removed from laboratory mesocosms with composted sandy loam soil regardless of the presence of plants (*Hymenocallis speciose*); adsorption by the filtration media was more important for metal retention than plant uptake. Wang et al. (2018) attributed nitrate, ammonium and P removal to the SZ with minimal removal by plant uptake, although, as the researchers point out, plants were young with limited rooting mass. Metal removal may be enhanced if the best performing plant species is selected. The combination of optimum plant species and filter media would likely enhance the overall function of a BR system.

In studies analyzing P removal effectiveness it has been found that without plants P can be leached from the soil and exported in the effluent. P removal is generally attributed to adsorption onto particles, however when adsorption sites are limited plants are able to sequester the excess P and remove it from BR system effluent (Lucas and Greenway 2008; Barrett et al. 2013; Glaister et al. 2016; Rycewicz-Borecki et al. 2017; Luo et al. 2019). Rycewicz-Borecki, et al. (2017) compared P uptake in six plant species (*Carex (2), Thypha, Helianthus, Phragmites, Scirpus)* and determined that all species studied were able to remove P from the influent. The two *Carex* species and the *Phragmites* had the highest concentrations of P in their above ground biomass enabling the nutrients to be easily removed from the system via annual above ground plant tissue harvesting (Rycewicz-Borecki et al. 2017). Plants significantly improved P removal from stormwater in two studies by Lucas and Greenway (2008, 2011). The first study (Lucas and Greenway 2008) used common filter media used in BR systems, i.e., loam, sand, or gravel planted with Swamp Foxtail Grass (*Pennisetum alopecurioides*) and Flax Lily (*Dianella brevipedunculata*), and two woody shrubs, Banksia (*Banksia integrefolia*), and Bottle-brush (*Callistemon pachyphyllus*), The authors found that N and P removal improved in all BR systems with the addition of plants (Lucas and Greenway 2008). In the other study, Lucas and Greenway (2011) analyzed three types of media, sand amended with a clay soil, red mud (high Fe oxides) or Al wastewater treatment residual

(WTR) (high Al oxides), to evaluate P removal, with and without vegetation. Improved removal of P for all media types was further enhanced when vegetation was included in the BR mesocosms. However, red mud was not effective since it leached P over the initial phase of the study (Lucas and Greenway 2011). Barrett et al. (2013) analyzed three media types, concrete sand, masonry sand, and a medium marketed for BR systems, with and without vegetation (buffalo grass and Big Muhly). These authors found that the vegetation within the columns significantly improved P removal for all media types, however, the type of plant was not found to influence results. Plant uptake was however influence by the media type where a competition between sorption surfaces and plant uptake was evident, i.e., better sorption to soil surfaces results in less plant uptake. A SZ also improved P removal by slowing pore water flow and enhancing P precipitation. Jurczak et al. (2018) used five plant types, including a *Carex* species and a *Typha* species, in floating mats in a hybrid BR system. They found that the plants reduced TP concentrations in the effluent by 57.6%. Cording et al. (2018) used sand (60%) with compost (40%) alone or with Sorbtive Media™, a proprietary oxide containing additives, with two vegetation combinations and found that the combinations with the greater total root surface area, associated with deep fibrous roots of switchgrass, performed better at pollutant removal. Barron et al. (2019) analyzed eight plant types and determined that *Carex appressa* and *C. generalis* performed best at TP removal, with >67% removal, in the BR systems studied. *Phragmites australis* removed only 13% TP, while the unvegetated BR systems provided no TP removal. Johnson and Hunt (2019) monitored a BR system after construction, then 15 years later and determined that the TP removal had improved over the life of the BR system. For the most effective removal of TP within a BR system, the inclusion of plants is essential.

Vegetated BR systems have also been shown to increase N removal from stormwater when compared to non-vegetated systems. Reported N removal ranges from 40 to 90% and is dependent on vegetation, media, and the presence of a water storage layer or SZ. As indicated above, a SZ within a BR system has been shown to be effective in increasing denitrification of various forms of N in BR systems. Wan et al. (2018) saw a significant reduction in TN and NO_x-N in the effluent of the BR system and attribute it entirely to the denitrification stimulated by the wood chips in the filter layer of the basin.

Bratieres et al. (2008), Lucas and Greenway (2008), and Rycewicz-Borecki et al. (2017) all found a 10 to 20% increase in N removal efficiency when plants were included in a BR system. Plant choice for BR systems is important in the design to increase the removal efficiency of N. Various sedge species (*Carex*) (Bratieres et al. 2008; Read et al. 2010; Rycewicz-Borecki et al. 2017; Jurczak et al. 2018; Barron et al. 2019) and cattails (*Typha*) (Rycewicz-Borecki et al. 2017) have been found to perform well at sequestering N in BR basins. For *Carex,* this may be due to the dense root structure that supplies more surface area for nutrient uptake. *Typha* also has larger root structures than other species enabling the plants to uptake more nutrients (Bratieres et al. 2008; Read et al. 2010; Rycewicz-Borecki et al. 2017; Jurczak et al. 2018). Nocco et al. (2016) evaluated 12 BR study cells with a mixture of topsoil, sand, and compost and found that the cell without vegetation leached the largest amount of dissolved inorganic N, while the cells with plants (19 prairie species, including one *Carex* species, six shrubs, and Kentucky bluegrass) removed similar amounts of N from the influent regardless of plant type. The turf grass had the highest plant uptake of N, but lower overall removal compared to the mixed prairie plants. Wang et al. (2017) found that all plant species performed better than an unplanted control, however, *Medicago sativa* performed poorly for N removal, while *Juncus effuses* performed the best of the five species tested. Cording et al. (2018) determined that a seven species plant combination did not perform as well as a two species plant combination in NO_3-N removal and actually exported NO_3-N in the effluent. The improved removal of NO_3-N in the two-plant combination is attributed to root characteristics. Barron et al. (2019) saw high N removal (>75%) in six of the eight species they studied. While *Phragmites australis* and *Phormium tenax* did not perform as well (9% and 2%, respectively) as the other six species, they did demonstrate removal compared to the unplanted BR system (-34%) that leached N during the study. These vegetated columns also outperformed the unvegetated columns for NO_3-N, NH_3-N and TDN removal for the two *Carex* species with denitrification accounting for <15% of N removal compared to the N removal associated with plant uptake. The added carbon as mulch did not improve treatment in systems with a SZ since the mature plants had extensive rooting systems that also provided exudates as a carbon source for microorganisms (Barron et al. 2019). Johnson and Hunt (2019) observed that the NO_3-N removal in a BR system constructed in 2001 had improved from 13% removal to 86% removal over 17 years. The authors propose that it may be due to plant root maturation and uptake and/or plant matter cycling through the fill media. The cycling of the plant matter would provide a carbon source for denitrification. Barrett et al. (2013) found that Big Muhly consistently outperformed buffalo grass for NO_x removal due to the roots penetrating throughout the media, although the plants were young. The researchers point out that the buffalo grass performance may improve with development of a more substantial rooting system.

Plants in studies conducted with designed or developed SZ provided improved N removal due to increased root structure in addition to increased denitrification. The increased retention time provided by a SZ enables plants to increase root structure and form a dense mat of root hairs within the column, improving nutrient uptake. The SZ zone also creates an anaerobic region within the columns where denitrification can occur, increasing the removal of N from the system (Barrett et al. 2013; Manka et al. 2016; Glaister, et al. 2017). Brown and Hunt (2011) found high levels of various forms of N in the effluent of the BR systems they analyzed. These BR systems did not have a saturation zone and were under designed and hence failed with pollutant removal. These BR systems exported large amounts of nitrate compared to the influent which may be attributed to the mulch that was placed in the basins or fertilizer applied on the plants (Brown and Hunt 2011).

Turk et al. (2016) compared the use of native plants to cultivars of the same species. The authors found that cultivars and native plants are both effective in nutrient removal, however, plants with larger biomass removed larger amounts of N than smaller biomass plants. The native variations of *Helianthis* and *Panicum* outperformed the cultivars for N & P removal. The cultivar *Betula* Dura-heat removed slightly more N than the native species while the *Magnolia* Sweet Thing cultivar removed twice the amount of N & P as the native variety. The authors also optimized plant selection by including cost into their metric. Woody plants performed better in N and P removal when price was included. However, when canopy cover was used in the metric the herbaceous plants performed best. Price, aesthetics, and hardiness to high pollutant loading are factors in optimizing plant choice for BR basins (Turk et al. 2016).

2.4 Filter media

Filter media in BR systems is a variable that can improve the effectiveness of pollutant removal from stormwater. Depending on the composition of a BR system's filter media, the removal efficiency for trace elements for the system could be as high as 90% (Davis et al. 2001a; Paus et al. 2014; Lim et al. 2015; Gulbaz 2015; Jiang et al. 2019). Particulate trace elements are removed from influent stormwater by filtering through the top layers of the BR system (Davis et al. 2001a; Lim et al. 2015). Dissolved metals are removed through sorption to soil particles and precipitation. The amount of sand, silt, clay and organic matter affect the adsorption capacity of the soil, which contributes greatly to the removal of dissolved metals (Lu and Xu 2009). Cu, Cd, Pb, and Zn are the metals found in stormwater that are frequently analyzed in studies for removal efficiencies of BR systems (Davis et al. 2001a; Davis et al. 2003; Muthanna et al. 2007; Lu and Xu 2009; Paus et al. 2014; Reddy et al. 2014; Gulbaz et al. 2015; Lim et al. 2015; Li et al. 2016; Ren et al. 2016; Liu et al. 2018; Wang et al. 2018; Jiang et al. 2019). Various studies have found that metal competitive sorption is in the order of Pb>Cu>Zn (McKay and Porter 1997; Srivastava et al. 2005; Gulbaz et al. 2015).

In studies that compared various BR media types, media containing organics removed the largest amounts of heavy metals (Paus et al. 2014; Gulbaz et al. 2015; Lim et al. 2015). Reddy et al. (2014) found that any one filter type was not completely effective in removal of all the trace metals of concern in stormwater. A combination of several filter types would be most effective in the removal of all metals of concern

(Reddy et al. 2014). Ren et al. (2016) analyzed five mixed substrates for trace metal removal. Fly ash, sludge, soil, gravel, fine cinder and fine sand were used in varying amounts for the five substrates. The substrate without fly ash had the highest removal capacity for Pb. The authors also determined that the ideal pH range for any of the substrates was between 8 and 10. Gravel improved the hydraulic conductivity but did not improve removal efficiency (Ren et al. 2016). Liu et al. (2018) analyzed fly ash, blast furnace slag and planting soil. The fly ash was the most efficient for removal of Cu, while the blast furnace slag performed poorly for the removal of Zn. Jiang et al. (2019) used fly ash, WTR, green zeolite, and coconut bran to optimize removal of heavy metals from BR systems. The coconut bran had the poorest performance for metals removal.

As indicated above, organic amendments, such as compost or wood chips, have also been added to a basin to increase the sorption of nutrients (Davis et al. 2009). However, compost within a soil mixture may increase the amount of P in the effluent (Lim et al. 2015; Mullane et al. 2015; Cording et al. 2018) despite it being used to aid in plant establishment and increased metal sorption. Engineered materials and native soils have also been shown to be sources of P load to groundwater. Lucas and Greenway (2011) reported that high Fe oxide red mud when used without vegetation leached P over the initial phase of their study. Barron et al. (2019) reported unvegetated BR systems provided no TP removal in their study of pollutant removal by eight different BR system plant species. Topsoil, sand, and compost mixtures have also been reported (Mullane et al. 2015; Nocco et al. 2016, Barron et al. 2019) to leach dissolved inorganic N when used without vegetation, and under designed, mulch-amended and fertilized systems studied by Brown and Hunt (2011) were found to export large amounts of nitrate compared to their influent concentrations.

Arsenic is not a constituent of stormwater runoff but bioretention systems can produce conditions conducive to solubilization of geogenic As. Many areas in the United States, i.e., the Great Basin Region which includes Utah, and other parts of the world have As enriched geology, and As mobilization to groundwater is specifically of concern. In these areas with naturally occurring As in the soil, As solubility can be enhanced under reducing conditions imposed with temporary inundation of a BR system and conditions selected for maximum metal retention, in particular pH, which enhances As release from geogenic sources. Arsenic is solubilized through reductive dissolution of host iron oxide minerals under imposed reducing conditions as in SZ of BR systems. Mechanism of solubilization are further discussed in Smedley & Kinniburgh (2002) and Meng, et al. (2017). Rycewicz-Borecki (2015) and Patterson (2019) both observed elevated As in pore water from a BR system in Northern Utah where temporary anaerobic conditions and the presence of plants solubilized As.

This variability in results from different media selected for pollutant removal indicates a need for more studies to be completed to determine the most effective media type or media combination for pollutant removal and mitigation of negative effects, i.e., pollutant mobilization, of stormwater treatment by BR systems.

2.5 Pollutant loading in BR systems

Location and size of BR systems lead to variable loadings and removal rates. Previous laboratory and field studies have added varying amounts of trace metals and nutrients to BR systems via synthetic storm events. Rycewicz-Borecki et al. (2016) used three loading rates for simulated storms to examine the uptake of trace metals by macrophytes. The three loading rates were to simulate event mean concentrations found in three regions of the United States. While certain plant species outperformed others at removal of trace metals, overall 92% of metals applied were removed during the study. Rycewicz-Borecki et al. (2017) also used three loading rates for total P and total N to determine uptake by plants in BR systems. Phosphorus removal ranged from 93% to 115% with no difference in removal between loadings. Nitrogen removal was lower than P removal, ranging from 42% to 62% among treatments, likely due to nitrification and denitrification. Lucas and Greenway (2011) administered much higher concentrations of total P ranging from 2.8 mg/L to 3.2 mg/L over an 80-week study period to determine the effectiveness of P removal of a BR system over time. Removal ranged from -109% to 99% depending on type of filter media. Davis et al. (2003) used two loading rates ranging from 64 µg/L to 140 µg/L for Cu and 550 µg/L to 650 µg/L for Zn. Removal efficiency was 94% or higher regardless of loading rate. Gilchrist et al. (2013) analyzed different design parameters for rain gardens and their impact on N removal. The administered concentration averaged 1.40 mg/L with improved removal occurring in the systems that had a SZ. Other studies administered much higher concentrations of N. Borin and Salvato (2012) used NO_3-N concentrations of 104 to 105 mg/L and 100 to 119 mg/L NH_4-N and reported that N removal improved over the 3-year course of the study suggesting plants need time to mature for effective N removal. Turk et al. (2016) used average concentrations of 81 mg/L of N and 15 mg/L P to determine the difference in nutrient uptake between native and cultivar plants. The authors report that 11 of the 16 plants studied could be recommended for BR systems based on the metrics of cost and nutrient uptake in the study. The range of applied concentrations for trace metals and nutrients in these studies shows that variations in BR systems, related to plant type, media, and loading impact pollutant removal.

2.7 Bioretention Research Needs

There have been a limited number of studies that have been completed at field sites with full-scale BR systems responding to natural runoff events (Fischer et al. 2003; Flint & Davis 2007; Yergeau & Obropta 2013; Lucke & Nichols 2015; Al-Ameri et al. 2018; Jurczak et al. 2018; Johnson and Hunt 2019; Costello et al. 2020). Many more studies have been conducted in small microcosms or in columns in greenhouses (Davis et al. 2001a; Davis et al. 2001b; Kim et al. 2003; Davis et al. 2006; Muthana et al. 2007; Hsieh et al. 2007; Lucas & Greenway 2008; Murakami et al. 2008; Blecken et al. 2009a; Blecken et al. 2009b Read et al. 2010; Borin & Salvato 2012; Gülbaz et al. 2015; Subramaniam et al. 2015; Lim et al. 2015; Lynn et al. 2015; Ren et al. 2016; Afrooz & Boehm 2017; Wu et al. 2017; Barron et al. 2019; Brenner et al. 2019).

While many field studies have been completed in warm, wet regions, with mild winters such as Florida and North Carolina (Mangangka et al. 2015; Strong & Hudak 2016; Manka et al. 2016; Turk et al. 2016; Lopez-Ponnada et al. 2020), few have been conducted in cold climates with large amounts of winter snowfall (Muthanna et al. 2007; Roseen et al. 2009; Houdeshel and Pomeroy 2014). Muthanna et al. (2007) conducted field research in Norway to evaluate the effectiveness of BR in late winter/early spring with frozen soils, dormant vegetation, and low bioactivity versus summer conditions. They found seasonal differences in water infiltration and movement but not in metal retention, i.e., BR system design was shown to be efficient in removing metals regardless of season since the main mechanism was soil sorption not plant uptake. Roseen et al. (2009) evaluated winter conditions of rain on snow increasing runoff, limited infiltration capacity due to frozen ground, road salt, reduced particle settling, and dormant vegetation on BR system performance and found that these systems using proper LID design provide a high level of functionality even in winter.

In a review completed by Roy-Poirer et al. (2010), the authors point out that although studies have been conducted in cold climate regions with a necessity for snow storage there is uncertainty of the effectiveness of bioretention areas in climates that differ significantly from that of the Eastern United States. They note that there is a lack of knowledge about BR systems in arid climates, as well as areas with large snow accumulation (Roy-Poirier et al., 2010), both conditions which can significantly affect the survival and growth of vegetation in planted BR systems, and their ultimate long-term pollutant removal performance. Davis et al. (2009) conclude that the BR technology is still immature and additional research is necessary with an emphasis in areas of fill media composition and vegetation selection. Ahiablame et al. (2012), in a review of low impact development, state that characterization of runoff and water quality from different urban land uses and continued data collection for evaluation of BR systems over different spatial scales, temporal scales and climate conditions are several areas that need continued research. LeFevre et al. (2014) found that more research is needed in media selection, vegetation selection, and performance and field monitoring. Kratky et al. (2017) recommend that more long-term field studies are needed to understand water quality performance in BR systems. They also recommend that BR systems need to be designed specifically for geographic regions but designed consistently so that systems can be compared across regions and be improved.

This study was designed to address some of the data gaps identified above, specifically focusing on performance of various engineered and natural media types in full-scale BR systems. These systems were monitored over a number of summer-fall seasons and planted with a range of vegetation types to document pollutant removal performance in response to natural and synthetic storm events that subjected these BR systems to pollutant loadings representative of runoff conditions expected in the Intermountain West.

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CHAPTER 3

IMPACT OF MEDIA SELECTION ON TRACE ELEMENT REMOVAL IN A BIORETENTION SYSTEM

Abstract:

Three field sites were used to evaluate the effectiveness of imported topsoil, imported topsoil with compost, pea gravel, and Utelite™ expanded shale on BR system performance. The Salt Lake City Public Utilities site contained a BR system with Utelite™ expanded shale and pea gravel. The 300 East site contained imported topsoil, while the Green Meadows site contained an imported topsoil-compost mixture. Well samples were collected at the Public Utilities site, while pore water samples were collected from the 300 East and Green Meadows sites to evaluate BR system performance for removal of Cu, Zn, and Pb. Media from the Public Utilities site contributed to trace element concentrations in well samples regardless of the levels of pollutants applied to the site. A Comparison Bay at the 300 East site verified pollutant attenuation through the Treatment Bays at that site, while removal at the Green Meadows site was not discernable until high loadings were applied and levels in the runoff exceeded the pollutant levels from the soil. Arsenic was generated from all sites due to dissolution of geogenic As, and dissolution was enhanced due to the vegetation in the BR systems.

1. Introduction

Stormwater runoff can be a source of pollutants that negatively impact a receiving surface water body or compromise groundwater quality, and some pollutants may pose a significant health risk to humans and aquatic organisms (Cohen et al. 2001; Gaffield et al. 2003). An increase in urban runoff creates an increase in pollutant loadings as the water flows over impervious surfaces such as parking lots, roads, sidewalks and roofs that may contain pollutants that come from pesticides, tire wear, brakes, engine lubricants, and auto exhaust (Davis et al. 2001b; Charters et al. 2016). Some of the pollutants of concern in stormwater include cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb) and zinc (Zn). These pollutants should be removed before water can be used for groundwater recharge or be allowed to enter surface water.

A predicted change in weather patterns due to climate change necessitates using a variety of strategies to capture runoff for reuse for agriculture irrigation or human consumption. By using bioretention (BR) systems for infiltration, stormwater runoff can be captured and harvested for reuse. Amended soil or engineered filtration media within a BR system may improve the effectiveness of these systems in removing metals from stormwater. The media must allow drainage within a reasonable time frame, allow for plant growth, and should aid in pollutant removal through providing an increase in surface area and increased sorption sites, and providing the optimal pH for adsorption and precipitation of metals. Sorption and precipitation of metals are favored by high pH and the presence of organic matter, clays, and carbonates contributing to the cation exchange capacity of the media. Native soils or imported topsoil are often augmented with additional materials to increase sorption capacity and improve flow.

Depending on the composition of a BR system's filter media, the removal efficiency for trace elements could be as high as 90% to 100%, specifically Cu, Zn, and Pb (Davis et al. 2001a; Davis et al. 2003; Paus et al. 2014; Reddy et al. 2014; Lim et al. 2015; Gulbaz et al. 2015). Cu, Cd, Pb, and Zn are the primary elements of concern in stormwater that are frequently analyzed in studies evaluating pollutant removal efficiencies of BR systems (Davis et al. 2001a; Davis et al. 2003; Muthanna et al. 2007; Lu and Xu 2009; Paus et al. 2014; Reddy et al. 2014; Gulbaz et al. 2015; Lim et al. 2015; Li et al. 2016; Ren et al. 2016).

Reddy et al. (2014) performed batch sorption studies with Cu concentrations from 2.5 to 50 mg/L and Zn concentrations between 25 and 500 mg/L, applying Freundlich and Langmuir isotherms, with sand, calcite, zeolite, and iron fillings. Sand was the least effective with removal rates from 8 to 58%, while the other tested media removed between 90 and 100%. Sloan et al. (2008) used a 50:50 mixture of expanded shale and quartz sand with the addition of sphagnum peat moss or zeolite in a greenhouse pot study with Bermuda grass and reported near 100% removal of Cd, Cu, Pb, and Zn applied at 250 µg/L of each metal. Jiang et al. (2019) used varying combinations of water treatment residuals (WTR), green zeolite, and coconut bran as soil amendments to enhance metal removal in pilot scale field studies at concentrations similar to those used in the current study for Cu (0.3 to 1mg/L) and Zn (0.5 to 1.5 mg/L). Cu, Zn, and Cd removal was enhanced with the addition of organic matter via WTR with average removal of 80%, although removal efficiencies were highly variable within treatments. These studies display the importance of selection of media for metal retention, but also the importance of the relevance of experimental design including concentrations tested and field versus lab controlled experiments.

Field studies involving designed BR systems are limited likely due to laboratory column and small microcosm studies being more economical and having more control over pollutant loading, media composition, plant species, etc. But while lab studies are useful to evaluate specific process, translation to field conditions is often lacking. Many active field BR sites are designed with limited considerations of local loading rates, soil, soil amendments, regional plant species, or pollutant constituents which can lead to a failure of pollutant removal within a BR system due to limited sorption capacity. Another consideration is that the soil, soil amendments, and other media, since they are geologic materials, contain metals that may mask the true removal of metal constituents in stormwater as they are leached from the media when subjected to stormwater runoff. Dietz and Clausen (2006) found the soil used in a rain garden was the source of Cu, Pb and Zn whereas the added mulch retained these metals. Mullane et al. (2015) found that compost used in a BR system leached Cu due to complexation to the DOC produced by the compost. Conditions within BR systems may also foster the release of other toxic components such as arsenic. Arsenic solubility is enhanced under reducing conditions that are imposed with temporary inundation of a BR system, and conditions created to maximum metal retention, in particular increased pH, can enhance As release from geogenic sources. Many areas in the US and other parts of the world have As enriched geology. Rycewicz-Borecki, (2015) and Patterson (2019) both observed elevated As in pore water from a BR system in Northern Utah where temporary anaerobic conditions and the presence of plants solubilized As.

This study evaluated the efficiency of trace element removal (Cu, Zn, and Pb) and potential release of As using three existing field sites containing four filter media types - two top soils from Cache Valley, Utah (one unamended and the other amended with compost), and a pea gravel or Utelite™ expanded shale as a subsurface storage layer. The soils used were both locally purchased topsoil, originating within Cache Valley, that were medium texture with circumneutral pH, that would be recommended for metal retention. BR systems at these sites were designed with the expectations that pollutant removal would occur given the media installed in each system. Two sites experienced natural rain events, while the third site was exposed to simulated storms.

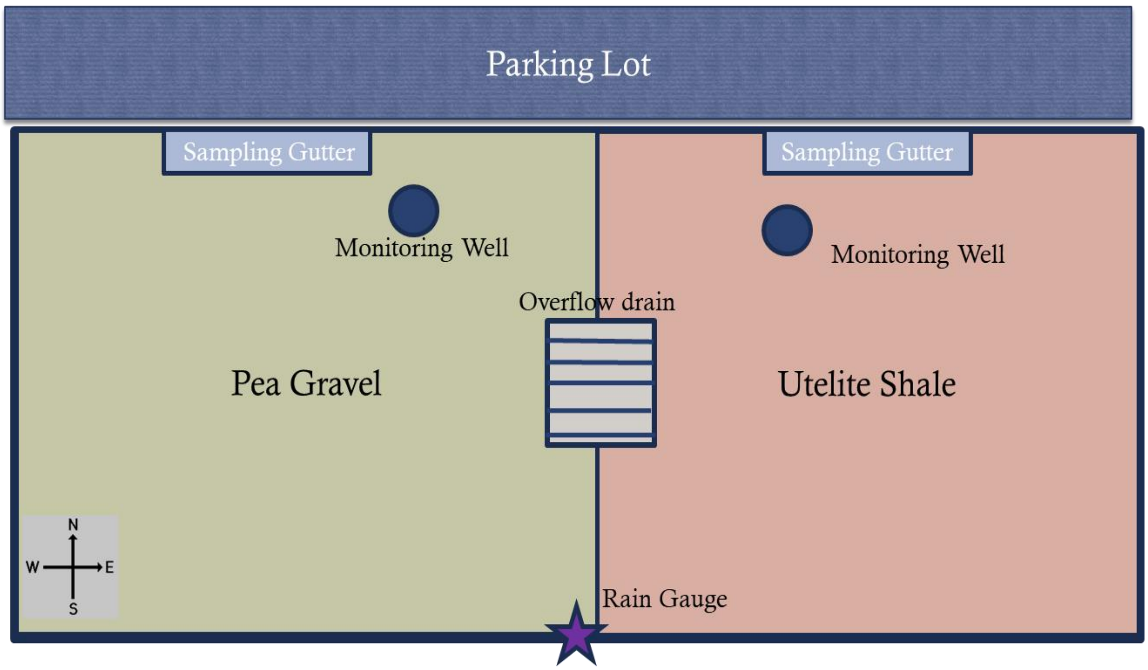
2. Materials and Methods

2.1 Study areas

The first study area is a BR system along a residential street in Logan, UT. There are three bays that contain curb cuts into which runoff can flow during a rain event (Figure 1). The BR system was designed by Logan City to hold the 100-year, 48-hour storm, a storm depth of 3.42 inches (8.69 cm) (Logan City 2016). As required by city code, infiltration should be complete within 72 hours after the end of a storm event. The entire system drains the west half of an asphalt paved road from 900 N to 1000 N encompassing a total drainage area of approximately 6,400 ft^2 (0.059 hectares). One individual bay was isolated from runoff with an added berm by the landowner (Figure 1c). This bay was used as a comparison bay since it did not receive runoff from the street. As the curb cuts are not uniformly spaced along the roadway, each receives varying quantities of runoff during a storm event based on their individual sub-drainages. There is no discharge to surface water; all BR systems drain below ground. Each bay contains topsoil from a location within Cache Valley, grass, and at least two ornamental pear trees (Figure 1a, 1b). The grass planted is a “cabin mixture” grass, which is recommended for areas of disturbance in the Intermountain West, including parking strips, and typically contains a variation of the following species mix: soder streambank wheatgrass, roadcrest crested wheatgrass, and sheep fescue. The landowner of the site watered the study area twice a week throughout the dry season and fertilized using Ferti-lome Crabgrass Preventer Plus Lawn Food 20/0/3 or Ferti-Lome Green Maker 18/0/6 once a month from April until August.

Figure 1: a. Small bay; b. Largest bay at south end of study area; c. Raised berm for comparison bay, 300 East, Logan, UT

The second study area was located at the Public Utilities office complex in Salt Lake City. The site consisted of a BR system 350 feet (107 m) long and 30 feet (9.1 m) wide that treats runoff from an adjacent 1-acre (0.40 hectare) asphalt parking lot. The parking lot can accommodate approximately 100 cars and during the work week is typically between 50 and 75 percent full. The west half of the BR system contained pea gravel in the subsurface storage layer, while the east half of the BR system contained Utelite™ expanded shale in the subsurface storage layer (Figure 2a).



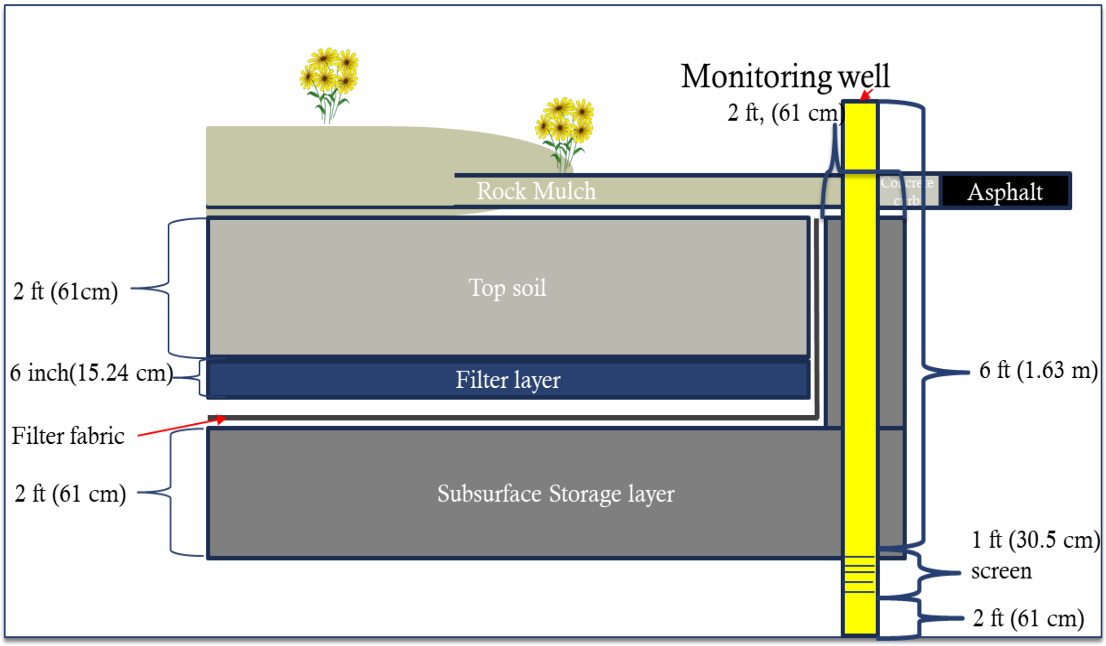


Figure 2: a. Schematic of Public Utilities BR system, Salt Lake City, UT, indicating the material used in each subsurface storage layer. Not drawn to scale. b. Profile of BR System, Public Utilities, Salt Lake City. The subsurface storage layer was composed of either pea gravel or Utelite™ expanded shale. Not drawn to scale.

The top layer in the BR system is a 6-inch (15.24 cm) layer of rock mulch, with the next layer being a 2 feet (61 cm) deep layer of topsoil, underlain by a 6 inch (15.24 cm) layer of topsoil/sand mix filter layer, all of which are separated from the 2 feet (61 cm) subsurface storage with either pea gravel or expanded shale layers by a layer of filter fabric (Figure 2b). The expanded shale used in the retention basin was purchased from the Utelite Corporation located in Salt Lake City, UT. The pea gravel was standard 3/8-inch (0.95 cm) washed construction pea gravel. The topsoil was locally sourced. For most rain events the runoff from the parking area only contacted the storage layer material. Runoff did not reach the soil or soil/sand layers within the systems and was not influenced by the plantings.

The third study area was an existing stormwater demonstration site in a southwest neighborhood of Logan, UT. The site was constructed to collect and treat stormwater from a 25-acre portion of the Green Meadows subdivision. Street drains collect stormwater from the neighborhood which is conveyed into a runoff distribution box (Figure 4) at the inlet of the stormwater treatment area. The water then overflows into two distribution channels, then overflows into each of 24 constructed bays. For this study the distribution channels were blocked off and simulated storms were administered with hoses using potable water supplied by Logan City.

Prior to the beginning of the study each bay was excavated to remove biomass and topsoil from previous studies conducted at the same location. Each bay was then reconstructed with topsoil, compost, and mulch. The topsoil was obtained from a local excavating company and the compost and mulch were obtained from the Logan City Landfill. The topsoil to compost mixture, with a ratio of 2:1, was applied to each bay to a depth of 9 inches (22.9 cm) then rototilled into the original soil. The plant starters were planted to a 3-inch (7.62 cm) depth, 12 inches (11.45 cm) apart, followed by a final 1-inch (2.54 cm) layer of mulch. Plants were allowed to grow to maturity for one growing season before the study began.

Fifteen bays (5 feet (1.5 m) wide by 15 feet 8 inches (4.78 m) long) established with four triplicate plant species and three control bays that contained no vegetation were used. The triplicate vegetated bays were randomly assigned and each contained a single species of plant that included: cattails (*Typha latifolia)*, small wing sedge (*Carex micropter*a*)*, Baltic rush (*Juncus balticus)*, or sunflower *(Helianthis maximillina)* (Figure 3).

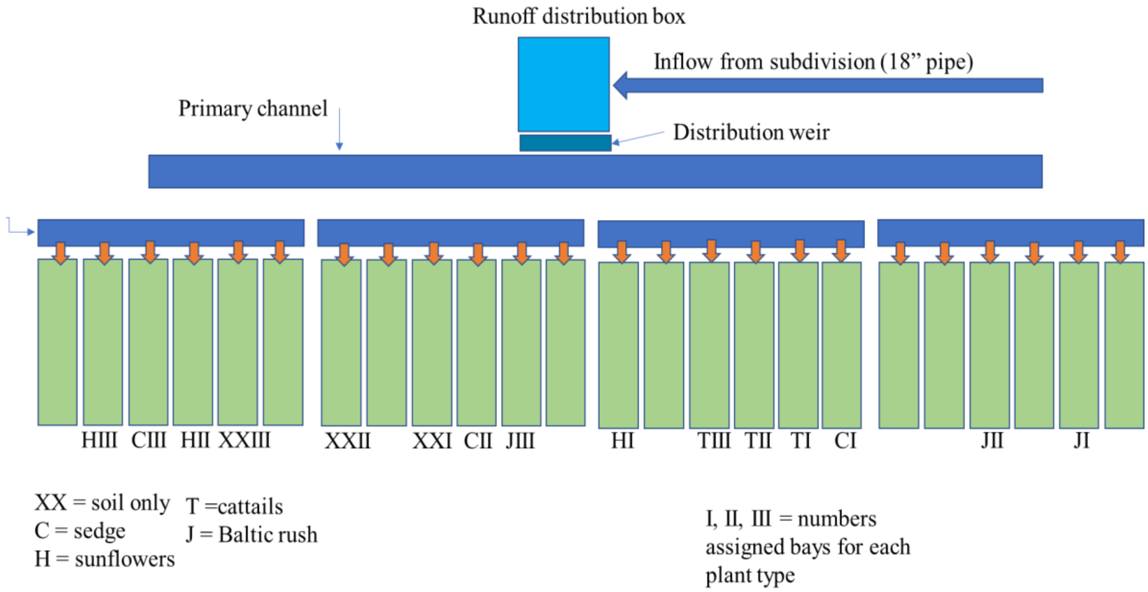


Figure 3: Schematic of stormwater treatment demonstration site showing bay location of plant types and unplanted controls evaluated at the Green Meadows site.

Synthetic, simulated storm events were used to analyze pollutant removal at this site. Storms were administered with three pollutant loads, with individual storm volumes simulating the 3 month, 45-minute storm, 0.202 inches (0.513 cm) of rain in Logan, UT. The surface area for runoff received by each bay for each storm event was calculated by assuming the BR system was 5% of an adjacent urban drainage area (USEPA 1999) with a 50% surface runoff coefficient, mimicking runoff volume from a housing development similar to the Green Meadows subdivision. These calculations resulted in a total volume per individual storm of 97.25 gallons (370 L). The first flush, assumed to be the first 10 percent of a storm (9.7 gallons, 37 L), contained the entire concentrated pollutant load, and was administered uniformly to each treatment plot using a hose end sprayer with a flow rate of 0.63 gal/min (2.4 L/min). Pollutant mixtures were made in Logan City tap water. A phosphorus solution was applied first followed by a nitrogen and trace metal solution, each with half of the first flush volume. The phosphorus and nitrogen data were analyzed and discussed in Chapter 4. These simulated pollutant loading solutions were applied separately to avoid precipitation of metals and phosphorus prior to application. Once the first flush solutions were applied, the remainder of the storm volume was applied using sprinkler hoses attached to a 3-foot (0.91 m) by 13 foot (3.96 m) frame within each bay that sprayed for 30 minutes with tap water at a flow rate of 2.32 gal/min (8.8 L/min). Logan tap water contains trace levels of Cu and Zn that contributed to the overall loading of these elements. Cu concentration added to the bay was 31% and Zn was 46% higher than intended for site loading calculations per application.

2.2 Precipitation data collection

At the 300 East site, precipitation data was recorded using an ONSET, HOBOware® rain gauge smart sensor (S-RGA-M002) with a U30 data logging station. At the Public Utilities site a HOBOware® RG3 data logging rain gauge was installed adjacent to the BR system. Any rain event data that were missing due to rain gauge malfunctions were supplied by the Utah Climate Center (USU, UCC, 2019). The weather station used for the 300 East location was from the Logan Cache Airport station (station ID USW00094128) located within 3.7 miles (6 km) of the site and for the Public Utilities site the climate station used was the Salt Lake Triad Center station (station ID USC00427606) located within 2.6 miles (4.2 km) of the site.

2.3 Sample collection procedures

At the 300 East location two Micro Rhizon pore water samplers (Soilmoisture Equipment Corp., Santa Barbara, CA. Soil Moisture Miniature Samplers – 1908D4.5L09) were installed at depths of 12 (30.5cm) and 20 (50.8 cm) inches in each bay, including the comparison bay. Samplers were installed per manufacturer instructions within 6 to 12 inches (15.2 cm – 30.5 cm) from the end of the concrete apron of each curb cut. Each lysimeter was connected to a length of plastic tubing with a Luer-Lock™ connector. The lysimeters were made of a porous polymer, internally strengthened by a wire or plastic fiber. The porous portion of the lysimeter was 3.5 inches (8.9 cm) long with an outer diameter of 0.98 (2.5 cm) inches and an inner diameter of 0.06 inches (0.15 cm).

To collect runoff from storm events entering each bay, funnels were fashioned from sheet metal and collapsible plumbers tubing to direct water into sixteen-quart (16.75 inches x 11.88 inches x 7 inches, [42.5 cm x 30.2 cm x 17.8 cm]) polystyrene (Sterilite™) sample boxes (Figure 4) from the curb cuts. A two-inch baffle was inserted in the sample boxes to create a collection area with a v-notch to allow flow to continue during storm event. Composite runoff grab samples were collected from the sample boxes after each rain event was complete.

Figure 4: Sampling boxes for runoff samples at the 300 East site.

At the Public Utilities site, modified sump wells (Figure 2b) were installed with a 2-feet (61 cm) collection chamber at the bottom to hold approximately 1200 mL of sample. The wells were installed 18 inches (45.7 cm) from the edge of the parking lot with the screened section beginning at the bottom of the subsurface storage layer, approximately 5 feet (1.5 m) below the soil surface. Small sampling gutters were installed at the edge of the parking lot (Figure 2) to collect runoff directly from the lot. Water level indicators were used to activate ISCO automated samplers to collect runoff for analysis when water was detected in the sampling gutters. The gutters were 2 feet (61 cm) in length and sealed at each end to prevent runoff from leaking out the sides of gutters during sampling.

At the Green Meadows site, each bay was instrumented with six Micro Rhizon pore water lysimeters, which were installed similar to lysimeters installed at the 300 East site. Three lysimeters were installed within the bay to a depth of approximately 3-6 inches (7.62 cm -15.24 cm) and three installed to a depth of 6-9 inches (15.24 cm - 22.86 cm). Each pair of lysimeters were co-located in a randomly assigned 1 ft^2 (930 cm^2) section of a bay, creating three pairs in each treatment bay.

For sampling at the 300 East site, immediately following rain events, four composite grab samples of runoff water were collected, one each from the sampling boxes, using 500 mL acid washed bottles. At the same time a vacuum was pulled to 70 kPa on the lysimeters using a hand vacuum pump, and samples were collected in 500 mL glass bottles fitted with #10 stoppers over a 24-hour period after vacuum was applied.

Samples at the Public Utilities site were collected during natural storm events from each gutter and sump well in the BR system using ISCO 6712 autosamplers with liquid level actuators. A sample hose was placed at the bottom of each sump well to collect samples when the water level reached 4 inches (10.2 cm) depth in the sump wells. Samples were collected at 15-minute intervals from both wells for the duration of a storm. Runoff from the parking lot ran over the curb and into the sampling gutters where BR influent samples were collected. An autosampler actuated by a separate level indicator collected samples when the water level reached 2 inches (5.1 cm) in the sampling gutters. The samplers also pulled samples at 15-minute intervals from the gutters for the duration of the storm event.

At the Green Meadows site, a vacuum of at least 70kPa was applied to each of the six lysimeters within the bay using a hand vacuum pump after all ponded water had infiltrated for each simulated storm event. A 1000 mL amber glass jar with #10 stopper was connected to each lysimeter to collect soil pore water captured by each lysimeter, and samples were collected for analysis within 24 hours after the vacuum was applied.

2.4 Sample processing and analysis procedures

Upon collection, runoff, well, and pore water samples from all locations were returned to the Utah Water Research Laboratory for analysis of electrical conductivity (EC) and pH. For total element concentrations, water samples were digested using a hot block, nitric acid digestion using the APHA Method 330E (APHA 2012). For total dissolved element concentrations, water samples were filtered using 0.2 µm nylon filter and preserved with nitric acid. An Inductively Coupled Plasma Mass Spectrometer (ICP-MS, Agilent 7700x, EPA Method 6020) was used to determine concentrations of trace elements in the samples (EPA 2007b). Dissolved metals are reported for Green Meadows site and total metals are reported for the other two sites.

To assess the potential source of metal leaching from the media at the Public Utilities, Utelite™ and pea gravel were extracted with deionized water. The Utelite™ sample was received directly from the Utelite Corporation, and common pea gravel purchased from a local hardware store. Water was added to cover the media and left to sit for 24 hours. The extractant was poured off, filtered using 0.2 µm nylon filter and preserved with nitric acid, then analyzed on the ICP-MS to determine the most mobile components of the BR media which could be affected by stormwater runoff and infiltration. Sequential extractions were also conducted on all field site soil samples, and the data and a discussion of those results can be found in the appendix.

2.5 Data Analysis

In this evaluation of media for effective removal of metals from stormwater, runoff data collected over time were averaged at 300 East and Green Meadows sites and the data were also averaged with depth. Statistical analysis of the pore water concentrations at both lysimeter depths at the 300 East site and the Green Meadows site for trace elements of interest showed no statistical difference between lysimeter depths. At the Green Meadows site, the pore water concentrations were not averaged over loadings. At all three sites, pore water and well concentration of trace elements were not affected by storm frequency, duration, or intensity. The lack of differences in the data allowed for the use of averages for pore water and well water concentrations at the three sites across time and depth.

Potential impact to groundwater was determined by analyzing the concentration of pollutants found in pore water lysimeters and wells after movement of runoff through the BR basins at all field site locations. Analysis of variance (ANOVA) and a Tukey's Honestly Significant Difference (Tukey's HSD) test were conducted using the SAS University Edition statistical software program on concentrations in runoff and pore water or well samples to determine pollutant removal through the BR system. Comparisons were made between soil pore water concentrations in treatment plots receiving roadway runoff and a comparison plot at the 300 East site that received only rainwater. Comparisons were also made among the two filter media and runoff at the Public Utilities site. Comparisons at Green Meadows were made among the planted bays, unplanted control bays and the applied concentrations within and across all loading rates. The data for the ANOVA analyses were first transformed, with recommendations from a Box-Cox transformation conducted in SAS, to ensure the normality of each collected data set. All trace elements data were log transformed before analysis based on the Box-Cox recommendation.

3. Results

3.1 Characterization of storm events and runoff

For the two sites receiving natural precipitation, rainfall events occurred from February to May and August to November. After November and before February precipitation in both study areas fell as snow, with below freezing temperatures, prohibiting field sampling. From June to August, very little precipitation fell, and no sampling events were conducted during this period.

Of the fourteen natural events that occurred at the 300 East location there were two 1-year storms, while the Public Utilities site experienced one 5-year storm, three 2-year storms and one 1-year storm out of eleven events that occurred over the course of the study. Green Meadows received four simulated storm events as described in section 2.1. Table 1 summarizes characteristics of storm events for the three sites. The average rainfall was similar across all three sites.

Table 1: Characteristics of storm events monitored at the three field sites in this study.

	300 East	Public Utilities	Green Meadows
Dates of storms	9/2017 – 11/2018	10/2016 – 5/2017	6-9/2018
Total storms sampled	14 natural events	11 natural events	4 synthetic events
Minimum rainfall depth	0.1 inches (0.254 cm)	0.3 inches (0.762 cm)	
Maximum rainfall depth	1.6 inches (4.09 cm)	1.82 inches (4.6 cm)	
Average rainfall depth	0.34 inches (0.864 cm)	0.5 inches (1.27 cm)	0.2 inches (0.5 cm)

Table 2 lists the characteristics of the runoff at the two field sites that received natural rain events and also the concentrations of the applied storms at the Green Meadows field site including the contribution for the tap water used for irrigation. Arsenic and Pb were not applied at the Green Meadows site beyond the trace amounts found in Logan City Tap water, but these elements were in the runoff at the Public Utilities and 300 East sites.

Table 2: Summary of trace element concentrations measured in stormwater runoff and applied during simulated storms throughout the study period at all three study sites. *As and Pb values are trace amounts found in Logan City water used at the Green Meadows site. <MDL indicates less than the method detection limit.

		Cu	Zn	As	Pb
		Totals, µg/L			
300 East	Min	3.9	17.6	0.22	0.38
	Max	217	1929	19.7	116
	average	39.4	243	3.1	12.5
	95% CI	±13.4	±107	±1.2	±6.1
Public Utilities	Min	2.6	8.7	0.02	0.19
	Max	149	296	4.0	35.4
	average	16.9	54.6	0.68	2.8
	95% CI	±3.1	±9.6	±0.13	±0.88
Green Meadows		Dissolved, µg/L			
	Low	10.2	67.6	1.3	<MDL
	Medium	16.3	98.7	1.3	<MDL
	High	26.2	150	1.3	<MDL

3.2 Water samples

The pH and EC values measured at the three field sites from well and lysimeter samples are listed in Table 3. All media are alkaline, with the Utelite™ and pea gravel having higher pH values than the topsoil. The pH of the soils and media would foster sorption and precipitation of Cu, Zn, and Pb, however, it would limit the sorption of As. The EC for Green Meadow site reflects the application of compost to the site.

Table 3: pH and EC results for pore water (PW) and well water samples from the three study sites.

		pH	EC (µS/cm)
Pore Water 300 East	average	8.0	557

	95% CI	±0.10	±68
Pea Gravel Well Public Utilities	average	10.0	578
	95% CI	± 0.26	±127
Utelite™ Well Public Utilities	average	8.6	1577
	95% CI	±0.29	±431
Pore Water Green Meadows	average	7.7	2325
	95% CI	±.06	±216

At the 300 East location, total Cu, Zn, and Pb concentrations were statistically lower in the treatment bay pore water compared to the runoff; these metals are removed within the BR system (Figure 7a). The concentration of total As however, was the same in the pore water as in the runoff. The 300 East field site was unique in that it included a Comparison Bay of the same soil and plant composition as the Treatment Bays but did not receive roadway runoff during the study period. This site then allowed direct comparison of subsurface pore water concentrations impacted by pollutant runoff and that only affected by rainfall infiltration. The concentration of total Cu, Zn, and Pb were the same in the Treatment Bays (Figure 5b) as the Comparison Bay. The Treatment Bays were effective at removing total Cu, Zn, and Pb from the stormwater (Figure 5a) with no effects on the water solubility of these metals compared to the Comparison Bay. Arsenic concentration in the pore water from the Comparison Bay was higher than the Treatment Bays, demonstrating the natural leaching of As from the top soil.

The pea gravel media at Public Utilities had no effect on removal of total Cu, Zn, or Pb from stormwater (Fig 5c). The total As concentration increased in the well compared to the runoff concentration. The Utelite™ contributed all trace elements to the well water (Fig 5d). This site was designed as a detention basin with no reliance on soil or other sorption media. Stormwater runoff does not interact with the top layer of soil nor with vegetation at this site. Stormwater immediately enters the subsurface layer where the alkaline pea gravel nor Utelite™ was not adequate to remove contaminants from the infiltrating stormwater.

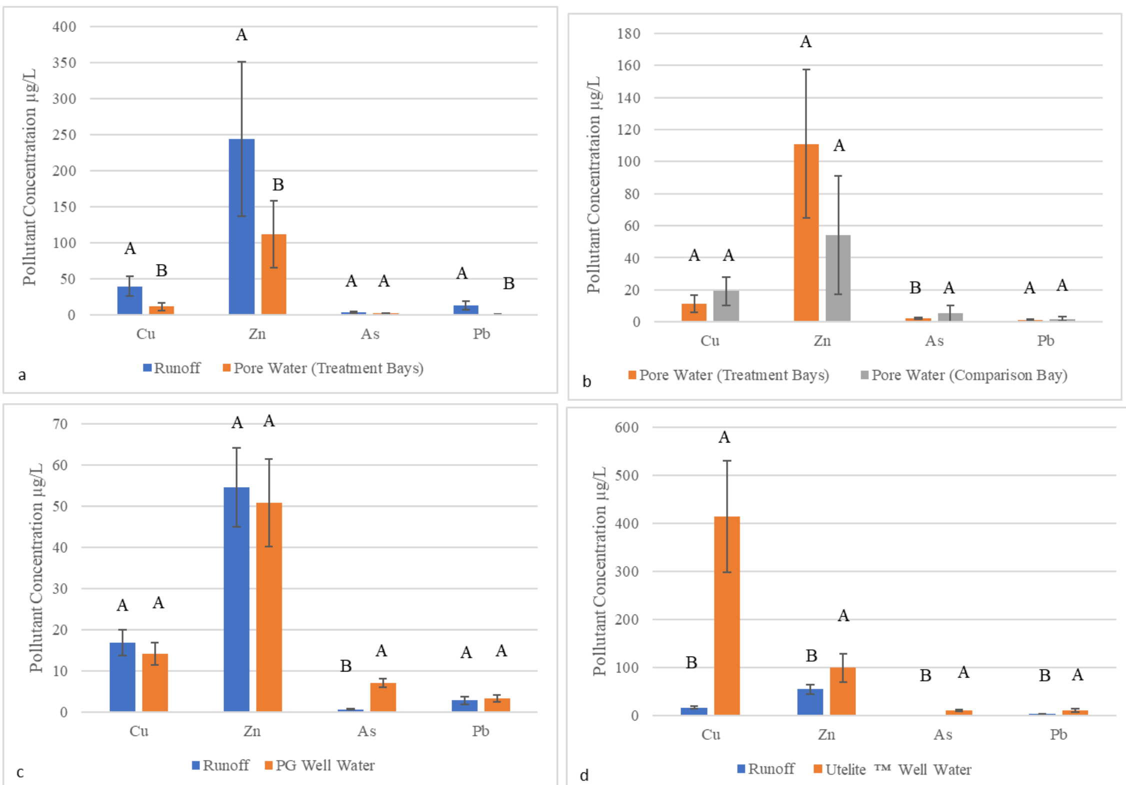


Figure 5: Runoff and pore water or well concentrations of total elements in a. Treatment Bays at 300 East site; b. Treatment Bays and Comparison Bay at 300 East site; c. Pea gravel (PG) storage layer at Public Utilities site. d. Utelite™ storage layer at Public Utilities site. Error bars are 95% confidence intervals; letters indicate significant difference $p \leq 0.05$ at individual sites. Note: Y axes differ among panels.

For the Green Meadows site with or without plants, all pore water and application concentrations for total dissolved Cu or Zn were the same at the low and medium loading rates (Figure 6a, 6b; capital letters). For the high application rate, planted bays removed more dissolved Cu and Zn compared to the applied and Control Bay pore water concentrations. This site lacks bays that did not receive the simulated stormwater treatments for direct measurement of pore water concentrations not influenced by runoff. The pore water concentration of dissolved Zn was not affected by the increasing concentrations added (Figure 6 small letters) within the control and planted systems. Dissolved Cu displayed a dependency on the concentration added but not in a consistent manner. The amount of dissolved Zn and, in general, dissolved Cu were reflective of the native solubility of these metals in the compost and imported topsoil and not related to the concentrations in the stormwater runoff applied, indicating that these metals were removed from the stormwater as it moved through the BR system.

Pore water dissolved As and Pb concentrations were above the applied concentrations at all loading levels in the planted and unplanted Control Bays (Figure 6c, 6d). The planted bays released more dissolved As to the pore water than the unplanted bays for the medium and high loading. The unplanted bays had higher concentrations of dissolved Pb for the high loading rates.

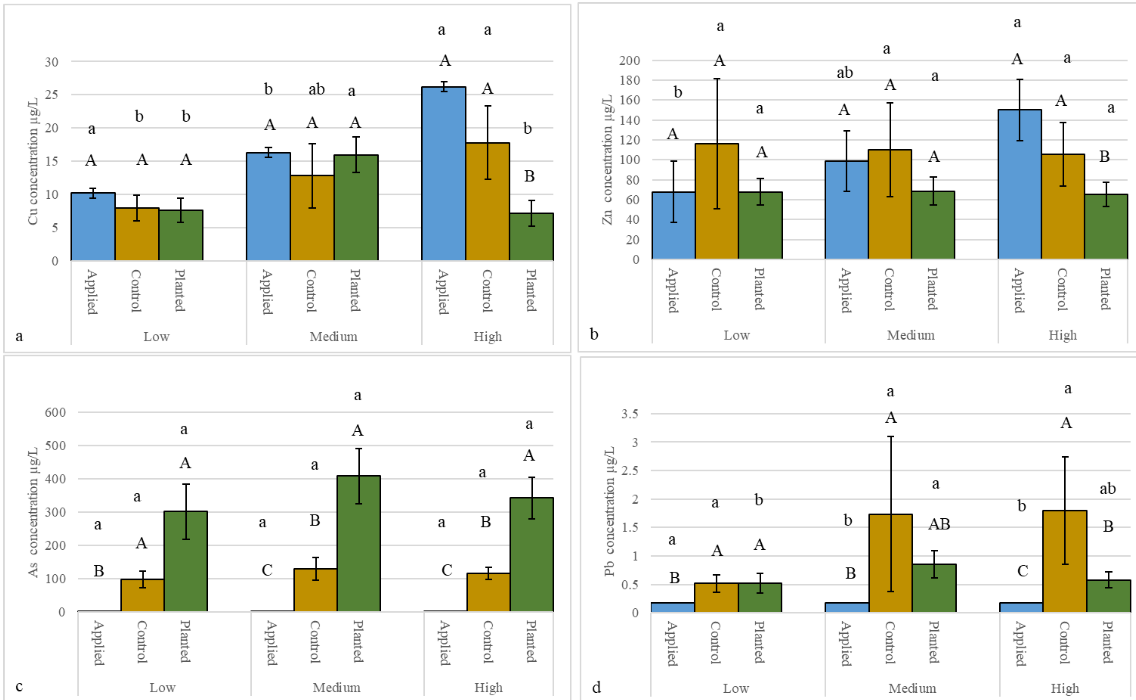


Figure 6: Applied and pore water concentrations in non-planted (control) and planted bays at Green Meadows site for dissolved a. Cu b. Zn c. As and d. Pb. One-way ANOVAs within a given application rate (capital letters), and across all applications rates (small letters) with post-hoc Tukey's HSD testing. Error bars are 95% confidence intervals; letters indicate significant difference $p \leq 0.05$.

3.3 Water Extractions

In order to determine the source of metals and As observed in the wells at Public Utilities, pea gravel purchased from a local hardware store and Utelite™ obtained from the manufacturer were extracted with water. The concentrations of Cu, Zn, and Pb in the water extract for Utelite™ and pea gravel were significantly lower than the concentrations found in both wells; however, as indicated above, the concentrations in the wells of these elements were the same as those found in the runoff for pea gravel and for Zn in Utelite™ (Figure 7a, 7b, 7d). Cu and Pb concentrations were higher in the wells than in the runoff or water extract for Utelite™ (Figure 7a, 7d).

Water extractions for Utelite™ at the Public Utilities site contained As concentrations that were not different than the concentrations in the Utelite™ well indicating that the source of the As in the well is the Utelite™ media (Figure 7c). Finally, As concentrations were higher in the pea gravel well than the corresponding runoff or water extraction.

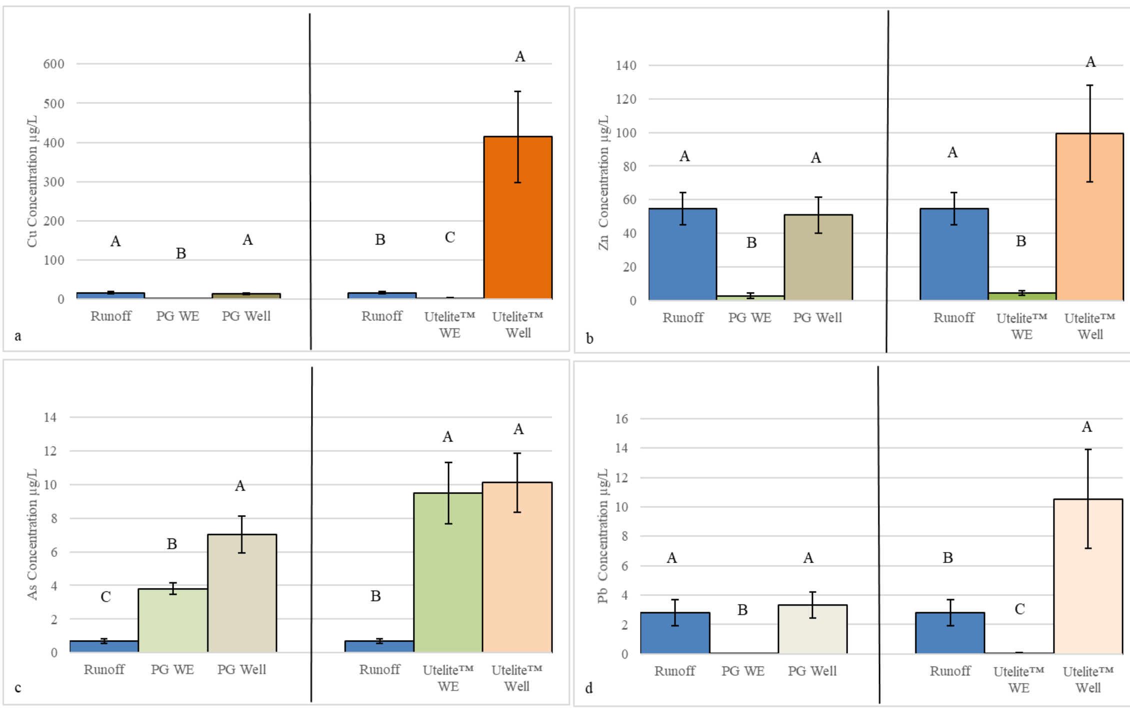


Figure 7: Runoff, water extraction, and well results for the Public Utilities site for a. Cu, b. Zn, c. As, and d. Pb. Error bars are 95% confidence intervals; letters indicate significant difference for each filter media type at $p \leq 0.05$ based on ANOVA with post hoc Tukey's results. (PG = Pea Gravel, WE = water extraction).

Discussion

The simple BR system with turf grass and pear trees at 300 East was shown to effectively remove a range of trace elements from stormwater runoff as it infiltrated to groundwater. Based on the comparison of Treatment Bay pore water concentrations below the planted root zone to those in the Comparison Bay not receiving roadway runoff it was found that all pollutants entering the Treatment Bays were attenuated in the 300 East BR system before reaching the 12-inch (30.5 cm) soil depth. None of the pollutants in the roadway runoff or within the Treatment Bay pore water exceeded the levels found in the field site soil in the Comparison Bay, subject only to rainfall infiltration, indicating that the concentrations of elements found in the soil pore water was from the soil and not from the runoff at the 300 East site.

Removal of pollutants was not discernable until the highest loading rates at the Green Meadows site. Cu and Zn concentrations in the pore water at the Green Meadows site were statistically the same as the concentrations that were applied in the synthetic storms in the Unplanted Control Bays for all application rates and for the Planted Bays at the low and medium application rates. The Planted Bays at the Green Meadows site improved pollutant removal of Cu and Zn at the highest loading rate when compared to the Unplanted Control Bays. The pore water concentrations across the low and medium loading rates were the same for all treatments and reflect the soil characteristics within the bays rather than the pollutant loading from the simulated rain events. This resulted in pollutant removal not being apparent at the low and medium loading rates because background pore water concentrations were equal to or greater than the applied concentrations at these lower loadings. It was not until higher concentrations of trace elements were applied at the highest loading rate that pollutant removal became measurable. A discussion of mechanisms and individual plant performance is given in Chapter 4.

The runoff concentrations observed in the current study are lower (Table 1) than what have been reported in previous studies, supporting the observation that the lack of Cu and Zn removal observed at the Green Meadows site for the low and medium loading rates is due to native pore water concentrations that are statistically the same as runoff concentrations applied at those loading rates.

Hatt et al. (2007, 2008) in studies using soil and soil amendments (vermiculites, compost, and mulch) found that while soil-based filters performed poorly for nutrient removal because of nutrient leaching from native soils, they were able to remove greater than 90% of applied Cu (50 µg/L), Zn (250 µg/L), and Pb (140 µg/L). The soil-based filters used in the Hatt et al. (2007, 2008) studies contained a sandy loam soil similar in texture to the soil type found at the Green Meadows and 300 East study sites. Sun and Davis (2007) with dosing Cu at 71 µg/L or 170 µg/L and Zn at 66 µg/L or 1,440 µg/L into laboratory pot studies with 50% potting soil and 50% leaf mulch observed removal of 88-97% of the metal added: plant uptake only accounted for 0.5 to 3.3% of the added metals; retention was due to sorption. Davis et al. (2001a) observed over 92% removal for applied Cu (80 µg/L), Zn (600 µg/L), and Pb (80 µg/L) in a study using synthetic stormwater where removal was due to sorption of the metals to the mulch that removed a factor of 6 times more Cu, 1.7 times more Pb and 17 times more Zn compared to the soil. The concentrations of Cu, Zn, and Pb in stormwater in the previous studies are higher than those measured in the current study that are representative of run-off in Northern Utah and none of the studies reviewed from the literature examined the extractable trace elements already in the media. Concentrations of Cu and Zn in the pore water measured in the current study represent the water soluble background levels of the native soil, and in part explain the lack of observable removal of these trace elements applied at low loading rates to the soil. At the high loading rates removal is discernable above the background level. Control bays that did not have pollutant loads administered would have helped to determine the source of the trace elements found in the pore water at the low and medium loadings at the Green Meadows site.

Only trace levels of dissolved As and no Pb were added to the bays at Green Meadows, but high concentrations of both of these trace elements were found in the pore water in the unplanted control bays indicating that the soil contains both mobile geologic As (Meng, 2017) and Pb. For As, the concentrations in the pore water exceed the drinking water standards. The geology of Northern Utah and much of the basin and range of the southwestern United State have geologies that are enriched in As. Conditions within the BR systems enhance solubilization of As containing minerals and long-term monitoring at these sites will be necessary to ensure that As migration to underlying aquifers is not enhanced with continued stormwater application. The concentrations of As in the pore water at Green Meadows were higher than the drinking water standard of 10µg/L while at 300 East the pore water As concentrations were below the drinking water standard, with neither site having high As concentrations applied. The potential for mobilization of trace elements from background soils in BR systems should also be considered in evaluating the feasibility and placement of BR systems in this geologic region.

The Utelite Corporation website for the expanded shale used in the Public Utilities BR system states that the shale in combination with compost, other organic amendments, or with the addition of soil, can remove "P, As, metals, grease oils and more” (Utelite™ 2019). None of these amendments were added at the Public Utilities site during construction however, and consequently the well samples from below the Utelite™ shale filter media contained higher concentrations of total As, Cu, Pb, and Zn than those found in the stormwater runoff. Results from this study vary considerably from other studies in which expanded shale with amendments was used. In studies by Ostrom and Davis (2019) and Sloan et al. (2008) their filter media containing expanded shale consistently removed Al, Cu Fe, and Zn from the influent, however, both studies included amendments added to the shale that resulted in the observed removal efficiencies. The expanded shale for the Ostrom and Davis study was from Cleveland, Ohio, produced by DiGeronimo Aggregates (Ostrom and Davis 2019) and the expanded shale from the Sloan et al. (2008) study was produced near Dallas, TX by Texas Industries. Sloan et al. (2008) added sphagnum peat moss or zeolite to the expanded shale in a greenhouse pot study and Ostrom and Davis (2019) used Al oxide based WTR with psyllium-based binder, both studies adding significant amounts of sorbing surfaces to their expanded shale media. The expanded shale used in the Public Utilities BR system was from the Coalville facility in Park City, UT, produced by the Utelite Corporation. This location may have high levels of geologic As and the process for creating the expanded shale appears to have changed the crystalline structure within the shale once it is expanded, enabling trace elements to be easily desorbed (Thiros et al. 2015). With no amendments to add sorption sites to the porous expanded shale performance at the Public Utilities site was in retrospect, likely to be poor at best.

Total Cu, Zn, and Pb concentrations in the pea gravel well water were the same as the concentrations in the runoff, indicating that the pea gravel was also ineffective at removing total Cu, Zn, and Pb at the Public Utilities site. This lack of pollutant removal by pea gravel is similar to results from previous studies that examined gravel and sand in BR systems. Gülbaz et al. (2015) reported that gravel and sand were the least effective of the media studied for removal of Cu, Zn, and Pb. The addition of soil and mulch improved the removal of Cu, Zn and Pb from the inflow, with the highest retention being for Cu (Gülbaz et al. 2015).

Arsenic release from the BR system observed at the Public Utilities site can be explained based on the water extraction results (Figure 10) which confirms that the Utelite™ media is a source of the increased pollutant concentrations. Cu and Pb concentrations in the Utelite™ well cannot be accounted for by the concentrations in the runoff or from the water extractions, the levels in the well are unexplainable and would need further study to determine its source. Zn concentrations in the Utelite™ well are the same as the concentrations in the runoff, exhibiting a lack of removal similar to the pea gravel.

4. Conclusions

As the results of this study the following conclusions can be reached regarding the impact of media on BR system pollutant removal effectiveness and system performance evaluation.

1. Engineered filter media within a BR system can be a significant source of pollutants and represent a potential groundwater threat. Geogenic sources of As can be released from soil by stormwater in areas where these elements exist in high concentrations within the soil.

2. Media and site soil should be evaluated using some form of water extraction before being used in stormwater treatment systems.
3. Background soil pore water concentrations in areas adjacent to a BR system containing native or imported soils should be determined to develop a baseline from which to evaluate the true pollutant removal performance at these BR sites.
4. The water extraction procedure used in this study clearly indicated that significant levels of As can be mobilized from the Utelite™ shale used at the Public Utilities site, and despite its high porosity and permeability, is not ideal when used without additional treatment amendments (compost, mulch, absorptive media).

From observation over the course of the study, the BR systems at both the 300 East and Public Utilities sites were able to contain and infiltrate all natural runoff generated during the field study, and completely eliminated large volumes of stormwater discharge to conventional stormwater systems and local surface water bodies. However, they provided significantly different levels of pollutant removal, driven by the specific media and vegetation which they contained. As seen in this study using realistic pollutant runoff concentrations measured in Northern Utah settings rather than high pollutant concentrations typical of most lab and greenhouse experiments, media choice can have a significant impact on apparent BR system performance. Careful evaluation of media and their naturally occurring background concentrations of trace metals is therefore necessary to ensure optimal stormwater treatment system design, valid BR system performance evaluation, and sustained groundwater quality protection.

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CHAPTER 4

EFFECTS OF PLANT SELECTION ON NUTRIENT AND TRACE ELEMENT REMOVAL FROM BIORETENTION SYSTEMS

Abstract

Two field sites were used to examine the impact of vegetation selection on nutrient (N, P) and trace element (Cu, Zn, and Pb) removal from stormwater runoff. The Green Meadows site was planted with four species common to BR systems in Northern Utah and was compared to Unplanted Control Bays while the 300 East site was planted with a cabin grass mixture and was compared to a bay (Comparison Bay) that was subjected only to rainfall infiltration. Pore water samples were collected at both sites using Micro Rhizon pore water samplers. Runoff samples were collected at the 300 East site from 14 natural storm events. Four simulated storms with variable loading rates were administered at the Green Meadows site. At the Green Meadow site Planted Treatment Bays outperformed Unplanted Control Plots for all nutrient and trace metal pollutants applied in the synthetic storm events. The cabin grass mixture at 300 East site was also shown to effectively remove nutrient and trace metal pollutants from stormwater runoff. No single plant species was able to completely remove all pollutants studied.

1. Introduction

Due to anticipated changing requirements of MS4 stormwater permits to incorporate water quality monitoring into stormwater management plans, municipalities and state agencies are examining ways to improve pollutant removal from stormwater runoff using bioretention (BR) systems. Using BR systems to capture and treat stormwater runoff can decrease pollutant loads into nearby surface water or groundwater (EPA 2017a). BR systems generally consist of vegetation for uptake of nutrients and trace metals, to control erosion, and to manage infiltration; soil and filter media to maintain an optimum filtration rate for pollutant removal and reduction of peak flows; and an optional underdrain system to increase the holding time for runoff within BR systems, thereby increasing nitrogen removal via denitrification and phosphorus removal through enhanced sorption to media surfaces (Prince George's County 2007; EPA 2016b).

Vegetation within BR systems is generally selected simply for plant survivability or aesthetics. However, enhancing pollutant removal using vegetation should also be considered when selecting plants for BR systems. Studies conducted on BR systems with and without vegetation have consistently shown that vegetation maintains infiltration rates and improves pollutant removal compared to unplanted systems (Barrett et al. 2013; Rycewicz-Borecki 2015; Rycewicz-Borecki et al. 2016, 2017; Glaister et al. 2017). Studies have also shown that different plant types vary in their ability to remove pollutants, suggesting that pollutant removal performance may be enhanced by strategically selecting plants for BR systems (Bratieres et al. 2008; Read et al. 2008; Barrett et al. 2013; Payne et al. 2014; Leroy et al. 2016; Wu et al. 2017; Rycewicz-

Borecki 2015, Rycewicz-Borecki et al. 2016, 2017; Wang et al. 2017; Shrestha et al. 2018).

The presence of vegetation significantly increases nitrogen (N) and phosphorus (P) uptake compared to unplanted control plots and increases the useful life of BR systems (Lucas and Greenway 2008). Unplanted controls consistently have decreased removal ability for most nutrients when compared with BR systems with vegetation (Lucas and Greenway 2008; Barrett et al. 2013; Rycewicz-Borecki 2015; Rycewicz-Borecki, et al. 2017; Barron et al. 2019; Luo et al. 2019). In studies analyzing P removal effectiveness it has been found that without plants P can be leached from the soil and exported in the effluent. P removal is generally attributed to sorption onto particles, however when sorption sites are limited, plants are able to sequester excess P and remove it from the effluent (Lucas and Greenway 2008; Barrett et al. 2013; Glaister et al. 2016; Luo et al. 2019). Vegetated BR systems have also been shown to increase N removal from stormwater when compared to non-vegetated systems. Reported N removal ranges from 40 to 90 percent and is dependent on vegetation, media, and the presence of a water storage layer or a saturated zone (SZ) below the plant root zone which enhances denitrification (Bratieres et al. 2008; Lucas and Greenway 2008; Rycewicz-Borecki et al. 2017; Wan et al. 2018).

For removal of total and dissolved metals in BR systems, removal effectiveness has been shown to be dependent on plant type. Read et al. (2010) compared different characteristics of plants with their ability to remove N, P and metals from soil. No characteristic was found to differentiate a plant’s ability to uptake metals, as all 20 plant species that were studied were effective in removing Cu, Pb and Zn from BR influent

(Read et al. 2010). N and P removal however was correlated with root length, root mass and high growth rate, with *Carex appressa* being the most effective in nutrient removal. Leroy et al. (2016) compared two BR systems, one planted with fescue (*Festuca arundinacea, Festuca rubra*) and ryegrass (*Lolium perenne*), and another planted with macrophytes, to analyze the systems for pollutant removal. The BR system planted with macrophytes performed better than the system planted with grass cover for removal of trace elements due to the higher root density of the macrophytes retaining particulate associated trace elements. Rycewicz-Borecki et al. (2016) found that *Carex* species were the most efficient of six species studied (*C. microptera, Helianthus maximilliana*, *Typha latafolia, Phragmites australis, Scirpus Validus, Scirpus acutus, Carex praegracilis*) at mobilizing metal in the rhizosphere and increasing the amounts taken up into both the below ground and above ground plant material. Rycewicz-Borecki et al. (2017) also found that *P. australis, C. praegracilis,* and *C. microptera* uptake significantly more TP and TN mass into harvestable tissue than *T. latifolia, S. validus,* and *S. acutus*. These results confirm that species selection can also optimize nutrient and trace metal retention and recovery from stormwater and decrease pollutant discharge to surface waters. However, some of these species are intolerant to Northern Utah's semi-arid climate or are invasive to this region.

With removal of above ground plant material at the end of a growing season, metals and nutrients that have accumulated within the above ground vegetation can be removed from the BR system, extending its operating life (Rycewicz-Borecki et al. 2015). Metal concentrations in the harvested plant material would not be expected to be at dangerous levels if harvested annually due to generally low annual loading of metal pollutants in urban runoff. Consequently, this harvested biomass could be incorporated in local composting programs without concern for BR system biomass adversely affecting the quality of the finished compost product.

Despite water quality benefits and improved aesthetics provided by vegetated BR systems, stormwater managers often perceive drawbacks to these systems that include significant maintenance requirements, increased local flooding potential and standing water, or negative groundwater impacts. In a concurrent study examining views of BR systems by stormwater managers and developers in Northern Utah, Jackson-Smith (2019) surveyed stormwater managers and found that concerns regarding excessive maintenance such as mowing and trash removal, lack of acceptability to developers, and cost and land requirements were disadvantages identified to have limited installation of BR systems in this rapidly developing urban area. These perceived disadvantages of commonly planted BR systems led to an interest in this study in the effectiveness of pollutant removal by conventional turf grass mixes which were identified as an acceptable planting choice by these stormwater managers for their BR systems despite turf grass being reported in the literature to not perform as well as other vegetation types for nutrient and metal due to low biomass and limited rooting systems (Sun and Davis 2007; Sloan et al. 2008; Leroy et al. 2016; Nocco et al. 2016).

As indicated above, plants have been demonstrated in the literature to improve stormwater quality and maintaining BR system infiltration rates over time. Data are generally lacking from the Intermountain West region and for studies monitoring pollutant loading and BR system performance under field-scale runoff conditions. This study was conducted at two field sites in semi-arid Northern Utah to contribute to knowledge regarding the pollutant removal effectiveness of infiltrating, vegetated BR systems, as a function of vegetation type. One field site received runoff from a road surface in response to natural rain events that contained a cabin-mix turf grass and ornamental pear trees considered an acceptable curbside planting scheme in urban neighborhoods in Northern Utah. The other field site contained a range of wetland and native plants common to more isolated BR systems treating runoff from large, neighborhood-scale drainage areas. Pollutant removal performance of these two systems were compared based on runoff versus pore water concentrations to determine if a turf grass planting scheme that required regular watering, fertilizer, and mowing in a semi-arid, Northern Utah climate could provide comparable pollutant removal to a more conventionally configured and vegetated BR system. Previous studies at the Green Meadow field site saw an increase of As in pore water with plants in the BR systems (Rycewicz-Borecki et al. 2015; Patterson 2019). Geogenic sources of As are discussed in Chapter 3 of this dissertation and must be considered as a possible limiting factor in the use of BR.

2. Materials and Methods

2.1 Study Areas

The two field sites used for this study are two of the sites described in the previous chapter, the 300 East BR system and the Green Meadows field demonstration site. The 300 East BR system consisted of curb cuts and bioswales, and contained three bays that received roadway runoff and a Control Bay that did not. All bays were watered twice weekly and were planted with a cabin grass mixture, containing a species mix of soder streambank wheatgrass, roadcrest crested wheatgrass, and sheep fescue, as well as ornamental pear trees. The Green Meadows site contained 15 bays (5ft x 15 ft 8 inches (1.5 m x 4.78 m)), with one of four plant types in each bay in triplicate: cattails (*T. latifolia),* small wing sedge (*C. microptera),* Baltic rush (*Juncus balticus)*, and sunflower *(H. maximillina),* along with three unplanted control bays. The exact specifications for each location are described in Chapter 3 of this dissertation. At both locations there was no discharge to surface water and all stormwater runoff drained eventually to underlying groundwater.

The 300 East site received runoff from natural rain events over the study period. Precipitation was recorded on site using an ONSET, HOBOware® rain gauge smart sensor (S-RGA-M002) with a U30 data logging station. To collect runoff at the 300 East site, funnels were fashioned to direct water from the curb cuts into sample boxes. Composite runoff grab samples were collected from the sample boxes after each rain event. At the Green Meadows location simulated storms with varying pollutant concentrations were administered at different frequencies to simulate different antecedent dry days typical of this arid Northern Utah region. Individual simulated storm volumes were 97.25 gallons (370 L) each, with the first 10% being applied as a concentrated pollutant mixture to simulate a first flush, and the remaining volume applied with sprinkler hoses for a 30-minute period. Exact pollutant concentrations for natural and synthetic runoff are listed in Chapter 3 of this dissertation.

2.2 Pore water sampling and analysis procedures

Pore water samples were collected from the vadose zone at Green Meadows using six Micro Rhizon pore water samplers (lysimeters) (Soilmoisture Equipment Corp., Santa Barbara, CA. Soil Moisture Miniature Samplers – 1908D4.5L09), co-located in pairs at

3-6 (6 inch) inch depth (7.62 cm -15.24 cm) and 6-9 (9 inch) inch depth (15.24 cm - 22.86 cm). Each co-located pair were randomly assigned to a 1 ft^2 (930 cm^2) section of a bay. At the 300 East location two Micro Rhizon pore water samplers were installed at depths of 12 (30.5cm) and 20 (50.8 cm) inches in both the Treatment and Control Bays. To collect pore water samples at each location a vacuum of at least 70kPa was applied to the lysimeters using a hand vacuum pump after all ponded water had infiltrated after each storm event. A 1,000 mL amber glass jar with #10 stopper was connected to each lysimeter to collect soil pore water captured by each lysimeter, and samples were collected for analysis within 24 hours after the vacuum was applied.

Upon collection, runoff and pore water samples from each location were returned to the Utah Water Research Laboratory (UWRL) and electrical conductivity (EC) and pH were measured (Table 1). Samples were filtered through a 0.2 µm filter then divided into various aliquots for analysis of total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), nitrate (NO_3-N+NO_2-N), ammonia (NH_3-N), dissolved copper (Cu), dissolved zinc (Zn), dissolved arsenic (As) and dissolved lead (Pb). For total element concentrations, unfiltered water samples were digested using a hot block, nitric acid digestion using the APHA Method 330E (APHA 2012). An Inductively Coupled Plasma Mass Spectrometer (ICP-MS, Agilent 7500c) was used to determine concentrations of total dissolved Cu, Zn, As, and Pb once samples were filtered, using SW-846 Method 6020a (EPA 2007b). Undigested, filtered water samples were analyzed on the AQ2 Discrete Analyzer (Seal Analytical) using Standard Method EPA 353.2 Rev 2.0 (1993) for NO_3-N+NO_2-N. Undigested, filtered water samples were analyzed for NH_3-N using the indophenol, low level method (Solorzano 1969). A 10 mL aliquot of each sample was digested using the persulfate oxidation method, modified from Valderrama (1981), for analysis of TN, TDN, TP, and TDP. Samples were then analyzed on the AQ2 using Standard Method EPA 353.2 Rev 2.0 (1993) for TN and TDN and the EPA Standard Method 365.1, Rev 2.0 (1993) for TP and TDP. Total metals and nutrients are reported for the 300 East site and dissolved metals and nutrients are reported for the Green Meadows site.

2.3 AG plant sampling and analysis procedures

Plant samples were collected from each treatment bay at Green Meadows and 300 East at the end of the field study. Above ground (AG) plant samples from both locations were cut to within 3 inches (7.62 cm) above the soil and were placed in dry, pre-weighed paper bags. Harvested wet plant weight was measured, then samples were placed into an oven at 60°C until dry, approximately 3 days. After drying, the bags were reweighed to determine the dry weight of the harvested plant material. Plant samples were ground to 0.2 mm using a Thomas-Wiley Model 4 Laboratory Mill, for analysis of trace metals, total N, and total P as described below.

Ground AG plant tissue from the two sites was analyzed at the USU Analytical Laboratory for total N content. For trace metal and P analysis, prepared plant samples were digested using the Jones and Case (1990) nitric acid, hydrogen peroxide hot block digestion method. Once digested, samples were analyzed for total metals and total phosphorus via ICP-MS using specific methods described above.

2.4 Statistical Analysis

Data collected from runoff, pore water, and plant samples were analyzed using SAS University Edition statistical program. A Box-Cox transformation analysis was performed to determine the best transformation for each data set. Based on the Box-Cox recommendations, all data were log base 10 transformed, then an analysis of variance (ANOVA) ($p<0.05$) was completed. Tukey's Honestly Significant Difference (Tukey's HSD) ad hoc testing was used to determine what significant differences exited among plant species pollutant removal rates at both sites, and to determine if significant differences existed between the control and the treatment areas.

In this evaluation of pollutant removal effectiveness as a function of vegetation type, runoff data were averaged over time and across Treatment Bays at the 300 East site. Statistical analysis of data from this site indicated that nutrient and trace elements pore water concentrations were not affected by storm frequency, duration, or intensity. This lack of differences among the data allowed for the use of averages for pore water concentrations across time and treatment location. At the Green Meadows site only the pore water results from the highest pollutant loading were analyzed in this paper as a worst case scenario and all other pollutant loadings were analyzed in Chapters 3 and 5 of this dissertation. Statistical analysis of nutrient and trace element pore water concentrations at both soil pore water depths at the 300 East Treatment Bays and the Green Meadows sites showed no statistical difference with depth, also allowing averaged pore water data to be used in system performance evaluation.

3. Results

3.1 Rainfall Events

At the 300 East field site, 14 individual natural storm events were sampled from September 2017 to November 2018. Storm sizes creating runoff and enabling sampling ranged from 0.1 (0.254 cm) inches to 1.24 (3.1 cm) inches with an average rainfall depth of 0.34 (0.86 cm) inches during the study period. In the Fall of 2018, two 1-year return period storms occurred, a 60-minute storm that contained 0.37 inches (0.94 cm) of rain, and a 24-hour storm, with 1.24 (3.1 cm) inches of rain. Rainfall events occurred from February to May and August to November. After November and before February precipitation in the study area fell as snow, with below freezing temperatures, prohibiting field sampling. From June to August, very little precipitation fell, and no sampling events were conducted during this period. At the Green Meadows site simulated storms were administered from June 2018 to September 2018 and four total events were used for analysis. Table 1 lists storm characteristics for both field sites.

Table 1: Storm characteristics for storm events at the 300 East and Green Meadows field sites

	300 East	Green Meadows
Dates of storms	9/2017 – 11/2018	6/2018 -9/2018
Total storm events sampled	14	4
Minimum depth	0.1 inches (0.254 cm)	
Maximum depth	1.6 inches (4.09 cm)	
Average depth	0.34 inches (0.864 cm)	0.2 inches (0.5 cm)

3.2 Pore water Concentrations

The pH and EC values measured at the two field sites in pore water lysimeter samples are listed in Table 2. Results shown are from the treatments bays at the 300 East site and from the planted bays at the Green Meadows site. All pore water samples were slightly alkaline as is typical for the Northern Utah region, and would foster sorption and precipitation of Cu, Zn, and Pb in the stormwater runoff. Conductivity values were significantly higher at the Green Meadows site due in part to the compost amendment used there. The pH of the soils and media would foster sorption and precipitation of Cu, Zn, and Pb, however, it would limit the sorption of As.

Table 2: pH and EC results ± 95% Confidence Intervals for pore water samples collected from the two field sites monitored in this study.

	pH	EC (µS/cm)
300 East, Treatment Bays	8.0 ± 0.10	557 ± 68
Green Meadows, Vegetated Bays	7.5 ± 0.05	2,407 ± 110

At the 300 East site, concentrations of TN, TP, NH_3-N, total Cu, Zn, and Pb were statistically the same across all Treatment Bay lysimeters at both depths. The pore water concentrations of TN, TP, NH_3-N, and Cu were lower than the concentration in the runoff across all storm events (Figure 1) displaying removal of pollutants. The Zn and NO_3-N+NO_2-N concentration was the same in the pore water as the runoff (Figure 1). Arsenic concentrations were the same in the pore water for the treatment and comparison bays, and in the runoff. These results indicate that most pollutants were attenuated in the 300 East BR system in the upper turf grass/soil zone before reaching the 12-inch (30.5 cm) lysimeter depth.

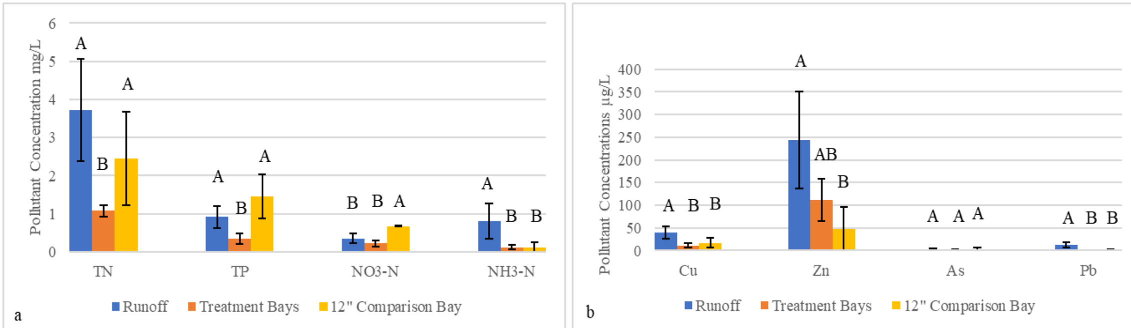

Figure 1: 300 East a. Nutrient runoff and pore water concentrations. b. Total trace element runoff and pore water concentrations. Letters indicate significant difference at $p \leq 0.05$ based on ANOVA with Tukey's HSD post-hoc test results. Error bars indicate 95% confidence intervals.

Table 3 lists the pore water concentration results from the treatment bays compared to the comparison bay at the 300 East site. The pore water concentrations in the comparison bay is either higher or the same as the pore water concentration in the treatment bays for all pollutants, indicating that the source of the pollutants is the soil.

Table 3: Comparison of pore water concentrations between treatment bays and comparison bay. Letters incidate significant difference at $p \leq 0.05$ based on ANOVA with Tukey's HSD post-hoc test results. Error bars indicate 95% confidence intervals.

	Treatment Bays	Comparison bay
TN	1.09 (b)	2.40 (a)
TP	0.36 (b)	1.56 (a)
NO_3-N+NO_2-N	0.23 (a)	0.69 (a)
NH_3-N	0.13 (a)	0.11 (a)
Total Cu	11.2 (a)	19.1 (a)
Total Zn	111 (a)	53.9 (a)
Total As	2.35 (b)	5.21 (a)
Total Pb	1.15 (a)	1.89 (a)

Data from all planted bays receiving the highest pollutant load at the Green Meadows site were combined and compared to the unplanted Control Bays to evaluate pollutant removal as affected by the presence of vegetation at this field site. Dissolved Cu, Zn, Pb, NH_3-N, NO_3+NO_2-N, TDP, and TDN all had significantly lower concentrations in pore water in the planted bays compared to pore water concentrations in the unplanted control bays (Figure 2). Dissolved Zn, dissolved Cu, TDP, and NH_3-N applied concentrations were higher than those found in pore water of the planted bays (Figure 2a, b, c). The concentrations of TDN, NO_3+NO_2-N, and, Pb are same in the applied stormwater and the planted bays, but lower in the Unplanted Control Bays, which shows assimilation of pollutants by the vegetation within the system. The removal of trace metal pollutants at lower concentrations are discussed in Chapter 3 of this dissertation, while overall pollutant removal as a function of applied loading rates is discussed in Chapter 5 of this dissertation. Arsenic concentrations in the Planted Bays were statistically higher than concentrations found in the Control Bays (Figure 2a), both being higher than the applied concentration. TDP concentrations in the pore water were higher in the Control Bays than the Planted Bays at the highest loading rate (Figure 2c). The concentration of dissolved Pb in the pore water was the same in the unvegetated Control Bays and the Planted Bays, both of which were higher than the applied amount, indicating the presence of low levels of solubilized Pb in the BR system soil (Figure 2b).

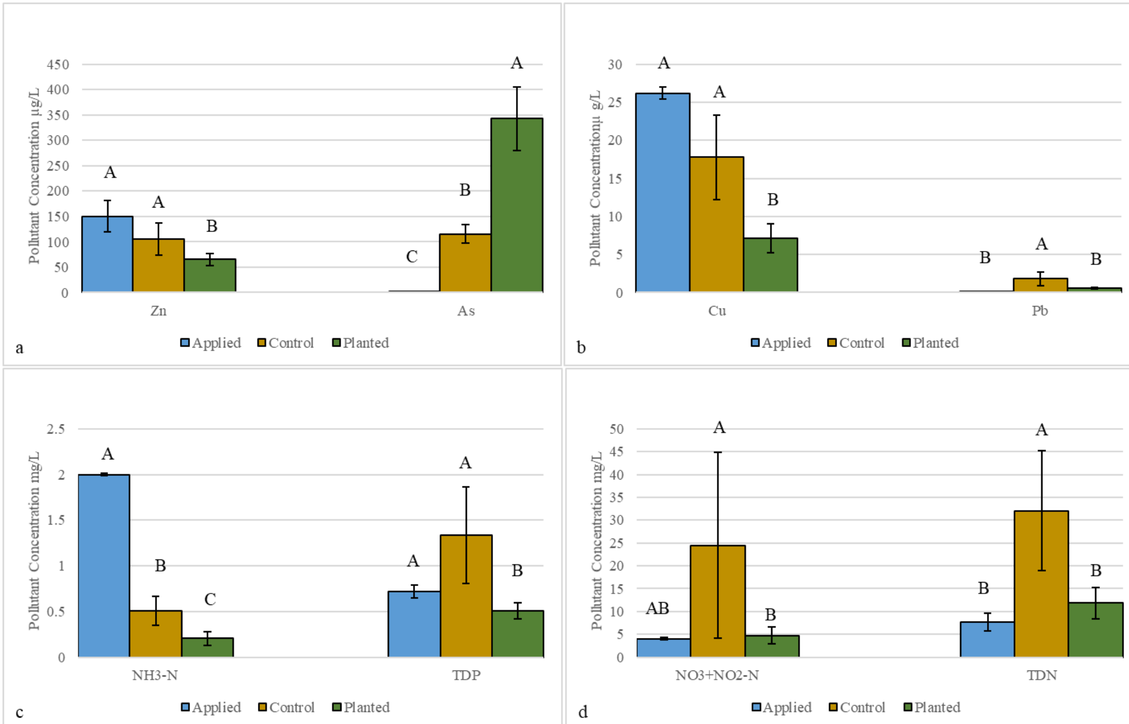

Figure 2: Pore water concentrations in planted treatments and unplanted controls at the Green Meadows field site.a. As and Zn, b. Cu and Pb, c. NH_3-N and TDP, d. NO_3-N + NO_2-N and TDN. Letters indicates significant difference at $p \leq 0.05$ based on ANOVA with Tukey's HSD post-hoc test results. Error bars indicate 95% confidence interval.

NO_3-N + NO_2-N, TDN, TDP, dissolved Zn and dissolved Pb pore water concentrations were not statistically different among plant types (data not presented). Cu pore water concentrations were significantly higher in sunflower and cattail treatments than in sedge and Baltic rush treatment bays (Figure 3a). NH_3-N and dissolved As pore water concentrations were statistically highest in the sedge and sunflower bays and lowest in the rush and cattail bays (Figure 3b, 3c).

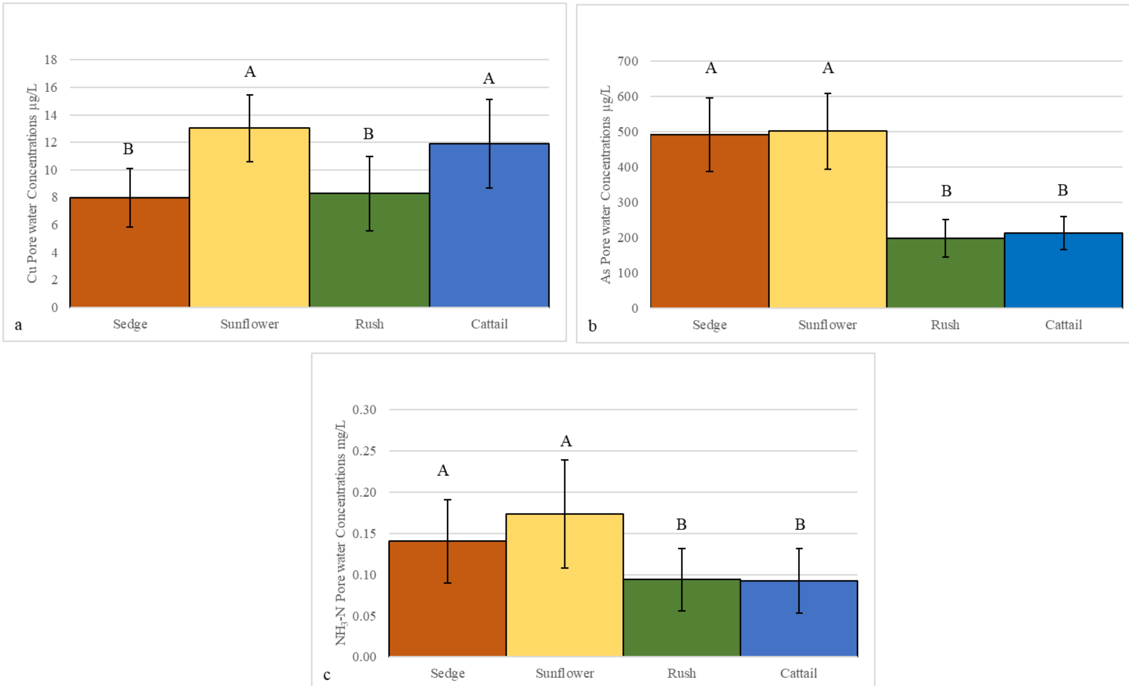

Figure 3: Concentrations in pore water at Green Meadows by plant type for dissolved a. Cu, b. As, and c. NH_3-N. Letters incidate significant difference at $p \leq 0.05$ based on ANOVA and Tukey's HSD post-hoc test results. Error bars indicate 95% confidence interval.

3.3 Above Ground Plant Tissue

AG plant tissue for sedge, rush, and cattail at Green Meadows and for mixed grass species at the 300 East site were analyzed for nutrients and trace element concentrations (Table 4). Sunflower AG plant tissue was not analyzed due to a similarity in pollutant removal to other species in the study and project cost constraints. Statistically, concentrations of TP within the AG plant material were higher in sedge than in cattail, with all other plants being the same. Sedge contained the statistically highest concentrations of As among all plant types, while Pb concentrations were highest in the sedge and grass. Zn concentrations were highest in the sedge and rush AG plant tissue, while the grass samples were statistically the same to sedge, rush and cattail. Cu concentrations were lowest in the cattail, with all other plant types being statistically the same. TN percentages were statistically highest in the grass AG plant tissue samples, all BR AG plant tissue samples contained the same percentage of TN.

Table 4: Summary statistics for nutrients and trace element concentrations for AG plant material as a function of plant type measured at the end of the study period. Letters indicate significant difference at $p \leq 0.05$ based on ANOVA with Tukey's HSD post-hoc test results.

			TP	TN	Cu	Zn	As	Pb
		Units	mg/kg	%	mg/kg	mg/kg	mg/kg	mg/kg
Green Meadows	Sedge	Min	2,511	0.81	3.10	12.28	0.86	0.09
		Max	4,320	1.6	10.0	86.58	7.28	0.74
		Average	3,311[a]	1.2[b]	5.59[a]	38.76[a]	2.77[a]	0.31[a]
		95% CI	±302	±0.14	±0.96	±15.9	±1.0	±0.23
	Rush	Min	1,729	0.92	3.2	22.2	0.06	0.04
		Max	3,545	1.3	6.8	91.6	1.6	0.24
		Average	2,424[a,b]	1.1[b]	4.7[a]	48.8[a]	0.43[b]	0.10[b]
		95% CI	±303	±0.06	±0.64	±15.2	±0.29	±0.06
	Cattail	Min	998	0.58	1.4	9.2	0.14	0.02
		Max	3,411	1.3	2.9	18.7	0.67	0.1
		Average	2,264[b]	0.91[b]	2.4[b]	12.3[b]	0.29[b]	0.04[b]
		95% CI	±418	±0.15	±0.26	±1.6	±0.07	±0.03
300 East	Grass	Min	2,087	1.78	4.7	20.2	0.12	0.29
		Max	2,864	1.98	6.4	27.3	0.14	0.36
		Average	2,554[a,b]	1.86[a]	5.7[a]	24.5[a,b]	0.13[b]	0.34[a]
		95% CI	±466	±0.12	±1.0	±4.3	±0.01	±0.05

4. Discussion

The simple curb cut with turf grass and pear trees BR system at the 300 East site was shown to remove nutrients and trace metals from stormwater runoff as it infiltrated through the soil profile and was removed by plant uptake. This BR system removed TN, TP, NO_3-N, NH_3-N, and total Cu, total Zn and total Pb as has been shown from other studies that included vegetation in their BR systems (Bratieres et al. 2008; Read et al. 2008, 2010; Zhang et al. 2011; Borin and Salvato 2012; Barrett et al. 2013; Rycewicz-

Borecki 2015; Glaister et al. 2016). Grass swales in previous studies have not been shown to significantly reduce pollutant loads similar to BR systems with BR specific plants, likely due to the low biomass and shallow rooting systems found in turf grass (Sun and Davis 2007; Leroy et al. 2016; Nocco et al. 2016). The results observed at the 300 East location indicate, however, that the removal of pollutants with a turf grass mixture in a BR system is highly effective when exposed to pollutant loadings measured in this study. The removal of pollutants through the upper soil layers and root zone can be accomplished with this turf grass mixture, which performed similar to BR specific plants observed in this study. Suggesting that the grass mixture and the BR specific plants will all work for pollutant removal in BR systems.

Vegetation is important for the removal of N species within a BR system. Payne et al. (2014), Rycewicz-Borecki (2015), Wang et al. (2017), and Vroom et al. (2018) found that planted systems performed better than the unplanted controls for NO_3-N removal in BR systems. Barron et al. (2019) saw high N removal (>75%) where all vegetated columns outperformed the unvegetated columns for NO_3-N, NH_3-N and TDN removal. Read et al. (2008), Borin and Salvato (2012), Zhang et al. (2011), Wang et al. (2017), and Barron et al. (2019) all found that the TDN removal efficiency in vegetated treatments was significantly higher than in unvegetated plots. Results observed in this study of high N species removal efficiency by the turfgrass mix at 300 East and Planted Bays versus Unplanted Control Bays at the Green Meadows site support these findings from the literature that vegetation provides significant N removal when used in BR systems under Northern Utah climate and pollutant loading conditions.

Several previous studies have shown that the presence of plants also improves TP and TDP removal in BR systems. Read et al. (2008), Bratieres et al. (2008), Lucas and Greenway (2008), Barrett et al. (2013), and Glaister et al. (2016, 2017) all saw improved TP and TDP removal with vegetation compared to systems without vegetation. At the 300 East location there was complete removal of TP from the runoff based on pore water concentrations observed at the site's Comparison Bay. At the Green Meadows site, the applied concentration of TDP was found to be statistically the same as the pore water concentrations in Unplanted Control Bays but statistically higher than the Planted Bays (Figure 2), suggesting enhanced TDP removal by the planted treatments as was observed at the 300 East site.

With regard to specific vegetation for pollutant removal, previous studies have reported no specific plant species is able to remove all pollutants of concern (Bratieres et al. 2008; Read et al. 2008; Read et al. 2010; Barron et al. 2019). However, various studies have found that different plants do improve removal for portions of the pollutant load entering a BR system and a combination of plant species would be most effective for complete pollutant removal (Rycewicz-Borecki et al. 2015; Zhang et al 2011; Wu et al. 2017). These results are similar to those found in the current study, with cattail and rush performing best for NH_3-N removal and sedge and rush performing best for Cu removal. Sedge and rush species have been identified as species that improve pollutant removal for nutrients and trace metals in BR system due to high biomass and fibrous root structure (Bratieres et al. 2008; Read et al. 2010). The difference in the ability of plants to uptake nutrients and mobilize As demonstrates that a variety of plants in a BR system would be optimal for overall pollutant removal. The interaction of plants with existing As in the soil necessitates evaluating the media to be installed within a BR system and evaluation for the placement of these systems as discussed in Chapter 3 of this dissertation.

The range of plant tissue concentrations of TP and TN and Cu and Zn found in this study are similar to that found in previous studies (Liu et al. 2007; Rycewicz-Borecki et al. 2015). Arsenic and Pb concentrations were highest in sedge, showing that sedge is adept at uptake of these two trace elements, however, root exudates produced by all plant species studied at the Green Meadows site, especially sedge and sunflower, appear to cause increased concentrations of As observed in the pore water at the Green Meadows site. Lower pore water concentrations of As in rush and cattail corresponded to less uptake by those species in their AG tissue.

The AG plant tissue analysis (Table 2) demonstrated that the cabin grass mixture was equally efficient at pollutant uptake for most nutrients and trace elements as BR specific plants studied at the Green Meadows site. The cabin grass mixture had a higher percentage of TN than any of the BR specific AG plant material. Sedge contained the highest As concentration among all plant types, while sedge and the grass mixture contained the highest concentrations of Pb. Plants used in BR systems that are able to incorporate nutrients and trace metals into the AG plant tissue can extend the lifespan of these BR systems and should be considered when selecting plants to optimize BR system performance. With removal of AG plant material at the end of a growing season, or on a regular frequency during the growing season as seen at the 300 East site, nutrients and trace elements that have accumulated within the vegetation can be removed from the BR system, extending its operating life (Rycewicz-Borecki et al. 2015). Based on results from this study as summarized in Table 2, sedge and rush from the Green Meadows site and the mixed grass species from the 300 East site all demonstrate pollutant enrichment in their above ground tissue that can be used to control pollutant accumulation over time in stormwater BR systems.

5. Conclusions

Based on the findings from this study, the following conclusions can be reached:

1. Results from the 300 East site confirm that a range of elements and nutrients can be removed from stormwater by turf grass vegetated BR systems that stormwater managers find acceptable for implementation in urban settings.

2. Results from the Green Meadows site comparing vegetated and non-vegetated treatment plot performance verified that plants improve TDN, NO_3-N + NO_2-N, NH_3-N, TDP, Cu, Pb, and Zn removal through plant uptake and retention in soil when compared to unplanted controls in the semi-arid Northern Utah climate.

3. Plant types evaluated at this field site (cattails, sedge, Baltic rush, and sunflower) did not perform significantly different for the removal of TDP, TDN, NO_3-N + NO_2-N or Zn from pore water. Sedge and rush did perform best for Cu removal, while for NH_3-N removal, cattails performed better than sedge. Arsenic was released in these planted BR systems due to plant solubilization of As from the native soil and not effectively taking up the released As into their biomass. An additional consideration for plant species selection for BR systems, AG plant tissue pollutant concentration, would suggest that sedge and rush from the Green Meadows site and the mixed grass species from the 300 East site all can be used to control pollutant accumulation over time in stormwater BR systems.

5. Finally, this study has shown the importance of evaluating unintended consequences of placing BR system in areas with geogenic source of As or other mobile metals. It is necessary to evaluate the leaching potential of BR media and native soils that can be affected by stormwater and vegetation used in BR systems for stormwater treatment to ensure long-term groundwater protection. A discussion of media effects on stormwater BR system pore water quality, and evaluation of groundwater contamination potential from the BR systems based on elevated pore water concentrations evaluated in this study is provided in Chapter 3 of this dissertation.

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CHAPTER 5

POLLUTANT REMOVAL IN BIORETENTION SYSTEMS AS A FUNCTION OF VARIABLE LOADING

Abstract

Pollutant loadings at two field sites in Northern Utah were analyzed for this study. The 300 East site was vegetated with a cabin grass mixture, experienced 14 natural rain events and included a Comparison Bay that did not receive runoff from adjacent roadway pavement. The Green Meadows site included planted and unplanted control bays and was subjected to four synthetic stormwater events at three pollutant loading rates. Pore water samples were collected and nutrient and Cu and Zn concentrations were compared to pollutant loading and pore water from the control treatments. The two sites effectively assimilated pollutants from natural or simulated storm events up to the peak loadings administered. Pore water concentrations generally reflected nutrient and trace metal concentrations generated by the media and were not related to stormwater pollutant loading. BR system sizing can be carried out from maximum pollutant loading rates applied to the sites, ensuring protection of groundwater resources from pollutant contamination in stormwater runoff in Northern Utah settings for the pollutants evaluated in this study.

1. Introduction

Urbanization has increased the amount of stormwater runoff by increasing the proportion of impermeable surfaces in these developed areas, creating a need to expand stormwater runoff capture and treatment to ensure minimal impacts to a receiving surface water body or groundwater. An increase in runoff creates an increase in pollutant loadings as the water flows over lawns, parking lots, roads, sidewalks and roofs. The pollutants found in these areas come from lawn fertilizer, pesticides, tire wear, brakes, engine lubricants, auto exhaust, etc. (Davis et al. 2001b; Charters et al. 2016). Some of the pollutants of concern in stormwater include nitrogen (N), phosphorus (P), copper (Cu), lead (Pb) and zinc (Zn). These pollutants should be removed before water can be used for groundwater recharge or be allowed to enter surface water.

Bioretention (BR) systems are considered best management practices by the EPA for pollutant removal which occurs by settling, filtration, adsorption and/or plant uptake (EPA 1999; Prince George's County 2007; EPA 2016). Many studies have been completed verifying the ability of BR systems to remove pollutants, including nutrients, trace metals, and suspended solids from stormwater runoff (Davis et al. 2001a; Davis et al. 2001b; Davis et al. 2003; Sun and Davis 2007; Bratieres et al. 2008; Read et al. 2008; Barrett et al. 2013; Rycewicz-Borecki et al. 2017; Glaister et al. 2017; Shrestha et al. 2018). But pollutant event mean concentrations (EMCs) found in stormwater vary nationally, and temporally, depending on region, season, antecedent dry days, storm volume or intensity, catchment size, and land use, along with several other basin characteristics (EPA 2007). Determining pollutant EMCs and corresponding pollutant loadings for a given area can ensure effective pollutant removal by BR systems when these systems are designed and sized to mitigate the loads that may be encountered. The regionally specific nature of pollutant loadings was particularly evident from the results of Fernandez-Valesquez (2018) that evaluated the use of the WinSLAMM stormwater modeling package for the Northern Utah region. The WinSLAMM model uses regionally specific input parameters that include pollutant probability distributions, particulate solids loadings, and runoff coefficients. Most of these default data were collected in the East Coast and the Great Lakes area, and essentially none were generated in locations hydrologically similar to the Intermountain Region. Fernandez-Valesquez (2018) found that default regional parameters in WinSLAMM did not adequately describe runoff and pollutant loading characteristics in the Cache Valley area of Northern Utah, and that Cache Valley calibrated runoff and pollutant loading parameter files did not accurately represent runoff and loading conditions in the Salt Lake Valley.

Removal of nutrients and trace metals by laboratory scale BR systems have been analyzed with the administration of different pollutant loads. Sun and Davis (2007) studied trace metal removal at two loading regimes in a laboratory bioretention system using three grass species; the high concentration was removed by sorption to the media while plant uptake was reported to be predominant at the low concentration. Barron et al. (2019) used a planted column study to determine the impact of gray water (high pollutant concentration) on a BR system’s pollutant removal abilities combined with events using simulated stormwater (lower pollutant concentration). Their system showed effective removal of nutrients and metals regardless of the water applied; the selection of plant species, however, was important in the success of these systems.

While lab studies show limited effects of loading, the field study reported by Shrestha et al. (2018) analyzed the performance of eight BR systems receiving roadside runoff in Vermont and did show some effect of loading rate on pollutant removal. The BR systems contained a variety of treatments including two plant varieties (low density with two plant species, and high density with seven plant species), two cells with SorbtiveMedia™ to increase P removal, and two cells received additional enhanced rainfall along with runoff that all bays received. Fifty individual storms were sampled with a range of small and large sized storms, with small storms making up 79% of the total. The authors report that the smaller storms showed over 60% removal for total N species but the removal of nutrients was mostly through the reduction of runoff, not the reduction in concentrations of input, while large storms always showed negative removal for N and P (Shrestha et al. 2018). Examining EMCs and loads data together, the authors concluded that the effects of vegetation and enhanced rainfall treatments were minimal compared to the soil media effects. The same research group (Cording et al. 2018) reported removal of nonlabile N and P, but labile N and P from the compost amended soil exceeded the mass load associated with the stormwater.

This study examined the impact of different field measured loading rates specific to the Northern Utah region on the pollutant removal efficiency at two vegetated BR field sites to develop pollutant loading criteria for future regional BR system design. One field site was planted with vegetation common to BR systems in the region and was exposed to simulated storms, while the other was planted with turf grass and ornamental trees and exposed to natural storm events.

2. Materials and Methods

2.1 Study Areas

Site 1, the 300 East site, is a BR system along a residential street in Logan, UT that contains a series of curb cuts to direct runoff into four vegetated bioswales during storm events. The entire system drains the west half of an asphalt paved road for one block encompassing a total drainage area of approximately 6,400 ft^2 (0.059 hectares). One additional bay was isolated from runoff with an elevated berm and was used as a comparison bay since it did not receive runoff from the street.

Site 2, the Green Meadows site, was an existing stormwater field demonstration site in a southwest neighborhood of Logan, UT. The site was originally constructed to collect and treat stormwater from a 25-acre portion of the Green Meadows subdivision. Fifteen bays (5 feet (1.5 m) wide by 15 feet 8 inches (4.78 m) long) established with four triplicate plant species and three non-vegetated control bays, were used in this study. The triplicate planted bays were randomly assigned and each contained a single plant species that included: cattails (*Typha latifolia),* small wing sedge (*Carex microptera),* Baltic rush (*Juncus balticus),* and sunflower *(Helianthis maximillina)* Exact specifications for each BR system's area are included in Chapter 3.

A total of 14 natural storm events were sampled at the 300 East site from September 2017 to November 2018, while results from four simulated rainfall events at three loading rates administered at the Green Meadows site from June to September 2018 were included in this study. For the simulated storms, concentrations of trace elements, phosphorus, and nitrogen species for a low loading event were calculated using EMC data collected from runoff from various locations throughout Logan, UT. Medium and high loadings at this site were scaled by a factor of 1.86 and 3.25, respectively, from the low loading rate based on historical rainfall characteristics in the study area.

2.2 Storm sizes and pollutant loading.

At the 300 East site, precipitation data were recorded using an ONSET, HOBOware® rain gauge smart sensor (S-RGA-M002) with a U30 data logging station. Any rain event data that were missing due to rain gauge malfunctions were supplied by the Utah Climate Center (USU, UCC, 2019). The weather station used was from the Logan Cache Airport station (station ID USW00094128) located within 3.7 miles (6 km) of the site.

At the Green Meadows site, synthetic storms were administered at three pollutant loads, with individual storm volume simulating the 3 month, 45-minute storm, 0.202 inches (0.513 cm) of rain in Logan, UT. This design storm resulted in a total volume per individual storm of 97.25 gallons (370 L) per plot. The first flush, assumed to be the first 10 percent of a storm (9.7 gallons, 37 L), contained the entire concentrated pollutant load, and was administered uniformly to each treatment plot using a hose end sprayer with a flow rate of 0.63 gal/min (2.4 L/min). Pollutant mixtures were made in Logan City tap water. The remaining volume of the storm was administered using sprinkler hoses attached to a frame temporarily placed on top of each plot.

Three loading rates were administered at the Green Meadows site at different storm frequencies during the study to represent varying pollutant loadings created by different antecedent dry day storms. Final synthetic storm concentrations (Table 1) were calculated based on EMC data plus background nutrient and trace element concentrations contributed by Logan City tap water. Individual storm and total pollutant loads applied to each bay over the duration of the study are shown in Table 1 for each loading rate. The medium and high loading rate concentrations for each simulated storm were scaled from the low loading rate storm, assuming that the increase in loading would be due to an increase in days between events. Thirteen applications of the low loading rate storm every 5 days, seven of the medium loading rate storm every 11 days, and four of the high loading rate storm every 23 days, were conducted over the course of the study. Because of the frequency of storm events, as shown in Table 1, the total pollutant load administered over the study period was actually highest for the low storm loading event compared to the high storm loading event due to background concentrations of most of the pollutants in the synthetic storm water (Logan City tap water) applied at the site. Samples were collected and analyzed from replicate field plots when all storm frequencies coincided, resulting in four total sampling events over the course of the study.

Table 1: Pollutant loading for low, medium, and high loading rate simulated storms at the Green Meadows field site. Organic-N was added as urea.

	Event Mean Concentration		Total pollutant load for each bay per storm (mg)			Total pollutant load for entire experiment (mg)
Analyte	Average	n	low	medium	high	
TDN	4.00 mg/L	165	1,487	2,116	3,152	19,332; 14,812; 12,608
NO_3-N	1.60 mg/L	112	594	870	1,326	7,717; 6,093; 5,305

	Event Mean Concentration		Total pollutant load for each bay per storm (mg)			Total pollutant load for entire experiment (mg)
Analyte	Average	n	low	medium	high	
NH_3-N	0.62 mg/L	114	231	422	738	2,997; 2,957; 2,953
Organic-N	0.51 mg/L	24	189	349	613	2,453
TDP	0.28 mg/L	304	105	171	280	1,363; 1,196; 1,119
Cu	10.2 µg/L	167	3.8	6.0	9.7	49.1; 42.0; 38.7
Zn	67.6 µg/L	169	25.0	36.5	55.5	325; 256; 222

2.3 Pore water sampling and analysis procedures

To collect runoff from storm events entering each bay at the 300 East site, funnels were fashioned from sheet metal and collapsible plumbers tubing to direct water into 16-quart (16.75 inches x 11.88 inches x 7 inches, [42.5 cm x 30.2 cm x 17.8 cm]) polystyrene (Sterilite™) sample boxes from the curb cuts. A 2-inch baffle was inserted in the sample boxes to create a collection area with a v-notch to allow flow to continue during storm event. Composite runoff grab samples were collected from the sample boxes after each rain event was complete. For pore water sampling, two Micro Rhizon pore water samplers (Soilmoisture Equipment Corp., Santa Barbara, CA. Soil Moisture Miniature Samplers – 1908D4.5L09) were installed at depths of 12 (30.5cm) and 20 (50.8 cm) inches in each bay, including the control bay. Samplers were installed per manufacturer instructions within 6 to 12 inches (15.2 cm – 30.5 cm) from the end of the concrete apron of each curb cut. Each lysimeter was connected to a length of plastic tubing with a Luer-Lock™ connector. The lysimeters were made of a porous polymer, internally strengthened by a wire or plastic fiber. The porous portion of the lysimeter was

3.5 inches (8.9 cm) long with an outer diameter of 0.98 (2.5 cm) inches and an inner diameter of 0.06 inches (0.15 cm). A vacuum of at least 70kPa was applied to each of the lysimeters using a hand vacuum pump after all ponded water had infiltrated following each storm event. Samples from the Comparison Bay at the 300 East site were limited due to lack of runoff infiltration.

At the Green Meadows site, each bay was instrumented with six Micro Rhizon pore water samplers using installation procedures per manufacturer instructions. Three pore water samplers were installed within each bay to a depth of approximately 3-6 inches (7.62 cm -15.24 cm) and three installed to a depth of 6-9 inches (15.24 cm - 22.86 cm). Each pair of lysimeters were co-located in a randomly assigned 1 ft^2 (930 cm^2) section of a bay, creating three pairs in each treatment bay. A vacuum of at least 70kPa was applied to each of the lysimeters using a hand vacuum pump after all ponded water had infiltrated following each simulated storm event. A 500 mL amber glass jar with #10 stopper was connected to each lysimeter to collect soil pore water captured by each lysimeter. All samples were taken to the Environmental Quality Laboratory at the UWRL for analysis.

2.4 Sample analysis, Pore water samples

Samples were analyzed for total nitrogen (TN), total dissolved nitrogen (TDN), total phosphorus (TP) total dissolved phosphorus (TDP), ammonia-N (NH_3-N), nitrate-N (NO_3-N), and total and dissolved metals. Undigested, filtered pore water samples were analyzed on an AQ2 Discrete Analyzer (Seal Analytical) using Standard Method EPA 353.2 Rev 2.0 (1993) for NO_3-N+NO_2-N. Undigested, filtered samples were also analyzed on an inductively coupled mass spectrometer (ICP-MS) (Agilent 7700x) for dissolved metals (EPA Method 6020). For total metal concentrations, water samples were digested using a hot block, nitric acid digestion for total As, Cu, and Zn, using the APHA Method 330E (APHA 1999). Undigested, filtered samples were analyzed for NH_3-N using the indophenol, low level method (Solorzano 1969). A 10 mL aliquot of the sample was digested using the persulfate oxidation method, modified from Valderrama (1981), for analysis of TN, TDN, TP, and TDP. Samples were then analyzed on an AQ2 using Standard Method EPA 353.2 Rev 2.0 (1993) for TN and TDN and the EPA Standard Method 365.1, Rev 2.0 (1993) for TP and TDP. Total metals and nutrients are reported for 300 E and dissolved metals and nutrients for Green Meadows.

2.5 Data analysis

Potential impact to groundwater was determined by analyzing the concentration of pollutants found in pore water compared to the pollutant loadings applied during natural or synthetic storm events. Percent removal efficiency was calculated using the runoff concentrations at each location and concentrations found in the BR system pore water. Comparisons were made among the three loading regimes at Green Meadows. Linear regression analyses were completed to determine relationships between pollutant loading normalized to the BR system treatment area and the pollutant pore water concentrations measured in these BR systems.

3. Results

3.1 Precipitation data

Samples were collected from the 300 East location with an average precipitation depth of 0.34 inches (0.864 cm). The storm events ranged in depth from 0.1 inches (0.254 cm) to 1.6 inches (0.4.09 cm) from September 2017 to November 2018. Four total synthetic storm events were sampled at the Green Meadows site with total storm characteristics (Table 1) for the low, medium and high loading rate storms.

3.2 Runoff concentrations and pollutant loading rates

Table 2 shows a summary of average pollutant concentrations in the synthetic runoff at the Low, High, and Medium Loading Rate applied at the Green Meadows site, along with the minimum, maximum, and EMC pollutant concentrations measured in the natural storm runoff observed at the 300 East site during this study. Table 2 also shows the corresponding pollutant loadings to the BR systems in units of g/hectare of treatment surface area reflecting pollutant runoff concentrations and loadings reflective of Northern Utah conditions.

Table 2: Summary of nutrient and trace element concentrations and corresponding loading rates measured in stormwater runoff and applied during simulated storms throughout the study period at the Green Meadows and 300 East study sites.

			TDN	TDP	NO_3-N	NH_3-N	Cu	Zn
GM	Concentration mg/L	Low	4.0	0.28	1.6	0.62	0.010	0.068
		High	8.5	0.76	3.6	2.0	0.026	0.150
		Medium	5.7	0.46	2.4	1.1	0.016	0.098
	Load g/hectare	Low	2,040	144	814	316	5.2	34.3
		High	4,324	384	1,819	1,013	13.3	76.1
		Medium	2,903	234	1,194	579	8.2	50.1
			TN	TP	NO_3-N	NH_3-N	Total Cu	Total Zn
300 E	Concentration mg/L	Minimum	0.28	0.06	0.05	0.01	0.004	0.02
		Maximum	21.1	4.4	1.41	8.1	0.22	1.9
		EMC	3.7	0.91	0.35	0.81	0.039	0.24
	Load g/hectare	Minimum	106	16.4	29.7	0.06	0.82	4.8
		Maximum	5,655	1,059	174	1,012	95.6	748
		EMC	1,341	311	85.4	167	18.3	117

3.3 Pore water concentrations and corresponding pollutant removal efficiency

Pollutant pore water concentrations at both sites showed little variability across loadings for Planted or Unplanted Control Bays at Green Meadows or Treatment Bays at 300 East, and Table 3 summarizes the average pollutant pore water concentrations for these treatments. While Table 2 emphasizes the range of loading observed in the study, Table 3 shows the averages across loadings due to the lack of statistical difference between loadings for both field sites.

Table 3: Average pore water concentrations measured at the Green Meadows and 300 East field sites. Letters indicate significant differences in pore water concentrations for each site based on results from Dunnett's Test at the 95% confidence interval. NA = Not analyzed

			TDN mg/L	TDP mg/L	NO_3-N mg/L	NH_3-N mg/L	Cu µg/L	Zn µg/L
GM	Planted	Ave	12.4^{b}	0.65^{a}	5.1^{b}	0.13^{b}	10.3^{b}	67.3^{b}
		95% CI	±1.9	±0.10	±1.51	±0.03	±1.3	±7.5
		n	257	257	275	275	276	276
	Unplanted	Ave	17.2^{a}	0.82^{a}	10.2^{a}	0.32^{a}	12.8^{a}	111^{a}
		95% CI	±4.9	±0.24	±6.9	±0.08	±2.7	±28.8
		n	52	52	63	64	70	70
300E	Treatment Bay		TN	TP	NO_3-N	NH_3-N	Total Cu	Total Zn
		Ave	1.08^{B}	0.356^{B}	0.23^{B}	0.13^{A}	11.2^{A}	111^{A}
		95% CI	±0.14	±0.20	±0.08	±0.06	±5.3	±46.4
		n	52	52	25	33	48	48
	Comparison Bay	Ave	2.5^{A}	1.7^{A}	0.69^{A}	0.04^{A}	18.6^{A}	39.6^{A}
		95% CI	±1.34	±0.71	NA	-	±14.2	±34.0
		n	5	5	1	2	4	4

Pollutant removal efficiency was calculated based on runoff concentrations and pore water concentrations for each storm then averaged to determine the percent removal for the entire study period for the 300 East site (data shown in Appendix I). At the 300 East site, the background concentrations of trace elements and nutrients could be accounted for by subtracting the average pore water concentration found in the Comparison Bay from the concentrations in the pore water in the Treatment Bays for each individual storm. Samples from the Comparison Bay were only available during large storm events due to the lack of runoff entering the bay, limiting the availability of the pore water. The resultant concentrations were then used to calculate removal percentages which ranged from 100% for TN, TP, and NO_3+NO_2, 90% for NH_3-N and Cu, and 66% for Zn. If the comparison bay concentrations are not accounted for the removal percentages decrease to 74% for Cu and 66% for NH_3-N and less than 50% for TN, NO_3+NO_2, and Zn. Since the pollutant removal efficiencies for the BR systems at Green Meadows (Appendix I) could not be corrected for background pore water concentrations as a background plot that did not receive simulated runoff was not available at this field site, pollutant removal efficiencies were not reported.

3.4 Loading rate and pore water concentration relationships

Regression analysis for nutrients and trace metals measured at the two field sites revealed no relationships for most pollutants between pore water concentrations averaged across pore water sampler depth and BR system aerial runoff loadings. Data at the Green Meadows site included Planted and Unplanted Control Bays from the low, medium and high loading events. Data from the 300 East site were averaged across the Treatment Bays for all natural rainfall events. Figure 1 shows some of these regression plots with all regression plots provided in Appendix J. Table 4 provides a summary of all regression results. At the Green Meadows site there was no relationship between the aerial runoff loading and the resulting Cu and Zn pore water concentrations (Figure 1a and b), but NH_3-N loading was positively correlated with the pore water concentrations at this site (Figure 1c). At the 300 East site; however, only Cu concentrations found in the pore water were positively correlated with the Cu loading rates applied to this BR system (Figure 1d). For all other trace elements and nutrients at both sites pore water concentrations were independent of loading (Table 4).

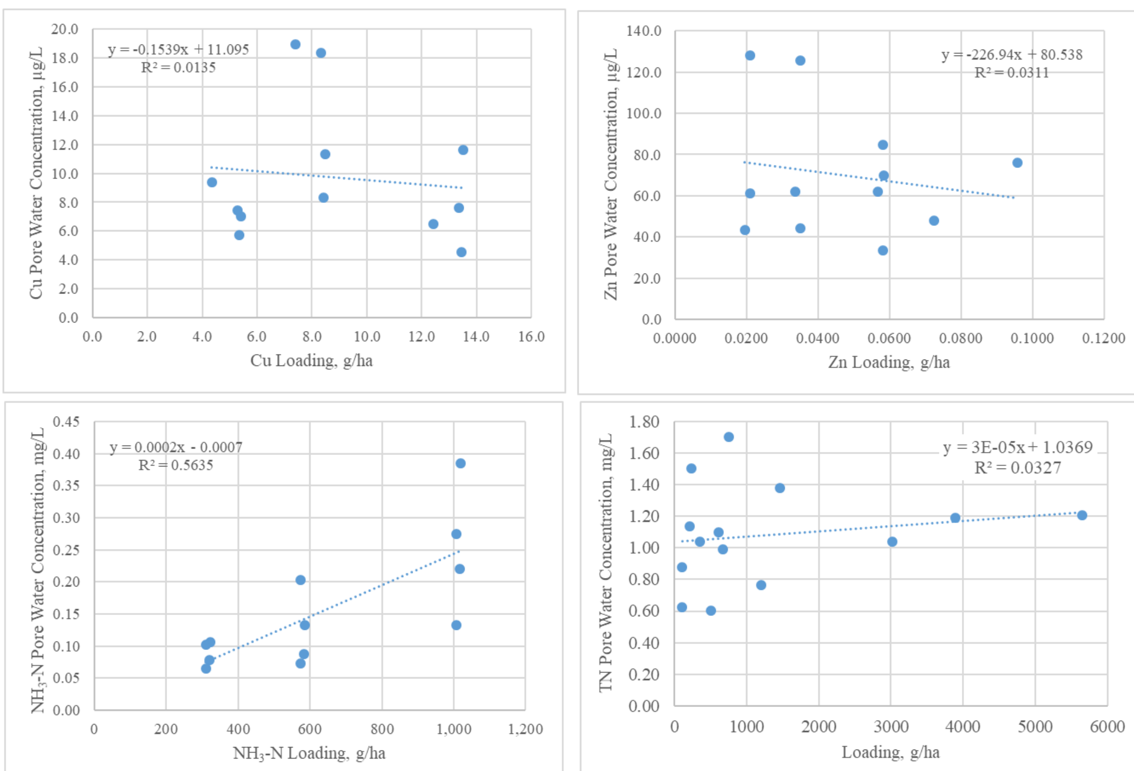

Figure 1: Regression analysis of loading (g/ha) versus pore water concentrations. a. Cu, b. Zn, and c. NH_3-N at the Green Meadows site; and d. TN at the 300 East site.

Table 4: Regression equation data for pollutant loading (g/ha) versus pore water concentration relationships for Green Meadows planted bays and 300 East treatment bays. Peak loading and average pore water concentrations are also included. Regulatory

standards shown are for drinking water except for TDP which is a regulated wastewater discharge standard in the State of Utah.

		TDN, mg/L	TDP, mg/L	NO_3-N, mg/L	NH_3-N, mg/L	Cu, µg/L	Zn, µg/L
Regulatory Standard		10†	1.0††	10	10†	1,300	5,000
GM Planted bays	R^2	0.005	0.085	0.1588	0.5635	0.0135	0.0311
	n	12	12	12	12	12	12
	Significant	N	N	N	Y	N	N
	Slope				0.0002		
	Intercept				-0.0007		
	Mean PW conc.	12.1	0.65	5.1	0.13	10.3	67.3
	Maximum Load g/ha	7,085	474	2,045	50,035*	13.5	107
		TN	TP	NO_3-N, mg/L	NH_3-N, mg/L	Cu, µg/L	Zn, µg/L
300 E Treatment bays	R^2	0.0327	0.1797	0.0856	0.0097	0.8171	0.0771
	n	14	14	9	12	15	15
	Significant	N	N	N	N	Y	N
	Slope					1.53	
	Intercept					1.32	
	Mean PW conc.	1.08	0.36	0.23	0.13	11.2	111
	Maximum Load g/ha	5,655	1,059	174	1,012	849*	748

† Drinking water standard related to NO_3-N assuming all N species converted to NO_3-N through nitrification in soil vadose zone.
†† Maximum wastewater discharge standard in the State of Utah.
*Maximum loading rates are based on regression equation and regulatory standard for that pollutant and are understood to be the maximum pollutant load that can be treated within a given system.

Along with R^2, n, and a significance determination of the regressions at the 95% confidence level, Table 4 provides slope and intercept values for the significant regression relationships. For pollutants with non-significant relationships the mean pore water concentrations and peak loading rates observed at the sites are listed along with relevant drinking water or wastewater standards when available. The mean pore water concentrations observed for most pollutants were significantly below any concentrations of concern except for TDN at the Green Meadows site, where pore water concentrations were 12.1 mg/L (corresponding to a 7,085 g/ha TDN loading) compared to a related NO_3-N drinking water level of 10.0 mg/L.

For those pollutants showing a significant relationship between loading and pore water concentrations, NH_3-N at Green Meadows and Cu at the 300 East site, the regression equations were used to extrapolate loading rates to the pore water concentrations associated with regulatory standards for that pollutant. Using the significant regression relationship for NH_3-N at the Green Meadows site, a calculated loading of greater than 50,000 g/ha would be necessary to produce a 10 mg/L NH_3-N pore water concentration there. For Cu at the 300 East site, the 1,300 µg/L drinking water standard within the pore water would be reached at a Cu loading of 849 g/ha. The maximum loading values in Table 4 provide design guidelines regarding maximum loadings to protect groundwater resources from pollutant contamination from stormwater runoff in Northern Utah settings.

4. Discussion

At the Green Meadows site, the concentrations of most pollutants found in the soil pore water were relatively constant over all loading rates as shown for Cu and Zn in Figure 1 and appear to be related to the soil and compost amendment used at this site rather than pollutants in the simulated stormwater runoff. ANOVA results also indicated that the planted systems were able to capture and remove most pollutants from the BR system pore more effectively, i.e., producing lower pore water concentrations (Table 3), than the unplanted control plots.

For the 300 East location all trace metals and nutrients showed a positive removal over the study period for all pollutant loads. As was seen even more clearly than at the Green Meadows, at the 300 East site pore water concentrations were controlled by the background concentrations in the site soil rather than by the concentrations that were input due to stormwater runoff. This observation is consistent with study reported by Shrestha et al. (2018) from the eight BR systems receiving roadside runoff in Vermont in which they concluded that the effects of vegetation and enhanced rainfall treatments on pollutant removal were minimal compared to the soil media effects.

Pollutant pore water concentrations in the Comparison Bay at the 300 East site generated from rainwater infiltration were statistically equal to or higher than pore water in the Treatment Bays receiving roadway stormwater runoff because stormwater diluted nutrient concentrations (Table 3). This BR system with turf grass was able to sequester and remove trace elements and nutrients from runoff up to the loading rates reported in Table 5. The use of a comparison bay that does not receive runoff was highly beneficial in demonstrating the effectiveness of this BR system so that background levels of trace metals and nutrients can be monitored and accounted for in system performance evaluation.

At both locations, removal for most nutrients and trace metals was independent of loading. At the Green Meadows site only NH_3-N pore water concentrations were dependent on loading. Similar results were found for the 300 East site where regression analysis of all trace elements and nutrients, other than Cu, showed that pore water concentrations were not dependent on what was loaded to the system up to the maximum loading rates observed in this study. The relationship between loading and pore water concentrations can be used to improve sizing of BR systems by determining a maximum load that the system can receive and sizing accordingly. The two field sites give a range of loading rates to consider in designing of BR systems with two difference sizing regimes. The results suggest that the highest loading rate observed in this study can be used without deterioration of treatment efficiency within the BR system as the design loading rate for sizing BR systems in this region.

Lucas and Greenway (2008) studied variable loadings of TDN and TDP in laboratory mesocosm studies. TDP ranged from 0.78 mg/L to 4.8 mg/L while TDN ranged from 4.8 mg/L to 5 mg/L in the simulated runoff they applied to their laboratory systems. The vegetated mesocosms in their study removed up to 92% TDP for both concentrations and TDN removal was 81%. Sun and Davis (2007) saw 88-97% removal in BR systems with three different plant species at two concentrations of Cu (71±5 μg/L and 170 ±19 μg/L), Zn (0.66 ±0.11 mg/L and 1.44 ±0.12 mg/L) and Pb (67±6.1 μg/L and 160±18 μg/L) with no significant loading effect on overall pollutant removal efficiency. The concentrations of trace metals and nutrients applied in these previous studies were within the range of concentrations observed in the runoff and applied in the synthetic storms in the current study (Table 2). Similar or better pollutant removal efficiency was observed in this field study at the 300 East site in comparison to the microcosm studies reported in the literature, when background pore water concentrations were accounted for, and no effect on pore water concentrations was observed for most pollutants over the range of pollutant loadings observed in this study.

The current literature focuses on concentrations of pollutants flowing into a BR system but because of the assimilative capacity of the treatment area in this study, loading rates in the form of mass/unit treatment area/time was determined to be a better way to explore performance and design of BR systems. This concept results in the sizing of treatment areas based on the “land limiting constituent,” that is the pollutant that requires the largest treatment area to provide required treatment efficiency.

5. Conclusions

Based on the findings from this study, the following conclusions can be made related to the effect of stormwater pollutant loading on vegetated BR system performance.

1. Planted BR systems at the two field sites analyzed in this study were able to effectively assimilate pollutants from natural or simulated storm events representative of multiple pollutant loadings in the Northern Utah region up to the peak loadings observed in this study without increasing pore water concentrations below the sites.
2. Pore water concentrations were found to reflect the nutrient and trace metal concentrations solubilized from the media and not what was added to them from the stormwater runoff. This is evident from the Comparison Bay at 300 East, and pollutant removal efficiency results that increased with increased loading that were observed at the Green Meadows site.
3. Pollutant runoff concentrations observed in this study can be used to improve model parameters in predictive models such as WinSLAMM by improving regional specific input parameters. The data collected during this study adds

information to the knowledge base for runoff concentrations in the Intermountain West.

Vegetated BR system performance appears to be robust, providing protection against surface or groundwater contamination under highly variable pollutant loading conditions that are normal for stormwater runoff in the region. Using runoff characteristics and peak loading rates reported in this study, rational sizing of BR systems can be carried out, with final design based on the largest BR system area required (the limiting constituent) for the range of pollutants being managed at a site.

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Bioretention (BR) systems have been identified by the EPA as a best management practice for pollutant removal for stormwater runoff. This dissertation's research design looked at three different BR systems to assess their effectiveness. The study analyzed the effectiveness of various plant types and three types of filter media for pollutant removal under variable pollutant loads and stormwater regimes both natural and synthetic.

This study consisted of three field sites. The Green Meadows site contained four typical BR species: *Typha latifolia* (Broadleaf cattail); *Juncus balticus* (Baltic Rush); *Carex microptera* (Smallwing sedge); *Helianthus maximiliana* (Sunflower). The 300 East site contained a common cabin grass mixture containing a species mix of soder streambank wheatgrass, roadcrest crested wheatgrass, and sheep fescue, and native soil, while the Public Utilities site contain no effective vegetation but two types of filter media: Utelite™ expanded shale and pea gravel.

Media selection in BR systems is important to limit leaching of pollutants from media selected to remove those same pollutants from the infiltrating stormwater. Native soils and engineered filter media within a BR system can be a source of pollutants and should be evaluated using some form of water extraction before being used in a stormwater treatment system. Background soil pore water concentrations should be determined in an adjacent area to a BR system to develop a baseline to evaluate true pollutant removal performance. The water extraction procedure used in this study clearly indicated that significant levels of As can be mobilized from the Utelite™ shale used at the Public Utilities site, and despite its high porosity and permeability, is not ideal when used without additional treatment amendments (compost, mulch, absorptive media). Media choice can have a significant impact on apparent BR system performance. Careful evaluation of media and their naturally occurring background concentrations of nutrients and trace metals is necessary to ensure optimal stormwater treatment system design, valid BR system performance evaluation, and sustained groundwater quality protection. Evaluation of unintended consequences of placing BR system in areas with geogenic source of As or other mobile metals is important. It is necessary to evaluate the leaching potential of BR media and native soils that can be affected by stormwater and vegetation used in BR systems for stormwater treatment to ensure long-term groundwater protection.

Pollutant removal varied with plant species and no one plant type was effective in removal of all pollutants monitored at the Green Meadows site, indicating that a variety of plant type would be most effective for pollutant removal. TDN, NO_3-N, NH_3-N, TDP, Cu, and Zn pore water concentrations were significantly higher in unplanted control bays compared to planted bays at the highest pollutant loading. Removal for a range of pollutants occurred at the 300 East site indicating that turf grass would be an effective implementation in BR systems that would be acceptable to stormwater managers.

Vegetated BR system performance appears to be robust, providing protection against surface or groundwater contamination under highly variable pollutant loading conditions that are normal for stormwater runoff in the region. Vegetated BR systems at the two field sites analyzed in this study were able to effectively assimilate pollutants from natural or simulated storm events up to the peak loadings observed in this study without increasing pore water concentrations below the sites. Pore water concentrations were found to reflect the nutrient and trace element concentrations solubilized from the media and not what was added to them from the stormwater runoff. This is evident from the Control Bay at 300 East, and pollutant removal efficiency results that increased with increased loading that were observed at the Green Meadows site.

Media and plant selection and knowledge of loading rates are important for design of BR systems. Use of regional-specific characteristics of each of these variables should improve BR system design and can be expected to improve the effectiveness of BR systems compared to design based on generic sizing criteria. As seen in this study, media selected in areas known to contain geogenic As, nutrients, and trace metals can negatively impact pollutant removal and leach pollutants from the media. Control plots near BR systems that do not receive runoff would be beneficial in the analysis of BR system pollutant removal effectiveness. Vegetation in a BR system can help to mitigate solubilization of pollutants via uptake into the plants and subsequent harvesting and plant biomass removal from the site. Finally, knowing pollutant loading from various runoff sources in a region, and the maximum loadings BR systems can assimilate without compromising underlying pore water and groundwater quality can improve sizing to optimize pollutant removal and long-term groundwater protection.

CHAPTER 7

ENGINEERING SIGNIFICANCE

This study evaluated the efficiency of three types of BR systems in Northern Utah. One aspect of the study compared filter media, while a second explored the effect of vegetation and plant type on the removal of nutrients and trace elements from stormwater. A third aspect examined the impact of pollutant loading rates on pollutant removal in these BR systems. A major motivation for the study was to generate regional-specific information about BR system performance to add performance data from this region to the literature, and to document for local stormwater manager's the functionality of these systems and design consideration relevant for stormwater management in Utah.

Two of the three systems studied (vegetated BR systems) demonstrated effective pollutant removal from stormwater runoff, while the BR system containing filter media exhibited significant leaching, especially from Utelite™ expanded shale. Plants were determined to have a positive impact on pollutant removal in the Northern Utah region as has been reported elsewhere throughout the United States. Installation of vegetation within BR systems is beneficial for nutrient and trace metal removal and protection of groundwater. Individual plant species provide variable removal results for specific pollutants, and a variety of plant types within a BR system would result in more comprehensive pollutant removal. The study also demonstrated that a diverse cabin grass mixture, more acceptable for implementation by municipal stormwater managers than commonly used BR system native vegetation, is effective in stormwater pollutant removal and can be used as a model planting scheme for expansion of BR stormwater systems throughout the state.

Pore water concentrations of nutrient and trace elements were generally independent of pollutant loadings observed in this study. Pollutant concentrations measured in pore water were more likely due to the background concentrations found within the filter media than from the stormwater runoff moving into the BR systems. Analysis of engineered filter media and native soils should be routinely conducted before installation in BR systems to alleviate any concerns of pollutant leaching into groundwater.

Finally, maximum loading rates observed in this study can be used along with consideration of regulatory standards appropriate for the pollutants evaluated in this study for optimum BR system sizing to ensure protection of groundwater resources from pollutant contamination in stormwater runoff in Northern Utah settings.

APPENDICES

APPENDIX A

Sequential Extraction results for filter media at Salt Lake City Public Utilities Bioretention System using the Huang and Kratzschmar (2010) method

		27 Al [He]	56 Fe [He]	63 Cu [He]	66 Zn [He]	75 As [He]	3 Pb [No Ga
		µg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg
top soil side 1	rep 1 extraction 1	1989.83	1119.52	25.50	139.26	83.92	6.76
top soil side 1	rep 2 extraction 1	1032.82	609.63	25.50	17.80	91.45	2.57
top soil side 1	rep 3 extraction 1	910.41	530.81	20.33	10.92	87.11	3.54
top soil side 2	rep 1 extraction 1	454.99	201.96	31.08	121.39	127.64	1.25
top soil side 2	rep 2 extraction 1	1684.58	1382.84	31.88	141.78	120.04	6.49
top soil side 2	rep 3 extraction 1	1255.65	829.91	35.52	41.08	148.89	3.65
	average	1221.38	779.11	28.30	78.71	109.84	4.04
washed pea gravel	rep 1 extraction 1	132.27	53.74	0.61	60.98	1.04	0.24
washed pea gravel	rep 2 extraction 1	244.73	15.40	2.85	14.55	2.17	0.80
washed pea gravel	rep 3 extraction 1	112.13	84.38	1.26	700.93	0.27	1.06
	average	163.04	51.17	1.57	258.82	1.16	0.70
unwashed gravel	rep 1 extraction 1	393.96	36.00	5.75	86.57	3.84	0.40
unwashed gravel	rep 2 extraction 1	315.25	50.90	1.09	2.60	4.09	0.11
unwashed gravel	rep 3 extraction 1	417.12	43.00	0.07	28.59	3.68	1.34
	average	375.44	43.30	2.30	39.26	3.87	0.62
utelite	rep 1 extraction 1	4246.32	196.55	0.06	42.54	118.16	0.59
utelite	rep 2 extraction 1	2982.11	3783.02	35.03	348.54	93.44	0.24
utelite	rep 3 extraction 1	3079.65	93.50	1.11	1121.38	77.33	5.28
	average	3436.03	1357.69	12.07	504.15	96.31	2.03
top soil side 1	rep 1 extraction 2	337.69	675.27	154.37	291.17	156.93	45.74
top soil side 1	rep 2 extraction 2	66.24	731.99	207.91	644.77	206.21	93.79
top soil side 1	rep 3 extraction 2	65.18	308.18	196.46	660.92	219.59	71.81
top soil side 2	rep 1 extraction 2	195.79	419.11	188.65	650.32	249.49	74.87
top soil side 2	rep 2 extraction 2	18.49	299.13	187.66	1159.51	244.19	81.45
top soil side 2	rep 3 extraction 2	160.06	289.30	198.09	450.68	282.76	105.69
	average	140.58	453.83	188.86	642.89	226.53	78.89
washed pea gravel	rep 1 extraction 2	100.74	432.67	150.76	5878.99	16.10	23.47
washed pea gravel	rep 2 extraction 2	175.22	380.30	153.52	725.64	20.70	13.72
washed pea gravel	rep 3 extraction 2	41.04	390.45	139.24	565.24	14.91	15.35
	average	105.67	401.14	147.84	2389.96	17.24	17.51
unwashed gravel	rep 1 extraction 2	54.54	354.53	131.71	988.63	31.01	13.23
unwashed gravel	rep 2 extraction 2	8.50	341.67	135.68	373.93	31.59	12.36
unwashed gravel	rep 3 extraction 2	10.53	1311.14	138.58	1422.24	29.32	13.83
	average	24.52	669.12	135.32	928.26	30.64	13.14
utelite	rep 1 extraction 2	118.76	1949.59	133.02	541.28	362.73	11.24
utelite	rep 2 extraction 2	75.53	390.19	196.24	571.93	381.97	14.37
utelite	rep 3 extraction 2	146.00	626.41	153.94	2057.14	263.72	10.65
	average	113.43	988.73	161.07	1056.79	336.14	12.09
top soil side 1	rep 1 extraction 3	1.70	1.70	238.79	736.32	423.76	593.40
top soil side 1	rep 2 extraction 3	3.92	3.60	299.97	1521.66	524.60	748.59
top soil side 1	rep 3 extraction 3	0.37	142.52	224.67	1050.46	541.15	651.26
top soil side 2	rep 1 extraction 3	2.68	5.90	192.42	2625.69	591.68	551.46
top soil side 2	rep 2 extraction 3	5.43	8.60	134.40	950.68	556.12	586.26
top soil side 2	rep 3 extraction 3	0.93	11.80	147.43	1029.79	654.75	718.02
	average	2.51	29.02	206.28	1319.10	548.68	641.50
washed pea gravel	rep 1 extraction 3	12.11	29.80	44.27	480.82	25.52	26.30
washed pea gravel	rep 2 extraction 3	7.27	24.40	44.56	662.02	46.81	16.94
washed pea gravel	rep 3 extraction 3	9.48	19.60	35.04	458.08	26.19	19.27
	average	9.62	24.60	41.29	533.64	32.84	20.84
unwashed gravel	rep 1 extraction 3	5813.17	10090.07	52.20	1127.81	122.78	224.99
unwashed gravel	rep 2 extraction 3	10840.53	42007.85	50.58	1715.86	123.92	274.27
unwashed gravel	rep 3 extraction 3	7212.05	6719.76	54.76	931.41	87.07	199.88
	average	7955.25	19605.89	52.51	1258.36	111.25	233.05
utelite	rep 1 extraction 3	327.33	59.80	142.59	3635.27	325.92	17.64
utelite	rep 2 extraction 3	21835.58	3208.21	189.42	1306.48	342.56	60.31
utelite	rep 3 extraction 3	197787.59	130886.91	200.06	2107.11	406.98	125.99
	average	73316.83	44718.31	177.35	2349.62	358.49	67.98

APPENDIX B

Storm event data from Salt Lake City Public Utilities

Start Time	End Time	Event Length (hours)	Total Precip (inches)	ADD	Intensity, in/hr	Return Period
10/16/2016 9:48	10/17/2016 7:56	22.1	0.3	10.0	0.01448	5 days
3/22/2017 22:59	3/23/2017 16:27	17.5	1.82	16.0	0.104	5yr storm
3/25/2017 8:54	3/25/2017 19:10	10.25	0.64	2.0	0.062	2 yr storm
3/27/2017 9:40	3/27/2017 17:14	7.5	0.83	2.0	0.111	1 yr storm
3/30/2017 9:14	3/31/2017 2:29	17.75	0.11	3.0	0.006	7 days
4/2/2017 11:54	4/2/2017 13:56	2	0.08	2.0	0.040	13 days
4/8/2017 4:39	4/8/2017 22:40	18	0.74	6.0	0.041	2 years
4/9/2017 9:01	4/9/2017 10:09	1	0.27		0.270	1.5 yr storm
4/18/2017 17:16	4/19/2017 3:28	10.25	0.7	9.0	0.068	2 yr storm
4/20/2017 11:11	4/21/2017 6:10	19	0.37	1.0	0.019	6 month
4/28/2017 12:28	4/28/2017 16:42	4.25	0.11	1.0	0.026	13 days
5/17/2017 0:52	5/17/2017 5:22	4.5	0.39	18.0	0.087	1.5 yr storm

APPENDIX C

Storm event data from 300 East. Columns with blue are data from Utah Climate Center

Start Time	End Time	Event Length (hours)	Total precip (inches)	Intensity	ADD (days)	Return Period
	9/14/2017		0.098			
	9/15/2017		0.13			
	9/18/2017		0.16			
	9/19/2017		0.42			
	9/21/2017		0.15			
	9/22/2017		0.01			
10/20/2017 13:49	10/20/2017 21:24	7.58	0.1	0.013	6.410	5 day
11/2/2017 23:59	11/3/2017 4:34	4.58	0.2	0.044	13.108	1 day
	11/4/2017 0:00		0.51			
	11/5/2017 0:00		0.07			
4/12/2018 5:09	4/12/2018 16:39	11.50	0.82	0.071	3.563	8 month
4/29/2018 23:24	4/30/2018 16:49	17.42	0.49	0.028	6.802	4 month
5/11/2018 1:19	5/11/2018 13:14	11.92	0.62	0.052	0.684	8 month
5/12/2018 0:29	5/12/2018 11:44	11.25	0.47	0.042	0.469	6 month
5/12/2018 20:39	5/12/2018 21:24	0.75	0.04	0.053	0.372	5 day
10/2/2018 19:59	10/2/2018 20:59	1.00	0.37	0.370	36.52431	1 year
10/3/2018 21:19	10/5/2018 3:04	29.75	1.24	0.042	1.013889	1 year
10/9/2018 19:39	10/10/2018 4:14	8.58	0.48	0.056	4.690972	6 month
11/4/2018 10:24	11/4/2018 12:04	1.67	0.08	0.048	2.020833	12.5 days

APPENDIX D

Sequential extraction data for 300 East soil using the Amacher (1996) method, most labile portion in soil

	Extraction step	As (µg/L)	As (mg/kg)	% As	Cu (µg/L)	Cu (mg/kg)	% Cu	Zn (mg/L)	Zn (mg/kg)	% Zn
0"-6" (0-15.2cm)	Exchangeables	4.2	0.23	11.2	77.9	4.3	1.3	78.3	4,350	4.8
	Carbonates	10.3	0.71	34.0	34.7	2.4	0.71	484	33,560	37.1
	Mn Oxides	1.5	0.12	5.8	11.6	1.0	0.31	160	14,300	15.8
	Organics	14.7	1.0	48.9	4,810	334	98.0	552	38,160	42.2
6"-12" (0-15.2cm)	Exchangeables	5.5	0.22	12.8	69.3	2.8	5.6	79.6	3,170	6.5
	Carbonates	12.5	0.61	35.4	36.4	1.8	3.7	352	17,360	35.6
	Mn Oxides	2.1	0.12	7.0	10.0	0.63	1.3	102	6,430	13.2
	Organics	15.6	0.77	44.9	902	44.9	90.8	439	21,740	44.6
12"-18" (30.5-45.7 cm)	Exchangeables	8.0	0.30	15.4	93.4	3.5	11.7	36.5	1,360	2.6
	Carbonates	19.7	0.89	46.0	162	7.2	24.3	681	31,630	59.3
	Mn Oxides	2.2	0.10	5.3	8.8	0.22	0.73	100	5,050	9.5
	Organics	13.8	0.64	33.3	407	19.0	64.0	330	15,260	28.6

APPENDIX E

Statistics for Green Meadows pore water and groundwater concentrations for nitrogen species

Planted bays, includes all four plant types				
	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)	Stand. Deviation
TDN 3”-6”	0.53	109	15.5	± 3.1
TDN 6”-9”	0.55	95.1	9.3	± 2.2
TDN GW	0.25	5.6	1.4	± 0.3
NH_3 3”-6”	0.001	2.5	0.14	± 0.05
NH_3 6”-9”	0.002	1.5	0.12	± 0.03
NH_3 GW	0.002	1.3	0.10	± 0.04
NO_3 3”-6”	0.002	99.1	5.1	± 2.1
NO_3 6”-9”	0.001	107	5.1	± 2.2
NO_3 GW	0.006	1.3	0.56	± 0.23
Unplanted control bays				
	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)	Stand. Deviation
TDN 3”-6”	2.1	79	19	±19
TDN 6”-9”	2.4	69	13	±15
TDN GW	0.25	2.5	0.95	±0.65
NH_3 3”-6”	0.003	1.2	0.33	±0.32
NH_3 6”-9”	0.007	1.3	0.29	±0.33
NH_3 GW	0.003	0.30	0.04	±0.07
NO_3 3”-6”	0.04	87.5	10.3	±19.1
NO_3 6”-9”	0.03	192	9.8	±36.3
NO_3 GW	0.01	2.1	0.54	±0.64

APPENDIX F

Phosphorus concentration statistics for Green Meadows pore water and groundwater samples

TDP in planted bays, all loadings				
	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)	Stand. Deviation
TDP 3”-6”	0.029	11.7	0.789	±0.185
TDP 6”-9”	0.049	3.31	0.504	±0.087
TDP GW	0.005	0.111	0.045	±0.007
TDP in unplanted control bays, all loadings				
	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)	Stand. Deviation
TDP 3”-6”	0.132	4.03	0.92	±0.94
TDP 6”-9”	0.117	3.35	0.58	±0.74
TDP GW	0.01	0.108	0.06	±0.03

APPENDIX G

Summary statistics for trace elements for pore water and groundwater samples from the Green Meadows study site

Planted bays, all depths, and all loadings					
Pollutant	n	Min (μg/L)	Max (μg/L)	Average (μg/L)	St. Dev
As 3”-6”	135	8.79	2039.8	281.4	±320
As 6”-9”	141	7.9	1883	417.6	±414
As GW	71	1.79	72.98	17.89	±20.2
Cu 3”-6”	135	0.27	56.9	13.3	±12.2
Cu 6”-9”	141	0.04	61.3	7.4	±9.7
Cu GW	71	0.03	5.56	0.95	±0.95
Zn 3”-6”	135	2.8	283.7	69.2	±58.3
Zn 6”-9”	141	0.17	402	65.4	±68.8
Zn GW	71	0.09	181.7	12.6	±28.7
Unplanted control bays, all depths, and all loadings					
Pollutant	n	Min (μg/L)	Max (μg/L)	Average (μg/L)	St. Dev
As 3”-6”	36	31.3	343.3	126.6	±78.4
As 6”-9”	35	28.9	232.6	102.8	±47.2
As GW	17	3.3	102	39.9	±36.3
Cu 3”-6”	36	0.43	54.7	14.4	±11.9
Cu 6”-9”	35	1.58	58.5	10.8	±10.6
Cu GW	17	0.07	8.8	2.8	±2.3
Zn 3”-6”	36	2.1	444.7	95.5	±100
Zn 6”-9”	35	7.6	723.5	124	±142
Zn GW	17	0.74	132	18	34

APPENDIX H

ICPMS data for trace elements for water extractions for Utelite™ expanded shale and pea gravel

PG=Pea Gravel, SS= Utelite™

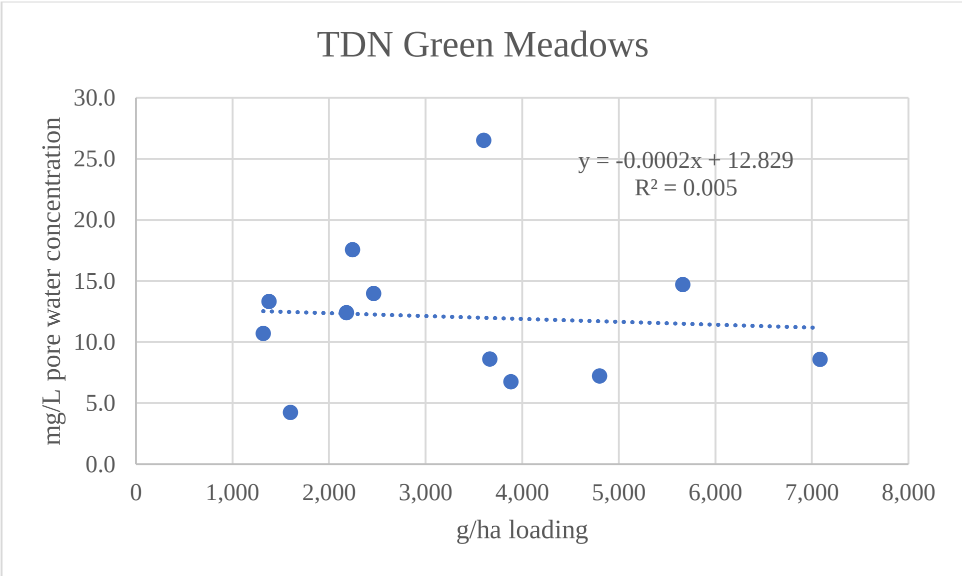
	63 Cu [He]	66 Zn [He]	75 As [He]	208 Pb [No Gas]
Top Limit	**500**	**400**	**200**	**100**
MRL	**0.63**	**2.00**	**0.25**	**0.06**
MDL	0.066	0.611	0.042	0.014
Sample Name	Conc. [ug/l]	Conc. [ug/l]	Conc. [ug/l]	Conc. [ug/l]
PG1	1.90	2.42	3.66	0.01
PG2	2.82	1.86	3.61	0.01
PG3	2.82	4.35	4.16	0.01
SS1 1:1	1.36	2.58	4.38	0.02
SS2 1:1	1.08	1.58	4.18	0.02
SS3 1:1	1.76	2.60	5.66	0.04

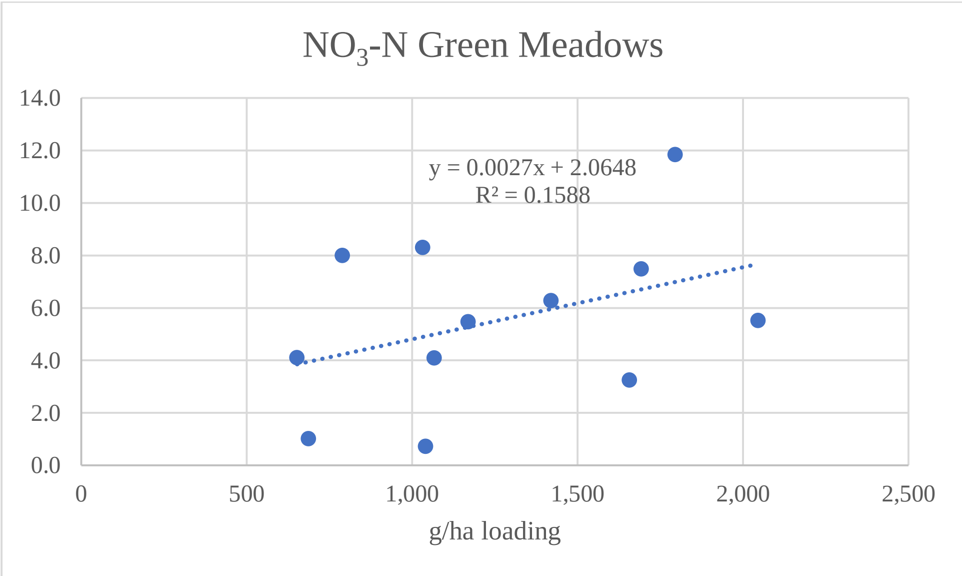
APPENDIX I

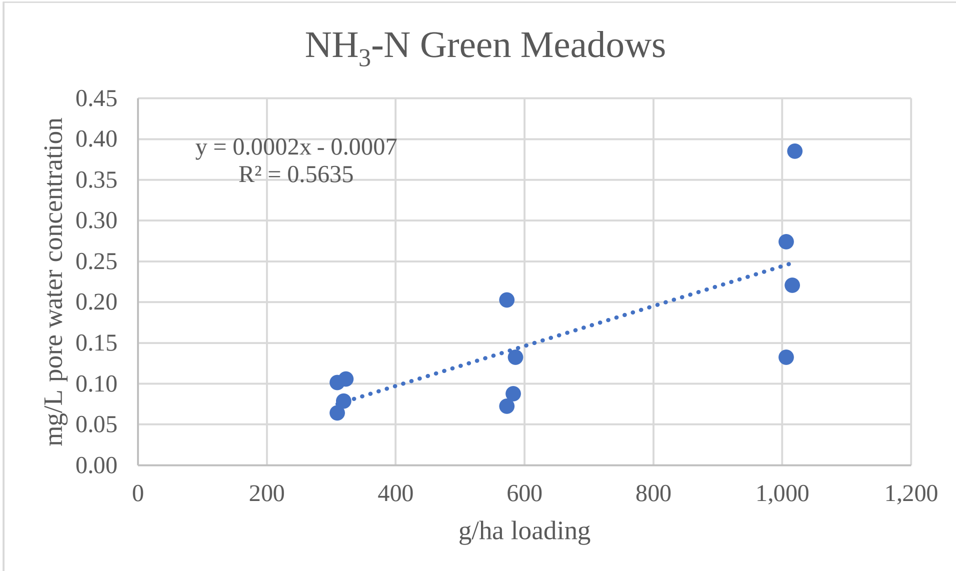
Summary of nutrient and trace element removal efficiency at the Green Meadows and 300 East field sites.

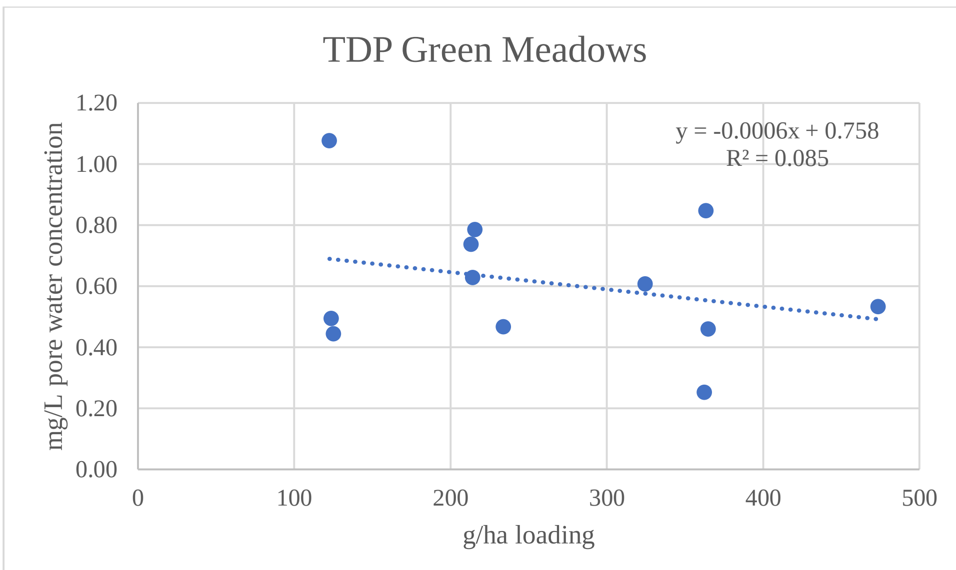
				TDN mg/L	TDP mg/L	NO_3-N mg/L	NH_3-N mg/L	Cu	Zn
GM	Low	planted	Ave Removal	-119%	-136%	-116%	90%	24%	-2%
			95% CI	95%	110%	253%	4%	18%	30%
		unplanted	Ave Removal	-190%	-150%	-110%	67%	22%	-72%
			95% CI	121%	93%	111%	16%	10%	133%
	medium	planted	Ave Removal	-196%	-73%	-192%	90%	2%	31%
			95% CI	46%	32%	109%	5%	39%	37%
		unplanted	Ave Removal	-106%	-24%	-80%	78%	22%	-11%
			95% CI	131%	19%	209%	21%	29%	82%
	high	planted	Ave Removal	-45%	33%	-33%	90%	72%	57%
			95% CI	90%	24%	99%	6%	10%	22%
		unplanted	Ave Removal	-272%	-73%	-590%	74%	32%	27%
			95% CI	180%	68%	301%	7%	18%	38%
300 East				TN mg/L	TP mg/L	NO_3-N mg/L	NH_3-N mg/L	Cu	Zn
			Ave Removal	100%	100%	100%	66%	79%	27%
			95% CI				62%	41%	70%

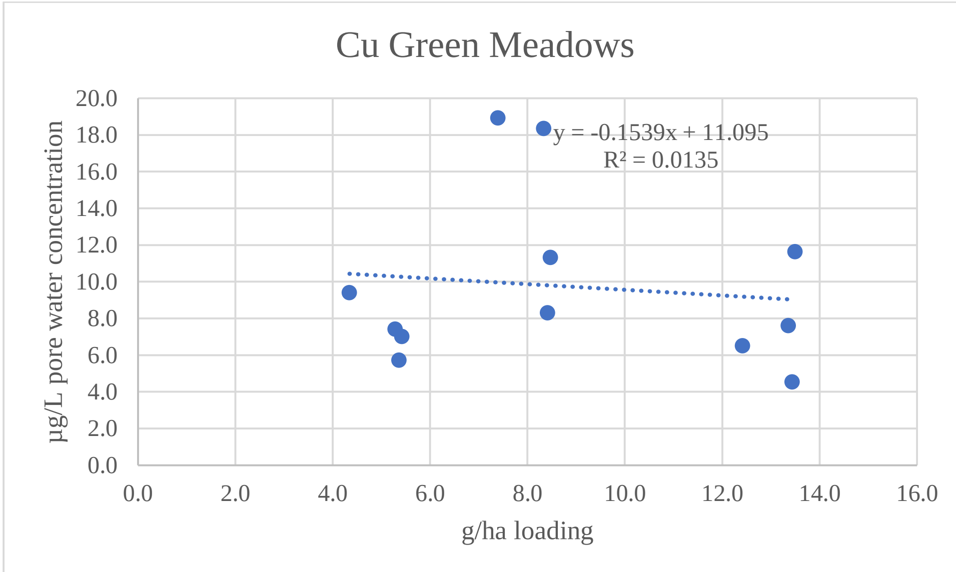
APPENDIX J

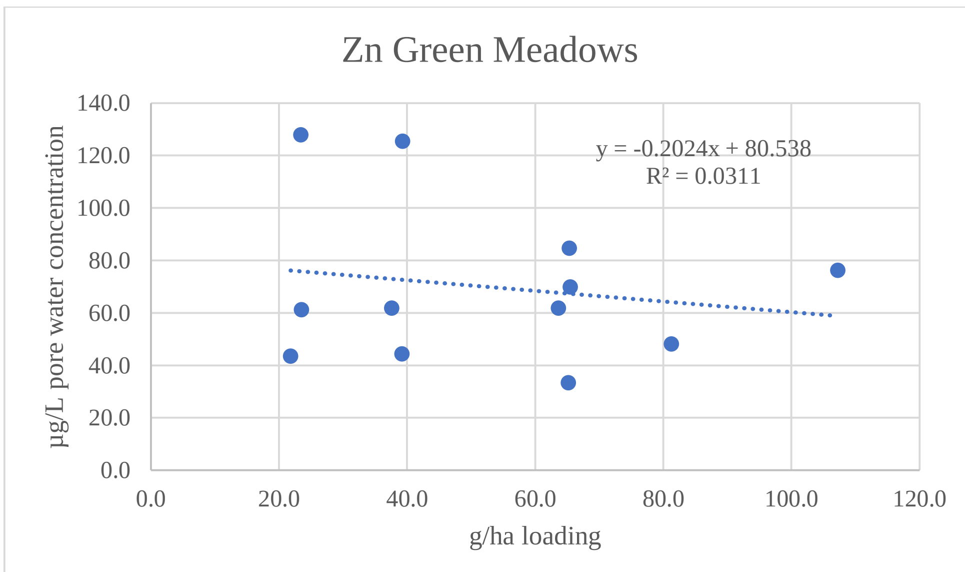

TDN Green Meadows
mg/L pore water concentration
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
g/ha loading
y = -0.0002x + 12.829
R² = 0.005

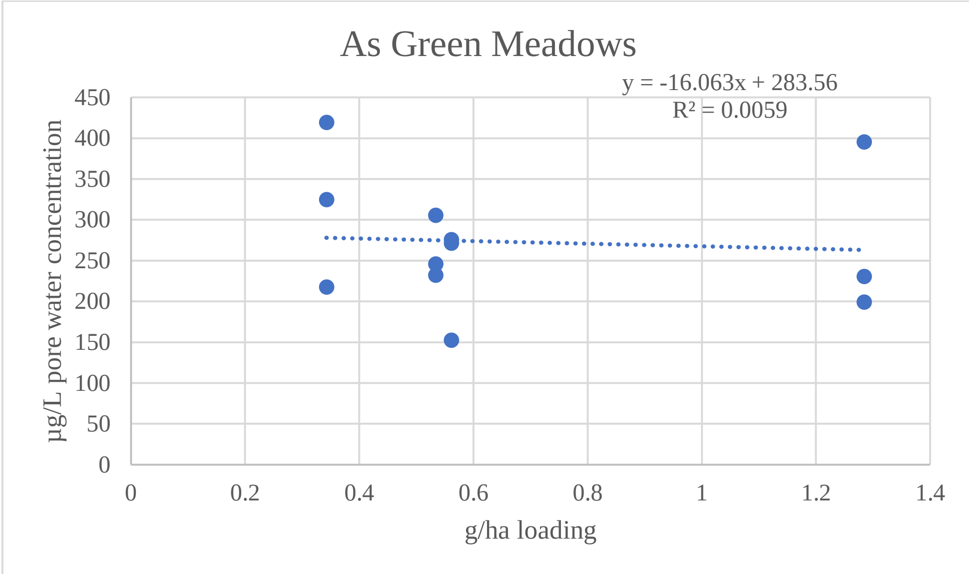

NO3-N Green Meadows
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
500
1,000
1,500
2,000
2,500
g/ha loading
y = 0.0027x + 2.0648
R² = 0.1588

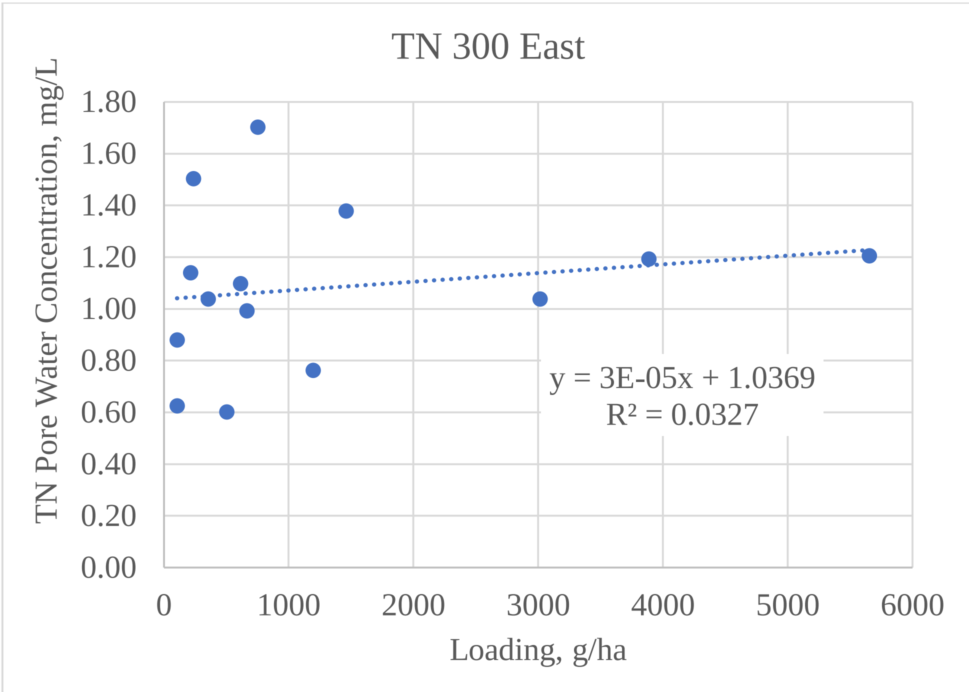

NH3-N Green Meadows
y = 0.0002x - 0.0007
R² = 0.5635
mg/L pore water concentration
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
200
400
600
800
1,000
1,200
g/ha loading

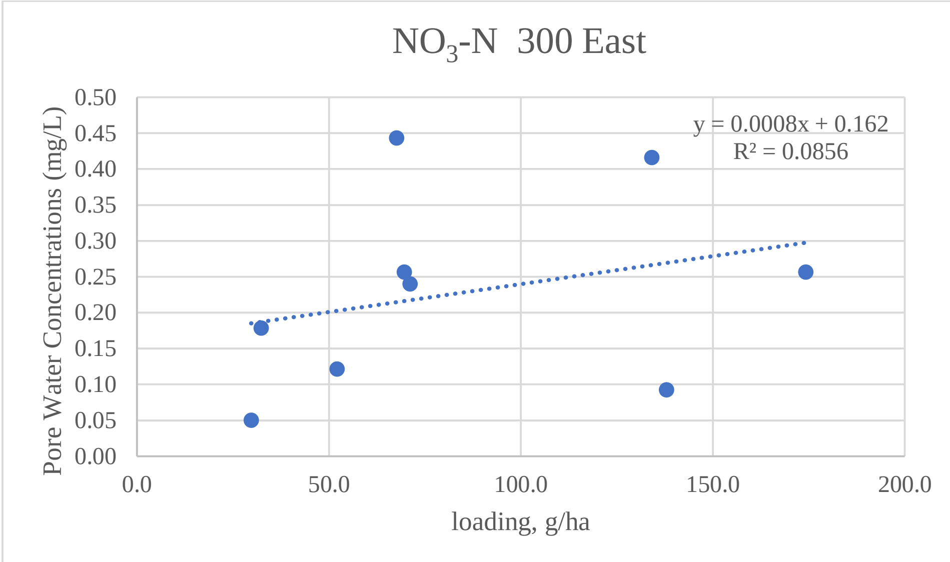

TDP Green Meadows
y = -0.0006x + 0.758
R² = 0.085
mg/L pore water concentration
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
100
200
300
400
500
g/ha loading

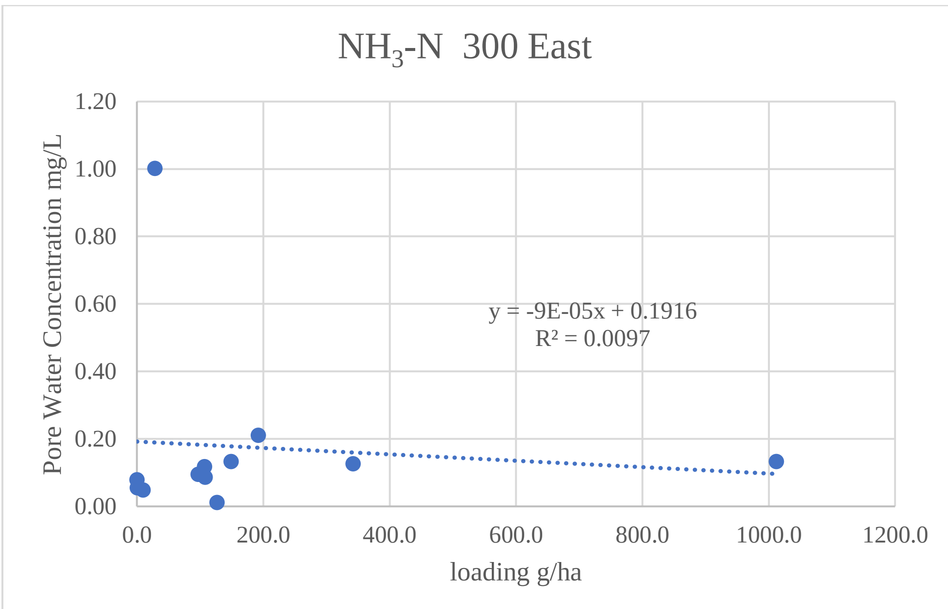

Cu Green Meadows
y = -0.1539x + 11.095
R² = 0.0135
µg/L pore water concentration
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
g/ha loading

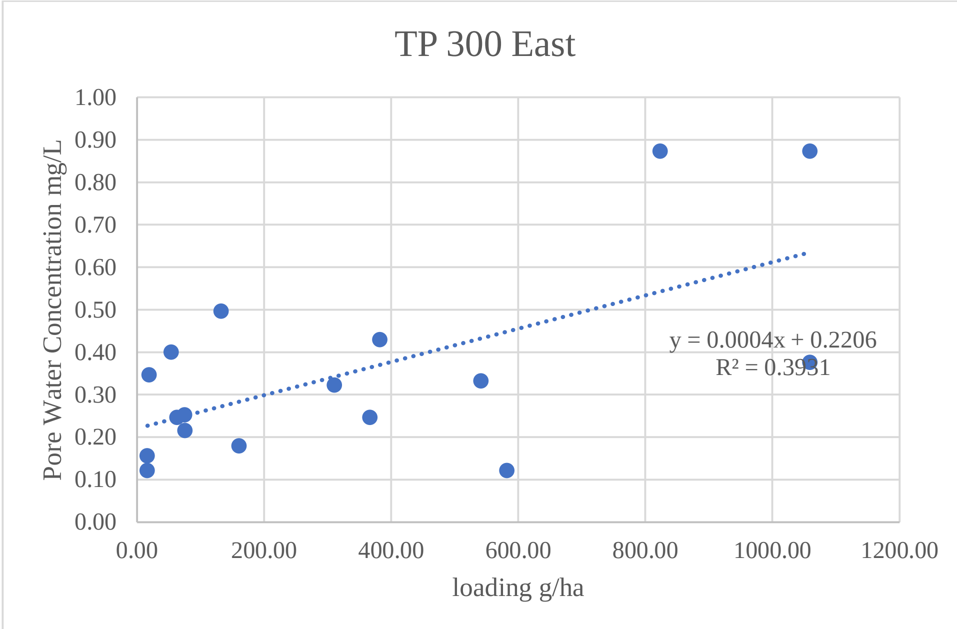

Zn Green Meadows
y = -0.2024x + 80.538
R² = 0.0311
µg/L pore water concentration
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
g/ha loading

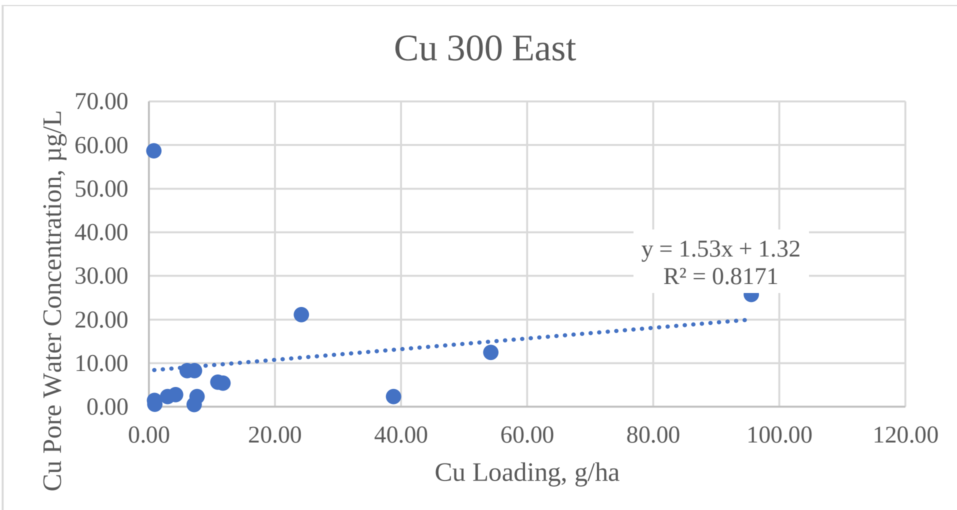

As Green Meadows
y = -16.063x + 283.56
R² = 0.0059
µg/L pore water concentration
450
400
350
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
g/ha loading

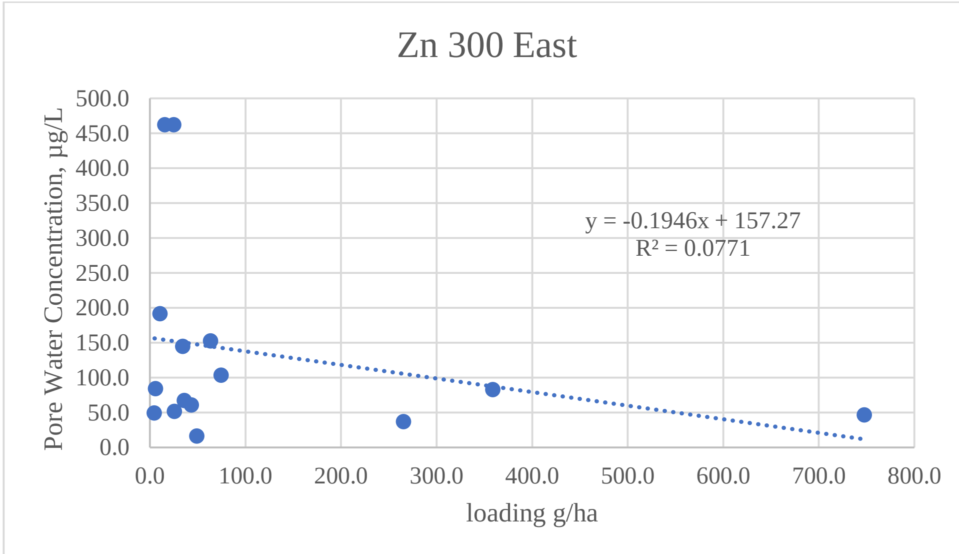

TN 300 East
TN Pore Water Concentration, mg/L
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
y = 3E-05x + 1.0369
R² = 0.0327
0
1000
2000
3000
4000
5000
6000
Loading, g/ha

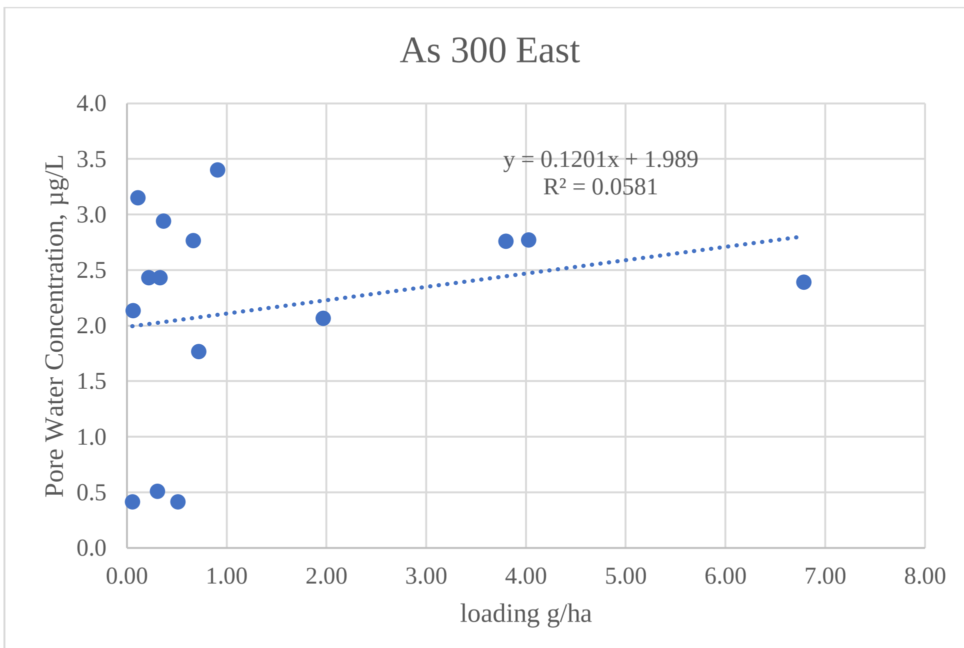

NO3-N 300 East
y = 0.0008x + 0.162
R² = 0.0856
Pore Water Concentrations (mg/L)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
50.0
100.0
150.0
200.0
loading, g/ha


NH3-N 300 East
y = -9E-05x + 0.1916
R² = 0.0097
Pore Water Concentration mg/L
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
loading g/ha


TP 300 East
Pore Water Concentration mg/L
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
200.00
400.00
600.00
800.00
1000.00
1200.00
loading g/ha
y = 0.0004x + 0.2206
R² = 0.3931


Cu 300 East
Cu Pore Water Concentration, µg/L
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
Cu Loading, g/ha
y = 1.53x + 1.32
R² = 0.8171


Zn 300 East
Pore Water Concentration, µg/L
500.0
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
loading g/ha
y = -0.1946x + 157.27
R² = 0.0771


As 300 East
Pore Water Concentration, µg/L
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
loading g/ha
y = 0.1201x + 1.989
R² = 0.0581

APPENDIX K

Nutrient and trace element removal at Green Meadows site, by application rate.

	Cu	Zn	As	Pb	NO_3+ NO_2-N	NH_3-N	TDN	TDP
Low	µg/L	µg/L	µg/L	µg/L	mg/L	mg/L	mg/L	mg/L
applied	10.2	67.6	1.3	0.018	1.6	0.62	4	0.28
Planted	7.61	67.86	301.37	0.52	3.52	0.06	8.70	0.65
control	7.91	116.04	96.88	0.51	3.37	0.21	11.77	0.68
%rmvl plant	25%	0%	-23083%	-2803%	-120%	90%	-118%	-131%
%rmvl control	22%	-72%	-7352%	-2754%	-110%	67%	-194%	-144%
Medium								
applied	16.2	98.7	1.3	0.018	2.4	1.1	5.7	0.46
Planted	15.97	68.63	408.15	0.85	6.98	0.11	16.93	0.80
control	12.80	109.91	129.59	1.73	3.92	0.24	11.65	0.56
%rmvl plant	1%	30%	-31296%	-4613%	-191%	90%	-197%	-74%
%rmvl control	21%	-11%	-9869%	-9529%	-63%	78%	-104%	-21%
High								
applied	26.1	150	1.3	0.018	3.6	2	8.5	0.76
Planted	7.15	64.94	342.44	0.58	4.71	0.20	11.88	0.51
control	17.78	105.87	115.29	1.79	24.49	0.51	32.07	1.34
%rmvl plant	73%	57%	-26242%	-3101%	-31%	90%	-40%	33%
%rmvl control	32%	29%	-8769%	-9870%	-580%	75%	-277%	-76%

APPENDIX L

References for raw data published in HydroShare for each study site.

Rife, T. (2021). Analysis of plant species in bioretention areas in Logan, UT, HydroShare, http://www.hydroshare.org/resource/ceae616026614bdc86701823a3d62d40

Rife, T. (2020). Analysis of bioretention area at 300 East in Logan UT, HydroShare, http://www.hydroshare.org/resource/3551eed4209645c29d640d834c876343

Rife, T. (2020). Analysis of two types of filter media in a bioretention system at Public Utilities, Salt Lake City, UT, HydroShare, http://www.hydroshare.org/resource/d8338d638ff34b35a7db1353bd0f7a4b

CURRICULUM VITAE

Trixie Rife

Trixwolf55@gmail.com

EDUCATION & CERTIFICATION

- PhD Civil/Environmental Engineering — Utah State University (May 2021)
- M.S. Civil/Environmental Engineering (2010) — Youngstown State University
- M.S. Ecology — Utah State University (2003)
- B.S. Education with minor in Biology — Duquesne University (1996)
- GIS Certificate — Penn State University (2010)

RESEARCH EXPERIENCE

***Research Assistant* Utah State University** — **July 2014 – present**
Logan, UT

- Working to complete doctoral research project involving soil water transport, plant uptake of pollutants, and water analysis
- Completed metal and nutrient digestion for water analyses using standard laboratory procedures
- Successfully completed course work in hydraulics, hydrology, structure design while conducting research

CONSULTING EXPERIENCE

***Environmental Consultant* Leonardo Technologies, Inc.** — **August 2010 – December 2014**
Pittsburgh, PA
NEPA Quality Analyst & GIS Analyst

- Using ESRI ArcMap, constructed maps of areas and project boundaries from latitude and longitude coordinates, oblique imagery, and site description for site area analysis, land ownership determination, and analysis of geologic structure location
- Developed PDF map documents, independent of the internet, with additional data file formats attached for additional analysis and presentation of locations presented on map
- Helped to conduct ISO14001 and OHSAS18001 audits
- Conducted NEPA categorical exclusion audits

TEACHING & COACHING EXPERIENCE

Science Teacher — **August 2006 – June 2007**
Middlesex High School, Middlesex, VA

- Used various labs and activities in class to enhance student learning. Completed a water monitoring activity, cultured oysters, and planned habitat construction for various areas near the school such as, woodlands, rain garden, and meadow

Assistant Women's Basketball Coach **July 2003 – April 2005**
Duquesne University, Pittsburgh, PA

Science Teacher **August 2000 – June 2001**
Riverside High School, Painesville, OH

- Used various labs and activities in class to enhance student learning. Taught General Science

Science Teacher **August 1998 – June 2000**
McCamey High School, McCamey, TX

- Used various labs and activities in class to enhance student learning. Taught Biology and Anatomy and Physiology

Science Teacher **August 1997 – June 1998**
West Charlotte High School, Charlotte, NC

- Used various labs and activities in class to enhance student learning. Taught Biology and Anatomy and Physiology

PUBLICATIONS

- **Master's Thesis Research:** "Modeling the Value of Ecosystem Services: Application to Soil Loss in Southeastern Allegheny County," Youngstown State University, August 2010
- **Master's Option B Project:** "Feral pigs and the Environment: An Annotated Bibliography," Berryman Institute Publication 21, Utah State University – Logan, UT; Mississippi State University – Starksville, MS