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Dynamics and Disconnects: Macronutrient Cycling in Ephemeral Constructed Stormwater Wetlands and National Patterns in Stormwater Management

by

Carolyn Macek

A thesis

submitted in partial fulfillment

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Committee Approval

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of CAROLYN MACEK find it satisfactory and recommend that it be accepted.

____

Dr. Rebecca Hale,
Major Advisor

____

Dr. Colden Baxter,
Committee Member

____

Dr. Morey Burnham,
Graduate Faculty Representative

Human Subjects Committee Approval

October 2, 2017

Carolyn Macek
Biological Sciences
MS 8007

RE: regarding study number IRB-FY2018-69: Stormwater Managers' Goals and Limitations, Information Sources, and Infrastructure Use Across the United States

Dear Ms. Macek:

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Sincerely,

Ralph Baergen, PhD, MPH, CIP
Human Subjects Chair

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Dynamics and Disconnects: Macronutrient Cycling in Ephemeral Constructed Stormwater Wetlands and National Patterns in Stormwater Management

Thesis Abstract – Idaho State University (2018)

As the ecologically detrimental effects of past water management practices have become evident, urban watershed managers across varied climates have used stormwater management infrastructure (SWI) projects to improve surface water quality. Climate may have significant implications both for the ability of SWI to remove pollutants and national patterns in SWI use. However, investigations on the pollutant removal efficiency of SWI have been generally restricted to humid settings and studies on factors influencing SWI distribution have been limited to case studies examining SWI-use within individual cities. As adequate understanding of SWI function across climates and patterns of use are vital to improving surface water quality, this study aimed to fill these research gaps. First, the nutrient dynamics of two constructed wetland SWI projects were investigated in a cold-desert climate. Second, this investigation used results from a nationwide survey to determine national patterns in stormwater management goals and SWI use.

Key Words: stormwater, water quality, stormwater management, climate, urban streams

Chapter 1. Introduction and Literature Review

As the ecologically detrimental effects of past water management practices have become evident over the last quarter century, urban watershed managers across varied climates have turned to river restoration and stormwater management projects to meet urban demands and improve broader watershed health. Despite the fact that these projects are common across the U.S. and globally, it is still not clear how many restoration and stormwater management projects function across diverse climates. The term river or stream restoration encompasses a remarkably wide range of projects with an equally varied set of objectives. Projects as diverse as stream bank restoration, the replanting of riparian trees, the creation of treatment wetlands, and a myriad of other techniques all fall under this umbrella of river restoration (Bernhardt et al. 2007; Newcomer Johnson et al. 2016). Equally as wide-ranging are the goals of river restoration; however, water quality management is a common primary goal of restoration projects (Bernhardt et al. 2007; Moreno et al. 2007). Although the specific measures of water quality vary from project to project, one common goal is limiting macronutrient loads entering surface waters. Of those macronutrients, nitrogen (N) and phosphorus (P) pollution are of major concern in both urban and rural areas (Carpenter et al. 1998; Walsh et al. 2005). These macronutrients can be major contributors to downstream problems like toxic algal blooms and eutrophication and can impair downstream macroinvertebrate and fish communities (Smith et al. 2006). The construction of wetlands for the treatment of storm- or wastewater is one restoration technique that is now common across the U.S. to reduce N and P loads (Moreno et al. 2007; Newcomer Johnson et al. 2016).

Climate may be a crucial factor that controls how effective particular river restoration and stormwater management techniques are at meeting the goal of mitigating high levels of macronutrients. Differences in climate support diverse organisms and create variation in hydrological characteristics that may be key components in nutrient dynamics and therefore critical to the performance of these projects. A substantial deficiency in current research is that the vast majority of studies on river restoration and stormwater management projects have been restricted to study sites in humid climates where perennial streams dominate (Newcomer Johnson et al. 2016). There are few studies that focus on stream restoration in arid, desert climates, and even fewer that focus particularly on ephemeral or intermittent constructed wetlands in these climates (Cerezo et al. 2001; Moreno et al. 2007). This research gap is significant because, as of 2010, greater than 20% of the global urban population lives in arid or semiarid climates (McDonald et al. 2011). Without these studies, managers in semiarid climates will be unable to make informed decisions about the design and implementation of restoration projects, and techniques implemented will likely be unable to meet desired water quality goals.

Although evaluating infrastructure and determining its effectiveness is important, it is also important to consider the social and political dynamics that drive the placement and effectiveness of stormwater management techniques. Understanding the factors and limitations that key stakeholders consider when implementing restoration projects provides insight into the ways that current regulations, financial limitations, and the flow and availability of information might result in the implementation of projects that do not adequately address regional concerns. By pairing an in-depth case study of two constructed stormwater wetlands (CSWs) in a semiarid climate with a nationwide stormwater manager survey about information sources and decision-making, we aim to understand both the ecological and hydrological factors that limit CSWs in a semiarid climate and the social processes that led to their implementation. This first chapter will introduce the ecological and socio-political complexities by examining previous literature in both the natural and social sciences.

Understanding how climate may impact river restoration efforts and stormwater management techniques is important not only to inform current stakeholders, but to change policy to incorporate regional climate variation as a critical factor. This is important not only for those places currently outside commonly-studied humid systems, but will be vital moving forward as climate changes and semiarid climates and ephemeral systems become more widespread throughout the U.S. and the globe (von Schiller et al. 2015). Facing these changes, protecting the integrity of the freshwater resources that remain will be increasingly important, both ecologically and because human consumption demands on freshwater resources will likely increase. Understanding the limits to current restoration practices will be a vital step in determining what will work in the future.

Nutrient Dynamics in CSWs

Ecological research over the past 20 years has identified a suite of problems in urban aquatic ecosystems that has been termed the urban stream syndrome (USS, (Walsh et al. 2005). These problems include increased stream flashiness, altered channel morphology, and elevated concentrations of nutrients—all of which lead to differences in ecosystem function (Meyer et al. 2005). The intensity of the USS is often linked to land use and impervious surface coverage. Impervious surface coverage changes the hydrology of a catchment by impeding infiltration.

During storm events, water that cannot infiltrate these impervious surfaces is efficiently conveyed via a network of stormwater infrastructure, leading to some of the major symptoms of USS (Walsh et al. 2005; Walsh et al. 2012). Of the problems associated with USS, water quality improvements are considered a top-priority concern across the U.S. (Bernhardt, et al. 2007) in part due to the fact that the Clean Water Act, implemented through programs such as the EPA's Total Maximum Daily Load (TMDL), focuses on these goals (Wagner 2005). Included among the pollutants of concern across many cities are N and P, which have both increased significantly in watersheds across the globe due to anthropogenic activities (Galloway et al. 2003; Filippelli 2008). Limiting these macronutrients from entering downstream surface and groundwater is a common goal with the installation of constructed wetlands (Brix 1994; Moreno et al. 2007).

Although the idea of using wetlands for waste mitigation is not new, public and scientific awareness of the benefit of wetlands has grown over the past 40 years, and the concept of engineering controlled wetland systems to deal with municipal waste and stormwater has spread throughout the world (Young 1996). Constructed wetlands are systems built on non-wetland sites that are specifically engineered for water treatment. Created wetlands are similar, except that the goal of these systems is to create wetland habitat to replace wetlands that have been elsewhere removed (Brix 1994). In recent years, many constructed wetlands have combined the goals of pollutant mitigation and habitat creation (Moreno et al. 2007). Wetland restoration, in contrast, includes projects that either improve existing wetlands or replant a site that previously supported a wetland community. It is important to note that while constructed wetlands can be a type of river restoration project (Helfield and Diamond 1997;

Newcomer Johnson et al. 2016), in the strict sense of these terms, they are not considered wetland restoration projects.

Before the early 1990s, most constructed wetlands were designed to mitigate pollutants from municipal wastewaters. The stochastic nature of stormwater delivery and the pollutant loads in stormwater required adaptations to the early wastewater treatment wetlands (Wong and Geiger 1997). CSWs generally perform well in terms of removal of suspended solids and organics, but the removal of macronutrients by CSWs is highly variable among projects (Brix 1994; Cerezo et al. 2001; Werker et al. 2002; Moreno et al. 2007; Choi et al. 2015). This variation is relatively unsurprising as macronutrient dynamics in aquatic systems occur through complex interactions of physical, hydrological, and biological components and processes (Fig. 1).

The unique aspect of directional flow in lotic environments means that nutrient dynamics are driven not only by the biotic and environmental conditions at a single location, but by the changes in these factors as nutrients move through a stream network. The concept of nutrient spiraling was devised to characterize nutrient dynamics in lotic systems (Webster and Patten 1979; Newbold et al. 1981), integrating transport into cycling. This concept includes metrics for describing nutrient spiraling, including spiraling length (*S*)— a measure of the efficiency of nutrient cycling along a reach. S is partitioned into uptake length (S_w) and turnover length. S_w increases with increased discharge (Q) and increasing nutrient concentration until saturation, at which point uptake efficiency levels off (Webster et al. 2003; Hall et al. 2009). Additionally, measures of S_w differ significantly among nutrient forms, such as ammonium and nitrate, because these forms are taken up via different uptake pathways (Peterson et al. 2001). S_w shortens with increasing gross primary production (GPP) (Hall et al. 2009).

Built to mimic natural wetlands, CSWs aim to increase nutrient uptake by reducing S_w, or increasing hydraulic retention time. This is achieved by slowing the flow velocity and utilizing macronutrient consumers (Phillips 1996; Wu et al. 2015). Decreased stormflow velocity allows pollutants attached to sediments suspended in the water column to settle out and provides more opportunities for biological removal (Somes et al. 2000; Carleton et al. 2001). Many CSWs are designed to decrease the velocity of flow creating a sinuous flowpath or adding barriers to streamflow (Chang et al. 2010; Choi et al. 2015; Newcomer Johnson et al. 2016). Because of the importance of plants for nutrient uptake (Wu et al. 2015), many CSWs are also designed with wetland vegetation (Maltais-Landry et al. 2009) that both creates physical barriers and takes up N and P directly. Different species have diverse nutrient requirements and the efficiency of nutrient cycling and uptake varies accordingly between species (Güsewell and Koerselman 2002; Alldred et al. 2016). The interactions of these different biotic communities and their environmental conditions work in combination to determine the nutrient dynamics of CSWs.

Differences in climate and precipitation regime and the plant, animal, and microbial communities that occur in response to these conditions not only determine the structure of streams, but also control the function (Dodds et al. 2014). Although ephemeral streams occur in all regions, they are particularly abundant in semiarid and arid climates (Larned et al. 2010; von Schiller et al. 2015). The majority of research in stream ecology, restoration, and CSWs has focused on perennial systems, but controls on nutrient cycling in perennial and ephemeral systems are likely to differ because of vast differences in both biotic communities and flow regimes (Moreno et al. 2007; Leigh et al. 2015). During connected periods, ephemeral streams may function similarly to perennial counterparts, cycling nutrients along the length of the stream. However, during contraction and fragmentation, disconnected pools may become anoxic because of high microbial activity and anaerobic bacteria may control nutrient processes. After complete drying, terrestrial processing dominates, including processing by terrestrial microbes and invertebrates, and degradation by solar radiation and desiccation (Larned et al. 2010).

Microbial communities dominate nutrient cycling in many wetland systems; however, microorganisms can be severely limited by frequent periods of wetting and drying. One study found that as much as three quarters of the microbial community can die during the desiccation of previously anaerobic sediments (Qiu and McComb 1995) and, as a result, the processing of nutrients in ephemeral streams during dry periods is extremely low compared to rates during flows (Larned et al. 2010). Additionally, lysis of bacteria can release N and P, which can later be flushed out of sediments during the initial rewetting (Qiu and McComb 1995; Austin and Strauss 2011; Bettez and Groffman 2012; Arce et al. 2014). With rewetting, many of the processes driving rapid nutrient cycling can recover (McClain et al. 2003; Larned et al. 2010). Although microbial communities in ephemeral sediments may be more resilient because they have adapted to frequent drying, this recovery is not instantaneous (Austin and Strauss 2011; Arce et al. 2014). In a stormwater context this could be particularly problematic, as the highest concentrations of pollutants and macronutrients in stormwater occur during the “first flush” (Barbé et al. 1996). If, during this period of highest nutrient concentrations, the microbial community is still in the process of recovering and, therefore, unable to play a significant role in nutrient cycling, the stormwater may leave the system with limited nutrient reduction. The frequent wetting and drying in CSWs in semiarid systems may not only inhibit the survival of wetland biota that play critical roles in nutrient uptake and cycling, but in some cases could actually cause these systems to become sources of N and P.

While climate controls the biological communities within CSWs, it can also interact with land use to determine the stormwater inputs to the CSW (Lohse et al. 2010). Increasing antecedent dry days, for example, has been shown to be correlated with increased pollutant loads in stormwater runoff (Gallo et al. 2013, Lewis and Grimm 2007, Hale et al. 2014). Termed pollutant washoff (Barbé et al. 1996), during dry periods many pollutants accumulate on impervious surfaces where they stay until transported during the next storm event. In a semiarid or arid climate, there may often be long periods between rain events, meaning that antecedent dry days may be an important factor to consider in pollutant dynamics in urban stormwater discharges. This factor could be an important one in effectively designing CSWs and other stormwater management infrastructure with water quality remediation goals.

Cycles of drying and rewetting are not the only environmental conditions that impact the response of microbial communities in CSW soils. Similar to semiarid conditions, there has been relatively little research on the effectiveness of various restoration and stormwater management structures in cold climates during winter (Semadeni-Davies 2006). However, research on nutrient cycling in streams suggests that biological activity is significantly reduced during cold winter temperatures (Werker et al. 2002). In a snowmelt-driven watershed, flow events primarily occur during cold temperatures which may limit many microbial processes. Looking at the nitrogen cycle, the growth of bacteria involved in nitrification ceases below 4-5°C and is impaired below 30°C (Vymazal 2007). Denitrification, too, slows significantly at temperatures below 5°C (Vymazal 2007). Adding further challenges to the design of stormwater infrastructure in the semiarid intermountain west is that the majority of the annual precipitation occurs as snow. Physically, the presence of ice could significantly decrease retention and the settling of particulates in detention structures if the water travelled overtop the ice, or significantly increase scouring if velocity of flows increased when water was forced beneath the ice (Oberts et al. 1989). In cold-desert climates, these reductions to nutrient cycling efficiency could be particularly problematic in terms of meeting nutrient reduction goals—the majority of water may be entering these systems at a time when nutrient uptake is the least efficient. On top of reduced efficiency, concentrations of pollutants in snowmelt may be higher than those found in runoff from rain events because snow can accumulate pollutants throughout the winter (Semadeni-Davies 2006). In a semiarid, snowmelt-driven climate, it is crucial to understand how both snowmelt and ephemeral flow impact nutrient cycling and uptake efficiencies in CSWs.

Lastly, it is important to consider that areas with semiarid and arid climate conditions are likely to expand in the U.S. with climate change (Field 2012). Climate change will not only increase semiarid and arid lands in the U.S. but, through changes in precipitation regimes, it may impact the pollutant loads entering stormwater systems as well (Jeppesen et al. 2009). The predicted increases in seasonal droughts and concomitant increases in extreme precipitation events could put particular stress on stormwater infrastructure (Pyke et al. 2011). Seasonal droughts translate to longer periods of antecedent dry days and the associated increases in pollutant washoff. Additionally, with more extreme flood events, more water will likely be entering CSWs and other stormwater infrastructure. With these higher volumes, hydraulic retention time in these systems may be limited, which has shown to negatively impact the uptake in these systems (Wu et al. 2015). A few studies directly address the potential impacts of climate change on current stormwater infrastructure in order to understand how cities might be able to implement infrastructure that proactively addresses potential climatic changes (Semadeni-Davies et al. 2008; Pyke et al. 2011; Sharma et al. 2016). While modelling and predicting changes associated with climate change can be difficult, understanding the pollutant and nutrient dynamics in currently implemented stormwater infrastructure in semiarid climates would be an important step to understanding how stormwater infrastructure might respond as arid climates expand.

Socio-Political Drivers of Stormwater Infrastructure Implementation

To address the water quality problems caused by urban stormwater in arid and semiarid climates and to implement infrastructure that adequately addresses future changes in climate, it is necessary to understand the social and political factors that control the implementation of stormwater infrastructure. The regulation of stormwater through the establishment of legislation or the implementation of infrastructure is influenced by both scientific understanding and social and cultural conceptions and boundaries (Finewood 2016). Water flows not only according to natural processes, but is controlled by social boundaries and processes that control the access, provisioning, and regulation of waters (Swyngedouw 2009). These social and cultural conceptions are often institutionalized in formal regulations and political policies.

Changes in the regulation of stormwater in the U.S. over relatively recent history exemplify how sociocultural shifts are reflected in built infrastructure and policy. The establishment of the city as the antithesis of nature and the subsequent push for the control of nature in urban spaces led to the conception of stormwater as a nuisance—something that threatened infrastructure and public health and should, therefore, be moved away from urban spaces as efficiently as possible (Karvonen 2011). This perception led to the installation of networks of so-called “gray” stormwater infrastructure—either combined (sewage and storm water) or separated sewer systems that carry water in a series of underground pipes away from the city, with outlets in nearby natural waterbodies (Karvonen 2011; Finewood 2016). The environmental movement of the 1960s shifted the focus from the separation of the city and nature towards the necessity of protecting natural water bodies that had become polluted from these practices (Karvonen 2011). The 1972 Clean Water Act (CWA) was the political and regulatory response to this sociocultural shift, and focused on water quality goals (Wagner 2005; Karvonen 2011). An amendment to the 1948 Federal Water Pollution Control Act, which had only limited success (Dolowitz 2015), the CWA more effectively addressed point-source pollution through the National Pollutant Discharge Elimination System (NPDES). Although the U.S. government recognized that stormwater contained pollutants that were potentially negatively impacting public and ecosystem health as early as the mid-1960s (Field and Struzeski Jr 1972), NPDES regulations failed to adequately address nonpoint source pollution. To respond to this, regulation was further expanded in 1987 to limit the pollutants entering freshwater systems via stormwater and other nonpoint sources (Adler et al. 1993).

Recognizing that gray stormwater infrastructure designed to efficiently move water away from cities and into the surrounding natural aquatic systems also efficiently moved pollutants, new technologies had to be developed and championed to meet these new pollutant reduction goals. Because stormwater runoff can cause a myriad of environmental problems and contains a mix of pollutants that all require different approaches to treatment, an equally diverse menu of treatment infrastructure needed to be created (Karvonen 2011). In response to this need, and the recognition that existing infrastructure was unlikely to mitigate pollution effectively, NPDES included recommendations to include green infrastructure (GI) or low impact development (LID) technologies into municipal stormwater plans (Dolowitz 2015). However, there are no current mandates that GI or LID technologies be implemented in place of traditional gray infrastructure, and their adoption has been relatively piecemeal (Brown et al. 2013). Additionally, there are no mandates that direct municipalities away from the "end of pipe" solutions that have had mixed success, and towards LID technologies that aim to limit the amount of water that enters the stormwater network during precipitation events (Karvonen 2011).

Although the CWA has been fairly successful throughout the U.S. at limiting the negative impacts of point source pollutants, this success has not translated to curbing the USS and stormwater's effects (Wagner 2005; Dolowitz 2015). This is in part because of the complexity of regulating nonpoint source pollutants. While with point sources it is easy to identify and monitor the precise amount of pollutants entering a waterbody from a particular source at a particular time, this is not the case with stormwater. Concentrations of pollutants vary not only among cities, but also vastly among and within storm events, seasons, and sub-catchments within cities (Barbé et al. 1996; Walsh et al. 2012; Gallo et al. 2013). Despite the lack of information, and the diversity of pollutant loads, NPDES regulations are structured similarly to point source pollutant regulations—cities are given limits on the total amount of pollutants that can enter a water body and are given lists of supposedly appropriate solutions for meeting those goals (Wagner 2005).

Complicating stormwater policy and regulation, different aspects of stormwater are often addressed by different departments within local government, sometimes with contrasting management preferences and discourses surrounding stormwater management (Karvonen 2011; Cousins 2017a). Despite these differences, recent research has found convergence among individuals in different departments on broader ideals surrounding stormwater management, such as the belief that sustainability will most benefit from management practices supported by scientific data (Cousins 2017b). However, different stakeholders often diverge in terms of the actions they consider most appropriate for achieving those ends (Cousins 2017c; Cousins 2017b). When different stakeholders and decision-makers disagree on the best course of action, the result is either inaction— in which case water quality in urban areas improves only incrementally (Wagner 2005)—or an imbalance of power in which the values of some groups are prioritized over others (Cousins 2017b). In cities with vastly different political and ecological realities, a crucial first step to creating effective regulatory policy is understanding those realities.

In addition to these ecological and political differences, there are also social and cultural differences between cities and regions that can determine the physical reality of the built environment. Research on the social drivers of stormwater infrastructure is limited. One influential cultural driver of stormwater infrastructure is the system of beliefs within a city surrounding public and private land (Berke et al. 2013). Although people may want clean water and understand the benefits that particular stormwater management practices may have, communities with a strong cultural identity connected to private lands are less responsive to regulations or mandates by federal or state governments (Berke et al. 2013). The disconnect between created, political boundaries and the boundaries of a watershed further complicate decisions in water quality initiatives and stormwater management. While decision-makers may understand the importance of managing for water quality at the landscape scale, political and social boundaries often prevent this from being executed (Keeley et al. 2013). Politically, borders and regulations may be structured so that downstream cities cannot implement infrastructure in places upstream of them that impact their water quality. Elected officials may be further discouraged from involvement outside their district because of social and cultural conceptions of their constituents; as constituents may view spending "their" tax money in other districts negatively, even if a project elsewhere improves their water quality as well (Keeley et al. 2013). Finally, the population dynamics of a city could play a role in forming the cultural values that are reflected in stormwater implementation (Karvonen 2011; Burkholder 2012). Space is often a limiting factor for stormwater managers working in the built, urban environment (Cousins 2017c; Cousins 2017b). In cities with rapidly declining populations, vacant lots have recently started to be viewed as opportunities for urban revitalization and green infrastructure implementation (Burkholder 2012; Keeley et al. 2013). Because of the many recognized benefits of green space in urban settings (Mandarano and Meenar 2017), some declining cities have begun to emphasize the multiuse aspects associated with stormwater GI in order to encourage their implementation (Burkholder 2012; Keeley et al. 2013). Rapidly growing cities, however, are often forced to expand quickly to accommodate growth. As a result, there has been more of an emphasis on getting new neighborhoods up to code for stormwater regulations, and less of an emphasis on the potential benefits that GI could bring to both residents and water quality (Karvonen 2011).

The political, social, and ecological realities of urban spaces are interwoven to determine both the problems with urban stormwater and the reality of water quality improvement possibilities. The complexity of factors involved in urban systems requires a multifaceted approach to study. The following chapter will be an in-depth investigation of soil and vegetation controls on nutrient dynamics in ephemeral CSWs, as well as an ecological case-study of two ephemeral CSWs in Pocatello, Idaho. The final chapter will examine regional differences in stormwater goals, information use, and stormwater infrastructure use across the U.S. using online survey methods.

Figures

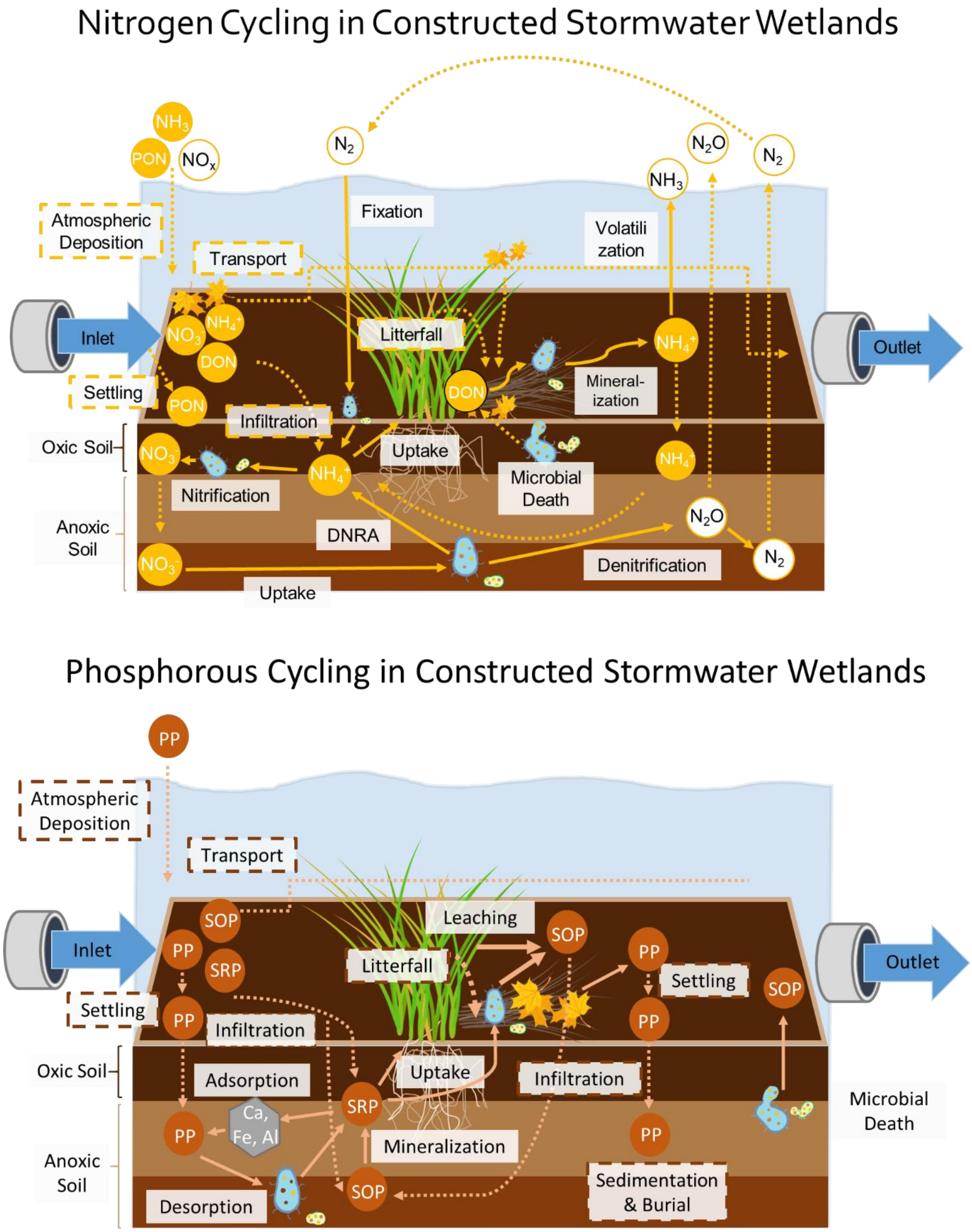

Figure 1. Conceptual diagrams of cycling of N and P in CSWs. Physical processes are depicted with dotted lines. Biological and chemical processes are depicted with solid lines. For nitrogen, forms in white with yellow outlines indicate N in the gaseous phase.

Chapter 2. Dry Wetlands: Nutrient Dynamics in Ephemeral Constructed Stormwater Wetlands

Abstract

Constructed stormwater wetlands (CSWs) are used in many cities to address concerns with contaminants in urban stormwater, such as macronutrients. Despite applications across a diversity of climates, research on the effectiveness of CSWs in macronutrient reduction has been largely limited to humid climates. In cold, semiarid regions, stormwater-fed CSWs may not maintain perennial flow, and a temporal mismatch between precipitation and the growing season may limit the ability of wetland vegetation to act as a sink for nutrients. We assessed whether wetland soils and vegetation acted as sources or sinks of nutrients within two ephemeral CSWs in Pocatello, ID, U.S.A. Soil and vegetation rewetting experiments were conducted to identify the contributions of each to CSW nutrient dynamics over a 1-week period. Evidence suggests that net nutrient release from CSW soils was a significant source of nutrients to stormwater during the initial rewetting period when stormwater concentrations are likely to be high due to the first flush. Although there was some evidence of NO_3^- and NH_4^+ removal in soil microcosms, it did not occur until 72 hours after inundation, when stormwater would have already drained to downstream systems. Senesced vegetation was a small nutrient source relative to soils, but vegetation may indirectly control nutrient processes by providing substrate and creating soil conditions conducive to macronutrient cycling. Solute concentrations from storm-event sampling suggest that antecedent conditions within the CSW—such as the presence of ice or desiccated soils—can cause changes in nutrient dynamics by altering physical or biological processes. By understanding the function of stormwater infrastructure across diverse climatic conditions, recommendations for improvement of current

projects can be made and better-informed decisions on stormwater infrastructure can be made in the future.

Introduction

Nitrogen (N) and phosphorus (P) loads in urban stormwater runoff have had detrimental effects on surface waters downstream of urban watersheds (Meyer et al. 2005; Walsh et al. 2005; Smith et al. 2006), and in the U.S., the National Pollutant Discharge Elimination System (NPDES) requires cities across climates to reduce these pollutant loads. The construction of wetlands for the treatment of stormwater is one technique commonly used to reduce N and P loads (Moreno et al. 2007; Newcomer Johnson et al. 2016). Built to mimic natural wetlands, constructed stormwater wetlands (CSWs) are designed to increase nutrient uptake by increasing uptake efficiency and hydraulic retention time. This is achieved by physically slowing flow velocity and using plant and microbial communities to sequester and transform macronutrients (Phillips 1996; Wu et al. 2015). CSWs generally perform well in terms of removal of suspended solids and organics, but despite widespread use for nutrient sequestration, removal of N and P by CSWs is highly variable among and within systems (Brix 1994; Cerezo et al. 2001; Werker et al. 2002; Moreno et al. 2007; Vymazal 2007; Choi et al. 2015). This variation is relatively unsurprising, as macronutrient dynamics in aquatic systems occur through complex interactions of physical, hydrological, and biological components and processes, which vary across climates and precipitation regimes (Moreno et al. 2007; Dodds et al. 2014; Leigh et al. 2015). The majority of research on CSWs has focused on perennial systems in humid climates (Moreno et al. 2007), but climate variation may lead to differences in the ecological structure and function of CSWs, with implications for nutrient removal performance.

Therefore, research is needed to assess CSW function in multiple climates. Here we address CSW function in a cold, semiarid climate.

Cold, semiarid climates present several challenges for CSW design due to the seasonality of precipitation. The desiccation of soils during long dry periods likely impacts microbially-mediated nutrient cycling, although the disconnect between peak precipitation and peak growing season means vegetation may play a limited role in direct uptake of nutrients. Microbial communities control important nutrient cycling pathways in many CSWs (Vymazal 2007); however, microorganisms can be severely limited by frequent periods of drying and rewetting (von Schiller et al. 2017). One study found that as much as three quarters of the microbial community can lyse during the desiccation of previously anaerobic sediments (Qiu and McComb 1995), and as a result, the processing of nutrients in ephemeral systems during dry periods is extremely low compared to rates during flows (Larned et al. 2010). While microbial communities in ephemeral systems that experience frequent drying and rewetting may be more resilient to lysis (Van Gestel et al. 1993), nutrient uptake is not instantaneous upon rewetting (Austin and Strauss 2011; Arce et al. 2014). In a stormwater context this could be particularly problematic, as the highest concentrations of macronutrients in stormwater occur during the first flush (Barbé et al. 1996), and microorganisms may not have yet recovered to optimal nutrient cycling levels at this time, allowing water to flow through the system without treatment. Soils in ephemeral CSWs may also act as a nutrient source. With drying, nutrients may accumulate in surface soils due to deposition from previous events, release from cell lysis (Qiu and McComb 1995; Schiller et al. 2011), salt precipitation due to evaporation (McLaughlin 2008), mineralization of soil organic P (Chepkwony et al. 2001), or desorption from sediments with soil oxygenation (Vymazal 2007). If not removed during the dry period, these nutrients would be easily released from surface soils upon rewetting.

There has also been relatively little research on the effectiveness of various stormwater management structures in cold climates during winter (Werker et al. 2002; Semadeni-Davies 2006). Research in wastewater treatment wetlands suggests that biological activity and nutrient cycling is significantly reduced during cold winter temperatures (Werker et al. 2002), and CSW vegetation is unlikely to play a strong role in storm-event nutrient uptake in cold desert climates where there are disconnects between peak growing season and peak precipitation. The cycling efficiency of the soil microbial community is also temperature dependent, particularly for N, with rates of both nitrification and denitrification approaching zero at temperatures below 5°C (Vymazal 2007). Furthermore, the presence of ice could significantly decrease nutrient retention and the settling of particulates in detention structures if the water travels overtop the ice, or significantly increase scouring if velocity of flows increases when water is forced beneath the ice (Oberts et al. 1989). In snowmelt-driven climates, these reductions to nutrient cycling efficiency could be problematic in terms of meeting nutrient reduction goals—the majority of water may be entering CSWs at a time when nutrient uptake is the least efficient. In addition to reduced efficiency, concentrations of pollutants in snowmelt may be higher than those found in runoff from rain events because snow can accumulate pollutants throughout the winter (Semadeni-Davies 2006). In a cold-desert climate, it is crucial to understand how both ephemeral flows and the dominance of snowmelt impact nutrient cycling and uptake efficiencies in CSWs.

This study aims to assess whether soils and senesced vegetation act as net nutrient sources or sinks within two CSWs in a cold desert climate in Pocatello, Idaho, U.S. We assess the following hypotheses addressing the impact of each of these factors:

We hypothesized that (H1a) in ephemeral CSWs, initial rewetting would cause a significant pulse of N and P because of the resuspension of nutrients in surface soils coupled with the absence of an active soil microbial community to remove nutrients. Given the frequent periods of desiccation and rewetting in these wetland systems, we additionally hypothesized (H1b) that although nutrient flux would be high immediately after rewetting, the microbial communities within the wetland sediments at the two CSWs would be able to quickly recover to pre-drying levels of nutrient processing. Therefore, we expected concentrations of nutrients in the stormwater to decrease as nutrient transformations and uptake occurred.

We also hypothesized that (H2) senesced vegetation accumulated in the bed of a CSW would provide a pulse of dissolved nutrients to stormwater during inundation, depending on organic matter (OM) composition. We expected (H2a) that vegetation would initially act as a source of nutrients and that leaching would increase over time due to the establishment and growth of microbial communities. However, (H2b) inundated vegetation could also provide substrate for microbially communities, leading to increased nutrient transformations and decreased nutrient concentrations.

Methods

Site Description

This study was conducted in two surface-flow CSWs in Pocatello, Idaho. Pocatello is a small city (~83.5 km^2) with the 2015 population estimated at 54,500 people (U.S. Census

Bureau 2016). Pocatello has a semiarid, snowmelt-driven climate, with average annual precipitation of 30.8 cm (National Climate Date Center, 30-year average). Only 33.4% of total annual precipitation occurs during peak growing season, from May to September. Pocatello is located in the Portneuf River Valley, between the Bannock and Portneuf Ranges, with a portion of the Portneuf River running directly through the city. Surrounded mainly by agricultural lands, Pocatello sits at a junction between the urban and rural, and the macronutrient loads within the Portneuf River and its tributaries reflect that junction (Ray 2010). High concentrations of both N and P have led to the implementation of Total Maximum Daily Loads (TMDLs) for these macronutrients in the main stem and tributaries of the Portneuf River (IDEQ 2010).

In addition to other management efforts, two CSWs were constructed in Pocatello over the past 20 years with the aim of improving water quality. Although the drainage basins of both wetlands are primarily residential, the catchment of the First Avenue Wetland (hereafter FA) is smaller than that of the wetland in Sacajawea Park (hereafter SJ), which also contains some undeveloped upland area (Fig. 1a). In addition to the differences between the catchments of each CSW, there are also differences in the characteristics of the wetlands themselves, primarily in the amount of vegetation present in the CSW (Fig. 1b). The two CSWs also vary in flow regime. At both FA and SJ large precipitation or snowmelt events are required for the stormwater to reach the outlet and flow into the Portneuf River. As a result, for most storms both FA and SJ act more like retention basins than flowing wetland systems. However, even when flow at SJ does not reach the outlet, flow is directional for the duration of inflow for most events, whereas FA generally appears much more pond-like in nature with slow flows that are not obviously unidirectional.

Study Design

This investigation pairs two lab-based manipulative experiments on CSW soils and vegetation with a case study of solute dynamics associated with three storm events in the two study CSWs. While the microcosm experiments allowed us to explore effects of drying and rewetting on individual components of ephemeral CSWs in isolation, storm-event sampling allowed us to assess nutrient source-sink dynamics across a variety of storm conditions and helps provide potential directions for future studies on ephemeral CSWs.

Release of N and P with sediment rewetting (H1a and H1b)

A controlled lab experiment was conducted with soil cores from each wetland site to assess the release and removal of N and P following the rewetting of dry wetland sediments. In August of 2017, 15 8 cm soil cores were collected from each site (total n=30). The study reaches were split into 15 even segments, and cores were randomly sampled from each segment along each reach. Proximity of samples to in-bed vegetation was noted, and cores were not taken from areas with dense vegetation. These samples were collected on the same day, 14 days after the last storm event, to ensure complete and uniform drying time. Cores were transported from the field on ice and kept refrigerated until inundated, no more than 24 hours after collection. Intact soil cores were left in plastic core sleeves with one end capped, and 2-inch PVC extenders were added to each sleeve to allow sufficient water to be added to each of the 30 microcosms. 500 mL of distilled water was added to each of the microcosms to submerge the sediments completely. While pollutant concentrations in stormwater may have interactive effects that change nutrient dynamics (Vymazal 2007), these concentrations vary significantly both across and within storm events and there was little justification for manufacturing water of a single concentration. Using distilled water allowed us to examine nutrient dynamics in soil cores in the absence of interactive effects. Because making the PVC extenders and soil core caps watertight was an issue, each core set up was placed into a separate container and any water collected was reintroduced to the microcosm at least once per day. Each core was loosely capped to limit evaporation without completely impeding airflow. 60 mL water samples were taken 1, 5, 24, 72 and 168 hours after inundation. These times were chosen because the study sites rarely stay inundated longer than 168 hours after a storm event. Samples were filtered with Fisherbrand mixed cellulose esters 45 µm syringe filters to minimize disturbance to the intact cores and immediately frozen until analysis. Samples were analyzed for NO_3^-, ammonium (NH_4^+), and soluble reactive phosphorus (SRP) on a Lachat QuikChem FIA system (Hach, Loveland, CO), and total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) on a Shimadzu TOC/TN analyzer at the Environmental Analysis Lab at Brigham Young University (BYU).

To provide insight as to what microbially-regulated nutrient processes were likely occurring in CSW soils, a series of 14 soil cores (7 per site) were taken in February 2018 and tested for soil pH. Approximately 15 g of soil were measured into a beaker and distilled water added to a 2:1 water to soil ratio. Samples were mixed for about one minute, covered, and allowed to sit on the benchtop for one hour before measurements were taken. The pH was measured using a glass electrode and pH meter and three independent measurements were taken for each sample.

Vegetation abundance, nutrient content, and nutrient leaching (H2)

Photo-point quadrat methods were used to estimate in-bed vegetation abundance and species composition(Janzen 2009) at both FA and SJ in the fall of 2017. Transects were positioned perpendicular to the direction of flow in each of the measured wetland reaches. A 1 m^2 quadrat was placed along the length of each transect and an overhead photograph of the quadrat at each position for the entirety of the reach was taken. A 0.01 m^2 grid was superimposed over photographs in imagej (Version 1.51k; Rasband 1997), and the point method was used to quantify ground cover and roughly categorize community composition. Studies have found that vegetation quantification using this method does not significantly differ from traditional point frame methods (Booth et al. 2006; Janzen 2009).

Each studied wetland reach was coarsely classified into five dominant vegetation communities and one m^2 quadrat was randomly selected from each community for aboveground vegetation harvest. Each sample was separated by species, dried at 60 °C for one week, and weighed to estimate dry mass of vegetation. Using the percent cover of the corresponding photograph for each sampled quadrat, the biomass of each identified species was calculated for SJ and FA. To quantify vegetation nutrient content, subsamples of collected vegetation were ground to pass through a 0.25 mm mesh sieve. Total nitrogen (TN) and TP of one unique SJ vegetation species (*Carex spp.*), 4 FA vegetation species (*Juncus balticus*, *Schoenoplectus acutus*, *Tribulus terrestris*, and *Convolvulus arvensis*), and a vegetation species common to both wetlands (*Rumex crispus*) was determined by nitric acid-hydrogen peroxide microwave digestion. An Ethos EZ Digestion System (Milestone, Shelton CT) was used, followed by quantification by ICP-OES using the iCAP 7400 (Thermo Scientific, Waltham, MA) at the

Environmental Analytical Lab at BYU. By combining the abundance and composition assessments with the calculated nutrient contents of each species, an estimate for total vegetation N and P content for each wetland at the beginning of the rainy, fall season was calculated. These values indicate the total amount of N and P that could potentially leach from the vegetation in each CSW.

During fall surveys, vegetation samples were also collected to assess dynamics of nutrient leaching from senesced vegetation. Common vegetation species from FA and SJ were identified from on-site assessments as *Carex spp.* at SJ and *Juncus balticus* at FA. Additionally, *Rumex crispus* was identified as a species common to both sites. To reduce variation in initial nutrient concentrations between plants of the same species, vegetation samples were collected from plants of a similar size. Microcosms were used to assess leaching, with 5 replicates each for *Carex spp.*, *Juncus balticus*, and *Rumex crispus*, and a control with no submerged vegetation (total n = 20), following methods similar to those outlined in Pan, et al. (2017). Roughly 5 g (dry mass) of a single vegetation species was submerged in 500 mL of distilled water in an acid-washed, 500 mL HDPE bottle. Bottles were covered with untightened caps to reduce evaporation and keep contaminants from entering the microcosm. Although water conditions have been shown to change nutrient dynamics for some analytes (Pan et al. 2017), distilled water was used in order to assess dynamics in the absence of interactive effects. A series of five 50 mL water samples were taken 1, 5, 24, 72 and 168 hours after inundation and filtered using Fisherbrand mixed cellulose esters 45 µm syringe filters to minimize disturbance and removal of vegetation. Water samples were analyzed by the Environmental Analysis Lab at BYU for NO_3^-,

NH_4^+, TDN, SRP, and DOC using the same methods as detailed in the sediment rewetting procedures above.

The estimated nutrients leached per gram of vegetation for the total wetland was calculated similarly to the total nutrient leaching potential of vegetation, as explained above. The mass of nutrients leached per mass of vegetation, as determined via the microcosm experiment, were multiplied by the estimated mass of each species at each site.

Storm Event Nutrient Dynamics in CSWs

To assess nutrient dynamics in the two CSWs during storm events of varying size, ISCO automated water samplers were placed at up and downstream locations on approximately 100 m reaches for both wetlands (Fig. 1c). The ISCO samplers were installed with liquid-level actuators and programmed to sample 500 mL of water every 10 minutes for 4 hours (a total of 24 samples) as soon as the actuator was submerged. This high-resolution sampling schedule was designed to catch the first flush during storm events. Grab samples were taken roughly every 12 hours after the end of fine resolution sampling to quantify changes in nutrient dynamics during ponding. These daily grab samples were taken until drying occurred at each site. Storm and snowmelt sampling occurred during 3 separate events from February to November 2017 (Fig. 2). Water samples were analyzed for dissolved nutrients and organic carbon, and total phosphorus. For dissolved nutrients, samples were filtered through ashed Whatman GF/F filters and frozen until analyzed at the Environmental Analysis Lab at BYU following procedures described in the sediment rewetting section. Unfiltered water samples for total phosphorus (TP) were digested using a nitric acid microwave digestion using an Ethos EZ system (Milestone, Shelton, CT) followed by quantification by ICP-OES (iCAP 7400, Thermo Scientific, Waltham, MA), also at the Environmental Analysis Lab at BYU.

Analysis

The rate of change in nutrient mass per gram of soil and vegetation for both microcosm experiments were calculated to evaluate variation in patterns of nutrient release and uptake between treatments (soil site or vegetation species) and over inundation time. Positive slopes indicated net release or leaching of nutrients, whereas negative slopes indicated net nutrient removal or uptake. Data were cube-root transformed to create a more normal distribution while preserving the negative slope values. Although the transformations improved normality of the distribution, data were still not entirely normal. The effects of treatments, inundation time, and the interaction between the two on dissolved nutrient contents were assessed using a repeated measures ANOVA (rmANOVA) using the “car” package in R (Fox et al. 2018). ANOVA is relatively robust to irregularities in normal distributions of data and allowed us to test for interaction effects in both the soils and vegetation experiments. Effects were considered statistically significant at $p < 0.05$.

The difference in nutrient concentrations between down and upstream locations were compared to elucidate general patterns of nutrient uptake and release during diverse storm events along the 100 m reach at each CSW. Correlation matrices were used within each storm event to determine correlations between up and downstream nutrient concentrations. These correlations allowed us to determine if nutrient transformations were likely occurring along each CSW reach in different storm events. Correlations greater than 0.5 or less than -0.5 were considered ecologically significant.

Results

CSW Soils

Nutrient release from soils varied significantly across inundation time for all measured analytes, between sites for most N forms, and with interactions among time and site with a few exceptions (Table 2). Across all analytes and at both sites, nutrient release rates were highest in the first hour after rewetting. Following this initial pulse, the majority of slopes remained close to zero, with a few periods across nutrients and sites clearly dominated by either removal (e.g. NH_4^+, hour 1-5, Fig. 4) or further release (e.g. DOC, Fig. 3). The dynamics of release and removal of N species from soils (excluding dissolved organic N) differed significantly between sites (Table 2). FA soils showed reduced rates of release during the first hour, as well as more consistent, distinct periods of net removal for NO_3^- and NH_4^+ later in the week (Fig. 4). For NO_3^-, these removal periods occurred more than 24 hours before removal dominated in SJ soils. While NH_4^+ concentrations increased throughout the weeklong period at SJ, NH_4^+ removal dominated at FA starting at 72 hours. Although the mean concentration of nutrients approached the detection limit in some cases at around 1 week after inundation (e.g. SJ SRP), in the majority of cases, concentrations were still well above 0 at the end of the week.

CSW Vegetation

Vegetation was much more abundant at FA (90% cover) than SJ (9% vegetation cover, Fig. 5). Vegetation at FA included some wetland species (namely *Juncus balticus* and *Schoenoplectus acutus*), while the little vegetation at SJ were terrestrial species (Fig. 5). Three of the vegetation species found at FA, making up a total of 35% of total vegetation cover, have been known to support N-fixing bacteria. These include *Juncus balticus* (Tjepkema and Evans

1976), *Schoenoplectus acutus* (Rejmánková et al. 2018), and *Tribulus terrestris* (Athar and Mahmood 1985). The total vegetation nutrient content at FA was more than an order of magnitude greater than that at SJ for both N and P (Fig. 6) primarily due to differences in vegetation abundance between the two sites. Total nutrient content of all measured vegetation species at FA was 7808.4 g N and 753.6 g P, while the totals at SJ were 481.8 g N and 50.3 g P.

Nutrient release from vegetation varied significantly across vegetation species, inundation time, and the interaction between the two, with some exceptions (Table 3). *Carex spp.* microcosms had the highest concentrations of most analytes and *Rumex crispus* microcosms the lowest. Release rates tended to be highest at the beginning of the experiment for all treatments and analytes (Fig. 7 and 8). However, the time it took for release to slow or for nutrient removal to become the dominant process varied between analytes and between vegetation types. Following leaching, there was little evidence of net removal for most analytes within a week-long period, with the exception of NO_3^- in *Carex spp.* microcosms (Fig. 7 and 8). By the end of the one-week inundation period, most analytes had not approached a concentration of 0, indicating net inputs of nutrients to water in the CSWs from vegetation even after 1 week of inundation. Notably, across all analytes, nutrient loss from vegetation was around 2 orders of magnitude higher than that from soils by mass.

Total Nutrient Contribution from CSW Vegetation and Soils

CSW soils and vegetation at both sites were net sources of nutrients to these systems during a week-long period of inundation. In the events in which these systems let out to the Portneuf River, connection was likely to happen within the first 24-48 hours, depending upon the storm event and the CSW. Within this timeframe, both rates of NO_3^- and SRP release peaked in both CSWs (Fig. 9 and 10). Total estimated contribution of nutrients from CSW vegetation was generally small for most analytes, between 0.00004 and 14.1% of the total nutrient addition (Fig. 9 and 10). The minimal contribution of vegetation was particularly notable at SJ (Fig. 9 and 10) due to the lack of vegetation available for leaching. Even at the more densely vegetated FA, soils were still a larger source for nutrients across all measured analytes over the week-long period. However, at 72 hours and a week after inundation, FA vegetation was a significant source of DON, contributing 41.7 and 40.8% of the total DON, respectively. Because of the generally small role of vegetation, patterns in total nutrient contributions were principally controlled by soil leaching dynamics described above.

Storm Event Patterns in Up- and Downstream Nutrient Concentrations

Based upon correlation matrices, up- and downstream nutrient concentrations were more often positively correlated at FA, while SJ showed fewer significant correlations. This indicated that while FA may be relatively inert, there may have been nutrient addition, removal, or processing occurring at SJ and those rates may have been changing over the course of an event. Although more data are needed to confirm this, it also appeared that correlations changed according to the size or conditions of the precipitation event. During the smallest measured event (0.51 mm; September 8, 2017), NO_3^-, TDN, TON, and TP all showed positive correlations between up and downstream concentrations at SJ, however during the largest snowmelt event only NO_3^- and TDN were substantially correlated (Table 4).

Comparisons of the concentration differences between up and downstream locations at each site revealed potential variation among analytes for different storm-event conditions and sites. For both SRP and NO_3^-, particularly at FA, concentration dynamics during the largest event

(Nov 16, 2017, 16 mm rain event) loosely matched the patterns observed for the respective nutrients in the soil leaching experiment (Fig. 3 and 4), as positive values within the first few hours indicated net leaching or release between the up and downstream locations (Fig. 11). This similarity in rain-event concentration dynamics and microcosm nutrient dynamics indicated that the observed patterns in the microcosm experiments may be scaled up successfully to explain function of the whole CSW during some events. However, storm event patterns across nutrients appeared more variable both during the large snowmelt event that occurred in February of 2017 and the small thunderstorm that occurred in September of that year (Fig 11). Both of these storm events did not match up closely with observed patterns of release from vegetation or soil microcosm experiments at SJ. For the February event, negative values within the first few hours of sampling for NO_3^-, SRP, and DOC indicated removal or uptake occurring within the reach at SJ, while FA stayed relatively stable (Fig 11). Cl^- concentrations for the February storm generally fluctuate around zero and were rarely strongly negative, indicating that there was limited physical removal occurring at either site (Fig. 12). However, there were a few periods during which decreases in Cl^- appeared to match up with dips in NO_3^-, for example, at around 120 hours (Fig.12). It is important to note that during this storm event at SJ, water was forced to flow both above and below a thick layer of ice and that samples were taken from the top layer that was disconnected from soils and most senesced vegetation until this layer melted. For the small thunderstorm event, solute concentration patterns were more variable over time, as NO_3^- showed a strong negative signal at the beginning of the event and DOC fluctuated more (Fig. 11). The difference in SRP from up- to downstream was positive within the first hour, indicating SRP addition over the reach, then declined over time (Fig. 11). This September storm was one of the first after the seasonal summer drought, and most vegetation had senesced in the CSW beds at this point.

Discussion

Nutrient Loading from Ephemeral CSWs to Downstream Surface Waters

Although many CSWs are implemented with goals of macronutrient retention and removal, our results indicate that conditions in CSWs in cold desert climates may not only inhibit the effectiveness of nutrient uptake but could actually increase N and P concentrations in stormwater before releasing it to downstream aquatic systems. Nutrient leaching and release were the main processes across time in the case of both soils and vegetation; however, the total nutrient contribution of vegetation to the entire wetland system was relatively small.

The studied CSWs impound water during smaller storm events, and therefore they may effectively be changing lower-concentration, chronic nutrient additions to lower-frequency, high-concentration additions. To our knowledge, there has been little study comparing the impacts of chronic versus acute P loading on biogeochemical processing rates in streams and rivers. However, one study on N found that frequent, short-term pulses of N could be retained by in-stream biota, but that acute inputs at high concentrations can surpass N-demand (O'Brien and Dodds 2010). When N surpasses biological demand, the excess N travels downstream, increasing the length of stream negatively impacted by the discharge. Additionally, the efficiency of in-stream denitrification decreases as NO_3^- concentrations increase (Mulholland et al. 2008). Ephemeral CSWs, then, may not only be ineffective themselves at reducing nutrient loading to urban rivers and streams, but the patterns of stormwater release may further reduce nutrient processing efficiency in these waters.

Nutrient Release from CSW Soils and Vegetation and Potential Environmental Controls

In the soil rewetting experiments, the patterns of nutrient release that we observed immediately following inundation were consistent with literature on the release of N and P with rewetting of semiarid soils (Austin et al. 2004; Meixner and Fenn 2004) and stream sediments (Larned et al. 2010; Arce et al. 2014; Kinsman-Costello et al. 2016). Previous research also suggests that soil microbes in these semiarid systems might be well-adapted to conditions of frequent drying and rewetting and therefore able to rapidly resume biogeochemical processing after inundation (Dodds et al. 2004; Austin and Strauss 2011; Arce et al. 2015). While some cores exhibited periods of nutrient removal around 24-72 hours after inundation, none of our microcosms reached concentrations at or below the detection limit within a week-long period, indicating net additions of all nutrients over time. While these microbial communities may have rapidly recovered, removal of nutrients in these systems was not sufficient to offset leaching at a timescale relevant to CSW function.

Our findings are consistent with those of Oberts (1994) and Semadeni-Davies (2006), suggesting that the characteristics of snowmelt may further change the function of stormwater infrastructure. In the observed February 2017 snowmelt event, decreases in nutrient concentrations along the CSW reaches likely indicate that the water was separated from soils and diluted due to the presence of melting ice in these systems, rather than biological nutrient removal. Because the water initially ran over the ice, interaction between water and the soils was limited, preventing nutrient addition and resuspension. Diurnal changes in flow to these systems due to repeated thawing and refreezing could further explain some of the variation in concentrations later in the week. Hydrologic and physical drivers likely explain changes in nutrient concentration during snowmelt events, rather than microbially-mediated processes, because of the reduction of microbially-mediated nutrient transformations in cold temperatures (Vymazal 2007). For example, below 5 °C both nitrification and denitrification cease and the optimal temperature range for ammonification is 40 – 60 °C (Vymazal 2007). This is particularly relevant to understanding the function of CSWs in cold desert climates, as the majority of flow events may be occurring when temperatures are below optimal range for microbially-based nutrient transformations. Further research on the function of CSWs in cold climates is needed to fully understand the suite of physical and biological factors that change as a result of climatic differences, and the implications for nutrient dynamics in cold desert CSWs.

Wetland vegetation is commonly used in CSWs to sequester nutrients (Kadlec and Wallace 2008), both through direct nutrient uptake and because vegetation indirectly creates conditions conducive to nutrient removal and cycling (Cole 2002; Vymazal 2007; Srivastava et al. 2008). Leaching experiments confirmed H2 that senesced vegetation in the studied CSWs is a source of both N and P. However, while the total calculated nutrient pool in vegetation was not insubstantial (Fig. 6), the leaching experiments indicated that senesced vegetation was likely not a significant source of nutrients to CSW systems. The significant differences in dynamics of nutrient release and removal between species across most analytes (Table 2) indicate that further leaching experiments should be conducted on other vegetation species present at each site. At FA, it would be particularly important to investigate leaching of nutrients from *Schoenoplectus acutus* as photo analysis revealed it was the most abundant species throughout FA (Fig. 5) and nutrient content measures of this species showed high concentrations of N and P (Fig. 6). Although some previous research found increases in most dissolved nutrient concentrations in water over time of inundation (Davis et al. 2006; Pan et al. 2017), we found nutrient release from senesced vegetation was immediate and did not exhibit the expected sustained increase with organic matter decomposition over time. This discrepancy could be because we examined nutrient release for a shorter time and on a much finer timescale than previous research. NO_3^- dynamics in vegetation microcosms differed from those observed in other nutrients. For both *Juncus balticus* and *Rumex crispus*, measures of NO_3^- were below detection limit for the duration of the study. NO_3^- levels in *Carex spp.* exhibited a significant flush within the first 5 hours, followed by relatively steep declines by the end of the weeklong inundation. These declines in NO_3^- were consistent with findings of Pan et al (2017), who observed declines NO_3^- in plant litter mesocosms after 1 week of inundation. They attributed observed NO_3^- decreases to carbon availability promoting denitrification (Pan et al. 2017). Concomitant decreases in TDN concentration in microcosms confirm this possibility, as they indicate that at least a portion of the NO_3^- has been entirely removed from the water in the microcosm, possibly with release as N_2 gas via denitrification. Many nutrient cycling processes require sources of DOC (Vymazal 2007), and high concentrations of DOC in vegetation microcosms (Fig. 7) indicated that denitrifying bacteria would not likely be DOC-limited in these systems.

Though the senesced vegetation at FA may support some nutrient cycling, it is important to note that the abundance of vegetation known to support N-fixation at FA is potentially problematic to the goal of removing N from these CSWs. If these species are supporting N-fixing microbes, they could not only be failing to remove N inputs to the system from stormwater via direct uptake, but adding atmospherically-derived N to the system after this vegetation senesces, becoming a net source of N to the CSW. However, N releases from FA soils versus those at SJ indicate that the presence of N-fixing plants may still be better than the complete absence of plants in terms of reducing the total amount of N released from a CSW system. Additionally, in a P-rich system, such as FA, the presence of N-fixing plants may actually be beneficial because it may allow for more uptake of P from soils (Rejmánková et al. 2018).

Although there is some direct release from and transformation of nutrients associated with CSW vegetation, the lower rates of N leaching upon soil rewetting and the distinct periods of uptake for NO_3^- and NH_4^+ that were observed at FA but not SJ (Fig. 4) suggest that vegetation may impact nutrient dynamics in CSWs in cold deserts in two distinct ways: first, through the direct and indirect effects on the soil nutrient pool between events and second, by changing the potential for nutrient transformation during events through support of microbial communities.

Direct plant uptake between events may have decreased the pool of NO_3^- and NH_4^+ available for leaching from soils in FA compared to SJ. Although soil cores were taken away from any aboveground patches of vegetation, belowground biomass may have been present and involved in nutrient uptake. Vegetation takes up N in various forms (Vymazal 2007), so active vegetation in the surrounding area may have contributed to lower concentrations of all N forms in FA versus SJ soil leachate. Furthermore, an active vegetation community may have indirectly helped maintain the microbial community during dry periods at FA. Although soil moisture was not directly measured at sites, vegetation cover has been shown to be one of the largest determinants of small-scale patterns in soil moisture (Cantón et al. 2004). Particularly at the end of summer, when vegetation has low water requirements (Vymazal 1995), but is still standing and provides cover for soils, soil moisture could be preserved longer than in bare soils and reduce microbial stress. Preserving soil moisture could allow the microbial community to stay active in soils longer, allowing them to remove or cycle more nutrients. If sufficient moisture is preserved it could prevent lysis entirely (Qiu and McComb 1995; Schimel et al. 2007) and make possible the quicker return to nutrient cycling after rewetting (Austin and Strauss 2011). Additionally, reducing moisture loss could prevent physical processes, such as evaporation, known to increase concentrations of nutrients in the top soil layers (O'Brien and Dodds 2010) and reduce their availability for resuspension upon rewetting.

Plant biomass may provide substrates that support microbial communities involved in nutrient cycling during stormflows. The observed decrease in NH_4^+ concentrations in FA soil leachate towards the end of the weeklong inundation period could be the result of interactions between belowground biomass and soil microbial communities. Previous research has shown that a diverse array of microbes that are commonly involved in the nitrogen cycle, including nitrification, are particularly abundant around the root structures of plants (Paul 2014). Nitrification at root sites in FA soil cores could explain this observed decline in NH_4^+. Soil OM is an important source of DOC for denitrification (Weisner et al. 1994; Paul 2014), and large accumulations of OM may have contributed to greater in-CSW NO_3^- transformation at FA compared to SJ and lower observed NO_3^- concentrations leaching from soils upon rewetting. Although we did not measure soil organic matter directly, plant litter is one of the most important sources of organic matter in soils (Kalbitz et al. 2000), and FA is densely vegetated compared to SJ. Senesced vegetation at FA may be providing a sustained source of DOC that is available throughout the flow event (Fig. 7), whereas at SJ, stormwater may be the major source of DOC. During both observed rain events, DOC concentrations at the upstream site at SJ peaked within the first two hours of inundation and declined over time. If DOC flushes through the system before the microbial community has the opportunity to recover from drying, microbial processing of nutrients may be DOC-limited.

While the evidence suggests that both soils and vegetation in ephemeral CSWs likely act as N and P sources instead of sinks, results from storm-event sampling suggests that event characteristics may influence nutrient dynamics in CSWs in cold desert climates. Antecedent conditions, particularly antecedent dry days, could have a significant impact on both the concentration of pollutants entering a CSW (Barbé et al. 1996; Gallo et al. 2013) and the time it takes for the microbial community to begin processing nutrients at pre-drying rates (Austin and Strauss 2011). The soil samples used in this experiment were taken at the end of summer to be representative of what occurs in the first rain event following the seasonal drought, and although these CSWs rarely retain water for long periods of time, soil moisture in wetter seasons might be sufficient to support some cycling in soils and quicker returns to nutrient removal post-rewetting. The influence of vegetation as a nutrient source likely also depends upon the timing and seasonality of storms. Although we observed relatively low total contributions from vegetation, our evidence suggests that nutrient release from vegetation likely plays the strongest role during the first storm event following senescence, as the easily leached nutrients are quickly released into the CSW. Later in the fall, the role of leaching from vegetation is likely diminished as nutrient availability in vegetation declines. Finally, the presence of ice within the bed of the wetland could be another important driver of nutrient dynamics in CSWs in cold climates in winter. Ice can both separate water from interacting with soils if it runs over the top and force increased interaction if it runs beneath (Oberts 1994)—with both sometimes occurring within the same event— as observed in the February 4 snowmelt event. While it is important to note that both soils and vegetation have the potential to be sources of nutrients in these systems, both storm-event and CSW conditions likely play a role influencing patterns of nutrient flux in cold desert, ephemeral CSWs.

Implications for CSW Design and Management

Findings from this study not only inform future research on the functioning of CSWs in cold desert climates but have implications for the design and management of these systems. Our results show that the frequent drying and rewetting of CSW soils can cause net nutrient release to downstream aquatic systems. Although it may take more planning and careful consideration before construction, having a supplemental, permanent source of water flow through these systems could promote net nutrient removal without the need to significantly extend retention time. However, even permanently-wetted stormwater structures have had variable results in macronutrient retention and can still be sources for some nutrients (Gold et al. 2017a; Gold et al. 2017b). Although permanent wetting alone may not be sufficient to make CSWs strong nutrient sinks, it would likely reduce the biotic and abiotic processes that cause easily leachable nutrients to concentrate in surface soils. Without drying, processes such as precipitation of N salts (McLaughlin 2008) and mineralization of soil organic P (Chepkwony et al. 2001) at surface soils would not occur and likely subsequently reduce the magnitude of nutrient leaching from soils when storm events flow through these systems.

In addition to water, microbial nutrient processing depends upon the presence of organic matter, meaning vegetation abundance likely also plays an important role. Vegetation in the studied CSWs did not appear to have strong direct influences on uptake or release for most nutrients; however, it could potentially indirectly influence nutrient dynamics by changing soil conditions. Vegetation has also been shown to provide substrate for microbially-mediated nutrient cycling processes in wetlands (Vymazal 2007), and this function may be more important than the impacts of direct vegetation uptake in cold-desert climates because of the disconnect between peak growing season and peak precipitation (Vymazal 2005). Excluding *Schoenoplectus acutus*, the measured species in these CSWs had relatively low N and P contents, but previous research on the nutrient contents of various wetland species (McJannet et al. 1995; Brix 1997) could be used to optimize nutrient sequestration potential in CSWs (Mitsch and Gosselink 2000). Additionally, the removal of any vegetation species known to support N-fixing microbial communities would likely be beneficial in systems with high concentrations of N in soils and stormwater. Conversely, in CSWs with high concentrations of P, the planting of species that support N-fixation may support P removal. It is important to consider that nutrient sequestration via direct uptake is only temporary. If the dead vegetation is allowed to decompose onsite, our results support previous findings that the nutrients that were taken up will be quickly released back into the system (Vymazal 2007). However, this contribution appears to be small compared to release from CSW soils and, if the presence of vegetation creates environmental conditions conducive to microbial removal of nutrients, the presence of vegetation may still be net beneficial. Semiarid climates may pose additional complications to vegetation-based solutions, particularly if the dry period coincides with peak vegetation growth, as wetland plants most efficient at nutrient uptake may be unable to survive long periods of drought without irrigation (Houdeshel et al. 2015).

Hybrid CSW designs that include both surface and subsurface flow have mainly been used for the treatment of wastewater in the past (Vymazal 2005); however their use in the treatment of stormwater has begun to emerge (Choi et al. 2015). Hybrid CSW systems have been shown to improve macronutrient removal, particularly N, due to the presence of combined aerobic and anaerobic conditions that support nitrification and denitrification (Vymazal 2005; Choi et al. 2015). However, hybrid CSWs are more expensive, less commonly used throughout the U.S. (Vymazal 2013), and may require more intensive and diverse maintenance and monitoring. Additionally, hydraulic conductivity in subsurface flow CSWs is critical to performance (Vymazal 2005), and high inputs of fine sediment from stormwater could potentially reduce effectiveness without proper design.

Even with proper design, any CSW that is not well monitored and maintained could receive unintended inputs that could have significant negative impacts on CSW function. While concentrations for N species were all higher in leachate from SJ soils, FA exhibited high SRP concentrations that were noteworthy. FA is located directly adjacent to a railroad yard, and during several storm events, subsurface flow from beneath the railroad tracks emerged to enter the CSW close to the inlet. A grab sample of this runoff had extremely high concentrations of TP (6.19 mg/L) and SRP (0.71 mg/L). The high SRP values observed in the soil core leaching experiment suggest that P from this runoff has built up in the soils within FA over time. Proper management of this point source, as well as removal of P-contaminated soils would be necessary to reduce the potential of this CSW becoming a significant point source of P to the Portneuf River.

Although the studied ephemeral CSWs may be a source of N and P to downstream surface waters, they may reduce the impacts of the urban stream syndrome in other ways. The Idaho Department of Environmental Quality has collected water quality data up- and downstream of the city both pre- and post-construction of SJ. Though there was no detectable significant difference between pre- and post-construction suspended sediment loads downstream of SJ, the CSW has appeared to reduce flashiness of the system (Idaho Department of Environmental Quality 2018). Prior to the construction of SJ, 30% of precipitation events caused flow peaks in the river whereas post-construction flow peaks were reduced to 22% of precipitation events. This reduction was most notable in large storm events where, post-construction, storm events larger than 1.3 cm caused 15% fewer flow peaks (Idaho Department of Environmental Quality 2018). Although conditions in ephemeral CSWs in cold desert climates may limit macronutrient retention and removal, CSWs may still benefit water quality in other ways.

Conclusions

CSWs are used across climates, commonly with the goal of reducing macronutrient loads entering downstream aquatic systems. In cold-desert climates, net nutrient release from CSW soils may dominate nutrient dynamics in these systems and cause further impairment instead of removing nutrients. Vegetation did not appear to play a significant role in the direct uptake and removal of nutrients from these CSW systems; however it could indirectly improve environmental conditions in soils that may allow microbial communities to recover more quickly following drying and potentially reduce concentrations of nutrients leached from soils following rewetting, particularly for NO_3^-. In cold-desert climates, a diverse array of antecedent conditions, such as long periods of drying and soil desiccation or the presence of ice within a system, likely alter nutrient cycling process in CSWs. Although the two studied CSWs effectively kept smaller runoff events from entering the river, this may reduce the river's ability to deal with nutrient contributions and acute inputs could cause negative impacts that last further downstream. While CSWs could be effective stormwater management infrastructure in semiarid, snowmelt-driven climates, their implementation may require more climate-specific planning and considerations than humid climate counterparts.

Tables

Table 1. A comparison of the two study sites, First Avenue and Sacajawea Park. Pocatello, ID, USA, 2018.

	First Avenue CSW (FA)	**Sacajawea Park CSW (SJ)**
Year Constructed	1998	2008
Approx. Wetland Area	~8,100 m^2	~18,500m^2
Approx. Catchment Area	~1.4 km^2	~4.9 km^2
Land Cover/ Land Use	Residential (60%), large cemetery (18%), university campus (16%)	Urban/residential (60%), exurban/undeveloped upland (32%)
Vegetation Composition and Abundance	18.8% willows, 14.5% grass, 14.5% vines, 12.5% bulrush, 10.5% Baltic rush, 6% curly dock, 6% low shrub, 5% other, 11% bare ground	92% bare ground, 2% *Rumex crispus*, 1.5% grasses
Soil pH	8.45	8.17

Table 2. Repeated measures ANOVA results, vegetation. Results of a series of repeated measures ANOVAs comparing the effects of vegetation type, time, and the interaction of the two on the cube root of the rate of change in nutrients in water in each microcosm. Vegetation was collected from First Avenue and Sacajawea CSWs in Pocatello, ID, USA, in the fall of 2017. Significant effects are noted in bold.

Nutrient	Source of Variation	DF	SS	F-value	p-value
SRP	Type	2	0.68	1.22	0.3458
	Time (t)	**4**	**75.59**	**108.89**	**< 0.0001**
	Type x t	**8**	**17.13**	**7.78**	**< 0.0001**
DOC	**Type**	**2**	**58.44**	**27.37**	**< 0.0001**
	t	**4**	**180.22**	**19.68**	**< 0.0001**
	Type x t	**8**	**63.02**	**4.63**	**< 0.0001**
NO_3	**Type**	**1**	**41.35**	**271.43**	**< 0.0001**
	t	**4**	**199.21**	**84.30**	**< 0.0001**
	Type x t	**4**	**364.87**	**81.49**	**< 0.0001**
NH_4	**Type**	**1**	**85.86**	**365.11**	**< 0.0001**
	t	**4**	**98.39**	**103.58**	**< 0.0001**
	Type x t	**4**	**66.16**	**13.63**	**0.0008**
TON	**Type**	**1**	**9.58**	**5.09**	**0.0375**
	t	**4**	**80.48**	**12.51**	**< 0.0001**
	Type x t	4	19.21	1.81	0.1108
TDN	**Type**	**1**	**52.84**	**55.79**	**< 0.0001**
	t	**4**	**287.29**	**64.81**	**< 0.0001**
	Type x t	**4**	**344.01**	**32.34**	**< 0.0001**

Table 3. Repeated measures ANOVA results, soils. Results of a series of repeated measures ANOVAs comparing the effects of soil core site, time (t), and the interaction of the two on the cube root of the rate of change in nutrients in water in each microcosm. Soil cores were collected from First Avenue and Sacajawea CSWs in Pocatello, ID, USA, in August of 2017. Significant effects are noted in bold.

Nutrient	Source of Variation	DF	SS	F-value	p-value
SRP	Site	1	0.59	4.28	0.1075
	Time (t)	**4**	**66.90**	**53.69**	**< 0.0001**
	Site x t	**4**	**13.42**	**14.83**	**< 0.0001**
DOC	Site	1	0.00	0.42	0.5258
	t	**4**	**0.56**	**76.45**	**< 0.0001**
	Site x t	4	0.01	1.78	0.1452
NO_3	**Site**	**1**	**0.01**	**7.68**	**0.0150**
	t	**4**	**0.05**	**100.74**	**< 0.0001**
	Site x t	**4**	**0.07**	**6.58**	**0.0002**
NH_4	**Site**	**1**	**0.00**	**7.65**	**0.0152**
	t	**4**	**0.08**	**129.58**	**< 0.0001**
	Site x t	**4**	**0.00**	**3.82**	**0.0082**
TON	Site	1	0.00	4.25	0.0584
	t	**4**	**0.21**	**39.14**	**< 0.0001**
	Site x t	4	0.00	0.52	0.7221
TDN	**Site**	**1**	**0.01**	**18.04**	**0.0008**
	t	**4**	**0.48**	**115.44**	**< 0.0001**
	Site x t	**4**	**0.02**	**4.84**	**0.0020**

Table 4. Storm-event correlation coefficients between up- and downstream samples.

Correlation coefficients between up and downstream locations at each CSW site for storm event samples for SRP, TP, DOC, NO_3^-, NH_4^+, TON, TDN, and Cl^-. Storm event samples were taken at First Avenue and Sacajawea CSWs in Pocatello, ID, USA, in February, September, and November 2017. Correlations were considered significant if greater than 0.5 or less than -0.5. Significant correlations are marked in bold text.

	February 2017		September 2017		November 2017	
Nutrient	**SJ**	**FA**	**SJ**	**FA**	**SJ**	**FA**
SRP	0.46	0.45	0.49	-	-0.03	**0.84**
TP	0.26	**0.73**	**0.93**	**-**	**-**	-
DOC	0.23	**0.73**	0.49	-	0.09	**0.89**
NO_3^-	**0.57**	**0.82**	**0.93**	-	-0.11	0.30
NH_4^+	0.11	0.47	0.30	**-**	**0.57**	0.00
TON	0.44	0.46	**0.52**	**-**	-0.14	**0.87**
TDN	**0.58**	**0.83**	**0.86**	**-**	0.33	**0.93**
Cl^-	0.23	**0.55**	**-**	**-**	**-**	**-**

Figures

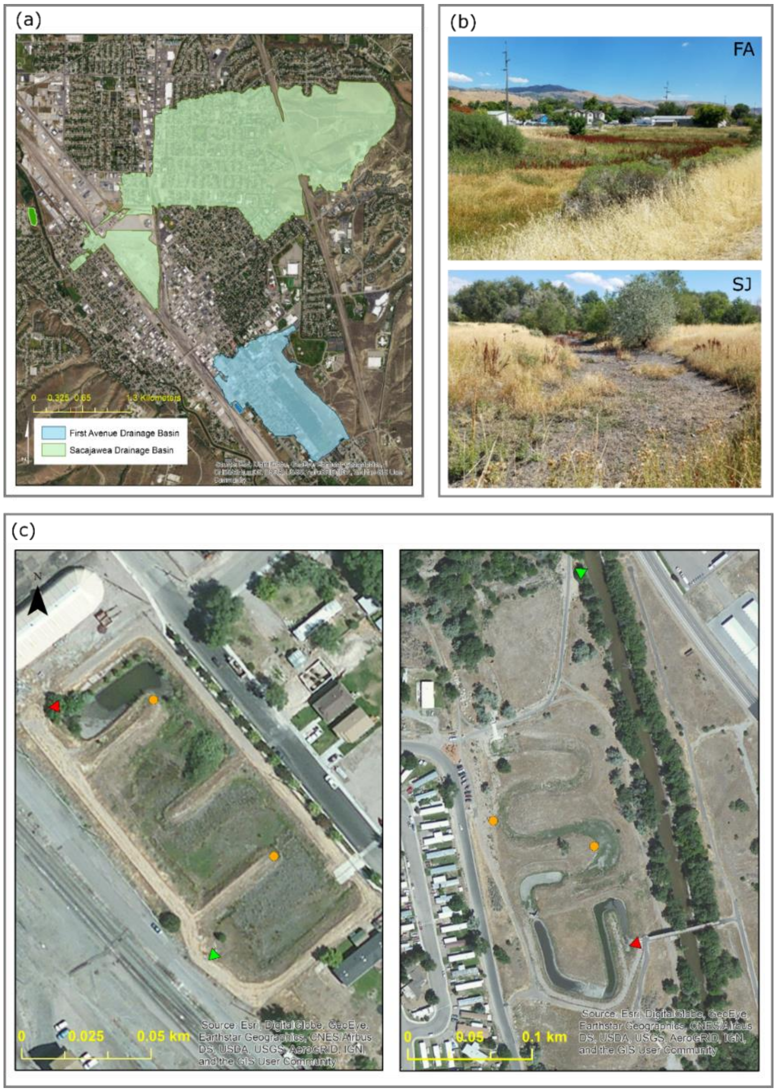

Figure 1. Site characteristics and conditions. (a) Total drainage basin area for the First Avenue (FA) and Sacajawea (SJ) CSWs in Pocatello, ID, USA. The CSWs are highlighted in dark blue (FA) and dark green (SJ), while the area that drains to each CSW is shown in light blue (FA) and light green (SJ). (b) Photographs from summer 2016 showing differences in CSW vegetation cover and dry CSW conditions common in summer and between storm events (top, FA; bottom, SJ). (c) Map of inlet (red triangle), outlet (green triangle), and ISCO automated water sampler (orange circle) locations at both CSWs. FA is shown on the left and SJ on the right.

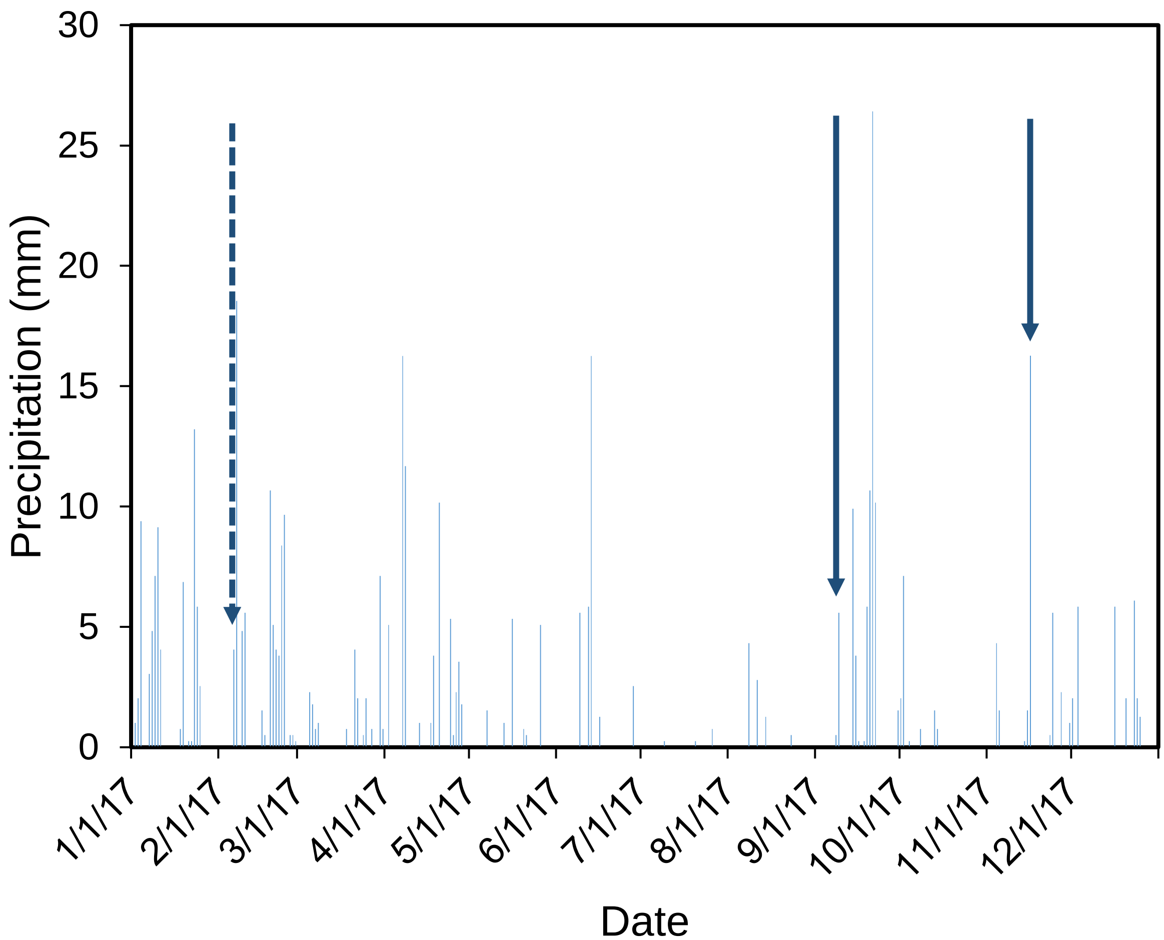

Figure 2. Hyetograph of sampled storm events at CSWs. Dashed arrow indicates a rain-on snow event and solid arrows indicate rain events. Precipitation data from the Pocatello Regional Airport weather station, Pocatello, ID, USA; retrieved via Weather Underground.

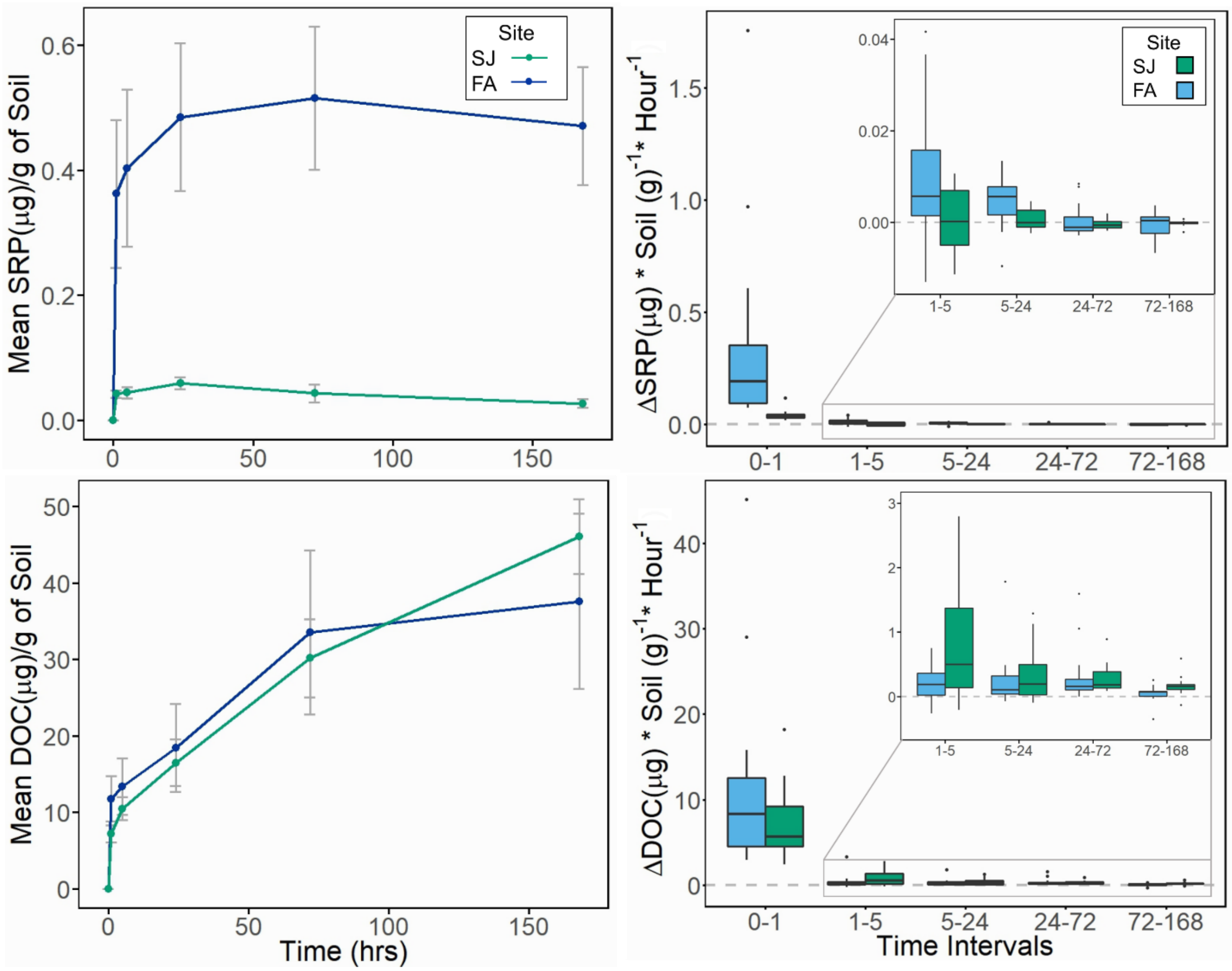

Figure 3. SRP and DOC leaching, soils. Concentrations (left) and rate of change (right) for SRP and DOC from soil leaching experiment. Soil cores were taken from First Avenue and Sacajawea CSWs in Pocatello, ID, USA, in August 2017. Error bars represent the standard error of the mean. Points on the rate of change plot signify outliers. Inset plots show the rate of change cropped to distinguish differences in 1 hour to 1 week. Outliers that fall outside of the gray box were excluded from the inset.

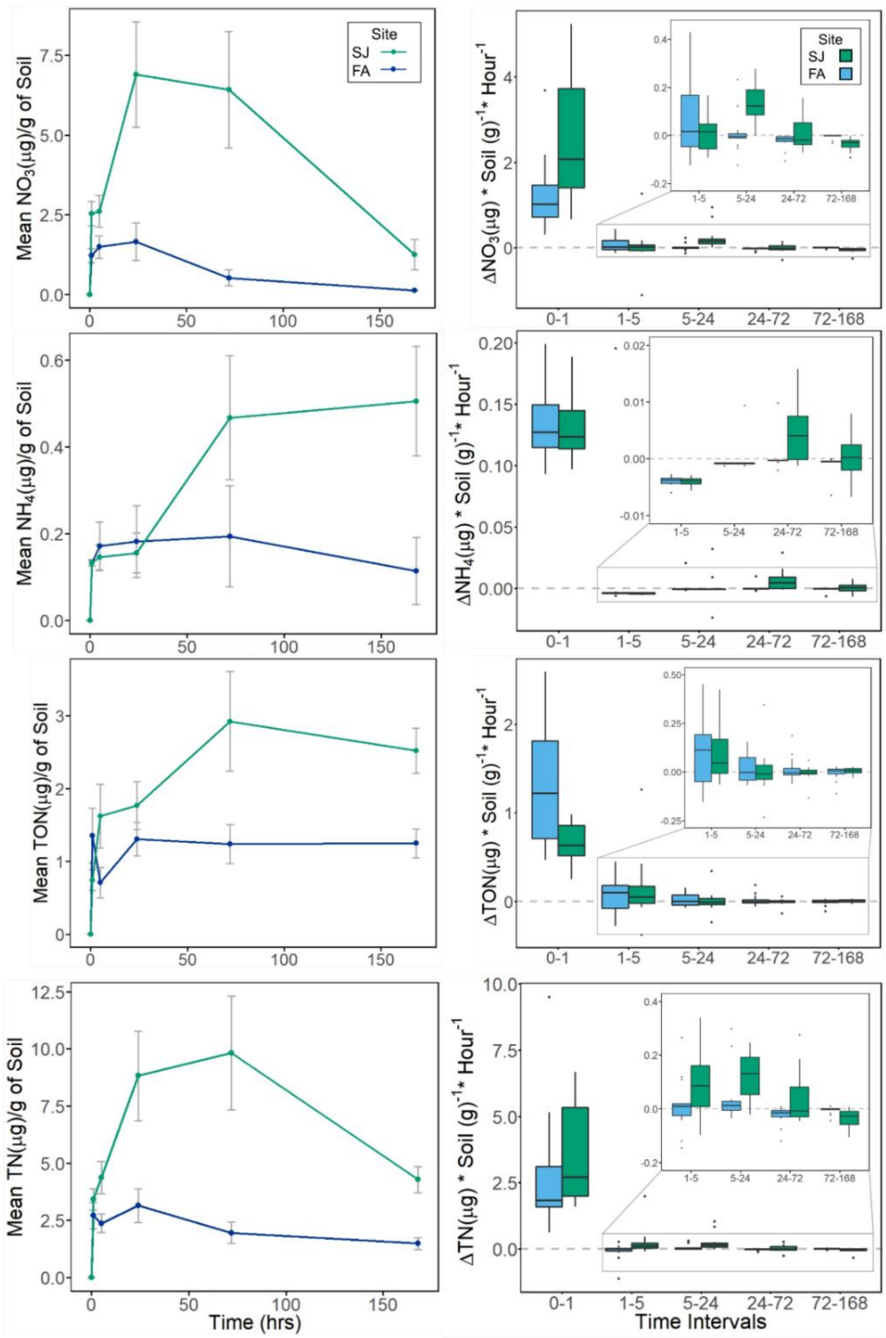

Figure 4. N leaching, soils. Concentrations and rates of change for N forms from soil leaching. Soil cores were taken from First Avenue and Sacajawea CSWs in Pocatello, ID, USA, in August 2017.Error bars represent the standard error of the mean. Points on the rate of change plot signify outliers. Inset plots show rates of change from 1 hour to 1 week. Outliers that fall outside of the gray box were excluded from the inset.

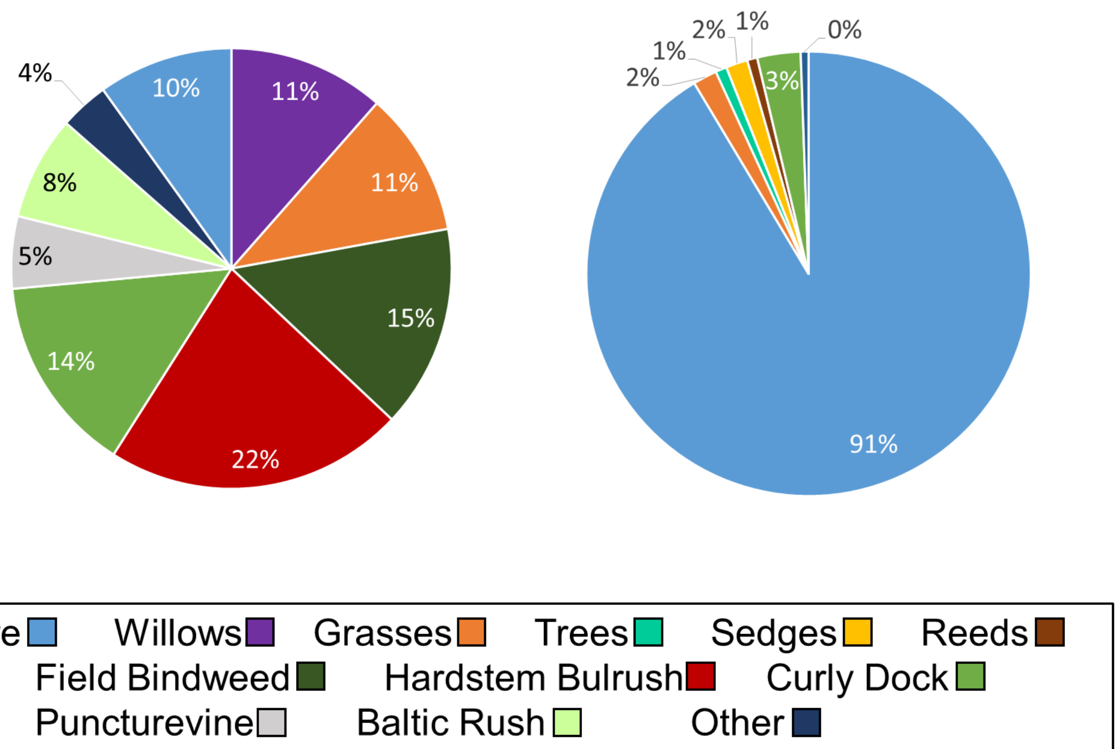

Figure 5. Vegetation abundance and composition. Vegetation abundance and composition for First Avenue and Sacajawea constructed stormwater wetlands in Pocatello, ID, USA, from photo analysis of vegetation surveys conducted at each site.

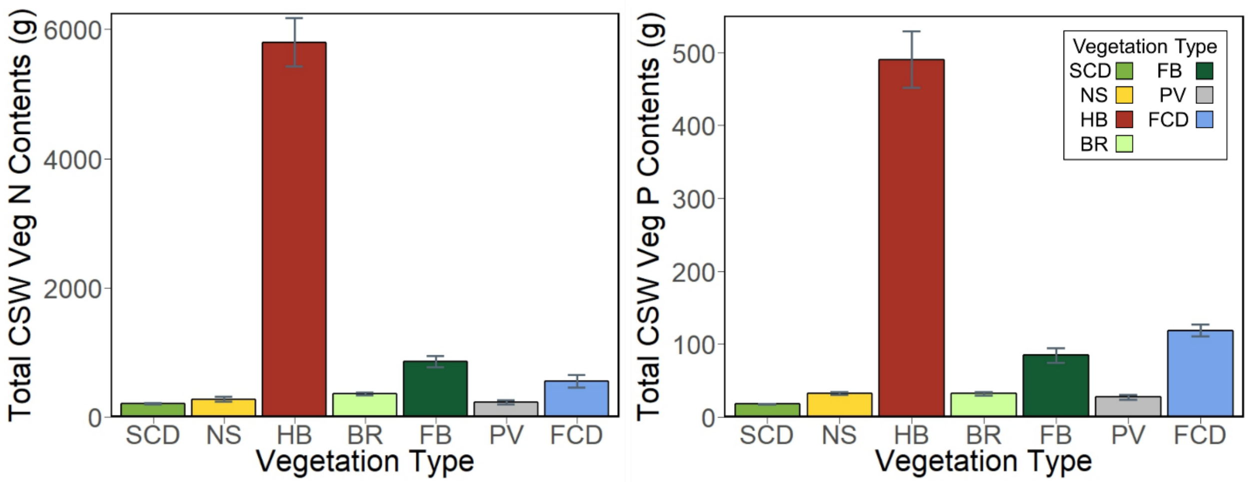

Figure 6. Nutrient content of total vegetation at First Avenue (FA) and Sacajawea (SJ) constructed stormwater wetlands in Pocatello, ID, USA. A selection of species from each site, collected in the fall of 2017, were used to represent the vegetation communities in each CSW. SJ vegetation included *Rumex crispus* (SCD) and *Carex spp.* (NS). At FA, *Schoenoplectus acutus* (HB), *Juncus balticus* (BR), *Convolvulus arvensis* (FB), *Tribulus terrestris* (PV), and *R. crispus* (FCD) were used.

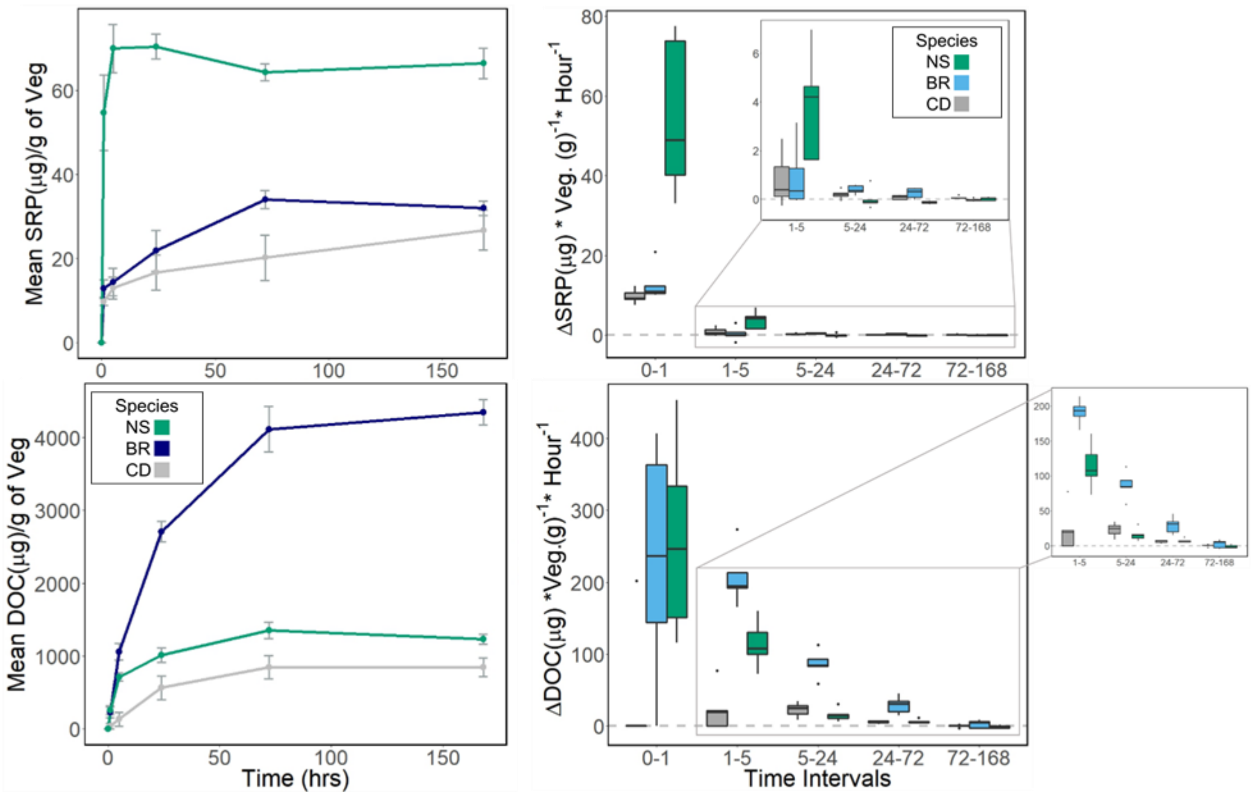

Figure 7. SRP and DOC leaching, vegetation. Concentrations (left) and rate of change (right) for SRP and DOC from vegetation leaching experiment. Vegetation was collected from First Avenue and Sacajawea constructed stormwater wetlands in Pocatello, ID, USA in the fall of 2017. Error bars represent the standard error of the mean. Points on the rate of change plot signify outliers. Inset plots show the rate of change cropped to distinguish differences in 1 hour to 1 week. Outliers that fall outside of the gray box were excluded from the inset.

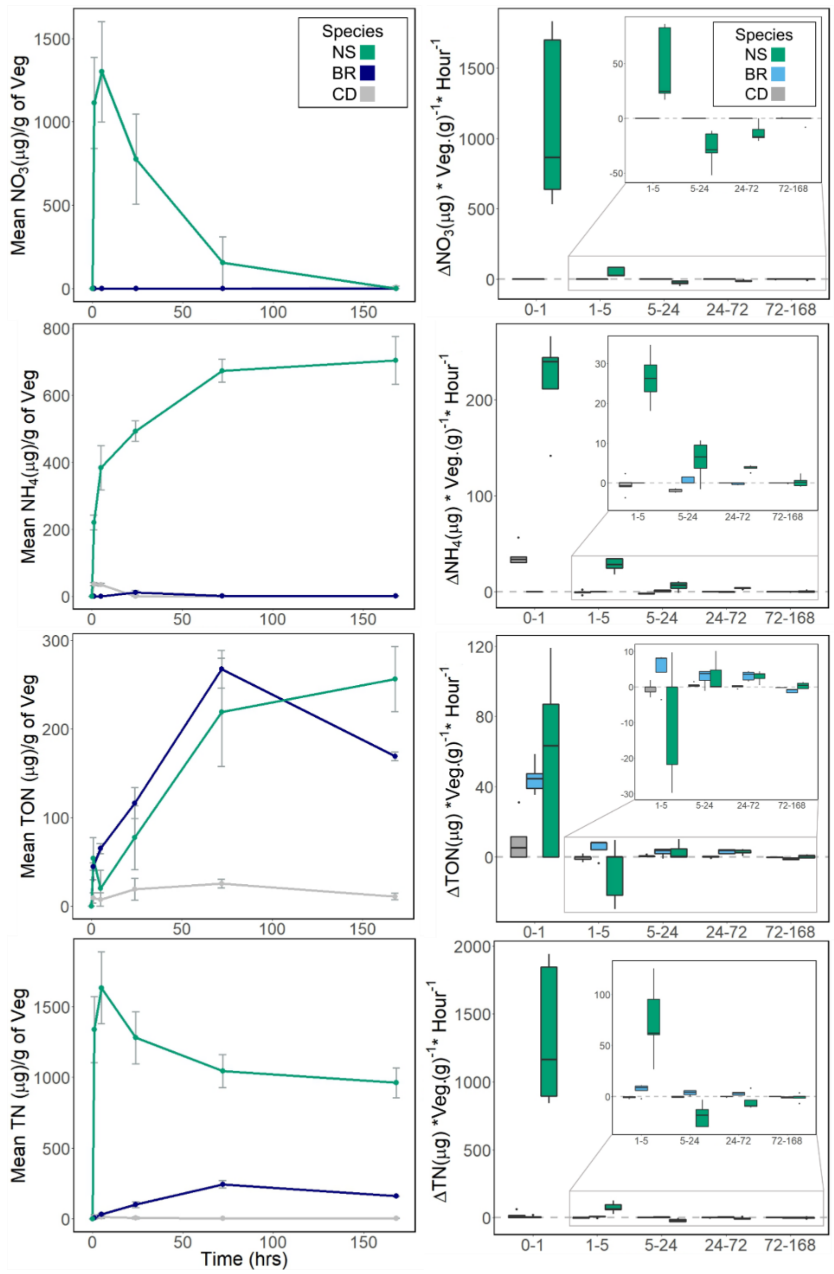

Figure 8. N leaching, vegetation. Concentrations (left) and rate of change (right) for N forms from vegetation leaching experiment. Vegetation was collected from First Avenue and Sacajawea constructed stormwater wetlands in Pocatello, ID, USA in the fall of 2017. Error bars represent the standard error of the mean. Points on the rate of change plot signify outliers. Inset plots show the rate of change cropped to distinguish differences in 1 hour to 1 week. Outliers that fall outside of the gray box were excluded from the inset.

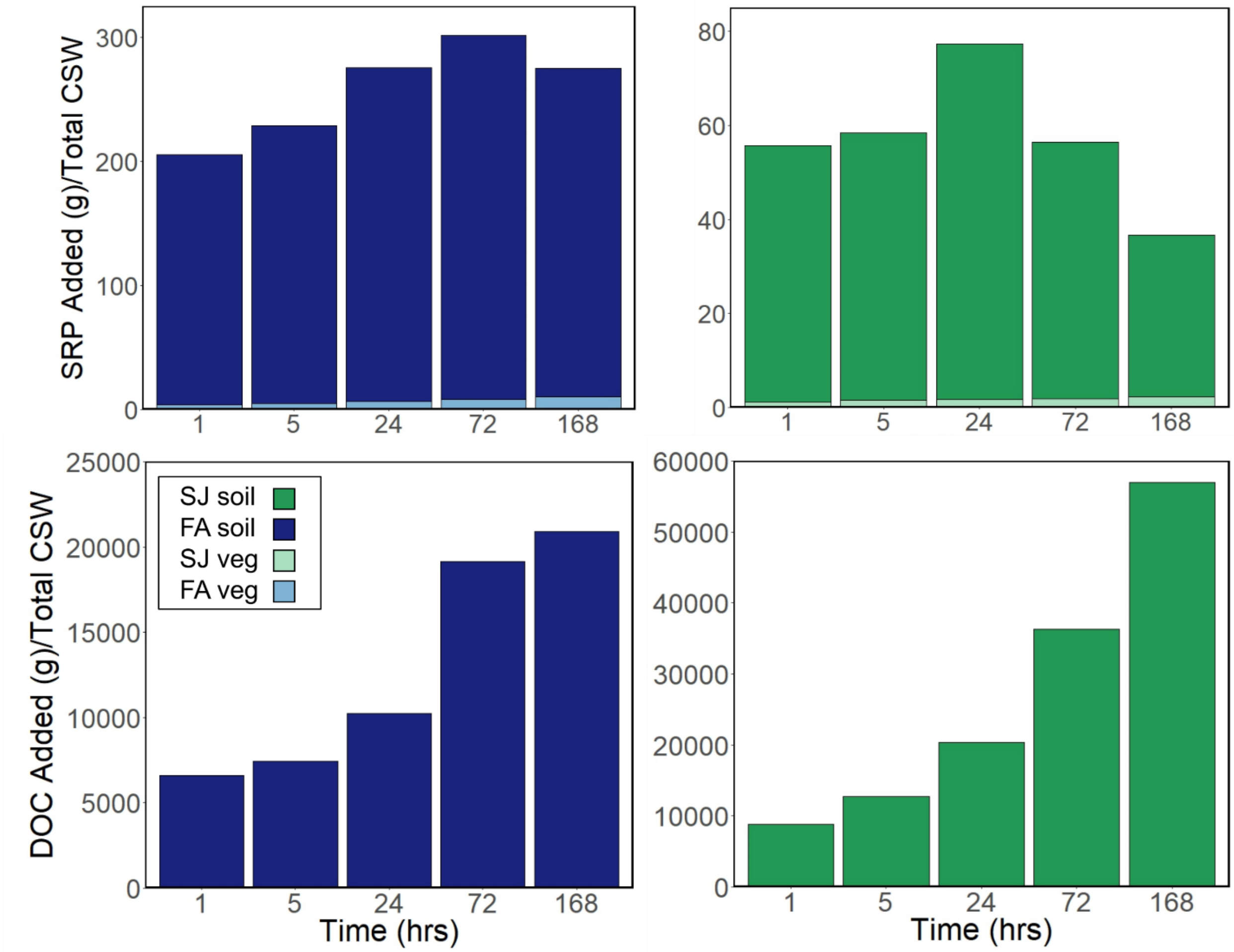

Figure 9. Total wetland contribution for SRP and DOC. Estimated SRP and DOC additions to water in First Avenue and Sacajawea constructed stormwater wetlands in Pocatello, ID, USA, from both soils and vegetation over a week-long inundation period. Soil contributions were scaled to the area of each CSW reach studied. Vegetation contributions were calculated using the vegetation survey and results from the leaching experiment. Vegetation contributions at both FA (light blue) and SJ (light green) were small compared to soil contributions.

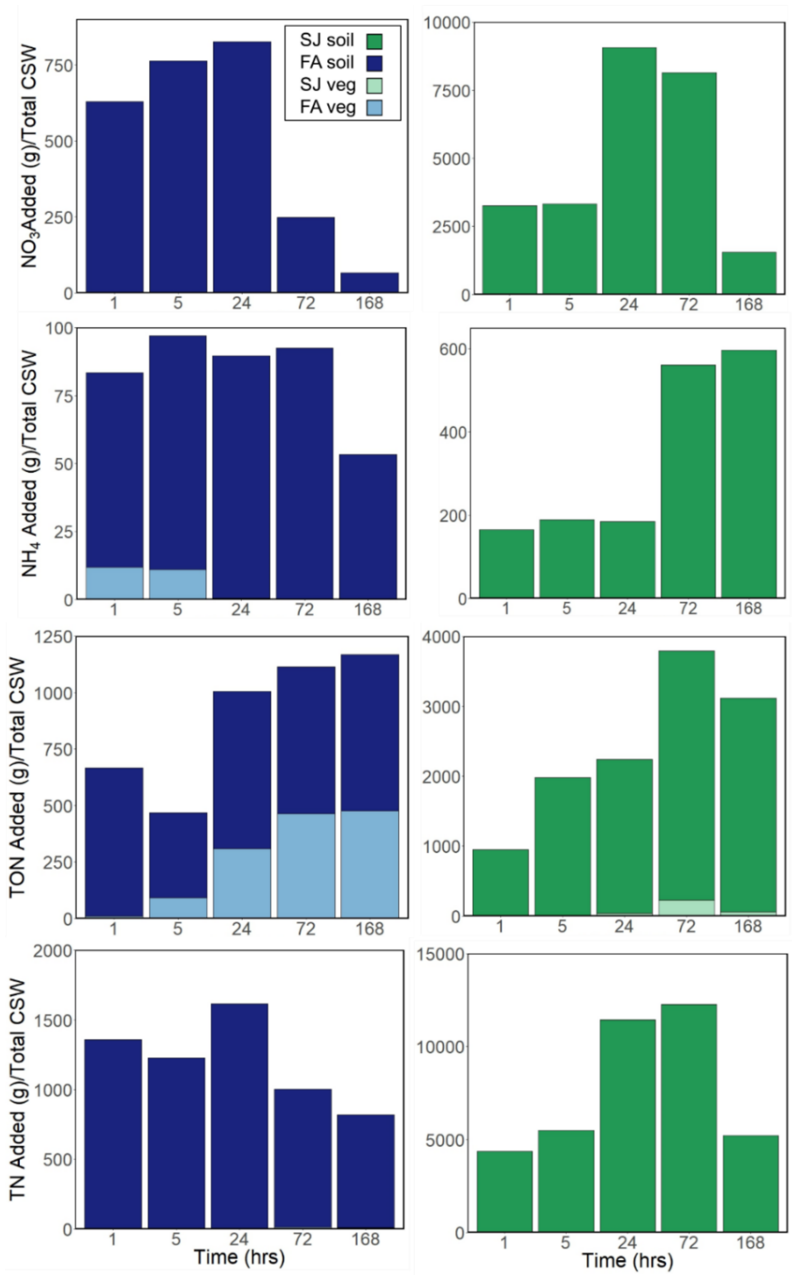

Figure 10. Total wetland contribution for N. Estimated N additions to water in First Avenue and Sacajawea constructed stormwater wetlands in Pocatello, ID, USA, from both soils and vegetation over a week-long inundation period. Soil contributions were scaled to the area of each CSW reach studied. Vegetation contributions were calculated using the vegetation survey and leaching experiment results. Vegetation contributions at both FA (light blue) and SJ (light green) were small compared to soil contributions, except for TON in FA.

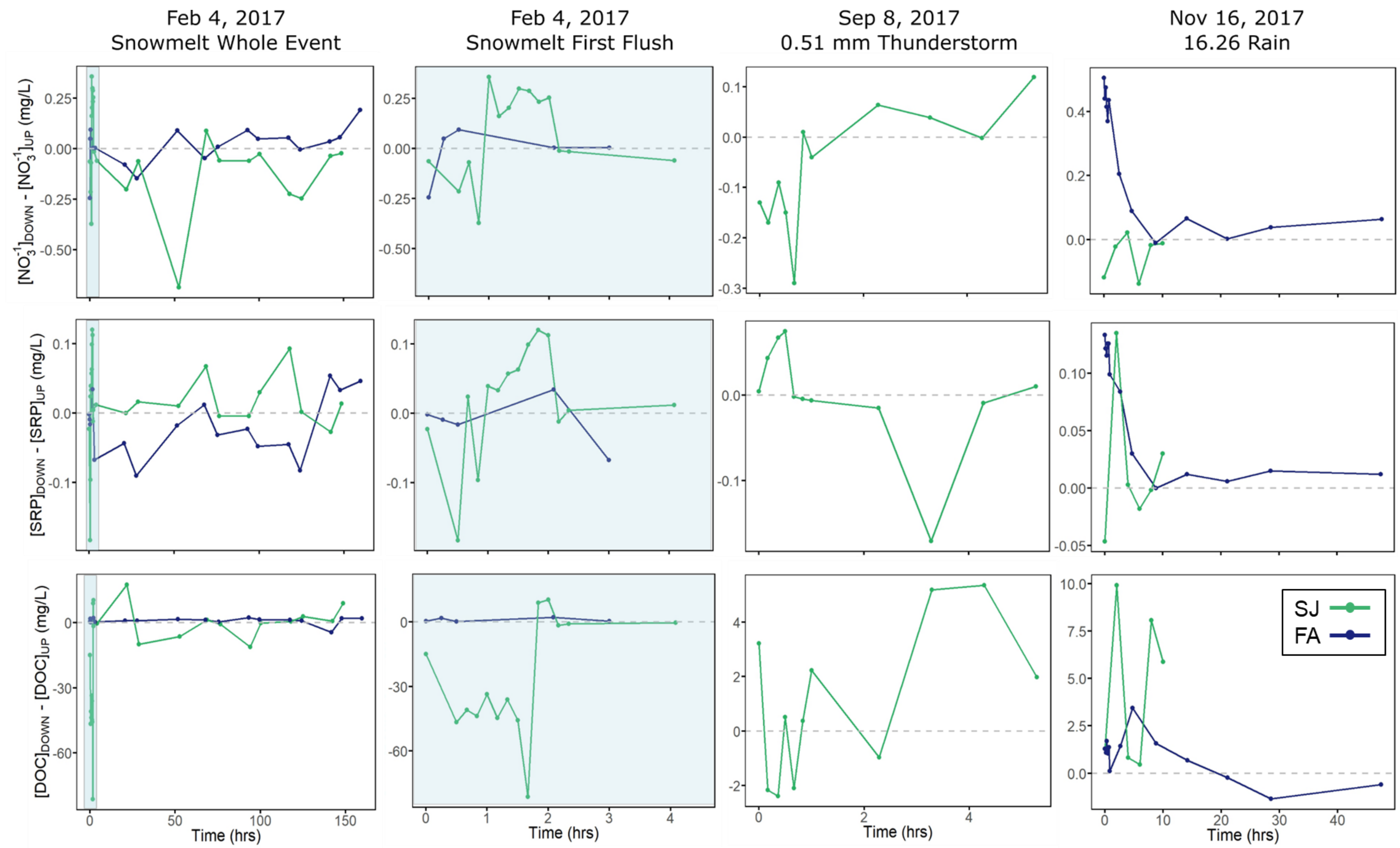

Figure 11. Storm event dynamics NO_3^-, SRP, and DOC. Differences between down- and upstream solute concentrations in mg/L at for 3 measured storm events over the time of the event in hours. Positive values indicate nutrient release or addition over the 100 m studied reach, while negative values indicate uptake and removal of nutrients. FA was not included in September 8, 2017, thunderstorm because the storm was too small to cause sufficient flow at FA.

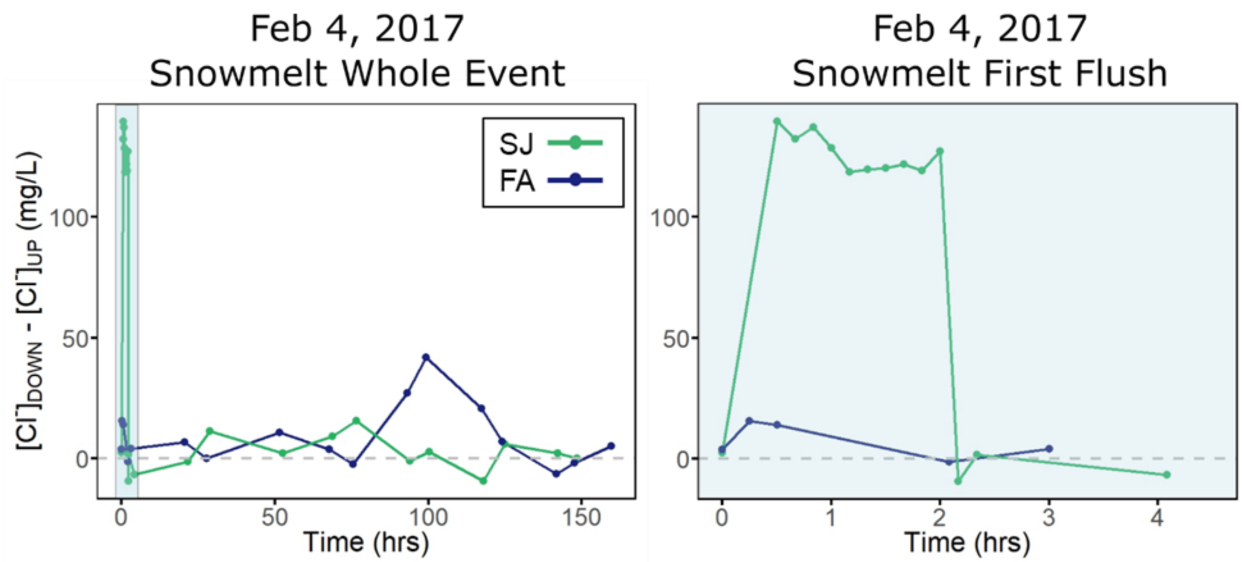

Figure 12. Storm event dynamics Cl^-. Differences between down and upstream solute concentrations in mg/L at First Avenue (FA) in dark blue and Sacajawea (SJ) in green for Cl^- for 1 measured storm event over the time of the event in hours. Positive values indicate addition over the 100 m studied reach, while negative values indicate removal of Cl^-.

Chapter 3. Management Mismatches: Nationwide Patterns in Stormwater Infrastructure Use and Management Practices

Abstract

Urban stormwater runoff has negative consequences for downstream aquatic systems and is managed in the U.S. through the National Pollution Discharge Elimination System (NPDES). Despite federal regulation, nationwide patterns in stormwater management practices and stormwater infrastructure (SWI) use— and the factors that drive these patterns— are not well understood. To address this gap, we distributed an internet-based survey to stormwater managers across the United States to assess: (1) broad patterns in stormwater management goals, SWI use, and information use across the U.S.; (2) regional or climatic differences throughout the U.S. in stormwater goals, SWI use, or patterns of management; and (3) factors that explain differences in SWI use across the U.S. Our results show some common stormwater goals, patterns of SWI-use and use of information sources across surveyed cities. However, climate did not appear to explain observed variation in responses, nor were there strong relationships with other city characteristics, indicating that many stormwater management practices are highly variable among cities, even when trying to achieve the same goals. Additionally, responses showed important disconnects common across cities between perceptions of success and monitoring efforts, and goals and allocated funding. The common patterns and problems in stormwater management identified in this study could be used to not only inform future research, but to inform improvements to the NPDES program.

Introduction

Urban stormwater runoff is recognized as a significant contributor to the ecological degradation of downstream aquatic systems (Walsh et al. 2005), and biophysical, political, and social drivers to the organization of urban space can change the degree and form of this degradation (Hale et al. 2015; Parr et al. 2015). In an attempt to reduce these negative impacts in the United States (U.S.), the 1972 Clean Water Act (CWA) and National Pollutant Discharge Elimination System (NPDES) were expanded in 1987 to regulate stormwater in cities larger than 50,000 people (National Research Council 2009). Local and city governments are tasked with meeting these pollutant reduction goals and, at the recommendation of NPDES, increasingly attempt to do so by utilizing "green" stormwater infrastructure (SWI) (Dolowitz 2015). Green or LID technologies include types of SWI that focus on controlling stormwater at the source and using systems that attempt to mimic the ecological function of soils and plants to remove pollutants (Finewood 2016). While federal regulation and standards could cause similar infrastructure use and management practices in cities across the U.S. (Wagner 2005), there are biophysical, political, and social differences between cities that could drive heterogeneity. However, nationwide patterns in infrastructure-use and the drivers of heterogeneity are not well known (EPA 2008).

U.S. cities are situated within a range of climate conditions (Karl and Koss 1984) and seasonal changes in amount, intensity, and form of precipitation can change the chemical composition of stormwater inputs (Barbé et al. 1996; Barbosa et al. 2012; Gallo et al. 2013) as well as the ability of SWI to treat those inputs (Heyvaert et al. 2006; Semadeni-Davies 2006; Vymazal 2007). The previous chapter investigated CSWs, a particular type of green SWI, and found these systems may become sources of macronutrient pollution rather than nutrient sinks in semiarid, cold desert climates. Although national patterns in SWI use have not previously been examined, we anticipated that regions with similar climatic conditions and constraints may have comparable problems with specific types of SWI, and therefore exhibit similar patterns of SWI use. Regions that are climatically comparable may also have similar goals for stormwater management. For example, water-limited regions may be more concerned with the potential for beneficial re-use of stormwater (Lohse et al. 2010; Walsh et al. 2015; Cousins 2017b) than those areas with ample freshwater available for use. These differences in goals across climates may in turn influence the patterns of SWI used across the landscape, as different types of green SWI are designed to address different goals. These biophysical differences between cities in different regions could be responsible for heterogeneity in stormwater management practices and patterns of SWI implementation.

Although climate may influence management practices and SWI use within cities, federal NPDES regulations may also influence patterns of SWI use across the U.S. Despite the fact that the NPDES does not specifically require that cities incorporate green SWI into management plans (Wagner 2005), it may influence implemented SWI through information sources provided to managers. The EPA provides regulated cities with guidance documents, best management practices, and fact sheets on green SWI that encourage utilization of green projects (US EPA 2013 Sep 26). As they are aimed to apply across the U.S., however, they are also oftentimes necessarily broad (Wagner 2005). Because specific factors like climate can play a strong role in the performance of implemented SWI, recommendations or assessments of SWI performance in this literature could be inaccurate for climates not commonly studied. Even in the academic literature, performance of green SWI in cold or arid climates has been rarely studied (Semadeni-Davies 2006; Moreno et al. 2007). Those studies that do look at climate-specific SWI performance may be inaccessible to managers. Though not specifically studied in the context of stormwater management to our knowledge, other studies on information-use of environmental managers have found that paywalls may render pertinent academic literature sources inaccessible (Cvitanovic et al. 2014). Managers may then be forced to rely on the information provided by the sources made freely available by the EPA and unaware of potential gaps in that information.

In addition to the biophysical and political variation, there are also social and cultural differences between cities and regions that can determine the physical reality of the built environment. Socioeconomic status can determine the major priorities surrounding water and, therefore, the infrastructure that gets built in a city. Often this translates to negative consequences for both people and the environment in lower socioeconomic neighborhoods or cities (Swyngedouw 2009; Parr et al. 2015). However, there has recently been a push to bring green SWI to lower income areas throughout the U.S. and globally due to the potentials for job creation with green SWI maintenance, reductions in crime, and potential health benefits (Burkholder 2012; Kondo et al. 2015; Finewood 2016; Mandarano and Meenar 2017). The cultural valuation of private property rights is a factor that can have implications for stormwater management infrastructure, as cities with residents that highly value private property may be less likely to support green SWI or sustainability initiatives as they may see initiatives as government interference (Berke et al. 2013). Conversely, cities that have a strong cultural identity surrounding a particular waterbody may have residents that are more likely to support green stormwater initiatives (Brown 2005; Karvonen 2011).

Although the social and cultural composition of a larger community may be important to determining the built infrastructure both within and among cities, the attitudes of those directly involved in stormwater management are at least equally important. Misinformation or stormwater manager perceptions of a particular type of infrastructure can result in reluctance to implement new projects. For example, with green roofs, the perception of risk associated with leaks was identified as a potentially significant barrier to implementation (Carter and Fowler 2008). Additionally, perceptions on the quality of information from stormwater managers in other cities, particularly regarding the effectiveness of SWI projects, may limit the transfer of knowledge between managers across cities (Dolowitz 2015). This reluctance to collaborate may further reduce the availability of climate-specific information on the performance of SWI.

Our literature review revealed no assessments of national patterns in stormwater management across the U.S. The vast majority of studies on the social and political aspects of stormwater involve focused case studies on particular cities (e.g. Brown, 2013; Cousins, 2017a; Cousins 2017b; Finewood, 2016) or broad, conceptual thought pieces incorporating anecdotal evidence and personal experience (e.g. Brown, 2005; Roy *et al.*, 2008). It is important to identify common practices, potential disconnects, and barriers to innovation that might allow a broader understanding of stormwater management in the U.S. To fill this gap, we conducted a survey of US stormwater managers to assess: (1) patterns in stormwater goals, SWI use, and information use across the U.S., (2) regional or climatic differences throughout the U.S. in stormwater goals, SWI use, or patterns of management, (3) factors and relationships that explain differences in SWI use across the U.S.

Methods

Survey Distribution and Organization

To investigate nationwide patterns of stormwater infrastructure, management goals, and information sources, an internet survey was distributed to stormwater managers across the U.S. using the Qualtrics Survey Software (Qualtrics, Provo, UT). The survey was distributed to a total of 435 cities under either Phase I or II of NPDES regulation. The complete list of cities under NPDES was obtained from the EPA website and contact information on stormwater managers was pulled from city government websites or online information on stormwater associations. Because cities rarely have a single department or individual in charge of stormwater, we looked for the mention of stormwater within department webpages and identified an appropriate individual within that department. Once identified, respondents were emailed a personalized link through the Qualtrics software to avoid duplicates and connect metadata such as city and city population to responses. The survey was open from December 2017 through March 2018 and included four sections addressing a variety of questions regarding stormwater management (See Appendix for full survey). Section I addressed challenges that managers face, resource allocation to particular stormwater goals, and limitations to meeting local goals. The second section focused on the communication of and access to information and stormwater managers' trust of different information sources. Section III examined specifics of stormwater infrastructure in a city, including frequency of infrastructure use and factors influencing placement of infrastructure. The final section focused on the use of constructed stormwater wetlands, however this paper will mainly discuss findings from the first three sections. Each section included a variety of questions types, including write-in responses, single- and multiple-selection multiple choice, and 100-point sliding-scale questions.

Data Analysis

To address our first objective, we used descriptive statistics to characterize general patterns in stormwater management across the U.S. Because many of our questions included multiple response categories, we used principal components analysis (PCA) to reduce these data and understand sources of variation across goals, information sources used to make capital improvement decisions, SWI use, factors influencing SWI placement and factors influencing the decision to build new SWI. All questions analyzed using PCA were continuous variables that asked respondents to rate each variable from 0-100. PCA was performed in R using the “princomp” function in the base package (R Core Team 2017) and plotted using the “ggbiplot” package (Vincent Q. Vu 2011). Only components with eigenvalues greater than 1 were selected for further comparisons (tables 1-5). To assess our second objective, PCA loadings were used to understand groupings and patterns driving responses and to determine if respondent metadata explained any patterns in response. Responses were grouped according to National Atmospheric and Oceanic Administration climate regions (Karl and Koss 1984), city population, average annual precipitation (PRISM Climate Group 2004), phase of NPDES implementation, and respondent’s department within city government. For city population and precipitation, cities were grouped into one of three categories for each, with roughly even distribution of respondents in each category. To meet our final objective, correlation matrixes were then used within survey sections to determine patterns of responses within cities, both between responses within a question and across questions. Correlation coefficients were considered meaningful at less than -0.5 or greater than 0.5. To understand relationships among aspects of stormwater management, we used linear regression to assess whether management goals, information used to make capital improvement decisions, and factors influencing new SWI projects and placement were associated with the frequency of use of stormwater capital improvement projects over the past 10 years. These questions were chosen for comparison because previous literature indicated that variables included in these questions might explain variation in patterns of SWI use. Responses for each question were reduced using PCA and data were log transformed to meet the assumption of normality. Regressions were performed in R using the base package (R Core Team 2017) and relationships were considered statistically significant at $p < 0.05$.

Results

A total of 60 respondents participated in the survey (response rate= 13.8%). However, only 32 of those completed the entire survey, likely due to the large number of questions, the length of time required to complete the survey, and because respondents were allowed to skip questions. As a result, each question had a variable response rate and the sample sizes for each question are included with all results, either in-text or in figure captions. Despite the low response rate, respondents were relatively evenly distributed both across NOAA climate regions and across city size (Fig. 1).

Broad Patterns in Stormwater Management and SWI Use

The majority of respondents indicated that flooding, sediment, and pollutant reduction were the top goals of stormwater management (Fig. 2a). Groundwater recharge had the lowest mean importance, and 23% of respondents identified that groundwater recharge was not addressed in their city. PCA analysis of stormwater goals showed that that the importance of community development and pollutant reduction were highly linked, and flood reduction was the most divergent from these goals (Fig. 2b). The relative proportion of funding allocated to these goals (S1Q6, Table 6) appeared to be associated with importance overall. Flood reduction received the most funding and groundwater recharge the least. However, identified goals and allocation of monetary resources to those goals were not highly correlated (Table 7). Only groundwater recharge and community development showed significant correlations between importance of goals and allocated funding to those goals (Table 7). Although stormwater managers identified urban runoff as the major source of pollution to downstream aquatic systems with an average importance response of 73.8 (S1Q12, Table 6), the weakest correlation was between pollutant reduction importance and funding to pollutant reduction (Table 7). Congruent with the lack of correlations between the importance of goals and allocated funding, insufficient funding and personnel, and excessive workloads were all identified as the top limitations both in terms of the degree to which they limited a city's ability to meet goals and in the frequency with which respondents identified them as limitations (Fig. 3). This indicated that establishing sufficient funding for stormwater management may be a critical gap in stormwater management across the U.S.

Retention and detention basins were identified as the most frequently used SWI within a city on average, followed by rain gardens and vegetated buffer strips (Fig. 4a). However, when we investigated the percentage of respondents who reported using SWI types in their city at all, rain gardens were the most commonly used across all cities, with retention and detention basins close behind (Fig. 4b). This indicated that while rain gardens were used in most surveyed cities, within any individual city they were used infrequently. PCA loadings for infrastructure use showed that retention and detention basin use was tightly coupled and diverged from frequency of use of other newer, green SWI technologies (Fig. 4c). The use of any given infrastructure type and the belief that that infrastructure was important to meeting stormwater goals were strongly correlated for all infrastructure types excluding green roofs, permeable pavements, and rain gardens (Table 8). While 80% of respondents (n= 40) indicated that stormwater infrastructure either slightly or moderately improved water quality, 46.3% of managers (n=41) indicated that monitoring on individual stormwater structures was done once a year or less. When asked about the types of monitoring done within the past year on the impacts of SWI on water quality, visual inspection was the most commonly identified, followed by grab sampling (S1Q15, Table 6).

In general, stormwater managers used a variety of information sources and tended to rely on different sources to make different types of decisions. For making specific decisions about new SWI projects, such as the type of SWI used, respondents indicated that federal mandates, local residents, departmental reports or resources, and local research or monitoring were used most frequently (Fig 5a). Trade magazines, stormwater conferences, academic literature, and internet searches on other city’s stormwater programs were used the least (Fig

5a). PCA loadings for these information sources revealed that local monitoring and residents were closely linked in frequency of use and somewhat separate from the rest of the information sources. To inform local monitoring practices, federal and state mandates were again identified as the top information source, followed by local research and monitoring (S2Q5, Table 6).

The potential for SWI to mitigate a problematic area had the highest average importance among respondents in terms of factors influencing placement of SWI within a city (Fig. 6a). Respondents indicated that opportunities for public access and zoning regulations were the least important to determining placement. PCA loading for this question showed a divergence between the importance of land cost and zoning and mitigation potential (Fig. 6b). Additionally, physical characteristics of the space and issues under community development appeared closely linked and fell between these two extremes (Fig. 6b). When asked what factors most influenced a decision to use a particular type of SWI for a new project, respondents indicated that previous success with a stormwater infrastructure type in their city was the top factor (Fig. 7a). Successful implementation of a technology by a city in their region was ranked at only 44.5 (Fig. 7a), indicating regional success was much less influential in terms of implemented infrastructure. The importance of a SWI type having a green image fell in the middle in terms of importance (Fig. 7a), however PCA loadings revealed that both city success and the green image of an infrastructure diverged substantially from other variables and were on opposite ends of the spectrum of loadings (Fig. 7b).

Regional and Climatic Differences in Stormwater Management

Despite anticipated variation, climatic differences between regions were not significantly associated with stormwater goals or SWI use. Correlation matrices across all sections of the survey revealed very few significant correlations between precipitation and survey variables. For goals, the correlation between precipitation and the importance of reducing flooding and groundwater recharge were both nonsignificant ($p=0.19$). There were no substantial correlations between precipitation and frequency of SWI use, however there was a positive correlation ($p=0.56$) between precipitation and the degree to which a city felt green roofs were important to meeting stormwater goals. In PCA, grouping responses by NOAA climate region and precipitation category revealed no significant patterns across all analyzed questions and indicated that there was significant overlap among regions for stormwater management practices and SWI use.

Factors Explaining Variation in SWI Use

There were few significant correlations between frequency of SWI use and other measured variables; however, those that were significant may be important to elucidating controls on SWI use across the U.S. City population was strongly and positively correlated with green roof use and negatively correlated with detention basin use (Table 9). Additionally, there was a strong, negative correlation (-0.74) between the frequency of use of green roofs and the use of detention basins. Regression analysis revealed a weak but significant relationship between frequency of infrastructure use and the types of goals in a city (Fig. 8), where the use of newer types of green infrastructure (permeable pavements, constructed wetlands, green roofs, rain gardens and vegetated buffer strips) was correlated with placing high importance on reduction of sediment and other pollutants, increasing groundwater recharge, and meeting community development goals. SWI use was also significantly associated with the information sources used to make specific decisions about SWI, where more frequent use of all information sources was associated with more frequent use of newer green technologies (Fig. 9). Additionally, cities that used retention and detention basins more frequently were less likely to report frequent use of information sources.

Discussion

Nationwide Patterns in Stormwater Management and SWI Use

Stormwater was most frequently identified as a significant contributor to poor water quality, indicating buy-in to the NPDES regulation and acceptance that stormwater negatively impacts downstream surface waters. This is crucial, as threat perception has been shown to be a key factor in motivating relevant planning and action at local government scales (Berke et al. 2013). The emphasis on water quality is further confirmed with the high importance values placed on both sediment and pollutant reduction goals (Fig. 2). While the potential for green stormwater infrastructure to benefit community development and multiuse functions has been recently recognized (Keeley et al. 2013; Kondo et al. 2015; Finewood 2016; Mandarano and Meenar 2017), the relatively low importance ranking of community development (Fig. 2) indicates that harnessing these benefits may still be a fairly new idea or that it is perceived as more of an additional benefit, rather than a primary goal of stormwater management in many cities.

Although stormwater goals may vary, the strong correlations between SWI use and the perceived importance of the SWI type in meeting stormwater goals appears to be common across the U.S. The LID approach pushes for the use of frequent, smaller projects throughout the landscape (Karvonen 2011; Dolowitz 2015), and the observed correlation between frequency and perceived effectiveness could be a reflection of this ideal. In the case of detention and retention basins, which both had particularly high frequency of use, it may simply be that these are the dominant structures in the landscape and, therefore, the majority of stormwater is treated by these types of SWI. Regardless of treatment efficiency, they may be seen as valuable due to the pure volume they treat. The nonsignificant correlations between use and perceived effectiveness for green roofs, permeable pavements, and rain gardens could be explained by the fact that these newer green technologies may generally be implemented as demonstration projects (Roy et al. 2008; Hopkins et al. 2018). Piecemeal implementation means that a small proportion of stormwater is likely treated by these systems in most cities, and managers may not be confident about their treatment efficiencies, in part due to relatively little monitoring.

Lack of Patterns with Climatic Conditions

As was investigated more fully in chapter 2, the amount, stochasticity, and form of precipitation, as well as other climatic variables such as temperature, may strongly influence the ability of certain SWI types to remove pollutants. However, climate does not appear to have a significant influence on stormwater goals or the frequency of SWI use. The correlation between average annual precipitation and groundwater recharge goals was weak, despite academic literature emphasizing potential benefits of stormwater recharge to water-limited cities (Dillon 2005; Lohse et al. 2010; Cousins 2017b). This may be because water limitations do not necessarily coincide with climatic differences but may be a question of access to water resources. Even within cities of a similar climate that are trying to address the same goals, there may be many ways in which cities approach stormwater problems and, as such, diverse arrangements of SWI implementation. This lack of patterns in SWI use within climate regions indicates that managers are likely unaware of the differences in SWI effectiveness with climatic variables and are not considering climate when making decisions surrounding SWI implementation. In terms of meeting future challenges, the diversity of SWI implementation could potentially be promising, as there does not appear to be a one-size-fits-all approach to stormwater infrastructure and management. However, the benefits of this diversity will only be reaped under a few conditions. First, resources need to be allocated to the monitoring of stormwater infrastructure in a variety of conditions to accurately understand which SWI projects are most effective across climates. Second, there should be honest communication between cities about what is working well and what needs to be improved upon so that cities with similar climatic conditions can learn from one another and mistakes are not repeated. Respondents indicated that they used communications with other stormwater managers in their region or internet searches on other cities' programs to learn about new SWI technologies 58% and 50% of the time on average, respectively (n=27). However, these communications were used less frequently when making infrastructure-specific decisions (Fig. 5). Open communication alone may not be sufficient for change to occur, and cities need to be receptive to using the information from other managers as a basis for making stormwater management and infrastructure-based decisions.

While climate might determine the physical conditions in which SWI is set, there are many social, cultural, and political factors that influence project implementation as well

(Karvonen 2011; Berke et al. 2013; Hopkins et al. 2018). We acknowledge that the relatively limited size of our dataset may have restricted our ability to pick up on climate-scale patterns in the presence of so many other variables, and further research on this is necessary to more fully understand how climatic conditions might or might not change the projects built to deal with stormwater runoff.

Factors Explaining SWI Use Patterns

The observed dichotomy between use of detention basins and green roofs and their relationship to city population is likely related to available city space. In densely populated urban centers, land is likely mostly built up, leaving little available space for large stormwater projects (Burkholder 2012; Cousins 2017c; Cousins 2017b). While construction of detention basins requires land, green roofs take advantage of the infrastructure that is in place (Carter and Fowler 2008). If cities with larger populations are more built up, with land that is less available and more expensive, managers likely see green roofs as a good solution to stormwater management. Additionally, the negative correlation and PCA indicate a direct trade-off between these types of SWI.

Despite relatively weak relationships, the regression on principle components revealed some interesting patterns that elucidate some potential controls on the types of SWI used across the U.S. The association between the use of newer technologies and a focus on goals outside of flooding (Fig. 8) offers a few insights. First, while older retention and detention technologies may be able to effectively deal with problems of water quantity, newer green technologies emerged in part because of their inefficiency in meeting water quality goals (Dolowitz 2015) or beneficial-use goals like community development (Moore and Hunt 2012). In addition to improvements in bioretention and bioremediation (Yang and G. Lusk 2018), newer green SWI can be designed and placed to support multiuse initiatives. Particularly in regard to community development, small-scale green infrastructure has been widely recognized for its ability to provide jobs, increase green space, and (when placed accordingly) benefit communities of lower socioeconomic standings (Dunn 2010; Finewood 2016; Cousins 2017c). Green SWI can meet a diverse array of goals, and stormwater managers in cities across the U.S. may be increasingly turning to these newer technologies to do so.

The regression on PCA scores for information sources versus SWI frequency of use indicates that managers more frequently use information sources when building newer, green SWI projects. While the role of information use in making SWI decisions has not previously been studied to our knowledge, research has shown that there is a perception of increased performance uncertainty with newer green infrastructures as opposed to gray infrastructure (Thorne et al. 2015; Hoang and Fenner 2016). In light of this uncertainty, the increased frequency of use of information with less-frequently used SWI potentially indicates that they feel that they need more information to build newer green SWI projects and are seeking that information. Additionally, this difference could indicate that cities more interested in exploring newer SWI are also more invested in using information sources to inform specific decisions on infrastructure, regardless of the type of infrastructure they are implementing. Importantly, the top-used types of information were federal or state mandates or locally-based information such as residents, department reports or documents, and local monitoring and research. This narrow scope of information is important to consider for anyone trying to communicate information on the effectiveness of different SWI technologies, new developments, or improvements in SWI

(Wagner 2005; Roy et al. 2008). Unless this information is locally-informed or passed down in the form of a regulation or mandate, it may be less likely to result in a change to SWI on the landscape.

Mismatches in Nationwide Patterns

Responses indicated several mismatches in terms of stormwater goals, management practices, and infrastructure use. First, the mismatch between allocation of funding to pollutant reduction and the identification of pollutant reduction as an important goal (Table 7) is striking, particularly considering the recognition of stormwater as a contributor to pollution and the emphasis of the NPDES program. This disconnect, however, matches up with results from a later question on factors limiting local goals (Fig 3). All of the top-identified limitations are either funding itself or are intrinsically linked with funding, which is consistent with findings from case studies that identified insufficient funding as a major barrier to adequately meeting stormwater goals (Roy et al. 2008; Dolowitz 2015; Cousins 2017c). When asked about funding sources for the establishment of new SWI projects, 50.9% of respondents indicated that their city utilized stormwater service or utility fees (n=55). Stormwater utility fees have been touted as a method for cities to get adequate funding for stormwater management programs (Keeley 2007). However, even in those cities that identified stormwater utilities as a funding source, excessive workloads and a lack of funding were identified as the top limitations on meeting stormwater goals (62/100 and 61/100, respectively). This indicates that utility fees may be insufficient for funding adequate stormwater management programs and that fee structures may need to be reassessed or other funding options explored.

Incongruities between perceived success and monitoring are evident as well. While visual inspection may be sufficient for evaluating certain goals, it is insufficient for assessing water-quality impacts, as detailed measurements are often required at fine temporal scales and across diverse storm-event characteristics in order to accurately assess water quality and pollutant-removal functions of SWI (Barbé et al. 1996; Gallo et al. 2013). Moreover, some types of infrastructure can vary in pollutant-removal efficiency over their lifespans, particularly some bioretention or green methods (Moreno et al. 2007; Vymazal 2007; Yang and G. Lusk 2018). Monitoring at a single point in time is insufficient to assess SWI function with respect to water quality. Although monitoring stormwater infrastructure has been recognized as important, it is also one of biggest challenges for water managers (Karvonen 2011), not only in stormwater but in other areas of water management as well. A study that focused on a series of interviews with river restoration practitioners across the U.S. in the mid-2000s (Bernhardt et al. 2007) found similar results, with practitioners believing that implemented projects worked well with limited monitoring data to support these assertions. Lack of resources was the top-identified reason why monitoring was not performed on restoration projects (Bernhardt et al. 2007), congruent with our findings on limitations to meeting goals and case studies by others (Karvonen 2011).

Lastly, there appears to be a disparity between the stormwater infrastructure most frequently used and the infrastructure managers would most like to implement within their cities. While detention and retention structures were most frequently used in cities across the U.S. (Fig. 4a), 36% of respondents indicated that they would most like to use rain gardens or bioswales. These types of SWI were used across most cities, although relatively infrequently within individual cities. Paired with the finding that previous success was considered the most influential factor in determining what new SWI projects to build (Fig. 7a), this indicates that local experiences likely strongly influence the suite of SWI projects used in a city. The relatively low valuation of regional successes with infrastructure reinforces this idea that local scale information exhibits strong controls on the built environment. This failure to use regional successes to inform new SWI does not appear to be explained by a lack of trust of other stormwater managers, as some previous literature suggests (Roy et al. 2008; Dolowitz 2015), as respondents ranked information from other managers in their region as highly reliable (average 75.4/100). This reliance on only findings from one's own city is problematic because it has the potential to seriously slow the adaptation of new stormwater technologies (Brown 2008; Roy et al. 2008), a process that is often necessary to meeting mitigation goals and adapting to changes (Fitzgerald and Laufer 2017). Given this reliance on only ones' own city, piecemeal implementation of green and LID technologies may further limit the ability of cities to adopt green infrastructure, as long-term monitoring may be necessary to confidently assess SWI's ability to meet goals. Additionally, problems with the design of a particular project could be to blame for lackluster results and may not reflect the potential of all technologies of that type. Although site conditions and design can have strong impacts on the pollutant removal capacity for stormwater infrastructure (Moreno et al. 2007; Vymazal 2007; Yang and G. Lusk 2018), failure to communicate with local cities with similar climatic and regulatory structures means that cities must "reinvent the wheel" with each new type of infrastructure implemented, stretching limited resources and potentially perpetuating the status quo.

Conclusions

Stormwater sits at a junction of ecological, social, and political components, making it an integrator between people and the environment within urban landscapes. If we hope to adequately address water quality problems caused by urban runoff, we need to understand the diversity of management practices and projects used across these landscapes and the factors that are responsible for these differences. Our research shows that, although stormwater may be a highly localized problem, there are also several patterns in management and SWI-use that are common across surveyed cities. Working within a federal system of regulation, these common points are crucial, because they give an idea of where improvements to the program can be focused. One important disconnect identified in this work is the mismatch between monitoring and perceived success of projects at meeting stormwater goals. Having sufficient, long-term monitoring data for SWI across diverse climatic and biophysical conditions is crucial as, without it, cities have no way of adequately judging success (Wagner 2005; Bernhardt et al. 2007). Because this appears to be a widespread issue across the U.S., the NPDES should emphasize the allocation of resources towards monitoring. However, as the lack of resources was the top-identified limitation to meeting stormwater goals, there should be a focus on helping municipalities meet funding needs and investigation of stormwater funding structures that work across diverse sociopolitical conditions. Additionally, increased regional cooperation surrounding SWI projects would likely be advantageous. Although stormwater management in every city may be uniquely challenging, the apparent tendency to only “trust” projects implemented within one’s own city is a serious impediment to progress and the adoption of new technologies (Ewing et al. 2000; Roy et al. 2008; Berke et al. 2013). Similarly, communication within cities across departments will be crucial to meeting the myriad of goals associated with stormwater (Karvonen 2011; Cousins 2017c; Cousins 2017b), as the vast majority of managers surveyed identified that they work across departments to deal with stormwater issues. Although in-depth looks at the complexities of stormwater management in individual cities is undoubtedly important, this survey shows that there are important commonalities that could inform improvements to the federal system of stormwater regulation.

Tables

Table 1. Importance of stormwater management goals PCA loadings.

Question:	**Importance of Stormwater Management Goals**	
Component:	1	2
Eigenvalues:	2.28	1.13
Management Goals	PCA Loadings per Component	
Flood Reduction	-	0.86
Erosion Reduction	-0.46	0.34
Pollution Reduction	-0.47	-0.24
Groundwater Recharge	-0.55	-
Community Development	-0.51	-0.29

Table 2. Frequency of stormwater infrastructure use PCA loadings.

Question:	**Frequency of SWI Use**		
Component:	1	2	3
Eigenvalues:	2.94	1.40	1.13
Infrastructure Type	PCA Loadings per Component		
Detention Basin	-	0.70	0.15
Retention Basin	-0.14	0.60	0.25
Dry Well	0.23	-0.18	0.67
CSW	0.37	0.29	-0.23
Permeable Pavement	0.53	-	-
Green Roof	0.33	-	-0.61
Vegetated Buffer Strip	0.44	0.10	0.12
Rain Garden	0.45	-0.14	0.17

Table 3. Importance of factors influencing SWI placement PCA loadings.

Question:	**Importance of Factors Influencing SWI Placement**		
Component:	1	2	3
Eigenvalues:	3.33	1.28	1.08
Factors Influencing Placement	PCA Loadings per Component		
Cost of Land	-	0.81	0.27
Proximity to Existing SWI	-0.40	0.20	0.47
Potential to Mitigate Problem Areas	-0.40	-0.26	-
Zoning Regulations	-0.33	-0.44	0.48
Opportunities for Public Access	-0.46	-	0.16
Physical Characteristics of Location	-0.43	0.16	-0.45
Community Interest	-0.42	0.12	-0.49

Table 4. Influence of factors on SWI project type PCA loadings.

Question:	**Influence of Factors on SWI Project Type**	
Component:	1	2
Eigenvalues:	4.06	1.04
Factors Influencing Project Type	PCA Loadings per Component	
Federal/State Recommendation	-0.31	0.14
Previous Success in Region	-0.44	-
Previous Success in City	-0.32	0.48
Community Interest	-0.37	0.27
Meets Community Development Goals	-0.46	-
Scientific Research or Literature Supports	-0.44	-0.24
Green Image	-0.26	-0.79

Table 5. Frequency of information source use for SWI decisions PCA loadings.

Question:	**Frequency of Information Source Use For SWI Decisions**	
Component:	1	2
Eigenvalues:	6.29	1.43
Information Sources	PCA Loadings per Component	
Local Residents	-0.17	-0.49
Federal or State Mandates	-0.27	-
Stormwater Manager in Region	-0.31	-
Watershed Partnerships or Associations	-0.35	-0.18
Departmental Reports	-0.31	-0.26
Federal or State Reports	-0.28	-0.10
Trade Magazines	-0.35	0.31
Stormwater Conferences	-0.29	0.39
Internet Searches	-0.35	0.27
Academic Literature	-0.35	0.16
Local Monitoring and Research	-0.24	-0.55

Table 6. Summary statistics for four survey questions. Three questions from section I and one from section II. Wording of question as well as responses are included as well as number of respondents who answered the question. Either % of response or mean response are reported depending upon the type of question—% response was used for questions without numerical answers, while mean response was used for sliding-scale questions with a numerical score from 0-100.

Question	Response	% Response	Mean Response	n
S1Q6 - Estimate the relative proportion of total departmental resources (funding, personnel, etc.) which are allocated to each of the following stormwater management goals in your city.	Reduction of Flooding	-	29.9	45
	Reduction of erosion	-	17.0	
	Reduction of pollutant loads	-	13.8	
	Increasing groundwater recharge	-	3.3	
	Community-development	-	5.6	
S1Q12 - Indicate the degree to which the following potential pollution sources contribute to any water quality problems in your area.	Sewage or wastewater	-	30.6	40
	Agricultural runoff	-	41.4	
	Urban runoff or stormwater	-	73.8	
	Point source pollution	-	26.9	
S1Q15 - Which of the following techniques were used in the past year to monitor how stormwater infrastructure impacts water quality in your city?	Visual inspection and observations	31.6	-	41
	Automated water quality measurements	10.3	-	
	Automated water quantity measurements	15.4	-	
	Grab samples	19.7	-	
	Storm event grab samples	16.2	-	
	Stormwater is not monitored for impact	3.4	-	
	Other	3.4	-	
S2Q5 - Indicate how often you use each of the following sources of information to inform water quality monitoring techniques.	Local residents	-	33.7	21
	Federal or state mandates	-	74.3	
	Managers in your region	-	45.0	
	Local watershed associations	-	57.3	
	Reports or documents from within your department	-	56.2	
	Initiatives from the state or federal government	-	40.4	
	Trade magazines or newsletters	-	13.6	
	Stormwater conferences or meetings	-	31.8	
	Internet searches on cities' stormwater programs	-	31.9	
	Academic literature	-	38.3	
	Local research and monitoring	-	67.6	

Table 7. Correlation coefficients for importance of stormwater goals vs. funding. These questions compared the importance of a goal versus the proportion of funding allocated to that goal. Meaningful correlations are marked in bold and were considered meaningful if greater than 0.5.

Importance of Goal X Proportion of Funding Allocated to that Goal	Correlation Coefficient
Flood Reduction	0.45
Erosion Reduction	0.41
Pollution Reduction	0.28
Groundwater Recharge	**0.61**
Community Development	**0.50**

Table 8. Correlation coefficients for frequency of use vs. importance in meeting goals. These questions compared the frequency of use of stormwater infrastructure and the importance of stormwater infrastructure in meeting stormwater management goals (e.g. flood reduction, groundwater recharge, etc.). Meaningful correlations are marked in bold and were considered meaningful if greater than 0.5.

Frequency of Use X Importance in meeting Goals	Correlation Coefficient
Detention Basins	**0.77**
Retention Basins	**0.68**
Dry Wells	**0.54**
Constructed Wetlands	**0.66**
Permeable Pavements	0.38
Green Roofs	0.45
Vegetated Buffer Strips	**0.73**
Rain Gardens	0.44

Table 9. Correlation coefficients SWI frequency of use vs. city population. Meaningful correlations are marked in bold and were considered meaningful if less than -0.5 or greater than 0.5.

City Population X Frequency of Use	Correlation Coefficient
Detention Basins	**-0.60**
Retention Basins	-0.19
Dry Wells	-0.13
Constructed Wetlands	0.05
Permeable Pavements	0.33
Green Roofs	**0.78**
Vegetated Buffer Strips	0.01
Rain Gardens	0.33

Figures

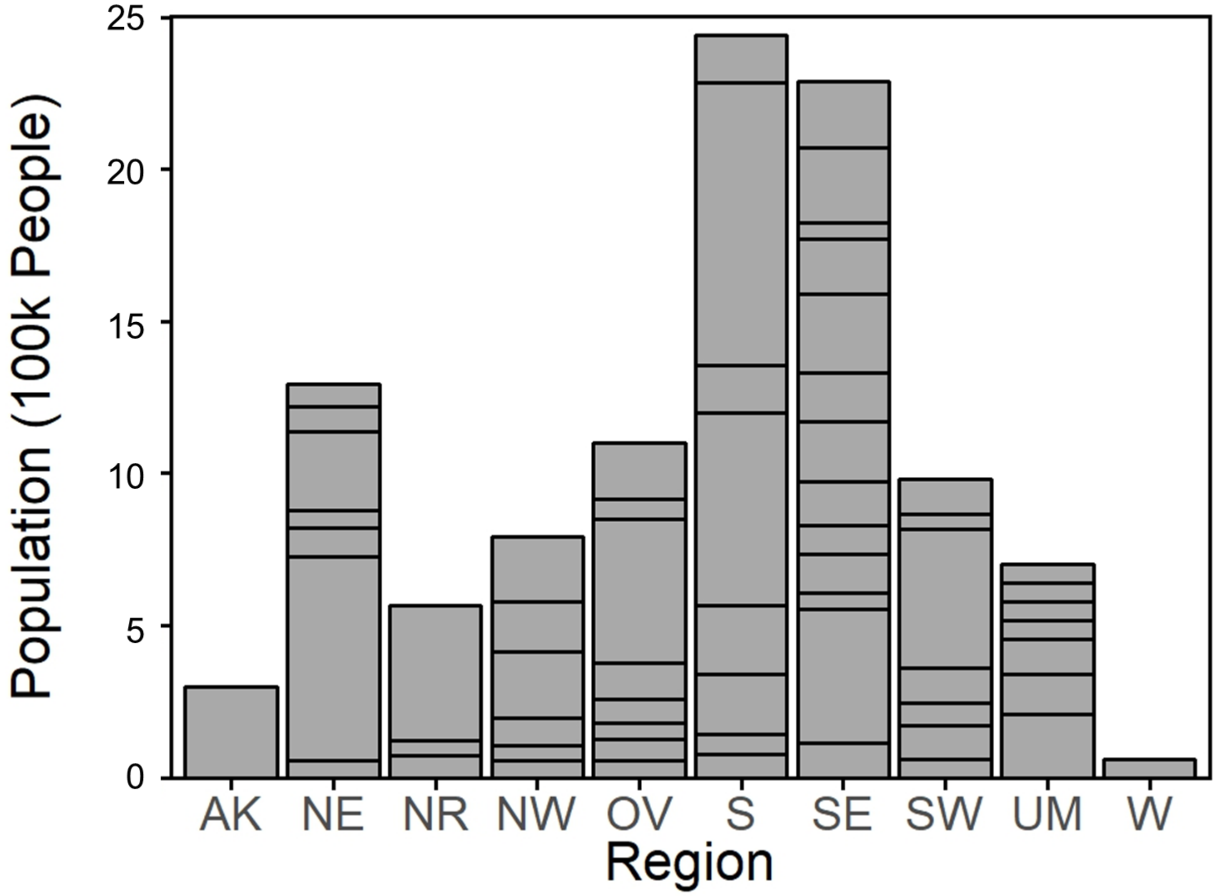

Figure 1. Distribution of survey respondents. National Oceanic and Atmospheric Administration climate regions are shown on the x-axis, including Alaska (AK), Northeast (NE), Northern Rockies (NR), Northwest (NW), Ohio Valley (OV), South (S), Southeast (SE), Southwest (SW), Upper Midwest (UM), and West (W). Population is on the y-axis in hundreds of thousands. Within each region, each box indicates a single city and the height of the box indicates the population of that city.

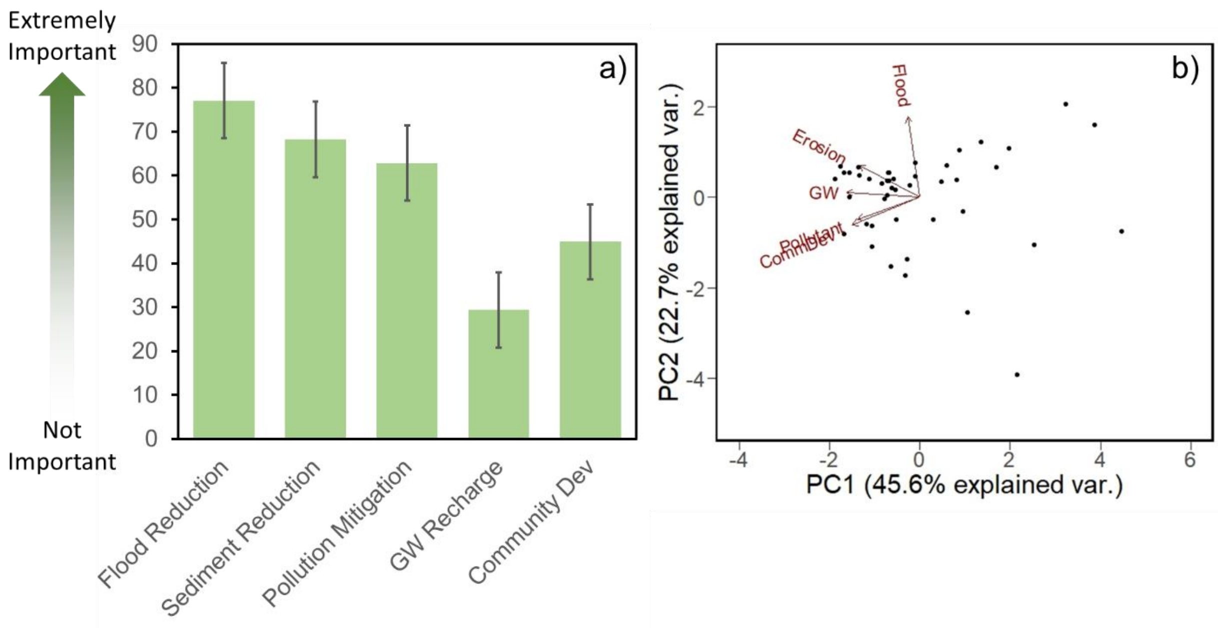

Figure 2. Importance of stormwater management goals. Average ratings of importance for stormwater management goals (a), including reduction of flooding, sediment loads, and other pollutants, increasing groundwater recharge, and community development initiatives (n=44). Respondents ranked each goal on a scale from 0 to 100, with 0 indicating that the goal was unimportant to their city, while 100 indicated that the goal was extremely important. PCA loadings for component 1 and 2 explaining a total of 68.3% of the variation (b). Loadings show a separation of flooding from other goals.

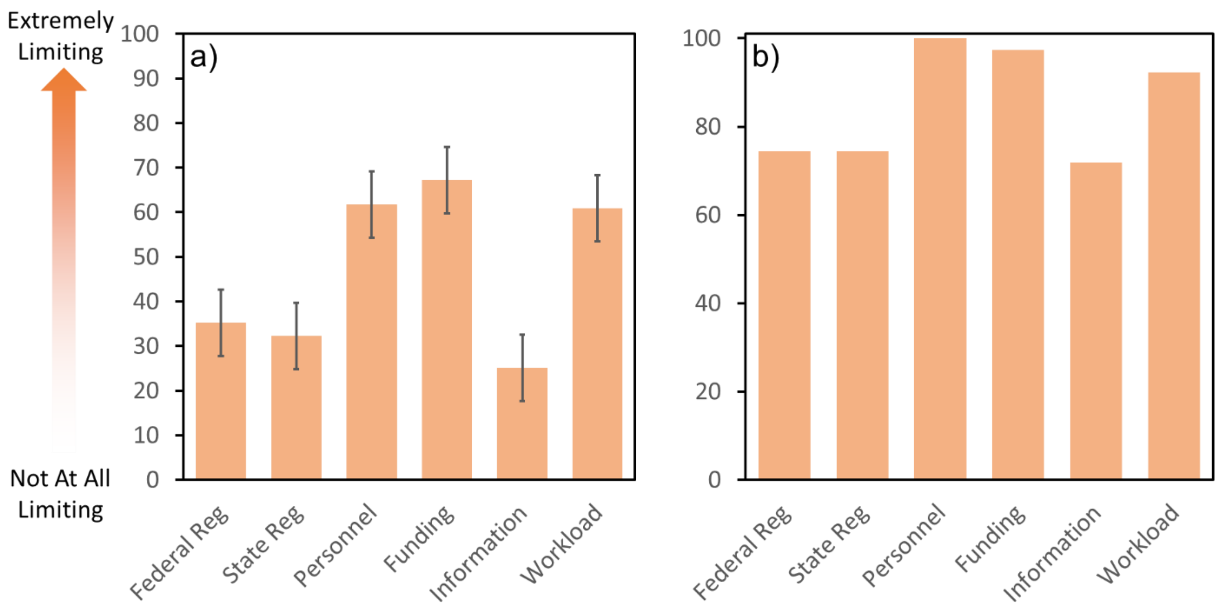

Figure 3. Factors limiting ability to meet stormwater goals. Average ratings of factors that limit stormwater management goals (a) and percent of respondents that identified that factor as limiting (b). Limiting factors include federal and state regulations or mandates, lack of personnel, lack of funding, lack of information on adequate solutions, and excessive workload (n=39). Respondents ranked each factor on a scale from 0 to 100, with 0 indicating that the factor did not limit the department's ability to meet local stormwater goals (such as reducing flooding, eliminating pollution, etc.), while 100 indicated that the factor was extremely limiting to their ability to meet local goals.

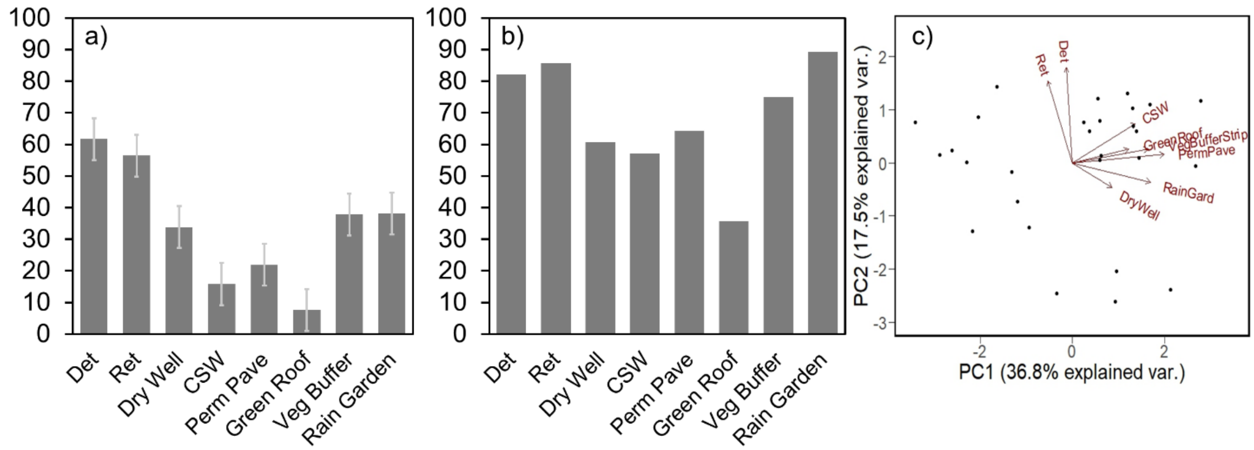

Figure 4. Frequency of SWI use. Average frequency of SWI use over the past 10 years (a) and percentage of respondents (b) that use detention (Det) and retention (Ret) basins, dry wells or underground infiltration (Dry Well), constructed wetlands (CSW), permeable pavements (Perm Pave), green roofs, vegetated buffer strips (Veg Buffer), and rain gardens or bioswales (Rain Garden, n=28). PCA loadings for component 1 and 2 explaining a total of 54.3% of the variation. Loadings show separation of retention and detention basins from other newer green infrastructure types.

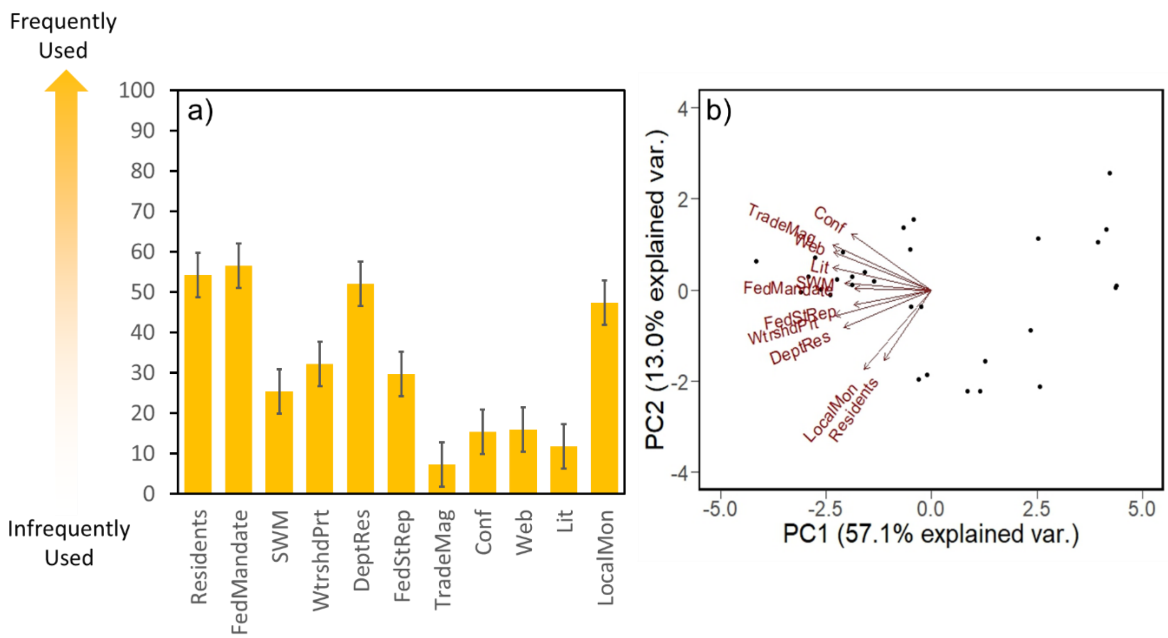

Figure 5. Frequency of information use for specific SWI decisions. Average frequency with which information sources are used to make decisions about specifics of stormwater projects (a). Information sources include local residents, federal or state mandates or recommendations (FedMandate), regional stormwater managers (SWM), watershed associations or partnerships (WtrshdPrt), resources from within their department (DeptRes), federal or state reports (FedStRep), trade magazines or newsletters (TradeMag), stormwater conferences (Conf), internet searches on stormwater programs of other cities (Web), academic or scientific literature (Lit), and local monitoring efforts (LocalMon, n=31). Respondents ranked each factor on a scale from 0 to 100, with 0 indicating that the source was not used to make decisions on specific infrastructure projects, while 100 indicated that the source was very frequently used. PCA loadings for component 1 and 2 explained a total of 70.1% of the variation (b). Loadings show that local monitoring and city residents are grouped together and separate from other information sources.

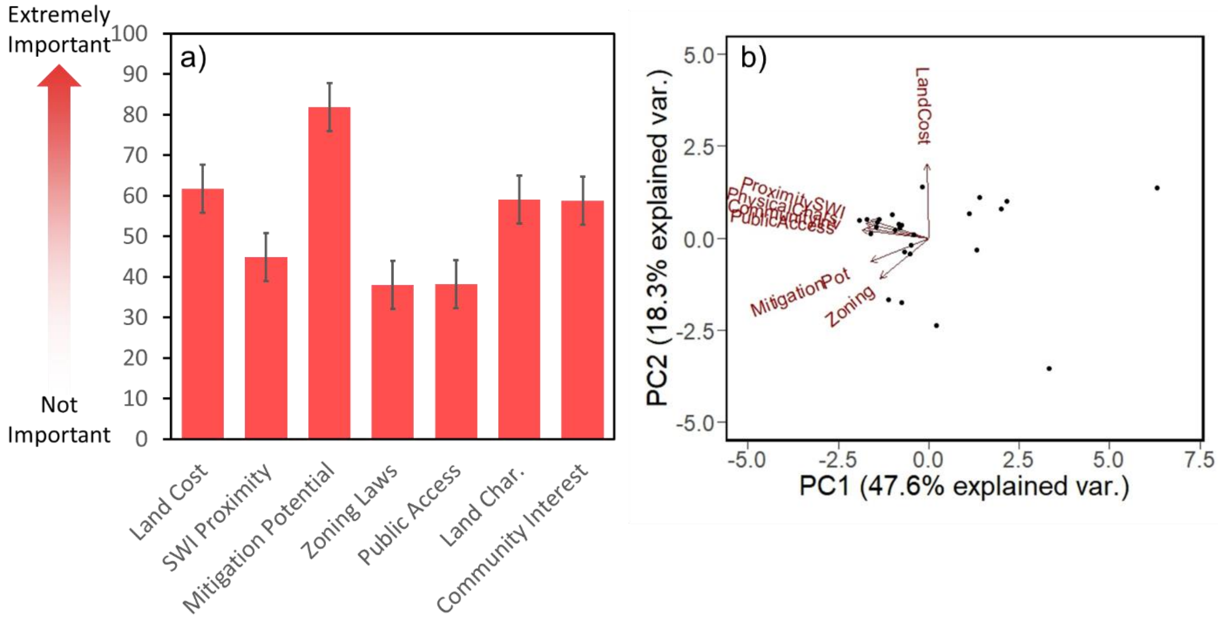

Figure 6. Importance of factors influencing SWI placement. Average importance of various factors influencing SWI placement (a) including land cost, proximity to other infrastructure (SWI proximity), potential to mitigate stormwater problems (Mitigation Potential), zoning laws, opportunities for public access (Public Access), physical characteristics of the land (Land Char.), and community investment in the project (Community Interest, n=26). PCA loadings for component 1 and 2 explaining a total of 65.9% of the variation (b). Loadings show separation of Land Cost from other factors.

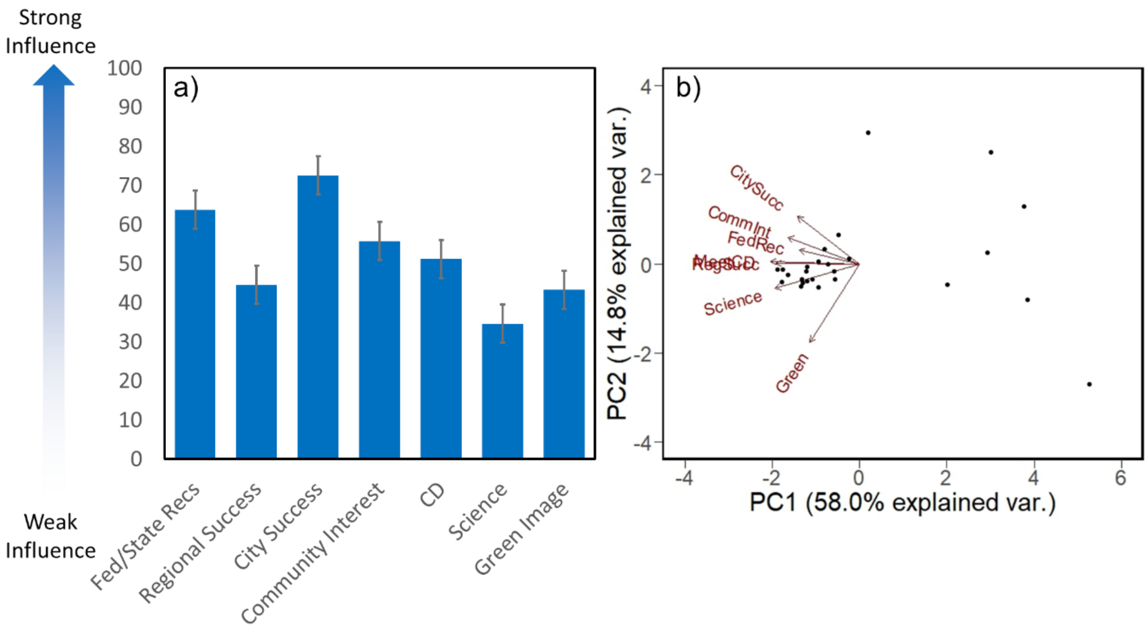

Figure 7. Influence of factors on type of new SWI project. Average ratings of factors that influence the construction of new stormwater infrastructure projects (a). Limiting factors include federal or state recommendations, success with a particularly SWI type in a city in their region, success with a particular SWI type in their city, community interest or investment in a particular type of SWI, ability for a particular SWI type to meet community development initiatives (CD), the support of a specific SWI type by scientific research (Science), and the image of a particular type of infrastructure as "green" (n=26). Respondents ranked each factor on a scale from 0 to 100, with 0 indicating that the factor did not influence the decision to build a specific type of SWI, while 100 indicated that the factor strongly influenced this decision. PCA loadings for component 1 and 2 explaining a total of 72.8% of the variation. Loadings show separation of green image and previous city success from other factors.

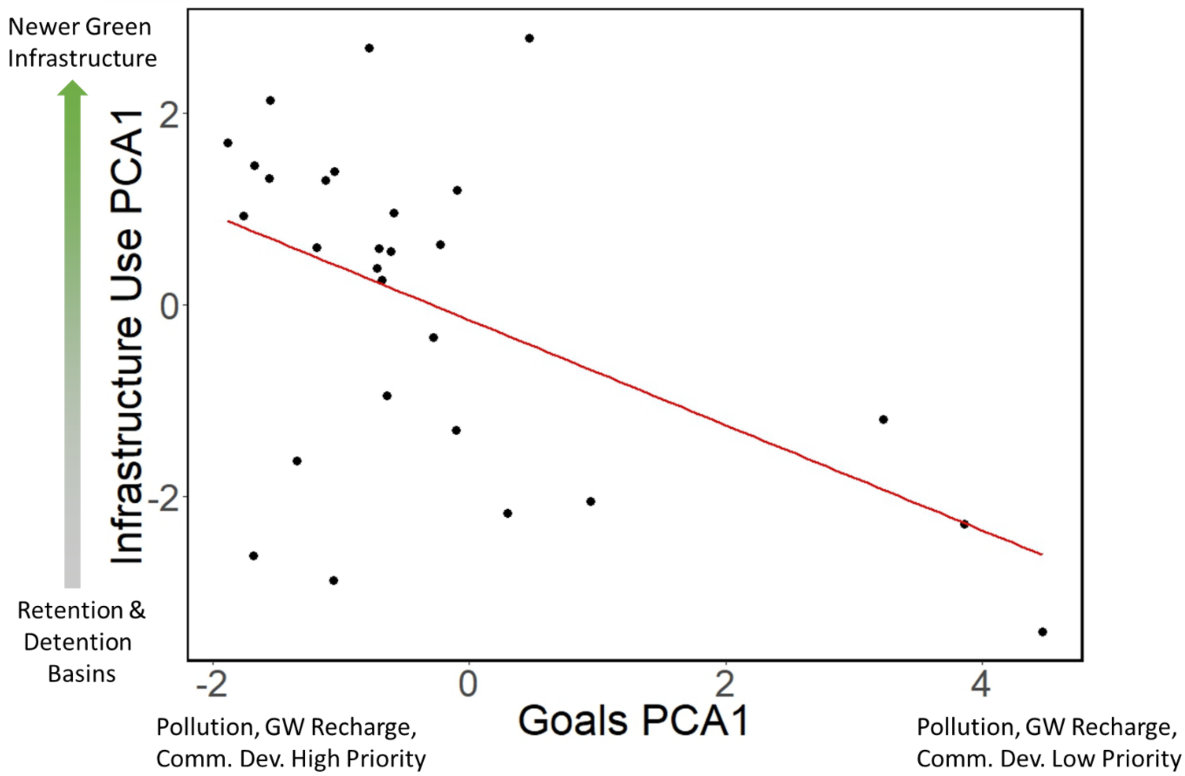

Figure 8. Linear regression of PC values for SWI use and management goals. Frequency of stormwater infrastructure use is shown on the y-axis and importance of stormwater management goals on the x-axis. For infrastructure, negative values corresponded with high frequency of use of detention and retention basins, while high numbers corresponded with use of newer green technologies. For importance of goals, more negative numbers were associated with prioritization of reduction of pollutants and sediment, increasing groundwater recharge, and community development initiatives. PCA1 for infrastructure use explained 36.8% of the variation, while goals PCA1 explained 45.6% of the variation. The correlation was highly significant ($p=0.006$), but weak ($R^2= 0.26$).

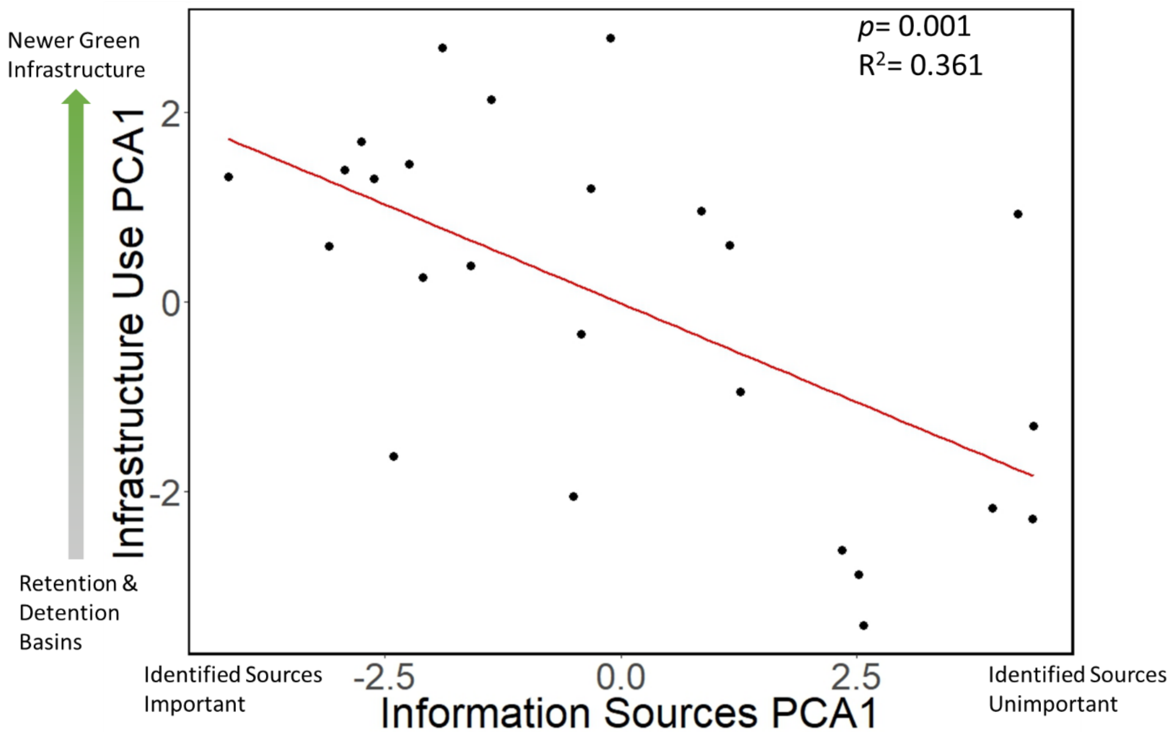

Figure 9. Linear regression of PC values for SWI use and information sources. Frequency of infrastructure use is shown on the y-axis and frequency of use of information sources when making specific decisions on SWI projects on the x-axis. For infrastructure, negative values corresponded with high frequency of use of detention and retention basins, while high numbers corresponded with use of newer green technologies. For information sources, more negative numbers indicate that the identified sources of information were used frequently whereas positive numbers indicate identified sources were infrequently used. PCA1 for infrastructure use explained 36.8% of the variation, while information sources PCA1 explained 57.1% of the variation. The correlation was highly significant ($p=0.001$), but relatively weak ($R^2= 0.36$).

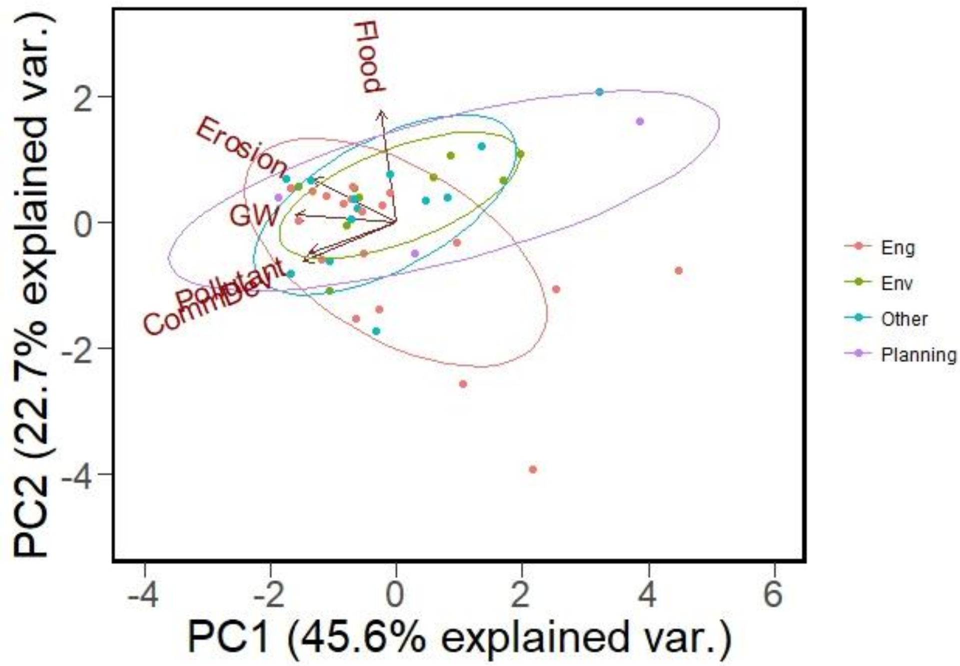

Figure 10. Biplot of PCA results for the importance of stormwater goals. Components 1 and 2 shown, accounting for 68.3% of the variation and grouped according to the department in which each respondent worked. Substantial overlap between departments is evident, indicating that departmental differences do not explain differences in the importance of stormwater management goals.

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Appendix A:

Stormwater Manager Survey

Start of Block: Informed Consent

IC1 You have been invited to participate in a web-based survey that is part of a project that aims to understand stormwater infrastructure use across the United States and the challenges stormwater managers face in implementing infrastructure. This survey is part of the “Managing Idaho’s Landscapes for Ecosystem Services” EPSCoR project being conducted by Idaho State University. Your participation in this survey is voluntary. There is no penalty for not completing the survey. If you choose to complete the survey, it will take approximately 30-45 minutes and your answers will be electronically recorded and stored in a password-protected, electronic database using the Qualtrics Survey Software.
The possible risks or discomforts of the study are minimal, however you may choose to quit the survey at any time and you are free to decline to answer any particular question you do not wish to answer, without penalty.
Your participation in the survey, any contact information, and survey responses will only be visible to the researchers on the project. Any information that would allow others to identify you will be removed before results are published, and results will be reported in aggregate form only. All data collected as part of this project will be stored on password-protected computers in order to maintain participant confidentiality. If you have any questions, concerns, or complaints about the survey or research, please contact Carolyn Macek at macecaro@isu.edu.

IC2 Please select either "I agree" or "I disagree" below to indicate your consent to participate in the research described above. Choosing the "I agree" option indicates that:
- You have read the above information
- You voluntarily agree to participate in this research
- You are 18 years or older

○ I agree (1)

○ I disagree (2)

End of Block: Informed Consent

Start of Block: Background Info

S1Q1 What do you enjoy most about working in stormwater?

____

S1Q2 Which of the following departments do you work?

- ○ Streets (1)
- ○ Environment (2)
- ○ Waste Management (3)
- ○ Planning (4)
- ○ Engineering (5)
- ○ Other (please describe): (6) ____

Q62 Which of the following departments do you work with in order to address stormwater? You may choose more than one.

- ▢ Streets (1)
- ▢ Environment (2)
- ▢ Waste Management (3)
- ▢ Planning (4)
- ▢ Engineering (5)
- ▢ Other (please describe): (6) ____

S1Q3 When building stormwater capital investment projects, which of the following are the major sources of funding? You may choose more than one.

- ▢ Gas taxes (1)
- ▢ Property taxes (2)
- ▢ Service or utility fees (based on property type or area) (3)
- ▢ System Development Charges (SDCs), connection fees, or tie-in fees (4)
- ▢ Grants (5)
- ▢ Loans (6)
- ▢ Other (please describe): (7) ____

S1Q4 What is the biggest challenge that you face as a stormwater manager in your city?

____

End of Block: Background Info

Start of Block: SWM Goals

S1Q5 Please indicate how important each of the following stormwater management goals are in your city to you as a stormwater manager.
Then, pick ONE of these goals that you think is the most important in your city.

	Not at all important		Extremely Important		Most Important	
	0	20	40	60	80	100
Reduction of flooding ()						
Reduction of erosion and sediment loads in runoff ()						
Reduction of other pollutant loads in runoff ()						
Increasing groundwater recharge ()						
Multi-use or community development initiatives ()						
Other (Please Describe) ()						

S1Q6 Please estimate the relative proportion of total departmental resources (funding, personnel, etc.) which are allocated to each of the following stormwater management goals in your city. The **sum of allocated resources should not exceed 100%**.

Reduction of flooding : _______ (1)
Reduction of erosion and sediment loads in runoff : _______ (2)
Reduction of other pollutant loads in runoff : _______ (3)
Increasing groundwater recharge : _______ (4)
Multi-use or community development initiatives : _______ (5)
Other (Please Describe) : _______ (6)

Total : ________

S1Q7 Please indicate how frequently you think your department is able to adequately address the following stormwater goals. If a stormwater goal is not addressed in your city, please mark "Not Applicable".

	Never Always Not Applicable 0 20 40 60 80 100
Reduction of flooding ()	
Reduction of erosion and sediment loads in runoff ()	
Reduction of other pollutant loads in runoff ()	
Increasing groundwater recharge ()	
Multi-use or community development initiatives ()	
Other (Please Describe) ()	

S1Q8 Please indicate how much the following factors limit your department's ability to adequately address local stormwater goals. Then, pick ONE of these factors that you think is the most important limitation to your department.

	Not at all Limiting	Extremely Limiting	Most Important Limitation
	0 20	40 60	80 100
Meeting federal regulations and requirements ()			
Meeting state regulations and requirements ()			
Lack of personnel ()			
Insufficient funding or budget ()			
Lack of information about appropriate solutions ()			
Lack of time or an excessive workload ()			
Other (Please Describe) ()			

S1Q9 What types of aquatic systems receive stormwater runoff from your city? You may choose more than one.

- ☐ Streams (1)
- ☐ Lakes (2)
- ☐ Rivers (3)
- ☐ Estuaries (4)
- ☐ Wetlands (5)
- ☐ Oceans or coastal areas (6)
- ☐ Aquatic systems do not receive runoff from my city (7)
- ☐ I am unsure what aquatic systems receive runoff (8)

S1Q10 Do any of the above areas that receive stormwater runoff from your city have impaired water quality?

- ○ Yes (1)
- ○ No (2)
- ○ I am unsure (3)

S1Q11 Which of the following are problems in these impaired aquatic systems? You may choose more than one.

- ☐ High sediment loads (1)
- ☐ High phosphorous (2)
- ☐ High nitrogen (3)
- ☐ Oil and grease (4)
- ☐ High E. coli or bacteria (5)
- ☐ Temperature impairment (6)
- ☐ Low dissolved oxygen (7)
- ☐ Heavy metals (8)
- ☐ PCBs (9)
- ☐ Other (please describe): (10) ____
- ☐ I am unsure (11)

S1Q12 Please indicate the degree to which the following potential sources of pollution contribute to any water quality problems in your area.

	Does Not Contribute			Major Contributor		
	0	20	40	60	80	100
Sewage or wastewater ()						
Agricultural runoff ()						
Urban runoff or stormwater ()						
Point source pollution (e.g. industrial waste) ()						
Other (please describe): ()						

End of Block: Water Quality Problems

Start of Block: Infrastructure Monitoring

S1Q13 How effectively does stormwater infrastructure in your city reduce the negative impacts of stormwater on water quality in impaired aquatic systems?

- It does not improve water quality (1)
- It slightly improves water quality (2)
- It moderately improves water quality (3)
- It significantly improves water quality (4)

S1Q14 Which of the following techniques were used in the course of the past year to monitor how stormwater infrastructure impacts water quality in your city? You may select more than one.

- ▢ Visual inspection and observations (1)
- ▢ Automated quality measurements (e.g. installed sensors or probes for dissolved oxygen, temperature, turbidity, etc.) (2)
- ▢ Automated quantity measurements (e.g. installed stage gauges or water level loggers) (3)
- ▢ Grab samples (4)
- ▢ Storm event grab samples (5)
- ▢ Stormwater is not monitored for its impact on water quality (6)
- ▢ Other (please explain): (7) ____

S1Q15 For the MAJORITY of stormwater projects in your city, over the course of a year, how frequently is monitoring of individual projects done in order to ensure that each project is meeting its goals and objectives?

- ○ Never (1)
- ○ Rarely (once a year or less) (2)
- ○ Sometimes (2-5 times/year) (3)
- ○ Frequently (every month or every other month) (4)
- ○ Extremely Frequently (more than once per month) (5)

End of Block: Infrastructure Monitoring

Start of Block: Federal Regulations

S1Q16 What are some of the key stormwater management goals on which federal stormwater regulations focus?

____

S1Q17 Are there any important stormwater management goals that ***federal*** stormwater regulations do not address or do not adequately address?

- Yes (1)
- No (2)
- I am unsure (3)

S1Q18 Please describe the important stormwater management goals that federal regulations miss or do not adequately address.

____

S1Q19 Do you think the focus of federal regulations matches the local stormwater management goals that are most important in your city?

- Yes (1)
- No (2)
- I am unsure (3)

S1Q20 How often do federal stormwater regulations focus on stormwater management goals that are NOT relevant to your city?

○ Rarely (1)

○ Sometimes (2)

○ About half the time (3)

○ Most of the time (4)

○ Always (5)

○ I am unsure (6)

End of Block: Federal Regulations

Start of Block: State Regulations

Q63 Does your ***state*** have additional stormwater regulations or mandates?

○ Yes (1)

○ No (2)

S1Q21 What are some of the key stormwater management goals on which state stormwater regulations focus?

____

S1Q22 Are there any important stormwater management goals that ***state*** stormwater regulations do not address or do not adequately address?

◯ Yes (1)

◯ No (2)

◯ I am unsure (3)

S1Q23 Please describe the important stormwater management goals that state regulations miss or do not adequately address.

____

S1Q24 Do you think the focus of state regulations matches the local stormwater management goals that are most important in your city?

◯ Yes (1)

◯ No (2)

◯ I am unsure (3)

S1Q25 How often do state stormwater regulations focus on stormwater management goals that are NOT relevant to your city?

- Rarely (1)
- Sometimes (2)
- About half the time (3)
- Most of the time (4)
- Always (5)
- I am unsure (6)

End of Block: State Regulations

Start of Block: Communication Source for Policy

S2Q1 Please indicate how often you use each of the following as a source for informing stormwater management policy, decisions, and practices (e.g. city stormwater regulations and policies, city standards, etc.). Then choose ONE source that is used most often to inform stormwater management policy, decisions, and practices.

	Never / Very Frequently / Used Most Frequently 0 25 50 75 100
Local residents ()	
Federal or state mandates ()	
Stormwater managers in your region ()	
Local or regional watershed associations or partnerships ()	
Reports or documents from within your department ()	
Initiatives, reports, or documents from the state or federal government ()	
Trade magazines and newsletters ()	
Stormwater conferences or meetings ()	
Internet searches on other cities' stormwater programs ()	
Academic literature ()	
Local research and monitoring ()	

End of Block: Communication Source for Policy

Start of Block: Communication Source for Identifying Local Issues

S2Q2 Please indicate how often you use each of the following sources of information to identify important local stormwater issues (e.g. particular problematic areas, impaired water bodies, etc). Then choose ONE source that is used most often to identify important local stormwater issues.

	Never		Very Frequently			Used Most Frequently
	0	20	40	60	80	100
Local residents ()						
Federal or state mandates ()						
Stormwater managers in your region ()						
Local or regional watershed associations or partnerships ()						
Reports or documents from within your department ()						
Initiatives, reports or documents from the state or federal government ()						
Trade magazines and newsletters ()						
Stormwater conferences or meetings ()						
Internet searches on other cities' stormwater programs ()						
Academic literature ()						
Local research and monitoring ()						

End of Block: Communication Source for Identifying Local Issues

Start of Block: Communication Source for Goal Setting

S2Q3 Please indicate how often you use each of the following sources of information to set stormwater goals and objectives (e.g. reduction of flooding, groundwater recharge, etc.). Then choose ONE source that is used most often in setting stormwater goals.

	Never		Very Frequently		Used Most Frequently	
	0	20	40	60	80	100
Local residents ()						
Federal or state mandates ()						
Stormwater managers in your region ()						
Local or regional watershed associations or partnerships ()						
Reports or documents from within your department ()						
Initiatives, reports, or documents from the state or federal government ()						
Trade magazines and newsletters ()						
Stormwater conferences or meetings ()						
Internet searches on other cities' stormwater programs ()						
Academic literature ()						
Local research and monitoring ()						

End of Block: Communication Source for Goal Setting

Start of Block: Communication Source for Infrastructure

S2Q4 Please indicate how often you use each of the following sources of information to make specific stormwater capital improvement project decisions (e.g. retention pond or stormwater wetland, project location and size, etc.). Then choose ONE source that is used most often to inform specific stormwater capital improvement decisions.

	Never	Very Frequently	Used Most Frequently

	0	20	40	60	80	100
Local residents ()						
Federal or state mandates ()						
Stormwater managers in your region ()						
Local or regional watershed associations or partnerships ()						
Reports or documents from within your department ()						
Initiatives, reports, or documents from the state or federal government ()						
Trade magazines and newsletters ()						
Stormwater conferences or meetings ()						
Internet searches on other cities' stormwater programs ()						
Academic literature ()						
Local research and monitoring ()						

End of Block: Communication Source for Infrastructure

Start of Block: Communication Source for Water Quality Monitoring

S2Q5 Please indicate how often you use each of the following sources of information to inform water quality monitoring techniques (e.g. techniques outlined in design manuals, city standards, etc.). Then choose ONE source that is used most often to inform water quality monitoring.

	Never	Very Frequently	Used Most Frequently
	0 20	40 60	80 100
Local residents ()			
Federal or state mandates ()			
Stormwater managers in your region ()			
Local or regional watershed associations or partnerships ()			
Reports or documents from within your department ()			
Initiatives, reports, or documents from the state or federal government ()			
Trade magazines and newsletters ()			
Stormwater conferences or meetings ()			
Internet searches on other cities' stormwater programs ()			
Academic literature ()			
Local research or monitoring ()			

End of Block: Communication Source for Water Quality Monitoring

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Start of Block: Communication Source for SW Technologies

S2Q6 Please indicate how often you use each of the following sources of information to learn about new stormwater treatment and flow control technologies. Then choose ONE source that is used most often to learn about stormwater technologies.

Never | Very Frequently | Used Most Frequently

0 | 20 | 40 | 60 | 80 | 100

Local residents ()	
Federal or state mandates ()	
Stormwater managers in your region ()	
Local or regional watershed associations or partnerships ()	
Reports or documents from within your department ()	
Initiatives, reports or documents from the state or federal government ()	
Trade magazines and newsletters ()	
Stormwater conferences or meetings ()	
Internet searches on other cities' stormwater programs ()	
Academic literature ()	
Local research or monitoring ()	

End of Block: Communication Source for SW Technologies

Start of Block: Information Reliability

S2Q7 Please use the sliding scale to indicate to what degree you feel that the information you receive from each source is reliable.

	Unreliable		Extremely Reliable		Used Most Frequently	
	0	20	40	60	80	100
Local residents ()						
Federal or state mandates ()						
Stormwater managers in your region ()						
Local or regional watershed associations or partnerships ()						
Reports or documents from within your department ()						
Initiatives, reports, or documents from the state or federal government ()						
Trade magazines and newsletters ()						
Stormwater conferences or meetings ()						
Internet searches on other cities' stormwater programs ()						
Academic literature ()						
Local research or monitoring ()						

End of Block: Information Reliability

Start of Block: Stormwater Infrastructure Frequency

S3Q1 Please rate how frequently each type of stormwater capital improvement project has been used in your city in the past 10 years. Then please select ONE type of project that is used most commonly in your city.

	Never	Very Frequently	Most Common Type

	0 10 20 30 40 50 60 70 80 90 100
Detention basins ()	
Retention or infiltration basins ()	
Dry wells or underground infiltration ()	
Constructed wetlands ()	
Permeable pavements ()	
Green roofs ()	
Vegetated buffer strips ()	
Bioswales or Rain gardens ()	

End of Block: Stormwater Infrastructure Frequency

Start of Block: Infrastructure Meeting Goals

S3Q2 Rate the following types of stormwater capital improvement projects according to how important you feel they are in meeting the stormwater goals of your city. If the project type is not used in your city, please mark the box under "Infrastructure Not Used".

	Not Important	Extremely Important	Infrastructure Not Used
	0 10 20 30 40 50 60 70 80 90 100		
Detention basins ()			
Retention or infiltration basins ()			
Dry wells or underground infiltration ()			
Constructed wetlands ()			
Permeable pavements ()			
Green roofs ()			
Vegetated buffer strips ()			
Bioswales or Rain gardens ()			

S3Q2a Which stormwater capital improvement project type is most important to meeting the stormwater goals in your city?

- ○ Detention basins (1)
- ○ Retention or infiltration basins (2)
- ○ Dry wells or underground infiltration (3)
- ○ Constructed wetlands (4)
- ○ Permeable pavements (5)
- ○ Green roofs (6)
- ○ Vegetated buffer strips (7)
- ○ Bioswales or Rain gardens (8)

Q64 Which stormwater capital improvement project type would you most like to implement to meet future stormwater goals?

- ◯ Detention basins (1)
- ◯ Retention or infiltration basins (2)
- ◯ Dry wells or underground infiltration (3)
- ◯ Constructed wetlands (4)
- ◯ Permeable pavements (5)
- ◯ Green roofs (6)
- ◯ Vegetated buffer strips (7)
- ◯ Bioswales or rain gardens (8)
- ◯ Other (please explain): (9) ____

End of Block: Infrastructure Meeting Goals

Start of Block: Infrastructure Location

S3Q3 Rate the importance of the following factors in determining the location of stormwater management projects. Then, pick ONE that is the most important driver of these decisions in your city.

	Not Important	Extremely Important	Most Important
	0 10 20 30	40 50 60	70 80 90 100
Cost of the land ()			
Proximity to other stormwater structures ()			
Ability to mitigate problem areas (e.g. areas with frequent flooding, erosion, or discharge of pollutants) ()			
Zoning regulations ()			
Opportunity for public access ()			
Natural and physical characteristics of land (e.g. hill slopes, sewer or gas lines, parking lots, etc.) ()			
Community interest or support ()			

S3Q4 Please list any other factors that are important considerations when deciding the location of stormwater management projects.

____

End of Block: Infrastructure Location

Start of Block: Infrastructure Development Decisions

S3Q5 When implementing a new stormwater capital improvement project, the decisions about the specifics of individual projects (e.g. where the projects are to be built, the type of stormwater project, etc.) are MOST OFTEN made by:

- ○ Stormwater permit managers (1)
- ○ Stormwater operations managers (2)
- ○ Engineers within your city (3)
- ○ Consultants (4)
- ○ A committee of individuals specific to making stormwater decisions (5)
- ○ Other (please explain): (6) ____

S3Q6 Please rate how strongly the following factors influence the decision to build new stormwater capital improvement projects in your city. Then choose ONE factor that you feel has the MOST influence on the decision.

	No Influence	Very Strong Influence	Most Influential
	0 10 20 30	40 50 60	70 80 90 100
Project type mandated by federal or state regulations ()			
Project was successfully implemented by other cities in your region ()			
Previous success with this project type in your city ()			
Community interest or support ()			
Multi-use or ability to meet community development initiatives ()			
Research or scientific studies supporting a project type ()			
The image of the project as "green" or focused on sustainability ()			

S3Q7 Please list or describe any other factors that influence the the decision to build a stormwater project.

____

End of Block: Infrastructure Development Decisions

Start of Block: Stormwater Wetlands Water Sources

S4Q1 Throughout the course of a year, how often do the MAJORITY of stormwater wetland projects in your city have water in them?

	Very Rarely			Always	
	0	73	146	219	292	365
Days with water in wetlands ()						

S4Q2 Are there sources of water, other than runoff during storm events, that are routed through the stormwater management wetlands in your city?

- ◯ Yes (1)
- ◯ No (2)
- ◯ I am unsure (3)

S4Q3 Which of the following are sources of the water that is routed through the stormwater wetlands? You may choose more than one.

- ☐ Groundwater (springs, etc.) (1)
- ☐ Surface water (streams, ponds, etc.) (2)
- ☐ Wastewater (municipal, industrial, etc.) (3)
- ☐ Other (please explain): (4) ____________________
- ☐ I am unsure (5)

End of Block: Stormwater Wetlands Water Sources

Start of Block: Wetlands Motivations

S4Q4 Which of the following were motivations for choosing to build stormwater management wetlands over another type of stormwater capital improvement project? You may choose more than one.

▢ Stormwater wetlands recommended by federal or state regulations or guidelines (1)

▢ Stormwater wetland projects were successfully implemented by other cities in your region (2)

▢ Stormwater wetland projects have had previous success meeting stormwater goals in your city (3)

▢ Public interest or support for stormwater wetland projects (4)

▢ Research or scientific studies supporting stormwater wetlands (5)

▢ The image of stormwater wetlands as a “green” type of infrastructure (6)

▢ Ability of wetlands to meet multi-use or community development initiatives (7)

▢ Low maintenance requirements of stormwater wetlands compared to other stormwater infrastructure types (8)

▢ Other (please explain): (9) ____

S4Q5 Below please select the project goals or objectives of stormwater management wetlands in your city.You may choose more than one.

- [ ] Reduction of flooding (1)
- [ ] Reduction of erosion and sediment loads in runoff (2)
- [ ] Reduction of other pollutant loads in runoff (3)
- [ ] Increasing groundwater recharge (4)
- [ ] Multi-use or community development initiatives (5)
- [ ] Other (Please Describe) (6) ____

End of Block: Wetlands Motivations

Start of Block: Wetland Maintenance

S4Q6 Which of the following types of regular (AT LEAST once per year) maintenance are done on the constructed stormwater wetlands in your city? You may choose more than one.

▢ Removing sediment (1)

▢ Trash or litter removal (2)

▢ Removing accumulated plant matter (dead wetland vegetation, leaf litter, etc) (3)

▢ Planting wetland vegetation (4)

▢ Care or maintenance of existing wetland vegetation (other than invasive removal) (5)

▢ Invasive species removal (6)

▢ Other (please describe): (7) ____

End of Block: Wetland Maintenance

Start of Block: Wetland Vegetation

S4Q7 Which of the following general types of vegetation are found in the constructed stormwater wetlands in your city? You may choose more than one.

- ▢ Algae (1)
- ▢ Aquatic plants (e.g. macrophytes, ribbon grasses, water lilies, etc.) (2)
- ▢ Reeds (e.g. cattails, phragmites, bamboo, harsetail, etc.) (3)
- ▢ Rushes (e.g. spikerush, creeping spikerush, etc.) (4)
- ▢ Grasses (5)
- ▢ Terrestrial vegetation (e.g. trees, shrubs, etc) (6)
- ▢ I am unsure (7)

End of Block: Wetland Vegetation

Start of Block: GIS Data

Q58 Would you be willing to share a PDF, map, or shapefile(s) showing the locations of the stormwater infrastructure in your city?

- ○ Yes (1)
- ○ No (2)

Q59 Please enter an email address below at which we can contact you in order to follow up about a PDF, map, or shapefile(s) showing the locations of the stormwater infrastructure in your city.

____

End of Block: GIS Data