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Optimizing Green Infrastructure: designing, managing, and evaluating green infrastructure to receive social, economic, and ecological benefits

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Optimizing Green Infrastructure: designing, managing, and evaluating green infrastructure to receive social, economic, and ecological benefits

Senior Project Submitted to
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by
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1.0 Introduction

Expanding population and impervious surfaces through urbanization has made managing stormwater runoff a topic of increasing priority for many US cities. Stormwater runoff is contaminated with a range of organic and inorganic pollutants and is increasingly characterized by higher flow rates and volumes, (Bell et al, 2018). Urbanization is made worse by human-induced climate change, particularly in places like the northeast United States where increased intensity and frequency of large storm events are occurring (Reidmiller et al., 2018; Fig. 1.0). This not only threatens and degrades the quality of aquatic ecosystems and their ecology, but also has an impact on humans who use these water resources and the infrastructure involved in managing them (Bell et al, 2018; O'Driscoll et al., 2010). To manage flooding, combined sewer overflow (CSOs), and other issues associated with polluted runoff, some cities are opting for low impact green infrastructure (GI) systems over the traditional gray infrastructure of combined or separated sewage systems. The purpose of GI is to capture stormwater runoff at the source and improve

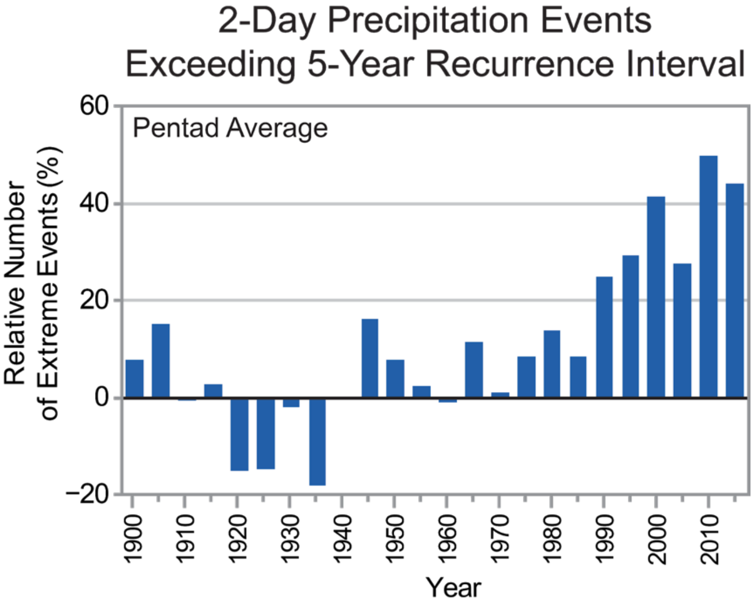

Figure 1.0: Number of 2-day precipitation events exceeding station-specific threshold for 5-year recurrence interval in the U.S., expressed as percent different from 1901-1960 mean. Source: USGCRP, 2017.

water quality by mimicking natural water cycle processes of filtration and evaporation with vegetation, soils, and other elements (USEPA, n.d.).

In addition to improving water quality in stormwater runoff, GI is touted for providing other ecosystem services, or co-benefits, depending on the type of GI system. While many evaluative cost-benefit studies of these systems focus on their performance in reducing stormwater volume or peak flow, very few cost-benefit analyses have examined other potential benefits, such as nutrient removal (Bixler et al. 2020; Bixler et al. 2019; Kapetas & Fenner, 2020). Quantifying the additional services provided by GI can be difficult, but it is ultimately necessary when making claims about the services. These systems must undergo performance evaluation, and the knowledge and data collected from the evaluation process must then be used to inform long-term management and help set realistic expectations for system maintenance (Ibrahim, et al. 2020; Spahr, et al. 2020; Van Oijstaeijen, et al. 2020, Sussams, et al., 2015).

However, studies of these systems after implementation have revealed substantial knowledge gaps regarding what the stated goals of the systems are and what they can provide. As such, it is crucial that we manage these systems while trying to fill in these knowledge gaps, and continuously adjust our management strategies as knowledge is developed. One management approach that adopts this ethos of flexibility and constant learning is adaptive management (Allen et al., 2011; Holling, 1978; Schreiber et al., 2004; Williams et al., 2009). Adaptive management applies a cyclical, learning-based approach to managing natural resources where we acknowledge uncertainty and knowledge gaps in order to inform our management decisions. Resource management decisions are increasingly made in the context of competing goals or objectives, constrained budgets and management capacity, dynamic ecological systems, and uncertainty (Williams et al., 2009). Given this context, the adaptive management approach provides guidance for making decisions in a complex environment.

Green Infrastructure as an environmental policy intervention lies at the intersection between scientific understanding of natural resources and civil society application (Sussams, et. al., 2015). As such, adaptive management provides an appropriate management structure to these systems, particularly because of the knowledge gaps regarding GI. The stated goals for the Green Infrastructure system at Bard include flood resilience, reduced erosion, recharging groundwater, improved water quality, moderating temperatures, enhancing habitat, and providing attractive green areas. While some of these goals have arguably been met, such as providing green areas and reducing erosion, the remaining goals have been partially met, unmet, or there remains uncertainty.

In order to identify the potential for adaptive management as an effective option for managing Bard's Green Infrastructure, this paper will first review the literature regarding GI implementation, management, and performance assessment in chapter two. Following the literature review, chapter three will provide an overview of the state of the system based on monitoring from the past two years. The final chapter will summarize these findings in the literature as well as the data on the state of the system, drawing conclusions and making the case for adaptive management as a potentially effective option for Bard's GI management. By explicitly adopting the adaptive management strategy for maintaining this system going forward, operators, students, and professors may solidify a plan to monitor the effectiveness of the system, make maintenance decisions based on this monitoring, and in turn assess the effects of these operations as a disturbance to the system.

2.0 Literature Review

In this review of the literature, I will examine two areas of study around optimizing the implementation and management of GI systems (1) design and spatial considerations and (2) social and economic assessments. I will first examine how design configuration and spatial characteristics of GI systems and their location impact the performance, emphasizing “blue” infrastructure systems with open water ponds and wetlands. Then, I will review the methods and parameters by which these systems are economically assessed and examine what should be included in these assessments to account for performance goals and co-benefits. This section will also examine how social values and directives should be incorporated into its design and implementation as well as reimagine how GI is managed in order to optimize performance across its life cycle.

2.1 Design Configuration and Spatial Considerations for Green Infrastructure

Green infrastructure can be best understood in terms of its difference from the grey infrastructure that has been standard in stormwater management for US cities. Grey infrastructure utilizes materials like concrete and steel in the form of pipes, dams, and water treatment plants in order to manage stormwater runoff. GI, while also manmade, incorporates nature-mimicking elements to not only capture and convey runoff, but also to allow runoff to infiltrate into the ground. GI encompasses a diverse range of interventions, including but not limited to rain gardens, green roofs, urban tree canopies, and constructed wetlands. Within these interventions are various natural elements, including trees, native plantings, grasses, ponds, stones, and more.

Often coupled with GI is a subset referred to as blue green infrastructure (BGI), which also refers to nature-mimicking stormwater management systems, but is more specific to those that use open water elements, such as rivers, canals, floodplains, retention ponds, and wetlands. Constructed wetlands (CWs) are a form of BGI that feature shallow basins containing different kinds of vegetation to slow stormwater runoff and filter out pollutants through various design components. This section will focus on understanding how to assess and optimize BGI systems (particularly CWs) for multiple benefits by determining how to best design and site them. Multiple benefits as they relate to GI refer to an intervention's ability to provide multiple environmental and social co-benefits in addition to their main purpose (Sussams, et. al., 2015). For example, the GI system at Bard purports benefits of enhanced habitat, flood resilience, moderating temperatures, and multiple others in addition to its main function as a stormwater intervention.

2.1.1 Landscape, Climate, and other Spatial Considerations

The context within which BGI systems are designed and implemented necessitates decision-making around which ecological functions are the most important or desired. In some instances, one design element may successfully provide multiple functions simultaneously; in other cases, there are tradeoffs between functions. How various design elements and configurations impact the performance of BGI is dependent on site-specific characteristics.[1] Often in deciding what design elements should be included depends on the landscape, climate, land use, or other factors specific to a region—and thus, specific to the environmental problems that a region faces (Houle et al., 2013). For example, an intervention that provides groundwater recharge might be more appropriate in an arid climate than in a location that has heavy precipitation throughout the year. In addition

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[1] Additionally, changes over time in the site-specific characteristics of a given GI site and catchment area—such as landscape and climate—make considerations of these changes integral to assessing performance (Bixler, Houle, Ballestero, & Mo, 2019).

to climatic factors, the suitability of a GI intervention could also be related to land use activity in the area, such as intensive agriculture or urban settings. In their study, Bixler et al. (2019) develop a model for Life Cycle Assessments (LCAs) of different forms of GI across these various spatial characteristics and changes. When assessing geospatial differences across a range of GI in a range of cities, performance varied with seasonal temperatures, precipitation patterns, and fertilizer application in the catchment area (Bixler et al., 2019).

Bixler et al. (2019) evaluated various parameters for BGI across spatial scales, in particular nutrient removal performances, more specifically that of nitrogen and phosphorus. As opposed to other forms of GI, the BGI systems they studied—constructed wetlands and wet ponds—had the highest nitrogen removal efficiency across their life cycle, regardless of geographical locations. However, phosphorus removal by the two BGI systems had greater variability across land use scenarios, with CWs performing best in agricultural settings. Bixler et al. (2020) expand on their assessment of GI effectiveness across spatial settings, this time examining stormwater reduction as well as nutrient removal, and estimating the cost-effectiveness based on these services. In particular, the authors calculated cost-effectiveness (CE) of the green infrastructure systems based on the volume of stormwater reduced, finding greater CE of wet ponds and wetlands than wastewater treatment facilities in four of the five US cities. Among these four cities was San Diego, which showed the greatest CE values for each intervention despite lower average annual runoff volumes (Bixler et al., 2020).

2.1.2 Design Configuration, Performance Impacts, and Maintenance

In different open water ponds and constructed wetlands, both forms of GI, pollutant removal efficiencies can be influenced by a range of design elements, including basin depth, plant coverage, hydraulic retention time, and aspect ratio (Houle et al., 2013). For constructed wetlands in particular, settling basins are a key design feature (Lee, et al., 2014). Settling basins are large, open troughs filled with water that collect runoff and allow for the settling of suspended solids. They have a range of mechanisms that serve a variety of different purposes, including filtering out pollutants and nutrients with emergent plants (Li, et al, 2019), reducing turbidity via sedimentation, and storing pollutants in the sediment (Lee, et al., 2014). In terms of water depth, shallow basin designs allow for greater nutrient and pollutant removal efficiencies as opposed to deep water designs (Chang et al., 2016; Li et al., 2019). This is because increasing depth negatively impacts hydraulic efficiency and emergent plants—a key mechanism of nutrient and pollutant removal—struggle more at greater water depths (Su et al., 2009).

Settling basin design performance is not only impacted by the engineered, physical characteristics of the basin, but also by the plant species that populate it. Here, plant coverage is considered in terms of how much area it covers in the design, and also the species that make up the configuration. Li et al. (2014) found improved nutrient removal efficiencies through a plant configuration of native plants and a mixed planting pattern covering 60-80% of the wetland compared to other planting configurations. The coverage and configuration of plantings in wetlands can impact the speed and direction with which water flows through a GI basin, with more plant coverage diverting and slowing down the flow of water through wetland channels. The percentage of plant coverage directly relates to another BGI performance aspect, known as hydraulic retention time (HRT). HRT measures the amount of time that a compound—in this case, stormwater runoff—is retained in a treatment basin, such as a constructed wetland. As a function of the volume and flow rate of water in a basin, an ideal HRT can be determined in terms of its ability to allow for optimal pollutant removal; in their assessment, Li et al. (2014) determine the ideal HRT for a CW to be 3 to 10 days.

Finally, HRT is closely related to the aspect ratio—that is, the length to width ratio of the flow path—of the basin. In other words, this is the difference between a long, narrow channel, and a basin more equal in length and width. Li et al. (2014) and Su et al. (2009) as well as other authors that they cite, make recommendations for aspect ratio based on pollutant removal optimization. With engineered features of CWs like aspect ratio, effectiveness is often determined with a parameter called hydraulic efficiency. Closely related to HRT, hydraulic efficiency is a more encompassing parameter that refers to the wetland's overall ability to regulate flow and retention in order to allow for optimal pollutant removal. Su et al. (2009) find that an ideal aspect ratio is in the range of 3:1 to 5:1 (wetland length: wetland width), and they warn that inappropriate aspect ratios can create dead zones and cut off flow, resulting in reduced hydraulic efficiency.

Further studies indicate that optimization of other design factors such as volume and area are more site-specific, and should be determined by the different types and amounts of runoff in the catchment area (e.g. agricultural, sewage) and the local governance and investment capacity (Zuniga-Teran et al., 2020). Sedimentation enhanced by increased hydraulic retention time is the source of more than 70% of the pollutant removal in CW settling basins (Lee et al., 2014). However, because of this pollutant storage, basins that are not dredged and maintained via removal of accumulated sediments are at risk of acting as pollutant sources of receiving water over time (Lijklema as cited in Lee et al., 2014, p. 1791). As such, maintenance of these types of blue infrastructure interventions should be anticipated and carried out regularly (Castonguay et al., 2018), with a dredging timeline of every 1-3 years of operation as recommended by Li et al. (2019).

This section has summarized several studies about BGI design configuration, with the authors considering a range of physical and biological design elements and making claims about how they can optimize effectiveness as well as examining how spatial factors like regional climate and land use characteristics can impact the effectiveness of different types of BGI in achieving stormwater management objectives. Here, economic value is assigned to services provided by the BGI system in the form of cost per unit function. The remainder of the paper will add to this discussion by exploring the literature on the valuation of ecosystem services provided by BGI.

2.2 Social Valuation of Green Infrastructure Ecosystem Services

The previous section summarized scientific findings and recommendations for BGI design based on how they influence system performance in achieving certain functions, in particular nutrient removal. In order to receive not only ecological, but also social and economic benefits, however, stakeholders involved in these processes must be deliberate in placing value on the various performance aspects of BGI systems. Scientific assessment should inform decision-making, but social and economic valuation for ecosystem services is also necessary to weigh options and make strategic decisions. For example, a city may have extensive impervious surface cover that causes increased stormwater runoff into CSOs, causing them to overflow. As a result, they may wish to install a BGI system to collect the runoff and drain it into the ground as opposed to the sewer. Additionally, the city might face challenges with biodiversity loss and want a BGI system that increases green coverage and natural habitats for native species. However, the system that would perform best for stormwater flow reduction in this specific city—with its individual climate and land use characteristics—may be different from one that would best support biodiversity. Or if these functions aren't mutually exclusive, there still may be additional costs in designing, implementing, and maintaining a system that is capable of performing all of these functions.

And then there are the economic costs and benefits of the new system. How do factors like lowering costs for treatment of CSOs compare to other factors like preserving a bird species that has social or cultural value to the area? Placing value on these factors becomes more difficult when one outcome (like lower treatment costs) has a determined economic value and another (like preserving a bird species) likely does not. On top of that, do these valuations at the outset of implementation account for maintenance and management costs down the line? Maintenance and management in the long term are often overlooked in the implementation of BGI systems, so it is important to consider these as part of a social and economic valuation.

Each of the following sections will explore different aspects surrounding the issue of co-benefit valuation, including co-benefit valuation systems, incorporating maintenance and management, social interactions with GI, and green governance.

2.2.1 Quantifying and Assessing Co-Benefits

Given the range of ecosystem services that GI can provide, having a clearly outlined framework for determining goals and evaluating success is integral. In most cases, this involves assigning an economic value to a co-benefit that has typically been valued for its ecological contributions. For example, Spahr et al. (2020) evaluate co-benefits through an ecosystem services framework in order to understand how BGI systems impact urban greenness[2]—that is, the quality and quantity

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[2] Urban greenness or urban greening is a green infrastructure concept that goes beyond stormwater management. Urban greening has been pointed to as a solution for a range of issues stemming from urbanization and the paving over of once natural environments (Spahr et al., 2020). A non-exhaustive list of its services includes reducing urban heat island effect, providing green spaces in crowded urban areas, and creating urban habitats for birds and other animals. For more research on the use of urban greenness as a measure of urban GI planning, see Liu & Russo (2021).

of vegetative land cover—across different climate and spatial characteristics. The ecosystem services framework is a useful tool for measuring co-benefits related to social outcomes, which have typically been difficult to measure and quantify. In this framework, an ecosystem service, such as the reduction of stormwater runoff, can connect the ecological benefit of reduced flooding to the social benefit of resilience in the face of heavy precipitation events (Spahr et al., 2020). Therefore, stormwater runoff reduction, the measurable parameter, can be tied to flooding resilience, the not-easily-quantified social co-benefit (Bell et al., 2019). In applying this framework, Spahr et al. (2020) found that in most cases, increases in urban greenness were directly related to an increase in the ecosystem services provided. They attribute this increase to the extended lengths of time that the BGI systems have been in place, since more recently installed systems indicated lower greenness—as it takes time for the vegetation components to develop. In cities that had recently implemented new BGI projects but also had decreasing greenness scores, such as Chicago, Philadelphia, and Washington D.C, often development and increasing population were outpacing these BGI advances (Spahr et al., 2020).

Kapetas and Fenner (2020) take a similar approach in designing a model that assesses the cost and benefits of a specific blue-green-gray[3] stormwater infrastructure intervention. The paper examines the "profile" of different BGI flood mitigation interventions, which includes their flexibility in implementation, costs of operation and maintenance, and provision of additional benefits. Their economic assessment is not purely performance-based, as they also incorporate social factors in decision-making regarding BGI. For example, an intervention may be assessed

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[3] Whereas blue-green refers to the use of natural elements to capture, transport, and allow infiltration of stormwater runoff, blue-green-gray infrastructure couples GI/BGI with gray infrastructure, e.g. pipes, dams, hard barriers, etc. This term becomes useful in conceptualizing a system of stormwater interventions and treatment, which is often the case at the city scale. The use of gray infrastructure for stormwater treatment is never replaced with only GI/BGI, but rather is retrofitted with it; as such, blue-green-gray infrastructure becomes useful in understanding stormwater treatment as a network of old and new, hard and soft interventions (Kapetas & Fenner, 2020).

for its performance in conveying and storing stormwater runoff as part of the criteria for success, but the decision is also guided by how well the intervention can create health, recreational, or educational benefits (Kapetas & Fenner, 2020; Ibrahim et. al. 2020). With these social considerations, the authors pose the question of how having multiple benefits can help guide the decision-making process for the preferred pathway. (Kapetas & Fenner, 2020). For example, a particularly water-stressed region may benefit from an intervention that can also recharge groundwater as an additional service. They make the point that traditional economic cost-benefit analysis is fundamental for stormwater mitigation but can often disregard the potential co-benefits, resulting in missed synergies with ecosystem services for social benefit.

2.2.2 Frequency and Costs of GI Maintenance

Considering the potential for ecosystem services to provide social co-benefits as a part of economic analysis and decision-making is an integral next step for optimizing BGI interventions (Bixler et al., 2019; Bixler et. al., 2020; Castonguay et. al., 2018; Van Oijstaeijen, et al. 2020). However, part of this optimization must include all facets of project and design implementation to improve decision-making (Bixler et al., 2019; Bixler et. al., 2020). Rather than simply accounting for upfront costs and estimated stormwater benefits, it is key that the costs associated with the potential for degraded performance and maintenance are considered (Kapetas & Fenner, 2020; Castonguay et al., 2018). Management of these systems that does not incorporate maintenance is subject to suffering from degraded performance to the point that the benefits provided by the system become negligible (Bixler et al., 2019). For example, systems that are intended to provide pollutant removal benefits may become saturated to the point that there is no longer a tangible net benefit (Lijklema as cited in Lee et al., 2014, p. 1791).

Designing, implementing, and managing a GI intervention with a life cycle perspective is therefore imperative to achieving stated goals and receiving co-benefits (Bixler et al., 2019). Bixler et al. (2020) develop a framework for assessing GI performance from cradle to grave so that it can be applied to different geographic and environmental conditions and inform design and decision-making related to GI implementation. Though intended for use prior to implementation, this framework can also be a useful tool during major, costly maintenance events such as dredging (Bixler et. al., 2020).

2.2.3 Social Interactions with Green Infrastructure

Determining GI design goals and the optimal configuration of a system necessitates the inclusion of a range of stakeholders who will interact with the system (Kapetas & Fenner, 2020; Zuniga-Teran, et al., 2020; Francesch-Huidobro et al., 2020; Ibrahim et al., 2020). The stakeholders involved range from those monitoring the performance of the system, those governing decisions around when maintenance can and should occur, laborers carrying out the maintenance, and those in the surrounding area who see and interact with the system (Van Oijstaeijen, et al. 2020). By looking at cities as socio-ecological systems[4]—with GI as one component of these systems—Zuniga-Teran et al. (2020) assess the policy, performance, connectivity, and social dimensions of GI for their contributions to the multiple facets of urban resilience: the institutional, climatic, economic, and ecological. As the authors point out, previous studies assess GI solely on the water quality performance dimension as it contributes to these four areas. Here, however, the authors

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[4] The socio-ecological system is a framework often used for analyzing local resource management, and it has come to encompass studies and authors from a range of social and physical science disciplines. Though definitions differ amongst users of the concept, it often refers to a complex, interconnected system of social institutions and ecological factors. The system is made up of social and ecological resources that are complex, dynamic, and connected through feedback loops. A more in-depth analysis of the discourse around socio-ecological systems is provided by Colding & Barthel, 2019.

review types of regulations and policies that promote GI and how they contribute to institutional urban resilience, how the connectivity of GI networks enhances urban resilience, and how GI contributes to social resilience, i.e. a community's ability to "withstand, respond, and adapt to change," (Zuniga-Teran et al., 2020, p. 44). They find that GI can support urban resilience when social aspects and context-specific planning are incorporated into the implementation of GI systems.

Relatedly, in an assessment of GI evaluation toolkits, Van Oijstaeijen et al. (2020) find that a more explicit economic valuation is key for communicating the best options to decision-makers and the public, especially for local authorities who need to see the economic benefits of these systems. By utilizing co-benefit valuation frameworks such as those discussed in section 3.1, social benefits can be quantified and valued, and this economic valuation can then be communicated to stakeholders (Spahr et al., 2020; Kapetas & Fenner, 2020). Rather than a co-benefit simply being expressed to the public in a supplemental anecdote, it is tied to the measurable stormwater management goals and is tailored to the interests of the stakeholders involved (Kapetas & Fenner, 2020). A final key factor policy-makers should consider incorporating into GI decision-making tool kits is how the management of these systems will work and what the governance structures will look like.

2.2.4 Green Governance

After accounting for the key ecological goals and social co-benefits, as a policymaker, the next step is coordinating governance over the system. Green governance refers to a governance approach that is able to coordinate a response to challenges that BGI systems face over time through multiple contexts in which challenges can occur. These contexts include the intended design goals, the institutional and political system in which the governance must operate, communication and collaboration across stakeholders, and legal frameworks (Ibrahim et al., 2020; Francesch-Huidobro et al., 2020; Schiappacasse, & Müller, 2015). In terms of intended design goals, green governance means understanding the scope and limitations of these systems, developing a framework to measure and monitor performance, and anticipating maintenance projects (Ibrahim et al., 2020; Schiappacasse, & Müller, 2015). This can be realized through some of the strategies and frameworks presented above. This could mean using an ecosystem services framework to bring together tangible and intangible goals (i.e. an ecological and social goal, respectively) so that the latter are more explicitly measured and monitored (Spahr et al., 2020). Another option is utilizing a life cycle perspective in arranging system management will ensure future maintenance does not go ignored (Bixler et al., 2019).

The second area is the institutional and political context, which encompasses challenges such as limited community involvement, lack of formal structures regarding management, and failing communication across institutions and jurisdictions. In this context, green governance calls for strengthened leadership and coordination across institutions that oversee GI maintenance and management (Ibrahim et al., 2020; Schiappacasse, & Müller, 2015). This may take the form of designated expert representatives for each relevant discipline (e.g. biologists, engineers, community leaders). These leaders must not only be able to represent their area of expertise, but must also have an interdisciplinary understanding of what the other experts bring to the table in the management of a GI system (Ibrahim et al., 2020). How the formal structures for management are realized is dependent on the scale and region, but what is certain is that deliberate actions must be taken to ensure all management and maintenance activities have a coordinating and governing body. Another common issue within the institutional and political context of a BGI project is coordinating governance and management around maintenance (Ibrahim et al., 2020). Some of the challenges that can arise often relate to communication and collaboration among stakeholders (Schiappacasse & Müller, 2015). In particular, there can be misunderstandings among stakeholders about project design goals and expectations for the system. Additionally, issues can arise when the maintenance required to achieve these goals is not properly coordinated among stakeholders (Zuniga-Teran et al., 2020).

Related is the context of stakeholder engagement, which can range given the size, complexity, and location of a GI project (Zuniga-Teran et al., 2020; Van Oijstaeijen et al., 2020; Liu & Russo, 2021). Success in the context is usually derived from a strengthened political and institutional system where there is strong leadership that can allow for coordination and collaboration among stakeholders (Ibrahim et al., 2020). To aid in reducing challenges here, again, the ecosystem services framework, as well as the GI profile developed by Kapetas & Fenner (2020) can be useful. As the article suggests, limited community involvement may be a result of limited relevancy (or inability to see the relevance) of the project to the public. Again, tying together ecological and social goals makes benefits more tangible, but incorporating the GI profile into the planning process can put public concerns at the fore of the project before ground is even broken (Kapetas & Fenner, 2020). In other words, these mechanisms in the planning process can help create a shared vision for the project that creates opportunities for inclusivity. If a local issue, such as being a water-stressed community, is directly addressed through designing and implementing GI that will aid with groundwater recharge, the community may have more reason to stay involved throughout the life cycle of the intervention.

2.3 Summary

Blue Green Infrastructure has the potential to not only provide its intended stormwater management benefits, but also additional ecosystem services ranging from enhanced biodiversity to groundwater recharge. Optimizing BGI in order to achieve the stated goals and also receive additional ecosystem services requires intentional goal setting and valuation in the design, implementation, management, and maintenance stages. Design elements and their configuration in BGI systems can influence their ability to achieve specific stormwater management outcomes, like improved pollutant removal efficiency (Li et al., 2019; Lee, et al., 2014; Su et al., 2009). The performance of a given BGI intervention in achieving its stated goals is also dependent on spatial factors, such as climate and regional land use (Bixler et al., 2019; Bixler et al., 2020). Given the range of potential ecosystem services with different BGI interventions, social and economic valuation then becomes important for implementation and management (Spahr et al., 2020; Kapetas & Fenner, 2020; Ibrahim et al., 2020). Some valuation frameworks presented include the ecosystem services framework (Spahr et al., 2020) and one based on the social, economic, and ecological profile of a BGI intervention (Kapetas & Fenner, 2020). Maintenance is also a key factor in achieving stated goals and receiving co-benefits, and can be incorporated into the design, implementation, and management when the infrastructure is viewed with a life cycle perspective (Bixler et al., 2019). For management over time, a green governance approach allows for a coordinated response to the various challenges that arise after implementing BGI interventions (Ibrahim et al., 2020).

Chapter 3.0 Bard Constructed Wetland State of the System

3.1 Project and Site Description

Through the NYS Green Innovation Grant Program, Bard College constructed a green infrastructure project, the *Bard Regional Demonstration Project for Improving Stormwater Management*. Completed in 2015, the project was carried out with the intention of providing the benefits of green stormwater intervention to the campus community, and also modeling operations and maintenance procedures for similar projects in the region. The Bard College campus is located in Annandale-On-Hudson, NY along the Hudson River and roughly midway between New York City and Albany. The campus is situated in the Saw Kill subwatershed, with the Saw Kill Creek running through the south of campus into South Tivoli Bay, a NYS protected wildlife management area, before entering the Hudson River. The Saw Kill, running through multiple towns before it reaches the Hudson, holds particular importance to the Bard community by providing the campus' drinking water. As such, the demonstration project was intended to provide stormwater management benefits to protect these significant local water bodies.

The project design includes a range of blue and green stormwater management components, all located on the east side of central campus behind an expanse of parking lots. The first component is a porous asphalt parking area (Fig. 3.1E), a type of pavement that is designed to allow rain and snow runoff to permeate through small pores in the asphalt and into the ground. Similarly, along the porous asphalt parking area is a permeable interlocking concrete pavement (PICP) sidewalk (Fig. 3.1D) that also allows for water infiltration through surface openings. Running along the rear of the parking lot is a riparian buffer (Fig. 3.1F) that separates the parking lot from the adjacent floodplain and provides a natural barrier to the invasive *phragmites Australis*. Located on the lawn next to this parking lot are two bioretention areas (Fig. 3.1A), or shallow basins containing plantings adapted to filter out pollutants from stormwater runoff.

Figure 3.1: Map of GI components in Bard Regional Demonstration Project for Improving Stormwater Management. Source: Bard College Office of Sustainability, 2015.

Running along the PICP sidewalk is a vegetated bioswale, a (Fig. 3.1B) channel that collects, conveys, and filters pollutants out of stormwater runoff. The final piece of the demonstration project is the constructed wetland (Fig. 3.1G). In addition to its role as the last link in the system, the constructed wetland has also been hailed to provide the bulk of the stormwater management benefits. Its proposed benefits include flood resilience, reduced erosion, recharging groundwater, improved water quality, moderating temperatures, enhancing habitat, and providing attractive green areas.

Since the installation in 2015, the constructed wetland has been studied by students and professors to examine the extent to which it provides these purported benefits. Monitoring of the constructed wetland has largely focused on water quality parameters, including conductivity/salinity/chloride concentration, dissolved oxygen (DO), turbidity, colored dissolved organic matter (CDOM), optical brighteners (OB), chlorophyll a, and phycocyanin. On a more irregular basis, the system has been monitored for enterococcus and coliforms, two kinds of sewage-indicating bacteria. Though not monitored formally, pictures of the wetland over time since its installation allow for visual inspection of plant growth. The monitoring over the past few years has led to the current understanding of how this system is functioning, including where it is failing and where it is fulfilling its sought-after goals. The following section will outline the monitoring data and what these trends and values indicate about the state of the system.

3.2 Monitoring and the State of the System

The monitoring data collected over the years can largely indicate the system's effectiveness in its goals of (1) improving water quality and (2) enhancing habitats. Often, the state of the water quality directly impacts the system's ability to achieve its goal of enhancing habitats. The stormwater that enters the constructed wetland is first drained into a settling pool (Fig. 3.2 A1), before flowing through the marsh area (Fig. 3.2 G2), the deep pool (Fig. 3.2 F0), and then through an outlet pipe into a natural wetland (Fig. 3.2 F1/FDrain/F2). Monitoring examined multiple sites throughout the system, with parameters related to road salt focusing on collection in the deep pool (F0) of the constructed wetland.

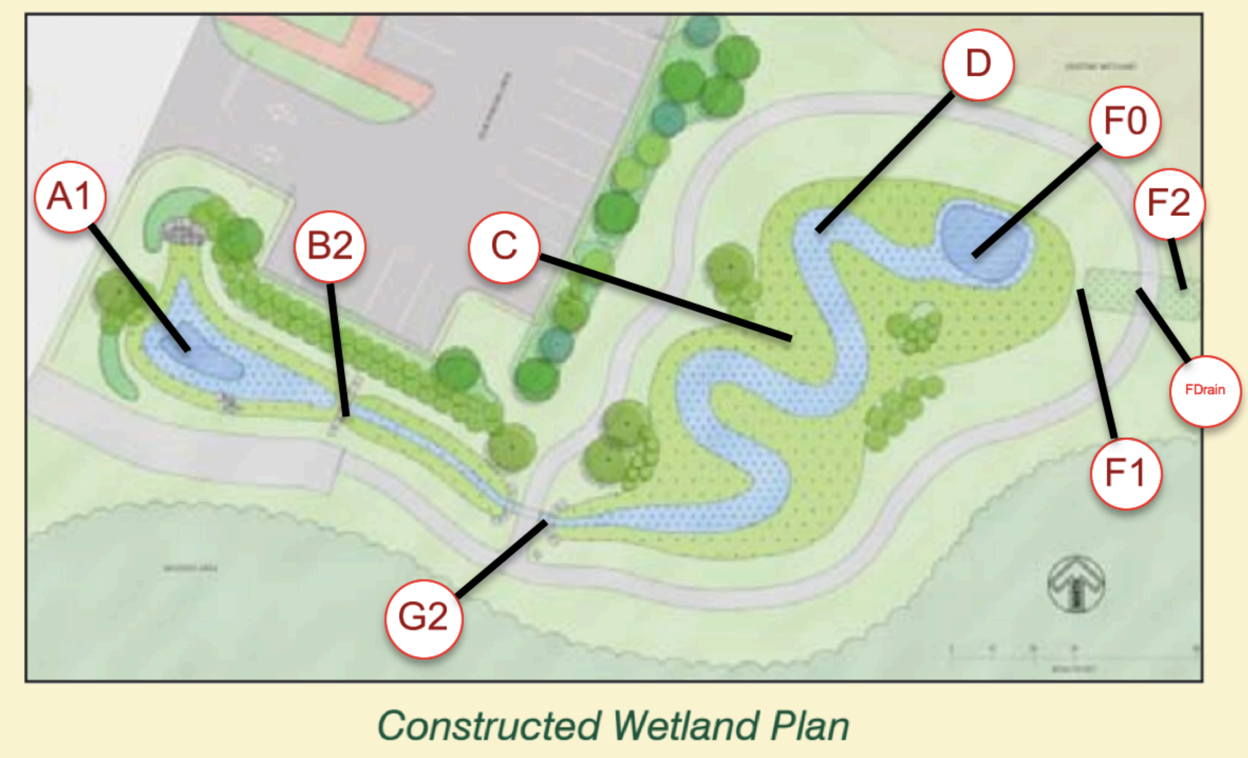

Figure 3.2 Map of constructed wetland sampling sites. Source: Bard College Office of Sustainability, 2015.

3.2.1 Visual Plant Growth Inspection

Though not a formal piece of the monitoring of the system, photographs of the system allow for visual inspection of plant growth in the system over time. Additionally, comparing more recent visual observations of plants in the wetland to the original plant palette from the GI plans not only allows for examination of plant growth, but also provides insight into which plants become dominant. The initial deep marsh plantings include *Iris versicolor* (blue flag iris), *Peltandra virginica* (arrow arum), and *Sagittaria latifolia* (broadleaf arrowhead). As of the summer of 2019, the deep marsh areas of the CW were dominated by wetland plants such as *Typha angustifolia* (narrowleaf cattail), *Typha latifolia* (broad-leaved cattail) and *Phragmites australis* (common reed), *Sagittaria latifolia* (broadleaf arrowhead), and *Peltandra virginica* (arrow arum). The initial shallow marsh plantings include *Acorus americanus* (sweet flag), *Carex crinata* (fringed sedge), *Carex stricta* (tussock sedge), *Glyceria canadensis* (Canada manna grass), and *Juncus effusus* (soft rush). In 2019, a visual inspection found *Carex crinita* (fringed sedge), *Juncus effusus* (soft rush), *Glyceria canadensis* (Canada manna grass).

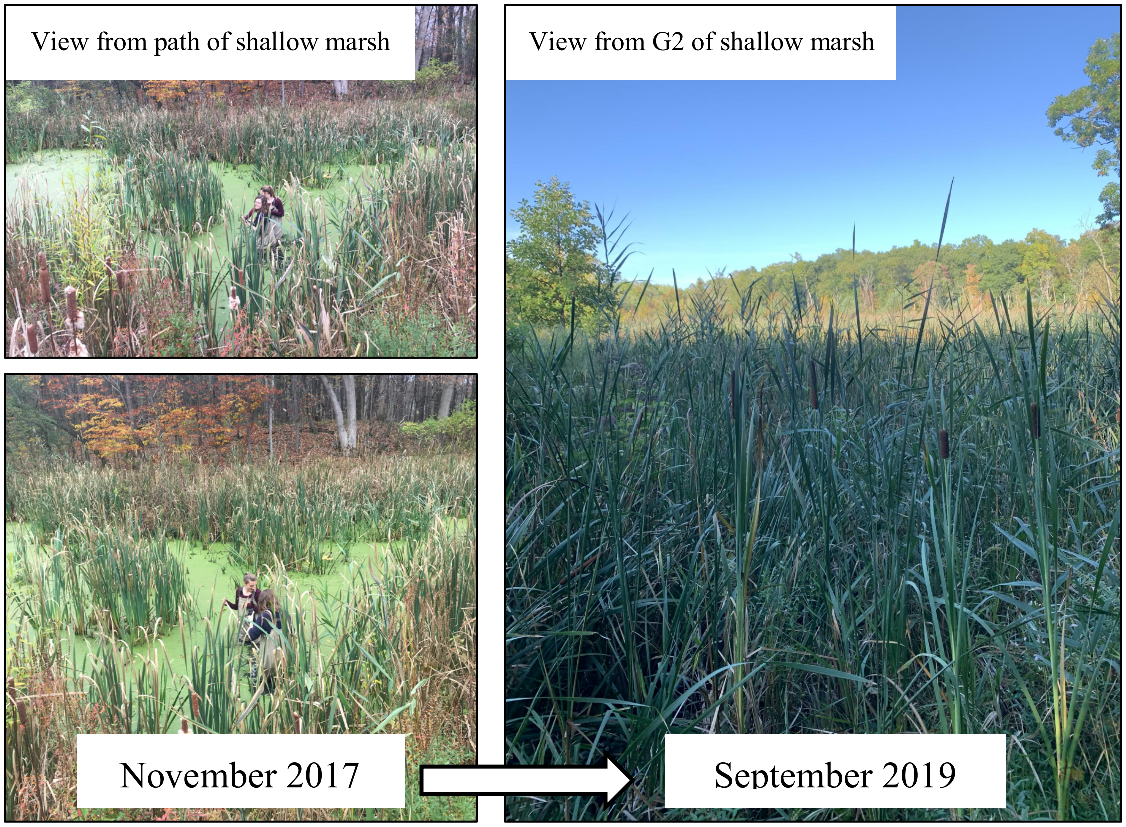

Figure 3.3: Plant growth in the shallow marsh of the constructed wetland over time.

The shallow and deep marsh areas of the wetland have seen substantial growth in wetland plantings, in particular the reed plants (Fig. 3.3, Fig. 3.4). The natural wetland into which the constructed wetland flows is dominated by *Phragmites australis* (common reed), and has likely resulted in the expansion of this plant species into the constructed wetland.

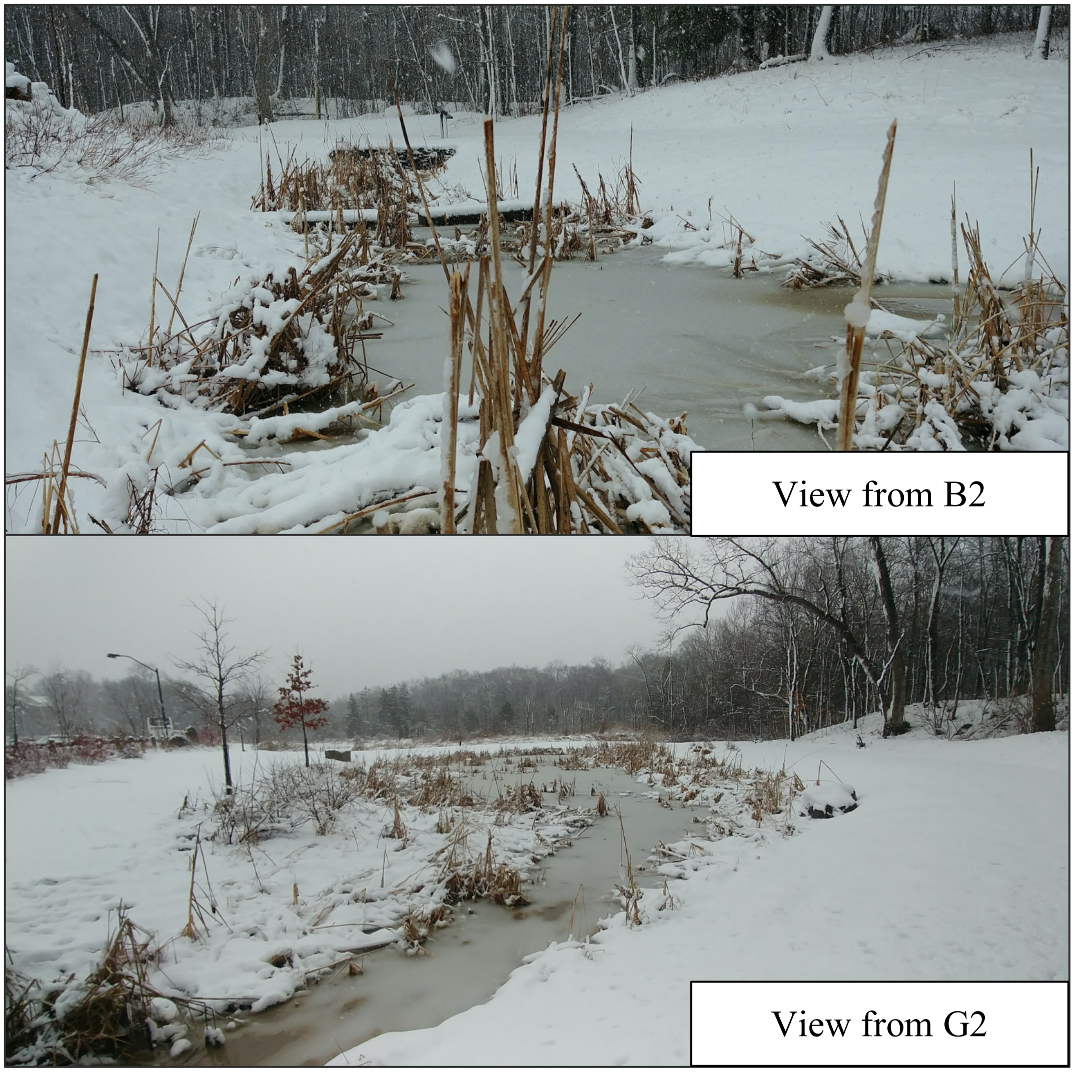

Figure 3.4: Pictures taken from site B2 and G2, 2018.

3.2.2 Oxygen & Suspended Sediments

This section will present data related to oxygen and suspended sediments monitoring, specifically dissolved oxygen (DO) and turbidity. DO is a measure of the concentration of oxygen molecules in a water sample. Oxygen is integral to support the biological functions of different freshwater organisms and can have negative impacts on some populations when concentrations dip below 5 mg/L, a state known as hypoxia. This state is typically observed in warmer, shallower, and more stagnant water bodies. During monitoring of the system, DO was collected using a YSI Pro 2030 weekly during the course of summer 2019.

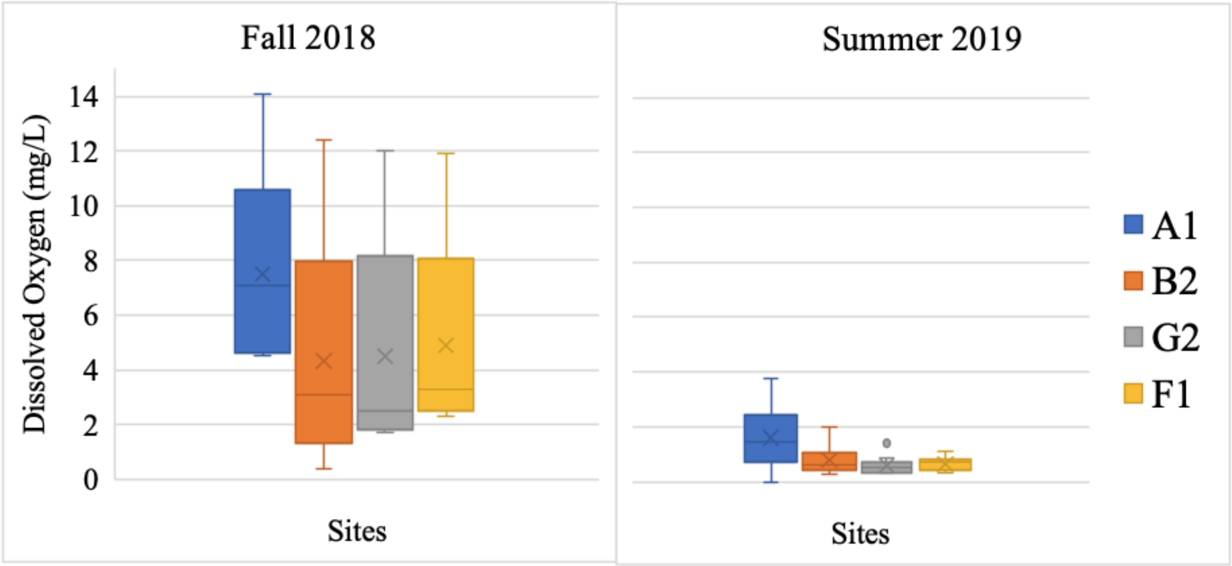

Figure 3.5: Dissolved oxygen measurements across sample sites during the fall of 2018 and summer of 2019. Hypoxia occurs when dissolved oxygen goes below the threshold of 5 mg/L.

Not only does the stagnancy of water affect oxygen, but flow and turbulence in water are also directly related to suspended particulate matter, measured by the parameter of turbidity. Turbidity reflects water clarity. Increased turbidity and diminished water clarity limit the amount of light entering a waterbody, preventing underwater photosynthesis, and limiting available food for aquatic species. Additionally, as suspended sediments absorb heat from the sun, water temperature increases and dissolved oxygen levels are lowered when turbidity is high. Suspended sediments also create surfaces for contaminants such as disease-causing organisms and heavy metals to attach to, allowing for pollutants to accumulate in the waterbody (Swenson & Baldwin, 1965). For constructed wetland monitoring, turbidity was measured from samples weekly with a Hach 2100Q turbidimeter in nephelometric turbidity units (NTU). The weekly data was collected at sites A1, B2, G2, and F1 throughout the constructed wetland during the fall of 2018 and summer of 2019.

Table 3.1: Max, median, and minimum turbidity measurements from the first flush (FF), composite (C), and grab samples (grab). FF and C measurements are from stormwater samplers.

		Turbidity (NTU)								
		Max. FF	Max. Grab	Max. Comp	Med. FF	Med. Grab	Med. Comp	Min. FF	Min. Grab	Min. Comp
Sites	A1	480	91.5	106	130	24.9	47.4	3.79	9.64	8.82
	B2	N/A	28.4	N/A	N/A	22.2	N/A	N/A	5.81	N/A
	G2	369	23.2	101	99.9	10.7	22.9	11.3	4.25	5.25
	F1	14.1	43.6	42.6	6.36	28.9	17.7	2.73	12.9	3.94
	F2	N/A	16.9	N/A	N/A	8.56	N/A	N/A	2.79	N/A

Average dissolved oxygen in the constructed wetland decreases from the inlet at A1 to the outlet at F1 during both the fall and summer (Fig. 3.5). During the fall, oxygen values on average were at or above the hypoxia threshold. However, during the summer, all data points collected at this time indicate that the wetland was hypoxic throughout, which can have an adverse effect on biological activity in the wetland (Rounds et al., 2013). In terms of turbidity, Table 3.1 and Figure 3.6 show overall higher turbidity values during the first flush of precipitation events at the inlet (A1) and midway (G2) points in the wetland than those collected from discrete sampling and the composite samples of precipitation events. All three sampling types (sample, FF, C) show a general decrease in turbidity from the inlet to the outlet, with the exception of the samples collected at F1.

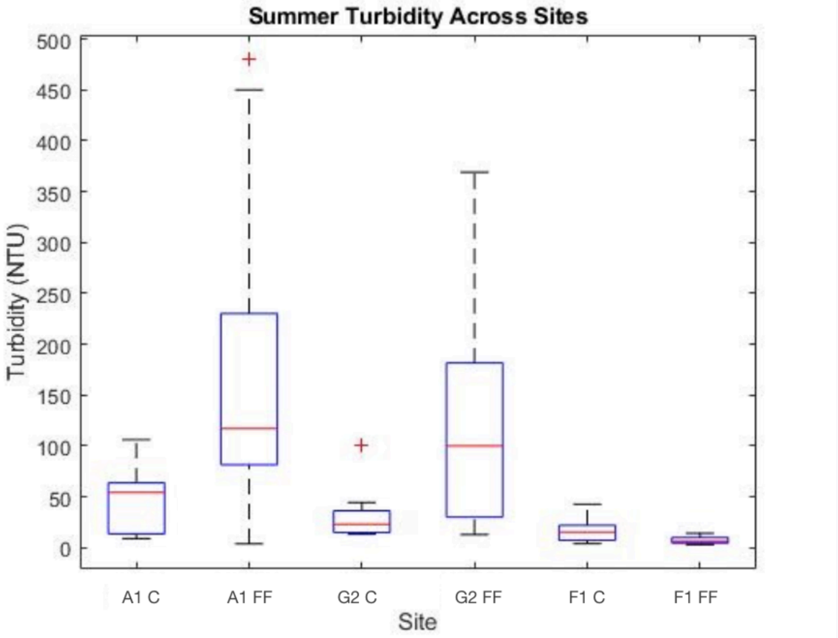

Figure 3.6: Turbidity measured from stormwater samplers across the constructed wetland, summer 2019. Composite samples are indicated by C, and first flush collections are indicated by FF.

3.2.3 Organic Matter

The section will present data related to the organic matter present in the constructed wetland, all of which are measured through their fluorescence: CDOM, chlorophyll a, and phycocyanin. Colored dissolved organic matter, or CDOM, is a measure of the visible dissolved organic matter (DOM) in a waterbody, composed of thousands of molecules from decaying organic matter. Much like turbidity, CDOM variation can result from natural processes like changes in precipitation, but it is also connected to human activities such as nearby effluent discharge or agricultural activity. Again, like turbidity, higher concentrations of CDOM can absorb light and limit photosynthesis, thus impacting all of the biological processes and organisms of the water body.

Whereas CDOM is a measurement of decayed organic material, chlorophyll a—the main type found in green plants and algae—is a measure of the number of algae growing in a waterbody. Algae growth is a natural component of most inland water bodies, but the presence of too much algae or certain types of algae (e.g. harmful algae blooms, HABs) can pose water quality issues, including lowering dissolved oxygen. Increased chlorophyll a—and thus, increased algae biomass—can be attributed in part to human activities such as effluent discharge, septic system leakage, and fertilizer runoff. Similar to chlorophyll a, phycocyanin is a fluorescent pigment found in photosynthesizing cyanobacteria. In water quality monitoring, phycocyanin can be indicative of HABs in freshwater. Each of these parameters was measured from water samples with a Turner Designs Aquafluor fluorometer in relative fluorescence units (rfu). The data collected for chlorophyll a was taken through weekly sampling at sites A1, B2, G2, F1, and F2 throughout the constructed wetland during the summer of 2019, with more intermittent sampling of CDOM and phycocyanin.

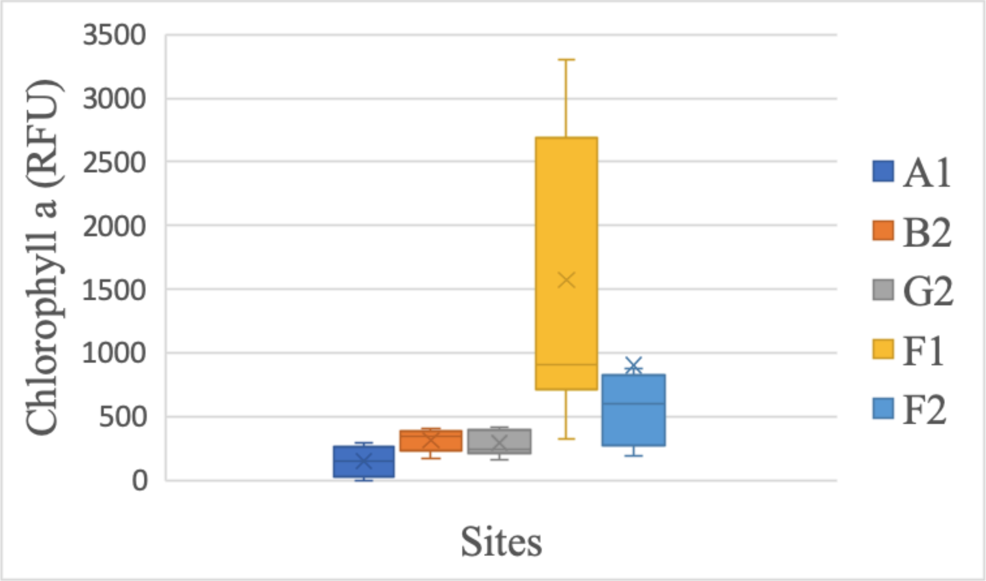

Figure 3.7: Measurements of chlorophyll a collected during the summer of 2019.

While the relative fluorescence units make it difficult to draw conclusions based on their values alone, the comparison across sites yields useful information. Site F1, the inside portion of the outlet pipe, shows on average greater values of chlorophyll a detected during the summer (Fig 3.7). Given that the deep pool receives the most direct sunlight of any area in the wetland and the water there remains relatively stagnant, the conditions are more ideal for algae growth here relative to the rest of the wetland where water is more turbid and shaded by emergent plants. The higher values of chlorophyll a collected at F1 reflect these observations of greater light availability.

Table 3.2: Average CDOM and phycocyanin values across seasons

Site	A1	G2	F1
Average CDOM (rfu)	159	178	169
Average Phycocyanin (rfu)	25	33	35

Average CDOM and phycocyanin values remain fairly consistent throughout the wetland (A1 to F1) across seasons (Table 3.2).

3.2.4 Sewage Leakage Indicators

This section will present data that is indicative of sewage leakage, including optical brighteners as well as enterococcus and coliforms fecal-indicating bacteria. Optical brighteners (OB) are fluorescent chemical compounds found in plastics and paper products such as a whitening/brightening agent. OBs are often used in laundry detergents and paper products such as toilet paper, so their presence in a water sample can indicate septic leakage or other forms of effluent discharge. Like the fluorescent organic materials, OBs are measured via water samples with an Aquafluor fluorometer in relative fluorescence units (rfu).

The IDEXX Enterolert and Colilert tests were performed on CW water samples periodically to measure Enterococci, as well as Total Coliforms and Escherichia coli (E. coli). Fecal coliforms are a group of bacteria found in the digestive tracts of warm-blooded animals, including humans, and are excreted in feces; E. coli is the best indicator of fecal pollution and the possible presence of pathogens. The Enterococcus group is also common in the intestinal tracts of warm-blooded animals, including humans, and is another important indicator of water contamination. The EPA recommends that bacteria levels within surface waters used for recreational purposes, such as swimming, should not exceed 35 colony forming units (cfu) per 100 mL of water for Enterococci and 126 cfu for E. coli (USEPA, 2011).

Table 3.3: Average most probable number (MPN) of E. coli, Coliforms, and Enterococcus measured in cfu, and optical brighteners (OB) measured in rfu. Data collected from sampling in Fall 2018.

** = exceeding EPA recreational water quality standards*

Sites	**E. Coli (cfu)**	**Coliforms (cfu)**	**Enterococcus (cfu)**	**OB (rfu)**
A1	1	131	50*	52
B2	1	190	41*	56
F1	53*	1242	836*	61

Per the EPA's standards, each site throughout the wetland during the sampling period had average enterococcus values that exceeded recreational water quality standards (RWQS). Additionally, the average for E. coli at F1 exceeded RWQS (Table 3.3). Overall, the outlet (F1) experienced on average greater numbers of fecal-indicating bacteria during this sampling period.

3.2.5 Road Salt Runoff and Collection

This section will present data that is indicative of road salt runoff and collection in the constructed wetland, in particular specific conductivity, salinity, and chloride concentration. Specific conductance refers to how well electricity is conducted through water with the measurement made at or corrected to 25°C. Specific conductance is directly proportional to the concentration of ions in a solution, the principal ions found in water being calcium, magnesium, sodium, sulfate, chloride, and nitrate. The data collected during the constructed wetland monitoring measures specific conductance in units of microsiemens per centimeter (µS/cm). Often, salinity is derived from measurements of specific conductance, as is the case here. Similar to specific conductivity, salinity is a measurement of the total dissolved salts in a given water sample. For inland waters—as opposed to the saltwater of the ocean—salts occurring here are categorized as either primary or secondary salinity. Primary salinity refers to the naturally occurring salinity of a waterbody due to salt sources in the watershed or high evaporation rates; secondary salinity refers to the human-induced salinity as a result of increased impervious surfaces or higher trafficking of the area (Likens, 2009). Another measurement taken to monitor salts in the wetland is chloride concentration. Chloride concentration is measured through performing chloride titrations on a water sample and is represented in units of milligrams per liter (mg/L).

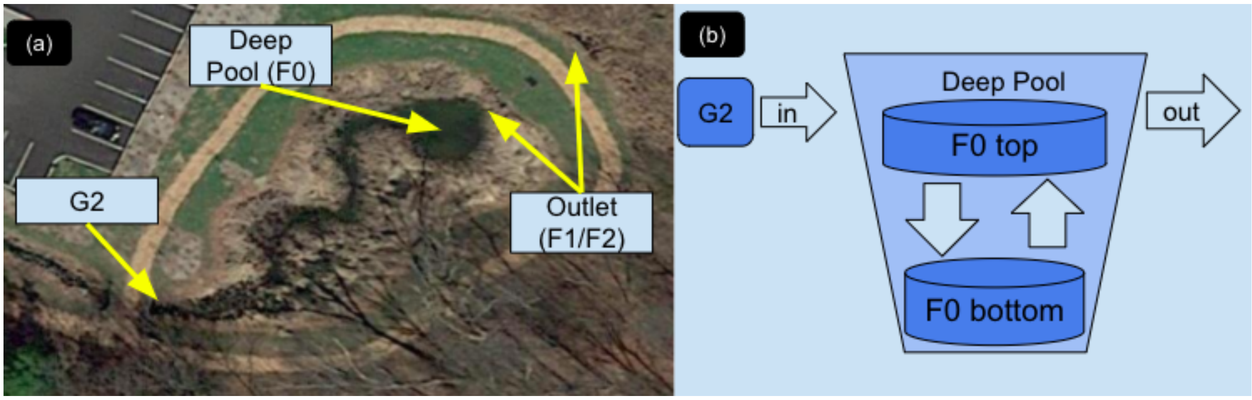

Figure 3.8: (a) Aerial map of sites where Onset sensors and stormwater samplers were launched (b) diagram of path of water flow from G2 into the deep pool (F0 top/bottom)

The data collected on specific conductance, salinity, and chloride concentration was taken both through weekly sampling of multiple sites throughout the constructed wetland as well as through the use of stormwater samplers during the summer of 2019. Weekly sampling for specific conductivity was collected using a YSI Pro 2030 at sites A1, B2, G2, F1, FDrain, and F2; samples from precipitation events were collected using three ISCO SS201 Stormwater Samplers placed at sites A1, G2, and F1. Additionally, three Onset conductivity/temperature sensors collected

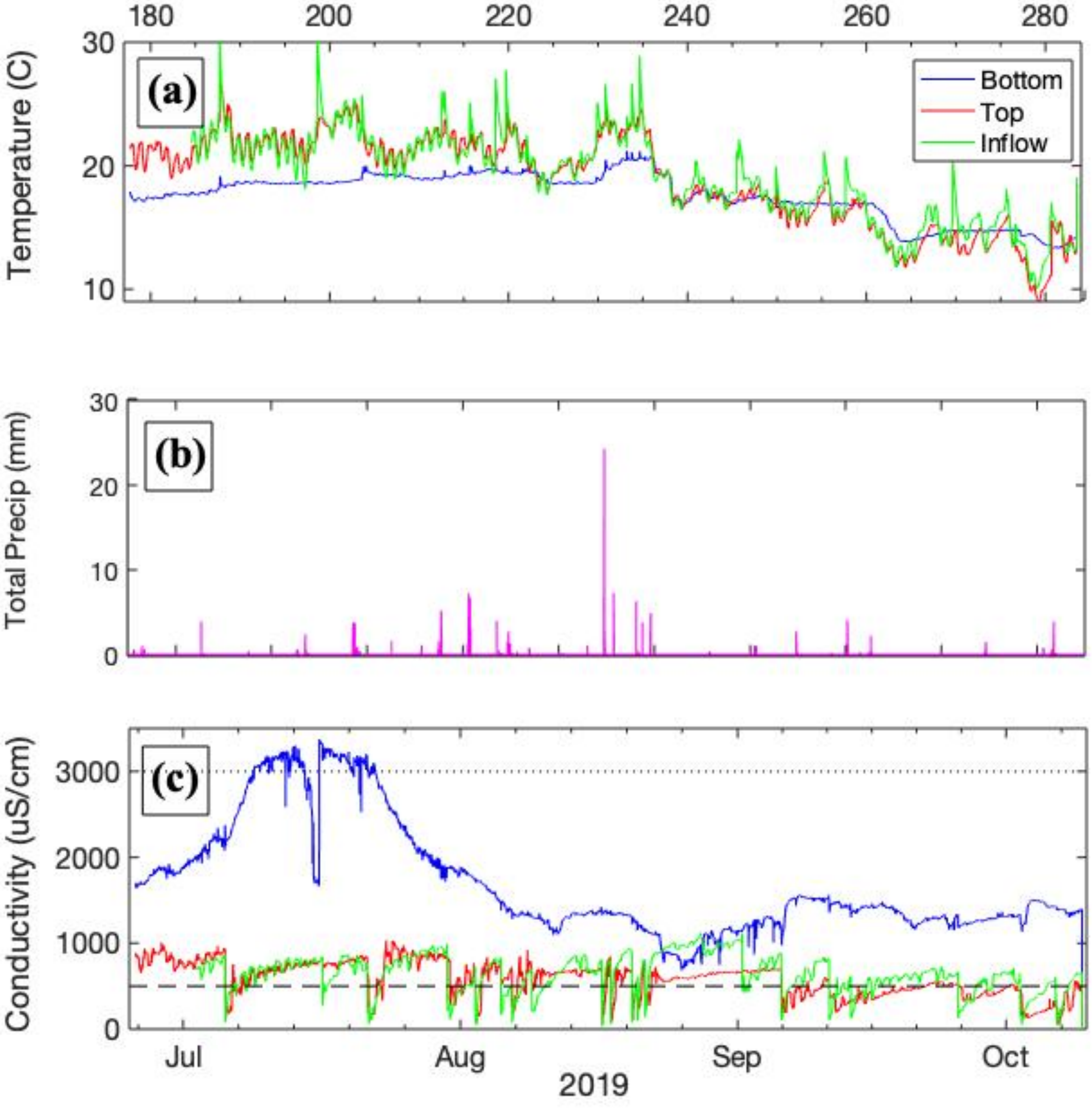

Figure 3.9: (a) Onset sensor temperature data (b) total daily precipitation data (c) Onset sensor conductivity data. Source (b): NOAA NERRS, n.d. Source (c): USEPA, 2012.

temperature and specific conductivity data at 15-minute intervals throughout the year at sites G2, F0 top, and F0 bottom.

The sensor data shown in Figure 3.9 represents the temperature, total precipitation, and conductivity at sites G2, F1 top, and F1 bottom over the course of summer 2019. EPA states specific conductance greater than 500 uS/cm (Fig. 3.9c black dashed) may not be suitable for some aquatic species (USEPA, 2012) while Karraker et al. (2007) reports significant developmental stress and malformation found in embryonic green frogs at 3000 µS/cm (Fig. 3.9c black dotted). Conductivity levels that remain high through the winter pose a threat to amphibians and reptiles that hibernate in shallow water bodies during the winter (Sievers et al., 2018).

3.3 Rhodamine Dye Flow Experiment

During the week of Wednesday October 14th through Wednesday October 21st, 2020, a tracer dye experiment was conducted in the CW. Rhodamine WT dye is commonly used for water tracing and leakage detection studies. In these types of studies, the dye is often visually detected with the naked eye, but due to the fluorescent properties of the dye, it can also be monitored with sensors that detect this fluorescence. This experiment used the Bright Dyes FWT 25 Rhodamine WT dye, 2.5% active ingredient with visual detectability of the active ingredient <100 ppb. Prior to deployment, the sensors were calibrated with a diluted solution of the Bright Dyes Rhodamine WT dye following the sensor manufacturer's instructions. We mixed and diluted the dye in pond water in a 5-gallon bucket and gently poured it into the wetland between G2 and the deep pool (F0) on 14 October 2020 at 4:00 PM, with one sensor at the bottom of the deep pool (F0 bottom) and one sensor at the outlet of the wetland (F1) measuring the fluorescence of the dye in PPT at 15-minute intervals. The sensors were collected on 21 October 2020 at 1:00 PM.

Figure 3.10 displays the detected rhodamine (ppt) during the week of deployment for the bottom sensor and the outlet sensor, respectively. For the bottom of the deep pool, there is a spike between DOY 291 and 293 when the rhodamine fluorescence is detected, and this detection wavers around 8-9 ppb for the remainder of the sensor's deployment. The outlet sensor shows a spike in rhodamine detection up to nearly 200 ppb between DOY 290 and 291, before dropping off to a detection of 10-20 ppb for the remaining time of the experiment. Various meteorological

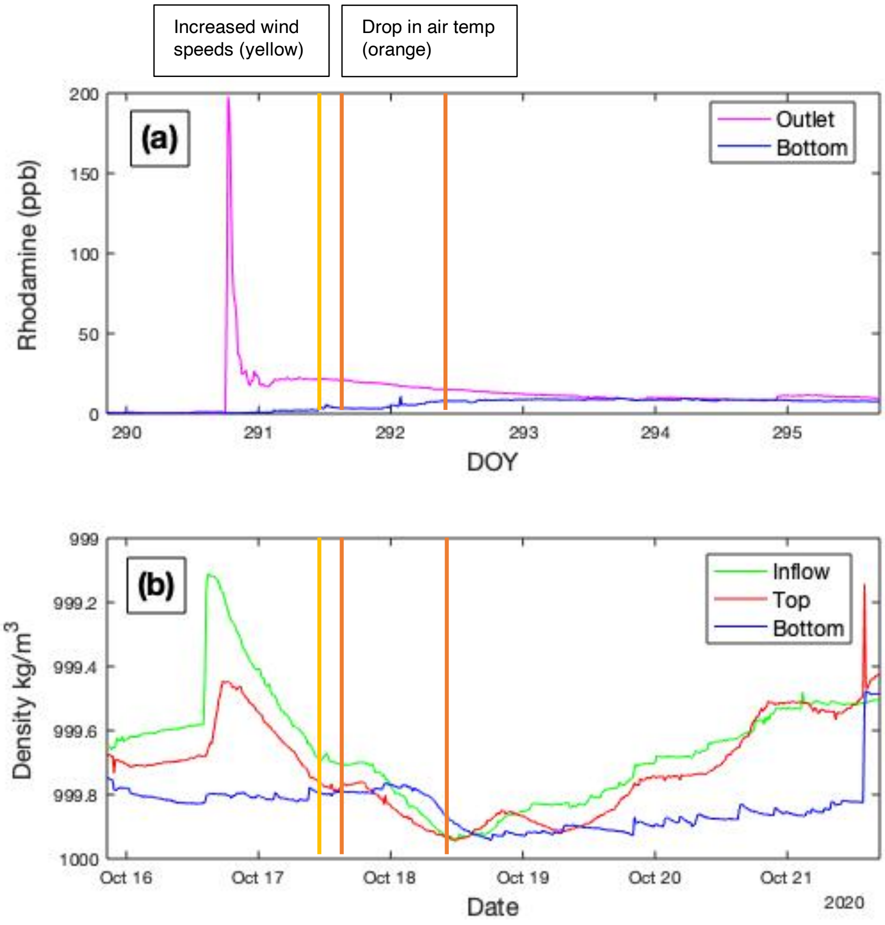

Figure 3.10: (a) Rhodamine detected at F0 bottom and F1(time series is DOY) (b) density calculated at inflow, F0 top, and F0 bottom during the experiment (time series is the equivalent date).

parameters were also modeled for the duration of the experiment (Fig 3.11), including wind speed, air temperature, total daily precipitation, and total photosynthetically active radiation (PAR).

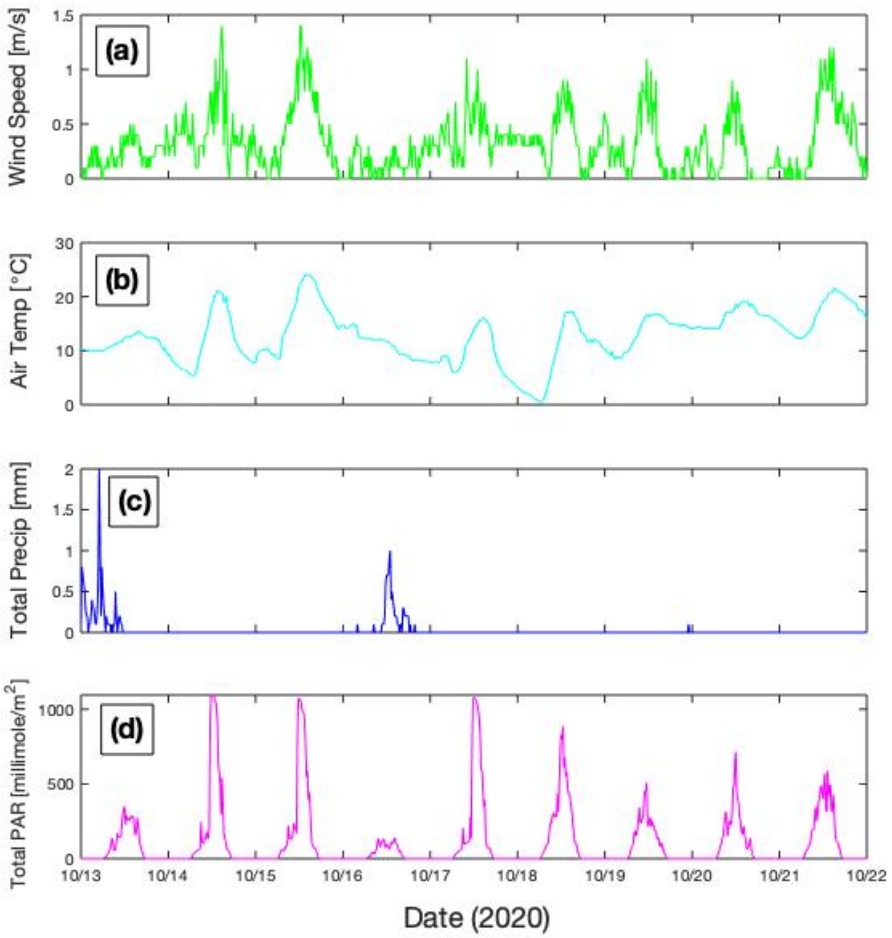

Figure 3.11: Meteorological data tracked during the rhodamine experiment (a) wind speed, (b) air temperature, (c) total precipitation, and (d) total PAR. Source: NOAA HERRS, n.d.

Comparing total precipitation to the spikes in rhodamine during the dye experiment, a rain event occurs on 16 October 2020 that appears to precede and/or coincide with the spikes in the rhodamine detection. This could indicate a flushing of the dye through the system due to the precipitation event. Between 17 October 2020 and 18 October 2020, there is a decrease in air temperature (Fig. 3.10 orange lines) with increased wind speeds immediately preceding (Fig. 3.10 yellow line). This coincides with the density of the top layer exceeding that of the bottom layer (Fig. 3.10b), an apparent mixing event between these two layers. In this timeframe of lower air temperatures and increased top layer density, the rhodamine sensor in the bottom indicates a small spike in rhodamine detection. This is likely a result of the density inversion and mixing event. Whereas throughout the majority of the experiment it appears rhodamine is flowing over the top layer and out through the outlet, this mixing of layers allows rhodamine to drop into the bottom layer.

4.0 Management Recommendations and Conclusions

4.1 Status of Bard CW in providing proposed benefits

Referring back to the GI project description, the proposed benefits of the system include flood resilience, reduced erosion, recharging groundwater, improved water quality, moderating temperatures, enhancing habitat, and providing attractive green areas. Based on the monitoring data collected over the past two years as well recommendations from the literature, each of these goals has been assessed and placed into the following categories: meeting goal, almost meeting goal, not meeting goal, or uncertain (Table 4.0). The following sections will discuss the goal(s) placed with the respective category, referring back to the literature review and state of the system data.

4.1.1 Goals Met

The proposed benefits defined as meeting their goals include reduced erosion, flood resilience, and providing green attractive areas. The transformation from a gravel to a porous asphalt parking lot evidently reduced erosion as the solid surface cannot be eroded (at least so easily) as the previous gravel surface during rain events (Fig. 4.1). Within the constructed wetland, substantial plant growth in the deep and shallow marshes has likely stabilized the banks of the wetland channel itself. During parts of summer 2019, the inlet would be completely dry, indicating that water flow has not channelized the system, but rather that it is filling with sediment. In terms of flood resilience, there have been no recorded events of flooding onto pedestrian pathways or parking areas near the GI installment, even when there was flooding in other areas of campus (Fig. 4.1a).

Finally, the aesthetic benefit of providing green attractive areas is generally being fulfilled, as the system has experienced extensive plant growth since the installation. However, to the extent that plant variety is integral to the aesthetic value of the constructed wetland, this may be hindered by the dominance of the common reed over original plantings.

Figure 4.1: (a, b, c) Site of GI project prior to installation showing flooded areas and erosion of the gravel parking area (d) Flooding of another parking area on Bard's campus (Nov. 2018).

4.1.2 Almost Meeting Goal

The proposed benefits defined as almost meeting their goals include improved water quality and flood resilience. The bulk of the monitoring effort over the years on the constructed wetland has been focused on various water quality parameters, as demonstrated in Chapter 3. While some parameters indicate improved water quality, such as the reduction of turbidity on average from inlet to outlet (Section 3.2.2), others indicate degraded water quality. Average cfu values of E. coli and Enterococcus bacteria were shown to be above the EPA's recreational water quality standards during the fall 2018 monitoring period. Multiple sites in the constructed wetland were found to exceed multiple conductivity thresholds for amphibian health and development (see Section 3.2.5). Finally, though dissolved oxygen showed seasonal variation, average values during the summer 2019 monitoring period consistently remained below the hypoxia threshold.

Table 4.1: Stated goals of Bard's GI, status regarding achieving objectives, and remaining uncertainty.

Stated Goal	**Status**	**Uncertainty**
Providing Attractive Green Areas	Meeting	How the state of vegetation in the wetland impacts recreational usage or perceived social value
Reduced Erosion	Meeting	Requires further study into before and after data/images
Flood Resilience	Almost meeting	Requires further study into before and after data/images
Improved Water Quality	Almost meeting	How other water quality parameters with relative units compare to water quality thresholds, e.g. OB, CDOM, etc. Pollutants in sediments unknown
Enhancing Habitat	Not meeting	If the constructed wetland constitutes an ecological trap, and to what extent it is impacting the fitness of specific amphibian species.
Moderating Temperatures	Unknown	Requires study
Recharging Groundwater	Unknown	Requires study

4.1.3 Not Meeting Goal

The proposed benefit defined as not meeting its goal is enhancing habitat. As noted in the previous section on water quality, the parameters of conductivity and DO both reflect poor habitat conditions, particularly for amphibian species. Consistently high conductivity levels during the winter can threaten amphibians and reptiles hibernating in shallow waters (Sievers et al., 2018).

Conductivity levels greater than 500 uS/cm may not be suitable for some aquatic species (USEPA, 2012), while those above 3000 μS/cm can result in significant developmental stress and malformation in embryonic green frogs (Karraker et al., 2008). DO reaching below the hypoxia standard of 5 mg/L threatens various aquatic species that need oxygen for ecological processes. Though it was not part of the monitoring process and there is no formal animal species inventory, amphibians and turtles (dead and alive) have been spotted in the wetland.

4.1.4 Remaining Uncertainty

Despite the monitoring efforts that have been made, uncertainties still exist regarding the system's ability to perform certain functions and achieve the stated goals. The purported goals of moderating air temperatures and recharging groundwater have not been monitored and further study is required to determine the status of these goals. It should also be questioned as to whether moderating temperatures should be a stated benefit of Bard's system, since typically GI used for moderating temperatures takes place within an urban setting to manage urban heat island effect. Additionally, the stated goals that have been given a status still have uncertainties. In providing green attractive areas, there is no formal assessment of how the state of the vegetation in the system impacts recreational usage or perceived social value. Improved water quality encompasses a wide range of parameters, many of which are measured in relative units (e.g. OB, CDOM, phycocyanin, chlorophyll a) and need further study to be measured against water quality standards or thresholds for freshwater bodies. Additionally, there has been no study of the sediments within the constructed wetland, which may contain heavy metals, hydrocarbons, and other pollutants settled out from the runoff passing through. Though the constructed wetland has been shown to surpass conductivity and DO thresholds that negatively impact various aquatic species, further study into the impacts on specific amphibians, reptiles, and birds is required, specifically whether or not it constitutes an ecological trap (Sievers et al., 2018).

4.2 Adaptive Management for Bard GI

Generating solutions to environmental problems necessitates being able to manage uncertainty and incorporate it into the problem-solving process. Climate change and other forms of anthropogenic environmental degradation have forced communities and policymakers to manage and improve the resilience of our human and natural systems in order to maintain functioning ecosystems and societies. Green Infrastructure has become an increasingly popular tool for mitigating and adapting to the effects of climate change and environmental degradation, particularly in urban areas. They have become particularly convenient for and attractive to policymakers in that they are sold as "multifunctional" solutions—that is, they are perceived to provide multiple environmental and social co-benefits in addition to their main purpose of managing stormwater (Sussams, et. al., 2015).

These perceptions of GI being a multifunctional solution have materialized in the *Bard Regional Demonstration Project for Improving Stormwater Management*. However, as outlined above, purporting multiple benefits without anticipating or monitoring for potential issues can result in perverse outcomes or missed synergies, and failure to achieve all of the stated objectives. To make strategic management decisions regarding resource management, the context within which management occurs can be understood in terms of uncertainty and controllability (Fig. 4.2). *Uncertainty* in natural resource management refers to the predictability of the effects of management decisions (Williams et al., 2009); for example, high uncertainty often occurs when there is limited knowledge about the ecological system or where there is limited data on the results of a given intervention on that system. The second aspect of the management context is *controllability*, which refers to the impact that a given intervention will have on the system (Williams et al., 2009; Peterson et al., 2003). Controllability in management scenarios is often impacted by various factors such as scale, governance structure, and stakeholders, to name a few. Bard’s GI is managed within the context of high uncertainty and high controllability. The novelty of GI as a stormwater management and urban planning tool creates uncertainty pertaining to its functions as a socio-ecological system. However, the smaller scale and confined management and maintenance structure of Bard’s GI allow for high controllability of system interventions.

Given this context of high uncertainty and high controllability, adaptive management is

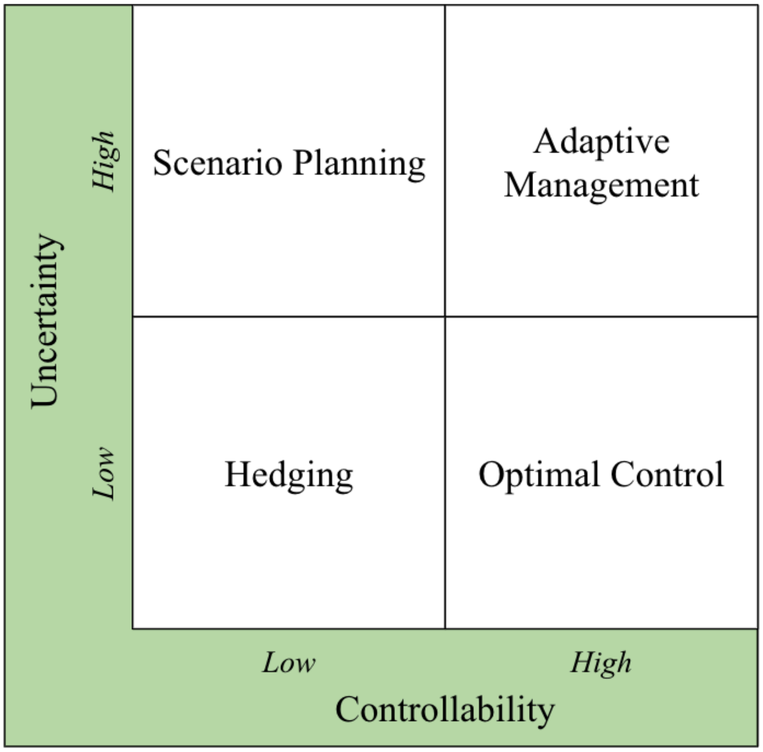

Figure 4.2: The appropriate management option depending on the level of uncertainty and controllability of the system or resource (adapted from: Williams et al., 2009; Peterson et al., 2003).

indicated as the appropriate management strategy (Baron et al, 2008; Peterson et al., 2003; Williams et al., 2009; Fig. 4.2). Wherein there is greater capacity for manipulating the system but uncertainty as to the outcomes, adaptive management allows managers to formulate and apply potential solutions, monitor results, and further develop understanding of the system. Other key aspects outlined in the operational definition of adaptive management include acknowledging uncertainties, improving knowledge, comparing expected and actual results, and engaging with stakeholders (Williams et al., 2009). The following sections will summarize these key features of the adaptive management approach, and how these individual characteristics relate and would be beneficial as a management strategy for Bard's GI. This is followed by consideration of potential drawbacks to the adaptive management approach, and how to navigate these challenges in this case.

4.2.1 Acknowledging Uncertainty

The operational definition of adaptive management for the U.S. Department of the Interior (DOI) states that, "Adaptive management promotes flexible decision-making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood," (Williams et. al., 2009). As pointed out by this definition, flexibility in the face of uncertainty is a key facet that shapes how every stage of the adaptive management process is executed (Fig. 4.3). In particular, four kinds of uncertainty can shape natural resource management: environmental variation, partial observability, partial controllability, and structural uncertainty (Williams, 2011; Williams & Brown, 2016). These forms of uncertainty are defined by Williams (2011) as follows:

- *Environmental variation* is the overarching uncertainty of the natural environment. Factors such as climate variability (e.g. precipitation patterns, light changes) indicate its nature as highly uncontrollable, often unanticipated, and potentially unrecognized.

- *Partial observability* refers to the incomplete understanding of the system or resource being managed. For example, monitoring a system at various sites creates a picture of the system, but cannot define it entirely as it actually exists.
- *Partial controllability* lies in the execution of management interventions. It refers to the difference in the intended effect and the resulting effect of a management decision, where uncertainty results from the misrepresentation of the intervention and its influence.
- *Structural uncertainty*, simply, is the lack of knowledge concerning system dynamics, typically relating to the functions of ecological aspects.

However, there is often a reluctance to acknowledge uncertainty in natural resource management because it is seen as limiting to getting actions through. The perception is that certainty as to the impacts of management decisions convinces involved parties to implement recommended actions and limits conflicts resulting from varying interests (Williams et al., 2009). With the adaptive management approach, uncertainty becomes not a limiting factor that needs resolution prior to action, but the impetus for action itself.

To understand how adaptive management can work for Bard in terms of how the approach handles uncertainty first requires an examination of how the four aforementioned types play out at Bard. Environmental variation is obvious as a system that exists within the natural environment. As noted above, monitoring has created a picture of the state of the system, but there remains the uncertainty of partial observability with monitoring tied to classes and short-term student research. Only one management intervention has been executed and examined in terms of Bard’s GI, that being the installation itself, so partial controllability will be more relevant with decisions going forward. Structural uncertainty with Bard’s GI takes the form of our limited knowledge of the functions and dynamics of green infrastructure and constructed wetlands in general, especially in the context of competing and/or conflicting functions. For example, providing habitat for various aquatic species implies water quality conditions that do not threaten these species. This may conflict with achieving the function of pollutant capture and removal since the habitat is being used to settle out constituents that may harm these species.

Due to its emphasis on "learning by doing" and reducing uncertainty regarding system dynamics through management decisions, adaptive management pays special attention to acknowledging and overcoming structural uncertainty (Williams, 2009). This is dually the case with the constructed wetland being a socio-ecological system, where uncertainty lies in its ecological as well as social functions, especially maintenance. Not only is there uncertainty in what functions it can provide and how different interventions impact its ability to provide these co-benefits, but there remains uncertainty as to which benefits it *should* provide or what stakeholders *want* it to provide. As outlined in Section 2.2.1, there are various methods for quantifying and assessing co-benefits, e.g. an ecosystem services framework as recommended by Spahr et al.

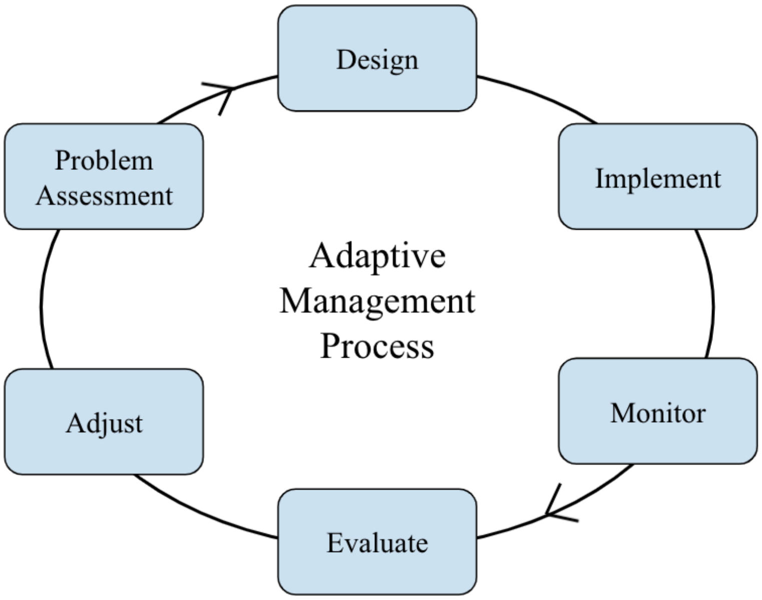

Figure 4.3: The adaptive management cycle.

(2020) or developing a stormwater infrastructure profile à la Kapetas & Fenner (2020). Both allow for a tailored cost-benefit analysis of GI co-benefits, but the uncertainty remains in which framework is suitable for Bard's GI from a social perspective. With adaptive management, a decision can still be made in order to determine the framework for defining goals to pursue and evaluating system success.

4.2.2 Improving Understanding of the System

Tying into the emphasis on embracing and learning from structural uncertainty, the adaptive management approach expands system knowledge by making predictions, performing management activities, and measuring predictions against monitoring data. As such, the decision-making process proceeds not only as a means of managing the system, but also as the foundation for learning—and thus, better informing future decision-making (Allen et al., 2011; Holling, 1978; Peterson et al., 2003; Williams et al., 2009). One of the most important aspects of learning through adaptive management is careful monitoring after implementing interventions (Schreiber et al., 2004; Williams, 2011). As described by Lyons et al. (2008), monitoring facilitates the cyclical nature of adaptive management through the stages of planning, intervention, and assessment. Referring back to the literature on GI monitoring and evaluation (Section 2.2.4), the importance of monitoring ties into the tenets of green governance, which calls for a framework to explicitly measure and monitor performance as it pertains to the stated goals (Ibrahim et al., 2020; Schiappacasse, & Müller, 2015).

The management structure with regards to Bard's GI is unique compared to other forms of natural resource management in that the project is confined to a college campus and managed by Bard Buildings and Grounds. Additionally, the system was implemented as part of a demonstration project, with the goal of also modeling operations and maintenance procedures for similar projects in the region. As such, learning is embedded in all aspects of the project's context, including its location, its management, and part of its stated purpose. Not only is adopting the adaptive management approach beneficial to achieving its stated purpose as a demonstration project, but the learning objectives of this management approach are synergistic with Bard as an institution of education. This has shown to be the case thus far with Bard's GI—despite the lack of explicit application of adaptive management as a management strategy—in that monitoring has been carried out as part of environmental science class curriculum as well as individual student projects. The philosophy of "learning by doing" adopted by adaptive management is complementary to that of Bard's interdisciplinary Environmental and Urban Studies and Center for Environmental Policy programs, which can provide the impetus for learning in the cycle of planning, implementation, and evaluation.

However, Schreiber et al., (2004) caution managers to not limit monitoring to a "plan-act-monitor-evaluate" cycle where modeling the impacts from interventions and stakeholder engagement are ignored. Alternatively, the active adaptive management approach compares potential policies or practices for direct intervention in ecological processes, with the goal of testing relationships, drivers, or other components of how the system operates (Baron et al., 2008; Schreiber et al., 2004; Williams, 2011). The following section will further discuss active adaptive management, how the active approach differs from the passive approach, and the importance of evaluation and comparison in this process.

4.2.3 Testing Hypotheses and Comparing Expected and Actual Results

Though adaptive management emphasizes the approach of testing hypotheses and evaluating results, this does not imply a "trial and error" method of decision-making (Williams et al., 2009).

Rather, because of its purpose in embracing—but working to reduce—uncertainty, adaptive management has knowledge development built into its structure for management. In particular, active adaptive management, sometimes referenced as the “horse race” approach (Allen et al., 2011), actively pursues the reduction of uncertainty through management decisions that directly manipulate functions of the system, often testing multiple approaches simultaneously (Schreiber et al, 2004; Williams, 2011). A hallmark example of this approach is the management program that conducted two flood release experiments of the Colorado River in the Grand Canyon in 1996 and 2004, as a means of better understanding sediment dynamics and how other variables impact native fish species (Hughes et al., 2014). Active adaptive management differs from passive adaptive management because the latter relies on historic data to develop conceptual models as opposed to direct manipulation, and often focuses on management objectives with reducing uncertainty perceived as an added benefit (Baron et al., 2009; Williams, 2011).

Despite their differences, both active and passive approaches contribute to knowledge development via the assessment of management decisions compared to assumptions made in hypotheses or conceptual models. Implementation of management interventions and comparing expected vs. actual results requires substantial controllability within the context of the resource management scenario (Fig. 4.2). Given the size of the constructed wetland at Bard, this allows for the manipulation of various physical or ecological elements of the system. For example, this could include mowing or trimming vegetation to augment the amount of light reaching the water, or more far-reaching interventions such as dredging out sediments.

With regards to Bard’s constructed wetland, we currently possess monitoring data on the status of sediment accumulation (Section 3.2.2) and the accumulation of road salt in the deep pool (Section 3.2.5), as well as the availability of literature on BGI design characteristics and maintenance (Section 2.1.2). Given the information from the literature as well as the impetus for making a management intervention in response to the state of the system, this is sufficient for developing and implementing adaptive management options. This is possible, so long as these options are carried out in a controlled manner—ideally with consensus and cooperation between stakeholders—and with consideration of the stated goals in evaluating the success of the intervention.

4.2.4 Stakeholder Participation

On the social side of managing natural resources, adaptive management is often appropriate where there is trust and a willingness among stakeholders to participate in testing out hypotheses as a means of learning and building foundational knowledge for future management decisions (Baron et al., 2008). While the focus of natural resource management is typically achieving objectives through manipulating ecological functions, many of these resources are socio-ecological systems where social objectives must be incorporated into management decisions and may be at odds with each other or with ecological objectives. In the adaptive management program carried out with the Grand Canyon and Colorado River, leaders in the program created opportunities for experimentation and learning in the management process, as opposed to top-down policy implementation. In a system with a range of stakeholders and management objectives in this complex socio-ecological system, the flexibility of this approach aided in developing trust among stakeholders for carrying out their interventions (Hughes et al., 2009).

In particular, adaptive management practitioners emphasize stakeholder engagement in the early planning stages of an intervention, as to identify realistic management options and potential limitations (Schreiber et al., 2004). Though other stakeholder perspectives may be less technically knowledgeable than project managers or scientists involved with the project, collaborating with and recognizing other stakeholder interests is an important aspect of management with knowledge-development objectives (Williams, 2011). Stakeholder collaboration is also synergistic with the cyclical nature of the adaptive management process. With knowledge developed over time through implementing and assessing intervention performance, new understandings of how the system operates can potentially impact social values or objectives. Additionally, stakeholder perspectives and values will change over time, so certain stages of the adaptive management cycle can allow for collaboration and re-assessment of values and objectives for the system (Williams & Brown, 2016).

Of particular convenience with stakeholder collaboration regarding Bard's GI is the encapsulation of stakeholders within the Bard community. Management, maintenance, and monitoring have thus far been contained within the campus itself, between Buildings and Grounds, the Office of Sustainability, professors, and students. Connecting back to the adaptive management tenet of knowledge development, this community of stakeholders in particular has a strong commitment to learning within the management process. This can be particularly useful in the process of defining goals and objectives for the system, and considering the tradeoffs. As outlined above in Section 4.1, the GI system has been purported to provide a wide, but evidently, unrealistic set of benefits, as there are tradeoffs between achieving certain goals. During my monitoring of the system, its ability to collect and contain road salt runoff has provided educational opportunities for other students and me to study the system as a stormwater management intervention. However, going forward, there may be more interest in studying Bard's GI as a constructed habitat and a potential ecological trap. By incorporating stakeholder interests—in this case, students–in defining system objectives, this can help shape and clarify future management decisions.

4.2.5 Challenges with the Adaptive Management Approach

As outlined in the previous sections, four of the core characteristics of adaptive management lend well to the context of Bard's GI. However, it is important to consider the potential challenges in operationally adopting the adaptive management approach as to avoid failure. In considering the various options for approaching natural resource management, many adaptive management practitioners and authors cited above have outlined potential areas for breakdown. In particular, Schreiber et al. (2004) describe the potential for failure at various stages of the adaptive management process, including:

- Risk aversion of some managers;
- Inadequate institutional structures and stakeholder participation;
- Incomplete or ineffectual implementation of a study plan;
- Lack of commitment to monitoring, evaluating, and reporting;
- Uncertain or inadequate funding for monitoring and analyses; and
- Institutional 'memory loss' regarding what has been learnt (Schreiber et al., 2004, p. 180)

In terms of risk aversion, this can undermine the main tenet of adaptive management as uncertainty must be embraced in order for it to be reduced. Developing the institutional structure for stakeholder engagement, in general, is more easily facilitated at the local level, but it must be consistently included in the iterative cycle of adaptive management, as stakeholder values and perspectives can change (Williams, 2011). Additionally, despite it being at a smaller scale, the larger ecological processes that affect the system must be considered and communicated to stakeholders, e.g. climate change. Issues that arise in developing and implementing a study plan often go hand-in-hand with a lack of commitment in the monitoring and evaluation process. This can take shape in constrained management preventing a fully developed experimental design, or a limited budget resulting in an inadequate monitoring plan—despite the integrity of monitoring in the adaptive management approach (Williams & Brown, 2016). Finally, even if all of these preceding steps face no challenges, if knowledge developed through management is not properly communicated, given credibility, and incorporated into future management decisions, this institutional "memory loss" then nullifies all of the work for experimental learning (Johnson et al., 2015). To avoid or limit these potential challenges, the following section will introduce ideas on how to practically realize the adaptive management process at Bard.

4.3 Operationalizing Adaptive Management at Bard

Now that a theoretical framework and areas for potential challenges have been identified, adopting the adaptive management approach at Bard can be examined in some concrete steps. The first useful step would be to consider where Bard's GI is in the cycle of adaptive management. In Chapter Three, the state of the system was outlined through data collected during monitoring and based on this information, conclusions were drawn as to how the system is meeting these goals. In the adaptive management process, this would refer to the monitoring and evaluation steps, leaving Bard at the adjustment stage (Fig. 4.3). This is ideal not only because there is information to apply to modify or maintain different management objectives, but it also provides an opportunity to incorporate stakeholders into the management regime and adjust to new interests and perspectives. As such, this might be an ideal opportunity to re-determine and focus on specific goals that can be mutually agreed upon by stakeholders, and develop a plan for determining how these goals can be measured for success. This can limit uncertainty and make learning possible after management decisions. While some goals from the original project implementation were able to be assessed, there remains limited capability to measure success in recharging groundwater (Table 4.1).

To give a concrete example of a potential management intervention, recall the visual inspection of plant growth in the constructed wetland (Section 3.2.1). There has been visible growth in various emergent plant species, with a noticeable expansion of the common reed throughout the shallow and deep marsh areas. As indicated by the literature in Section 2.1.2, plant coverage (type and amount of area covered) can impact the system's effectiveness in achieving certain objectives, such as nutrient or pollutant removal Li et al. (2014). Relative to other management interventions, plant covering is a fairly easily manipulated ecological function that can be modeled and monitored through methods as simple as visual inspection and documentation. Stakeholders can determine what benefits the system can realistically provide when adjusting plant coverage, consult the literature for formulating hypotheses, determine parameters for success, and then design and implement a plan for manipulating the plant coverage in the system. An example of active adaptive management, this kind of intervention can then be monitored over time and evaluated for success.

Of the potential challenges listed above by Schreiber et al. (2004), Bard should be aware of a few of these. Providing the institutional structures for stakeholder collaboration can be threatened if there is limited communication or limited formal structures for facilitating communication between stakeholders. If this is not considered, some stakeholders may be left out of the loop and management decisions could go forward without consensus, potentially leading to mistrust. Next, with an incomplete study plan, the opportunity for learning could be lost. In particular, the plan should be clear as to what our hypotheses are, what is being tested, and how success will be measured. Lack of commitment to monitoring, evaluating, and reporting can also render the study plan ineffectual; hopefully with student commitment and involvement, though, these processes can be carried out consistently. Finally, if the hypotheses, monitoring, and lessons learned are not carried over into the design and implementation of new management interventions as a result of institutional "memory loss", then the cycle has failed to reach back around to the start.

4.4 Conclusions

Managing stormwater is an issue of increasing priority in the face of urbanization and climate-exacerbated storm events. As a result of this growing stormwater problem, GI has emerged as an attractive alternative to traditional gray infrastructure due to its ability to not only perform stormwater management functions, but also to provide additional social and ecological benefits. Since the ensuing implementation of GI systems, researchers have examined various aspects of their effectiveness, many focusing on their ability to act as multi-functional systems. There is still limited knowledge as to the effectiveness of GI over space and time, but what has become clear is that not all purported benefits can be provided at all times, and that there exist tradeoffs among different co-benefits.

Throughout this paper, the issue of GI tradeoffs and co-benefits has been examined, using Bard as a case study. Chapter Two reviewed the literature of designing, managing, and evaluating GI to receive socially, economically, and ecologically beneficial outcomes. Chapter Three introduces Bard's GI and constructed wetland, establishing the state of the system based on monitoring data from the past few years. Finally, Chapter Four reviews that stated goals in light of the conclusions drawn by the state of the system, and introduces adaptive management as a potential management strategy given the context of Bard's GI. Further study will allow for improved understanding, design, implementation, and management of stormwater with GI approaches. Through the adaptive management approach of learning by doing, we have an opportunity to achieve learning and management objectives simultaneously.

Bibliography

Allen, C. R., Fontaine, J. J., Pope, K. L., & Garmestani, A. S. (2011). Adaptive management for a turbulent future. *Journal of Environmental Management*, *92*(5), 1339–1345. https://doi.org/10.1016/j.jenvman.2010.11.019

Bard College Office of Sustainability. (2015). *Bard Regional Demonstration Project for Improving Stormwater Management* [Brochure].

Baron, J. S., Gunderson, L., Allen, C. D., Fleishman, E., McKenzie, D., Meyerson, L. A., Oropeza, J., & Stephenson, N. (2009). Options for National Parks and Reserves for Adapting to Climate Change. *Environmental Management*, *44*(6), 1033–1042. https://doi.org/10.1007/s00267-009-9296-6

Bixler, T. S., Houle, J., Ballestero, T., & Mo, W. (2019). A dynamic life cycle assessment of green infrastructures. *Science of The Total Environment*, *692*, 1146–1154. https://doi.org/10.1016/j.scitotenv.2019.07.345

Bixler, T. S., Houle, J., Ballestero, T. P., & Mo, W. (2020). A spatial life cycle cost assessment of stormwater management systems. *Science of The Total Environment*, *728*, 138787. https://doi.org/10.1016/j.scitotenv.2020.138787

Castonguay, A. C., Iftekhar, M. S., Urich, C., Bach, P. M., & Deletic, A. (2018). Integrated modelling of stormwater treatment systems uptake. *Water Research*, *142*, 301–312. https://doi.org/10.1016/j.watres.2018.05.037

Chang, T.-J., Chang, Y.-S., Lee, W.-T., & Shih, S.-S. (2016). Flow uniformity and hydraulic efficiency improvement of deep-water constructed wetlands. *Ecological Engineering*, *92*, 28–36. https://doi.org/10.1016/j.ecoleng.2016.03.028

Francesch-Huidobro, M., Dabrowski, M., Tai, Y., Chan, F., & Stead, D. (2017). Governance challenges of flood-prone delta cities: Integrating flood risk management and climate change in spatial planning. *Progress in Planning*, *114*, 1–27. https://doi.org/10.1016/j.progress.2015.11.001

Holland, J. F., Martin, J. F., Granata, T., Bouchard, V., Quigley, M., & Brown, L. (2004). Effects of wetland depth and flow rate on residence time distribution characteristics. *Ecological Engineering*, *23*(3), 189–203. https://doi.org/10.1016/j.ecoleng.2004.09.003

Holling, C. S., & United Nations Environment Programme (Eds.). (1978). *Adaptive environmental assessment and management*. International Institute for Applied Systems Analysis ; Wiley.

Houle, J. J., Roseen, R. M., Ballestero, T. P., Puls, T. A., & Sherrard, J. (2013). Comparison of Maintenance Cost, Labor Demands, and System Performance for LID and Conventional Stormwater Management. *Journal of Environmental Engineering*, *139*(7), 932–938. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000698

Hughes, T. P., Gunderson, L. H., Folke, C., Baird, A. H., Bellwood, D., Berkes, F., Crona, B., Helfgott, A., Leslie, H., Norberg, J., Nyström, M., Olsson, P., Österblom, H., Scheffer, M., Schuttenberg, H., Steneck, R. S., Tengö, M., Troell, M., Walker, B., … Worm, B. (2007). Adaptive Management of the Great Barrier Reef and the Grand Canyon World Heritage Areas. *AMBIO: A Journal of the Human Environment*, *36*(7), 586–592. https://doi.org/10.1579/0044-7447(2007)36[586:AMOTGB]2.0.CO;2

Ibrahim, A., Bartsch, K., & Sharifi, E. (2020). Green infrastructure needs green governance: Lessons from Australia's largest integrated stormwater management project, the River Torrens Linear Park. *Journal of Cleaner Production*, *261*, 121202. https://doi.org/10.1016/j.jclepro.2020.121202

Johnson, F. A., Boomer, G. S., Williams, B. K., Nichols, J. D., & Case, D. J. (2015). Multilevel Learning in the Adaptive Management of Waterfowl Harvests: 20 Years and Counting. *Wildlife Society Bulletin*, *39*(1), 9–19. https://doi.org/10.1002/wsb.518

Karraker, N. E., Gibbs, J. P., & Vonesh, J. R. (2008). IMPACTS OF ROAD DEICING SALT ON THE DEMOGRAPHY OF VERNAL POOL-BREEDING AMPHIBIANS. *Ecological Applications*, *18*(3), 724–734. https://doi.org/10.1890/07-1644.1

Kapetas, L., & Fenner, R. (2020). Integrating blue-green and grey infrastructure through an adaptation pathways approach to surface water flooding. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2168), 20190204. https://doi.org/10.1098/rsta.2019.0204

Lee, S., Maniquiz-Redillas, M. C., & Kim, L.-H. (2014). Settling basin design in a constructed wetland using TSS removal efficiency and hydraulic retention time. *Journal of Environmental Sciences*, *26*(9), 1791–1796. https://doi.org/10.1016/j.jes.2014.07.002

Li, D., Chu, Z., Huang, M., & Zheng, B. (2019). Multiphasic assessment of effects of design configuration on nutrient removal in storing multiple-pond constructed wetlands. *Bioresource Technology*, *290*, 121748. https://doi.org/10.1016/j.biortech.2019.121748

Likens, G. E. (2009). *Encyclopedia of inland waters. [Volume 1] [Volume 1*. Elsevier. http://site.ebrary.com/id/1045618

Lyons, J. E., Runge, M. C., Laskowski, H. P., & Kendall, W. L. (2008). Monitoring in the Context of Structured Decision-Making and Adaptive Management. *Journal of Wildlife Management*, *72*(8), 1683–1692. https://doi.org/10.2193/2008-141

NOAA National Estuarine Research Reserve System (NERRS). System-wide Monitoring Program. Data accessed from the NOAA NERRS Centralized Data Management Office website: http://cdmo.baruch.sc.edu/; accessed 12 October 2012.

O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., & McMillan, S. (2010). Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States. *Water*, *2*(3), 605–648. https://doi.org/10.3390/w2030605

Peterson, G. D., Cumming, G. S., & Carpenter, S. R. (2003). Scenario Planning: A Tool for Conservation in an Uncertain World. *Conservation Biology*, *17*(2), 358–366. https://doi.org/10.1046/j.1523-1739.2003.01491.x

Reidmiller, D. R., Avery, C. W., Easterling, D. R., Kunkel, K. E., Lewis, K. L. M., Maycock, T. K., & Stewart, B. C. (2018). *Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II*. U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018

Rounds, S.A., Wilde, F.D., and Ritz, G.F., 2013, Dissolved oxygen (ver. 3.0): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6.2, https://doi.org/10.3133/twri09A6.2.

Schiappacasse, P., & Müller, B. (2015). Planning Green Infrastructure as a Source of Urban and Regional Resilience – Towards Institutional Challenges. *Urbani Izziv*, *26*(supplement). https://doi.org/10.5379/urbani-izziv-en-2015-26-supplement-001

Schreiber, E.S.G., Bearlin, A.R., Nicol, S.J. and Todd, C.R. (2004), Adaptive management: a synthesis of current understanding and effective application. Ecological Management & Restoration, 5: 177-182. https://doi.org/10.1111/j.1442-8903.2004.00206

Sievers, M., Parris, K., Swearer, S., Hale, R. (2018). Stormwater wetlands can function as ecological traps for urban frogs. Ecological Applications. 28. 10.1002/eap.1714.

Spahr, K. M., Bell, C. D., McCray, J. E., & Hogue, T. S. (2020). Greening up stormwater infrastructure: Measuring vegetation to establish context and promote cobenefits in a diverse set of US cities. *Urban Forestry & Urban Greening*, *48*, 126548. https://doi.org/10.1016/j.ufug.2019.126548

Sussams, L. W., Sheate, W. R., & Eales, R. P. (2015). Green infrastructure as a climate change adaptation policy intervention: Muddying the waters or clearing a path to a more secure future? *Journal of Environmental Management*, *147*, 184–193. https://doi.org/10.1016/j.jenvman.2014.09.003

Swenson, H. A., & Baldwin, H. L. (1965). A primer on water quality. General Interest Publication. https://doi.org/10.3133/7000057

USEPA (n.d.). What is Green Infrastructure? Retrieved November 20, 2020, from https://www.epa.gov/green-infrastructure/what-green-infrastructure

USEPA (2011). *Recreational Water Quality Criteria*. https://www.epa.gov/sites/production/files/2015-10/documents/rwqc2012.pdf

USEPA (2012, March 6). What is conductivity and why is it important? Water: Monitoring & Assessment. https://archive.epa.gov/water/archive/web/html/vms59.html

USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp.

Van Oijstaeijen, W., Van Passel, S., & Cools, J. (2020). Urban green infrastructure: A review on valuation toolkits from an urban planning perspective. *Journal of Environmental Management*, *267*, 110603. https://doi.org/10.1016/j.jenvman.2020.110603

Williams, B. K. (2011). Adaptive management of natural resources—Framework and issues. *Journal of Environmental Management*, *92*(5), 1346–1353. https://doi.org/10.1016/j.jenvman.2010.10.041

Williams, B. K., & Brown, E. D. (2016). Technical challenges in the application of adaptive management. *Biological Conservation*, *195*, 255–263. https://doi.org/10.1016/j.biocon.2016.01.012

Williams, B. K., R. C. Szaro, and C. D. Shapiro. 2009. Adaptive Management: The U.S. Department of the Interior Technical Guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

Zuniga-Teran, A. A., Gerlak, A. K., Mayer, B., Evans, T. P., & Lansey, K. E. (2020). Urban resilience and green infrastructure systems: Towards a multidimensional evaluation. *Current Opinion in Environmental Sustainability*, *44*, 42–47. https://doi.org/10.1016/j.cosust.2020.05.001