EXPLORING SOCIAL AND TECHNICAL INSIGHTS OF STORMWATER MANAGEMENT PROFESSIONALS ON OPERATIONS AND MAINTENANCE

by

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(Under the Direction of Jon Calabria)

ABSTRACT

This study explores the organizational and technical factors that impact the success of green stormwater infrastructure (GSI) operations and maintenance (O&M) needs. While research exists on the ecological, social, and economic benefits of green stormwater infrastructure (GSI), more knowledge is needed on the long-term success factors of (O&M) throughout its life cycle. Respondents (n=241) across various disciplines contributed experiences, attitudes, and perceptions to identify challenges and opportunities of GSI O&M. Results suggest the importance of monitoring and evaluation, strengthened interdisciplinary communication, and community engagement to streamline designs and foster support. Further research with broader discipline representation is recommended to enhance our understanding of O&M practices in GSI.

INDEX WORDS: Green Stormwater Infrastructure, Interdisciplinary Cooperation, Low-impact Development, Operations and Maintenance

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DEDICATION

I dedicate this thesis to every creature inhabiting and depending on clean and healthy waterways, to every human who has shared their knowledge and excitement about them with me, and to the indispensable pairs of rainboots and pieces of snorkel gear that have allowed me to experience them firsthand.

Furthermore, I would also like to dedicate this thesis to my family, friends, and partner, whose unwavering support and encouragement have been instrumental in my journey to completion.

Finally, this thesis is dedicated to Cornelius, who spent many late-night hours in studio with me, keeping me company during more tireless hours than any other soul. He became the unofficial mascot of our cohort and was always ready for a good walk when it was time to take a break.

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CHAPTER 1

INTRODUCTION

Increased precipitation from climate change inundates communities and causes flooding, increased runoff, decreased water quality, and rising sea levels. It is conversely depriving communities via drought and pollution (IPCC 2023). One of the most significant environmental concerns is how communities respond to water challenges and the increasing extremes of flooding, runoff, and pollution. Conventional or gray stormwater management, which includes gutters, drains, pipes, and retention basins (EPA 2024), treats excess water as a "waste product" by funneling it away from a site as quickly as possible (Echols and Pennypacker 2015). We need to transition our management approach from getting rid of increased runoff as quickly as possible to understanding how to keep as much of it on site, mirroring predevelopment hydrological conditions as closely as possible.

Urbanizing land and population growth drive urban stormwater issues because increased urbanization generally involves increasing impervious surfaces. Urban populations have been steadily growing for decades. In 1950, estimates reported that 64% of the US population lived in urban areas. Current estimates reveal that 83% of the population lives in urban areas, and projections anticipate an increase to 89% by 2050 (United Nations 2019). From 2000 to 2010 alone, urban land area in the US increased by 15% (US Census Bureau 2012). Urban land currently accounts for approximately 3% of the total land area in the US, and according to current growth patterns, urban development is projected to more than double by 2060 (J.C. Davis et al. 2023; US Census Bureau 2012).

Due to the impacts of increased impervious surface, communities face decisions about managing stormwater best and meeting federal water quality regulations. The untreated stormwater runoff associated with urbanization and increased imperviousness alters the hydrological cycle. This alteration to natural water processes increases stormwater volume runoff, decreases groundwater recharge, decreases water quality, and impacts biological diversity, affecting local and global scale hydrologic processes (Abbott et al. 2019; Project 2007; New Hampshire Estuaries Project 2007). In attempts to lessen the impacts of urban stormwater runoff on urban systems, the US Environmental Protection Agency (EPA) has systematically strengthened stormwater management standards through more stringent federal regulation criteria for municipal separate storm sewer systems (MS4), combined sewer overflows (CSOs), and Total Maximum Daily Loads (TMDLs) (Meng, Hsu, and Wadzuk 2017). Municipalities support federal regulations through two main types of stormwater infrastructure – gray and green. Alterations to conventional gray infrastructure include upgrades to existing sewer systems and expansions in system capacities. In addition to gray infrastructure improvements, more and more cities integrate a second prong to their stormwater runoff management approach through green stormwater infrastructure (GSI) (Meng, Hsu, and Wadzuk 2017).

GSI manages stormwater by mimicking natural hydrologic processes. This is accomplished by capturing water on site, slowing the movement of water via retention, and slowing the release of water into surrounding soils (EPA 2007). Examples of GSI include green roofs, bioretention systems such as rain gardens, permeable pavements, vegetative swales, and more (EPA 2024). This reduces runoff, erosive potential, and pollution compared to gray infrastructure, contributes to mimicking predevelopment hydrology, and works to maintain and recharge groundwater levels (EPA 2007).

National support for green stormwater infrastructure presents itself in numerous funding opportunities to research and implement green infrastructure. For example, the American Recovery and Reinvestment Act (ARRA), signed in 2009, designated $4 billion to the EPA's Clean Water State Revolving Fund to support projects focused on "green infrastructure, water efficiency improvements, energy efficiency improvements, and environmentally innovative activities" (EPA 2013). Most recently, significant government investments support the creation and implementation of pollution prevention practices through the Inflation Reduction Act (IRA) and the Bipartisan Infrastructure (BIL) Pollution Prevention grant. The IRA designated almost $1.9 billion towards neighborhood access and equity grants that contribute to "natural infrastructure, pervious, permeable, or porous pavement, or protective features to reduce or manage stormwater runoff," among other climate change based actions (118th Congress 2023-2024). The BIL Pollution Prevention grant has designated $13.8 million to equip businesses with knowledge, training, and tools to promote technologies such as GSI (EPA 2022-2023). Research demonstrates various ecological, social, and economic benefits, including watershed restoration, recreational prospects, community amenity creation, cleaner air and water, wildlife habitat support, and more (Echols and Pennypacker 2015; Keeley et al. 2013; Benedict and McMahon 2002; Vick et al. 2012). GSI has the potential to become more widespread with support such as this. The next step in supporting GSI systems is developing a better understanding of maintenance and operational (O&M) needs so that these systems can provide many long-term benefits.

Objectives and Justification

While research supports the ecological, social, and economic benefits of GSI, less is known about the long-term success of GSI throughout its life cycle. Acceptance of assessment as an industry standard for measuring GI sustainability has begun over the last decade or so (Ahern 2011; Shifflett et al. 2019; Allen P Davis, Hunt, and Traver 2022). Practitioners understand maintenance needs for conventional gray infrastructure, but the growing body of assessment research has not fully realized GI's O&M needs. There is a vast array of GSI, such as vegetated roofs, infiltration basins, bioretention, swales, filter strips, and more. Maintenance plans and courses of action inevitably vary by project type and individual project considerations. However, GSI system performance relies on proper maintenance to ensure the practice optimizes ecological, social, and economic benefits. "Whether green infrastructure activities are implemented to meet regulatory requirements or as a voluntary effort to improve water quality, establishing written plans and procedures to assure long-term maintenance is important in ensuring the success of the project" (EPA 2013, 2). The success of any GSI project relies on the proper understanding of O&M, which is why more research is needed to help practitioners inform management decisions.

GSI systems are multidisciplinary, involving many different skill sets and stakeholders throughout their lifecycle. Champions tout GSI as capable of addressing multiple urban issues and providing many services, and it also tends to involve various stakeholders. Gray infrastructure generally falls under the purview of civil engineers. In contrast, GSI commonly relies on contributors from many disciplines, including "property developers, urban planners, landscape architects, ecologists, and public relations specialists" (Keeley et al. 2013, 1095). Confusing policies and jurisdictional questions arise due to GSI's integrated nature into many aspects of the urban fabric, so multidisciplinary collaboration is essential to integrating the infrastructure into surrounding landscapes, acquiring the land and land use rights to implement these solutions, and communicating their function and importance to policy maker and the public alike (R.R. Brown 2005; Keeley 2007; Carmon and Shamir 2010; de Graaf and van der Brugge 2010).

The objectives of this thesis are two-pronged. The first objective is to examine the status of existing operations and maintenance research of GSI in the literature. After thoroughly reviewing operations and maintenance concerns, constraints, and opportunities, I will compare this knowledge to those working with GSI to determine practitioners' access and exposure to existing research and identify future research gaps. The second objective is determining values and perspectives across varied disciplines engaged in GSI.

Higher levels of collaboration are needed across and among disciplines to appropriately meet the challenges of GSI and ensure their longevity (Ahern 2011). This thesis presents an opportunity to explore what opportunities exist to support practitioners when making GSI management decisions.

Purpose and Significance

As humans continuously move to and densify urban environments, incorporating nature into these environments, more explicitly enhancing or uplifting ecological function, becomes more imperative. The disruption of human and natural life via stormwater runoff through flooding, pollution, and environmental degradation will only worsen if we do not develop sustainable and resilient infrastructure alternatives. We can no longer treat stormwater as a waste product by funneling it downstream as quickly as possible. Our infrastructure must encourage infiltration and maintain water on site where it falls as much as possible. GSI's evidence as a tool that promotes infiltration and water retention is clear. We must ensure that this infrastructure can continue functioning as optimally as possible throughout its life to support these goals.

This thesis explores the knowledge of the operations and maintenance needs of GSI practitioners. It intends to identify ongoing differences among practitioners to discern opportunities for reducing management challenges and encouraging the realization of the numerous benefits of GSI.

Research Question

This study addresses the following research questions to help support the long-term viability of GSI:

1. Which disparities exist between the literature on GSI operations and maintenance and practitioners' practical implementation?
2. To what extent do the different disciplines that work with GSI differentiate values and goals that impact the sustainability, resilience, and long-term usability of GSI?

Outcomes

Many factors determine the success of GSI, including design, regulation requirements, financing, and ongoing operations and maintenance (Bell et al. 2019). Surveying practitioners and gaining feedback on infrastructure management challenges is essential because it can help guide other practitioners in navigating similar challenges elsewhere (Keeley et al. 2013). Understanding stormwater practitioners' current values and challenges and supporting disciplines will help identify opportunities for better design within the systems and how professionals design their collaborations and management plans. Better stormwater infrastructure design and management translates to healthier watersheds, ecosystems, and communities and better stewardship of the built environment.

Limitations Overview

This project utilized an online survey distributed via email and shared on various professional network forums, including LinkedIn and the American Society of Landscape Architect's (ASLA) 'The Field' blog. The University of Georgia College of Environment + Design shared the survey during the Landscape Architecture Short Course as part of the Landscape Architecture Continuing Education System. Survey respondents were contacted based on their location in the Piedmont and Coastal Plains bioregions within the Southeast, considering their relevance to stormwater infrastructure. Subsequent contacts evolved through a snowball sampling approach based on recommendations from initial survey respondents. While this convenience sampling method radiated to capture national and even limited international participation, it primarily reached stormwater practitioners in the Atlanta metro area. As a result, the conclusions drawn from this survey cannot be generalized to all types of stormwater practitioners or all regions nationally and internationally (Dillman 2007; Dillman, Smyth, and Christian 2014). The survey was conducted between January and March 2024.

Overview

This thesis explores the operations and maintenance needs of GSI and the gaps between existing literature and practitioners. It also compares discipline differences to GSI approach and value. Chapter 1 provides an overview of the research explored in this thesis and the overarching context for its purpose.

Chapter 2 explores the literature on GSI. The chapter will thoroughly examine definitions of GSI and what constitutes gray and green infrastructure. It will also review management challenges and identify current operations and maintenance research.

Chapter 3 details the methodology employed by surveying stormwater professionals, including the survey design and data analysis.

Chapter 4 presents the survey results and discusses discipline differences regarding the perceived purposes, benefits, and management challenges of GSI. It also explores utilizing these findings to streamline GSI management and improve design and interdisciplinary communication.

Chapter 5 concludes this thesis by summarizing overarching findings and ideas and presents future research opportunities and suggestions.

This research intends to improve the understanding of the operations and maintenance needs of GSI and emphasize its importance to stormwater management professionals and stakeholders to encourage proper planning and resource delegation in support of O&M. By developing a better understanding of GSI O&M, stormwater management professionals can ensure the proper functioning and longevity of these systems so that they can adequately contribute to making our urban environments more resilience to climate pressures.

CHAPTER 2

LITERATURE REVIEW

Green Stormwater Infrastructure

Infrastructure is the foundation or framework of a system (Merriam-Webster.com Dictionary 2024). In the context of the built environment, infrastructure is all the social, economic, and physical systems that support the function of the society that created them. The US Federal Emergency Management Agency (FEMA) focuses on public built infrastructure from a broad national perspective that includes everything from “structures, facilities,…public transportation,… water systems, including drinking water and wastewater systems,…and buildings and real estate property” among others (FEMA 2024). A subset of infrastructure, “green infrastructure,” has risen in popularity alongside international goals prioritizing sustainable development (UN General Assembly 2015). While interest in green infrastructure (GI) has surged among planners, policymakers, and designers within the last few decades, it is not new.

Context

In the US, Frederick Law Olmsted introduced the concept of interconnected greenways as early as the late 1800s and early 1900s (Eisenman 2013). He believed connected green spaces had vital implications for local and regional planning. Olmsted foresaw the continued growth of urban spaces and recognized the health issues that arose when ordinary citizens did not have access to clean air, clean water, and nature. He championed the idea of interconnected strings of greenspace throughout his career (Olmsted 1970). Because of its adoption and introduction by Olmsted, landscape architects have implemented greenway projects throughout the US. Their benefits have been found to support ecologically important natural systems, provide recreational networks within urban settings and connecting rural ones, and contribute to historical heritage and cultural values (Fabos 2004). While many distinct types of greenway projects respond to project-specific needs and topographic constraints, overarching consistencies of greenways include linearity in form and ecosystem services, emphasizing recreational opportunities in function (Little 1990). The green infrastructure movement evolved from the concept of greenways.

Although GI originates from the same ideas behind greenway and greenbelt systems, it does differ on a few key points. GI emphasizes ecology over recreation; it depends on major ecological hubs and connecting links and can inform growth by anticipating the most impactful places of ecological significance and development opportunities (Benedict and McMahon 2002). Exploring GI through ecological and planning lenses reveals a degree of required foresight and interconnectedness. The components of GI center around the concepts of "hubs" and "links." Infrastructure anchor points for ecological processes and connections that generate enough interaction between these anchors allow the entire system to work as designed (Benedict and McMahon 2002). Multiple scales of GI elements work together across a built fabric to compound ecological functions and benefits (Little 1990; Hilty 2019; Grabowski et al. 2022; Benedict and McMahon 2002). GI is the comprehensive "ecological framework needed for environmental, social and economic stability," and its main departure from conventional planning is its integration of "conservation values in concert with land development, growth management and built infrastructure planning" (Benedict and McMahon 2002, 12). As GI has grown as a concept and in popularity among practitioners, it has shifted, developed, and expanded to incorporate these ideas across many adjacent terms and definitions, all exploring this framework from different angles.

Definitions

As more municipalities and organizations adopt "green infrastructure" language and tactics to promote sustainability and resilience, it is important to consider what this term means. The concept emerged from landscape design, planning, and ecological principles, and as it has evolved, it has primarily focused on its hydrologic functions through stormwater management (Grabowski et al. 2022). As the national US environmental enforcement agency, the EPA designated green infrastructure specifically as practices relating to stormwater. Much of this hydrologic focus is due to the Clean Water Act and Water Infrastructure Improvement Act, which defined GI as "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate [sic] stormwater and reduce flows to sewer systems or to surface waters" (*Water Infrastructure Improvement Act* 2019). While there are arguments for a more conceptually inclusive definition among US policymakers, planners, and practitioners that incorporate landscape and integrative concepts, this thesis explores GI through a stormwater focus.

Green stormwater infrastructure (GSI) is a subset of management tools and terminology stemming from GI and conventional stormwater and wastewater management terms used throughout the literature. Best management practices (BMPs) designate historic stormwater management facilities and are still commonly used to describe any overarching stormwater management implementation or practice (Allen P Davis, Hunt, and Traver 2022). Stormwater control measures (SCMs) have been adopted more recently by the National Academies to include structural and nonstructural stormwater control methods, including infrastructure like bioswales and community education programs, respectively (National Research Council 2009). Low impact development (LID) refers to infrastructure that closely resembles and mimics natural processes concerning stormwater management to keep hydrology on a site as close to predevelopment processes as possible (EPA 2007). These terms are often used interchangeably or without definition among stormwater organizations and researchers. Throughout this thesis, the primary definition of GSI follows that of the EPA in the Water Infrastructure Improvement Act unless otherwise indicated.

Types of Green Stormwater Infrastructure

Common GSI includes various engineered, conventional, and LID solutions designed to promote different functions, such as infiltration, bioretention, detention, collection, and more (Allen P Davis, Hunt, and Traver 2022; Vick et al. 2012). These functions preserve and restore rainfall, vegetation, and soil interactions, improve water quality, promote groundwater recharge, maintain predevelopment hydrologic flows, minimize potable water use, and promote water reuse on-site (Vick et al. 2012). Implementation can be with or without nonstructural methods of GSI, including design improvements, community education, community outreach, practitioner education, stormwater infrastructure evaluation and assessment, operations and maintenance, etc. (National Research Council 2009; Ahern 2011; EPA 2013).

Vegetated and blue roofs (see Figure 1) collect and slow water runoff via the temporary storage and slow release of water using vegetation or other media on top of a built structure

(Vick et al. 2012). Vegetated roofs provide vegetated cover on rooftops, whereas blue roofs have no vegetation and use water storage compartments to reduce or slow runoff. These roof systems can be used separately or in tandem (van der Kolk et al. 2023; Allen P Davis, Hunt, and Traver 2022). Depending on the system, they are designed to contend with water quantity and may have secondary effects on improving water quality (Allen P Davis, Hunt, and Traver 2022). A significant constraint is weight, divided into intensive or extensive categories. Intensive systems utilize six or more inches in growing media, which requires more robust building engineering but allows greater plant flexibility and diversity. In comparison, extensive systems use less than six inches of media and have more limited planting options. They can be implemented in highly urban environments where other greenspace may not be possible (Vick et al. 2012).

Figure 1: Vegetated Roof System. (EPA 2013).

Rainwater harvesting is the process of gathering, storing, and reusing runoff collected from impervious surfaces (Allen P Davis, Hunt, and Traver 2022). Harvesting system elements can include the catchment area, filtration, holding cells, and subsequent water distribution.

Holding cells (see Figure 2) can consist of "rain barrels, cisterns, dry wells, harvesting ponds," bladders, etc. (Vick et al. 2012, 111). Collection is most commonly captured from roofs. However, it can also be collected from parking lots, sidewalks, or landscaped areas. The benefits of rainwater harvesting include application in highly urbanized environments and higher elevations. It can be integrated into energy generation systems and used as a primary and secondary water supply for irrigation and indoor plumbing in the appropriate circumstances (Allen P Davis, Hunt, and Traver 2022).

Figure 2: Rainwater Harvesting Cistern. Photo by Author.

Permeable pavements include pervious pavers and pervious pavements (see Figure 3). They are used in load-bearing applications while providing permeability for stormwater to seep through the material. These systems typically allow limited water storage within the foundational substructure beneath the permeable pavement (Vick et al. 2012). Many paver, concrete, and asphalt products can provide aesthetic and cost-effective options (Vick et al. 2012; Allen P Davis, Hunt, and Traver 2022). They can be implemented in almost any area with gentle slopes that require pavement, which makes them ideal for urban environments, and their high visibility provides educational opportunities for communities. Clogging of permeable pores is one of the most considerable limitations of these systems over time and in high-pollution areas (Vick et al. 2012).

Figure 3: Pavers Made from Permeable Concrete. Photo by Author.

Infiltration basins and trenches (see Figure 4) are often used in areas with sandy soils (Allen P Davis, Hunt, and Traver 2022). These systems require excavation to allow room for clean, coarse aggregate. Larger aggregate creates an interconnected system of voids that accrues water as it is conveyed across it before exfiltration to surrounding soils. Infiltration basins and trenches succeed in runoff reduction and groundwater recharge. Still, they are generally less aesthetically pleasing and are prone to clogging due to their reliance on larger voids within the aggregate (Vick et al. 2012).

Figure 4: Infiltration Basin. Photo by Author.

Sand filters use sand or a sand mixture with other engineered media to filter out large particulates and dissolved pollutants (see Figure 5). They primarily enhance water quality as particulates settle on the sand layers as water moves through them (Allen P Davis, Hunt, and Traver 2022).

Figure 5: Sand Filter Under Construction. (EPA 2021).

Bioretention systems are shallow landscaped basins designed to retain, infiltrate, and filter water through vegetation and exceptionally permeable soils (see Figure 6). Rain gardens are small 6-8-inch-deep installations that typically do not integrate underdrains and are most effective multiple rain garden sites are used as stormwater nodes throughout a site (Vick et al. 2012). Bioretention systems are typically larger systems that can claim 5-10% of the land of the catchment area they serve. These systems often use underdrains and overflow connections to gray stormwater infrastructure. The larger footprints can collect more significant amounts of rainwater and provide larger pockets of wildlife habitat (Vick et al. 2012).

Figure 6: Bioretention System. Photo by Author.

Swales and filter strips are primarily designed for stormwater conveyance (see Figure 7). They can be lined with vegetation that adds to filtration and evapotranspiration potential or planted with turf (Vick et al. 2012). Media or check dams can slow water and filter out larger pollutants, although they fall short in dissolved pollutant filtration (Allen P Davis, Hunt, and

Traver 2022). Swales provide more stormwater visibility and act as a pretreatment system, as stormwater is directed to other systems designed for retention and infiltration (Vick et al. 2012).

Figure 7: Grass Swale with Some Rock Armoring. Photo by Author.

Stormwater wetlands (see Figure 8) mimic natural wetland systems' function by collecting larger water quantities and dependence on copious wetland plantings for pollutant filtration and habitat creation (Vick et al. 2012). The aerobic and anoxic pockets created throughout a stormwater wetland system encourage the microbial processes needed for water quality treatment (Allen P Davis, Hunt, and Traver 2022). Stormwater wetlands rely on precipitation to maintain water levels and are designed for slow drawdown to maintain wetland conditions (Vick et al. 2012). The slower release is more efficient at cooling water temperatures before its release into receiving water bodies (Allen P Davis, Hunt, and Traver 2022).

Figure 8: Stormwater Wetland. (EPA 2013).

Each system can be used separately or in concert to manage stormwater. Environmental factors, space constraints, aesthetic goals, water quality and quantity considerations, operations and maintenance constraints, and amenity co-benefit opportunities all contribute to management decisions regarding which measures are most appropriate for stormwater management goals.

Benefits and Challenges of Green Stormwater Infrastructure

As urban development continues to outpace population growth throughout most of the developing world, we see increased development impacts on the environment and community health (UN General Assembly 2015; US Census Bureau 2012; Frumkin, Frank, and Jackson 2004). Sprawling development has resulted in a myriad of adverse environmental impacts, including loss of natural areas, fragmentation of open spaces, degradation of water resources, decreased resiliency of biological processes, loss of natural services, increased conventional infrastructure public service costs, and increased taxes (Benedict and McMahon 2002; Hilty 2019; Allen P Davis, Hunt, and Traver 2022; EPA 1982; Chang 2010). GSI helps address all these issues by creating a developmental framework that supports ecosystems to provide environmental, economic, and social benefits.

The overarching environmental impact of stormwater in our urban environments comes from the increase in impervious surfaces. More impervious surfaces mean less opportunity for water infiltration and, therefore, more water with nowhere to go, often resulting in downstream flooding and pollution conveyance. Conventional stormwater infrastructure has focused on taking this water away from a site as quickly and directly as possible, which has only increased runoff, exacerbated non-point pollution, aggravated downstream erosion, and prevented groundwater recharge (EPA 1982). Capturing water via GSI on-site or as close to its origination is essential in addressing these issues by allowing on-site water treatment, providing more time for infiltration, and reducing downstream flooding (Pereira, David, and Galvão, 2019). For example, constructed wetlands and bioretention are good at retaining water quantity, while green roofs, biofiltration, and rain gardens focus on improving water quality through sedimentation, plant uptake, and filtration (Gonzalez-Meler et al. 2013; Allen P. Davis 2008; Hunt, Davis, and Traver 2012). While individual GSI impacts on water quality and quantity depend on its designed purpose and individual site variables, hydrologic impacts (i.e., water levels, infiltration capability, peak flows, etc.) and pollution mitigation (i.e., total suspended solids (TSS), total nitrogen (TN), total phosphorous (TP) pathogen-indicator species, metals, hydrocarbons, and temperature) is well documented (Allen P Davis, Hunt, and Traver 2022; Gallet 2010; Hunt, Davis, and Traver 2012). Other environmental benefits of GSI include increased wildlife habitat and habitat connectivity, carbon sequestration, and improved air quality (Gonzalez-Meler et al. 2013).

GSI delivers economic benefits that range from site-specific savings to broader impacts on infrastructure and communities. In a synthesis of 17 case studies, with few exceptions, sites using GSI experienced development savings due to differences in “site grading and preparation, stormwater infrastructure, site paving, and landscaping” compared with gray-only stormwater infrastructure. Most of the examined cases saw 15-80% total capital cost savings (Myles 2014). Examination at a larger municipal or regional scale reveals cost benefits through savings related to water, energy, air quality, and climate change. Reduced gray infrastructure-related costs demonstrate water-related savings. Energy costs decrease with more efficient evaporative temperature regulation and reduced potable water generation needs. The value added through system services becomes clear when evaluating air quality and climate change-related impacts. Additional benefits include increased property values due to improved amenities such as recreational opportunities, reduced urban heat island effect, reduced noise pollution provided by GSI, and labor income via job creation (Myles 2014; Galvin and BenDor 2023).

Social benefits include aesthetic improvements, community cohesion, educational and recreational opportunities, and environmental equity opportunities. Because GSI has more surface interaction than gray infrastructure, which is hidden behind fences or pipes underground, there are more opportunities to integrate GSI into site designs and community amenities. Integrating visible stormwater management into a site design does augment the experience of site topography by creating another layer of site interactivity (Backhaus and Fryd 2013). Creating interactive amenities creates opportunities for art installations and educational programming that can work independently or in concert with art, creating community gathering places and increasing the overall community aesthetic (Echols and Pennypacker 2008). Practitioners considering social equity within the planning process can be used to promote equity via infrastructure spending justifications and services such as reduced flooding and amenity development (Reu Junqueira, Serrao-Neumann, and White 2022).

With the many benefits of GSI documented in the literature and enjoyed by communities, many challenges and potential drawbacks of GSI deserve consideration. From a technical perspective, challenges primarily pertain to long-term care and assessment deficiencies. Studies attribute the wide variability in GSI effectiveness to an abundance of individual project variables, which involves more site-specific planning than gray infrastructure requires (Gonzalez-Meler et al. 2013). A lack of long-term vision for GSI projects often means little monitoring or evaluation of stormwater management infrastructure (R.R. Brown and Farrelly 2009). Practitioners have established maintenance needs for most gray stormwater infrastructure types; however, many gaps still exist for appropriate operation and maintenance programs for GSI (EPA 2013). While installation costs are lower for GSI over gray infrastructure, this is not the case in all scenarios (EPA 2007). These technical gaps can prevent the long-term efficiency of these systems, thereby reducing system benefits to water quality and quantity.

Many community and land planning issues also stem from GSI’s reliance on social system integration to realize its full potential benefits. Aesthetically, forcing stormwater management to be the primary design consideration and failing to integrate it into a complete design often results in an unsuccessful design (Backhaus and Fryd 2013). Communally, GSI may fail to garner public support if too much land space for stormwater management fails to provide recreation and aesthetics (Junker and Buchecker 2008). Education in the community is also often lacking due to limited community engagement, empowerment, and participation (R.R. Brown 2005). Failure to consider spatial equity during the planning and funding processes can exacerbate community inequities. Omission from interventions can exclude communities from the benefits of GSI, while a non-holistic implementation plan can intensify the effects of green gentrification (Reu Junqueira, Serrao-Neumann, and White 2022; Shokry, Connolly, and Anguelovski 2020). Institutionally, support can also be complex with the public and policymakers if stiff land use competition exists, especially in dense urban areas (Reimer and Rusche 2019). Because GSI crosses boundaries between traditional built infrastructure and managed landscapes, uncoordinated and limited regulatory frameworks, unclear and fragmented responsibilities, lack of adaptive management knowledge, and poor communication hinder GSI implementation and long-term viability (R.R. Brown 2005). Lack of coordination, institutional support, or public will can stop GSI implementation before it can benefit the communities it might support.

Stormwater Reporting Requirements

The Environmental Protection Agency dictates annual reporting requirements for wastewater and stormwater discharge in the US. These requirements are designed for compliance with the Clean Water Act concerning stormwater, which impacts certain industrial facilities, construction sites, and municipal separate storm sewer systems (MS4), impacting the installation or retrofitting of GSI. The EPA works with federal, state, and tribal entities to monitor sites and maintain compliance. Compliance monitoring is designed to support the enforcement of clean water and environmental regulation via permits and regulations, evidence collection, enforcement orders and decrees, deterrence creation, and by providing critique and comments to permit and rule writers (EPA). The EPA regulates point source pollution emitters via the National Pollutant Discharge Elimination System (NPDES). The NPDES tackles pollution issues by fostering compliance. This is achieved through Discharge Monitoring Report reviews, on-site evaluations, and assistance in attaining appropriate compliance.

Stormwater reporting requirements vary by the type of industry involved in stormwater polluting activities and the specifics of an individual project. Most GSI-related projects would fall under the purview of construction site regulations or be employed to assuage MS4 pollution. Most states have agreements with the EPA to implement permits and regulations, with the EPA acting as the parent organization over states with authority and as the direct authority over remaining states and territories (Construction Industry Compliance Assistance Center).

NPDES permits are required for projects that will disturb one or more acres or for smaller sites incorporated into a larger development plan. Development activities that result in land disturbance include clearing, grading, and excavating. The three overarching requirements for the permitting process include permit application submittal before construction takes place, a thoroughly planned and executed erosion and sediment control plan before construction activities begin, notification of the removal of erosion and sediment controls, and a proper indication that no further activities will contribute to sediment and pollution discharges into surface waters once work is completed (Construction Industry Compliance Assistance Center). In addition to erosion and sediment control plans, infrastructure developers must stabilize soils, manage dewatering activities, ensure pollution prevention measures, maintain surface water buffers, prevent certain discharges from entering waterways, and use appropriate outlets for basin and impoundment discharges. If a GSI project is smaller than the one-acre constraint and considered to have an inconsequential impact on erosion, the EPA and state authorities may waive permitting requirements (Construction Industry Compliance Assistance Center).

GSI Planning System Integration

Importance of Long-Term Viability

Communities often face overwhelming impacts from climate change, such as flooding, increased precipitation, heat, drought, developmental pressures, and environmental degradation. Given the present organization of our urban areas, these challenges can exceed their ability to respond effectively. The discrepancies between community stressors and the ability to respond result in more frequent disaster declarations and prolonged recovery periods. Disaster management has been shifting away from a reactionary response to a proactive response to decrease susceptibility to community environmental stressors and to increase resilience (Keim 2008). Reducing many aspects of climate change susceptibility is achieved through preventative measures (Keim 2008). GSI is recognized as an effective preventive measure to increase urban climate resilience by buffering precipitation-based climate changes (Mosleh, Negahban-Azar, and Pavao-Zuckerman 2023). As practitioners develop GSI to contend with today's stormwater management issues, we must also ensure that we plan, design, and maintain them to account for the long-term pressures anticipated in the evolving climate of tomorrow. Long-term viability is essential for realizing and reaping its ecological and social benefits while maximizing the payout from economic impacts. Ensuring the long-term viability of GSI, therefore, contributes to community resilience.

Assessment approaches are valuable tools in appraising what aspects of GSI should be focused on to strengthen their resilience. Frameworks are expanding to include ecosystem service-based aspects as just part of a more holistic view of the elements that make GSI successful (Raymond et al. 2017; Dong, Guo, and Zeng 2017). Different dimensions of resilience include "population and demographics, environmental/ecosystem, organized governmental services, physical infrastructure, lifestyle and community competence, economic development, and social-cultural capital" (Renschler et al. 2010). Factors that are essential to longevity under stress or disturbance, yet often underexplored and overlooked, are social factors and maintenance. The five overarching categories that embody elements of resilience come down to policy, design, maintenance, economics, and social factors (Mosleh, Negahban-Azar, and Pavao-Zuckerman 2023).

Several longitudinal studies examine the resilience of GSI that fall within these major resilience categories. Setting up policies that protect GSI closer to areas needing ecosystem services, such as flood protection, is invaluable. Preserving existing GSI and appropriate strategizing for determining the location and timely implementation of this infrastructure is essential in the long-term realization of ecosystem benefits (Sohn, Bae, and Newman 2021). Regarding design, GSI attracts people by creating a sense of place. These become amenities that encourage community (Hagen et al. 2017). The design also impacts function. The size, placement, spatial relationships, regimented versus organic design, and connectivity all impact system function over time (Sohn, Bae, and Newman 2021). From a maintenance perspective, the ability of a media system to absorb water and the amount of water it can retain directly impacts the pollutant load it can carry. The better the system media is at accepting pollutants, the faster it becomes loaded with them, and the bigger the impacts on soil microbes and their functioning within the soil are (Zhaoxin et al. 2021). As intuitive as these findings may seem, they have significant implications on the types of soil media used in GSI, when maintenance should occur, and what constitutes a maintenance event. While much research has focused on increasing pollutant uptake, there is less on what maintenance should entail when higher loads impact these systems (Zhaoxin et al. 2021). Because studies often focus on immediate functionality more than long-term functionality, there is a lack of technical maintenance advice.

Elevating the importance of long-term care of GSI from a policy and social angle may assist in functional longevity and social acceptance by maintaining performance (Flynn, Linkous, and Buechter 2012; Mosleh, Negahban-Azar, and Pavao-Zuckerman 2023). Economically, green space and water-related features correlate with increased property value. Increased water retention within a community also enjoys economic benefits associated with the required water supply needed by development and existing community needs. Increases in property values reliably correlate with social acceptance of GSI (Hagen et al. 2017). Socially, GSI installations correlate with an increase in public safety. Significant declines in narcotic possession, narcotic manufacturing, and thefts were reported as far as a half mile from stormwater management sites (Kondo et al. 2015). While there are many gaps in the knowledge of the social benefits of GSI, research such as this indicates it can be a powerful tool in promoting equity and resilience within communities (Mosleh, Negahban-Azar, and Pavao-Zuckerman 2023).

Many practitioners agree that more longitudinal studies are needed to fully understand the long-term implications of GSI and how to ensure the continuation of established benefits (Sohn, Bae, and Newman 2021; Kondo et al. 2015; Zhaoxin et al. 2021; Hagen et al. 2017). It is also clear that GSI provides significant benefits that impact communities across health, safety, and welfare dimensions (Vick et al. 2012). The resilience of these communities depends on the strength of the system they use, highlighting the significance of ensuring their long-term viability.

Interdisciplinary Collaboration

Implementing GSI presents both benefits and challenges due to its interdisciplinary nature. Successful integration of GSI requires stakeholders' and practitioners' input at various stages, including planning, design, policy, construction, and maintenance. This involvement should include professionals, watershed management groups, and communities (Shifflett et al. 2019). The input of diverse community stakeholders enhances GSI's ability to provide environmental, economic, and social co-benefits. At an organizational level, effective project outcomes depend on the cooperation between government entities and implementing systems. This collaboration ensures that individual professionals and organizations can contribute meaningfully to successful projects (Backhaus, Dam, and Jensen 2012).

One of the most considerable barriers to the widespread adoption of GSI is the institutionally established inter-organizational lack of ability and motivation to communicate and collaborate (Brown and Farrelly 2009). Traditional governmental implementation of policies affecting infrastructure follows a top-down organizational strategy with strong functional independence between departments (Fitzgerald and Laufer 2017). This top-down strategy intrinsically results in strong vertical relationships between various levels of government. The long-established standing relationships encourage the dominance of limited professional communities over a governmental system component. For example, the field of engineering dominates conventional stormwater management. This governmental and organizational system naturally dissuades cross-departmental communication and collaboration, inhibiting the flow of ideas and technological ideation (R.R. Brown 2005). Managing stormwater quantity has fallen under the purview of engineers with gray infrastructure development, while stormwater quality has typically been relegated to stormwater management and planning divisions (R.R. Brown 2003).

The traditional government divides in duty have confused roles and implementation with conventional methods tending to win out (R.R. Brown 2005).

To advance GSI, implementation must be holistic and collaborative. Not only do governmental organizations need to promote horizontal and vertical coordination, but the integration of nongovernmental organizations, community stakeholders, practitioners, academics, etc., needs to be infused into GSI decision-making through vertical and horizontal processes (R.R. Brown 2005; Vlachos and Braga 2001; Backhaus, Dam, and Jensen 2012). Including the public and various technical disciplines is essential to breaching organizational barriers, cultivating community advocacy, and promoting championing relationships (R.R. Brown 2005). Creating coordinating programs whose goals are institutional learning and assimilating operational knowledge should expose administrative gaps and conflicts, which will uncover how to improve cooperative frameworks and degrade disciplinary boundaries. These processes will not only help establish new GSI projects but also establish procedures for long-term monitoring and evaluation to ensure the longevity of these systems over time (R.R. Brown and Farrelly 2009; Carmon and Shamir 2010).

Three major disciplinary schisms must be tackled to encourage interdisciplinary collaboration, including communication, competing disciplinary values, and regulatory environments (Fitzgerald and Laufer 2017). Assigning congruent rights, budget considerations, and understandings is essential in achieving this end. Researchers recognize that interdisciplinary learning and communication are complex and take investment (Huang, Lim, and Misra 2022). Professional openness and awareness of individual and organizational roles and positionality can increase interdisciplinary project effectiveness and success (Stokols 2015). Examples are emerging in cities that have created multidisciplinary teams, like Portland, Seattle, and the Ruhr district in Germany, which have successfully implemented interconnected and influential GSI projects (Backhaus, Dam, and Jensen 2012).

Diffusion of GSI

As the concept of GSI has gained popularity over the last few decades, organizations and government entities are implementing GSI. It is worth exploring how ideas and new technologies spread. Understanding the dissemination of ideas, concepts, and technologies through professional disciplines and organizations can guide management decisions and raise awareness on improving practitioners' knowledge and experiences with new GSI developments. This understanding is essential to help improve the functionality, efficiency, and longevity of GSI as technological and procedural advancements improve.

The Diffusion of Innovation theory defines "Diffusion [a]s the process by which an innovation is communicated through certain channels over a period of time among members of a social system" (Rogers 2003, 11). According to Rogers' theory, diffusion rates depend on several factors. How does the technology or idea compete with existing products? The relative advantage of a new product is important. Compatibility is essential with the adopters' prior experiences and values. The complexity of a system or product impacts its adoption. The more confusing or complicated something is, the more resistance to its spread. The ability of a product to be divided and used in smaller amounts increases flexibility and requires less of a resource-impacting commitment. Finally, potential adopters need to witness results within a reasonable time. People believe what they see, so experiencing a product's impact is also integral to its adoption (Rogers 2003; Di Benedetto 2010).

The actors involved in the diffusion can be understood through a series of adopter categories based on their willingness to adopt and the speed at which they do so. The first people to try a new technology are considered innovators and opinion leaders who strongly influence whether later users will adopt the technology. After the initial innovators experiment with a technology, it spreads to early users, then the majority, split into an early and late majority. Finally, there are the laggards as the technology is finally embraced by most people (Di Benedetto 2010).

The Moore diffusion model explored a different breakdown of user types, one of the most significant extensions developed from the Rogers Diffusion of Innovation theory (Di Benedetto 2010). The most important departure in diffusion archetypes is that of the visionaries and pragmatists, which most closely align to the Moore equivalent of both initial innovators and early adopters and then the early majority, respectively. Visionaries and pragmatists experience a significant gap between their willingness to adopt an idea or technology. There is a broader departure in expectations and needs of the two groups, which means that pragmatists may not look to visionaries as leaders and, therefore, not use them as a reference point for adoption. Bridging the "chasm" between the excitement of the visionaries and the references and motivations the pragmatists require is essential in adopting an idea into mainstream use (Di Benedetto 2010).

Professional perceptions, formed by training, experience, and everyday working conditions, play a crucial role in studying GSI within a practical context. These perceptions influence professionals' capacity to embrace innovative ideas, impact their willingness to contend with infrastructural challenges, and inform decision-making in management. Understanding mechanisms by which ideas spread in conjunction with professionals' perceptions of GSI guides present infrastructure needs and helps determine future research priorities. This insight is valuable for focusing on pressing issues and adopting effective strategies for the sustainable implementation of GSI.

Many of these GSI-specific findings correlate with broader theories of diffusion. First and foremost, one of the primary recognized motivating factors for GSI implementation is as a stormwater management tool. A survey of practitioners based in New Jersey found that they most frequently cited combating stormwater runoff as the primary driving force for implementing GSI despite its many other benefits (Rowe, Rector, and Bakacs 2016). A sole focus on GSI over conventional gray stormwater management is impractical. The diversity of infrastructure, ranging from traditional gray engineering practices to more progressive green solutions, must work in tandem to tackle stormwater management challenges effectively across different communities (Bell et al. 2019).

One of the most impactful influences on GSI adoption by local officials is how useful they believe it will perform in combating infrastructure and stormwater management issues. The complexities involved with implementing GSI are less critical than a practitioner's belief that they have access to the skills and resources required to reach project success (Carlet 2015). Confidence in resource access initiates a positive feedback loop in the confidence of the benefit impacts within a community because they are equipped to appraise the outcomes of GSI regarding their stormwater management goals (Carlet 2015). Despite occasional confusion about how to conform with stormwater mandates and the lack of state incentives for GSI-specific solutions, a belief in the effectiveness of GSI benefits has propelled its adoption in many municipalities (Rowe, Rector, and Bakacs 2016).

Surveys and interviews nationwide have identified many perceived challenges associated with GSI. Practitioners see difficulties in financing and maintenance responsibilities when GSI crosses property lines or resides entirely on private property (Keeley et al. 2013). Unclear organizational responsibilities and communications increase challenges in trans-jurisdictional funding. This extends to projects that exist in whole or in part on privately owned land (Keeley et al. 2013). The public's willingness to provide financial support via taxes and fees to improve stormwater management services is impacted by their familiarity with and understanding of its function and benefits (Keeley et al. 2013). Given funding concerns, it is surprising that many municipalities also fail to apply for grants to support GSI projects, perhaps indicating a lack of resources to do so or proper knowledge of the process (Rowe, Rector, and Bakacs 2016). Larger municipalities generally have more flexibility in navigating these challenges as there is less economic and competitive pressure and more resources to implement new or exploratory policies. Their willingness to take on these challenges often affects surrounding communities and their resource knowledge and capabilities in implementing GSI projects (Shipan and Volden 2008).

While the scattered nature of GSI creates other logistical maintenance issues, fragmentation of GSI sites does have the surprising benefit of working against the artificial deflation of stormwater fees as their prevalence around the community is more visible. Smaller-scale projects were also reported with favor due to smaller amounts of available urban land and ease of management (Keeley et al. 2013). Maintenance is a lower priority than developing new GSI or existing gray infrastructure repairs (Shifflett et al. 2019). Officials also observe inconsistent lifetime GSI performance that requires varied amounts of potentially labor-intensive maintenance (Meng, Hsu, and Wadzuk 2017).

Despite all the perceived challenges, positive views about GSI and its evolving technologies are repeatedly seen. Understanding the challenges different practitioners perceive about GSI makes it easier to know where to focus energies supporting their implementation.

Community Engagement and Education

Engaging the public and communities throughout planning and implementation is an essential ingredient in the success of GSI. Communities deserve to participate in the GSI programs and infrastructure development resolutions that impact their lives (Arnstein 2009). Communities bring crucial context to the knowledge of local conditions that can strengthen plans and designs (Crewe 2001; Van Herzele 2004). They can effectively use social networks to spread information and collect input (Cross et al. 2001). Engaging in local knowledge expands the knowledge that informs local policy and addresses environmental justice by employing democratic decision-making and acknowledging environmental inequities by including voices previously unheard from (Corburn 2003).

Integrating the public into stormwater management decisions creates a knowledge feedback cycle between practitioners and local actors. When the public does not understand how actions and urban design impact stormwater, they may actively work against practitioners working to rectify the problems. For example, there is significantly more resistance to taxes and fund generation needed to manage GSI properly, and even active fights against it, when communities do not recognize the levels of complexity interacting with these systems and the operational and maintenance needs to have them function properly over their lifespan (Keeley et al. 2013). Communities need a higher level of understanding to benefit as well as provide financial support to practitioners. Workers from various backgrounds can fill job requirements at every stage in the GSI life cycle, filling GSI-related labor shortages. Professionals can expand their knowledge based on inputs from these different backgrounds, and a more comprehensive public understanding of GSI function and maintenance can develop from a broader labor Input (Shifflett et al. 2019).

As the public gains a better understanding of GSI systems and the operations and maintenance they require, it better positions citizens to influence support of GSI in other realms. Issues of planning, investments, conservation, restoration, and recreation can all be approached in a GSI-friendly way. Professionals not directly engaged in stormwater management have noted that education in GI terminology was a boon to factoring it into decisions that impacted GSI through their work. Adapting different stakeholder institutions to water management needs contributes to a more holistic strategy for improved community-watershed integrity (Shifflett et al. 2019).

"Green" infrastructure has captured the interest and imagination of more citizens throughout the Western world (Carmon and Shamir 2010). A scarcity of educational and workforce development programs is one of the most considerable barriers to maintaining this interest, as ongoing investment in these programs for community stakeholders is required for sustained success (Shifflett et al. 2019; Carmon and Shamir 2010). Integrating the community into the environmental management decisions supporting GSI can forge a connection between behaviors and the resulting ecological impacts (Shandas and Messer 2008). A partnership between stormwater management professionals and the local knowledge and experiences provided by community members can work in tandem to prevent unsustainable infrastructure choices from undesirable consequences for future members of the community as well as communities downstream (M. White and Langenheim 2021).

Operations and Management of GSI

Life Cycle Financial Considerations

When making any infrastructure decision within any realm of the built environment, the one consistent and reliable question is cost. Any GSI element will have the direct capital costs associated with construction materials, processes, and size. Still, decision-makers need to understand the range of life cycle costs to appropriately plan for long-term success, "which include[s] planning and permitting, construction, operation, maintenance, and decommissioning" (Bell et al. 2019, 7). Soft costs pertain to planning, design, engineering, and administrative elements that go into a project before breaking any ground. Hard costs refer to construction, operations and maintenance, large-scale rehabilitation projects, and possible decommissioning at the end of a system's life (Clary and Piza 2017). Once there is an understanding of the type of economic responsibilities of a project, it is necessary to determine how and where to gather funds. More information on performance and costs is needed to support practitioners in their management decision-making (Meng, Hsu, and Wadzuk 2017).

There is a variety of existing tools and manuals designed to help estimate the costs of GSI elements. However, direct comparisons from one GSI element to another (i.e., comparing costs of a rain garden to a green roof) or from green to gray infrastructure can be difficult when sources don't report metrics like expected life span, non-point vs single point pollution impacts, life cycle related emissions, etc. (Tavakol-Davani et al. 2016; Brudler et al. 2019). Some tools examine GSI elements within a specific geographic context, such as by municipality, county, state, or region, while some have been developed from national data stores (Bell et al. 2019). Comparing costs becomes more feasible when tools can normalize costs across service time, location, maintenance, and replacement fees (Yu, Montalto, and Behr 2018; Bell et al. 2019).

While financial tools are improving, very few still attempt to incorporate the entire life cycle (Bell et al. 2019).

Capital and construction costs of GSI are often compared to those of gray infrastructure. A report directed to the Illinois EPA found that the average construction costs of GSI are 5-30% less than gray infrastructure (Jaffe et al. 2010). Gray infrastructure generally incorporates larger construction costs due to using hard infrastructure elements (i.e., curbs, pavement, gutters, piping, etc.). In contrast, GSI focuses on emulating natural hydrologic features. Conservation design can quickly reduce the materials required for stormwater management (EPA 2007; Brudler et al. 2019; Vineyard et al. 2015). In some cases, GSI does incur higher costs associated with "plant material, site preparation, soil amendments, underdrains and connections to municipal stormwater systems, and increased project management" (EPA 2007, 9). However, most GSI cases benefited from development and construction phases due to reduced need for site grading, site preparation, hard infrastructure, paving, and landscaping, resulting in 5-80% cost reductions compared to gray infrastructure alone (EPA 2007; Jaffe et al. 2010). Reducing stormwater volume requirements through decreasing permeable surfaces with consistent site integration of GSI can also reduce the land needed to be set aside to comply with stormwater regulations. Reducing the land required for permanent ponds or large-scale wetland projects can result in increased housing or commercial units and higher real estate profits (EPA 2007).

Lifetime O&M needs of green and gray infrastructure are very different due to the design components. Larger-scaled stormwater infrastructure is typically more cost-efficient when comparing operating costs to capital cost ratios. Gray stormwater infrastructure tends to be larger in scale compared to GSI, which translates to 1.00-2.50% of operational expenses compared to capital costs. The landscaping maintenance and media remediation of GSI results in a full range of 0.1-300% with an average of 2-12% of operations and maintenance compared to capital investment (Bell et al. 2019). When considering the entire lifespan of these systems, GSI has been found to cost 25% less on the whole life cycle (Jaffe et al. 2010). Combined gray-green systems maximize scale and natural hydrologic process efficiencies, which maximize costs when considering both economic and hydrologic factors (Tavakol-Davani et al. 2016; M. Wang et al. 2023; R. Wang, Eckelman, and Zimmerman 2013).

GSI can be funded via federal infrastructure support programs such as the Clean Water State Revolving Fund and the Inflation Reduction Act. This funding has historically been used to implement or renovate wastewater and stormwater systems (EPA 2013; 118th Congress 2023-2024). To support O&M needs, 36% of reviewed projects supplied funding and labor via public-private partnerships. Only 59% of GSI projects had a dedicated, stable funding source, including municipal and district general funds and stormwater utility fees. Stormwater utility fee collection rates varied from project to project, with structures that included flat fees and rates dependent on impervious surface coverage ratios (EPA 2013).

Stormwater compliance regulations impart environmental impact fees for the negative effects development has on the environment (EPA 2007). GSI can assuage those fees by counting towards regulatory compliance credits or initiating streamlined permit processes, among other incentives. One example from Maryland pertains to permanent wet pond volume requirements. Implementing a vegetated roof can reduce the required volume because the vegetated roof decreases impervious areas within the site. The gray infrastructure of a combined sewer or detainment pipes has significantly higher infrastructure impacts than the limited material and operational demand of GSI (Brudler et al. 2019; Vineyard et al. 2015). The smaller environmental impact of GSI infrastructure results in smaller impact fees in this way (EPA 2007).

Performance Monitoring and Evaluation

One of the barriers to proper GSI implementation and management is a deficiency in longitudinal monitoring that impedes appropriate maintenance and restoration regimes (Sohn, Bae, and Newman 2021; R.R. Brown and Farrelly 2009). This is related to the perception that implementing new GSI sites and gray infrastructure repairs is more critical than evaluating and monitoring existing sites (Shifflett et al. 2019). Monitoring and evaluation practices are imperative to ensure that GSI performs as it should over time and after substantial impacts from large storm events. The process involves "monitoring the site for metrics relevant to project goals, analyzing monitoring results, and potential adaptive management if needed" (Shifflett et al. 2019, 12). The monitoring methodology depends on the type of studies being conducted and the type of GSI, and it will be unique to these variables and infrastructure goals. Regardless of time and labor constraints, the quality of the monitored data is more important than unreliable data in large quantities (Barbosa, Fernandes, and David 2012).

Stormwater management criteria should be established so that management professionals know what aspects of GSI to monitor and adequately evaluate its performance. Different jurisdictions and municipalities may have other criteria depending on local needs, regulatory requirements, and retrofit goals. Standard criteria include water-quality improvement, runoff volumes, surface discharge, groundwater recharge, flow rates, evapotranspiration, and stream protection and are affected by "climate, soils, land form, vegetation, and surroundings" (Allen P Davis, Hunt, and Traver 2022, 183). GSI control measures allow practitioners to evaluate if the watershed’s baseline hydrologic and environmental conditions are impacted by the GSI system as designed (Allen P Davis, Hunt, and Traver 2022; Barbosa, Fernandes, and David 2012). Following this intent, resources such as the International Stormwater Best Management Practices Database have begun to develop a repository of field studies and internet tools to provide monitoring guidance ("International Stormwater BMP Database" 2024). The information collected from monitoring and evaluation is integral in providing evidence-based knowledge to determine appropriate GSI selection, design elements, construction methods, and maintenance needs and how each contributes to stormwater management goals under diverse conditions (M. Wang, Sun, and Zhang 2023).

O&M Considerations

To fully harness GSI’s potential benefits via efficient and long-lived performance, they require consistent and appropriate O&M (Gallet 2010; Homet, Kremer, Smith, and Strader 2022). The need for maintenance accentuates the importance of a comprehensive understanding of GSI’s O&M needs via research and proper planning (Homet, Kremer, Smith, and Strader 2022). The literature is only just starting to delve into the impacts of O&M, which is needed to support this infrastructure long-term (Homet, Kremer, Smith, Ampomah, et al. 2022; Wadzuk, Gile, Smith, Ebrahimian, Strauss, et al. 2021). With so many different and unique applications of GSI, there is a lot of variability in appropriate maintenance actions and schedules. A review of 22 different GSI projects highlighted common themes that contributed to successful O&M programs, including a defined O&M plan that established accountability and maintenance schedules, logging records of maintenance activities, continued GSI-centered training to keep up with new technology and understandings, compliance mechanisms, and pre-established designations of responsibility and funding specifically for O&M (EPA 2013).

Maintenance of a system may start after its construction. Still, decisions in the initial design process influence the breadth, intensity, and cost of maintenance activities that a GSI system will require throughout its life (Chow et al. 2014; Echols and Pennypacker 2008; EPA 2013). The correct type of infrastructure must be designated for a project that considers local climate, precipitation patterns, planting material, anticipated water volumes, and pollutant loads (EPA 2013; Hunt et al. 2010). While designs should consider aesthetics, recreational opportunities, and educational potential, they cannot be the sole focus without having an effect on overall functionality (Backhaus and Fryd 2013). Systems should consider capacity for a predetermined storm event, controlled overflow mechanisms, and permeability of local or mediated soils based on conveyance, detention, and retention needs (EPA 2013; Hunt, Davis, and Traver 2012).

Designing functional considerations such as these can help reduce erosion, plant viability, pollutant loads, and more maintenance needs. Site placement is essential. The proximity of GSI to the stormwater generation point reduces flooding, erosion, and sediment movement, thereby reducing cleanup and restoration costs (EPA 2007; Huang, Lim, and Misra 2022). Local or engineered substrates must be appropriately secured to prevent erosion, and slopes need to be graded to manage different flow rates (EPA 2013; Hunt et al. 2010). Plantings should be integrated into the system based on survivability. Native plants that can handle the extremes of water levels, temperatures, and pollutants are ideal to encourage plant establishment and survival and to reduce replenishment maintenance (Hunt, Davis, and Traver 2012; Perrin et al. 2009). Plant establishment also helps mediate erosion concerns by stabilizing soils, increasing system pollutant uptake by establishing mature root zones, encouraging infiltration with root growth, and reducing the need for pesticides by providing habitat and contributing to biodiversity (EPA 2013).

While designing for maintenance concerns is essential, so is developing an accountability and O&M plan to ensure that long-term maintenance is adequately funded and carried out. Strong community support can establish the importance of maintenance without a written plan, but sustainability through changing government or organizational officials requires more forethought. Clearly defined maintenance responsibilities, funding sources and obligations, and community benefits help hold officials and managers accountable as organizational priorities shift with time (EPA 2013; Carmon and Shamir 2010). Plans should include O&M activity descriptions and schedules, monitoring procedures, record-keeping logs, labor requirements, cost estimates, and review plans for existing procedures at defined intervals or after substantial system alteration (Feehan 2013). These plan components intend to extend the GSI system's life by ensuring all system components operate as they should and prevent unnecessary and costly repairs or restorations (EPA 2013).

Documenting systems can range from simple paper tracking to integrated software systems that track maintenance trends, integrate with GSI, and generate reports (Feehan 2013). Tracking is its own form of accountability, but it also provides opportunities to develop more efficient preventative maintenance strategies based on system feedback (EPA 2013). Tracking can help managers determine when changes in staffing, additional resources, specialized equipment, replacement media, planting material, etc., are needed. Records should include maintenance activity logs, labor and time requirements, existing GSI conditions, newly identified system issues, and associated costs to formally direct maintenance decisions (Feehan 2013).

Maintenance activities fall within two major temporal categories, which include routine or preventative maintenance and non-routine or reactionary maintenance. Routine maintenance is carried out regularly to prevent more significant systematic issues and depends on the GSI type and technologies involved. Maintenance activities occur on different timelines, from daily activities to those occurring annually or every few years (Feehan 2013). Non-routine maintenance responds to a specific performance issue often initiated by inconsistent routine maintenance or unexpected events such as an extreme weather event or residents performing guerilla maintenance or planting. Non-routine maintenance events cannot always be planned but should be considered when estimating maintenance costs (Feehan 2013).

Many maintenance activities impact the GSI's ability to contribute to pollutant uptake, stormwater storage, and infiltration rates as designed (EPA 2007). These activities can occur within or outside the system to ensure less impact within them. Maintenance activities that impact most GSI systems fall within a few major categories, including debris management, erosion control, plant maintenance, and pest control.

Debris, such as trash, sediments, leaf litter, and chemicals, can impact all GSI systems and their ability to intake, permeate, and clean water (Homet, Kremer, Smith, Ampomah, et al. 2022). Some system components are designed to accumulate debris to prevent them from getting into other system components. For example, catch basins are designed to collect sediment, trash, and leaf litter as they settle out of the water (Homet, Kremer, Smith, Ampomah, et al. 2022). Catch basins require periodic emptying, which can be done manually or via vacuum trucks (EPA 2007). As in natural wetland systems, ponds and constructed wetlands can accumulate sediments, fats, oils, and organic matter buildup over time, which decreases storage capacity, alters water flows, and impacts previously settled sediments and the ability to settle out new sediment. Excessive buildup can block drainage outlets, detract from aesthetics, and cause odor pollution with the buildup of organics. Debris accumulation rates can require cleaning anywhere from 2-20+ years depending on surrounding land uses and soil stabilization and the rate of infiltration and capacity decline (EPA 2007)

Impervious surfaces are critical sources of contaminants for GSI regardless of land use (Bannerman et al. 1993). Because streets and parking lots comprise a considerable portion of impermeable surfaces, sweeping programs can help reduce debris materials on the surfaces that generate so much polluted runoff (EPA 2007). External infrastructure activities such as road salt and sanding add to sediment and salt runoff. As ice and snow melt, they are carried into stormwater systems, resulting in toxic conditions within GSI aquatic environments and making soil conditions too hostile for vegetation to survive (EPA 2007). Road and street surfaces can become debris when they break down due to infrastructure erosion caused by friction, freeze-thaw impacts, and frost heaving. Proper maintenance of such an impactful runoff source affects the maintenance needs of the receiving GSI (EPA 2007).

Vegetative maintenance can vary throughout the life of GSI. It is crucial to account for different stressors on vegetation throughout the life cycle of GSI, and they are an important component to the function of bioretention sites, vegetated filter strips, vegetated swales, and stormwater wetlands via pollutant uptake, erosion control, and evapotranspiration functions (Hunt, Davis, and Traver 2012). The establishment period of GSI vegetation is typically one to three years and is one of the most critical times in maintenance. Increased monitoring is recommended to ensure that systems are not overwhelmed by different inputs as plants establish themselves. Weeds need to be controlled to reduce species competition, watering level needs may be higher, and reduced use of pesticides is necessary while roots are established (EPA

2013). Larger, more mature plants may be needed in places where there are shorter growing seasons. Where inflow controls are incorporated into a system, more moderation of stormwater input may also be necessary not to overwhelm new plantings. It may take multiple growing seasons of planting and re-seeding to maximize the naturalization of GSI systems. Once vegetation is established, weeding and manual, chemical, or mechanical removal of invasives and excessive plant growth need to be integrated into maintenance programs (EPA 2013). Proper establishment will lower intensive maintenance needs such as persistent monitoring and irrigation (EPA 2007)

Pests can cause damage to GSI systems and be a point of concern for communities considering GSI (Frumkin, Frank, and Jackson 2004; H.E. Brown et al. 2022). Healthy insect populations indicate GSI system health and contribute to ecological function and biodiversity (Pham et al. 2023). Improper design and deterioration of system maintenance can contribute to mosquito populations and the spread of disease vectors for vegetation and surrounding communities when slow-moving and pooled water cannot infiltrate within a few days (H.E. Brown et al. 2022). Providing habitat for mosquito predators such as bats and birds and discouraging other nuisance species such as muskrats and deer with fencing can protect GSI ecosystems and assuage community concerns (EPA 2013).

Erosion, pollution, vegetation, and pest control are all significant aspects of design and maintenance with implications for monitoring, accountability, planning, and funding throughout GSI's lifespan (EPA 2013). A wide breadth of disciplinary input from design, construction, operations, and maintenance can result in neglected upkeep without clear organizational direction and responsibility (Shifflett et al. 2019). Communities need to understand the importance of maintenance so that appropriate funding will be designated for these systems, which will allow them to achieve the many benefits they are intended to provide for a community (Shifflett et al. 2019; Bell et al. 2019).

O&M Examples for Different GSI Systems

Specific operations and maintenance activities depend on the type of GSI system in place and the many variables that impact the system, including size, placement, pollutant loads, vegetation, pest pressures, media, local soils, flow levels, erosion concerns, etc. (Flynn, Linkous, and Buechter 2012). This section explores common maintenance activities and scheduling suggestions for different types of GSI. Specific O&M programs should be tailored to the unique system and responsive to system feedback collected through consistent monitoring and evaluation (Feehan 2013; Wadzuk, Gile, Smith, Ebrahimian, and Traver 2021; Wadzuk, Gile, Smith, Ebrahimian, Strauss, et al. 2021)

Vegetated roofs are extremely vulnerable to weed pressure as many vegetated roof systems employ smaller plants, so regular inspections and weed removal are essential, especially during vegetation establishment or upon exposure to growing media. Removing dead plant material is also important in reducing excess nutrients that might support weeds (Snodgrass and McIntyre 2010). The smoothening out and supplementation of media should be done as needed, often indicated by desirable plant diebacks. Regular checks on irrigation systems are also essential to prevent plant diebacks, especially as they adjust to local conditions. Biannual checks can account for frozen, cracked, or otherwise impaired irrigation lines for systems that continue irrigation past establishment (Snodgrass and McIntyre 2010). Inspecting growing media composition and depth as needed is important in combatting nutrient imbalances, wind scour, and compression (Snodgrass and McIntyre 2010).

Permeable pavements only work if they can continue permeating runoff. Measuring infiltration rates will indicate when debris buildups are impacting permeation. Inspection of the surrounding drainage area is important for tracking sources of sedimentation and debris (J.T.R. Brown and Brown 2020). Debris should be kept clear via quarterly street sweeping. Pressure washing annually can help maintain infiltration rates (Utilities 2009). Milling may be necessary when street sweeping fails to restore filtration rates. Pavement settling may indicate the need to remove and re-level base materials as needed. Reducing or forgoing sanding and salting during the winter helps prevent clogging (Erickson, Taguchi, and Gulliver 2018). Lifespans can last around 20 years with proper maintenance (Perrin et al. 2009).

Infiltration systems such as basins, trenches, bioretention systems, and rain gardens have five primary inspection points, including the drainage areas, inlets, underdrains, outlets, and the main treatment area (J.T.R. Brown and Brown 2020). As-needed maintenance includes the removal of debris, sedimentation, and oils from inlet, outlet, and underdrain components. Excess vegetation and invasive removal should take place semi-annually. A buildup of dead or decaying plant material within the system can indicate filtration issues (Erickson, Taguchi, and Gulliver 2018). Extended dry periods are encouraged if a bypass component is integrated into the GSI system every five years for more thorough inspections and increased filtration (Erickson, Taguchi, and Gulliver 2018).

Media filtration systems such as sand filters require inspection annually and after major storm events. Other annual maintenance includes the removal of trash and debris, vegetation from the filter surface, and sampling of filtration media (Erickson, Taguchi, and Gulliver 2018). Removing or replacing filter media with excessive sedimentation or cementation may be needed every five to ten years, depending on the system, to ensure filtration and prevent stormwater tunneling (Erickson, Taguchi, and Gulliver 2018; Flynn, Linkous, and Buechter 2012).

Stormwater wetlands can accumulate large amounts of sedimentation, which may require large-scale removal using large equipment and dredging processes, which could necessitate action every five to ten years in typical watersheds (Flynn, Linkous, and Buechter 2012; Erickson, Taguchi, and Gulliver 2018). Removing excess plant material and woody plant material as needed can reduce mosquito breeding habitat and invasive species presence (Perrin et al. 2009). Outlet inspections are recommended to prevent trash buildup, clogging, and altered water levels. Regular inspections are recommended in addition to those after large storm events (Perrin et al. 2009).

	Weeding, Mowing, & Watering	Trash & Debris Removal	Sediment Removal, Draining, & Flushing	Re-grading & Erosion Control	Seasonal Considerations	Plan & Component Replacement	Monitoring & Inspection
Bioretention Cells/Rain Gardens	Necessary on a regular basis; more frequent for manicured cells, in urban areas, or near roads/walkways	Necessary on a regular basis, particularly in urban settings	As-needed; if water is standing for long periods of time	As needed for prevention of channel formation or to repair erosion damage	Snow removal if necessary; monitor to prevent channel formation during snowmelt	Plant replacement as necessary; regular mulching to minimize weed growth	Regular monitoring and inspection to ensure adequate infiltration rate
Wetlands	Seasonal mowing of emergent areas; maintain adequate water levels for habitat; regular removal of weeds/ woody growth	Regular trash and debris removal; debris should be prevented from creating areas of pooled water	Sediment removal at a predetermined depth of sediment accumulated (6-12"); flushing of inflow/ outflow mechanisms when clogged	As needed for prevention of channel formation	System will be less effective in winter, inflow should be slowed; irrigate during dry periods	As needed; Plant replacement as necessary to maintain 85% vegetation cover of emergent land	Several inspections/yr and following major rain events and snowfalls; Every 2-3 weeks during establishment
Swales	Necessary on an occasional basis for vegetated swales	Removed as quickly as possible to prevent channel blockage	Not necessary unless swale is damaged	Regularly during establishment; as needed subsequently to prevent channel blockage	As needed after high volume winter storms or snowmelt	Plant replacement as necessary if the channel is damaged by erosion	Inspect regularly to ensure water is not pooling and channel is not eroded or damaged
Infiltration Basins	Mowing and weeding should be conducted on average once per month	As needed	Necessary any time water is not infiltrating within 72 hours	As needed basis if damage is Incurred during a high volume event	Monitor during snowmelt to ensure infiltration rate is maintained	May be necessary after basin has been in use for several years	Monitor to ensure water infiltrates within 72 hours. Inspect 1-2x yr for contaminant build-up
Rain Barrels/ Cisterns	N/A	Mesh screen can filter out debris	Water should be removed 7-10 days after a rain event	Water should drain onto stable, non-eroding soil	If freezing is common, rain barrels should be disconnected, and stored upside down; mosquito dunk may be needed during summer	As necessary	Periodically ensure water is not running into house foundations or erodible areas
Pervious Pavement	Controlled herbicide as necessary so as not to disturb pavement	Necessary on a regular basis	Vacuuming at a min. of 1-2x/yr and, where present, flushing of drainage system	Sediment should be prevented from eroding directly onto pavement	Mechanical snow removal (plowing); sand not recommended	Damaged pavers replaced with spares; small areas can also be repaired with traditional pavement. Infill, can be replaced with a broom	1-2x a year; no standing water should be on surface after a rain event
Green Roofs	Irrigation and fertilization regularly during establishment; weeding on a regular basis subsequently	Necessary on a regular basis. Critical if debris or dead vegetation creates a fire hazard	Drains should be inspected regularly	N/A	As needed during high snowfall volumes	As needed; frequency will depend on vegetation type and roof design	Regular inspections; ensure compliance with local guidelines and/or building codes

Figure 9: Summary of O&M Requirements (Modified from EPA 2013)

The figure above presents a slightly modified summary table of recommended O&M practices for GSI practices (see Figure 9).

Capacity Building and Training

As the country's stormwater infrastructure ages and urban pressures stress capacities, there is a greater and more imminent need for new construction, repairs, maintenance, and restoration of gray stormwater infrastructure and GSI (Kane and Tomer 2018). In 2016, a wide breadth of industries and sectors employed almost 1.7 million workers who contributed to these systems' design, construction, governance, operations, and maintenance (Kane and Tomer 2018). Projections forecast declines in "water infrastructure workers" (Kane and Tomer 2018) as skilled labor needed throughout the lifecycle of stormwater infrastructure increases. This is due to various forces, including an aging workforce, a lack of industry visibility to the general public, and a pipeline deficit for new skilled talent (Kane and Tomer 2018).

Approximately 52,000 water-related systems serve as foundational community structures, and their required operational upkeep and maintenance provide several opportunities to benefit the community (Kopaskie 2016). The proper education workers need to construct, operate, and maintain GSI facilities, support the economic mobility of individual workers, and improve the visibility and maintenance understanding of communities (Shifflett et al. 2019; Kane and Tomer 2018). Academic institutions and workforce programs can capitalize on the opportunity to develop multidisciplinary training opportunities to improve the education of GSI professionals and strengthen inter-institutional relationships (Shifflett et al. 2019). Some GSI-specific certificate programs have recently been developed. However, their impacts are uncertain, and there is a lack of consistency in training as stormwater management techniques continue to evolve and expand over the gray-green stormwater infrastructure spectrum (Shifflett et al. 2019; Bell et al. 2019). To support aging infrastructure and the implementation of newer GSI technologies, designers, stormwater utilities, policymakers, operations, and maintenance workers will need intentional, integrative, and collaborative training (Kane and Tomer 2018).

Tailored Design Method

The survey design used in this study is based on the Tailored Design Method (TDM) (Dillman, Smyth, and Christian 2014). The TDM depends on the concept of mutual social exchange. A perception of respondent payoff, costs, and mutual benefits for respondents and surveyors is important to encourage participation. Ideal communications include four contact instances considering timing, personalization, question order with increasing importance, and minimal graphics to reduce perceived length. People are more likely to participate in self-administered surveys, believing that the payoff will be larger than the individual cost. This methodology consistently produces higher response rates (Dillman, Smyth, and Christian 2014).

CHAPTER 3

METHODS

This thesis is composed of a GSI professional study evaluating two different aspects of practitioner relationships to this infrastructure: 1) disparities that exist between O&M literature and practical implementation experience and 2) what extent different disciplines differentiate values and goals that impact the sustainability, resilience, and long-term usability of GSI. The following section outlines methods used to assess perceptions and explains the survey design and analysis methods.

Overview

Data for this thesis was collected via a web-based survey. The survey was developed as a cross-sectional survey, designed to capture the experiences, attitudes, and perceptions of different GSI practitioners across various disciplines working with GSI through different lenses (Dillman, Smyth, and Christian 2014). It was intended to gather information on how practitioner experiences and beliefs impact GSI O&M, with the goal of determining where future research relating to O&M should be focused and what interdisciplinary opportunities exist to support O&M activities. It was created using Qualtrics, a web-based survey tool that allowed for University of Georgia branding ("Qualtrics" 2024). The survey received a total of 241 responses. The complete survey is attached in Appendix B: Survey.

Ethical Considerations

The Institutional Review Board (IRB) for the Protection of Human Subjects gave this research an Exempt determination on January 26, 2024 (PROJECT00008929). The entire approval letter is attached in Appendix A: IRB Approval Letter.

The survey began with a notification informing respondents that participation was voluntary and they were free to not participate or end the survey at any time without penalty. Respondents were required to indicate that they were over the age of 18 to participate in the study. Those under the age of 18 would have prompted the survey to end immediately.

Survey Design

The complete survey comprised 57 questions and was divided into three main sections. The first section gathered demographic information about the respondent and defined their role as it pertained to GSI. The second section intended to determine the respondents' general understanding and beliefs on green stormwater infrastructure. The third section explored the respondent's experience with GSI systems, their opinions, and perceptions of their implementation. Question themes and components such as definitions, system elements, system benefits or purposes, design guidance considerations, life-cycle activities, monitoring, evaluation, maintenance plans, community outreach, and training opportunities were all informed from GSI O&M-related themes that emerged from the literature review that was explored in Chapter 2.

Within the first section, respondents were asked about their demographics and background. Questions explored age, gender, race/ethnicity, educational background, employment status, and current work discipline. Respondents were asked to share their current job titles, the roles and responsibilities associated with said role, related background experience, and how long they have been working within their current field. This section concluded with an inquiry about involvement with any environmental groups.

The second section sought to understand the respondents' understanding of GSI and their relationship to it. Respondents were asked to generate their own definition of GSI. They were asked to indicate and rank the purposes of GSI and rank what system elements contributed to long-term viability. Familiarity with the Clean Water Act was assessed. After that determination, the GSI definition set by the EPA was presented to ensure all further questions relating to GSI were approached from the same definitional understanding. As the Clean Water Act sets compliance standards on stormwater infrastructure, respondents were asked if they believed GSI is an effective stormwater management tool and if it improves water quality. They could share why they indicated their choices. They were then asked about their awareness of GSI design guidance, access to guidance, and the types of guidance available to them.

The final section was more practical, exploring system experience and procedures involved with their implementation and throughout the systems' life cycle. Questions focused on respondent involvement with different GSI system types, system life-cycle stages, time working with a system, system quantities, and system sizes. They were asked if their job was adequately considered in the design process of GSI. Then, they were asked if they monitored and evaluated their projects and, if so, at what frequency and components they assessed. Maintenance questions explored who performed it, if an O&M plan was put in place, when the plan was developed and incorporated, and if the plans were ever evaluated. These considerations were explored concerning community engagement plans and improvement areas for maintenance and community engagement plans. Respondents were consulted on what other professions or disciplines they worked with in relation to GSI. They were given the opportunity to share their thoughts on desired training opportunities, successful or unsuccessful design elements, inhibitors of O&M success, and examples of projects they believed did maintenance well. Finally, respondents were asked if they were open to sharing the contact information of other stormwater management professionals interested in participating in the survey so that I might also contact them.

The survey used several different question types. Various question types were intended to address each research question by generating information well-suited for response analysis (Dillman, Smyth, and Christian 2014). Most questions were either close- or open-ended questions. Close-ended questions are more structured by providing a predetermined list of choices. The set choices create a basis for standardization that is easier to analyze (Dillman, Smyth, and Christian 2014; Story and Tait 2019). Open-ended questions allow respondents to present their beliefs and experiences in their own words with less interference or expectation from the surveyor. They can also inform the predetermined responses for close-ended questions (Dillman, Smyth, and Christian 2014; Story and Tait 2019).

Other question types included a short series of Likert scales, a rank order question, and a matrix table. The Likert Scale question garnered categorical and ordinal response data (Story and Tait 2019). The rank order question and matrix table are also scale questions. Respondents ranked the rank order question concepts according to their beliefs and preferences. The matrix table evaluated two row items using the same set of criteria preset within a list of column choices (Story and Tait 2019).

To reduce question fatigue, the survey employed skip logic. Skip logic directs respondents to subsequent questions based on their responses to previous ones (Feeney and

Feeney 2019). In this way, respondents were not exposed to questions that did not pertain to their experience once that indication had been made (Dillman, Smyth, and Christian 2014; Story and Tait 2019).

Before sending the survey out to a broader audience, question validity was sought via feedback from three stormwater professionals who have each had experience developing surveys (Story and Tait 2019). Their feedback was taken to improve the wording and legibility of survey questions to promote understanding and help determine if questions were set to measure what was intended.

Sampling Population and Population Strategy

One of the goals of this survey was to capture feedback from different disciplines involved with GSI over its life cycle, including community outreach, conservation, construction, ecology, education, engineering, environmental science, landscape architecture and design, landscape management, planning, stormwater management, students, and volunteerism. The sampling population includes stormwater practitioners falling within any of those disciplines.

Survey distribution was initiated via convenience sampling. The survey was distributed primarily online via an anonymous link and QR code. Initial contacts were selected by location within the Piedmont and Coastal Plains ecoregion in the southeast ("Level III and IV Ecoregions of the Continental United States" 2024). These regions were chosen based on the researcher’s familiarity with stormwater management organizations within these regions and existing contact points within them. Initial contacts included organizations and individuals involved with stormwater management via professional organizations, government, universities, and university extensions that provide classes and training for the wider community. Contact modes included email and professional network forums, including LinkedIn and ASLA's 'The Field' blog. Appendix C: Survey Contact List contains a complete list of those contacted. It was also shared during the Landscape Architecture Short Course as part of the Landscape Architecture Continuing Education System hosted by the College of Environment + Design at the University of Georgia. The survey was introduced to participants before a short course session during which they were presented with QR codes and the option to complete it surrounding short course events.

Consecutive contacts were gathered via snowball sampling. This snowball sampling method relied on contacting those I knew and on respondents sharing the contact information of others working in stormwater management who might be interested in taking the survey via a submission option at the end. Respondents were also contacted with an anonymous survey link, and the survey request included a note that encouraged the forwarding of the survey. Initial contacts, therefore, had the potential to act as seeds who could use their network to expand the reach of participants (Parker, Scott, and Geddes 2019).

Multiple survey contact requests have been documented to improve response rates (Dillman, Smyth, and Christian 2014). Initial contacts were contacted again to request survey participation and share the survey with anyone they may have reached out to previously and any new potential respondents between two and three weeks after the first survey request.

Analysis

The analysis used JMP Pro 17.2 statistical software ("JMP Statistical Discovery" 2024). Analysis methods vary depending on the question type and how the data is used to answer the survey questions.

I used the Text Explorer capabilities within JMP as an automated text analysis method. Automated text analysis provides advantages over traditional qualitative measures by removing researcher bias via its systematic approach, being fast, and simplifying the transparency of evaluation methods (Chakrabarti and Frye 2017). The Text Explorer provided word and phrase lists by analyzing the frequency of terms and phrases in question responses. It tracked the number of responses for each text question, the number of word and phrase cases, the number of tokens (or smallest piece of text), the number of cases (responses with at least one term), and the proportion of non-empty cases ("Text Explorer" 2023). Stemming was used to reduce words to their root or base to count similar word frequencies with like meanings. Word clouds were used to visualize the prevalence of term and phrase themes within responses. Word sizes within the world cloud represent relative frequency based on size. Sentiment analyses were performed where applicable. Open-ended question text responses were also read through in their entirety after the initial automated text analysis to gather any themes and important considerations.

To compare practitioners' responses from different disciplines, I used JMP to perform cross-tabulations to create contingency tables comparing discipline types to responses across many questions throughout the survey. As a fundamental empirical method to analyze qualitative data, these cross-tabulations helped to discern different goals and priorities of different disciplines depending on their responses (D.R. White 2004; Momeni, Pincus, and Libien 2018). Analysis of the raw data presented in the contingency tables via chi-squared tests and logistic regressions was performed when relevant.

The Likert scale, matrix table, and rank order questions were analyzed in JMP for central tendency, variability, and associations where appropriate using applicable statistics such as determining standard deviations, logistic regressions, cross tabulations, etc. (Boone Jr and Boone 2012).

Limitations

Limitations of this study arise from the convenience and snowball sampling methods employed in the survey distribution. The initial contact convenience sampling was directed throughout the Southeast's Piedmont and Coastal Plains topographic regions due to the researcher's familiarity with institutions and established contacts. While there were responses from practitioners throughout the US and even a few international responses, there is a strong bias of respondents whose practice is located within the Southeast, especially the Atlanta-Athens metropolitan corridor. Because of this, results are not applicable to all stormwater management professionals or within a specific region.

Three stormwater management professionals reviewed survey questions before distribution. Survey questions were derived from themes and conclusions from the literature, but a lack of a pilot study impacts the validity evaluation of the survey questions.

Survey respondents indicated representation for almost all pre-chosen disciplines (i.e., community outreach, conservation, construction, ecology, education, engineering, environmental science, landscape architecture and design, landscape management, planning, stormwater management, students, and volunteerism) except for student or volunteer representation. However, sample sizes are too small to generalize to their respective disciplines. There were also vast sample class imbalances between landscape architecture and landscape design compared with any other discipline. Because of this, results may be biased in favor of landscape architects.

This small sample bias also indicates a lack of statistical power when comparing groups and the inability to generalize findings among all GSI practitioners (King and Zeng 2001).

CHAPTER 4

RESULTS AND DISCUSSION

Overview

An online survey was distributed between January and March of 2024. The study's goal was capturing responses from various disciplines working with GSI, including community outreach, conservation, construction, ecology, education, engineering, environmental science, landscape architecture and design, landscape management, planning, stormwater management, students, and volunteerism. The survey was distributed via convenience and snowball sampling techniques, resulting in 241 responses. The survey contained three main sections: demographics and job roles, conceptual understanding of GSI's benefits and challenges, and personal experiences with practical GSI O&M aspects.

Results

Initial respondents (n=241) accessed the survey, and about a quarter broke off after the second question. Of the 72.61% of survey respondents (n=175) who interacted with the survey, 78% met the initial screening for an age restriction of 18 years or older and participated through completion, resulting in a 22% break-off rate. The survey platform suggests a 50% response quality based on result filters of ambiguous text, potential bots, unanswered questions, completion rates, respondent speeding, and straight lining ("Qualtrics" 2024). The most significant impact on the response quality score was due to ambiguous text responses. One survey response was marked as a potential bot and excluded from the results. No speeding or straight lining was detected, and completion rates were good ("Qualtrics" 2024).

The anticipated survey duration is 12-15 minutes. The box and whisker plot (Figure 10) shows that respondents' median time to do the survey was 23 minutes. The interquartile range is between 15 and 42 minutes. This indicates that many respondents required more than the anticipated time to complete the survey, which may have contributed to break-off rates. For clarity, the outliers were excluded visually from the box and whisker plot.

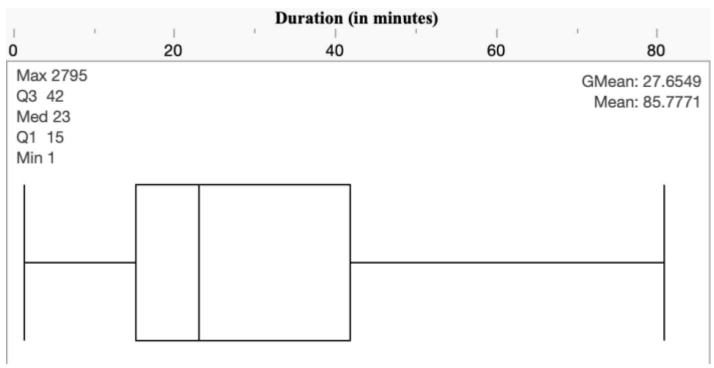


Figure 10: Survey Duration (in minutes) Box and Whisker Plot. ("JMP Statistical Discovery" 2024).

Demographic Results

The following results are derived from the first survey section covering demographics, professional background, and current position.

Table 1: Survey Demographic Distribution

Gender	
Female	32%
Male	68%
Non-Binary	0.6%

Race/Ethnicity	
Asian	1.2%
Black or African American	1.2%
Hispanic, Latino, Spanish Origin	2.3%
Some other race or ethnicity	3.5%
White	92%

Length in Field	
0-<1 years	1.7%
1-<3 years	8.1%
3-<5 years	3.5%
5-<10 years	10%
10-<15 years	19%
15+ years	58%

Age	
18-30	10%
30-45	35%
45-60	29%
60+	25%

Marital Status	
Single (Never Married)	16%
Married or Domestic Partnership	72%
Divorced	9.8%
Widowed	1.7%

Environmental Group Involvement	
Yes	42%
No	58%

Education	
High School Diploma or Equivalent	0.6%
Some College	1.2%
Associate Degree	0.6%
Bachelor’s Degree	56%
Master’s Degree	41%
Doctorate Degree	0.6%
Other	0.6%

Employment	
Employed or self-employed full-time (40+ hours/week)	81%
Employed or self-employed part-time (<40 hours/week)	11%
Unemployed (currently looking for work)	0.6%
Unemployed (not currently looking for work)	0.6%
Retired	7%

The gender of respondents (n=174) was unequal in distribution, with 68% male, 32% female, and 0.6% non-binary. Due to such a minute proportion of non-binary representation, this category is excluded in gender breakdowns in all analyses to prevent potential identification of the respondent. Comparing demographics to Georgia distributions, where the majority of respondents are located, the population is 48.8% male and 51.2% female, which further highlights the gender disparities in this survey’s responses ("Quick Facts: Georgia" 2024). The race of respondents (n=171) was overwhelmingly White at 92%; Hispanic, Latino, or Spanish Origin fell at 2.5%; Black and Asian American each at 1.2%, and those marked as “Some other race or ethnicity” as 3.5%. Georgia’s race and ethnicity distributions are White at 59%, Black or African American at 33.1%, Asian at 4.1%, and Hispanic, Latino, or Spanish Origin at 10.5% ("Quick Facts: Georgia" 2024). Age (n=153) skewed older, with only 10% between the ages of 18-30, 35% 30-45, 29% 45-60, and 25% 60 or older. The median age fell within the 45-60 age range. Georgia age distributions include adults aged 18-65 at 56.1% and those aged 65 and older at 15.1% ("Quick Facts: Georgia" 2024).

Most surveyed (n=174) hold a four-year degree or higher at 97.6%. Those having a high school diploma or less fell at 0.6%. Those marked as Other within education are excluded from analysis due to inaccurate non-adherence to the question instructions. Full- or part-time employment accounts for 92% of respondents (n=174), and 7% are retired and no longer actively working with GSI.

The distribution of disciplines that responded to the survey (n=174) is represented in Figure 11. Most respondents work in landscape architecture and landscape design, accounting for 65.2%. The next largest groups include engineers at 6.9%, stormwater management at 5.8%, planning at 4.6%, and construction at 4%. Those under 2% of survey respondents include community outreach, conservation, ecology, education, environmental science, and landscape management. Approximately 6.9% described themselves working in other disciplines, including development, regulation, government administration, golf course design, sales, and manufacturing.

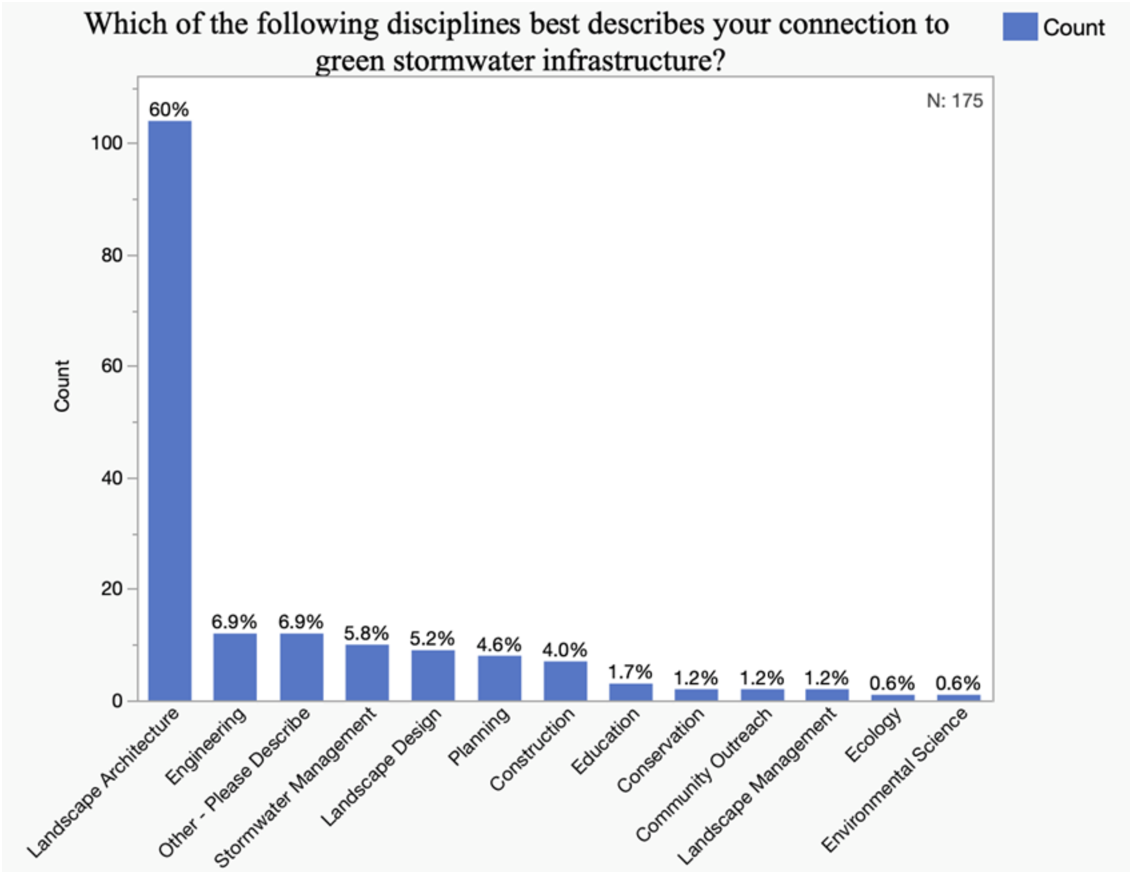


Figure 11: Survey Distribution of GSI-Related Disciplines. ("JMP Statistical Discovery" 2024).

Most respondents recorded many years of experience, with 58% having (n=173) worked in their field for 15 or more years. Job titles covered an extensive range of positions (n=137). Landscape architects accounted for 64 position titles, and because of this, the phrase was excluded from the job title word cloud to promote clarity in the prevalence of other job title words and phrases (see Figure 12). 31.58% of job titles were related to senior management, indicating leadership positions including “principal” (17), “owner” (14), “senior” (11), and “director” (7), as well as stemming variations of “manager” (13).

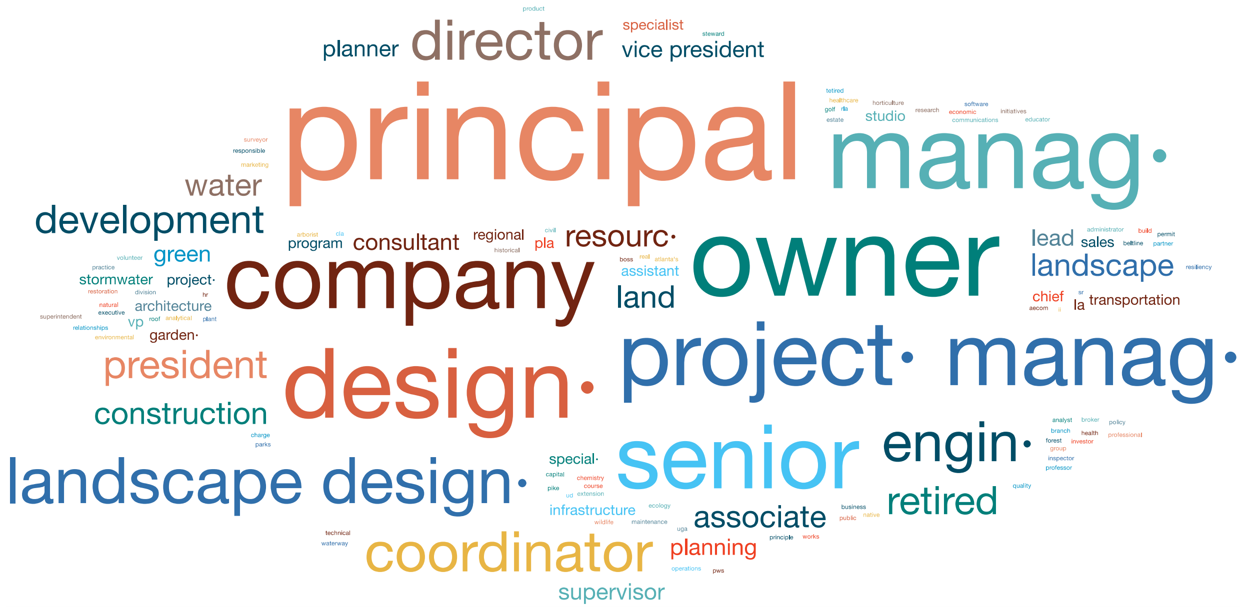


Figure 12: Job Title Word Cloud. ("JMP Statistical Discovery" 2024).

Respondent (n=163) roles and responsibilities trended towards activities earlier in the life cycle of GSI (see Figure 13). "Design" stems appear 82 times, followed by "management" stems 56 times. "Construction" stems, differentiated from "construction documentation" stems, appeared only 18 times in comparison.

Figure 13: Job Roles and Responsibilities Word Cloud. ("JMP Statistical Discovery" 2024).

Respondent’s (n=117) background experience covered various education, licenses, and exposures. Many highlighted their years of experience, while others listed a variety of certifications and professional associations such as AICP, ISA, ASLA, PLA, LEED, etc. Stems of “certifi·” (“certified,” “certification,” “certificate”) appeared 41 times, “licens·” (“license,” “licensed”) 22 times, and “registered” 15 times, as seen in Figure 14. “Year·” (“year,” “years”) of experience was recorded 13 times with a range of one and a half to over 40 years of design experience.

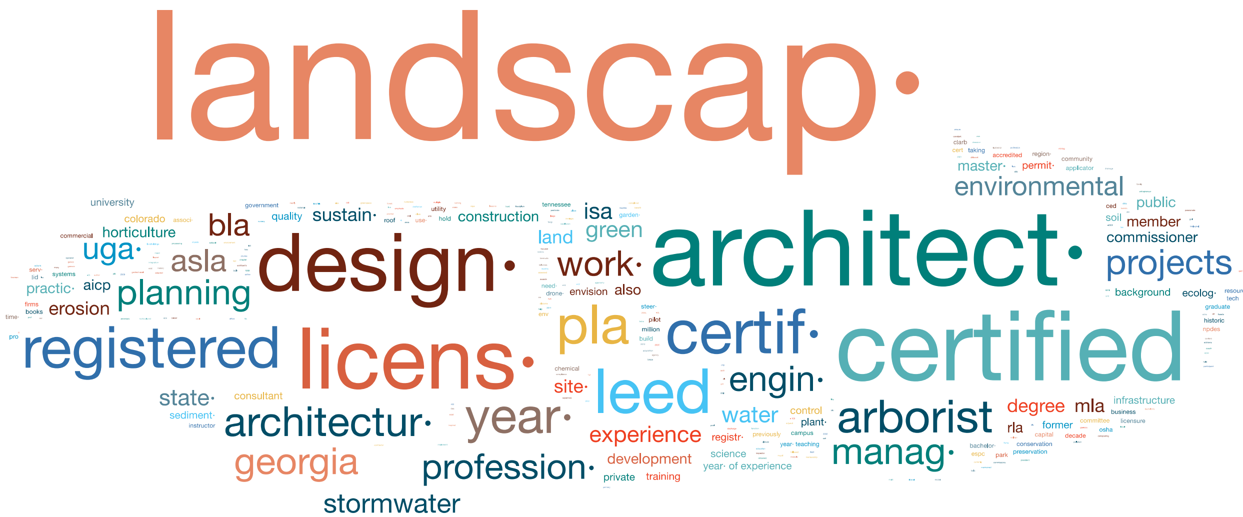


Figure 14: Background Experience Word Cloud. ("JMP Statistical Discovery" 2024).

Ninety-four percent of respondents (n=150) considered their work related to the environment, conservation issues, or water management, while 6% did not. Figure 15 depicts the breakdown of those who did and did not consider their work related to the environment, conservation issues, or water management. A chi-square test showed that this model was not statistically significant when comparing disciplines to a yes or no relational designation.

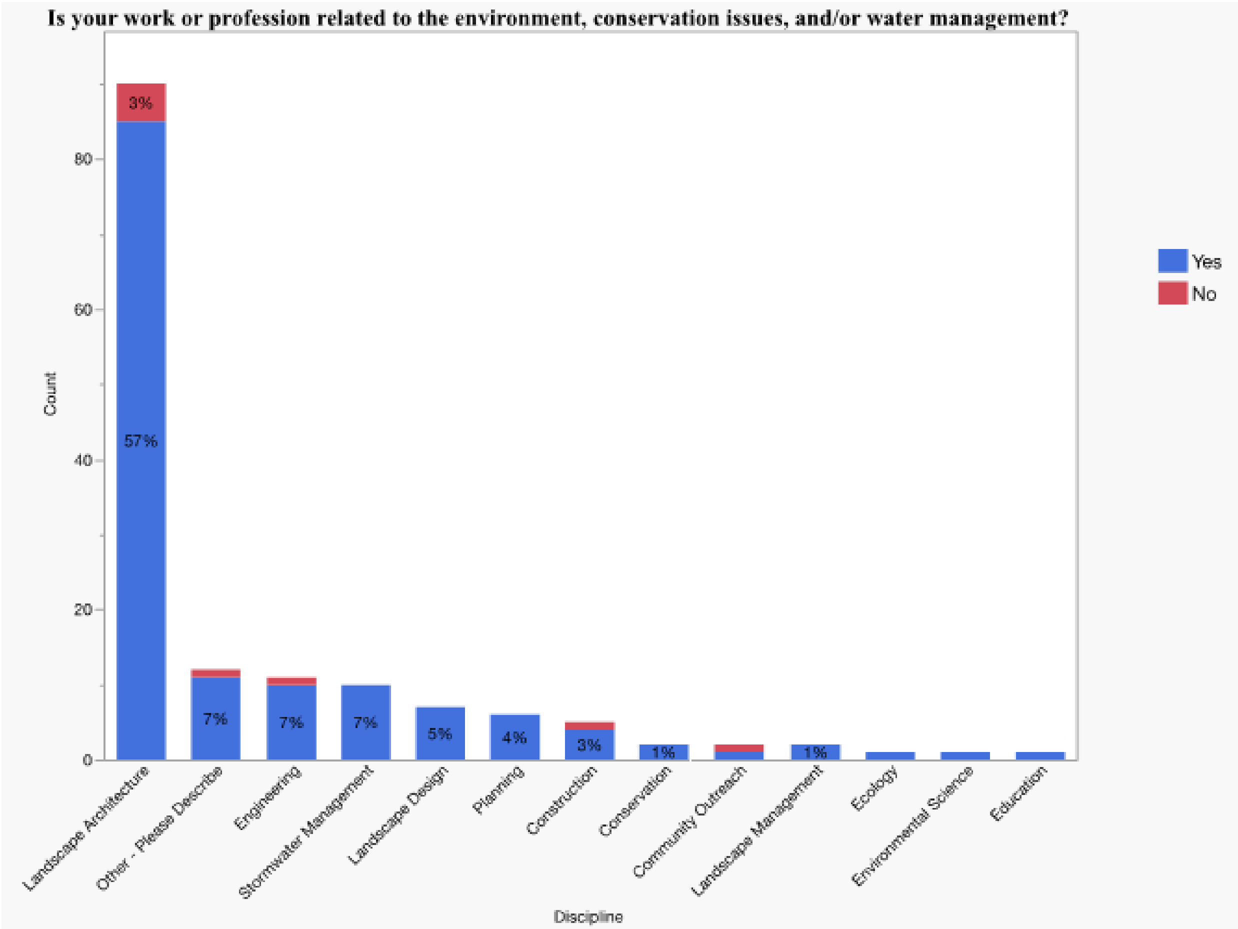


Figure 15: Relationship to Environment, Conservation Issues, or Water Management by Discipline. ("JMP Statistical Discovery" 2024).

Respondents' (n=151) work is based nationwide, as shown in Figure 16. Exclusions are due to nonresponse or to non-US respondents who did not have a US zip code. Most of those surveyed have work based out of the Southeast, with the highest density in the Atlanta-Athens metropolitan corridor. Other cities with higher densities of respondents include Charleston, Asheville, Chattanooga, Albuquerque, Denver, New York, and Washington DC.

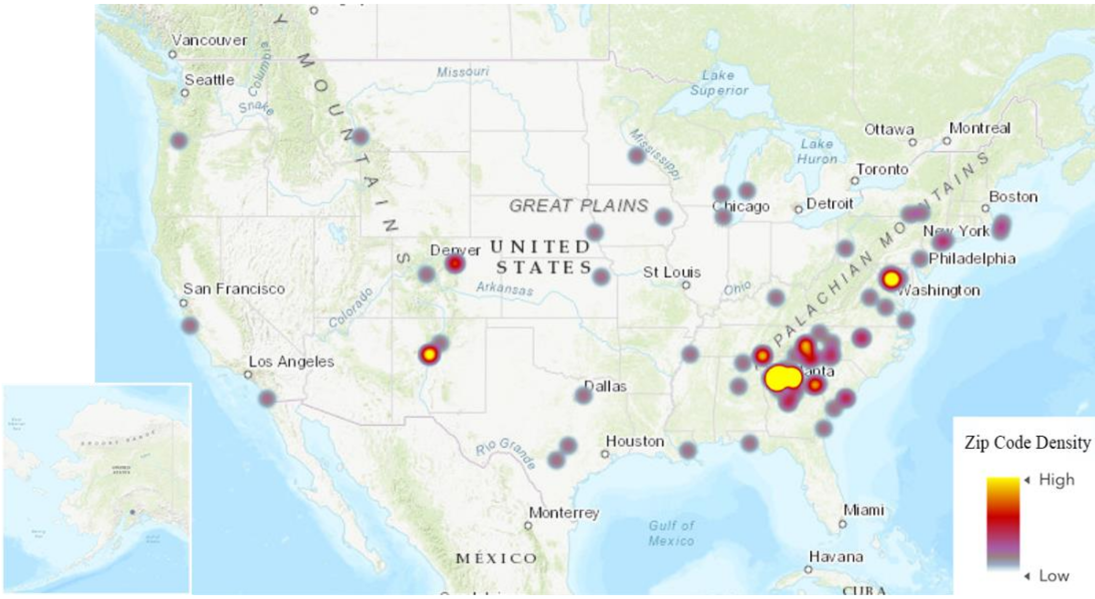


Figure 16: US Survey Respondent Practice Location Density Map. ("Create and use a heat map" 2024). ESRI accessed on March 12, 2024.

Conceptual Understanding

The following results are developed from the second section of the survey, which sought to present the respondents' understanding of GSI and their relationship to it.

Because so many variations and terms relate to GSI, respondents (n=146) were asked to define GSI. This was before they were presented with the EPA's definition of GSI, "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate [sic] stormwater and reduce flows to sewer systems or to surface waters," which was used for subsequent questions throughout the survey (*Water Infrastructure Improvement Act* 2019). Respondents (n=146) used the term "stormwater" 132 times either on its own or concerning management or infrastructure, seen in Figure 17. Stems of “natur·” such as “natural,” “naturally,” and “nature” and phrases including “processes” and “systems” appear 62 times. Other high-frequency terms include variations of “runoff,” “infiltration,” and “system.”

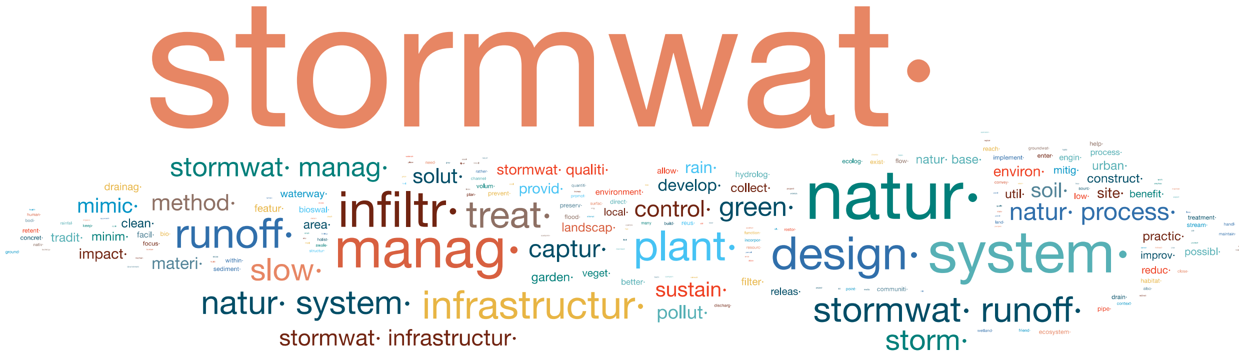


Figure 17: Respondent GSI Definition Word Cloud. ("JMP Statistical Discovery" 2024).

The purposes of GSI were predefined as capturing excess rainwater, reducing stormwater runoff, improving water quality, community resource, source of nature, source of beauty, reducing infrastructure costs, providing wildlife habitat, and others, as seen in Figure 18. Other purposes defined by respondents included improving environmental equity. The top indicated purposes (n=162) of GSI were reducing stormwater runoff and improving water quality, with 16% and 15% of the total purpose votes.

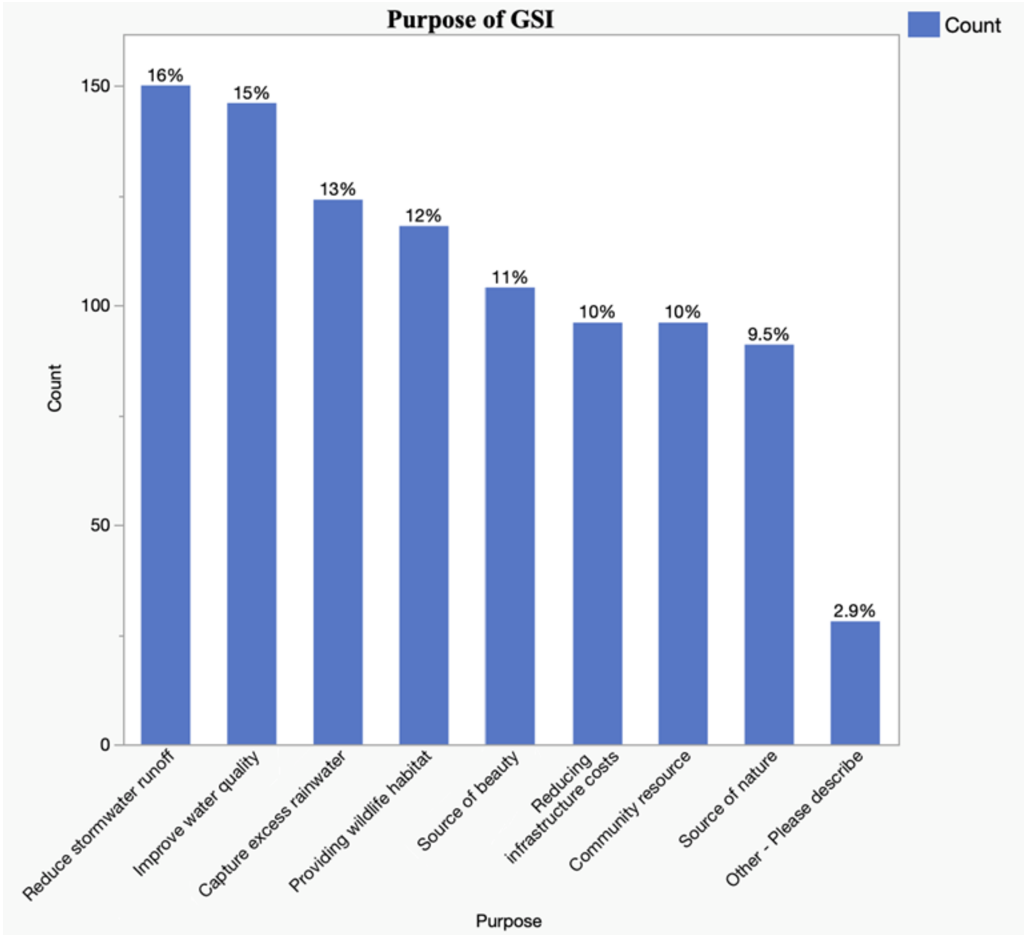


Figure 18: Purpose of GSI. ("JMP Statistical Discovery" 2024).

Respondents (n=137) ranked their chosen purposes from most important (1) to least important (9). Figure 19 shows the proportion of each purpose ranked with what level of significance. The model presents the purposes from the lowest average rankings to the highest. The most important purposes of GSI by ranking were capturing excess rainwater, reducing stormwater runoff, and improving water quality. Reducing infrastructure costs and providing wildlife habitat were the next most important, followed by GSI as a community resource, source of nature, and source of beauty.

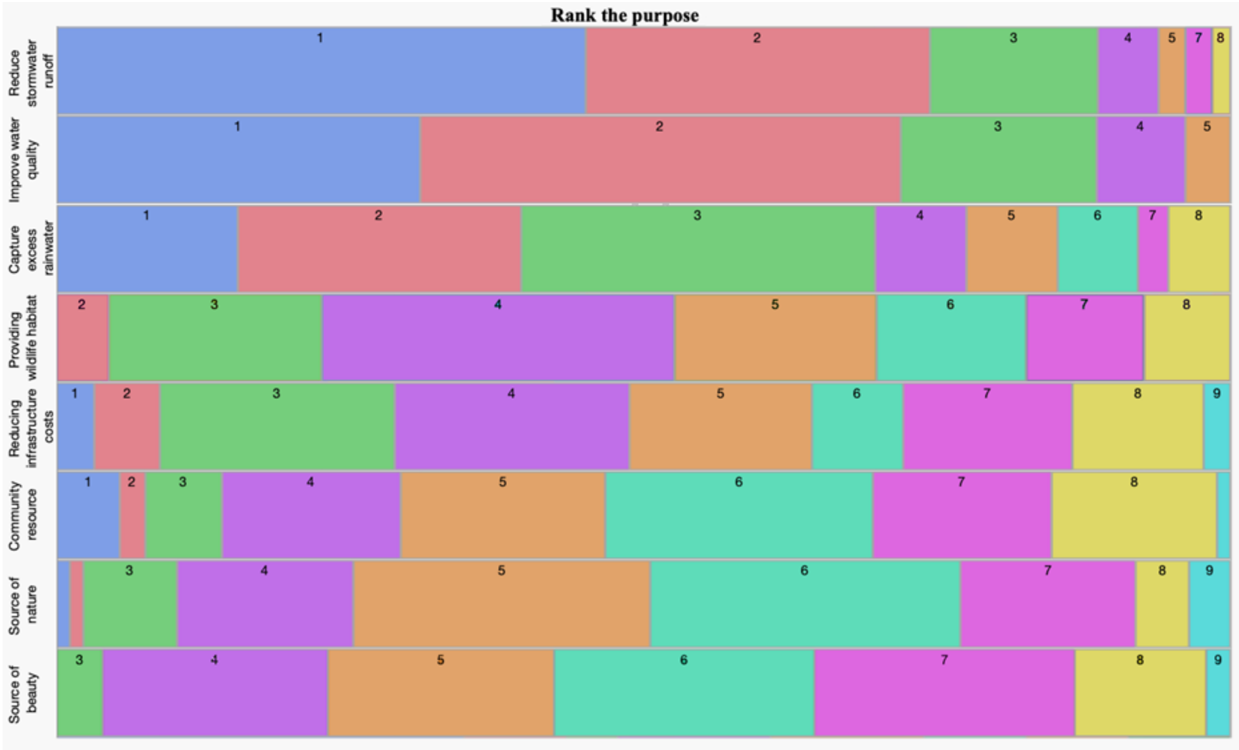


Figure 19: Ranked Purposes of GSI. ("JMP Statistical Discovery" 2024). The numbers represent rank order frequency by category.

The following table (Table 2) displays the mean rankings for each GSI purpose. The lower the mean ranking value, the higher the importance of that purpose.

Table 2: Mean Rankings of GSI Purposes

	Reduce stormwater runoff	Improve water quality	Capture excess rainwater	Providing wildlife habitat	Reducing infrastructure costs	Community resource	Source of nature	Source of beauty
Mean	2.07	2.11	3.25	4.74	4.89	5.43	5.44	5.81

The model shown in Figure 20 shows the purposes of GSI as ranked by the different disciplines. All disciplines were included in the model calculations; however, the graph excludes disciplines with fewer than five respondents for clarity. A chi-square test showed that this model is statistically significant ($p<0.0001$). Capturing excess rainwater, reducing stormwater runoff, and improving water quality were often indicated by all disciplines as the purpose of GSI.

However, the model was unstable due to a lack of respondents. A significant association between landscape architects, landscape designers, and engineers was indicated with GSI functioning as a source of beauty (p=0.0176, p=0.0267, and p=0.0402, respectively).

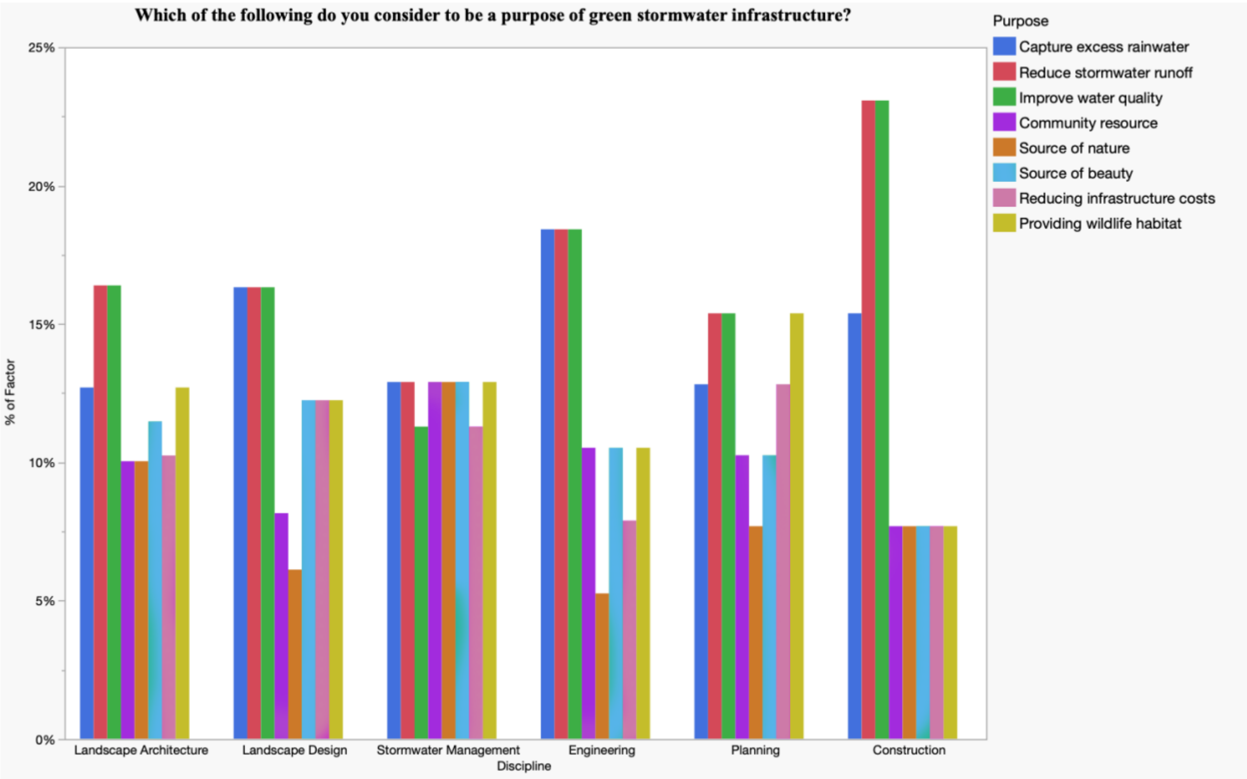


Figure 20: Purpose of GSI by Discipline. ("JMP Statistical Discovery" 2024).

When presented with a list of elements that impact the long-term viability of GSI, respondents were asked to evaluate maintenance (n=160), daily operations (n=157), design (n=160), aesthetics (n=159), ecological function (n=160), maintenance staff education (n=159), design team education (n=158), community education (n=159), and community outreach (n=157) using a Likert scale rating. A (1) rating indicated the element was least necessary, while a (5) rating was most important. All Likert scale questions included a "Not Applicable" box. The highest-rated factors were maintenance, design team education, and maintenance staff education based on mean rating scores of 4.63, 4.56, and 4.52, respectively (see Table 3). A logistic regression was not significant when comparing the Likert ratings between disciplines.

Table 3: Long-Term Viability Elements Mean Likert Rating

	Maintenance	Design Team Education	Maintenance Staff Education	Design	Ecological Function	Community Education	Community Outreach	Daily Operations	Aesthetics
Mean	4.63	4.56	4.52	4.51	4.39	3.94	3.85	3.71	3.59

The overwhelming majority of respondents (n=158) are familiar with the Clean Water Act at 96%, with 4.4% indicating a lack of familiarity (see Figure 21). Landscape architects, landscape designers, and engineers were the only disciplines to note any unfamiliarity with the Clean Water Act. A chi-square test showed that this model found no statistical significance.

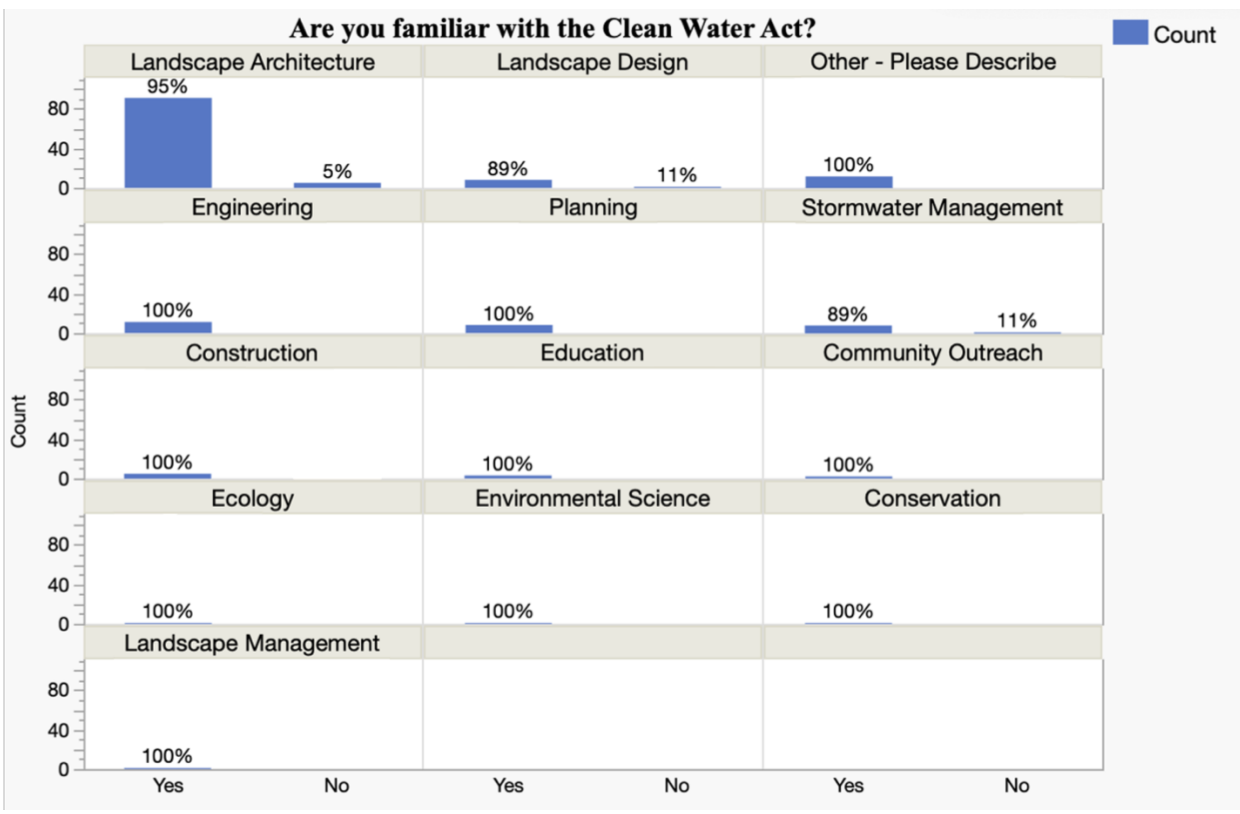


Figure 21: Familiarity of the Clean Water Act by Discipline ("JMP Statistical Discovery" 2024).

GSI is primarily viewed (n=156) as an effective stormwater management tool (see Figure 22). Rating options included “definitely not,” “probably not,” “might or might not,” “probably yes,” and “definitely yes.” No “definitely not” column indicates that no respondents chose that option. A logistic regression was not significant when comparing the Likert ratings between disciplines.

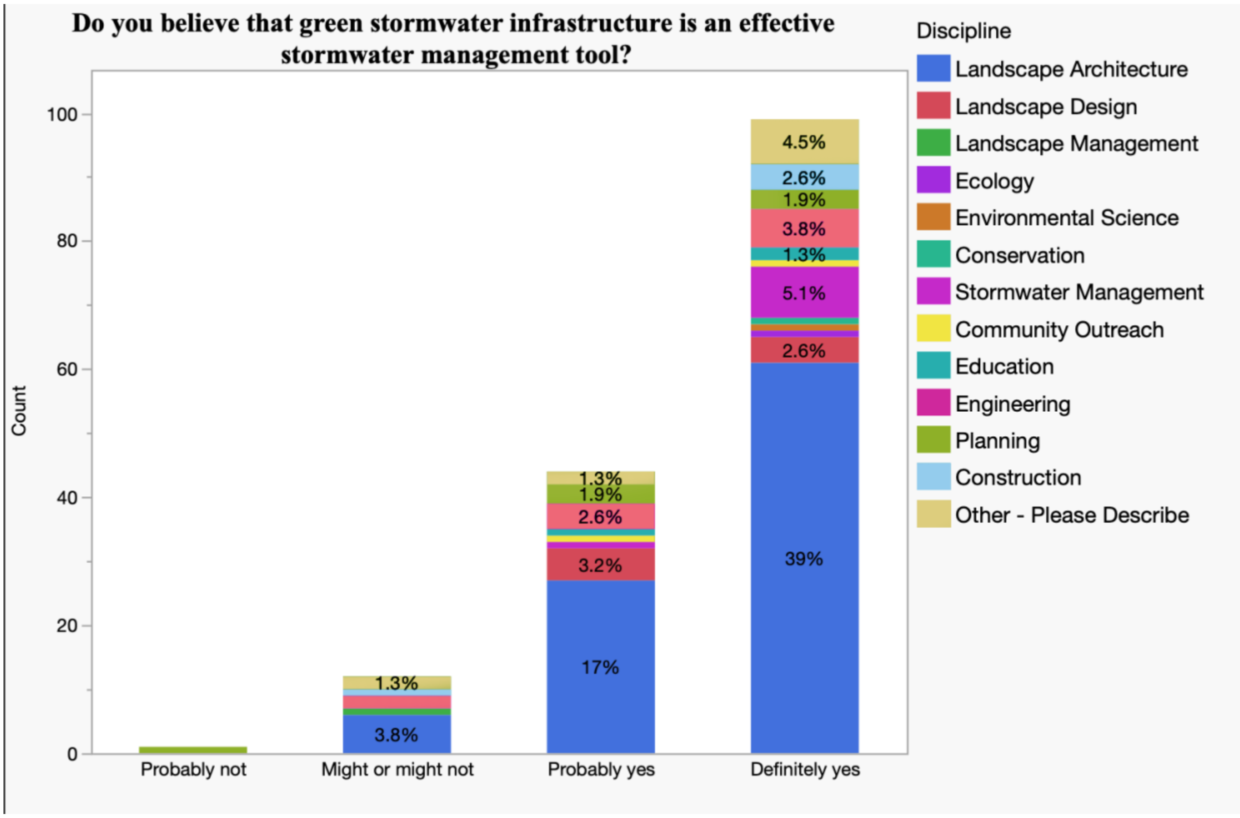


Figure 22: GSI as Effective Stormwater Management Tool by Discipline. ("JMP Statistical Discovery" 2024).

When asked to explain respondent rating (n=108), a sentiment analysis revealed a net positive score of 38.6 on a scale of -100 to 100 (see Table 4 and Figure 23).

Table 4: GSI as Effective Stormwater Management Tool Sentiment Analysis ("JMP Statistical Discovery" 2024).

	N	Mean Score
All Scored Documents	21	38.6
Net Positive Documents	16	66.3
Net Negative Documents	5	-50.0
No Sentiment Documents	154	0.0

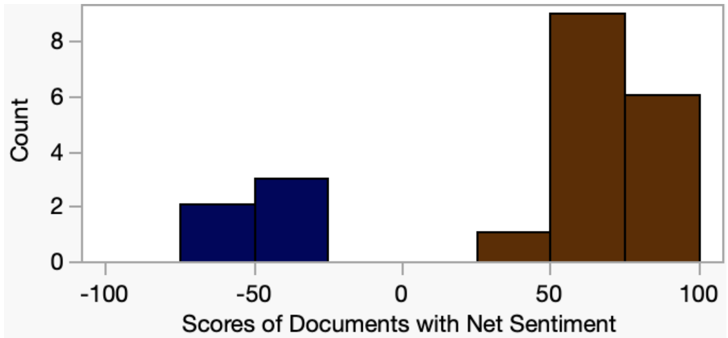


Figure 23: GSI as Effective Stormwater Management Tool Sentiment Analysis. ("JMP Statistical Discovery" 2024).

GSI is viewed (n=156) as improving water quality (see Figure 24). Rating options included "definitely not," "probably not," "might or might not," "probably yes," and "definitely yes." The lack of a "definitely not" and "probably not" column indicates that no respondents chose that option. All answers were affirmative or neutral in the belief that GSI improves water quality. A logistic regression was not significant when comparing the Likert ratings between disciplines. When asked to explain respondent scoring (n=108), a sentiment analysis revealed a net positive score of 26.3 on a scale of -100 to 100 (see Table 4). A sentiment analysis provided no new insights.

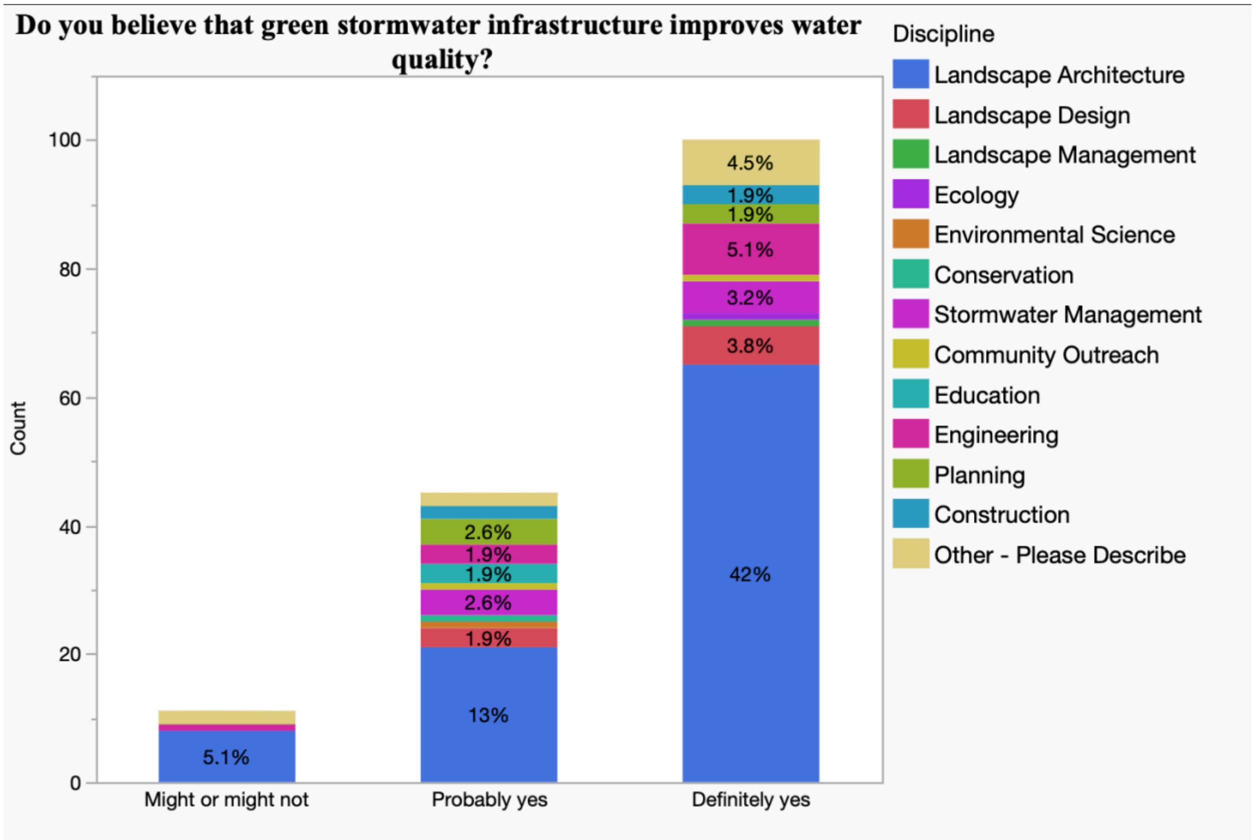


Figure 24: GSI Impact on Water Quality by Discipline. ("JMP Statistical Discovery" 2024).

Eighty percent of respondents (n=132) are aware of design guidance for GSI. Of those aware of design guidance, 94% of practitioners (n=105) have access to guidance, whereas 5.7% do not (see Figure 25). 62% of practitioners (n=127) with access to design guidance rely on local and regional guidance (see Figure 26). 22% indicated access to other types of guidance. When reviewing the open-ended responses to what kinds of different design guidance practitioners utilized, many indicated a combination of guidance types or listed specific organization guidance tools. A chi-square test showed that the models for awareness of design guidance by discipline, access to design guidance by discipline, and type of design guidance by discipline found no statistical significance.

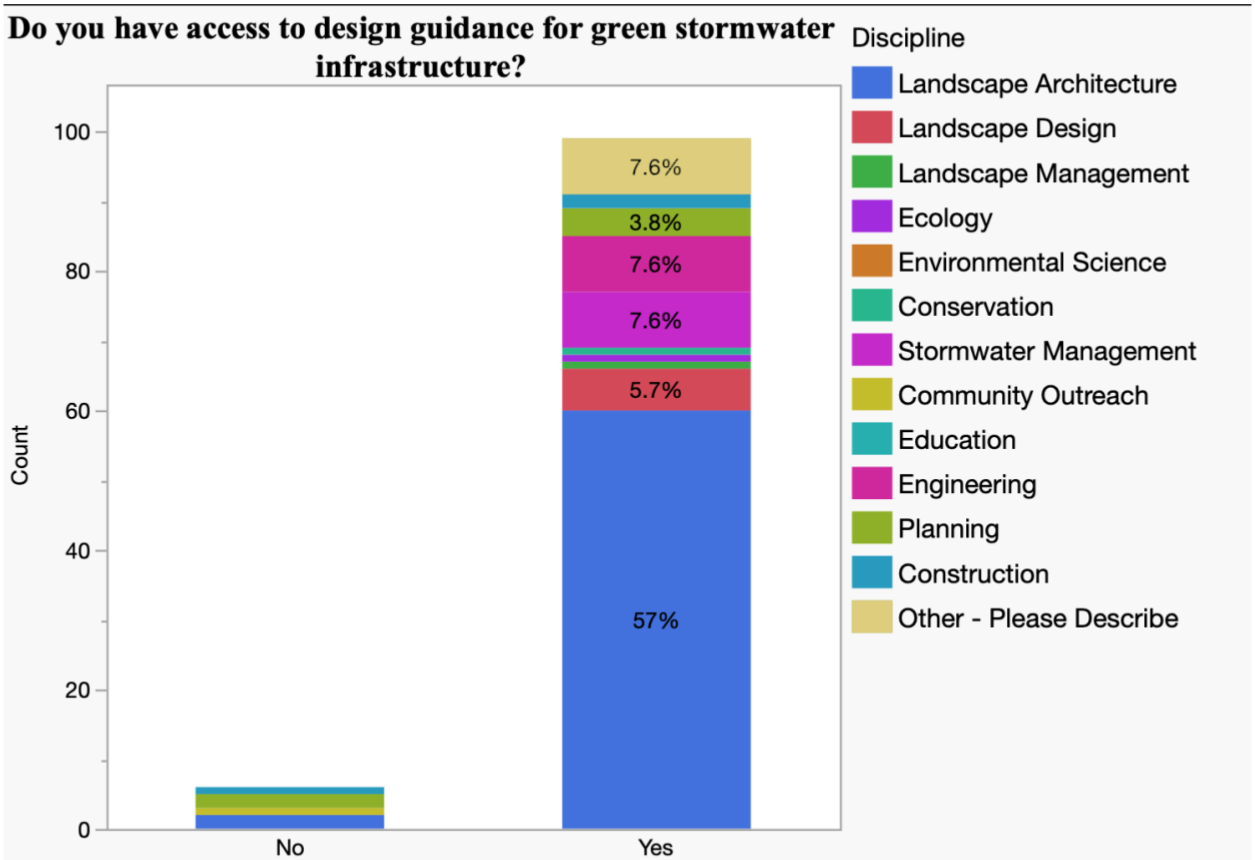


Figure 25: Access to Design Guidance by Discipline. ("JMP Statistical Discovery" 2024).

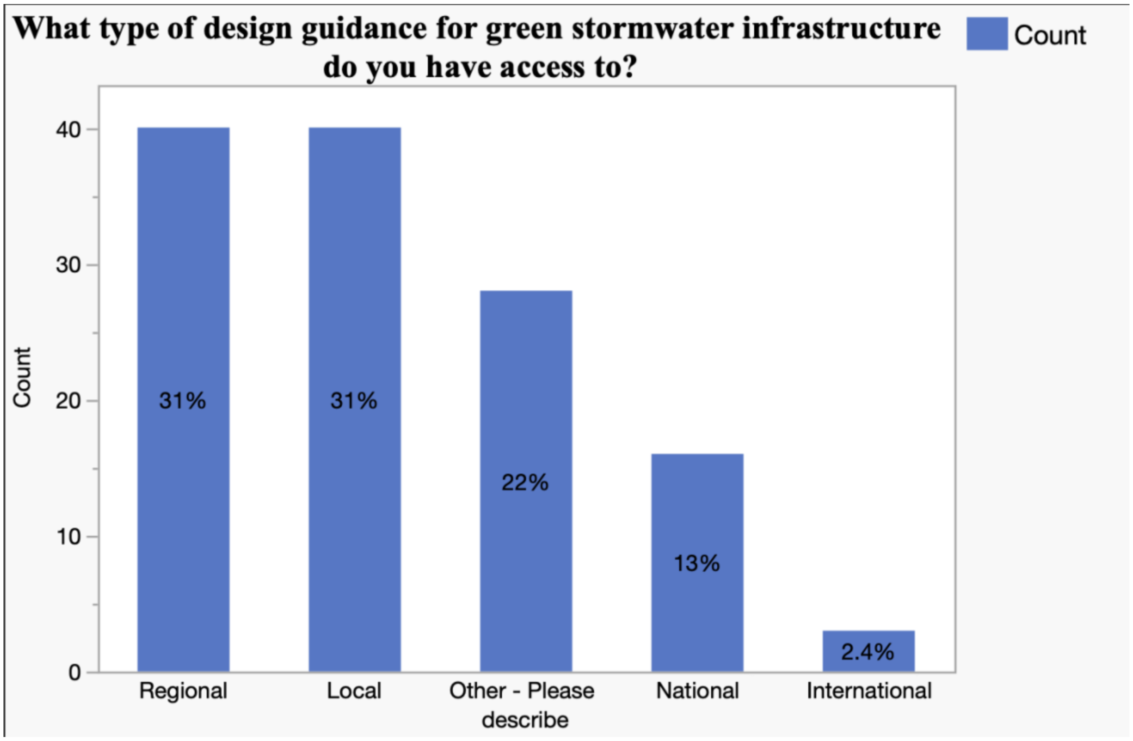


Figure 26: Type of Design Guidance. ("JMP Statistical Discovery" 2024).

Procedural Experience

The following results address section three of the survey, which explored system experience and procedures involved with their implementation throughout the systems' life cycle.

The most frequently worked with types of GSI (n=148) are bioswales, rain gardens, and permeable pavements, each accounting for approximately 17% of all GSI types worked with and 51% of all total types (see Figure 27). Biofiltration ponds follow this at 14%, stormwater wetlands at 9.7%, cisterns at 9.1%, vegetated roofs at 8.3%, and sand filters at 4.8%. Other types of GSI worked with include bioslopes, tree wells, greenbelts, linear parks, and level spreaders. A chi-square test showed that this model found no statistical significance.

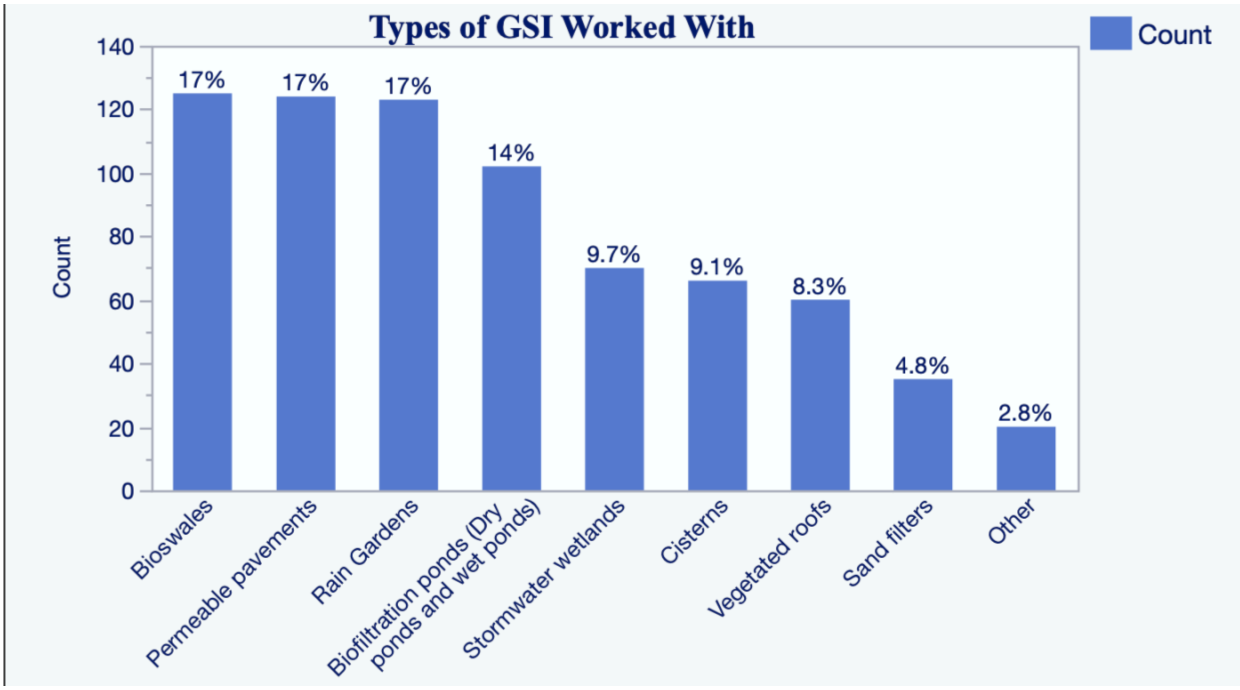


Figure 27: Types of GSI Worked With. ("JMP Statistical Discovery" 2024).

Most respondents (n=148) are involved with life phases before ground is broken at 59% via design and planning (see Figure 28). Construction and design implementation accounts for 24% of practitioner involvement, while intermittent and ongoing O&M accounts for 17.1%. Respondent information entered in the "Other" free response was either recoded to be included in the appropriate life cycle stage or omitted due to inaccurate non-adherence to the question instructions. A chi-square test showed that this model found no statistical significance. This coincides with the time practitioners (n=142) work with GSI systems (see Figure 29). The most common length of time, held by 41% of people, is only a few months of interaction with the system. Only 13.7% of practitioners work with a system for over half its life. A chi-square test showed that this model is statistically insignificant.

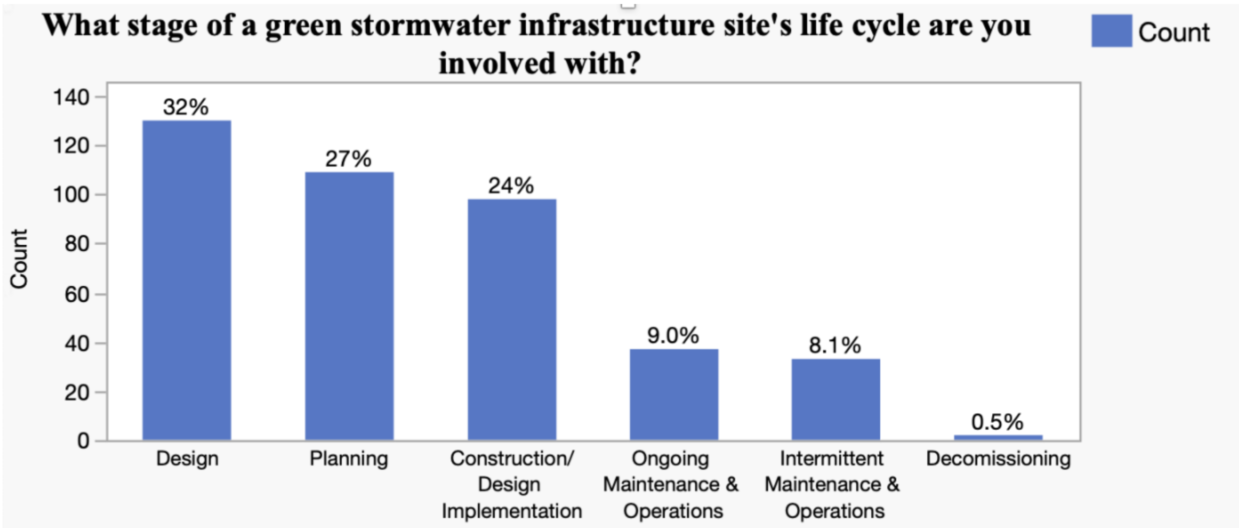


Figure 28: GSI Life Cycle Stage Involvement. ("JMP Statistical Discovery" 2024).

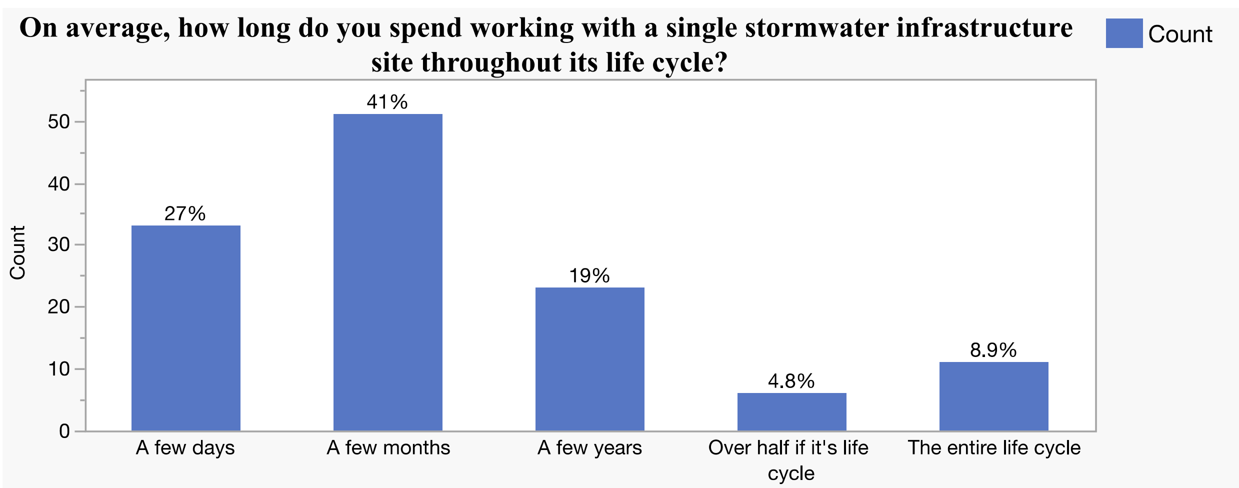


Figure 29: Amount of Time Worked with an Individual System. ("JMP Statistical Discovery" 2024).

Most practitioners (n=146) only work with 2-5 systems at a given time at 44%. Ten to 20 sites and more than 20 sites comprise 6.2% of practitioners each (see Figure 30). A chi-square test showed that this model is statistically significant (p=0.0002), indicating a statistical association between discipline and the number of GSI sites worked on.

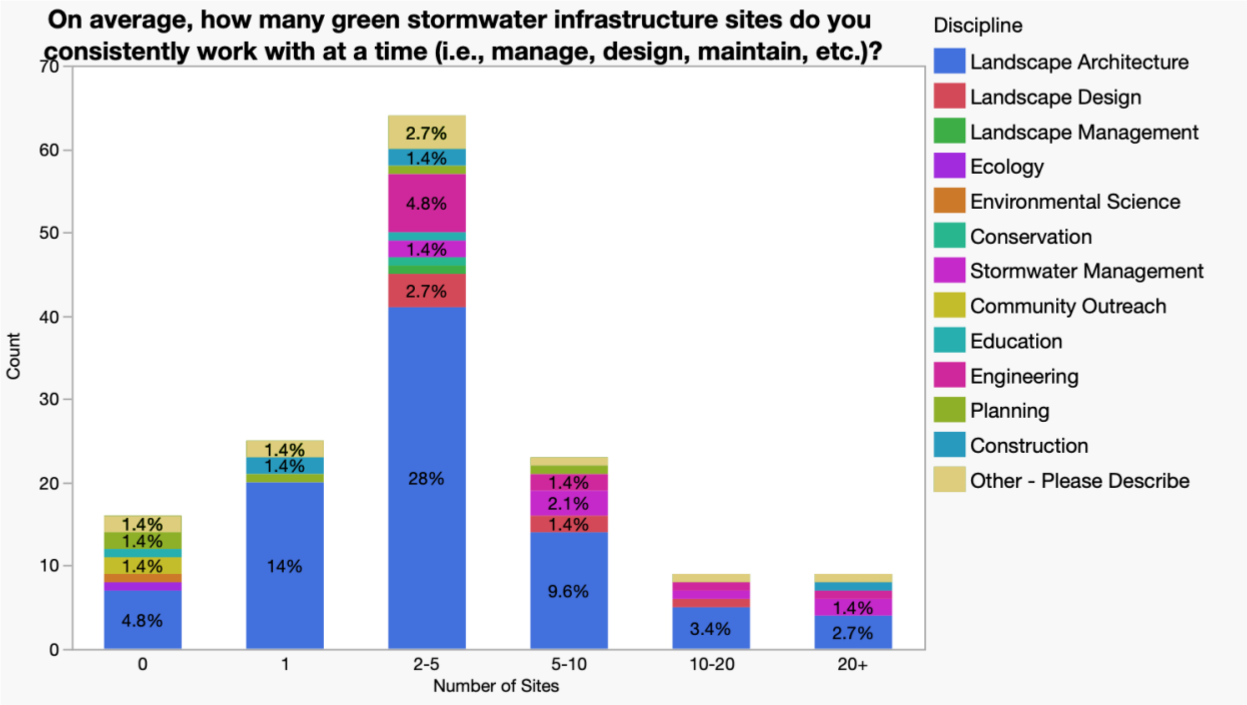


Figure 30: Number of Sites Worked with at a Time. ("JMP Statistical Discovery" 2024).

Respondents (n=145) work on the smaller scale of GSI sites (see Figure 31). 67% of sites fall under 1 acre in size—large sites of 50 acres and more account for 10.2% of projects.

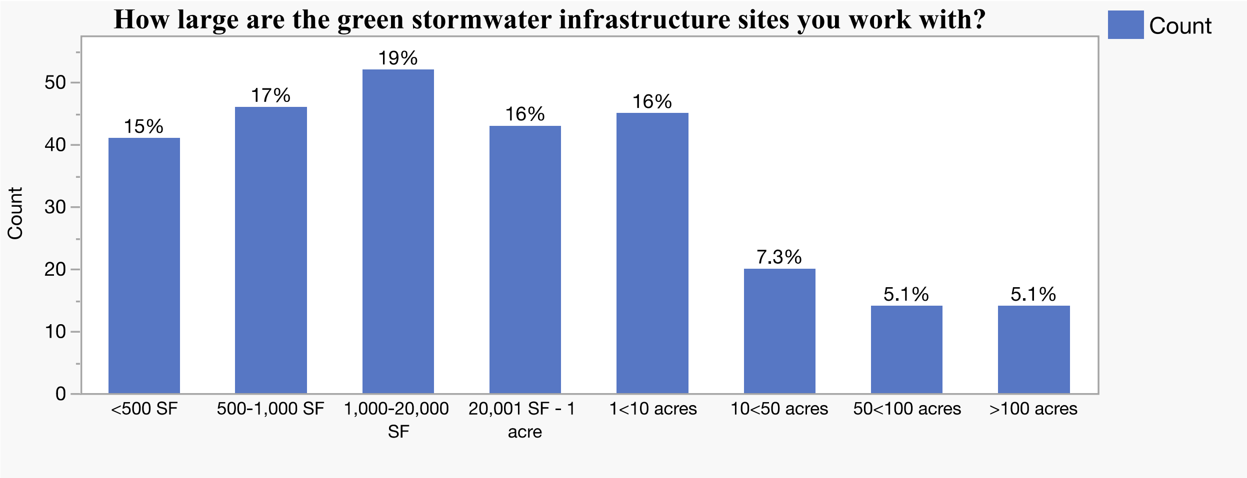


Figure 31: Site Size. ("JMP Statistical Discovery" 2024).

After asking about the stage of life and types of projects worked on, respondents (n=148) were asked if they believed their jobs or roles were adequately considered during the design process (see Figure 32). Just over half of practitioners believed their job or role was adequately considered in the design process, with 51% choosing “probably yes” or “definitely yes.” A third of respondents were neutral, and 16.1% responded negatively with “probably not” and “definitely not.” Community outreach and environmental science each only indicated negative sentiments. Landscape architects, designers, and engineers had the highest frequency of responding to the open-ended why or why not question, and the theme of lack of disciplinary cooperation and communication was recurring. A logistic regression was significant when comparing the Likert ratings between disciplines (p=0.0047). A word cloud and sentiment analysis did not provide new insights due to response intricacies.

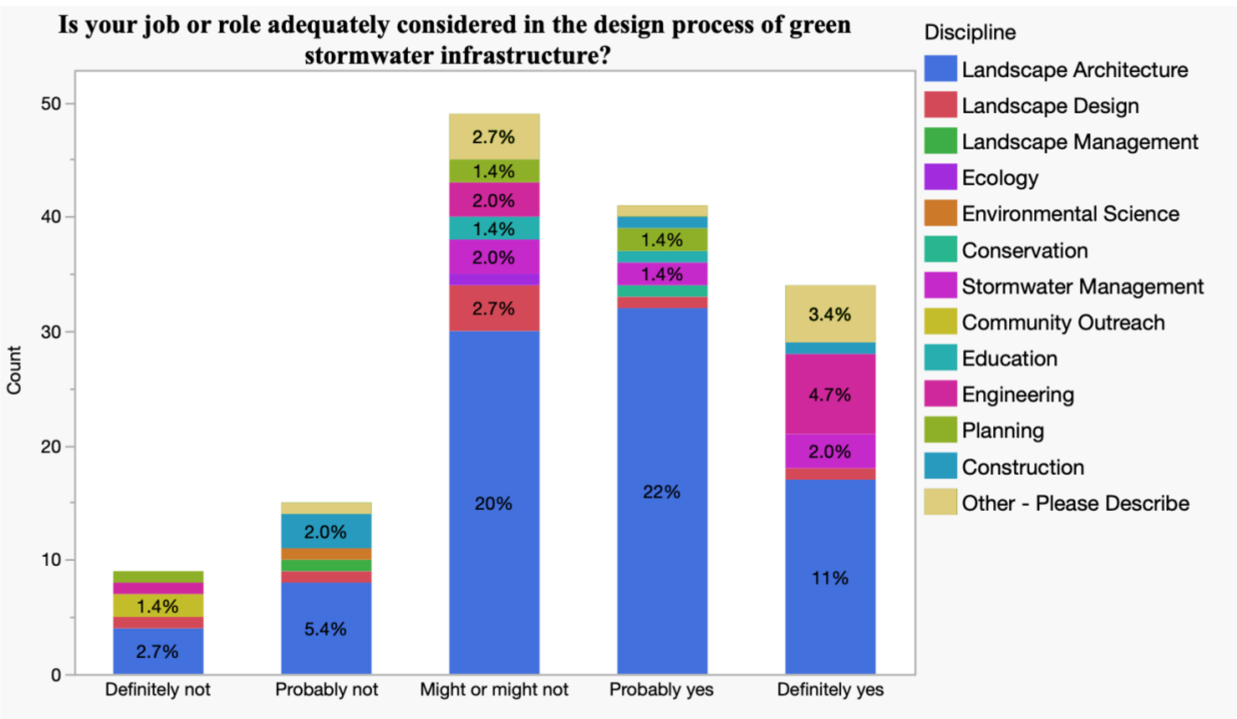


Figure 32: Job Consideration within the Design Process by Discipline. ("JMP Statistical Discovery" 2024).

Respondents were split on whether they participated in post-installation monitoring (n=118) or evaluation (n=118) (see Figure 33). Just shy of an equal divide, 48% of practitioners monitor their GSI projects, and 54% evaluate their systems. A chi-square test showed that the models for monitoring and evaluation found no statistical significance compared to discipline, although monitoring is almost significant. Distributions of those who do monitor (n=69) and evaluate (n=62) have similar distributions in the frequency of each activity (see Figure 34). No daily monitoring was indicated, and only 1.6% of evaluation activities occurred daily. Most monitoring and evaluation activities occurred yearly at 36% and 34%, respectively. Monitoring and evaluation both had quarterly activities at a 29% frequency. A chi-square test showed that the model for monitoring frequency was not statistically significant, whereas the model for evaluation frequency was statistically significant (p=0.0348). A significant association between daily, monthly, yearly, and every other year (p<0.0001, p<0.0001, p=0.0017, and p<0.0001, respectively) was indicated with engineers (p=0.0157).

The most frequently monitored elements (n=62) include state of design integrity at 20%, plan success/failure at 19%, and O&M issues at 20%. Water flow followed at 17% while water quality (8.1%), recreational usage (5.7%), art/educational signage condition (5.7%), and other (3.9%) trailed behind. Other monitored elements include community perception and acceptance as well as wildlife support. The most frequently evaluated elements (n=63) followed in distribution with state of design integrity, plan success/failure, and O&M issues, all at 20%. Water flow followed at 17% while water quality (9.4%), recreational usage (5.7%), art/educational signage condition (4.5%), and other (3%) trailed behind. Other evaluation elements include construction compliance with design. A chi-square test showed no statistical significance in the models for monitoring and evaluation elements concerning discipline.

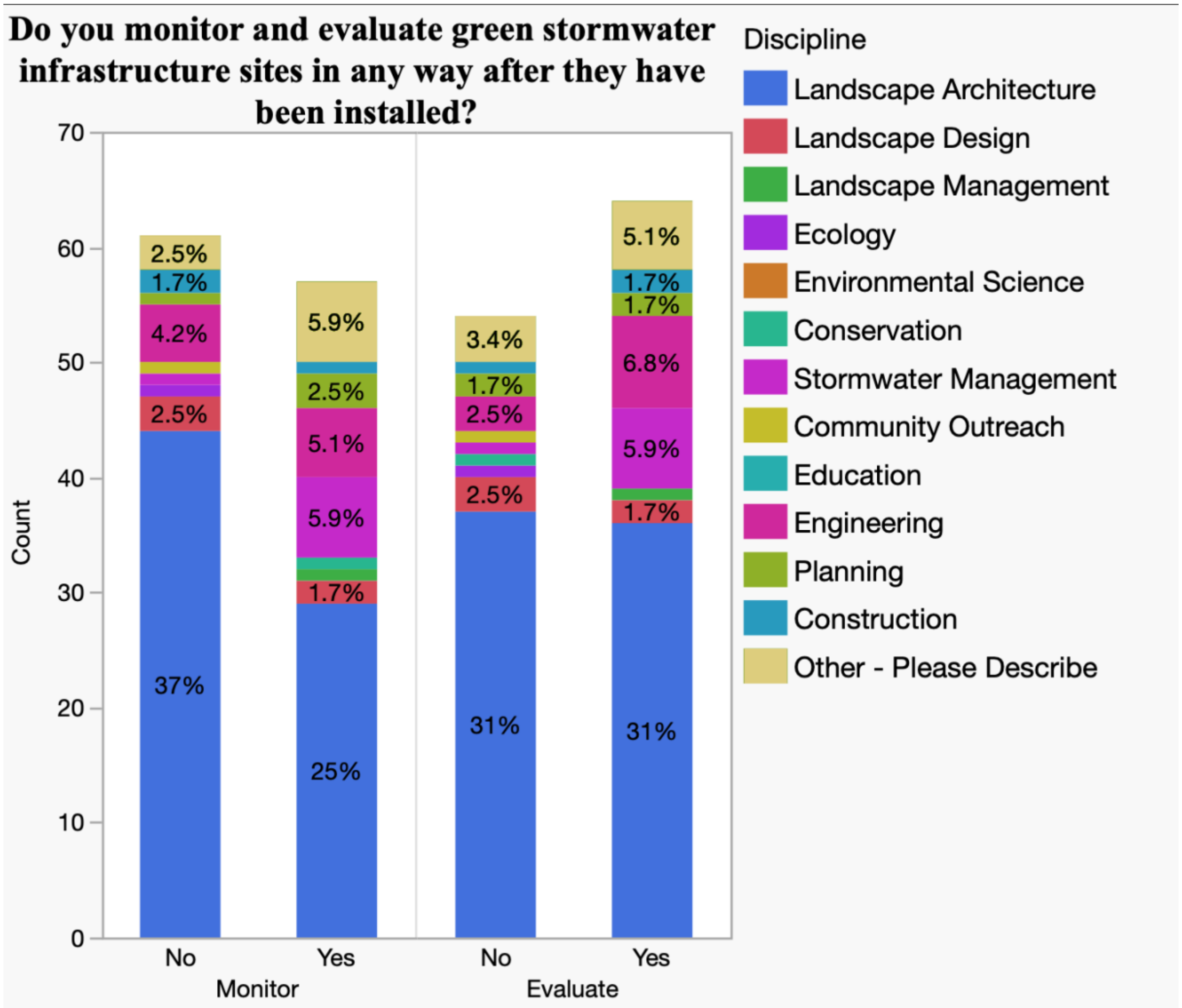


Figure 33: Monitoring and Evaluation of GSI by Discipline. ("JMP Statistical Discovery" 2024).

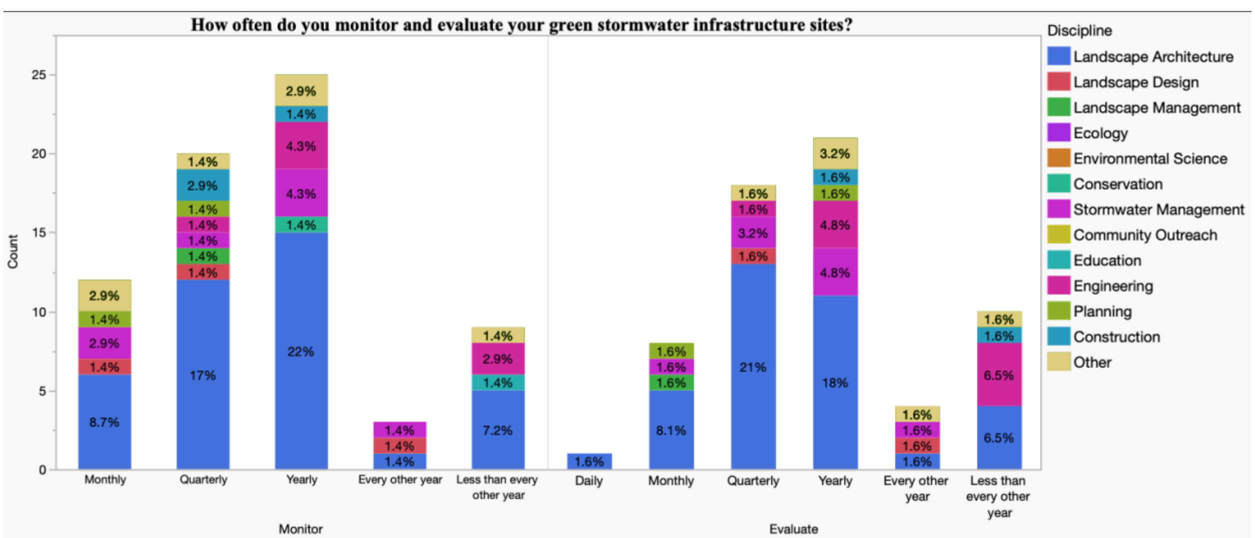


Figure 34: Monitoring and Evaluation Frequency of GSI by Discipline. ("JMP Statistical Discovery" 2024).

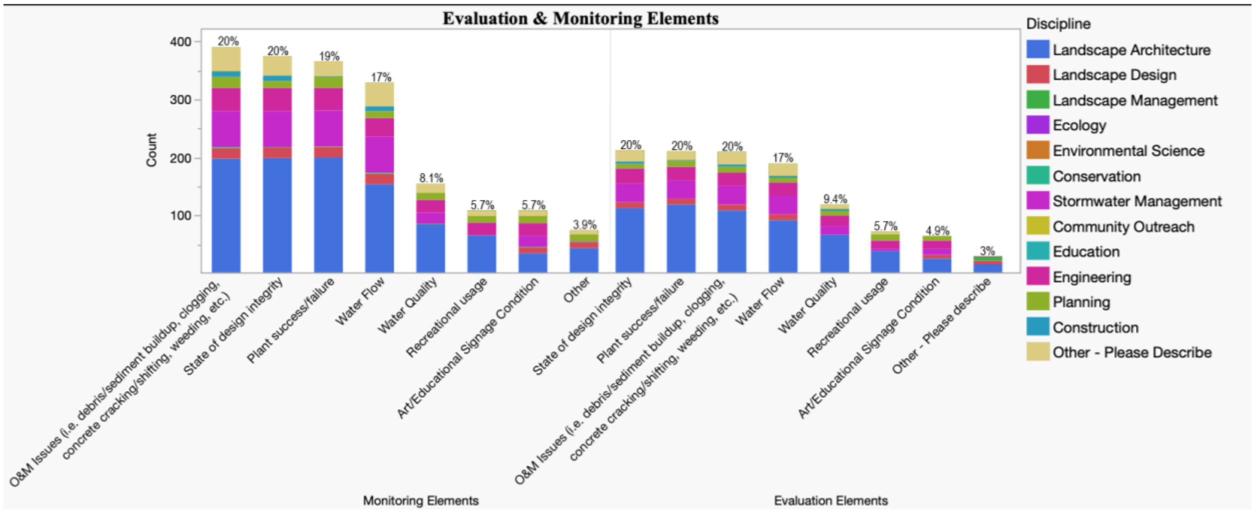


Figure 35: Monitoring and Evaluation Elements of GSI by Discipline. ("JMP Statistical Discovery" 2024).

According to respondents (n=116), general maintenance companies perform maintenance activities most of the time at 37%, while specialty green infrastructure accounts for the smallest portion of maintainers at only 7.9% (see Figure 36). Community members are relied upon 15% of the time, while maintenance is forgone entirely 14% of the time. Other maintenance providers comprise 27%, including government staff and private owners. Because the “other” category comprised such a large percentage and was comprised primarily of those two categories, it is evident that there were issues with the design of this survey question. This question may not accurately represent the experiences of the survey population due to the omittance of relevant options.

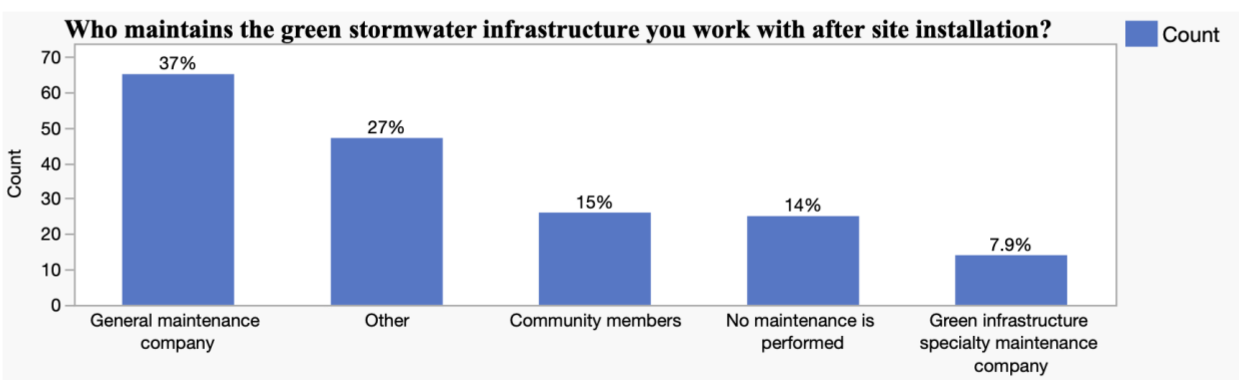


Figure 36: Who Maintains GSI. ("JMP Statistical Discovery" 2024).

O&M plans are only incorporated (n=115) into a project 52% of the time. Less than half (46%) of all practitioners (n=69) have integrated O&M plans before construction (see Figure 37). 35% of plans are initiated only once maintenance needs have already begun. While this question included an “Other” free response option, it was omitted from the analysis because these answers only indicated a lack of knowledge of when plans were incorporated. 67% of all O&M plans are never evaluated based on site needs (n=111).

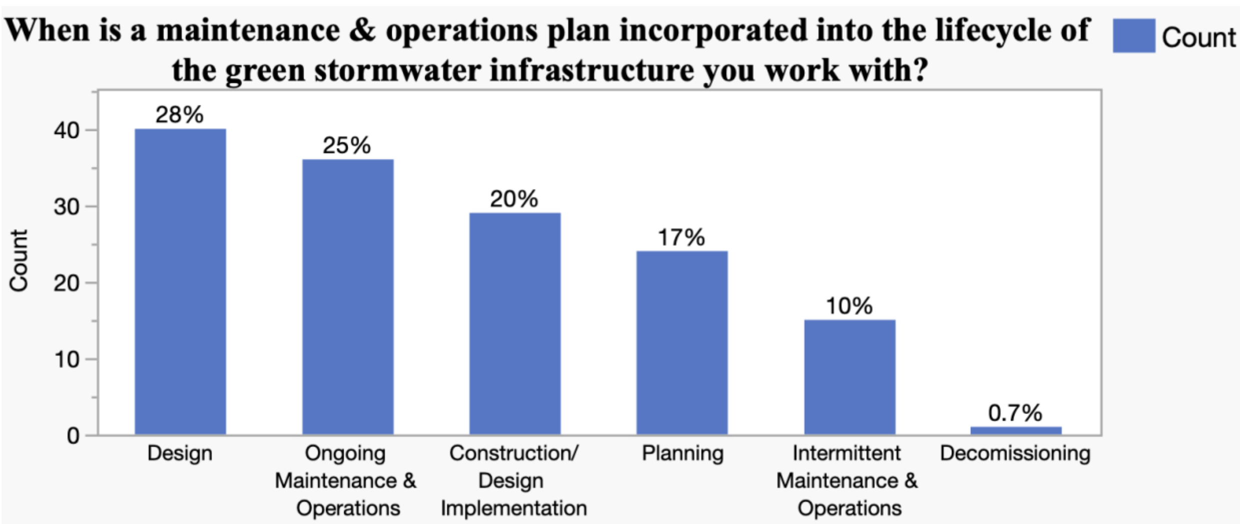


Figure 37: O&M Plan Lifecycle Integration. ("JMP Statistical Discovery" 2024).

Community education and outreach are incorporated into the life cycle of GSI 48% of the time (n=114). Of respondents (n=68) who have worked with community education and outreach plans, it has been integrated into the design and planning stages of implementation 50% of the time (see Figure 38). 22% of community engagement happens during construction and design implementation, and 18% occurs during maintenance activities. Other community education and outreach plan methods include regularly ongoing meetings or communications set up by municipalities or in response to community complaints about a project. Community education and outreach plans are evaluated (n=112) according to site needs only 20% of the time.

Aspects of O&M and community education and outreach plans needing improvement were not addressed due to software malfunctioning with the data.

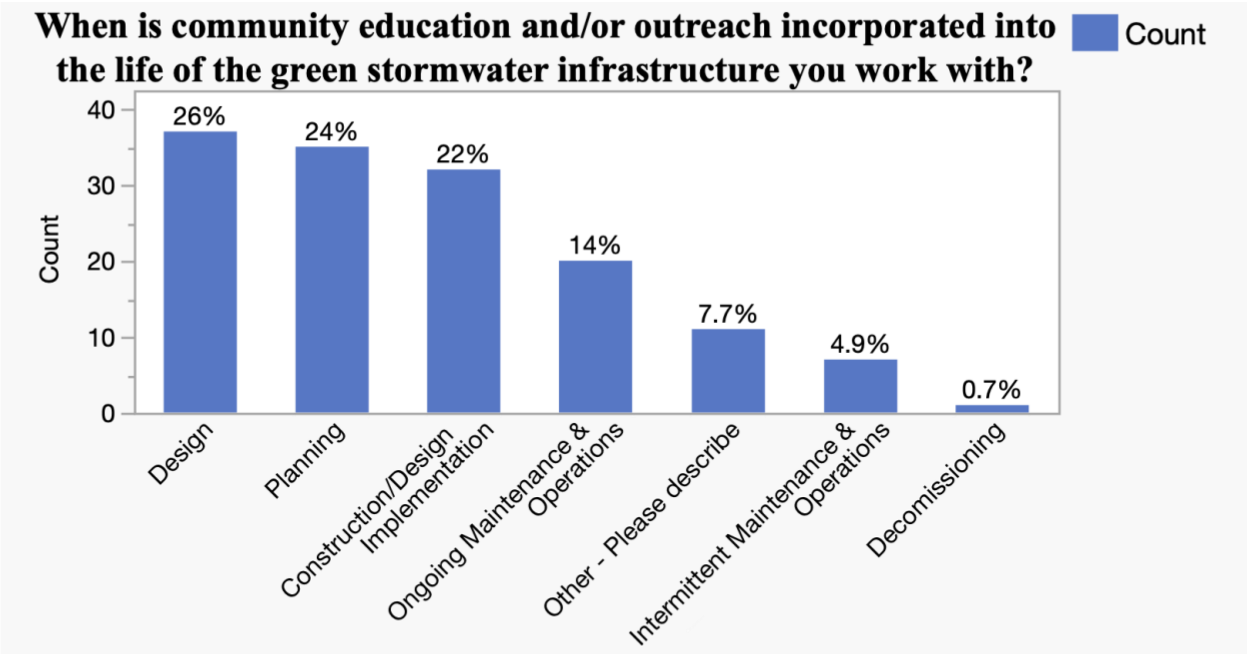


Figure 38: Community Education and/or Outreach Lifecycle Integration. ("JMP Statistical Discovery" 2024).

When asked what other professions respondents (n=134) work with, it becomes clear that a lot of interdisciplinary interaction is happening. The top disciplines worked with include engineering at 13%, construction at 12%, and landscape architects at 11% (see Figure 39). A chi-square test found that the model for other disciplines worked with in relation to discipline was not statistically significant.

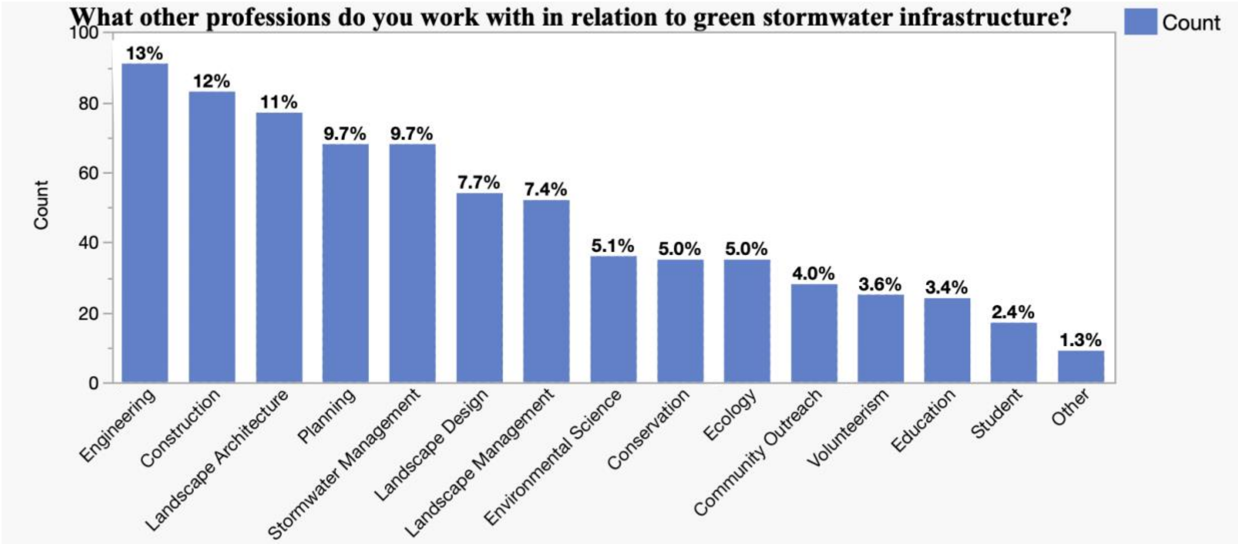


Figure 39: Other Professions Worked With. ("JMP Statistical Discovery" 2024).

When asked what training opportunities would further respondent work in GSI, 25 respondents (n=81) indicated a desire for more training courses and opportunities for themselves, maintenance workers, or the public. Desired learning opportunities via continuing education, conferences, seminars, field demonstrations, and volunteer opportunities were all described. Other responses focused on training content. Topics included appropriate plantings, soil and hydrologic health, funding opportunities, permitting, and different GSI system mechanics and products. There was also a desire to learn more about developing monitoring, evaluation, and maintenance programs.

Of responses (n=87) to what design elements aid or detract from the long-term functioning of GSI, the term plant and stemming variations was noted 26 times, highlighting the importance of appropriate plant selections, densities, and placement for GSI systems. Maintenance and stemming variations appeared 25 times. Maintenance themes included maintenance plans, maintenance complexity, and intention to perform maintenance as crucial for the long-term functioning of GSI. Other themes included designing for the entire life cycle of a GSI system, as well as access and interactivity for the public and maintenance workers.

The responses (n=86) volunteered for the most significant inhibitors for O&M success were approached from many angles. The largest reported inhibitors were cost and funding, as implications were brought up approximately one-third of the time. Education of skilled maintenance labor was brought up in 12 different responses. Other themes included maintenance concerns, improper planting choices, and education across disciplines of system components and life cycle implications.

Discussion

Gender breakdowns between different water management sectors vary greatly, but distributions of gender did have a higher representation of females when compared to all water infrastructure workers. The gender breakdown of water infrastructure workers is approximately 85% male and 15% female (Kane and Tomer 2018). Water infrastructure workers do have a disproportionately White workforce, accounting for around two-thirds of the industry, so this survey is severely overrepresented with White respondents. Black and Asian American workers comprise the lowest share of water infrastructure workers at 11% (Kane and Tomer 2018). While Black and Asian Americans did make up the smallest proportion of survey respondents, their combined 2.4% representation also falls short of water infrastructure worker distributions. Many sectors of water infrastructure workers have a higher median age than the national average of 42.2 years of age, so the respondent age data is similarly matched (Kane and Tomer 2018). Water infrastructure workers across all occupations holding a high school diploma or less equates to 53%, while nationally, only 32.5% of workers fall within that category (Kane and Tomer 2018).

Survey demographics mimic national water infrastructure worker demographics needing more diversity and younger representation. For the survey, this is likely because the convenience sampling methods used tended to reach individuals with higher authority positions within their organizations who are more likely to have higher levels of education and be White (US Bureau of Labor Statistics 2024). One indication is that 58% of all respondents worked in their field for 15 or more years.

When considering water infrastructure worker demographics, studies have found that "people of color, women, and less-educated respondents had a greater willingness to participate in stormwater management than White, male, and more-educated respondents" (Scarlett et al. 2021, 1). This appears to be related to personal experiences and vulnerabilities to stormwater management issues, as lower-income communities and communities of color historically experience environmental justice inequities (Corburn 2003; Scarlett et al. 2021). This highlights the importance of diversity in stormwater management and underscores the lack of representation this survey managed to capture.

Most respondents work in landscape architecture or landscape design. When evaluating job roles and responsibilities, there is a heavy emphasis on the design and planning aspects of GSI. Very few landscape architects or designers indicate involvement with the construction process through construction monitoring or evaluation. Even fewer mention any post-installation monitoring or evaluation. The lack of monitoring and evaluation indicates a need for a strengthened connection between those involved in the design and planning process and O&M needs and processes.

When respondents considered whether their work was related to the environment, conservation issues, or water management, they indicated it was across disciplines. There was a 50/50 divide among those working in community outreach, suggesting a disconnect between those working in community outreach and how they impact the success of GSI. Community organizers and educators are essential in helping the public understand the impacts of GSI. Public support plays a significant role in prioritizing funding supporting O&M needs.

It was evident that the respondents were familiar with GSI as a concept before they were presented with the EPA's definition. Respondents understood that GSI is meant to mimic natural hydrologic systems, with stems of natur· (natural, naturally, and nature) appearing 42 times. High frequencies involving stemmed variations of runoff, infiltration, and system demonstrate an understanding that GSI systems are designed to manage water by encouraging infiltration. They are designed to manage runoff and work within the context of hydrological systems.

While respondents acknowledged the pre-defined purposes of GSI, lower percentages of responses may indicate a lack of understanding of GSI's co-benefits. Respondent selection of GSI purposes supports the idea that these disciplines do not highly value GSI as a source of beauty compared to other GSI purposes. A lower ranking of "source of beauty" is interesting, given that creating beauty through aesthetics is a foundationally important concept within landscape architecture and design (Echols and Pennypacker 2008). Reducing infrastructure costs has the most equal distribution of all rankings, indicating a lack of agreement on whether GSI reduces or does not reduce infrastructure costs. Community resources and producing wildlife habitats also have a wide spread of ranking designations. These results contribute to the idea that a more robust understanding of realizing the co-benefits of GSI is essential. GSI systems that tackle more of these system benefits can produce better designs and provide greater justification to secure funding.

Each of the long-term viability elements received mean ratings above a (3), indicating that all disciplines believe each aspect contributes to the long-term viability of GSI. Interestingly, design team education was the only longevity element that did not receive a single (1) or least important rating. Most respondents are involved in the design process, indicating a certain self-awareness level among practitioners. They require more training and education on different aspects of GSI to strengthen their success and functionality.

Most respondents were aware of the Clean Water Act, which sets standards for stormwater infrastructure. This is important as designs must meet legal requirements for site runoff. This is encouraging as many practitioners are aware of stormwater standards.

GSI was viewed as an effective stormwater management tool by practitioners regardless of discipline. The sentiment analysis revealed that even though practitioners think GSI is an effective stormwater management tool, a few caveats are involved. Sentiments contributing to the negative scores involved warnings that GSI is only most effective when implemented correctly. Consistent themes were designing infrastructure to fit site constraints and local environmental factors, having persistent maintenance, and implementing consistent policy to create interconnected management systems throughout municipalities. When respondents were asked about GSI's effectiveness in addressing water quality, open-ended responses provided a general understanding of GSI's functionality, replicating natural hydrological processes and the ability of vegetation to filter out pollutants from runoff. Concerns emphasized the need for the long-term efficacy of these systems to provide ecological services and improve water quality.

Because only 80% of GSI practitioners are aware of design guidance for GSI, there is room for improvement in distributing guidance among stormwater professionals. Those with access to design guidance heavily relied on local and regional guidance. As future design guidance is developed, research must account for how regional differences impact design standards and O&M programs to maximize effectiveness.

Bioswales, rain gardens, and permeable pavements are the most used form of GSI. Developing larger amounts or more accessible information on less commonly implemented GSI types might help spread these alternatives and ensure the appropriate usage of GSI types through different site constraints. Because most respondents only work within the planning and design phases of a GSI system's life, greater integration into subsequent life cycle stages or targeted training on other life cycle training may be beneficial in promoting a better understanding of different life cycle needs during the planning and design processes.

The independent disciplines involved with GSI generally only spend a few months working with a system throughout its life. Very few respondents have long-term interactions with GSI; therefore, there are life cycle needs and considerations that many designers do not have direct experience. Most respondents work with only two to five sites at a time. Some work with more significant amounts ranging from 10 to 20 or in groups greater than 20. A chi-square test showed this model is statistically significant ($p=0.0002$). The disciplines who work with increasingly large numbers of sites may have less time to learn about or consider system needs outside of the life cycle period they work with.

When asked about considering each respondent's role throughout the job process, it became apparent that there is a lack of communication and consideration for different disciplines throughout the design process for GSI. Landscape architects and designers experience varying amounts of consideration when making stormwater management decisions. Even when practitioners of different disciplines were brought into a project, they were not always brought in at a point where their input could make a significant impact. One respondent ascertains that "landscape design often times [sic] should be integrated into the design process earlier than they sometimes are since the design of adjacent landscaping and hardscape could be important for the success of the green stormwater infrastructure." Other disciplines, such as community engagement and environmental science indicated that their roles were "probably not" and "definitely not" considered throughout the design process with no positive sentiment representation at all. Another respondent summed up these issues nicely by saying, "Depending on the client(s)/stakeholder(s) involved, there is still an engineer-centric mindset in the professional world that can inhibit team inclusion of landscape architects and planners at the optimal stages of project delivery." While this dynamic highlights the dichotomy between designers and planners concerning engineers, there appear to be disconnects between other disciplines throughout the stormwater management process.

There is much opportunity for improvement in monitoring and evaluating GSI as only approximately half of respondents participate in either activity. Implementing more robust monitoring and evaluation methodologies can help determine how GSI systems respond to more frequent or intense barrages of runoff and the resulting impacts on their efficiency and functionality over time (M. Wang, Sun, and Zhang 2023). This can impact future design and O&M considerations as local hydrological conditions are affected by climate change over time. Those participating in monitoring and evaluation activities appear to do so in frequencies that align with everyday O&M activities, with 65% and 63% of the respective activities occurring in quarterly and yearly frequencies. Interestingly, water quality each received less than 9% of the looked-at evaluation and monitoring elements as water quality was rated within the top three purposes of GSI. A disconnect between how practitioners know if they are meeting the purpose goals of GSI systems is highlighted if those elements are lower priority for evaluation and monitoring when they do occur. Smart GSI technologies are just starting to be developed and are capable of impacting sensing, controls, communications, and computing of large-scale systems or interconnected systems with many individual GSI components over a large area (Meng and Hsu 2019). Smart GSI technologies may be an effective tool to help bridge this gap.

Because O&M plans are only developed for projects 52% of the time, there is much room for improvement as O&M plans are considered essential throughout the literature to implement and continue long-term maintenance activities. Many plans are developed after sites are built, which signifies a lack of forethought and planning for maintenance activities. Two-thirds of plans are never evaluated based on site conditions, so plans in place may not account for unique site impacts. This reduces their long-term effectiveness as well.

Community education and outreach are incorporated into the life cycle of GSI less than half the time. When implemented, it tends to be in the earlier stages of the GSI lifecycle. Infusing outreach and education activities through later life stages, such as during maintenance, can help communicate to the community the importance of such activities over the lifetime of a system. Greater execution of community education and outreach can create the community support needed to help secure appropriate funding for maintenance activities.

GSI involves a considerable variety of interdisciplinary collaborations. Respondents worked with a wide breadth of different disciplines throughout their work with different GSI projects. This highlights the importance of the continued improvement of interdisciplinary communication and education so that all disciplines can work towards the most effective management practices for GSI.

Many survey respondents reported inhibitors to GSI O&M, including a lack of maintenance workers' knowledge of appropriate maintenance activities and procedures and a lack of designers' understanding of different GSI types and appropriate applications considering unique site constraints. Most water infrastructure workers need extensive training, with 78.2% requiring a minimum of one year of related experience and 16% necessitating four or more years of experience. This underscores the specialized knowledge necessary for effective GSI O&M and highlights the need for applied and integrated training and learning opportunities as institutional understanding of these systems progresses (Kane and Tomer 2018).

Recommendations

Based on the results of this study, the following recommendations have been developed for consideration as implementable action items.

Firms involved in the planning, design, and engineering processes can prioritize diversity hiring so that those involved in these processes represent the people who rely on the proper functioning of the infrastructure. As a part of proper landscape management techniques, all stakeholders involved in the design process must be identified and included early in the design process where applicable so that the appropriate information can be incorporated into the process as early as possible. Those involved in the design process should implement monitoring and evaluation policies as a standard aspect of their design work. Incorporating monitoring and evaluation policies can also be an effective business acquisition tactic. This can be implemented as another service for clients and utilized by the firm to justify future projects. Integrating individuals from different departments into a singular space can also encourage conversations about how the different disciplines work through similar problems or how different constraints impact design and management decisions. Firms can also encourage and support continuing education opportunities for their employees by bringing representatives from other disciplines in to lead workshops or give talks.

Educators must emphasize the importance of different disciplines throughout the GSI lifecycle as many different skill sets work together to support it. Educators can involve representatives from different disciplines to give talks or lead workshops to provide a more well-rounded understanding of GSI systems to students of various backgrounds. They can include discussions and units that focus on the different co-benefits of GSI, outside of the benefits most focused on by a discipline. Landscape management techniques that emphasize stakeholder integration should be emphasized. Workshops focusing on different GSI types can be held so that the considerations for each unique type can be deeply explored.

Future Research

With so many components affecting O&M practices, future research could develop in many directions. The findings from this study could be validated and corroborated by capturing larger samples of the varieties of disciplines that work with GSI. More input from those outside the landscape architecture and design world might reveal more insights into disciplinary clashes and present opportunities for more comprehensive disciplinary inclusion throughout different components of these systems' development and life cycle.

Different projects could explore the relationship between demographics and practitioner resilience to resistance against GSI implementation, which poses an interesting line for future research. Relating issues of GSI O&M to proximity and location within different socioeconomic neighborhoods could enhance understanding of access resources and funding opportunities.

Developing a system that analyzes existing training opportunities and their impact on practitioner knowledge and interdisciplinary communication could expose opportunities to improve and expand GSI-specific training. Further research into the adoption trends of organizations and stormwater management individuals could also support the spread of these new technologies.

Practitioner rankings of purposes and long-term viability factors also indicate a lack of understanding or advocacy for the co-benefits of GSI. This underscores the need for further research exploring the impacts of GSI on social, economic, and public health components (M. Wang, Sun, and Zhang 2023). This includes persistent issues with infrastructure policy barriers and minimum requirements that fail to incorporate the design requirements needed to support multifunctionality. Future research could explore the specifically designed elements required to realize the co-benefits of GSI to inform policy requirements and minimum design standards.

CHAPTER 5

CONCLUSION

The objective of this thesis was to gain insights into sustainable GSI O&M needs by exploring the social and technical perspectives of stormwater management professionals. While industry standards and policy systems are established to support maintenance needs for gray infrastructure, the growing body of assessment research has not fully realized GSI's O&M needs and translated them into infrastructure systems to help them. The objectives set by this research were to (1) determine what disparities exist between the literature on GSI O&M and practitioners' practical experiences, attitudes, and perceptions and (2) explore the extent to which different disciplines that work with GSI differentiate values and goals that impact the sustainability, resilience, and long-term usability of GSI.

A survey was distributed to various practitioners representing a breadth of industries who work with GSI, including landscape architecture, landscape design, engineering, stormwater management, planning, construction, community outreach, conservation, ecology, education, environmental science, and landscape management. Analysis of the data gathered from 175 professionals examined demographic information, job function as it pertained to GSI, conceptual understanding, and experiences, perceptions, and opinions on their implementation.

Analysis of respondents' perceptions of GSI reveals a generally cohesive understanding among practitioners regarding what GSI entails and its primary functional purposes, which fundamentally deal with water quality and quantity. While most practitioners understand how their work relates to environmental, conservation, and stormwater management aspects of GSI, it was interesting to see that some practitioners did not. All disciplines involved must understand how their work contributes to the broader purpose of GSI and its integration into communities. Recognition of the economic, environmental, and social benefits of GSI can influence those working in policy, community engagement, technical research, and system implementation. This emphasizes the need to increase the understanding and awareness of the co-benefits of GSI among all related disciplines.

Monitoring and evaluation need to be emphasized in guidance measures being developed for GSI. Only half of all practitioners monitor or evaluate the GSI systems they work with. Monitoring and evaluation programs are a necessary component of developing O&M programs that are based on actual system feedback and variables. Feedback between system design and real-world performance is essential in developing sustainable design practices and O&M regimes. For those who did execute any form of monitoring and evaluation, it is counterproductive that less than 9% of practitioners assessed water quality during monitoring and evaluation procedures. Professionals cannot know how their systems meet water quality goals and appropriately assess what O&M procedures need to occur without knowing if they function as designed.

Many overarching issues surrounding GSI O&M stem from the independent nature of work performed by different disciplines. Most practitioners work with a system for only a few months and within a specific portion of its lifetime, such as design, construction, or reactive maintenance. It is difficult for any practitioner to understand all the components and elements that must be considered when viewed from limited angles.

There is also a significant lack of communication and consideration of the lenses of all the disciplines working with GSI. Engineers were cited as being the primary decision-makers for many GSI projects. When other disciplines, such as landscape architects, planners, and environmental scientists, are incorporated into the development process too late, opportunities are missed to consider technologies and values that can increase the benefits a system can provide. It is worth directing future research and policy to include more stakeholders and fields of knowledge from the beginning of GSI system development to better their impacts on stormwater management.

This survey provided many interesting insights from practitioners across a variety of fields. To expand on this study's research, larger populations from the related GSI disciplines are needed to produce statistically significant and verifiable data. The very nature of this survey highlights the interdisciplinary communication issues surrounding GSI, as the convenience and sampling methods did a poor job of gathering significant frequencies of responses outside of landscape architecture.

As our urban systems continue to expand and confront evolving climate challenges, building and designing them in ways that promote sustainability and resilience is essential. GSI is an effective tool in mitigating stormwater runoff and improving water quality, thereby impacting the health of our waterways, environments, and communities. The co-benefits of GSI, encompassing ecological, economic, and social spheres, are contingent on its continued efficiency and long-term viability. Interdisciplinary collaboration, communication, cooperation, and mutual consideration are integral in developing O&M programs needed for GSI to manage stormwater within the dynamic environmental shifts within our urban landscapes.

REFERENCES

118th Congress. 2023-2024. Inflation Reduction Act of 2023. edited by H.R.

Abbott, Benjamin W., Kevin Bishop, Jay P. Zarnetske, Camille Minaudo, F. Stuart Chapin Iii, Stefan Krause, David M. Hannah, Lafe Conner, David Ellison, and Sarah E. Godsey. 2019. "Human domination of the global water cycle absent from depictions and perceptions." *Nature Geoscience* 12 (7): 533-540.

Ahern, Jack. 2011. "From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world." *Landscape and Urban Planning* 100 (4): 341-343. https://doi.org/https://doi.org/10.1016/j.landurbplan.2011.02.021.

Arnstein, Sherry R. 2009. "A ladder of citizen participation." *Hunch: the Berlage Institute report* (13): 130-141.

Backhaus, Antje, Torben Dam, and Marina Bergen Jensen. 2012. "Stormwater management challenges as revealed through a design experiment with professional landscape architects." *Urban Water Journal* 9 (1): 29-43.

Backhaus, Antje, and Ole Fryd. 2013. "The aesthetic performance of urban landscape-based stormwater management systems: a review of twenty projects in Northern Europe." Great Britain, 2013/01/01/.

Bannerman, Roger T., David W. Owens, R. B. Dodds, and Nancy J. Hornewer. 1993. "Sources of pollutants in Wisconsin stormwater." *Water Science and technology* 28 (3-5): 241-259.

Barbosa, A. E., J. N. Fernandes, and L. M. David. 2012. "Key issues for sustainable urban stormwater management." *Water Research* 46 (20): 6787-6798. https://doi.org/10.1016/j.watres.2012.05.029.

Bell, Colin, Katie Spahr, Emily Grubert, Jennifer Stokes-Draut, Elizabeth Gallo, John McCray, and Terri Hogue. 2019. "Decision Making on the Gray-Green Stormwater Infrastructure Continuum." *Journal of Sustainable Water in the Built Environment* 5: 04018016. https://doi.org/10.1061/JSWBAY.0000871.

Benedict, Mark, and Edward McMahon. 2002. *Green Infrastructure: Smart Conservation for the 21st Century*. Vol. 20.

Boone Jr, Harry N., and Deborah A. Boone. 2012. "Analyzing likert data." *The Journal of extension* 50 (2): 48.

Brown, Heidi E., Ladd Keith, Valerie Madera-Garcia, Anissa Taylor, Nicholas Ramirez, and Irene Ogata. 2022. "Greening up for mosquitoes: a comparison of green stormwater infrastructure in a semiarid region." *Journal of the American Mosquito Control Association* 38 (2): 109-112. https://doi.org/10.2987/21-7055.

Brown, Jessica T.R. , and Robert A. Brown. 2020. *Photo-based operations, inspection and maintenance tools for stormwater green infrastructure practices in coastal Georgia*

Brown, Rebekah R. 2003. "Institutionalisation of integrated urban stormwater management: Multiple-case analysis of local management reform across metropolitan Sydney."

---. 2005. "Impediments to integrated urban stormwater management: the need for institutional reform." *Environmental management* 36: 455-468.

Brown, Rebekah R., and Megan A. Farrelly. 2009. "Delivering sustainable urban water management: a review of the hurdles we face." *Water science and technology* 59 (5): 839-846.

Brudler, Sarah, Karsten Arnbjerg-Nielsen, Michael Zwicky Hauschild, Christian Ammitsøe, Justine Hénonin, and Martin Rygaard. 2019. "Life cycle assessment of point source emissions and infrastructure impacts of four types of urban stormwater systems." *Water Research* 156: 383-394. https://doi.org/10.1016/j.watres.2019.03.044.

Carlet, Fanny. 2015. "Understanding attitudes toward adoption of green infrastructure: A case study of US municipal officials." *Environmental Science and Policy* 51: 65-76. https://doi.org/10.1016/j.envsci.2015.03.007.

Carmon, Naomi, and Uri Shamir. 2010. "Water-sensitive planning: integrating water considerations into urban and regional planning." *Water and Environment Journal* 24 (3): 181-191.

Chakrabarti, Parijat, and Margaret Frye. 2017. "A mixed-methods framework for analyzing text data: Integrating computational techniques with qualitative methods in demography." *Demographic Research* 37: 1351-1382.

Chang, Ni-Bin. 2010. *Effects of urbanization on groundwater: an engineering case-based approach for sustainable development*. American Society of Civil Engineers.

Chow, J. f, D. Savić, D. Fortune, Z. Kapelan, and N. Mebrate. 2014. "Using a Systematic, Multi-criteria Decision Support Framework to Evaluate Sustainable Drainage Designs." *Procedia Engineering* 70: 343-352. https://doi.org/10.1016/j.proeng.2014.02.039.

Clary, J., and H. Piza. 2017. *Cost of maintaining green infrastructure*. Edited by J. Clary and H. Piza. Book. Reston, USA: American Society of Civil Engineers (ASCE).

Construction Industry Compliance Assistance Center. "Construction Industry Compliance Assistance." **Stormwater**. Construction Industry Compliance Assistance Center. Accessed March 11. https://www.cicacenter.org/stormwater.php.

Corburn, J. 2003. "Bringing Local Knowledge into Environmental Decision Making: Improving Urban Planning for Communities at Risk." 420-433.

"Create and use a heat map." 2024. https://doc.arcgis.com/en/insights/latest/create/heat-maps.htm.

Crewe, Katherine. 2001. "The Quality of Participatory Design:<i>The Effects of Citizen Input on the Design of the Boston Southwest Corridor</i>." *Journal of the American Planning Association* 67 (4): 437-455. https://doi.org/10.1080/01944360108976251.

Cross, Rob, Andrew Parker, Laurence Prusak, and Stephen P. Borgatti. 2001. "Knowing What We Know: Supporting Knowledge Creation and Sharing in Social Networks." *Organizational Dynamics* 30 (2): 100-120. https://doi.org/10.1016/S0090-2616(01)00046-8.

Davis, Allen P, William F Hunt, and Robert G Traver. 2022. *Green Stormwater Infrastructure Fundamentals and Design*. John Wiley & Sons.

Davis, Allen P. 2008. "Field Performance of Bioretention: Hydrology Impacts." *Journal of Hydrologic Engineering* 13 (2): 90-95. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:2(90).

Davis, James C., John Cromartie, Tracey Farrigan, Brandon Genetin, Austin Sanders, and Justin B. Winikoff. 2023. "Rural America at a Glance 2023 Edition."

de Graaf, Rutger, and Rutger van der Brugge. 2010. "Transforming water infrastructure by linking water management and urban renewal in Rotterdam." *Technological Forecasting and Social Change* 77 (8): 1282-1291.
Di Benedetto, A. 2010. "Diffusion of innovation." *Encyclopedia of technology and innovation management*: 113-116.
Dillman, Don A. 2007. *Mail and internet surveys : the tailored design method*. 2nd , 2007 update with new internet, visual, and mixed-mode guide. ed. BibliographiesNon-fiction. Wiley.
Dillman, Don A., Jolene D. Smyth, and Leah Melani Christian. 2014. *Internet, phone, mail, and mixed-mode surveys: The tailored design method*. John Wiley & Sons.
Dong, Xin, Hao Guo, and Siyu Zeng. 2017. "Enhancing future resilience in urban drainage system: Green versus grey infrastructure." *Water Research* 124: 280-289. https://doi.org/10.1016/j.watres.2017.07.038.
Echols, Stuart, and Eliza Pennypacker. 2008. "From stormwater management to artful rainwater design." *Landscape Journal* 27 (2): 268-290.
---. 2015. *Artful Rainwater Design : Creative Ways to Manage Stormwater*. Book. Washington, DC: Island Press.
Eisenman, T. S. 2013. "Frederick Law Olmsted, Green Infrastructure, and the Evolving City." 287-311.
EPA. "Clean Water Act (CWA) Compliance Monitoring." https://www.epa.gov/compliance/clean-water-act-cwa-compliance-monitoring.
---. 1982. *Results of the nationwide urban runoff program*. Vol. 1. Water Planning Division, US Environmental Protection Agency.
---. 2007. "Reducing stormwater costs through low impact development (LID) strategies and practices." *EPA 841-F-07-006*.
---. 2013. The importance of operation and maintenance for the long-term success of 526 green infrastructure.
---. 2021. Sand and Organic Filters. edited by Office of Water.
---. 2022-2023. "Pollution Prevention Grant." Accessed March 11. https://www.epa.gov/p2/pollution-prevention-grant.
---. 2024. "Green and Gray Infrastructure Research." https://www.epa.gov/water-research/green-and-gray-infrastructure-research.
Erickson, Andrew J., Vinicius J. Taguchi, and John S. Gulliver. 2018. "The Challenge of Maintaining Stormwater Control Measures: A Synthesis of Recent Research and Practitioner Experience." *SUSTAINABILITY* 10 (10): 3666. https://doi.org/10.3390/su10103666.
Fabos, J. G. 2004. "Greenway planning in the United States: its origins and recent case studies." *LANDSCAPE AND URBAN PLANNING* 68 (2-3): 321-342. https://doi.org/10.1016/j.landurbplan.2003.07.003.
Feehan, Caitlin 2013. "A Survey of Green Infrastructure Maintenance Programs in the United States." Master of Environmental Management Candidate, Forestry and Environmental Studies, Yale University.
Feeney, Griffith, and Samuel Feeney. 2019. "On the logical structure of census and survey questionnaires." *Genus* 75 (1): 19.
FEMA. 2024. "Infrastructure." FEMA.gov. Accessed February 22, 2024. https://www.fema.gov/glossary/infrastructure.

Fitzgerald, Joan, and Joshua Laufer. 2017. "Governing green stormwater infrastructure: the Philadelphia experience." *Local Environment* 22 (2): 256-268. https://doi.org/10.1080/13549839.2016.1191063.

Flynn, K. M., B. W. Linkous, and M. T. Buechter. 2012. "Operation and Maintenance Assessment for Structural Stormwater BMPs." 2012/01/01/.

Frumkin, Howard, Lawrence Frank, and Richard J. Jackson. 2004. *Urban Sprawl and Public Health : Designing, Planning, and Building for Healthy Communities*. 1st ed. OnlineNon-fictionElectronic document. Island Press.

Gallet, Danielle. 2010. "The value of green infrastructure: A guide to recognizing its economic, environmental and social benefits." 2011.

Galvin, Emily M., and Todd K. BenDor. 2023. "The economic impacts of green stormwater infrastructure: An evaluation of novel stormwater management policies in Washington, D.C." *Land Use Policy* 134: N.PAG-N.PAG. https://doi.org/10.1016/j.landusepol.2023.106915.

Gonzalez-Meler, Miquel A., Lisa Cotner, Dean A. Massey, Moira L. Zellner, and Emily S. Minor. 2013. "The environmental and ecological benefits of green infrastructure for stormwater runoff in urban areas."

Grabowski, Zbigniew J., Timon McPhearson, A. Marissa Matsler, Peter Groffman, and Steward T. A. Pickett. 2022. "What is green infrastructure? A study of definitions in US city planning." *Frontiers in Ecology and the Environment* 20 (3): 152-160. https://doi.org/https://doi.org/10.1002/fee.2445. https://doi.org/10.1002/fee.2445

Hagen, Bjoern, David Pijawka, Mihir Prakash, and Shreyash Sharma. 2017. "Longitudinal analysis of ecosystem services' socioeconomic benefits: Wastewater treatment projects in a desert city." *Ecosystem Services* 23: 209-217. https://doi.org/10.1016/j.ecoser.2016.12.014.

Hilty, Jodi A. 2019. *Corridor ecology: linking landscapes for biodiversity conservation and climate adaptation*. Edited by Annika T. H. Keeley, William Z. Lidicker, Jr. and Adina Maya Merenlender. Second edition. ed. BibliographiesNon-fiction. Island Press.

Homet, K., P. Kremer, V. Smith, R. Ampomah, and S. M. Strader. 2022. "Mapping predicted areas of common maintenance impacts to green stormwater infrastructure in Philadelphia, Pennsylvania." *Journal of Sustainable Water in the Built Environment* 8 (3). https://doi.org/10.1061/JSWBAY.0000986.

Homet, K., P. Kremer, V. Smith, and S. M. Strader. 2022. "Multi-variable assessment of green stormwater infrastructure planning across a city landscape: Incorporating social, environmental, built-environment, and maintenance vulnerabilities." *Frontiers in Environmental Science* 10: 958704. https://doi.org/10.3389/fenvs.2022.958704.

Huang, Lechuan, Theodore Chao Lim, and Shalini Misra. 2022. "Interdisciplinary Inquiry and Spatial Green Stormwater Infrastructure Research." *SUSTAINABILITY* 14 (3): 1198. https://doi.org/10.3390/su14031198.

Hunt, W. F., A. P. Davis, and R. G. Traver. 2012. "Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design." 698-707.

Hunt, W. F., R. G. Traver, A. P. Davis, C. H. Emerson, K. A. Collins, and J. H. Stagge. 2010. "Low impact development practices: designing to infiltrate in urban environments." edited by N. B. Chang, 308-343. Reston, USA: American Society of Civil Engineers (ASCE).

"International Stormwater BMP Database." 2024. https://bmpdatabase.org/.

IPCC. 2023. Climate Change 2023: Synthesis Report. edited by II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team Contribution of Working Groups I, H. Lee and J. Romero (eds.)]. Geneva, Switzerland: IPCC.

Jaffe, M., M. Zellner, E. Minor, M. Gonalez-Meler, L. Bucci Cotner, D. Massey, H. Ahmed, and B. Miller. 2010. "The Illinois Green Infrastructure Study, A Report to the Illinois Environmental Protection Agency on the Criteria in Section 15 of Public Act 96-0026, The Illinois Green Infrastructure for Clean Water Act of 2009." *University of Illinois at Chicago, Chicago Metropolitan Agency for Planning, Center for Neighborhood Technology, University of Illinois at Urbana-Champaign*.

"JMP Statistical Discovery." 2024. https://www.jmp.com/en_us/home.html.

Junker, Berit, and Matthias Buchecker. 2008. "Aesthetic preferences versus ecological objectives in river restorations." *Landscape and Urban Planning* 85 (3): 141-154. https://doi.org/10.1016/j.landurbplan.2007.11.002.

Kane, Joseph, and Adie Tomer. 2018. *Renewing the water workforce: improving water infrastructure and creating a pipeline to opportunity*. Metropolitan Policy Program at Brookings.

Keeley, Melissa. 2007. "Using individual parcel assessments to improve stormwater management." *Journal of the American Planning Association* 73 (2): 149-160.

Keeley, Melissa, Althea Koburger, David Dolowitz, Dale Medearis, Darla Nickel, and William Shuster. 2013. "Perspectives on the Use of Green Infrastructure for Stormwater Management in Cleveland and Milwaukee." *Environmental Management* 51 (6): 1093-1108. https://doi.org/10.1007/s00267-013-0032-x.

Keim, M. E. 2008. "Building human resilience: the role of public health preparedness and response as an adaptation to climate change." *American Journal of Preventive Medicine* 35 (5): 508-516. https://doi.org/10.5555/20083276831.

King, Gary, and Langche Zeng. 2001. "Logistic Regression in Rare Events Data." *Political Analysis* 9 (2): 137-163. https://doi.org/10.1093/oxfordjournals.pan.a004868. https://www.cambridge.org/core/product/1E09F0F36F89DF12A823130FDF0DA462

Kondo, Michelle C., Sarah C. Low, Jason Henning, and Charles C. Branas. 2015. "The Impact of Green Stormwater Infrastructure Installation on Surrounding Health and Safety." *American Journal of Public Health* 105 (3): e114-e121. https://doi.org/10.2105/AJPH.2014.302314.

Kopaskie, Andrea. 2016. "Public vs private: A national overview of water systems." *University of North Carolina School of Governance, Environmental Finance Center. Retrieved January* 23: 2022.

"Level III and IV Ecoregions of the Continental United States." 2024. https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

Little, Charles E. 1990. *Greenways for America*. BibliographiesNon-fiction. Johns Hopkins University Press.

Meng, Ting, and David Hsu. 2019. "Stated preferences for smart green infrastructure in stormwater management." *Landscape and Urban Planning* 187: 1-10. https://doi.org/https://doi.org/10.1016/j.landurbplan.2019.03.002.

Meng, Ting, David Hsu, and Bridget Wadzuk. 2017. "Green and Smart: Perspectives of City and Water Agency Officials in Pennsylvania toward Adopting New Infrastructure

Technologies for Stormwater Management." *Journal of Sustainable Water in the Built Environment* 3 (2): 05017001. https://doi.org/doi:10.1061/JSWBAY.0000824.
Merriam-Webster.com Dictionary. 2024. Infrastructure. In *Merriam-Webster.com Dictionary*.
Momeni, Amir, Matthew Pincus, and Jenny Libien. 2018. "Cross tabulation and categorical data analysis." *Introduction to statistical methods in pathology*: 93-120.
Mosleh, Leila, Masoud Negahban-Azar, and Mitchell Pavao-Zuckerman. 2023. "Stormwater Green Infrastructure Resilience Assessment: A Social-Ecological Framework for Urban Stormwater Management." *Water (20734441)* 15 (9): 1786. https://doi.org/10.3390/w15091786.
Myles, Kirsty. 2014. *Economic Benefits of Low Impact Development and Green Infrastructure : Case Studies*. Book.*Economic Issues, Problems and Perspectives*. New York: Nova Science Publishers, Inc.
National Research Council. 2009. *Urban stormwater management in the United States*. National Academies Press.
New Hampshire Estuaries Project. 2007. The Impacts of Impervious Surfaces on Water Resources, NHEP. *PREP Reports & Publications*: New Hampshire Estuaries Project.
Olmsted, Frederick Law. 1970. *Public parks and the enlargement of towns*. BibliographiesNon-fiction.*The Rise of urban America*: Arno Press.
Parker, Charlie, Sam Scott, and Alistair Geddes. 2019. "Snowball sampling." *SAGE research methods foundations*.
Pereira, Bárbara, Luís Mesquita David, and Ana Galvão. "Green Infrastructures in Stormwater Control and Treatment Strategies." 2019.
---. 2019. "Green Infrastructures in Stormwater Control and Treatment Strategies." 2019.
Perrin, C., L. Milburn, L. Szpir, W. Hunt, S. Bruce, R. McLendon, S. Job, D. Line, D. Lindbo, S. Smutko, H. Fisher, R. Tucker, J. Calabria, K. Debusk, K.C. Cone, M. Smith-Gordon, J. Spooner, T. Blue, N. Deal, J. Lynn, D. Rashash, R. Rubin, M. Senior, N. White, D. Jones, and W. Eaker. 2009. *Low Impact Development A Guidebook for North Carolina.* NC Cooperative Extension Service, NC State University.
Pham, Michelle A., MaLisa R. Spring, Frances S. Sivakoff, and Mary M. Gardiner. 2023. "Reclaiming urban vacant land to manage stormwater and support insect habitat." *Urban Ecosystems* 26 (6): 1813-1827. https://doi.org/10.1007/s11252-023-01418-9.
Project , New Hampshire Estuaries. 2007. The Impacts of Impervious Surfaces on Water Resources, NHEP. *PREP Reports & Publications*: New Hampshire Estuaries Project.
"Qualtrics." 2024. Qualtrics. https://eits.uga.edu/web_and_applications/qualtrics/.
"Quick Facts: Georgia." 2024. https://www.census.gov/quickfacts/fact/table/GA/PST045223.
Raymond, Christopher M., Niki Frantzeskaki, Nadja Kabisch, Pam Berry, Margaretha Breil, Mihai Razvan Nita, Davide Geneletti, and Carlo Calfapietra. 2017. "A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas." *Environmental Science and Policy* 77: 15-24. https://doi.org/10.1016/j.envsci.2017.07.008.
Reimer, Mario, and Karsten Rusche. 2019. "Green infrastructure under pressure. A global narrative between regional vision and local implementation." *European Planning Studies* 27 (8): 1542-1563. https://doi.org/10.1080/09654313.2019.1591346.
Renschler, Chris S., Amy E. Frazier, Lucy A. Arendt, Gian Paolo Cimellaro, Andrei M. Reinhorn, and Michel Bruneau. 2010. *A framework for defining and measuring resilience at the community scale: The PEOPLES resilience framework*. MCEER Buffalo.

Reu Junqueira, Juliana, Silvia Serrao-Neumann, and Iain White. 2022. "Using green infrastructure as a social equity approach to reduce flood risks and address climate change impacts: A comparison of performance between cities and towns." *Cities* 131. https://doi.org/10.1016/j.cities.2022.104051.

Rogers, Everett M. 2003. *Diffusion of innovations*. 5th ed. BibliographiesNon-fiction. Free Press.

Rowe, Amy Ann, Patricia Rector, and Michele Bakacs. 2016. "Survey Results of Green Infrastructure Implementation in New Jersey." *Journal of Sustainable Water in the Built Environment* 2 (3): 1-6. https://doi.org/10.1061/JSWBAY.0000810.

Shandas, Vivek, and W. Barry Messer. 2008. "Fostering Green Communities Through Civic Engagement: Community-Based Environmental Stewardship in the Portland Area." *Journal of the American Planning Association* 74 (4): 408-418. https://doi.org/10.1080/01944360802291265.

Shifflett, S. D., T. Newcomer-Johnson, T. Yess, and S. Jacobs. 2019. "Interdisciplinary collaboration on green infrastructure for urban watershed management: an Ohio case study." *Water (20734441)* 11 (4): 738. https://doi.org/10.3390/w11040738.

Shipan, Charles R., and Craig Volden. 2008. "The mechanisms of policy diffusion." *American journal of political science* 52 (4): 840-857.

Shokry, Galia, James J. T. Connolly, and Isabelle Anguelovski. 2020. "Understanding climate gentrification and shifting landscapes of protection and vulnerability in green resilient Philadelphia." *Urban Climate* 31. https://doi.org/10.1016/j.uclim.2019.100539.

Snodgrass, Edmund C., and Linda McIntyre. 2010. *The green roof manual : a professional guide to design, installation, and maintenance*. BibliographiesNon-fiction. Timber Press.

Sohn, Wonmin, Jinhyun Bae, and Galen Newman. 2021. "Green infrastructure for coastal flood protection: The longitudinal impacts of green infrastructure patterns on flood damage." *Applied Geography* 135. https://doi.org/10.1016/j.apgeog.2021.102565.

Stokols, Daniel. 2015. "The transdisciplinary orientation scale: Factor structure and relation to the integrative quality and scope of scientific publications." *Journal of Translational Medicine and Epidemiology* 3 (2).

Story, David A., and Alan R. Tait. 2019. "Survey research." *Anesthesiology* 130 (2): 192-202.

Tavakol-Davani, Hassan, Steven J. Burian, Jay Devkota, and Defne Apul. 2016. "Performance and Cost-Based Comparison of Green and Gray Infrastructure to Control Combined Sewer Overflows." *Journal of Sustainable Water in the Built Environment* 2 (2): 4015009-1-4015009-12. https://doi.org/10.1061/JSWBAY.0000805.

"Text Explorer." 2023. JMP Support. https://www.jmp.com/support/help/en/17.2/index.shtml#page/jmp/text-explorer.shtml#333591.

UN General Assembly. 2015. "Resolution adopted by the General Assembly on 11 September 2015." *New York: United Nations*.

United Nations. 2019. World Urbanization Prospects 2018 Highlights. edited by Department of Economic and Social Affairs Population Division. New York.

US Bureau of Labor Statistics. 2024. "Labor Force Statistics from the Current Population Survey." https://www.bls.gov/cps/cpsaat18.htm.

US Census Bureau. 2012. *United States Summary, 2010: Population and housing unit counts*. US Department of Commerce, Economics and Statistics Administration, US ….

Utilities, Seattle Public. 2009. Green Stormwater Operations and Maintenance Manual. Seattle Public Utilities Seattle.

van der Kolk, Henk-Jan, Petra van den Berg, Thijs van Veen, and Martijn Bezemer. 2023. "Substrate composition impacts long-term vegetation development on blue-green roofs: Insights from an experimental roof and greenhouse study." *Ecological Engineering* 186. https://doi.org/10.1016/j.ecoleng.2022.106847.

Van Herzele, A. 2004. "Local Knowledge in Action: Valuing Nonprofessional Reasoning in the Planning Process." 197-212.

Vick, Alfred, Jon Calabria, Stuart Echols, Michael Ogden, and David Yocca. 2012. "Site Design: Water." In *The sustainable sites handbook : a complete guide to the principles, strategies, and practices for sustainable landscapes*, edited by Meg Calkins. Wiley.

Vineyard, Donald, Wesley W. Ingwersen, Troy R. Hawkins, Xiaobo Xue, Bayou Demeke, and William Shuster. 2015. "Comparing Green and Grey Infrastructure Using Life Cycle Cost and Environmental Impact: A Rain Garden Case Study in Cincinnati, OH." Journal of the American Water Resources Association, United States, 2015/01/01/.

Vlachos, Evan, and Benedito Braga. 2001. *The challenge of urban water management*. IWA Publishing, London.

Wadzuk, Bridget, Bridget Gile, Virginia Smith, Ali Ebrahimian, Micah Strauss, and Robert Traver. 2021. "Moving toward dynamic and data-driven GSI maintenance." *Journal of Sustainable Water in the Built Environment* 7 (4): 02521003.

Wadzuk, Bridget, Bridget Gile, Virginia Smith, Ali Ebrahimian, and Robert Traver. 2021. "Call for a Dynamic Approach to GSI Maintenance." *Journal of Sustainable Water in the Built Environment* 7 (2): 02521001. https://doi.org/10.1061/JSWBAY.0000945.

Wang, Mo, Zhiyu Jiang, Dongqing Zhang, Yu Zhang, Ming Liu, Qiuyi Rao, Jianjun Li, and Soon Keat Tan. 2023. "Optimization of integrating life cycle cost and systematic resilience for grey-green stormwater infrastructure." *Sustainable Cities and Society* 90: 104379.

Wang, Mo, Chuanhao Sun, and Dongqing Zhang. 2023. "Opportunities and challenges in green stormwater infrastructure (GSI): A comprehensive and bibliometric review of ecosystem services from 2000 to 2021." *Environmental Research* 236: N.PAG-N.PAG. https://doi.org/10.1016/j.envres.2023.116701.

Wang, Ranran, Matthew J. Eckelman, and Julie B. Zimmerman. 2013. "Consequential Environmental and Economic Life Cycle Assessment of Green and Gray Stormwater Infrastructures for Combined Sewer Systems." *Environmental Science & Technology* 47 (19): 11189-11198. https://doi.org/10.1021/es4026547.

Water Infrastructure Improvement Act. 2019. LegislationNon-fictionGovernment documents. [U.S. Government Publishing Office].

White, Douglas R. 2004. "A Student's Guide to Statistics for Analysis of Cross-Tabulations." *World Cultures* 14 (2).

White, Marcus, and Nano Langenheim. 2021. "A ladder-truss of citizen participation: re-imagining Arnstein's ladder to bridge between the community and sustainable urban design outcomes." *Journal of Design Research* 19 (1): 155-183. https://doi.org/10.1504/JDR.2021.121067.

Yu, Ziwen, Franco Montalto, and Chris Behr. 2018. "Probabilistic green infrastructure cost calculations using a phased life cycle algorithm integrated with uncertainties." *JOURNAL OF HYDROINFORMATICS* 20 (5): 1201-1214. https://doi.org/10.2166/hydro.2018.107.

Zhaoxin, Zhang, Li Jiake, Li Yajiao, Wang Dongqi, Zhang Jingyu, and Zhao Lingzhi. 2021. "Assessment on the cumulative effect of pollutants and the evolution of microecosystems in bioretention systems with different media." *Ecotoxicology and Environmental Safety* 228 (112957-). https://doi.org/10.1016/j.ecoenv.2021.112957.

APPENDIX

A IRB APPROVAL LETTER

UNIVERSITY OF GEORGIA

Tucker Hall, Room 212
310 E. Campus Rd.
Athens, Georgia 30602
TEL 706-542-3199 | FAX 706-542-5638
IRB@uga.edu
http://research.uga.edu/hso/irb/

Human Research Protection Program

NOT HUMAN RESEARCH DETERMINATION

January 26, 2024

Dear Jon Calabria:

On 1/26/2024, the Human Subjects Office reviewed the following submission:

Title of Study:	Perceptions of Stormwater Management Professionals in Relation to the Effectiveness of Maintenance and Operations to Improve Design of Green Stormwater Infrastructure in the Southeast Piedmont Bioregion
Investigator:	Jon Calabria
Co-Investigator:	Allison Krausman
IRB ID:	PROJECT00008929
Funding:	None

We have determined that the proposed activity is not research involving human subjects as defined by DHHS and FDA regulations. The project focus is practice, not a population.

University of Georgia (UGA) IRB review and approval is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If changes are made and there are questions about whether these activities are research involving human subjects, please submit a new request to the IRB for a determination.

Sincerely,

Kimberly Fowler, Director
Human Subjects Office, University of Georgia

APPENDIX

B SURVEY

Introduction

Welcome!

Dear Participant,

My name is Allison Krausman and I am a student in the College of Environment + Design at the University of Georgia under the supervision of Dr. Jon Calabria. I am inviting you to take part in a research study as part of my master's degree.

I am conducting research about the current state of perceptions of stormwater management professionals on the effectiveness of long-term maintenance and operations of green stormwater infrastructure. I am interested in your experience and resulting opinions on these systems. Your responses will help us understand the cultural and technical elements that impact green stormwater infrastructure's long-term viability and success.

You must be 18 or older to participate in this study. If you agree to be part of this study, you will be asked to complete a survey with 3 sections. The first section will ask you questions about yourself. The second section will discuss your understanding and beliefs on green stormwater infrastructure in general. The third section will ask questions about the green stormwater systems you work with and your perception and your opinions on their implementation. The survey should take about 12 to 15 minutes.

Participation is voluntary. You can refuse to take part or stop at any time without penalty. Some questions may make you uncomfortable. You can skip these questions if you do not wish to answer them. Your responses will be kept confidential and aggregated with others to inform non-individually identifiable results. If you decide to stop or withdraw from the study or the investigator terminates your participation, the information/data collected from or about you up to the point of your withdrawal will be kept as part of the study and may continue to be analyzed.

This research involves the transmission of data over the Internet. Every reasonable effort has been taken to ensure the effective use of available technology; however, confidentiality during online communication cannot be guaranteed. Research records will be labeled with study IDs that are linked to you by a separate list that includes your name. This list will be destroyed once we have finished collecting information from all participants.

If you have any questions about this research, please contact me at:

Allison Krausman,
Master of Landscape Architecture Candidate
University of Georgia
College of Environment + Design
285 South Jackson Street
Athens, GA 30602 USA
Email: allison.krausman25@uga.edu

You must be 18 years or older to participate in this survey. Are you 18 years or older?

- ○ Yes
- ○ No

Continuing to the next sections indicates your consent to participate in this survey.

Section 1 Introduction

We will ask you about yourself and your work background in Section 1. Please click "Next" to begin the section.

Section 1

What gender do you identify with?

- ○ Male
- ○ Female
- ○ Non-binary / third gender
- ○ [ ] Other - Please describe

What is your age in years?

- ○ 18-30
- ○ 30-45
- ○ 45-60
- ○ 60+

What is your marital status?

- ○ Single (Never married)
- ○ Married or Domestic Partnership
- ○ Divorced
- ○ Widowed

What is your race or ethnicity?

- ○ Native Hawaiian or Pacific Islander
- ○ Asian
- ○ Hispanic, Latino, Spanish Origin
- ○ Middle Eastern or North African
- ○ Black or African American
- ○ American Indian or Alaska Native
- ○ White
- ○ ________ Some other race or ethnicity

What is the highest degree or level of schooling you have completed? If you are currently enrolled in school, please indicate the highest degree you have achieved.

- ○ Some High School
- ○ High School Diploma or Equivalent (e.g., GED)
- ○ Some College
- ○ Associates Degree
- ○ Bachelors Degree
- ○ Masters Degree
- ○ Doctorate Degree
- ○ [ ] Other - Please describe

What is your current employment status?

- ○ Employed or self-employed full time (40+ hours a week)
- ○ Employed or self-employed part-time (<40 hours a week)
- ○ Unemployed (currently looking for work)
- ○ Unemployed (not currently looking for work)
- ○ Student
- ○ Retired
- ○ Unable to work

Is your work or profession related to the environment, conservation issues, and/or water management?

- ◯ Yes
- ◯ No

Which of the following disciplines best describes your connection to green stormwater infrastructure?

- ◯ Community Outreach
- ◯ Conservation
- ◯ Construction
- ◯ Ecology
- ◯ Education
- ◯ Engineering
- ◯ Environmental Science
- ◯ Landscape Architecture
- ◯ Landscape Design
- ◯ Landscape Management
- ◯ Planning
- ◯ Stormwater Management
- ◯ Student
- ◯ Volunteerism

○ [ ] Other - Please Describe

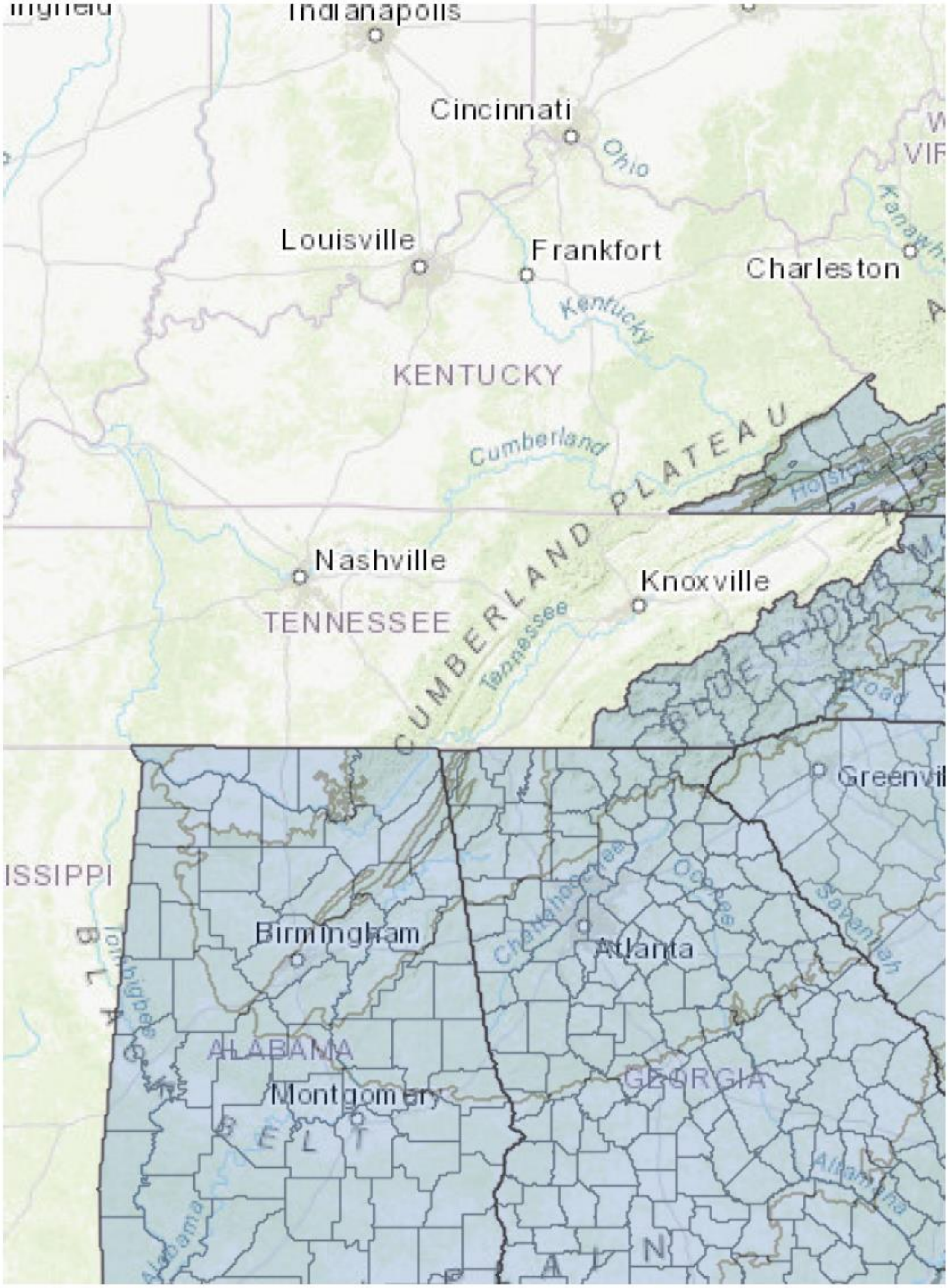
What is your current job title?

[ ]

What zip code is your place of work based out of?

[ ]

Where is the majority of your work based?



Indianapolis
Cincinnati
Ohio
Louisville
Frankfort
Charleston
Kentucky
KENTUCKY
Cumberland
CUMBERLAND PLATEAU
Nashville
Knoxville
TENNESSEE
Tennessee
BLUE RIDGE
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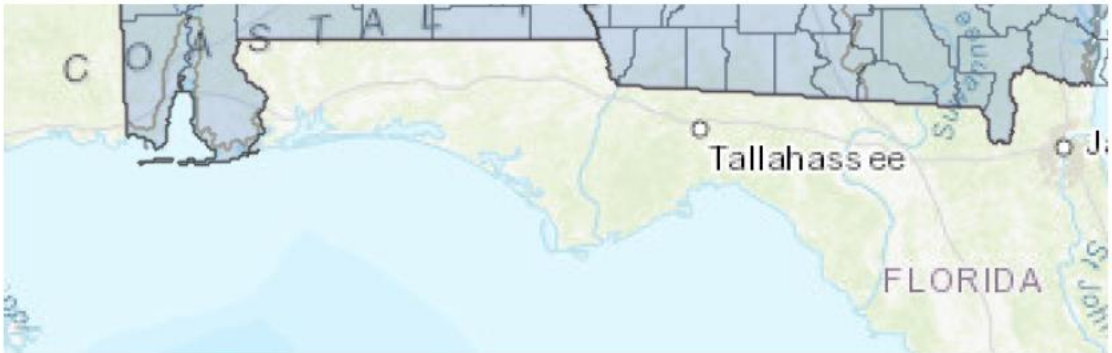
Montgomery
BELT
Alabama



Please describe your current roles and responsibilities.

Please describe any other aspects of your professional background that are relevant to your current position (i.e., qualifications, accreditations, certifications, etc.)

How long have you been working in your current field of work?

- 0 - <1 years

- ◯ 1 - <3 years
- ◯ 3 - 5 years
- ◯ 5 - 10 years
- ◯ 10 - 15 years
- ◯ 15+ years

Do you belong to any environmental groups? If so, please specify.

- ◯ No
- ◯ [ ] Yes

Section 2 Introduction

In Section 2, we will ask you about your understanding and beliefs on green stormwater infrastructure.

Section 2

How would you define green stormwater infrastructure?

Which of the following do you consider to be a purpose of green stormwater infrastructure?

- ☐ Community resource
- ☐ Improve water quality
- ☐ Reduce stormwater runoff
- ☐ Source of nature
- ☐ Other - Please describe
- ☐ Capture excess rainwater
- ☐ Source of beauty
- ☐ Providing wildlife habitat
- ☐ Reducing infrastructure costs

Rank the purpose of green stormwater infrastructure purposes you chose from most to least important. Click and drag each option to re-order them.

» Source of beauty

» Providing wildlife habitat

» Community resource

» Reduce stormwater runoff

» Other - Please describe

» Source of nature

» Capture excess rainwater

» Reducing infrastructure costs

» Improve water quality

On a scale of 1-5, with 1 being the least important and 5 being the most important, how vital do you think the following elements are for the long-term viability of green stormwater infrastructure?

	Less Impotant 1	2	3	More Important 4	5	Not Applicable	
Maintenance						☐	5
Daily Operations						☐	5
Design						☐	5
Aesthetics						☐	5

	Less Impotant			More Important		Not Applicable	
	1	2	3	4	5		
Ecological Function						☐	5
Maintenance Staff Education						☐	5
Design Team Education						☐	5
Community Education						☐	5
Community Outreach						☐	5

Are you familiar with the Clean Water Act?

- ○ Yes
- ○ No

As it pertains to the following questions, the working definition of green stormwater infrastructure is as follows:

As defined by the Water Infrastructure Improvement Act of 2019, green stormwater infrastructure is "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters."

Do you believe that green stormwater infrastructure is an effective stormwater management tool?

- Definitely not
- Probably not
- Might or might not
- Probably yes
- Definitely yes

Why or why not?

Do you believe that green stormwater infrastructure improves water quality?

- Definitely not

- ○ Probably not
- ○ Might or might not
- ○ Probably yes
- ○ Definitely yes

Why or why not?

[ ]

Are you aware of any design guidance for green stormwater infrastructure?

- ○ Yes
- ○ No

Do you have access to design guidance for green stormwater infrastructure?

- ○ Yes
- ○ No

What type of design guidance for green stormwater infrastructure do you have access to?

- ○ International
- ○ National
- ○ Regional
- ○ Local
- ○ [ ] Other - Please describe

Section 3 Introduction

In Section 3, we will ask you about the green stormwater systems you work with and your opinions on their implementation.

Section 3

What types of green stormwater infrastructure do you work with? Check all that apply.

- ☐ Vegetated roofs
- ☐ Sand filters

- ☐ Biofiltration ponds (Dry ponds and wet ponds)
- ☐ [ ] Other - Please describe
- ☐ Cisterns
- ☐ Bioswales
- ☐ Rain Gardens
- ☐ Stormwater wetlands
- ☐ Permeable pavements

What stage of a green stormwater infrastructure site's life cycle are you involved with? Check all that apply.

- ☐ Planning
- ☐ Design
- ☐ Construction/Design Implementation
- ☐ Ongoing Maintenance & Operations
- ☐ Intermittent Maintenance & Operations
- ☐ Decomissioning
- ☐ [ ] Other - Please describe

On average, how long do you spend working with a single stormwater infrastructure site throughout its life cycle?

- ○ A few days

- ○ A few months
- ○ A few years
- ○ Over half if it's life cycle
- ○ The entire life cycle
- ○ [ ] Other - Please describe

On average, how many green stormwater infrastructure sites do you consistently work with at a time (i.e., manage, design, maintain, etc.)?

- ○ 0
- ○ 1
- ○ 2-5
- ○ 5-10
- ○ 10-20
- ○ 20+

On average, how large are the green stormwater infrastructure sites you work with? Check all that apply.

- ☐ <500 SF
- ☐ 500-1,000 SF
- ☐ 1,000-20,000 SF
- ☐ 20,001 SF - 1 acre

☐ 1<10 acres
☐ 10<50 acres
☐ 50<100 acres
☐ >100 acres

Is your job or role adequately considered in the design process of green stormwater infrastructure?

○ Definitely not
○ Probably not
○ Might or might not
○ Probably yes
○ Definitely yes

Why or why not?

Do you monitor green stormwater infrastructure sites in any way after they have been installed?

○ Yes
○ No

Do you evaluate green stormwater infrastructure sites in any way after they have been installed?

- Yes
- No

How often do you monitor your green stormwater infrastructure sites?

- Daily
- Monthly
- Quarterly
- Yearly
- Every other year
- Less than every other year

How often do you evaluate your green stormwater infrastructure sites?

- Daily
- Monthly
- Quarterly
- Yearly

○ Every other year
○ Less than every other year

What do you look for when monitoring green stormwater infrastructure sites?

☐ State of design integrity
☐ Plant success/failure
☐ Maintenance/Operations Issues (i.e. debris/sediment buildup, clogging, concrete cracking/shifting, weeding, etc.)
☐ Water Flow
☐ Water Quality
☐ Recreational usage
☐ Art/Educational Signage Condition
☐ [ ] Other - Please describe

What do you look for when evaluating green stormwater infrastructure sites?

☐ State of design integrity
☐ Plant success/failure
☐ Maintenance/Operations Issues (i.e. debris/sediment buildup, clogging, concrete cracking/shifting, weeding, etc.)
☐ Water Flow
☐ Water Quality

- ☐ Recreational usage
- ☐ Art/Educational Signage Condition
- ☐ Other - Please describe

Who maintains the green stormwater infrastructure you work with after site installation?

- ☐ General maintenance company
- ☐ Green infrastructure specialty maintenance company
- ☐ Community members
- ☐ No maintenance is performed
- ☐ Other

In general, is a maintenance and operations plan used for any of the green stormwater infrastructure sites you work with? (i.e. maintenance schedules, inspection checklists, etc.)

- ○ Yes
- ○ No

When is a maintenance and operations plan incorporated into the lifecycle of the green stormwater infrastructure you work with?

- ☐ Planning
- ☐ Design
- ☐ Construction/Design Implementation
- ☐ Ongoing Maintenance & Operations
- ☐ Intermittent Maintenance & Operations
- ☐ Decomissioning
- ☐ Never
- ☐ [ ] Other - Please describe

Are maintenance plans evaluated or periodically reviewed for updates depending on site needs?

- ◯ Yes
- ◯ No

Is community education and/or outreach incorporated at any point in the lifecycle of the green stormwater infrastructure you work with?

- ◯ Yes

○ No

When is community education and/or outreach incorporated into the lifecycle of the green stormwater infrastructure you work with?

☐ Planning
☐ Design
☐ Construction/Design Implementation
☐ Ongoing Maintenance & Operations
☐ Intermittent Maintenance & Operations
☐ Decomissioning
☐ Never
☐ [ ] Other - Please describe

Are community education or outreach plans evaluated or periodically reviewed for updates depending on site needs?

○ Yes
○ No

What aspects of green stormwater infrastructure maintenance & operations and community education & outreach have the most room for improvement? Check all that apply.

	Maintenance & operations	Community education & outreach
Implementing a procedural plan	☐	☐
Improving existing procedural plans	☐	☐
Changes to budgeting	☐	☐
Worker/Volunteer Training	☐	☐
Community engagement	☐	☐
Identifying community educational opportunities	☐	☐
Monitoring methods	☐	☐
Evaluation methods	☐	☐
Other - Please describe	☐	☐

What other professions do you work with in relation to green stormwater infrastructure? Check all that apply.

☐ Volunteerism

- ☐ Landscape Management
- ☐ Environmental Science
- ☐ Community Outreach
- ☐ Ecology
- ☐ Conservation
- ☐ Stormwater Management
- ☐ Student
- ☐ Landscape Design
- ☐ Landscape Architecture
- ☐ Planning
- ☐ Education
- ☐ Engineering
- ☐ [ ] Other - Please describe
- ☐ Construction

What training opportunities would help further your work in green stormwater infrastructure?

[ ]

What design elements aid or detract from the long-term function of green stormwater infrastructure?

What inhibits the successful maintenance of green stormwater infrastructure?

Is there a project(s) you find successful in terms of maintenance that could be used as a precedent for future maintenance plans?

Survey Conclusion

Please share any other green stormwater infrastructure industry professionals or organizations within the Southeast you know who might contribute to this survey. Please provide a name and method of contact where possible. Thank you!

	Contact Name	Contact Email
Contact 1		
Contact 2		
Contact 3		
Contact 4		
Contact 5		

If we have any questions on survey responses, may we contact you?

- ◯ Yes
- ◯ No

Please provide the following information:

First Name	
Last Name	
Email	

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APPENDIX

C SURVEY CONTACT LIST

Name of Person/Organization	**Industry**	**Location**
CED Alumni Listserv	LA/Education	Athens, GA
GAASLA Listserv	LA	Atlanta, GA
UGA IRIS	Multidisciplinary	Athens, GA
NEWN	Multidisciplinary	Athens, GA
UGA River Bason Center	Multidisciplinary	Athens, GA
ASCE	Engineering	Reston, VA
ASLA	Landscape Architecture	National
AEES	Ecology	Athens, GA
SITES	Multidisciplinary	
North Carolina Licensing Board for General Contractors	Contracting	Raleigh, NC
South Carolina Contractor's Licensing Board	Contracting	Columbia, SC
Georgia Board of Engineers & Land Surveyors	Engineering	Atlanta, GA
Georgia Board of Landscape Architects	Landscape Architecture	Atlanta, GA
Individual Practitioner	Engineering	Athens, GA
Alabama Licensing Board for General Contractors	Contracting	Montgomery, AL
Individual Practitioner	Policy	Atlanta, GA
Design Firm	Multidisciplinary	Athens, GA
City of Chattanooga	Multidisciplinary	Chattanooga, TN
Design Firm	Engineering	Chattanooga, TN
Design Firm	Landscape Architecture	Chattanooga, TN
Design Firm	Landscape Architecture	Chattanooga, TN
Design Firm	Multidisciplinary	Chattanooga, TN
Sales Company	Playground Equipment Sales	Chattanooga, TN
Design Firm	Landscape Architecture	Atlanta, GA
Design Firm	Landscape Architecture	Chattanooga, TN
Consulting Firm	Developer	Chattanooga, TN
Design Firm	Landscape Architecture	Chattanooga, TN
Design Firm	Landscape Architecture	Clevelend, TN
City of Chattanooga Engineers	Engineering	Chattanooga, TN

Suggestions from Survey Respondent		Atlanta, GA
Community Outreach Organization	Education	Atlanta, GA
Individual Practitioner	Multidisciplinary	Predominantly Atlanta, GA
ARCSA	Multidisciplinary	Flower Mound, TX
Individual Practitioner	NA	NA
LinkedIn: ASLA Women in Landscape Architecture PPN	Landscape Architecture	NA
LinkedIn: ASLA Water Conservation PPN	Landscape Architecture	NA
LinkedIn: ASLA Ecology and Restoration PPN	Landscape Architecture	NA
Individual Practitioner	Green Roof Supplier	Atlanta, Georgia
Georgia Association of Water Professionals	Multidisciplinary	Marietta, Georgia
Coastal Resources Division	Multidisciplinary	Brunswick, Ga
Coastal stormwater management users group	Multidisciplinary	Brunswick, Ga